Three-dimensional hydrodynamic modeling of an industrial coastal area in United Arab Emirates

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Abstract

The coastal flow pattern around a coastal industrial compound in United Arab Emirates (UAE) has been studied using a three dimensional hydrodynamic model. The study area is 100 km$^2$ and partially sheltered from the open sea by salt marshes and islands. Such configuration increases the risk of marine pollution near the industrial site. The region is ecologically diversified and therefore understanding the physical dynamics of the area is important for any assessment work on the impact of industrial and port operation. The utilized model has a size of 232x164 and employs a curvilinear sigma grid system. The setup is nested inside a regional model that covered the entire Arabian Gulf. A $k$-$L$ module estimates the depth variation of the turbulence field. The model is calibrated against the water level and current data. A sensitivity analysis is done for different wind conditions. The results show that a weak mean current is developed due to tidal action in the deeper section of the coastal basin. The tidal influx occurs from the north of the area. The current frequency is found semidiurnal under diurnal tidal action.

1 Introduction

Due to special geographical features, a gully of more than 20 m depth is extended from the central Arabian Gulf almost up to the coastline. A major port and other industrial activities exist in the compound’s region such as a small township with amenities and municipal facilities. The obvious implication of
such development is the increased potential threat to the coastal ecosystem. Discharge of industrial effluents, spillage in the port and release of brine and warm water may have considerable impact on the marine habitat. The marine habitat in this part of the Gulf supports diversified flora and fauna community. Hence, understanding the hydrodynamics is a pivotal task for assessment of the impact of ongoing activities. Although the present paper reports only the hydrodynamics of the study area, it represents a part of ongoing effort that analyzes the physical, biological and chemical behavior under intense anthropogenic interference. A three-dimensional model study is conducted to understand the baseline hydrodynamic conditions of the coastal study area. As the wind is a critical forcing for the Gulf region, series of simulations are done with various wind conditions to find the response of the study area.

2 Modeling theory

The used model, DELFT3D, is a sigma-layer model that solves the classical equations of mass and momentum equations after being transformed from rectilinear into curvilinear system so that the model grids better fit the natural land boundaries. The rectilinear forms of continuity and momentum equations are shown below.

\[ \frac{\partial \eta}{\partial t} + \frac{\partial u h}{\partial x} + \frac{\partial v h}{\partial y} = 0 \]  

Momentum equation in x-direction is:

\[ \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = -g \frac{\partial \eta}{\partial x} + \frac{1}{h^2} \frac{\partial}{\partial z} \left( \frac{\partial (v \eta)}{\partial z} \right) + F_w + \frac{\rho_a}{\rho_w} C_w W W_x + S \]  

Momentum equation in y-direction is:

\[ \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = -g \frac{\partial \eta}{\partial y} + \frac{1}{h^2} \frac{\partial}{\partial z} \left( \frac{\partial (v \eta)}{\partial z} \right) + F_y + \frac{\rho_a}{\rho_w} C_w W W_y + S \]  

where \( u, v \) and \( w \) (m/\text{s}) are velocities in x-, y- and z-directions, respectively. \( t \) (s) is time, \( x, y \) and \( z \) (m) are Cartesian coordinates, \( h \) (m) is water depth, \( g \) (9.81 m/s\(^2\)) is acceleration due to gravity, \( \eta \) (m) is the sea surface elevation, \( \nu \) is eddy viscosity, \( \rho_w \) and \( \rho_a \) (kg/m\(^3\)) are the air and water densities, respectively, \( C_w \) is the wind friction factor, \( W \) (m/s) is the wind speed, \( f \) (\(-5.2 \times 10^{-5}\) s\(^{-1}\)) is Coriolis parameter, and \( p_a \) (kg/m/s\(^2\)) is atmospheric pressure. \( F_w \) and \( F_y \) are the imbalance of horizontal Reynolds's stress. \( S \) is source or sink terms.

