CHAPTER 5
MODEL SETUP AND VALIDATION
5 MODEL SETUP AND VALIDATION

Modelling the hydrodynamic processes such as tides and currents is an essential tool to understand the physical, chemical and biological process in a coastal environment. Modelling studies have been carried out to assess the tidal currents, amplification and resonance in the Gulf of Kachchh. A vertically integrated 2D, hydrodynamic model, namely MIKE21 HD has been applied to simulate the water level variation and currents generated by tidal forcing. The vertically integrated form of momentum equations are simplified by assuming that the waters are vertically homogeneous and there is no stratification or vertical density gradient. MIKE21 is a standard software for advanced numerical modelling of hydrodynamics, waves, sediment transport and ecological modelling (User Guide for MIKE21, 2001). This model has been extensively used in the simulation of hydrodynamics, water quality, wave dynamics and related processes in estuaries, bays and coastal areas (Chubarenko and Tchepikova, 2001). There are numerous studies available where MIKE21 software has been applied and the tidal heights and currents reproduced successfully. Recently Madsen and Flemming (2004) applied the MIKE21 flow model to simulate cyclone induced storm surge and flood in the northern Bay of Bengal.

5.1 Formulation of the problem

The dynamics of fluid flow is governed by Newton's second law of motion. According to Newton's second law of motion, the resultant force acting on a fluid in motion will be equal to the product of mass (M) and acceleration (a) of the fluid. i.e. the resultant force, \( F = M a \). The acceleration will be in the resultant direction of the force.

Considering the various forces such as pressure, gravity, viscous and turbulent forces acting on the fluid, the above law can be expressed as:

\[
\sum F = F_p + F_g + F_v + F_T = Ma
\]

where the subscripts \( p, g, v \) and \( T \) represent pressure, gravitational, viscous and turbulent forces, respectively.

This can be split into components acting in the three directions, considering a rectangular Cartesian coordinate system with its origin at the sea surface and x, y and z axis pointing east, north and vertically upward, respectively.

\[
Ma_x = F_{px} + F_{gx} + F_{vx} + F_{Tx}
\]

i.e. \( Ma_x = F_{px} + F_{gx} + F_{vx} + F_{Tx} \)
\[ Ma_y = F_{py} + F_{gy} + F_{vy} + F_{ty} \]  \hspace{1cm} 5.3

\[ Ma_z = F_{pz} + F_{gz} + F_{vz} + F_{tz} \]  \hspace{1cm} 5.4

These equations are known as the Reynolds' equations as they contain turbulent forces. If we remove the turbulent force term we get the Navier-Stokes equation. For 2D case, it can be written as equal to the resultant force if we assume the equation for unit volume.

\[ a_x = F_{px} + F_{gx} + F_{vx} \]  \hspace{1cm} 5.5

\[ a_y = F_{py} + F_{gy} + F_{vy} \]  \hspace{1cm} 5.6

The acceleration can be considered as having a local acceleration and an advective acceleration. Then the L.H.S of the above equations become:

\[ a_x = \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + z \frac{\partial u}{\partial z} \]  \hspace{1cm} 5.7

\[ a_y = \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + z \frac{\partial v}{\partial z} \]  \hspace{1cm} 5.8

where \( u \) and \( v \) are velocity components in x and y directions respectively.

Considering the pressure gradient, gravitational, viscous, frictional and Coriolis forces the R.H.S of 5.7 and 5.8 can be written as

\[ a_x = -gH \frac{\partial \eta}{\partial x} - \Omega v + A_H \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + A_v \left( \frac{\partial^2 u}{\partial z^2} \right) + \frac{\tau_{wx} - \tau_{hx}}{H} \]  \hspace{1cm} 5.9

\[ a_y = -gH \frac{\partial \eta}{\partial y} + \Omega u + A_H \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + A_v \left( \frac{\partial^2 v}{\partial z^2} \right) + \frac{\tau_{wy} - \tau_{hy}}{H} \]  \hspace{1cm} 5.10

where \( H \) is depth, \( \eta \) water level, \( A_H \), \( A_v \) horizontal and vertical eddy viscosities and \( f \) Coriolis parameter.

