A Three-dimensional Numerical Modeling of Contaminant Dispersion from Arvand Rood River into the Persian Gulf

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Abstract

The Persian Gulf is an important economic and geo-political region. Owing to its oil and gas resources, it is one of the busiest waterways in the world. There are many operating oil wells in the northern part of the Persian Gulf. As a result, the risk of contaminant dispersion is high. The deliberate discharge of 6.3 million barrels of crude oil during the 1991 war against Kuwait in this region was an extreme act of environmental terrorism an example to show that this region is at risk of pollution. The Arvand Rood River is the only navigable river located at the northwestern extremity of the Persian Gulf and the biggest river discharging into it. Many vessels transport huge amount of oil from this river daily. To study the contaminant dispersion from the Arvand Rood River into the Persian Gulf, a three-dimensional hydrodynamic model (COHERENS) was employed. Our findings contributed to an understanding of circulation patterns in the northern part of the Persian Gulf to aid ship traffic and managing of oil spills. Results of the model are in close agreement with previous field data.

Keywords: Arvand Rood, Numerical modeling, Persian Gulf, Contaminant dispersion

1. Introduction

The Persian Gulf is an important economic and geo-political region. The United Arab Emirates, Qatar, Bahrain, Saudi Arabia, Kuwait, and Iraq border the Persian Gulf along its southern coastline and Iran is situated along the northern coastline (Figure 1). This region contains about 65% of the world’s oil reserves and is one of the most important shipping lanes in the world. Approximately one ship in every six minutes passes through the Strait of Hormuz (Alhajiri 1991).

An estimated 250,000 barrels of oil pollutes the Persian Gulf each year (Ackleson et al., 1992). The Persian Gulf is about 990 km long and has an average and maximum depth of 36 m and 120 m, respectively. It is broadest (370 km) in its middle and narrowest (56 km) across the Strait of Hormuz. The Persian Gulf is a semi-enclosed marginal sea in an arid, sub-tropical region. The major river discharging into the Persian Gulf is the Arvand Rood River (ARR) located at the northwestern extremity of the Persian Gulf. Estimates of river discharge vary between 36 and 110 km³/yr (Hartmann et al., 1971; Reynolds, 1993). The current discharge rate is unknown due to a lack of field data acquired after the introduction of major river regulations such as, the Atatürk Dam built by Turkey on the Euphrates.
River in 1990. On the basis of a comprehensive suite of hydrographic data acquired a year after the Persian Gulf War in 1991, Reynolds (1993) proposed a sketch of the Persian Gulf’s general circulation (Figure 2) that has been confirmed by most subsequent studies.

Fig.1: Bathymetry (m) of the Persian Gulf (CI20 m; ETOPO-2 data smoothed). Maximum water depth is set to 150 m.

Knowledge of the Persian Gulf’s circulation is of great significance for managing of frequent oil spills. Influenced by the Earth’s rotation, inflow of surface water from the Gulf of Oman leans against the Iranian coastline whereas the bottom outflow escapes the Persian Gulf along the coasts of the United Arab Emirates and Oman. This creates an overall cyclonic circulation in the Persian Gulf with a salinity front separating in- and outflow regimes.

Fig.2: Sketch of the general circulation in the Persian Gulf. Modified from Reynolds (1993).

This front roughly follows the 40-m depth contour (Figure 1). Spatial salinity distributions shown by Johns et al. (2003) suggest that the cyclonic circulation extend the full length of the Persian Gulf during the summer. In addition to this general circulation, the combined discharge from the ARR creates a classical river plume that typically runs along the coasts of Kuwait and Saudi Arabia. Year-round northwesterly winds, known as the Shamal, are believed to create a southeastward coastal upwelling jet along the Iranian coast between 28°–29°N, but observational evidence thereof is sparse. The principle objective of this paper is to derive a three-dimensional model under realistic forcing to show the speed and direction of the dispersion of contaminants from ARR into the Persian Gulf.

2. Materials and Methods

In this study, the three-dimensional hydrodynamic model, COHERENS (Coupled Hydrodynamic-Ecosystem Model for Regional Seas) (Luyten et al., 1999) which is based on sigma coordinates is used. Also 10 sigma levels on an ETOPO-2 bathymetry (Figure 1), being interpolated and slightly smoothed onto a 4-minute grid is employed. Cartesian lateral grid spacing are 6.6 km (north-south) and 7.4 km (east-west). The model was forced by climatologic monthly mean atmospheric forcing (wind speed and direction, air temperature, humidity, cloud cover and precipitation) derived from 54 years of NOAA data.

