Three-Dimensional Simulation of Qeshm Channel Currents

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Abstract
Qeshm Channel is a shallow and narrow waterway located between Qeshm Island and the mainland in the vicinity of Hormuzgan Province, Islamic Republic of Iran. This channel is important because of its economic, industrial, fisheries and navigation role it plays as well as environmental issues it presents in the region. A prognostic study was performed to simulate currents in this channel, using COHERENS model. This model is a three-dimensional hydrodynamic model. Simulation of currents was carried out in 20 sigma levels from the seabed to the water surface during one month. It was assumed that the variations of seawater temperature and salinity, four main tidal constituents and the regional wind were the most effective factors in the numerical simulation. Finally, sensitivity analysis was carried out for each factor and the outputs of simulation were verified using the field data recorded by the experts from Iranian National Center for Oceanography. Very good agreements were found between the numerical results and the field data.

Keywords: Tide, Physical parameters, Currents, Qeshm channel

1. Introduction

In the past decades, a variety of mathematical and hydrodynamic models were developed as demands from scientists and researchers increased. Some of these models were developed based on fundamental equations of motion such as Navier-Stocks equations. COHERENS (COupled Hydrodynamic Ecological REgioNal Shelf Seas), however, was a three-dimensional, N-S based hydrodynamic model which also included biology, contaminant and sediment modules.

COHERENS has been used by many investigators in the Persian Gulf region and other seas; for example, modeling of North Sea (Patrick and Luyten, et.al, 1999), modeling the impact of the Scheldt and Rhine/Meuse plumes on the salinity distribution in Belgian waters (Lacroix and Ruddick, 2004), hydrodynamic investigation of Sacca di Goro coastal lagoon (Marinov and Norro, 2005), circulation of the Persian Gulf (Kämpf and Sadrasab, 2005), dispersion of contaminant from Karoon estuary in the Persian Gulf (Poorkiani and Sadrasab, 2007) and three dimensional dispersion of pollutants in the Persian Gulf (Mahmoudi and Sadrasab, 2008). Furthermore, this model was also used in a study that investigated the two-dimensional modeling of Khuran Strait employing CECAD in Cartesian coordinate (Ghiyasi, 2006). Sabagh Yazdi and Sharbati(2008) applied NASIR
software in modeling of tidal currents in Qeshm Channel. In this study, however, the hydrodynamic module of COHERENS was applied to study the current hydraulics of the Qeshm Channel.

2. Materials and Methods

2.1. Description of the Study Area

Hara Biosphere Reserve and Mangrove forests in the Qeshm area are important ecosystems of national and international importance in the region; however, Qeshm Channel is located in a region ecologically vulnerable to damaging activities such as, oil spill, inland tank leakage and ships ballast water flushing and development occuring around it. Because of construction of several ports in this region, gaining knowledge of current induced sediment transport in this region is quite necessary. The study area extended from 55°16' to 56°16' longitude and 26°39' to 27°10' latitude (Fig. 1). The east-west bound channel is 110 Km long and is extended between Bandar Abbas and Qeshm City towards Bandar-Lengeh and Bandar-Khamir and Basaeedu area. Maximum and minimum widths of the channel are 25 and 3.5 Km, between Bandar-abbas and Qeshm city and between Pohl and Laft ports in Khuran Strait, respectively. Maximum depth of the channel is about 33 m near eastern throat and overall it is considered shallow.

Records of weather stations at Qeshm airport (N: 26°45'- E: 55°54') and synoptic stations located south of Qeshm city (N: 26°57’- E: 56°16’) were used as meteorological data in the simulation. Since the direction of prevailing wind was north-south, perpendicular to the channel, the effect of wind on currents was considered not to be intensive. Climate of this region is usually warm and humid. In summer, heat reaches up to 45 °C and in winter, temperature rarely falls below 12 °C. The average number of rainy days per annum is about 12 days and the annual precipitation is less than 175 mm. Salinity of water in this region is influenced by currents from the Persian Gulf and the Sea of Oman (Johns, 1998). Local variation of salinity is poor due to narrow width and shallow depth of the channel. Average salinity is 38 PSU and seasonal fluctuation is about 4 PSU. Average seasonal water temperature fluctuates between 22 °C in winter up to 32 °C in summer with a diurnal fluctuation of about 0.2 °C to 1.2 °C (Hajizade Zaker, 2005).

Tide is mixed type because of the influence of the Persian Gulf (Najafi, 1997). The main diurnal and semi-diurnal constituents are M2, S2, O1 and K1 (Foreman, 1977). Each constituent has its specific amplitude, period and phase. However, amplitudes and phases differ per location. Tidal characteristics at Bandar-Abbas (east of channel) and Basaidu (west of channel) are presented in Table 1.

