

Chapter 5
Hydrodynamic modelling - west coast of India

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Chapter 5

Hydrodynamic modelling - west coast of India

A hydrodynamic model for the west coast of India is tested with a radiative boundary condition. The model is driven with level and velocity components from the global tidal model TPXO. The results are compared with the predicted tides from ATT of standard ports as well as secondary ports and available tidal streams at the Diamond Points. An attempt has been made to establish a working model with tidal boundary conditions. The model validity compares well with the ATT predicted tides and tidal steams of Admiralty Chart No. 1486. The Flow model uses wind from QuickSCAT, wave forces from SWAN hindcasted waves and boundary levels from TPXO global model.

5.1 Introduction

Hydrodynamics is study of the motion of water. A hydrodynamic model is a tool that enables us to describe or represent the motion of water. Before the advent of wide availability of computer systems, hydrodynamic models used to be physical models built to scale. All hydrodynamic models in use today are computational numerical models. With the technological development of numerical models along with advanced computational systems, hydrodynamic modelling has become part of the larger field of computational fluid dynamics.

The basis of computational hydrodynamic models is a set of equations that describes the motion of fluids: the Navier-Stokes equations. These equations are derived from Newton’s laws of motion and describe the action of force applied to the fluid; that is, the resulting changes in flow. This is the property of conservation of momentum and is simply Newton’s second law: acceleration is dependent upon the force exerted and is proportional to its mass. Computational hydrodynamics also imposes the continuity principle: mass and energy are conserved unless they pass out of the domain. For hydrodynamic modelling in the context of coastal engineering, the Navier-Stokes equations are simplified by the specific properties of coastal ocean. The resulting equations are the shallow water equations, so called because the scale of features in the horizontal is much greater than in the vertical. Oceans and estuaries are much larger in length and width than they are in depth. They are much more like a puddle than a bucket, and motions in them are predominantly horizontal than vertical (e.g., tides and currents). The shallow water equations allow for more efficient numerical solution of flow in this environment.
The complexity of the system of interest (river, estuary, or ocean) prevents solution of the governing equations analytically. Scientific computing has enabled researchers to address these complex problems through numerical methods. However, computers can perform only discrete calculations and, therefore, the governing equations that are continuous must be broken into small individual problems which can be solved quickly on a computer. This procedure is governed by the numerical method used for a particular model. Two approaches are common in hydrodynamic models: structured grid approaches (primarily finite difference algorithms) and unstructured grid approaches (including finite element and finite volume methods). Numerical methods deal with the domain by separating it into numerous components through a discretization process that produces model grids. Structured grid models tend to use quadrilateral grid cells that limit the grid's flexibility in resolving the complex shoreline problems, but are characterized by their straightforward and efficient algorithms. Unstructured grid models have much more flexibility in their grid resolution by employing variable triangular elements, but tend to be more time-consuming and more sensitive to numerical errors. Both types of numerical methods have been applied to high performance computing systems, enabling simulation of complex coastal regions with high resolution.

These coastal hydrodynamic models can be applied to many different ecological problems by using a range of model configurations and forcing functions. For example, these models can be efficiently used in depth-averaged two-dimensional (2D) solutions or in full three-dimensional (3D) forms. For well-mixed systems, the effects of density variations due to temperature and salinity can be ignored and the model is run in barotropic mode. The baroclinic (density) effects can also be included if necessary by solving for temperature and salinity effects. Furthermore, equations describing transport and fate of constituents in the water (e.g., contaminants such as oil or biota such as fish larvae) can be coupled to the hydrodynamic equations.

The accuracy of a coastal ocean model is closely related to inputs provided to it, such as bathymetry and meteorological conditions. Coastal ocean models use a wide range of observational data and meteorological models to define the forcings for the model. Similarly, for driving the model, data such as river inflow and tidal signals are required at the boundaries. The accuracy of the model is limited by the quality of data input. The model developer will have to apply the best data sources available in order to generate high quality output.
5.2 Flow modelling with TELEMAC modelling systems

TELEMAC-2D is a sophisticated flow model developed by the National Hydraulics and Environment Laboratory (Laboratoire National d’Hydraulique et Environnement - LNHE) of the Research and Development Directorate of the French Electricity Board (EDF-DRD) in Paris, for free surface flows. It solves the 2D depth-integrated shallow water equations that are used to model flows in rivers, estuaries and seas. It uses finite element techniques so that flexible, unstructured triangular grids can be used. It has been developed under a quality assurance system including the application of a standard set of validation tests.

