Desk Studies and Modelling Sedimentation Pattern in Gulf of Khambhat

L. R. Ranganath, A. V. Sriram and M. Karthikeyan

Abstract Gulf of Khambhat (GOK) is a very complex region with high tidal range and varied bed material along eastern and western coastline within the Gulf. In this study, a process-based model for the GOK is constructed to study the sediment transport pattern covering the entire Gulf. The investigation at hand showed that modelling sediment transport is an important tool for the decision makers and designers when it comes to interferences on coastal water bodies. As we know Gulf is a portion of the ocean that penetrates into the land and is generally larger and more deeply intended than bays, so they often make excellent harbours. The major rivers flowing in the Gulf of Khambhat are Sabarmati, Mahi, Vishwamitri and Narmada. All these rivers carry huge sediments and are dumped in the Gulf of Khambhat. Due to rapid industrialization along the Gulf huge coastal infrastructural development has been executed and planned along the Gulf coast which has induced a change in the morphology of this region. A morphological study based on hydrodynamic model was carried out and the model was calibrated and validated with the various measured data sets available at CWPRS, Pune. Hence, the results of the morphological study were reviewed for plausibility using the hydrodynamic results. A hydrodynamic flow modelling system based on a cell-centered finite volume method on an unstructured mesh has been used to simulate sediment transport and bed morphological changes under actions of currents and waves along the GOK coast. In the horizontal plane, an unstructured grid is used.

Keywords Waves · Tides · Current · Sediment transport · Gulf · Morphodynamic

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1 Introduction

Gulf is a large area of sea or ocean partially enclosed by land, especially a long landlocked portion of sea opening through a strait. Coastlines in the Indian gulf region are subjected to high tidal variations with large mud flats. As a result, waves, tides and wind-driven currents are the dominant mechanisms contributing to mud/sediment transport and determining the nearshore morphology. In addition, other physical phenomenon, such as significant river discharge into the river mouth plays a major role in the dynamic behaviour of the coastal zone, especially in the Gulf region. Natural sediment mobilisation is an important process in the development and maintenance of coastal habitats, including wetlands, lagoons, estuaries, seagrass beds, coral reefs, mangroves, dunes and sand barriers. Overall, the degradation of coastal ecosystems and coral reefs from increasing or decreasing in sediment loads may lead to important losses in revenue caused by impacts on the tourism, fishing industries and on coastal infrastructure development.

Historically, city development, especially large cities, was based on coasts due to the economic benefits of the ports. Coastal communities are concerned about sedimentation, sometimes linked to habitat change such as mangrove expansion or due to human intervention in nature such as coastal infrastructure and construction of dams. The bottom topography variation plays an important role in determining the distribution of residual current velocity and thereby sediment distribution [1], found that the resuspension parameters such as settling velocity, critical shear stress, and erosion rate constant were also important and they may cause up to a 40% difference in suspended sediment concentration. Gelfenbaum et al. [2], Sravanthi et al. [3] and Sanilkumar and Ashok kumar [4] said that the strong instantaneous and residual tidal currents are responsible for the transport and dispersal of fine-grained and sand-sized sediments across the delta. Samiksha et al. [5] and Sri Ram Kumar et al. [6] concluded that the sedimentation varied with monsoon, onshore current component was more pronounced, but tidal variations were masked to a great extent by the wind-driven circulation.

Numerous researchers viz., Kunte and Wagle [7], Misra et al. [8], have monitored the sedimentation along Gulf of Khambhat based on remote sensing and geospatial techniques. The main objective of the present study is to assess sedimentation changes along Gulf of Khambhat coast, in a view to identify the erosion and accretion areas. Numerical Modelling with field observed data can be used as an effective tool to identify the areas that are vulnerable to coastal sedimentation within the Gulf and along the coast.

2 Study Area

Gulf of Khambhat lies in the central west coast of India bordering the state of Gujarat. The Gulf of khambhat is in the shape of inverted funnel with Sabarmati, Mahi river flowing from north and northeast, respectively, and vishwamitri, Narmada rivers

Fig. 1 Location map

flowing from east to west into the Gulf of Khambhat. The length of the Gulf is around 145 km, while its width varies between 20 and 110 km. Gulf of Khambhat covers approximately an area of 3120 km^2 with a maximum depth of 35 m (Fig. 1).

3 Desk Studies and Analysis of Prototype Data

The prototype data collected for the proposed Ethelene terminal of IPCL near Jageshwar in Bharuch channel have been given in two reports by M/s Elcome Surveys Pvt. Ltd., entitled—Final Report on Seabed and Oceanographic Investigation of the proposed Import/Export Terminal off Jageshwar for IPCL (June 1993) and Final Report on Float Studies, Current Measurements and Water Sampling for Jetty at Jageshwar for IPCL (October 1993). The important findings from the analysis of the prototype data from these reports which are considered important for the present studies are described in brief. The data in respect of the bathymetry of the area of 1932, 1973 and 1979, upland discharge data etc. available with CWPRS have also been analysed.