Combining the above equations, i.e eqn. 5.7 with 5.9 and eqn. 5.8 with 5.10, we get the vertically integrated form of the Navier-Stokes equation for 2D case for shallow water region of depth \( H \). Including the continuity and hydrostatic balance equations

\[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \]  \hspace{1cm} 5.11
\[
\frac{\partial p}{\partial z} = -\rho g
\]  

we get a set of three equations with three unknown variables.

\[
\frac{\partial p}{\partial t} + \frac{\partial}{\partial x} \left[ \frac{p^2}{h} \right] + \frac{\partial}{\partial y} \left[ \frac{pq}{h} \right] + gh \frac{\partial \eta}{\partial x} + \left[ \frac{\sqrt{\frac{p^2 + q^2}{2}}}{C^2} \right] - fV \frac{\partial p}{\partial x} - \frac{\partial p_a}{\partial x} - \Omega q - EddyViscosity = S_x
\]

\[
\frac{\partial q}{\partial t} + \frac{\partial}{\partial x} \left[ \frac{q^2}{h} \right] + \frac{\partial}{\partial y} \left[ \frac{pq}{h} \right] + gh \frac{\partial \eta}{\partial y} + \left[ \frac{\sqrt{\frac{p^2 + q^2}{2}}}{C^2} \right] - fV \frac{\partial q}{\partial y} - \frac{\partial p_a}{\partial y} + \Omega p - EddyViscosity = S_y
\]

\[
\frac{\partial \eta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = S - e
\]

These equations are solved to obtain the \( u, v \) and \( \eta \) at all grid points for the simulation period. For 2D modelling, the solutions can be obtained for the vertically integrated flux \( p \) and \( q \) in the \( x \) and \( y \) directions.

The abbreviations used in these equations:

- \( p, q \) - flux in the \( x \) and \( y \) directions
- \( t \) - time;
- \( x, y, z \) - Cartesian co-ordinates;
- \( u, v \) - depth averaged velocity components in the \( x \) and \( y \) directions,
- \( \Omega \) - Coriolis parameter
- \( g \) - acceleration due to gravity
A_x, A_y - diffusion coefficients in the x and y directions respectively;
η - water elevation with respect to mean sea level
h - water depth
p_a - atmospheric pressure
ρ_w - density of sea water
S - source magnitude
e - evaporation rate
C - Chezy's coefficient
f - wind friction factor
E - eddy viscosity coefficient
S_{ix}, S_{iy} - source impulse in x and y directions
τ_b, τ_w --- bottom stress and wind stress respectively.

Eddy viscosity coefficient, E is expressed as a time varying function of the local gradient of the velocity, using the Samagorinsky scheme.

\[ E = C_s^2 \Delta^2 \left[ \left( \frac{\partial u}{\partial x} \right)^2 + \frac{1}{2} \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + \left( \frac{\partial u}{\partial y} \right)^2 \right] \]  

5.16

In the present study, velocity-based Smagorinsky scheme with a constant value of Cs=0.5 has been applied.

For dynamic stability of the solutions, the well known stability criteria, known as the Courant-Friedrichs-Lewy (CFL) criterion has been used based on the celerity of shallow water waves \( c = \sqrt{gh} \). Based on this, the stability number known as the Courant number has been estimated from the relation

\[ C_R = \frac{c \Delta t}{\Delta x}, \]

where, \( C_R \) is the Courant Number, \( \Delta t \) the time step and \( \Delta x \) the grid size.