Table 1- Characteristics of Main Tidal Constituents at Bandar-Abbas and Basaidu

<table>
<thead>
<tr>
<th>Location</th>
<th>lat</th>
<th>log</th>
<th>T(h)</th>
<th>A(m)</th>
<th>f(g)</th>
<th>01</th>
<th>k1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandar-Abbas</td>
<td>26°39'N</td>
<td>55°16'E</td>
<td>12.42</td>
<td>1.01</td>
<td>0.43</td>
<td>203.8</td>
<td>25.82</td>
</tr>
<tr>
<td>Basaidu</td>
<td>27°10'N</td>
<td>56°16'E</td>
<td>12.42</td>
<td>0.85</td>
<td>0.43</td>
<td>339.0</td>
<td>25.82</td>
</tr>
</tbody>
</table>

As for biological aspects, this area has the greatest...
Hara forest in the Persian Gulf which is the breeding ground and habitat for seasonal migrant sea birds such as herons and flamingoes. More than 93 bird species and 32 species of fish, marine turtles, marine snakes, jackals and hyenas inhabit the region. Also, several species of crustaceans, lobsters and mollusks live in the area.

3. The Model

3.1. Governing Equations

In this study, simulation was performed by the three-dimensional version of COHERENS. This model is based on vertical sigma coordinate. The model is established on the hydrostatic version of Naveir-Stokes equations, continuity and standard equation for scalar parameters. The Boussinesq approximation is included in horizontal momentum equations. The governing equations are as follows:

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x_1} + v \frac{\partial u}{\partial x_2} + w \frac{\partial u}{\partial x_3} = -\frac{\partial p}{\partial x_1} + \frac{\partial }{\partial x_1} \left( \nu \frac{\partial u}{\partial x_1} \right) + \frac{\partial }{\partial x_2} \left( \nu \frac{\partial u}{\partial x_2} \right) + \frac{\partial }{\partial x_3} \left( \nu \frac{\partial u}{\partial x_3} \right) + f v
\]

(1)

\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x_1} + v \frac{\partial v}{\partial x_2} + w \frac{\partial v}{\partial x_3} = -\frac{\partial p}{\partial x_2} + \frac{\partial }{\partial x_1} \left( \nu \frac{\partial v}{\partial x_1} \right) + \frac{\partial }{\partial x_2} \left( \nu \frac{\partial v}{\partial x_2} \right) + \frac{\partial }{\partial x_3} \left( \nu \frac{\partial v}{\partial x_3} \right) - f u
\]

(2)

\[
\frac{\partial p}{\partial x_3} = -\rho g
\]

(3)

\[
\frac{\partial u}{\partial x_1} + \frac{\partial v}{\partial x_2} + \frac{\partial w}{\partial x_3} = 0
\]

(4)

\[
\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x_1} + v \frac{\partial T}{\partial x_2} + w \frac{\partial T}{\partial x_3} = \frac{1}{\rho_0 c_p} \frac{\partial }{\partial x_1} \left( \rho_0 c_p \frac{\partial T}{\partial x_1} \right) + \frac{\partial }{\partial x_2} \left( \rho_0 c_p \frac{\partial T}{\partial x_2} \right) + \frac{\partial }{\partial x_3} \left( \rho_0 c_p \frac{\partial T}{\partial x_3} \right)
\]

(5)

\[
\frac{\partial S}{\partial t} + u \frac{\partial S}{\partial x_1} + v \frac{\partial S}{\partial x_2} + w \frac{\partial S}{\partial x_3} = \frac{1}{\rho_0 c_T} \frac{\partial }{\partial x_1} \left( \rho_0 c_T \frac{\partial S}{\partial x_1} \right) + \frac{\partial }{\partial x_2} \left( \rho_0 c_T \frac{\partial S}{\partial x_2} \right) + \frac{\partial }{\partial x_3} \left( \rho_0 c_T \frac{\partial S}{\partial x_3} \right)
\]

(6)

where \( u, v \) and \( w \) are velocity components of the current, \( T \) stands for temperature, \( S \) the salinity, \( f = 2 \Omega \sin \phi \) the Coriolis frequency, \( \Omega = 2\pi / 86164 \) rad/s the earth rotation frequency, \( g \) the gravity acceleration, \( p \) the pressure, \( \nu_T \) and \( \lambda_T \) the vertical eddy viscosity and diffusion coefficients, \( \lambda_H \) the horizontal diffusion coefficient for salinity and temperature, \( \rho \) the density, \( \rho_0 \) a reference density, \( c_T \) the seawater specific heat at constant pressure and \( I(x_1, x_2, x_3, t) \) solar irradiance. The horizontal components of the stress tensor are defined by:

\[
\tau_{11} = 2 \nu_H \frac{\partial u}{\partial x_1}
\]

(7)

\[
\tau_{12} = \tau_{21} + \nu_H \left( \frac{\partial u}{\partial x_2} + \frac{\partial v}{\partial x_1} \right)
\]

(8)

\[
\tau_{22} = 2 \nu_H \frac{\partial v}{\partial x_2}
\]

(9)

where \( \nu_H \) is the horizontal diffusion coefficient for momentum.