The bathymetric data obtained from the Admiralty charts of 1932, 1973, 1979 have been compared. It is found that during 1932 there existed two channels in the Narmada Estuary. The dominant of the two was the Broach channel (now called Bharuch channel) which is located on the northern part of the estuary and a smaller channel existed on the southern side of the estuary. The southern channel though smaller in width, had a clear waterway detaching the Aliabet Island from the mainland even during the low tidal waters. There also existed large and small tidal flats in the Bharuch channel. From the Admiralty charts of 1973 and 1979, it is found that the southern channel deteriorated into a very narrow channel. It is also found that during 1970s, small Islands appeared at the location where the off-take of the southern channel existed, thus closing the waterway during low water and there was a clear waterway for Bharuch channel. It is found that most of the smaller Islands along the Bharuch channel except Kerselea bank have disappeared.

The shoreline mapping of 1963, 1977 and 1984 of the Narmada Estuary available with CWPRS was analysed. It was observed that the southern channel was much wider than Bharuch channel in 1963. The Aliabet Island which was of size 9.5 km × 22.5 km in 1963, grew in size, both in length and width, mostly encroaching the southern channel. The increase in length has taken place on the riverside indicating that most of the sediment deposited has been brought by the river. There is an increase in the width of the Bharuch channel. At the sea end, the channel is 10 km wide. The channel width gradually reduces to about 5–20 km upstream and then there is an abrupt reduction in width from about 5–1.3 km within a stretch of 1 km. The comparison of the 1977 and 1984 shoreline plans show that there is further narrowing of the southern channel whereas Bharuch channel has remained fairly stable.

Subsequently, M/s ELCOME Surveys Pvt. Ltd. has carried out the bathymetric surveys of the Bharuch channel in the vicinity of the proposed terminal off Jageshwar during the month of February 1991, February 1993 and October 1993. The findings from the comparison of the bathymetry of the surveyed area are described in the ELCOME report mentioned above. It is found from the survey that the Bharuch channel has many shoal patches with minimum depths varying from dry heights to 2 m in the deep channel portion. The shoal patches are found to be spread in the NE–SW direction indicating the direction of the tidal flows in the region. It is also found that the northern portion of the area shows greater depths close to the northern bank of the river Narmada. The detailed comparison of the contour lines has indicated that there has been considerable swallowing of the bed from 1973 to the present survey period. The Kerselea Bank has extended considerably in the northwestern direction and has narrowed the Bharuch channel. Comparison of the bathymetric chart of February 1991 and February 1993 shows that in the vicinity of the existing coastal infrastructure development in the Dahej region there is a tendency of accretion. The depths have increased from about 8 m in 1991 to about 12 m in 1993.

River Narmada joins Gulf of Khambhat on the eastern side and is the largest river of the region. It has a very high peak discharge and picks up a large amount of sediments as it flows east to west. With the construction of various dams on the upstream, both in Madhya Pradesh and Gujarat, the reservoir storages have reduced the peak flows considerably. In the pre-dam scenario, the annual peak flow of about 80,000 cumecs was carrying an annual silt load of about 70 million m^3, which has now reduced to about 6–7 million m^3. It may also be noted that recently the completion of Sardar Sarovar Dam (Sept 2017) with full-fledged gates may as well lead to further reduced flow into the Narmada estuary. This reduction in the supply of sediments is probably making the river morphologically unstable and erosive. The instability in flow and sediment has led to erosion at upstream of the river, development of several sandbars in the middle of the reaches and erosion in lower parts of the river.

The river is today characterised by wide mud flats and shallow areas along the right bank, which widens as it travels downstream. The river bed is in general muddy, with traces of sand found near the Gulf region. The river has a high tidal range of about 8 m, with MSL level of 5.1 m (near IPCL Jetty) relative to chart datum. The wave penetration into the river is very less due to the numerous bars, which act as attenuators. However, the high tidal range and associated high tidal currents keep the clay/silt in suspension making the estuary waters muddy. The tidal flows inside the Gulf are in a north–south direction. The tidal flow traps sediments in suspension in the estuary and the sediment moves up and down the estuary with the tide. The high TSS content of the Narmada estuary water, the strong tidal currents and river runoff makes the sediment regime unstable with shifting bars, characteristics of a region of excessive erosion and deposition. From the desk studies, it can be inferred that the study area is dynamic in nature and the morphological changes are prevalent and continuous in nature.

4 Data Sources

4.1 Bathymetry

The field observed bathymetric information available at various locations in conjunction with the CMAP data of the study area was used in the preparation of the bathymetry. The depth contours show that there is a wide stretch of tidal flats and also shoals in the vicinity of the study area. As the tidal range is more than 6 m, a large area is subjected to flooding and drying. The contours towards south are spread apart indicating wide tidal flats. This depth information was used for setting up the computational model (Fig. 2).

4.2 Tides

Field data collected during June and September 2016 was used for studies (Fig. 3). The tide data shows that the tidal range is of the order of 8.5 m during June and 9 m during the month of September. The tides in the region are very high which renders the Gulf highly dynamic and well-flushed.