5.2 Model setup

A detailed description of the study area is given in Chapter 2. Tide gauge stations and meteorological measurement locations and current meter mooring locations are
shown in Fig.4.1. The computational domain of the model extends from Okha to near Navlakhi between the longitudes 69°02'E and 70°18'E and the latitudes 22°11'N and 22°53'N. The model domain is divided into 500 m² grids in x and y directions respectively. Fig. 5.2.1 shows the computational grid of the entire model domain. Bathymetry of the study area was prepared by extracting depth data from MIKE-CMAP and Naval hydrographic Office (NHO, Dehra Dun, India) charts. The interpolated bathymetric depth contours are shown Fig.5.2.1. Surface elevations at the coastal tidal stations Okha and Godia along the western boundary were predicted using the four major constituents M2, S2, K1 and O1 given in the International Hydrographic Bureau, Spec. Pub, Monaco (Anonymous, 1930). Eastern Boundaries at Navlakhi and Kandla were considered closed. Model runs were carried out using the following calibration coefficients: wind friction factor = 0.0026 and horizontal eddy viscosity = 0.5 m² s⁻¹. Considering the irregular bathymetry, a time step of 30s was selected which yielded a Courant Number of 1.3. Initial surface elevations at the model grid points were interpolated from the predicted tides.

5.3 Method of solution

For solving the equations for dependent variables such as the velocity flux p and q and the surface elevation η, the equations are spatially discretised over a staggered rectangular grid as shown in the Fig.5.3.1. Scalar quantity such as water level η is defined halfway between adjacent grid nodes in the respective directions. The equations 5.13, 5.14 and 5.15 are formulated as a system of implicit expressions for the unknown values at the grid points. A tri-diagonal system of equations are generated and they are solved by double sweep algorithm using alternate direction implicit (ADI) method. The initial conditions for the model are selected based on still water conditions. The vertical density gradients are negligible since the water column is well mixed and there is no significant river discharge into the Gulf.

Along the western open boundary starting at Okha to Godia and Okha to Dwarka, the boundary conditions selected are as follows. (i) The predicted tide at Dwarka and Godia and (ii) no flux along the northern, southern and eastern boundaries of the Gulf. Time series predicted tides at Dwarka and Godia have been used to prepare a line series along the western boundary by applying cubic spline interpolation.
5.4 Model calibration

After setting up the model with initial and boundary conditions for water elevation, initial runs have been carried out with known values of bottom friction parameter estimated based on the bottom roughness. The bottom roughness in the Gulf of Kachchh varies according to bed sediment grain sizes. The bed consists of various sizes of clay, sand, silt and rock soils. The bed roughness depends on the sediment/particle size, defined as the d50 size. The bed resistance increases for small values of Manning number (M) and subsequently the velocity decreases. MIKE21 model uses reciprocal of the Manning number and M can be used to tune the velocity. Chezy's coefficient, C is calculated based on Manning's roughness and water depth using the following relation \[ C = M h^{1/3} \] and the Manning's roughness is calculated based on the d50 size (Reddy, 1994).

Calibration of the model has been carried out by using various values of bed roughness coefficients (Manning number) representing the combined effect of d50 sediment size and bed configuration. The bottom roughness coefficients are selected in such a way that close agreement with the measured values are obtained. In order to calibrate the model, the following experimental runs were carried out with varying Manning roughness parameter and the model results are compared with the currents measured at three different locations situated in the western, central and eastern regions.

5.4.1 Case-1: Manning's roughness parameter =32 m\(^{1/3}\)s\(^{-1}\)

In order to calibrate the model water levels and currents were simulated using a Manning roughness parameter M=32 and the results compared with measured values at three locations: LOC2, LOC5 and LOC10, where time series measurements were carried out. The flood and ebb maximum of measured and modeled current components and water level ranges are given in Table1 5.1 and 5.2, respectively.
The locations LOC2, LOC5 and LOC10 are situated near the eastern, central and western Gulf respectively. The accuracy of the model has been estimated as a percentage of the measured maxima of flood and ebb currents. At LOC5, the westward component (negative u-component) was simulated in the model with 82% accuracy while eastward component (positive u-component) were simulated with 92% accuracy. The northward (positive) and southward (negative) v-components were simulated to an accuracy of 48% and 9% accuracy respectively (Table 5.1). Results of LOC2 and LOC10 also suggest a similar pattern, i.e. higher accuracy for u-components compared to v-components. Lower percentage of accuracy in v-components are noticed when the currents are weak.