The model can simulate depth integrated tidal flows in estuaries and seas including the presence of drying banks. It can also simulate flows in rivers including turbulence structures resulting from flow obstructions and transcritical flows. The advantage of using finite elements lies primarily in the possibility of using a highly flexible grid. This is superior to using an orthogonal curvilinear grid as the user has far more complete control over grid refinement with a finite element system. The applications of TELEMAC include studies on tidal flows, storm surges, floods in rivers, dam break simulations, cooling water dispersion and infill of navigation channels.

5.2.1 Theoretical background and solution methods

TELEMAC solves the shallow water equations on an unstructured finite element grid (usually with triangular elements). The various variables (bed elevation, water depth, free surface level, and \(u\) and \(v\) velocity components) are defined at the nodes (vertices of triangles) and their linear variations within the triangles are assumed.

Basically, the TELEMAC code solves the following basic dynamic equations: continuity equation, momentum equations (x and y directions) and tracer conservation equations. It has the Cartesian form

\[
\frac{\partial h}{\partial t} + u \frac{\partial h}{\partial x} + v \frac{\partial h}{\partial y} = S_h \tag{5(1)}
\]

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -g \frac{\partial Z}{\partial x} + S_x + \frac{1}{h} \text{div}(hv, \vec{v}) \tag{5(2)}
\]
\[ \frac{\partial v}{\partial t} + \vec{v} \cdot \nabla v = -g \frac{\partial Z}{\partial Y} + S_v + \frac{1}{h} \text{div}(hv \nabla v) \]

\[ \frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T = S_T + \frac{1}{h} \text{div}(hv \nabla T) \]

Figure 5.1 Model bathymetry and domain (in UTM)

where \( h \) is depth of water; \( u \) and \( v \) are velocity components; \( T \) is the tracer; \( g \) is gravity; \( t \) is time; \( S_h \) is tracer source/sink; \( S_v \) and \( S_T \) are source/sink terms in dynamic equations; \( S_t \) is source/sink of tracer. \( h, u, v, T \) are the unknowns. \( S_v \) and \( S_T \) are the source terms representing wind, Coriolis force, bottom friction and source/sink of momentum within the domain. These terms are processed in one or more of the following steps: (i) advection of \( h, u, v \) and \( T \); (ii) propagation, diffusion and source terms of dynamic equations; (iii) diffusion and source
terms of tracer transport equation. Any of these steps can be skipped. In addition, the variables $h, u, v$ and $T$ may be advected separately.

5.2.2 Model set-up and domain

The model domain covers the area lying between 7°N and 26°N latitudes and 62°E and 78°E longitudes. A combined set of C-map bathymetry reduced to mean sea level for nearshore and shelf areas and e-topo2 data for offshore regions are used for interpolation of bathymetry. Mesh size varies from 500m inside the gulf through 5 km along the other parts of the coastline to 50km offshore. Figure 5.1 presents the model domain and bathymetry in Cartesian coordinate system. The model was set up for the period from December 1-31 of 2008.

5.2.2.1 Tidal model and boundary conditions

Tides are the periodic motion of the water of the sea due to changes in the attractive forces of moon and sun upon the rotating earth. A large fraction of the variance in many oceanographic parameters is due to tides. The rise and fall of tides are accompanied by horizontal movements of water called tidal currents. It is necessary to distinguish clearly between tide and tidal current, for the relation between them is complex and variable. The tide rises and falls, the tidal current floods and ebbs. Tidal circulation in estuaries determines the mixing and salinity structure of estuarine waters. Tidal currents may help progress or hinder it; may set the ship toward dangers or away from them. The navigator is concerned with the range and time of the tide, as it affects access to shallow ports. Time, speed and direction of the tidal currents will affect the ship’s position, speed and course. By understanding tides, and by making intelligent use of predictions published in tide and tidal current tables and of descriptions in sailing directions, the navigator can plan an expeditious and safe passage.