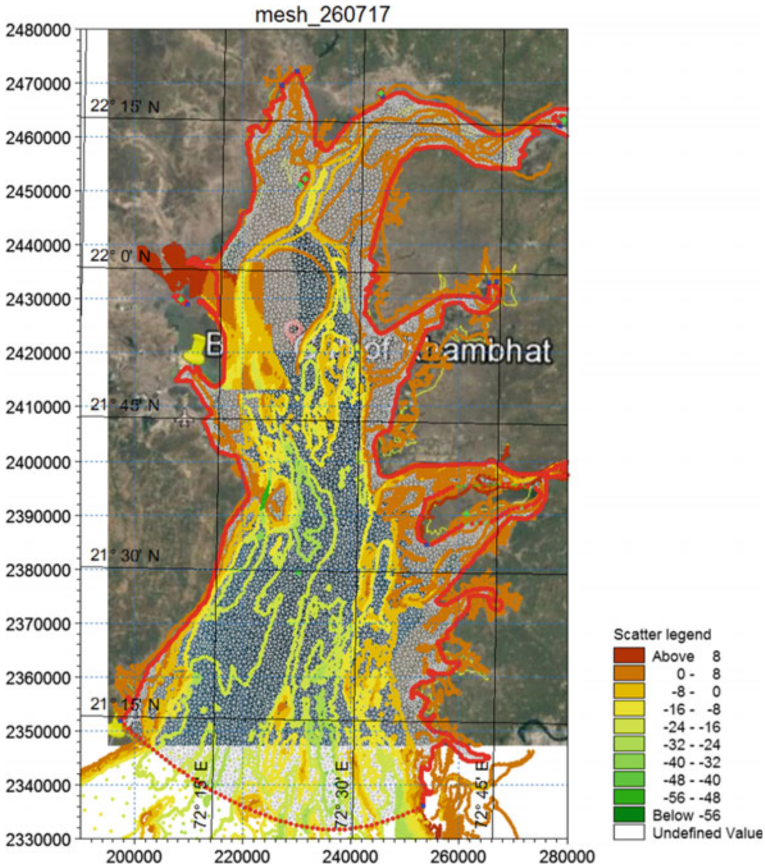


Fig. 2 Georeferenced bathymetry

4.3 Tidal Currents

Recently observed, (September 2016) current data at two locations, i.e. one at the Mithivirdi (C1) on the western shoreline and the other at Dahej (C2) on the eastern shoreline was used in the calibration and validation of the model. The currents near Dahej were in the range of 0.02–1.44 m/s and the observed current near Mithivirdi was in the range of 0.04–1.65 m/s. The actual time history of velocities observed was used for the calibration of the model as shown in Fig. 4.

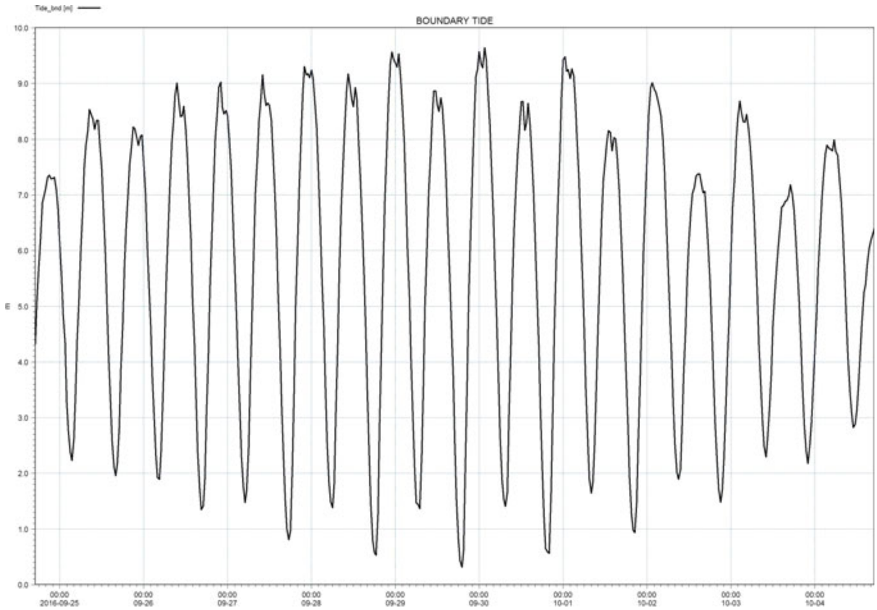


Fig. 3 Boundary tide

4.4 Discharge Data

Based on the analysis of the upland discharge data available at CWPRS over the period 1981–1990, the projected discharge during stage-1 and stage-2 development of Sardar Sarovar Project indicated that higher discharge occurs during the months of July, August, September and October. The maximum average monthly discharge before the development of Sardar Sarovar Project was about 5500 cumecs and after first stage development the maximum monthly discharge is expected to reduce to about 1200 cumecs which occurs during the month of September. After stage-2, development of the Sardar Sarovar Project the discharges are not likely to be higher than 200 cumecs throughout the year. These aspects are important from the point of view of the long-term stability of natural channels within the Gulf. The maximum discharge through the Narmada River during peak monsoon is expected to be around 10,000 cumecs. Similarly, the minimum discharge of 200 cumecs occurs during non-monsoon period. At the river mouth, the freshwater discharge was prescribed based on available observations. The average runoff into the Gulf from Narmada River is nearly 800 cumecs [9]. The discharge considered during the model setup for the monsoon are given in Table 1.