5.4.2 Case-2: Manning’s roughness parameter=34 m$^{1/3}$/s$^{-1}$

In case-2, the Manning roughness parameter is assigned a value of 34 and simulation runs have been continued. Comparison between measured and modelled water level variations at the mooring locations are given in Table 5.2. Marginal increase in water levels is noticeable at LOC2 and LOC5 when the bottom roughness parameter is increased. However, at LOC10, water levels reduced from 90% to 73% when the bottom roughness parameter is increased to 34. But the accuracy of current components increased significantly (Table 5.3). The model results show improvement in Case –2 where the U-component accuracy increases to 90-98%. The V-components also showed marginal increase in their accuracy.
Table 5.2 Comparison between recorded and modeled water levels at the mooring locations

<table>
<thead>
<tr>
<th>Mooring locations</th>
<th>Water level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Recorded</td>
</tr>
<tr>
<td>LOC2</td>
<td>-0.25 to 3.97</td>
</tr>
<tr>
<td>LOC5</td>
<td>-0.50 to 3.94</td>
</tr>
<tr>
<td>LOC10</td>
<td>-0.93 to 5.01</td>
</tr>
</tbody>
</table>

Table 5.3. Comparison between measured and modeled current components at three mooring locations in the western, central and eastern Gulf of Kachchh (values in brackets denote modeled currents as % of measured currents)

<table>
<thead>
<tr>
<th>Mooring Locations</th>
<th>U-component (ms⁻¹)</th>
<th>V-component (ms⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured</td>
<td>Modeled</td>
</tr>
<tr>
<td>LOC2</td>
<td>-1.45</td>
<td>-1.32 (91%)</td>
</tr>
<tr>
<td></td>
<td>1.42</td>
<td>1.297 (90%)</td>
</tr>
<tr>
<td>LOC5</td>
<td>-1.65</td>
<td>-1.51 (92%)</td>
</tr>
<tr>
<td></td>
<td>1.66</td>
<td>1.59 (95%)</td>
</tr>
<tr>
<td>LOC10</td>
<td>-1.21</td>
<td>-1.13 (93%)</td>
</tr>
<tr>
<td></td>
<td>1.32</td>
<td>1.30 (98%)</td>
</tr>
</tbody>
</table>

The above comparisons indicate that the model accuracy increases when the manning roughness number is increased from 32 to 34. The model accuracy is higher when the current speeds are higher. In the Gulf, the predominant flow driven by the tidal flooding is in the east-west direction (u-component) and consequently the v-components are much lesser in magnitude. Maximum model accuracy (95-98%) is obtained at LOC5 and LOC10 where the u-components are relatively higher (1.66 ms⁻¹ and 1.32 ms⁻¹ respectively). However, the accuracy of v-component is in the range of 14-70%. As the western half of the Gulf is aligned along an east-west axis the tidal propagation is parallel to this axis and the flood and ebb flows are in the east and west direction respectively. The predominant current component, i.e. u-component constitutes 75% of the current stream and this component is well captured in the model. The north-south
component (v-component) becomes prominent during the intervening period between ebb and flood tides. It is reproduced with a lesser accuracy. It is clear from the measurements that the v-components exhibit fluctuations especially during the flood and ebb maxima at LOC5. These features are absent in the model results. The difference between the model results and measurements indicates lower model accuracy in the case of v-component. Further, analysis is needed to find out the reasons for the uncertainties present in the simulation of v-component of the currents. The above comparison of modeled and measured values were based on the maximum values without taking into account the entire data set, especially the variations between spring and neap. Hence, statistical analysis of two data sets have been carried out, computing the bias and correlation coefficient and the values are given in Table 5.4. The modeled and predicted water levels showed very good correlation at all the three locations. The u-component of velocity showed very high correlation at all the three locations. The v-components exhibited lower correlation at LOC2 and LOC5 and showed very good correlation coefficient at LOC10 (Table 5.4). Water level and velocity components showed lower bias, except for water level at LOC10. These analyses indicate that the model is well calibrated for the water level and u-component of the currents and the model accuracy of v-component is less near the western boundary.

Table 5.4 Bias, RMS error and correlation coefficient estimates for water level, and current components.