5.2.2.2 Levels and currents from TPXO global model

TPXO is current version of a global model of ocean tides, which best-fits, in a least-squares sense, the Laplace tidal equations along track-averaged data from TOPEX/Poseidon and Jason (on TOPEX/POSEIDON tracks since 2002) obtained from OSU Tidal Inversion Software(OTIS). The tides are provided as complex amplitudes of earth-relative sea surface elevation for eight primary ($M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1$), two long period ($M_f, M_m$) and 3 non-linear ($M_4, MS_4, MN_4$) harmonic constituents on 1/4 degree resolution full global grid. At each node of the open boundary, tides are extracted from global TPXO and used as
boundary condition for driving the Arabian Sea model to obtain realistic information on tidal currents and tide levels near coastline and shelf. I used a radiative boundary condition on the model as explained in the following section.

5.2.2.3 Radiative boundary

It was found that the initial runs with simple tidal elevations did not give proper amplification of tides in the Gulf of Cambay. Hence I used an alternative method, radiative boundary condition, to drive the tides. This is as simple as correcting the level at the boundary with the help of the velocity normal at the boundary node. Instantaneous regional model levels at the boundary nodes were adjusted using velocity normals from the global tidal model TPXO as follows:

\[ \text{level} = \text{level(global)} + \alpha \times (\text{velocity(model)} - \text{velocity(global)}) \]

where level (global) and velocity (global) are from the global model (velocity positive northward or eastward) and

\[ \alpha = \sqrt{\frac{\text{depth}}{\text{gravity}}} \]

Blow ups initiated from southwest corner node were corrected by averaging levels based on adjacent nodes.

5.3 Tidal Characteristics

When the tide propagates in shallow water, there can be considerable asymmetry in the free surface elevations and velocities during flood and ebb conditions. Flood dominance generally occurs in estuaries characterized by a high ratio between tidal amplitude and water depth (Dyer, 1997). This mechanism can be explained by the fact that tidal wave celerity is a function of water depth. It follows that higher flow velocities are observed at high water crest of the tidal wave, than its low water trough. This causes the ebb duration to become longer than the flood duration, producing an asymmetrical tidal curve. In tidal analysis, tidal asymmetry corresponds to creation of additional harmonics (e.g., M4 component) modulating the main tidal signal. Peaks in flood velocity are about 0.9 m/s, whereas peaks in ebb flows are about 0.6 m/s. Tidal asymmetry leads to enhancement in resuspension and transport during the flooding tide the so-called tidal pumping (Uncles et al., 2002).
Velocity values obtained in this study are in reasonably good agreement with data from field surveys conducted at Jamnagar in October 2006, off Mumbai in December 2004 and at Vallarpadam container terminal site in March 2000 (data property rights do not allow reproduction of original data in this thesis). To compare the model for levels and flows at more locations, predicted ATT tides of 2008 were used. Model results were compared for levels and tidal streams at different locations using British Hyrdographic office (BHO) Chart 1486.

5.3.1 Tide Level

Free surface of the model was compared with the ATT predicted tides at Karachi (Figure 5.2) Sikka (Figure 5.3), Okha (Figure 5.4), Pipavav (Figure 5.5), Dahej (Figure 5.6), Rewas (Figure 5.7), Trombay (Figure 5.8), Ravadanda (Figure 5.9), Ratnagiri (Figure 5.10), Murud (Figure 5.11), Karwar (Figure 5.12), Kumta (Figure 5.13), Batkal (Figure 5.14), Kundapur (Figure 5.15), Mangalore (Figure 5.16) and Cochin (Figure 5.17). As the bathymetry and coastline near Bhavnagar were not well resolved, model comparison could not be carried out at this site. The model was run with an updated bathymetry to resolve the tides at Bhavnagar. Except at Okha, the predicted levels are in good agreement with the model results. ATT components at Dahej (Figure 5.6) are based on a point located inside the creak where the coastline is not fine to represent the creek; hence the levels have been compared against values outside the creek. Time mentioned in the figures is in seconds from 01/01/01 00:00:00.
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</tr>
<tr>
<td>B</td>
<td>848973.2</td>
<td>2400096</td>
</tr>
<tr>
<td>C</td>
<td>853819.7</td>
<td>2399648</td>
</tr>
<tr>
<td>D</td>
<td>838726.9</td>
<td>2378073</td>
</tr>
<tr>
<td>E</td>
<td>844073.6</td>
<td>2370610</td>
</tr>
<tr>
<td>F</td>
<td>835704.2</td>
<td>2348449</td>
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<td>G</td>
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<td>J</td>
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<tr>
<td>M</td>
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Table 5.1 Location of Admiralty Diamonds on BHO Chart No. 1486
Figure 5.2 Model free surface versus ATT predicted tides at Karachi