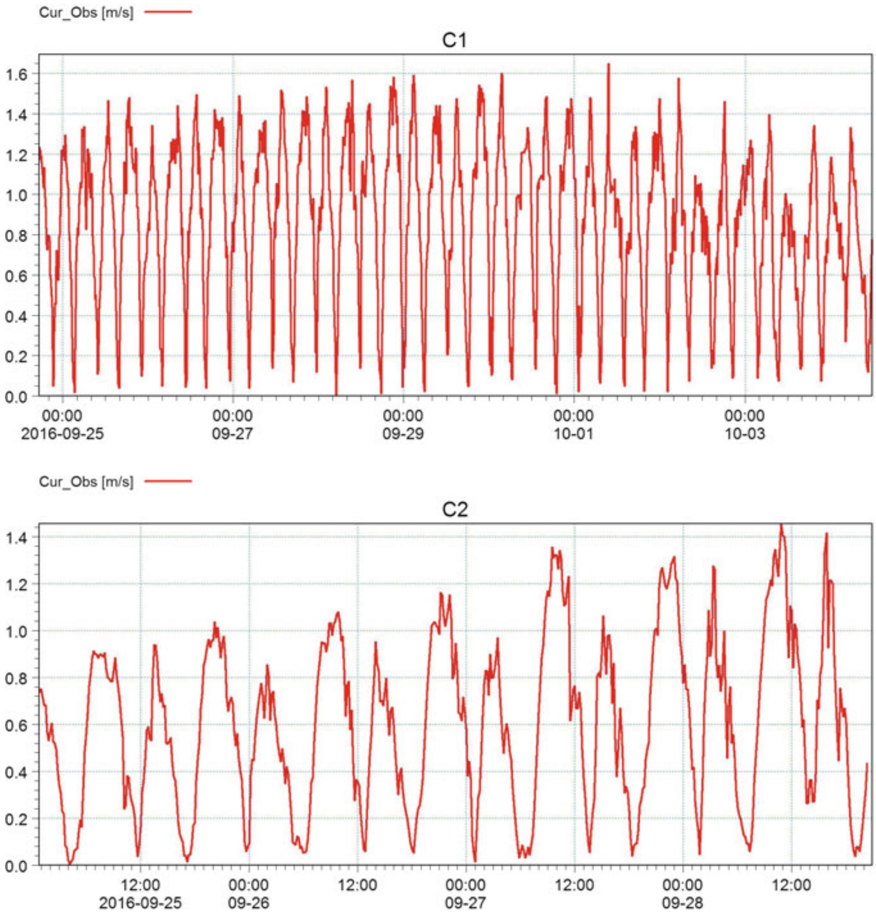


Fig. 4 Time history of current observation at C1 and C2

Table 1 Discharge of the rivers into Gulf of Khambhat

River	Discharge (m^3/s)
Sabarmati	400
Mahi	400
Narmada	800

4.5 Sediment Data

The bed sediments in the Tapi estuary are reported to be sandy with low percentage of silt and clay. The bed sediments in the jetty area are at Dahej is found to be silty clay. From the field survey reported, it is observed that the water at the Dahej site is highly turbid and muddy. The concentration of suspended solids is very high and variable. The analysis of suspended solids observed from the year 1985–2002 available at CWPRS is considered. The survey conducted by National Institute of Oceanography (NIO) during the year 2011 and 2012 near Mithivirdhi shows that the maximum suspended solids at average mid-depth is 1960 mg/l. Evaluation of sediment characteristics and contamination based on analysis of surface sediments indicated that the sediment texture of the region varied considerably in space and time. Further field studies conducted during May 2013 indicated that the average suspended solid concentration near Reliance Jetty at Dahej is of the order of 200 mg/l during nonmonsoon season and the same was considered for the model studies. Average Values of SS (mg/l) at different zones of the study area during 1993–2014 are given in Table 2.

4.6 Dispersion Coefficient

Dispersion studies were carried out in two phases during 2011–2012 by NIO to assess the longitudinal and transverse dispersion coefficients (Kx and Ky) of the study region. Because of high tidal current in this region, the dye dispersion is rapid which is observed by the rate of change of concentration within 1–2 h. It is also observed that the longitudinal dispersion coefficient Kx 6 is greater than the lateral direction Ky. The values of Kx range between 3.9 and 30.12 whereas Ky ranges between 0.19 and 0.71. Based on this observation, we have assumed the dispersion is proportional to the currents in the model studies.

4.7 Waves

The Gulf of Khambhat is well protected from the waves emanating from the Arabian Sea, since the Gulf faces south, between the Saurashtra Peninsula and mainland Gujarat. The dominant direction of waves in the open sea south of the Narmada mouth is from the southwest in May/June, swinging to west in July/August and veering to the northwest for the remaining part of the year. January and February are the calm months and the waves gradually pick up from mid-March onwards. The magnitude of the wave in the Narmada estuary is not very high. The significant wave height while entering into the Gulf from the Arabian Sea is 5 m which reduces to 0.5 m significant waves at Dahej. The period of these waves lies in a short bandwidth of 5–6 s.