The vertical velocity is computed from the continuity equation represented by

\[ \frac{\partial w}{\partial z} = \frac{h(q_{\text{in}} - q_{\text{out}})}{\partial t} \]  

where \( q_{\text{in}} \) and \( q_{\text{out}} \) are ingoing and outgoing discharges of local sources per unit volume (1/s), respectively. The momentum balance in the vertical direction is introduced into the model by equating the pressure gradient with hydrostatic pressure i.e. vertical acceleration is neglected, as the horizontal scale is much larger than the vertical scale.
The advection-dispersion transport equation is formulated in a conservative form in three directions and considering the sigma \( \sigma \) vertical axis as:

\[
\frac{\partial c}{\partial t} + \frac{\partial uc}{\partial x} + \frac{\partial vc}{\partial y} + \frac{\partial wc}{\partial \sigma} = \frac{\partial}{\partial x} \left( h \cdot D_x \cdot \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left( h \cdot D_y \cdot \frac{\partial c}{\partial y} \right) + \frac{\partial}{\partial \sigma} \left( h \cdot D_{\sigma} \cdot \frac{\partial c}{\partial \sigma} \right) + c_s \tag{5}
\]

where \( c_s \) is a source/sink. The horizontal diffusion coefficients \( (D_x, D_y) \) are defined as the superposition of two parts, i.e., a part due to turbulence and a part due to molecular diffusion. The vertical eddy diffusivity \( (D_{\sigma}) \) is the combination of three-dimensional turbulence-generated diffusivity and molecular diffusivity. A first order turbulent closure scheme, k-L model \[1\] is used to compute vertical diffusivity. The mixing length \( (L) \) is prescribed analytically. The model formulates the conservation of turbulent kinetic energy \( k \) using the following relation.

\[
\frac{\partial k}{\partial t} + u \frac{\partial k}{\partial x} + v \frac{\partial k}{\partial y} + w \frac{\partial k}{\partial \sigma} = \frac{1}{h^2} \frac{\partial}{\partial \sigma} \left( \left( \nu_m + \nu \right) \frac{\partial k}{\partial \sigma} \right) + P_k + B_k - e \tag{6}
\]

where \( P_k \) is a production term, \( B_k \) is a buoyancy term and \( e \) is a dissipation term.

In the heat flux model, the short wave radiation is transmitted to deeper water. The longer waves are absorbed at the water surface. Therefore the incoming radiation is separated into two portions, i.e., the longer wave portion and the remainder part. The absorption of the heat in the water column is an exponential function of the distance from the water surface and given by:

\[
Q_{sw}(z) = (1 - \beta)Q_{sw}e^{-\gamma}
\]

with, \( \gamma \) = extinction coefficient \([\text{m}]\), \( z \) = distance to the surface \([\text{m}]\).

\[
Q_{sw} = 30 + 5.2 (T_s - 273.1)
\]

\( T_s \) is the surface water temperature in K.

The evaporation rate \( E \) defined as the volume of water evaporated per unit area per unit time is computed using Dalton’s law of mass transfer:

\[
E = f(U_{w10}) (e_s - e_a)
\]

The saturated vapor pressure \( e_s \) and the actual vapor pressure \( e_a \) are given by the following relations:

\[
e_s = 23.38e^{\left(18.1 - 5303.3/T_s\right)}
\]

\[
e_a = r_{hum}e_s
\]

\( U_{w10} \) is the wind velocity at 10 m above the surface. The wind speed function \( f(U_{w10}) \) is estimated as follows \[2\]:

\[
f(U_{w10}) = \left( \frac{5.01 \times 10^6}{S_{area}} \right)(3.5 + 2.0U_{w10})
\]

\( S_{area} \) is the total surface area. To estimate \( C_w \), the wind shear on the surface is determined by the quadratic expression:

\[
\tau_s = \rho_a C_d U_{10}^2
\]

where \( \rho_a \) \([\text{kg/m}^3]\) is the density of air, \( U_{10} \) \([\text{m/sec}]\) is the wind speed 10 m above the surface and \( C_d \) is the wind drag coefficient which is 0.00063 for non-storm condition. The wind shear and bed shear are introduced in to the model as boundary conditions.
3 Study area

The coastal study sea is a sheltered zone of the Southern Arabian Gulf with an area of 144 km$^2$ (Figure 1). Island A is located at the northwest while large tidal flats in the east separate the area from the UAE eastern coastal seas. An amphidromic points for M2 and S2 tides exist at the north of the study area where the area is subject to diurnal tide. Tidal wave enters the Arabian Gulf through the Straights of Hormuz and develops varying tidal pattern along the coastline in combination with the incidental and reflective tides. Earlier studies show that the tide does not create any mean flow in the southern in the central gulf. However spatial density variation caused by high evaporation and influx of fresher water from the Arabian Sea in the east develops residual flows [3].

