Numerical simulation of oil pollution due to optimum pattern of turbulent flow, wind and tide effects

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Abstract

Oil spill advection and dispersion occur because of chemicals, physicals and biological processes related to the properties of oil, hydrodynamics, meteorology and other environmental factors. In this paper, oil pollution was simulated in Assaluyeh port. The spreading and diffusion of oil pollution was investigated due to wind forces and tide effects as well. The model, MIKE3, as a three dimensional model based on the finite volume method was invoked for oil spill fate including spreading, advection, diffusion and determination of evaporation rate, emulsification, oil dissolution in water and remaining oil spill thickness. First, the current pattern was determined according to the water level fluctuations. Using water level variations in Hangam Island, the tidal components as the open boundary initial conditions were applied to the model. In addition, to solve the turbulence hydrodynamic equations, the Smagorinsky formula was used which was fairly in accordance with the experimental results. Furthermore, the results showed that wind velocity could have the greatest effect on oil fate. Contingency plans indicated that oil spill moved toward shore lines and damaged beaches near the Assaluyeh port mostly in Bandar-e Siraf and Bandar-e Kangan in 2008 and Nayband Gulf in 2012.

Keywords: Oil pollution; Numerical modeling; MIKE software; Assaluyeh Port.

1. Introduction

Investigating on oil spill spreading and its fate has increased in recent two decades, which causes different numerical models' development. Most of the oil spreading and oil distribution models focus on the oil spill horizontal motion on the surface. The pollution discharges from a point source to the environment, and begins to spread in vertical and horizontal directions according to its properties, temperature, other material density, wind flow, and other environmental factors (Mehr Motlagh, 2012). Chao *et al.* (2001) developed two and three dimensional models of oil spill fate in coastal water. Moreover, they designed a three dimensional model

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for oil spill expansion according to mass transfer equations. Fingas and Fieldhouse (2004) designed a new model based on the experimental data and knowledge of emulsion formation. Furthermore, photo-oxidation and biodegradation processes were considered for oil spill modeling (Wang *et al.*, 2008).

In another research, using partial Brownian motion the oil spill fate was modeled (Guo *et al.*, 2009). Moreover, the risk map of oil pollution was utilized to predict the oil spill transmission and wind critical direction (Elshorbagy and Elhakeem, 2008). Furthermore, the results of the oil spill fate modeling in the Persian Gulf showed that during the mixing of wind and waves forces, the oil spill transmission increased about 95%. In addition, the percentages of the effects of wind, tides, and currents on the oil spill motion were reported about 80, 15, and 5, respectively (Wijayaratna and Hajisalimi, 2013). Lynge and her colleagues performed a three dimensional model of particle emission due to tidal currents and investigated the effects of horizontal meshing on to particle dispersion (Lynge *et al.*, 2010).

2. Material and methods

In this paper, to consider the climatic factors and preparing an instruction for gathering oil spill, the local meteorological data were used in Mike3 to prevent of possible risks' expansion in Iran shorelines. Additionally, the model was calibrated with validating the data in accordance with the experimental results of current pattern in Assaluyeh. The direction of oil spill movement in Assaluyeh was analyzed as an example. Moreover, tidal currents were investigated using water level fluctuations in the Persian Gulf. For this, the averages of water level fluctuations in the Persian Gulf (Hormuz Strait) in a 19-day period, from August 22 to September 9 in 2008, were applied to the model. Actually, Assaluyeh is one the most important regions in producing, storing, and displacing of oil, thus, the study area was considered as a high-pollution region.

2.1. Oil spill modeling

In the study model, the Hormuz Strait has been considered as an open boundary of the Persian Gulf. For this, the water level fluctuations of Hengam Island were selected as the closest island to the open boundary. Bathymetry data were inserted to the model as an individual file and the average water salinity, water temperature, and air temperature were considered 39 psu, 20 ºC, and 50 ºC, respectively (Hassanzadeh *et al.*, 2011). In addition, the Smagorinsky formula was used to solve the hydrodynamic equations of the turbulence currents. Heat flux was analyzed in the model as an important factor in the evaporation and emulsion processes for water and pollution movements in the Persian Gulf. For validation process, the model results contain currents' velocity and water level variations in the study area were compared with the data obtained from buoys and vessels.

2.2. Modeling based on the oil spill propagation and depreciation

2.2.1 Hydrodynamical model

The Mike3 hydrodynamical model is utilized for numerical modeling of the currents in coasts, ports, gulfs, and ponds. This software can model the unsteady three-dimensional flows based on the variations of density, depth, and external forces from atmosphere, tides, and currents. To model the Newtonian fluid flows, the equations of mass continuity, conservation of momentum, continuity of salinity and temperature; and the relations between density and salinity, temperature and pressure are considered and applied. Thus, the governing equations contain seven equations along with seven unknown-parameters. Mass continuity equation and Navier-Stokes equations in three dimensions can reflect the turbulence effects and density variations in continuity equations of salinity and temperature. The details of the model are available in the software user guide (Mike3 hydrodynamic model, 2012).