Table 2 Average values of suspended sediments at different zones of the study area

SS (mg/l)									
Zone	Oct 1993	Feb 1997	Feb 2006	Oct 2007	Apr 2009	Jan 2012	Mar 2012	Sept 2012	Oct 2014
Offshore	566	11,284	986	979	704	914	5060	2072	241
Nearshore	1021	7301	1053	1083	822	13,220	3205	1782	396
Narmada estuary	699	16,495	1585	1345	1388	285.5	2697	2252	160

5 Model Studies for Tidal Hydrodynamics

Hydrodynamic studies include simulation of the flow field for the entire Gulf. The studies were carried out to assess changes in the hydrodynamic condition and formation of tidal circulations if any over a period of month. The model was run for two different seasons (i.e., Monsoon and Nonmonsoon Data). The Nonmonsoon field observed data was used for the calibration of the hydrodynamic model. The results of the hydrodynamic studies are the basic input for the sediment transport studies.

5.1 Computational Model

The computational model considered for tidal flow and sediment simulation covered an area of 88,000 m by 140,000 m. The model limit extends from 0 to 44 m depth contour in the offshore in the south direction and 0–8 m depth in the north direction. The model area covers the entire Gulf of Khambhat and adjoining open sea as shown in Fig. 5. The complete model area has been discretised into computational mesh of maximum element area of 3,750,000 m^2 with the smallest allowable angle of 30 and maximum number of nodes of 100,000. The bathymetry in the Gulf region is quite irregular and there are many shallow zones followed by deep channels on either side were reproduced satisfactorily.

5.2 Tidal Boundary Condition

The Gulf has an open boundary at the seaward end connecting 71.750 E and 72.640 E at 210 N (Fig. 5). At the landward end, there are three open boundaries of the analysis area connecting Sabarmati, Mahi, and Narmada rivers. The discharge from Vishwamitri is ignored due to its low discharge. A realistic tidal boundary condition, used at the southern boundary and freshwater discharges from the three rivers, is provided at the river mouths. Initially, the model was simulated for non monsoon season with the above-mentioned boundary conditions and appropriate tidal input at the southern open boundary.

5.3 Calibration of Model with Non-monsoon Data

The simulations were repeated by altering the fine-tuning parameters like bed friction coefficients until the observed and computed water levels as well as currents reached reasonable agreement with the field observed data. The currents were monitored and extracted at three locations, i.e. at Mithivirdi (C1), Dahej (C2) and at the centre of

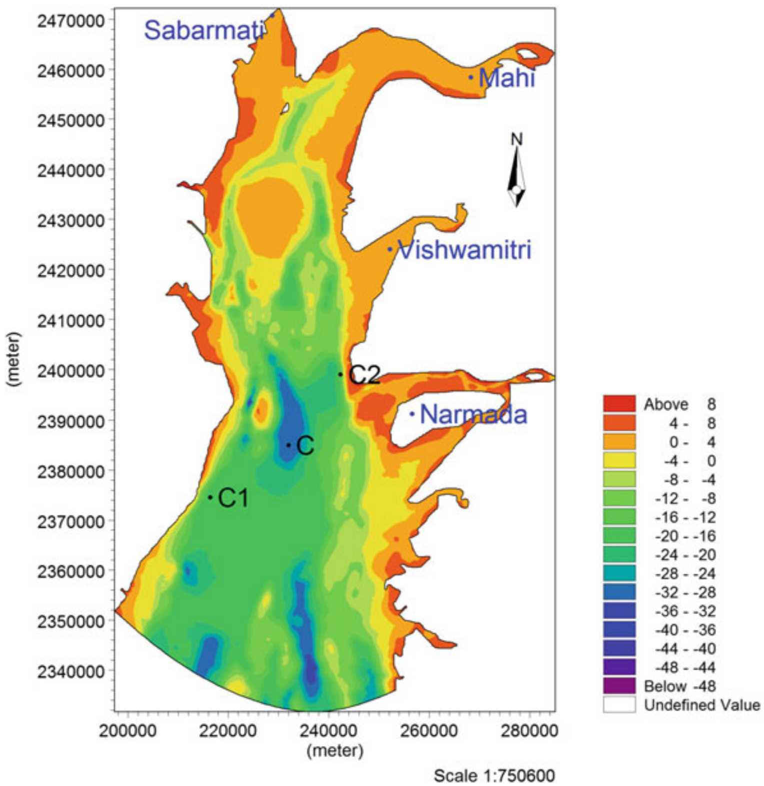


Fig. 5 Computational model showing monitoring points C, C1 and C2

the Gulf of Khambhat (C). The computed current is in good agreement with the field observed current and was found to vary from 0.01 to 1.68 m/s at the C1 point and it was in the range of 0.02–1.4 m/s at the C2 point. The magnitude of currents in the centre of the Gulf, i.e. at monitoring point C it varied in the range of 0.04–2.1 m/s indicating that the currents are strong in the middle region and it becomes weak as it approaches the coast due to friction factors. The comparison of observed and computed currents is shown in Fig. 6. The flow field during peak flooding and peak ebbing during nonmonsoon month is shown in Fig. 7.