The Arabian Gulf is affected by extra-tropical weather system from the northwest. A NW wind, more well known as shamal, occurs year around [4]. The winter shamal brings some of the strongest winds and highest seas to the gulf region. It seldom exceeds 10 m.s$^{-1}$ (<5% frequency) but lasts several days [5]. The summer shamal is usually continuous from early June through July. Coastal winds in the UAE are dominant between west and north directions. The landward winds are driven by the intense temperature difference between land and water surface. The salinity and temperature in the Arabian Gulf are highest in the coastal waters of the UAE and Qatar. The temperature is found to vary over the study area between 20 and 34°C while the salinity changes from 44 to 46 psu over one year. The salinity increases up to 50 psu at the west of study area near Qatar peninsula. These figures have been reported from conducted filed measurements to be discussed in the following section.
4 Model setup

The study area for the model is selected from the south of Island A at the west to the edge of the shallow salt marsh zone at the east (Figure 1). The seaward extent of the model is about 15 kilometers. The model employs curvilinear grid for the horizontal plane. The numerical grid consists of 31,331 cells with side dimensions 231 and 163 along east-west and north-south directions respectively. The vertical dimension is modeled in sigma co-ordinate with 5 layers. The smallest grid size is about 40 m \( \times \) 40 m. The bathymetry of the model is digitized from a navigational chart, Admiralty Chart 3780 [6]. The central part of the area is deep with a depth up to 18 m and the areas at the east and the west are very shallow. The deep sections provide suitable entrance for large tankers. One tiny island exists in the deeper section.

The model is nested inside a larger regional model developed for the entire Arabian Gulf to adopt boundary flow data. The regional model has its boundary at the Straits of Hormuz. An earlier study [3] showed the hydrodynamic results of that mode and conducted sensitivity tests to show the effect of different parameters on the model results. It was shown that the salinity gradient generated an anticyclonic net circulation in the central gulf. The flow was found to decrease with the introduction of radiation induced temperature dynamic into the model. The rate of flow almost doubled when the Coriolis effect is removed from the model showing that the clockwise forcing trend of the Coriolis force obstructs the oppositely rotating salinity driven flow.

By observing the nature of mixing in the coastal sea, constant salinity of 45 psu and temperature of 28°C over the selected model are found reasonable for simulation in the current study.

5 Field measurement

A field program was designed to collect a hydrodynamic synopsis for the study area. The survey was conducted covering a period of two weeks (16th June - 30th June, 2002) that included one neap tide and one spring tide. Three water level gauges were deployed at three locations. The instrument at location 3 also recorded the salinity and temperature. An Acoustic Doppler Current Profiler ‘ADCP’ was used to measure the vertical profile of the current at two locations. The ADCP was mounted at the seabed by attaching it to an acoustic release device and a disposable weight. A buoy attached to the setup was also submerged during installation and it lifted up the setup when the weight was released by emitting acoustic commands from the sea surface. The upward facing setup measured the current from the sensor level up to the surface. In the first location, which was 20.5 m deep, the deployment period was 3 days (16th to 19th June). In the other location, which was 17 m deep, measurement was done for next 6 days (19th to 25th June). The elevation of the sensor from the bottom was 2.5 m. The measurable water depth was divided into a number of bins (layers) of 2 m thickness.
6 Hydrodynamic calibration

The model is calibrated by adjusting parameters within practical ranges to attain agreement with measured hydrodynamic data. A bed friction coefficient map is developed with Chezy Number ranging from 50 to 70 m$^{1/2}$/s. Comparison of the measured and simulated water level data at coastal location 1 is shown in Figure 2 where a satisfactory agreement can be noticed. The computed depth-averaged eastward and westward currents are compared with measured data at location 1 (see Figure 3). The match of the estimated eastward current with observation appears to be satisfactory. The north current exceeds the measured value during some parts of the day developing diurnal peaks. Such deviation can be attributed to the poor contouring resolution of the old considered bathymetry in many areas in the Gulf water and has not been upgraded for decades.

Figure 2. Measured and computed water levels at the western coast

Figure 3. Measured and computed depth-averaged currents at location 1 (a) Eastward and (b) Northward components.
7 Flow pattern

Time dependent eastern and western velocities show semidiurnal frequencies both in the field and the model, although the tidal frequency is diurnal. The magnitude of the current at location 1 is considerably low and predominantly eastward. The wind measurement showed that the prevailing condition was calm during the 1st week (16 to 22 June) of the study period. Therefore, the current observed during this period is mainly tide driven. The eastward motion is developed due to the tidal influx across the section at the south of Island A. The maximum currents in the eastward and northward direction are found to be $+14.5 \text{ cm/s}$ and $-10.1 \text{ cm/s}$ respectively within 14 days simulation period.