3.2. Mesh Generation and Bathymetry

Considering extension and water mass of Qeshm Channel, computational domain was generated with 100 x 60 uniform structural square meshes with a length of 1000m in both x and y directions (Fig. 2). Also, 20 sigma levels were assumed from seabed to surface in vertical to correspond the location of current metering instruments at different depth to computational cells. Coordinates of computational cells vary from \((i=1, j=1, k=1)\) to \((i=100, j=60, k=20)\), in which \( i, j \) and \( k \) are standard Cartesian coordinate indices.

Hydrographic data was prepared by transforming Iranian National Geographical Organization
information to digitized format. COHERENS was conflicted with becoming dry cells where supposedly were wet, therefore, fatal error was caused and running was suspended. As such, it was supposed that cells with depth of less than 80 (cm) were dry and cells with a depth of 80 (cm) to 120 (cm) were 1.2 (m).

Fig. 2. Mesh Generated for Computational Domain

3.3. Initial and Boundary Conditions

The initial conditions of problem such as temperature, salinity and density were adjusted based on measurements of physical parameters in that area by Iranian National Institute for Oceanography (INCO), as 32 °C, 37.5 PSU and 1025 Kg/m³. Also, physical parameter profiles at open boundaries were adjusted uniformly in depth, temperature (32.7 °C) and salinity (37.9 and 38.2 PSU at the eastern and western ends, respectively). Wind characteristics based on Qeshm Airport and synoptic weather stations data for six years, were set as uniform values in space and time.

Tidal details at open boundaries were set as uniform values based on the tide table prepared by Iranian National Cartographic Center, for Bandar-Abbas and Basaidu (Table 1).

Physical parameters, such as direction of prevailing winds, low fluctuation of local and seasonal water salinity and temperature, were assumed negligible and effects of tidal current were considered more prominent than other factors. In this area, tide is mixed type and tended to semidiurnal (average form number is 0.42; as recommended by Dietrich (1963). Hence, time period for simulation was designated to be 31 days so to incorporate the tidal effects for two neap and spring tides.

3.4. Numerical Methods

The numerical methods used in COHERENS are based on studies by Blumberg and Mellor (1987), Deleersnijder (1992), Beckers (1992) and Ruddick (1995). The Lagrangian particle method has been implemented following the original work by Mirbach (1997). Finite difference method was used for discretisation of equations in space. To obtain accurate results, sigma coordinates were utilized in vertical direction. So, seabed and water surface were transformed to constant levels leading to equal number of responses in columns of water.

4. Results and Discussion

4.1. Observations

The main parameters studied were magnitude and proportion of horizontal vectors of speed in two directions of East-West (u) and North-South (v). Results of model were verified by physical current meters such as Recording Current Meter(RCM90 and Acoustic Doppler Current Profiler (ADCP). Therefore, the time step of exports was selected as 10 minutes equal to current meter instruments. Figure 3 shows u, v and surface elevation for a random surface cell.

Two continuous neap and spring tides with a 14 days interval in a month are quite visible in Figure 3. A complete oscillation of currents and surface elevation is shown in detail in Figure 4.
Fig. 3. Variation of Currents Velocity Components and Water Surface Elevation for a Random Cell

Fig. 4. Variation of Currents Velocity Components and Water Surface Elevation in a full Period

It can be seen in Figure 4 that $u$ and $v$ currents are nearly in the same phase with a $u$ magnitude three times greater than $v$ in a period.

4.2. Sensitivity Analysis

The numerical modeling was carried out by assuming that the following factors were the most important factors affecting the results of the simulation: local tide, local wind field, variations of seawater temperature and salinity. Therefore, it was necessary to determine the relative importance of each factor on the results. In order to obtain this objective, the model was set up as follows: Modeling with all of factors (Model)

1. Modeling without effect of wind (no-wind)
2. Modeling without effects of salinity and temperature variation (Proless)
3. Modeling without effects of wind, salinity and temperature variation (Tide)

The direction of currents in the channel is east-west. Therefore, $u$ value is greater than $v$ and its variation is more tangible. A time span of $u$ is plotted for all categories for a random cell in Fig. 5. It is evident that results of all categories were coincidental. Thus, it could be concluded that tidal currents had the maximum effect on the generation of currents in the channel. So, the effects of salinity and temperature variations and wind could be considered negligible in comparison with the tidal effect. Despite this, the quantitative results were presented for average of $u$ values, for all categories in domain during the modeling time. In this way, the correlation coefficient and Root Mean Square Error (RMSE) were computed for each category and main model. The results are shown in Table 2.