<table>
<thead>
<tr>
<th></th>
<th>Water level (m)</th>
<th>U-component (ms⁻¹)</th>
<th>V-component (ms⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOC2</td>
<td>-0.14</td>
<td>0.28</td>
<td>0.97</td>
</tr>
<tr>
<td>LOC5</td>
<td>0.01</td>
<td>0.43</td>
<td>0.94</td>
</tr>
<tr>
<td>LOC10</td>
<td>-0.57</td>
<td>0.70</td>
<td>0.96</td>
</tr>
</tbody>
</table>

5.5 Model validation

In order to validate the model-simulated tides, harmonic analysis of the modelled water elevation has been carried out to obtain the amplitude and phase of the tidal constituents $M_2$, $S_2$, $K_1$, and $O_1$. These constituents are compared with the values available for the coastal tide-gauge stations given in the Monaco tide tables (Anon,
A comparison of $M_2$ tide amplitude and phase is given in Table 5.5. In most of these locations, the tide gauges are located well inside the narrow creeks, which are not included in the model domain. Hence for comparison, the model results from the nearest grid location are selected. The comparison shows very good agreement between the modeled and tide-gauge based $M_2$ constituents. Horizontal distribution of $M_2$ tide amplitude and phase over the Gulf is given in Fig. 5.5.1. As the tidal wave propagates from the west to east it gets amplified eastwards in the shallow regions of Kendal and Navlakhi. $M_2$ amplitude of 0.9m off Okha increases to 2.25m near Kandla. It is also noticed that the phase of the tidal wave as it moves from Okha to Kandla undergoes a shift of 100° (i.e. -30° to 70°) which corresponds to a phase delay of ~3.3 h; the tidal wave takes about 78% time to travel from Dwarka to the central Gulf -off Mandvi (i.e. 80°phase shift) and remaining 22% (20° phase shift) time to travel from Mandvi to Kandla. This result indicates that the irregular bottom topography caused by shoals and reefs decrease the tidal wave propagation significantly in the western half of the Gulf and in the eastern shallow regions, the wave propagates much faster.

A comparison between the modeled and measured u-v components of currents have been carried out using the measured currents at LOC2, LOC5 and LOC7, situated located in the western, central and northeastern Gulf respectively. The predicted tides at a nearby tide gauge station (Okha) compared very well with the model simulated water levels at LOC2. The model simulated current components showed very close comparison with the measured current components (Fig.5.5.2). The measured values of u-component vary between -1.16 and 1.06 m/s, while the model u-components vary between -0.95 and 0.93m/s. The measured v-components vary between -0.25 and 0.34 and the modeled values between -0.27 and 0.30 m/s. Similar comparisons have been obtained also at LOC5 and LOC7 (Figs. 5.5.3 and 5.5.4).

A comparison between the modeled and measured u-v components of currents have been carried out using the measured currents at LOC1 which is located in the northwestern Gulf. The comparison showed very good agreement between both the measured and modelled currents (Fig.5.5.5). u-component of the measured current showed a maximum flood and ebb currents of 1.0 and -0.97 ms$^{-1}$, respectively while the modelled values 0.81 and -0.77 ms$^{-1}$. The differences between the measured and modelled v-components were very negligible. v-component of the measured current showed flood and ebb maximum of 0.46 and -0.41 respectively. The corresponding model values were 0.47 and 0.42 ms$^{-1}$.

The data obtained from the RCM7 mooring at LOC2 was used to compare the model results. Spring-neap variations of the current components are well replicated in
the model. Though the mooring location LOC2 is situated near the western boundary of
the model domain, the modeled water levels and u-component of the currents showed
close agreement with the measurements (Fig. 5.5.6a). Though we cannot expect good
results close to the boundary of the model domain, but the results show very good
agreement with the measured currents, thereby confirming the reliability of the model
close the boundary. The v-component of the modeled currents showed very low values
close to the measured v-component during flood and ebb phase of the tide (Fig. 5.5.6b).