5.4 Simulation of Flow Field During Monsoon

The simulations were repeated for monsoon conditions by considering appropriate river discharges from Sabarmati, Mahi and Narmada rivers. Vishwamitri River discharge was ignored as its magnitude was negligible during the period of observation.

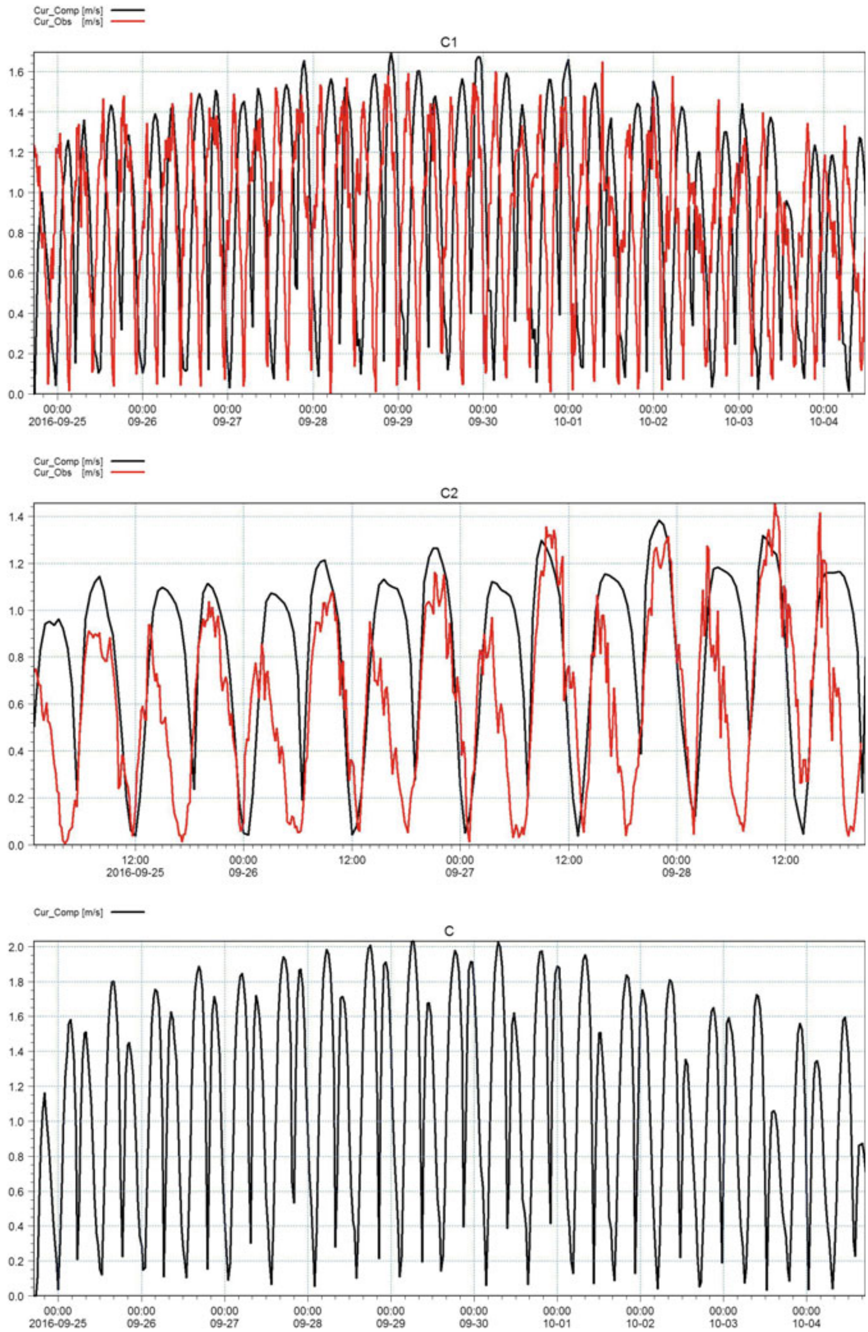
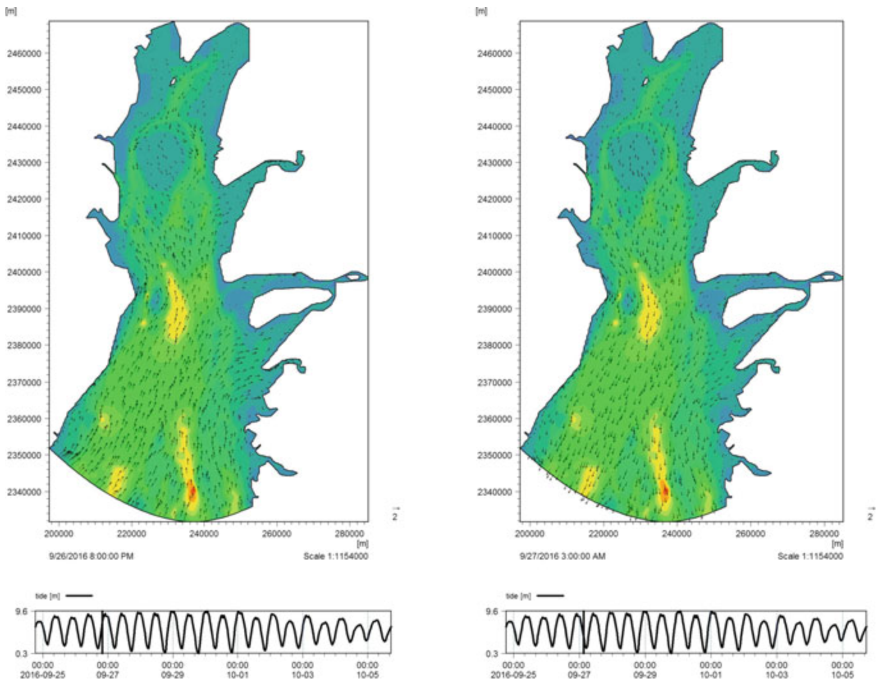