Figure 5.3 Model free surface versus ATT predicted tides at Sikka
Figure 5.4 Model free surface versus ATT predicted tides at Okha

Figure 5.5 Model free surface versus ATT predicted tides at Pipavav
Figure 5.6 Model free surface versus ATT predicted tides at Dahej

Figure 5.7 Model free surface versus ATT predicted tides at Rawas
Figure 5.8 Model free surface versus ATT predicted tides at Trombay

Figure 5.9 Model free surface versus ATT predicted tides at Ravadanda
Figure 5.10 Model free surface versus ATT predicted tides at Ratnagiri

Figure 5.11 Model free surface versus ATT predicted tides at Murud
Figure 5.12 Model free surface versus ATT predicted tides at Karwar

Figure 5.13 Model free surface versus ATT predicted tides at Kumta
Figure 5.14 Model free surface versus ATT predicted tides at Batkal

Figure 5.15 Model free surface versus ATT predicted tides at Kundapur
Figure 5.16 Model free surface versus ATT predicted tides at Mangalore

Figure 5.17 Model free surface versus ATT predicted tides at Cochin
5.3.2 Tidal streams

Tidal streams on BHO Chart No. 1486 were also compared against the model velocities during spring and neap stages of the tide. Figure 5.18 shows locations of the Admiralty Diamonds on BHO Chart 1486. Table 5.1 shows their coordinates as per UTM Zone 42. The velocity values obtained from Admiralty Diamonds during spring and neap tides are based on very short-term observations. Since the estimates are based on data collected during different periods, it could be used as an estimate of the tidal currents only in the absence of other data. Figures 5.19 to 5.28 show the tidal streams during spring tide at the Diamond points A, C, D, E, F, G, H, J, K and L. Expect at the Diamond E the model velocities match with the chart values during spring tides. Tidal streams during neap tide at these Diamond points A, C, D, E, F, G, H, J, K and L are shown in Figures 5.29-5.38. Model over-estimates the neap currents at all Diamond points.
Figure 5.18 Locations of Admiralty Diamonds on BHO Chart 1486 (Please see Table 1 for more details).
Figure 5.19 Model velocity magnitude (blue) versus BHO chart tidal stream (pink) at Admiralty Diamond A during spring tide. Time in seconds starting from 01/01/01 00:00:00

Figure 5.20 Model velocity magnitude (blue) versus BHO chart tidal stream (pink) at Admiralty Diamond C during spring tide. Time in seconds starting from 01/01/01 00:00:00
Figure 5.21 Model velocity magnitude (blue) versus BHO chart tidal stream (pink) at Admiralty Diamond D during spring tide. Time in seconds starting from 01/01/01 00:00:00

Figure 5.22 Model velocity magnitude (blue) versus BHO chart tidal stream (pink) at Admiralty Diamond E during spring tide. Time in seconds starting from 01/01/01 00:00:00

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Figure 5.23 Model velocity magnitude (blue) versus BHO chart tidal stream (pink) at Admiralty Diamond F during spring tide. Time in seconds starting from 01/01/01 00:00:00

Figure 5.24 Model velocity magnitude (blue) versus BHO chart tidal stream (pink) at Admiralty Diamond G during spring tide. Time in seconds starting from 01/01/01 00:00:00
Figure 5.25 Model velocity magnitude (blue) versus BHO chart tidal stream (pink) at Admiralty Diamond H during spring tide. Time in seconds starting from 01/01/01 00:00:00

Figure 5.26 Model velocity magnitude (blue) versus BHO chart tidal stream (pink) at Admiralty Diamond J during spring tide. Time in seconds starting from 01/01/01 00:00:00
Figure 5.27 Model velocity magnitude (blue) versus BHO chart tidal stream (pink) at Admiralty Diamond K during spring tide. Time in seconds starting from 01/01/01 00:00:00.