The u-component of the currents at LOC5 situated in the central channel off
Mandvi shows higher values during spring and relatively lower values during neap tide
(Fig. 5.5.7a). However, v-components always show very low magnitudes compared to
the u-component (Fig. 5.5.7b). The water levels rises upto 3.6m during spring and 2.8 m
during neap. An important feature is the fluctuations in the V-component of the current.
These fluctuations are seen only in the central Gulf where bathymetry features such as
shoals, pinnacles and narrowing of the central channel are prominent. The turbulence
and eddy formation in this area will be probably the reason for the fluctuation seen at this
location (LOC5). These fluctuations in v-component are present in the western Gulf
(LOC2); but absent in the eastern Gulf (LOC10).

The model results show neap and spring water levels (14 and 22 November
2002 respectively) at LOC10 situated near the eastern boundary of the model domain,
off Navlakhi on (Fig. 5.5.8). The tidal range obtained from the model is 5.76m and tide
measurement at is 5.94m. The current components also exhibit minimum and maximum
values associated with the neap and spring tides, on those days. A comparison between
the measured and modeled current components shows close agreement between the
two - the u-components are underestimated by about 2% and the v-components by
about 30% in the model.
Table 5.5 Comparison of $M_2$ tide amplitude and phase obtained from the model and from predicted tides at coastal tide gauge stations

<table>
<thead>
<tr>
<th>Location</th>
<th>$M_2$ tide amplitude</th>
<th>$M_2$ tide phase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tide gauge</td>
<td>Model</td>
</tr>
<tr>
<td>Dwarka</td>
<td>0.82</td>
<td>0.84</td>
</tr>
<tr>
<td>Okha</td>
<td>1.11</td>
<td>1.02</td>
</tr>
<tr>
<td>Salaya</td>
<td>1.59</td>
<td>1.53</td>
</tr>
<tr>
<td>Sikka</td>
<td>1.82</td>
<td>1.79</td>
</tr>
<tr>
<td>Rozi</td>
<td>2.10</td>
<td>1.90</td>
</tr>
<tr>
<td>Kandla</td>
<td>2.34</td>
<td>2.29</td>
</tr>
<tr>
<td>Mundra</td>
<td>1.81</td>
<td>1.89</td>
</tr>
<tr>
<td>Mandvi</td>
<td>1.24</td>
<td>1.09</td>
</tr>
<tr>
<td>Godia</td>
<td>0.86</td>
<td>0.86</td>
</tr>
</tbody>
</table>
Fig. 5.2.1 Model domain and bathymetry (depth contours are in metres).
Fig. 5.3.1 Velocity fluxes $p_j, q_j$ and surface elevation ($\eta_j$) terms on a staggered grid in x- and y-directions
Fig. 5.5.1 \( M_2 \) tidal constituent (a) amplitude (a) phase derived from model results (amplitude is in meters and phase in degrees).
Fig. 5.5.2 Comparison between currents (modeled & measured) and tides modeled and predicted using the tidal constituents of nearest tide gauge station: (a) u-component of currents, (b) v-component of currents and (c) water levels at location LOC2 during April 2002
Fig. 5.5.3 Comparison between currents (modeled & measured) and tides modeled and predicted using the tidal constituents of nearest tide gauge station: (a) u-component of currents, (b) v-component of currents and (c) water levels at location LOC5.
Fig. 5.5.4 Comparison between currents (modeled & measured) and tides modeled and predicted using the tidal constituents of nearest tide gauge station: (a) u-component of currents, (b) v-component of currents and (c) water levels at location LOC7.
Fig. 5.5.5 Validation of model results at LOC1: (a) comparison and u-component of currents and (b) comparison of v-component of currents
Fig. 5.5.6 Comparison between currents (modeled & measured) and tides modeled and predicted using the tidal constituents of nearest tide gauge station in November: (a) u-component of currents, (b) v-component of currents and (c) water levels at location LOC2
Fig. 5.5.7 Comparison between currents (modeled & measured) and tides modeled and predicted using the tidal constituents of nearest tide gauge station in November: (a) u-component of currents, (b) v-component of currents and (c) water levels at location LOC5.
Fig. 5.5.8 Comparison between currents (modeled & measured) and tides modeled and predicted using the tidal constituents of nearest tide gauge station in November: (a) u-component of currents, (b) v-component of currents and (c) water levels at location LOC10