As for ARR discharge, a reduced river discharge of 10 km$^3$/yr was used as an estimate of flow rates after dam construction. Monthly mean vertical profiles of temperature and salinity of the eastern open boundary in the middle of the Persian Gulf was extracted from previous field data (Alessi et al., 1999). Tidal boundary forcing was included using the four major constituents: $M_2$, $S_2$, $O_1$, and $K_1$. The
part of the model was calibrated against previous tidal studies (Najafi, 1997).

The model was run in a fully prognostic mode for all variables. Simulations cover a period of 20 years to reaches to steady state. Then, salinity, temperature and circulation patterns were compared with those of previous observations. The model tested perfectly. Next, the load of contaminant was released on the river for a period of one year to simulate the speed and direction of its dispersion.

3. Results

Seasonal circulation patterns were in good agreement with previous observations such as Reynolds (1993) and Kaempf and Sadrinasab (2004). Results of the model with contaminant dispersion for different months of the year in surface and bottom layers are shown in Figures 3 and 4, respectively. Indeed, dispersion of contaminants depended directly on the nature of the circulation pattern. During winter time, the circulation in the northern part of the Persian Gulf is variable and sensitive to winds. Flow at the north end can be easterly or westerly, with clockwise or counterclockwise circulation (Reynolds, 1993). It can be seen from figures 3 and 4 that during winter time (January and February) contaminants introduced from the river mouth slightly shifts toward the Iranian side then moves to the right, which is in agreement with Reynolds (1993). In spring, when river discharge increases, the Coriolis force deflects river runoff to the right and hence, contaminant moves toward Saudi Arabian coasts. Reynolds in his comprehensive study expressed that during spring and summer a southward coastal jet exists between the head of the Persian Gulf and Qatar, and extends to the east of Qatar. This is obviously admissible with the output of this model in the spring and summer (figures 3 and 4).

As mentioned previously, cyclonic circulation extends along the full length of the Persian Gulf during the summer. In addition to this general circulation, the combined discharge from the ARR creates a classical river plume that typically runs along the coasts of Kuwait and Saudi Arabia (shown in figure 2). At this stage, the cyclonic circulation creates maximum surface current at the river mouth and minimum contaminant remains at the river mouth (see figure 3 for July, August and September). When the river plume in figure 2 is compared with output of the model in summer, a strong agreement between the model and observed data manifest itself. Penetration of the water from the Gulf of Oman into the northern part of the Persian Gulf reduces in late summer and extends only to the middle of the Persian Gulf in late autumn. Therefore, cyclonic circulation in the northern part of the Persian Gulf gradually diminishes from late summer to autumn. Consequently, contaminant again accumulates in the river mouth from late autumn to the end of winter.

4. Discussion and Conclusions

On the basis of our simulations and re-interpretation of observational evidence, the circulation pattern in the northern part of the Persian Gulf is in agreement with previous studies, i.e.; Hughes and Hunter (1979), Chao and Al-hajiri (1992), Reynolds, (1993), Johns et al. (2003) and Sadrinasab and Keampf (2004). The contaminant was released on the surface layer of the river at its juncture with the Persian Gulf in winter. Surface water becomes denser and as such, a vertical movement of contaminants took place and more pollutants accumulated in the bottom layer (figures 3 and 4 for November and December). Due to increase of river discharge in spring and diminishing northwesterly wind, the contaminant along with river plume would deflect to the right and would move along the Saudi Arabian coast. By mid-summer (July), surface inflow of low salinity surface water from the Gulf of Oman, leaning against the Iranian.
Fig. 3: Surface distribution of contaminant concentration (g/m³) in different months of the year.
Fig. 4: Bottom distribution of contaminant concentration (g/m³) in different months of the year.
coastline, reaches the far northwestern extremity of the Persian Gulf, where it combines with the river plume to form a cyclonic gyre. This gyre transports surface contaminants with the river plume and the bottom layer remains nearly stationary. Therefore, the amount of contaminant will be much more in the bottom than on the surface of river mouth in the summer. These show that a Gulf-wide cyclonic overturning circulation establishes during summer in agreement with observational evidence (Johns et al., 2003). Notice that the model also predicts a river plume running along the coasts of Kuwait and Saudi Arabia which is in a very good agreement with Raynolds (1993) (see river plume in figure 2). During autumn and into winter, on the other hand, the Persian Gulf’s cyclonic circulation becomes dynamically unstable and breaks up into mesoscale eddies.

Sadrinasab and Käempf (2004) discussed three-dimensional flushing times of the Persian Gulf, employing the same model application as described in this paper. Future modeling studies should investigate effects of varied river discharge on circulation and flushing times in the Persian Gulf. Moreover, our simulation assumed spatially uniform atmospheric conditions. Future studies should address effects of spatially variable atmospheric parameters.

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References


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