Figure 5.28 Model velocity magnitude (blue) versus BHO chart tidal stream (pink) at Admiralty Diamond L during spring tide. Time in seconds starting from 01/01/01 00:00:00.
Figure 5.29 Model velocity magnitude (blue) versus BHO chart tidal stream (pink) at Admiralty Diamond A during neap tide. Time in seconds starting from 01/01/01 00:00:00

Figure 5.30 Model velocity magnitude (blue) versus BHO chart tidal stream (pink) at Admiralty Diamond C during neap tide. Time in seconds starting from 01/01/01 00:00:00
Figure 5.31 Model velocity magnitude (blue) versus BHO chart tidal stream (pink) at Admiralty Diamond D during neap tide. Time in seconds starting from 01/01/01 00:00:00

Figure 5.32 Model velocity magnitude (blue) versus BHO chart tidal stream (pink) at Admiralty Diamond E during neap tide. Time in seconds starting from 01/01/01 00:00:00
Figure 5.33 Model velocity magnitude (blue) versus BHO chart tidal stream (pink) at Admiralty Diamond F during neap tide. Time in seconds starting from 01/01/01 00:00:00

Figure 5.34 Model velocity magnitude (blue) versus BHO chart tidal stream (pink) at Admiralty Diamond G during neap tide. Time in seconds starting from 01/01/01 00:00:00
Figure 5.35 Model velocity magnitude (blue) versus BHO chart tidal stream (pink) at Admiralty Diamond H during neap tide. Time in seconds starting from 01/01/01 00:00:00

Figure 5.36 Model velocity magnitude (blue) versus BHO chart tidal stream (pink) at Admiralty Diamond J during neap tide. Time in seconds starting from 01/01/01 00:00:00
Figure 5.37 Model velocity magnitude (blue) versus BHO chart tidal stream (pink) at Admiralty Diamond K during neap tide. Time in seconds starting from 01/01/01 00:00:00

Figure 5.38 Model velocity magnitude (blue) versus BHO chart tidal stream (pink) at Admiralty Diamond L during neap tide. Time in seconds starting from 01/01/01 00:00:00
5.4 Results and discussion

Velocity colour maps of the models results for selected regions are presented in Figures 5.39-5.48. Velocity maps for the Gulf of Kutch during flood (Figure 5.39) are up to 3m/s and it is 2.5m/s at the deeper regions (Figure 5.40). Gulf of Cambay also experiences the same upper limits of velocity during the peak flood (Figure 5.41) and peak ebb (Figure 5.42). Tidal levels as well as current magnitudes reduce consistently as we move out of the gulf regions. Figures 5.43 and 5.44 represent the peak flood and ebb respectively near and off Mumbai. Offshore tidal velocity graphs during flood and ebb off Karnataka and those near the southern waters are presented in Figures 5.45 to 5.48.

The ATT predicted levels are in strikingly good agreement with the results obtained for the model free surface. At Okha, however, such pronounced agreement is not indicated between the ATT and model values. But here also, the maximum variation is of the order of half a metre only. ATT components at Dahej are based on a point located inside the creak where the coastline is not fine to represent the creek; hence the levels have been compared against values outside the creek. Still, they exhibit reasonably agreeable trends.

Comparisons between model current speeds and BHO chart values of tidal streams indicate good matching during spring tides while during neap tides the model over-estimates the current speeds at all Diamond points. Variations in tidal current velocities between peak flood and peak ebb at Gulf of Kutch, Gulf of Cambay, Mumbai, Karnataka coast and Cochin convincingly indicate diurnal reversal of the tidal streams.

Figure 5.39 Modelled velocity during peak flood (left) and peak ebb (right) – Gulf of Kutch

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Figure 5.40 Modelled velocity during peak flood (left) and peak ebb (right) - Gulf of Cambay

Figure 5.41 Modelled velocity during peak flood (left) and peak ebb (right) - Mumbai