Fig. 6 Comparison of observed and computed currents at C1 and C2



Peak Flooding Peak Ebbing

Fig. 7 Flow field during nonmonsoon

From the literature, it was inferred that with monsoon conditions the magnitude of currents that did not change much in the centre of the Gulf and the same trend was observed in model simulations as the currents varied in the range of 0.02–2.23 m/s and were found to be reasonable. At the river inlet and inside the estuary the magnitude of currents increased considerably due to the river discharge. The flow field during peak flooding and peak ebbing during Monsoon month are shown in Fig. 8.

6 Sedimentation Studies

6.1 Introduction

For any development in Gulf, sedimentation studies are very essential as the nature of sediment movement is very dynamic due to the characteristic nature of sediments and typical flow conditions. Siltation in the approach channel and the harbour basin is a serious problem in west coast, which is being experienced by ports on the west coast of India. In this regard, flow field and sedimentation studies are an important element

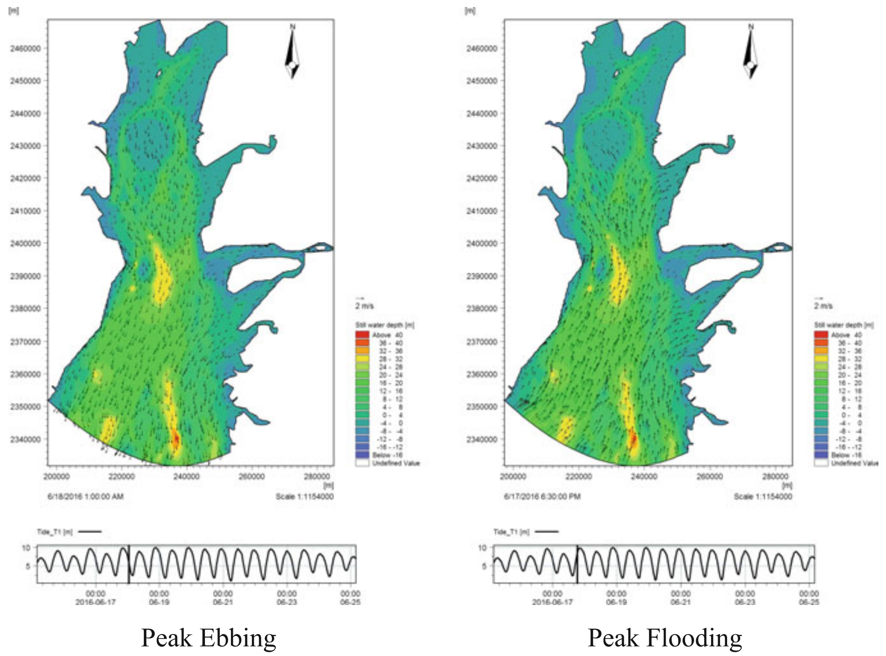


Fig. 8 Flow field during monsoon

in any port development during the design and implementation stage. Remote sensing studies [10] has been carried to map suspended sediment concentration (SSC) along the Indian Coast and it indicated that in Gulf of Khambhat (GOK) the sediments as well as pollutants under the influence of strong tidal currents are dispersed and settle within the Gulf of Khambhat. The inference from the study is that the Gulf of Khambhat is getting silted up swiftly which needs to be validated by model studies. Further studies conducted by researchers [11] indicated that the dispersion of sediment largely depends upon wind and wave patterns. Net landward transport of sediment occurs in this region which is can be understood from the presence of a number of mudflats within the estuary along with the siltation in the channels.

High tidal range is the distinguishing feature of the Gulf because of this tidal currents dominate the flow. The tides are of semi-diurnal type with a large diurnal inequality and varying amplitudes, which increase from the south to north along the Gulf coast. The height of the tide increases tremendously from the mouth to the upstream end because the width of Gulf decreases towards the upstream end. Tidal currents are with two dominant directions; towards upstream during flood and downstream during ebb in all oscillatory motions. The maximum currents occur during mid-tide, which is around 2.5 m/s in the Gulf, and associated with high wave energy [12]. The Gulf is more or less homogeneous which is caused by the shallowness of the depths and medium to high tidal amplitudes associated with tidal currents and turbulence.