![Depth averaged flow patterns](image)

Figure 4. Depth averaged flow patterns at (a) Ebb tide (b) Low tide (c) Flood tide (d) High tide. Results represent a spring tide condition.
Velocity patterns at four different phases of a daily tidal cycle are shown in Figure 4. During the ebb tide, the water flows outside the western section of the northern boundary by developing a pronounced flow diagonal to the model area. A narrow band of strong flow enters through the deeper central section of the northern boundary but immediately turns west to meet the out-flowing stream. During the low tide, similar but weaker flow is observed at the boundaries. The flow pattern is drastically changed with the initiation of high tide. A strong tidal influx is observed across the shallow western border. Inflow also occurs at the western section of the north border. The western influx is attributed to the approaching tidal wave reflected by the Qatar Peninsula. Although some irregular patterns are observed at the north, the overall flow trend is found southeastward during this phase of tide. During high tide, the west border flow is still maintained but the coastal currents become extremely low. The east boundary shows reversal of flow and practically it represented draining out of the semi-enclosed shallow basin located outside the model area. Flow is outward across the north border during high tide.

8 Wind effect

An initial simulation is done without any wind where the tide-induced (no wind) net flows are +298 and -2230 m$^3$/s through the western section and eastern section, respectively. The positive value implies an eastward flow and vice versa. A complicated pattern of coastal flow is revealed from such outcomes. The eastward net flow through western section is developed by the tidal forcing from the west and the flow is not continued up to the eastern section. An opposite flow in the eastern section could be a result of westward return flow from the west boundary. The opposite flows through western and eastern sections demonstrate that the combined flow may be directed towards north.

To test the sensitivity of the hydrodynamics to the wind forcing, series of tests are done with winds of varying speeds and directions. Selected wind directions are west, northwest, and north which are the dominant directions over the year in the Arabian Gulf region. Three wind speeds; 5, 10, and 15 knots (2.57, 5.14, and 7.72 m/s), are applied from each direction and the net flow is observed across two sections close to the coast (Figure 1). The sections are prolonged 5 kilometers towards north from the coastline.

The changes in the net flow across the eastern and western sections with the change of wind field are plotted in Figure 5. At the western section, the flow is slightly increased when 2.57 m/s wind is applied from three directions. Large increases of flow occur with further increase of wind speed to 5.14 m/s and 7.72 m/s. Amplification of flows is found maximum for the case of northwest wind and response to the north wind at this section is least. As a result, the strongest current across the western section is developed by northwest wind in comparison to those by west and north winds. The reason behind that is the closer alignment of that northwest wind to the shoreline and coastal contours. On the other hand, a
pure westerly wind exerts a force component off the shore and thus becomes less sensitive along the shore.

At the east section, similar to the west section, the change in mean flow is not large for 2.57 m/s wind. The westward flow decreases significantly when the wind speed is increased to 5.14 m/s for both west and northwest wind. Further increase of wind to 7.72 m/s from these two directions reverses the flow towards east. However, increasing the north wind within the same range does not result in reversing the flow towards east in addition to having minimum effect on the flow magnitude. The eastern section responded almost equally to the western and northwestern winds.

Since the northwest wind is most dominant in the Gulf particularly in the winter, the mean coastal currents across the selected sections will be eventually westward.

![Graph showing effect of wind field variation on net flow](image1)

![Graph showing effect of wind field variation on net flow](image2)

Figure 5. Effect of wind field variation on net flow across (a) the western section and (b) the eastern section.

9 Conclusion

A three dimension modeling is conducted to understand the flow pattern and water dynamics of an industrial coastal area in United Arab Emirates. The boundary condition of that model was adopted from a larger regional model for
the entire Gulf that recognizes an anticlockwise net circulation in the central gulf as evidenced by some earlier studies. The current simulation effort revealed a satisfactory agreement between the measured and modeled tides at three locations within the study area. Model calibration produced a spatial-distributed Chezy map for the study area that ranges from 50 to 70 m$^{1/2}$/sec. Semidiurnal frequencies for the eastern and western components of velocity both in the field and the model are noticed although the tidal frequency is diurnal. The impact of north and west winds on the coastal currents is minimum while the northwest wind is found to have maximum impact. It is found that a maximum current and net eastward flow across a section perpendicular to the coast and located toward the western side of the study area is developed by northwest wind.

It can be stated that an anticlockwise net flow prevails in the coastal basin of the study area. The flow is mainly induced by the tidal influx from the west and significantly strengthened under the influence of wind. According to the common dominant directions known in the area, the mean coastal currents within many parts of the study area are expected to be westward.

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