Table 2- Quantitative comparison between effects of different factors

<table>
<thead>
<tr>
<th>Model number</th>
<th>Correlation ratio</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$\alpha = 0.99966126$</td>
<td>0.42 cm/s</td>
</tr>
<tr>
<td>3</td>
<td>$\alpha = 0.99994046$</td>
<td>0.35 cm/s</td>
</tr>
<tr>
<td>4</td>
<td>$\alpha = 0.99975103$</td>
<td>0.39 cm/s</td>
</tr>
</tbody>
</table>

The calculation has also shown that the effects of seawater salinity and temperature variations were less than wind effect in the study area. However, all of these factors are secondary in comparison with tidal effects. This fact could be justified by the fact that local variations of seawater salinity and...
temperature were very minimal due to shallowness of the channel and similarly of wind effect.

4.3. Verification of the Results

Results were verified using the field data recorded simultaneously by INCO experts in summer of 2005. The current was measured using one RCM9 current meter installed at (N: 27º04' – E: 56º03') for 35 days and one ADCP current meter installed at (N: 26º43' – E: 55º25') for 8 days. The seawater salinity and temperature variations were measured by INCO using CTD\textsuperscript{1} instrument.

Considering geographic location of installation and recorded pressure by RCM9 and using hydrostatic relation \( P = P_0 + \rho gh \), the mean depth of RCM9 installation was confirmed. Similarly, considering the ADCP profiles characteristics, the integrity of the instrument location could be obtained. Finally, cells with coordinates of (17, 12, 6) and (80, 48, 8) were found to coincide with ADCP and RCM9 locations. The values of \( u \) and \( v \) current speeds at two cells are shown in Fig. 6 & 7.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure6}
\caption{Outputs of \( u \) & \( v \) Currents at Cell (17,12,6)}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure7}
\caption{Outputs of \( u \) & \( v \) Currents at Cell (80,48,8)}
\end{figure}

It is evident from these figures that, for these cells, magnitude of \( u \) reaches up to 100 and 120 cm/s; however, for \( v \) it reaches up to 28 and 32 cm/s, respectively. Fig. 8 to 11 compare \( u \) and \( v \) values of model with field measurement.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
\textbf{Comparison} & \textbf{\( u \)} & \textbf{RMSE (cm/s)} & \textbf{\( v \)} & \textbf{RMSE (cm/s)} \\
\hline
Cell (17,12,6) & 0.93 & 6.9 & 0.86 & 2.6 \\
Cell (80,48,8) & 0.92 & 7.3 & 0.87 & 2.5 \\
\hline
\end{tabular}
\caption{Quantitative Comparison between Model Outputs and Field Current Metering}
\end{table}

In table 3, correlation coefficients and RMSE are calculated for these comparisons.

When spring tide occurred and current speeds were strong (in 2nd and 16th days of the month), output of model was more reliable. However, when neap tide occurred and current speeds were low (in 10th and 24th days of the month), the model was less

\textsuperscript{1} Conductivity, Temperature & Depth meter
accurate. This might be because of neglecting some less-important tidal constituent factors in the simulation. Nevertheless their effects in low current speeds were more sensible.

5. Conclusion

In this study, modeling of marine currents of Qeshm Channel was performed using COHERENS model during 31 days in 20 sigma levels from the seabed to the water surface. Currents were influenced by 4 main tidal constituents, seawater salinity and temperature variations and wind field. Verification of the model was carried out using the field data of INCO. The results of the modeling were in a very good agreement with field data and no calibration of numerical model was necessary. The correlation factor and RMSE were calculated as 90% and 8%, respectively. For strong current speeds when spring tide occurred, agreement of the model output and the field data was rated excellent, but during neap tide, the accuracy was less than the time of spring tide occurrence; this was attributed to neglecting some of less-important factors in the simulation. So, it could be concluded that the results of the model were reliable and thus, application of other modules of COHERENS for this area is recommended. Furthermore, incidence of each neap and spring tide, twice a month with about 14 days interval for each continuous phenomenon, is evident. Sensitivity analysis revealed that the main factor of currents appearance was tidal currents and other factors were relatively negligible. Although, in this case wind effect is negligible, but it is more important than salinity and temperature variations to generate currents.

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