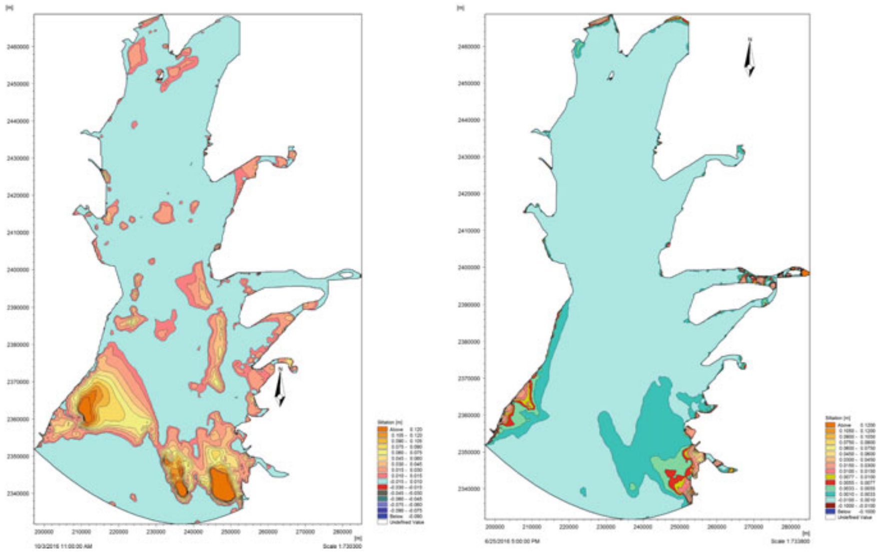
Photo 1 Seabed features near in Mudflats and berthing at Dahej

The rivers draining into the Gulf of Khambhat carry an enormous amount of sediments in their discharges. Sabarmati, Mahi, and Narmada rivers drains into the Gulf. These rivers discharge a large volume of sediments as also the suspended load. The bottom consists of mainly the river-borne fine to coarse-grained sand. The western and northern parts of the Gulf consist of largely soft sediments of Quaternary rocks. With this background sedimentation studies were conducted for assessing the siltation pattern in the Gulf of Khambhat region. Photo1 shows the seabed features and wide tidal flats near Dahej.

An average suspended solid concentration of 200 mg/l and 1900 mg/l is considered for the model studies during nonmonsoon and monsoon seasons, respectively. The sedimentation studies were conducted using Mike-21 MT module of DHI software.

6.2 Sediment Model Simulations and Interpretation of Results

The siltation studies were carried out with the prevailing conditions in the Gulf of Khambat considering the infrastructure facilities in the vicinity of Dahej and adjoining areas. The model simulations were carried out for Monsoon and Nonmonsoon weather conditions separately for duration of 30 days each. The siltation trend during different phases of the tide was monitored. The computed sedimentation pattern observed during both the seasons can be seen in Fig. 9. In general, it is noticed that the sediments tend to deposit around the mudflats around the mainland, also in the depressions of seabed and natural channels in the vicinity of Dahej infrastructural development region during Nonmonsoon season. It is also noticed that the southern part of the Gulf experiences a tendency of sediment deposition. It may be attributed to the reduction of the flow velocities as the width of the Gulf expands. Further, during monsoon season it is noticed that the trend of sedimentation has considerably reduced. From the model results, it can be inferred that this decreasing trend may be due to the flushing action of considerable river discharges during Monsoon.



Non-monsoon Monsoon

Fig. 9 Sedimentation pattern in the Gulf of Khambhat

During the flood, the suspended sediment concentrations varied from 120 to 900 mg/l and it varied from 160 to 1020 mg/l during ebb in Monsoon season. As expected, the concentrations were higher during the ebb than during the flooding period. This is because of the joining of the three rivers, namely Sabarmati, Mahi and Narmada, in the Gulf.

7 Conclusions

A depth-averaged numerical model with flexible mesh was used to compute the tidal circulation, sedimentation pattern and suspended sediment transport in the Gulf of Khambhat by including three rivers, namely, Sabarmati, Mahi and Narmada. Meanwhile, the computed mean suspended sediments were validated with the available observations in the Narmada estuary. Reasonable circulation pattern and suspended sediment concentrations have been simulated in the model. The observed data available at CWPRS on the eastern and western part of the Gulf was used for the simulations. However, additional data in the northern region would have been more appropriate. The sedimentation pattern in the Gulf of Khambhat has been simulated well as shown in Fig. 9. It is observed that trends of siltation are noticed during non-monsoon season in the natural channels and depressions near Dahej, and the mudflats surrounding the mainland are prone to siltation. Further, the southern region of the

Gulf has shown tendency of siltation and it may be due to the expansion of Gulf width which results in reduction of the flow velocities. Similarly, during monsoon season it was observed that the tendency of siltation has reduced considerably and it was inferred that it may be due to the flushing action by the monsoon discharges from all the rivers considered in the simulation.

The model result implies that there is a significant deposition and resuspension processes within the estuary controlled by the varying tidal ranges. The complexity in bathymetry and the coastline plays a vital role in influencing the tidal currents and sediment distribution patterns in the Gulf region. Deep tidal scour channels in the mid Gulf are found to be devoid of high suspended sediment concentrations throughout the observations. Further, the impact on the present coastal infrastructure in GOK of proposed Kalpasar project needs to be studied.

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