In this paper, the modeling section was performed in two parts, hydrodynamics and pollution analyses. The study area, Persian Gulf, was divided in horizontal plan into 5000-meter nets with the dimensions of 165×145. The Hormuz Strait was considered as an open boundary and the time series of water level of Hengam Island, where the closest place to the strait is, were applied to the hydrodynamical model during the study period. To achieve the results independent from the gridding, the 10-second time intervals were selected.

2.2.2 Turbulence model

The Smagorinsky formula (Equation 1) is the most famous equation used for the viscosity of subnet turbulence, and represented by Smagorinsky in 1963 (Faghihifard and Badri, 2013).

$$\upsilon_T = \ell^2 \sqrt{S_{ij}.S_{ji}} \qquad S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{1}$$

which u_i and u_j are the velocities in “i” and “j” directions, is the network size that is replaced with . The is the network size and is the Smagorinsky constant which has two values; 0.088 in horizontal direction, and 0.176 in vertical direction.

2.2.3 Oil pollution analysis model

This model uses random steps to solve the Fokker-Planck equation for the Suspended particles (Deigaard and Hansen, 1994). Moreover, physical and chemical processes affect on the movement of each particle. Actually, the particle path is traced relative to the time and a constant reference. In addition, the Fokker-Planck equation has been solved for suspended oil by the Lagrangian discretization method (Mike3 spill model, 2012).

In this paper, the processes such as evaporation, emulsion, and penetration in water column are investigated, which affect on the depreciation of oil spill.

2.3. Oil spill depreciation processes

2.3.1 Evaporation

The most mass reduction of oil spill in the early days of its formation is due to evaporation. The amount of oil evaporation is related to the wind, air temperature, and the oil type. In general, lighter oil products such as gasoline and jet fuel; evaporate faster than the heavier oil products like petroleum. Thus, the petroleum is more stable in the nature. The evaporation is calculated by McKee formula (Equation 2):

$$N_i^e = K_{ei}.p_i^{SAT} / RT.\frac{M_i}{\rho_i}.X_i\left[m^3/m^2s\right] \tag{2}$$

which N^e is evaporation process; K_e is mass transfer coefficient, p^{SAT} is saturation pressure, R is gas constant, T is temperature, m is molecular weight, X is Mole fraction, ρ is oil fractional concentration, and i refers to the ith elements specifications.

2.3.2 Emulsion

Emulsion is the formation process of oil particles in the water caused variations in the oil profiles. Generation of oil and water emulsion is the most important process caused the oil stability over the water surface. Thus, the water penetration into the oil converts the oil to a very viscous mixture. The emulsion can contain of more than 80% of water. The emulsion formation and its stability are related to oil characteristics and environmental conditions. The emulsion mechanism is not completely known, but in the calm condition and without wind, the emulsion process can be ignored. In addition, the emulsion formation is associated with water conditions and oil chemical properties. The oil penetration into the water is calculated by following formula:

$$\frac{dy_w}{dt} = R_1 - R_2 \tag{3}$$

which R_1 the water absorption that increases with increasing of wind speed and temperature; and R_2 is the water releasing process that reduces with rising the Mol% of asphaltenes, waxes, and surfactants;

$$R_1 = K_1 \frac{(1+U_W)^2}{\mu_{oil}} (y_W^{max} - y_W)$$

$$R_2 = K_2 \frac{1}{As.Wax.\mu_{oil}} . y_w \tag{4}$$

which U_w is wind speed, μ_{oil} is oil viscosity, y^{max} is the highest capacity of water inlet, y_w is the real capacity of water, K_1 is approximation coefficient, A_s is asphaltenes capacity in oil, Wax is wax capacity in oil (wt%), K_2 is approximation coefficient. The emulsion constants of K_1 and K_2 were estimated as follows, which obtained from laboratory data of a controlled oil spill in Haltenbanken (Audunson *et al.*, 1984):

$$K_1 = 5 \times 10^{-7}\ {kg}/{m^3}$$

$$K_2 = 1.2 \times 10^{-5}\ {kg(wt\%)}/{s}$$

2.3.3 Solubility

Dissolution of the oil in water is negligible in comparison with other processes. Thus, the thickness of oil, which leaves the spill due to solubility, is calculated. Assuming that the real density of hydrocarbons is minimal compared to their solubility, the solubility obtains by:

$$\frac{dV_{dsi}}{dt} = K_{si} C_i^{sat} X_{mol} \frac{M_i}{\rho_i} A_{oil} \tag{5}$$

which X_{mol} is mol fraction of i^{th} component, C_i^{sat} is solubility of i^{th} component, M is the element mol-weight, ρ is its density, A_{oil} is the surface oil area in m^2, and K_{si} is mass transfer coefficient with amount of 2.3×10^{-6} ei.

2.4. Horizontal diffusion processes

Horizontal expansion of oil spill due to mechanical forces such as gravity, inertia, viscosity and turbulence distribution, is known as diffusion phenomenon. During the process, the shape and direction of oil spill movement are dependent on the factors like wind, surface currents, and waves. The oil spill penetration into the water column occurs by different mechanisms such as surface evaporation and vertical distribution. The vertical distribution decreases the oil spill volume and the amount of evaporation. In fact, the motion of each particle because of wind, wave, and tidal currents were calculated and the total velocity (U) can obtain by Equation (6).

$$\vec{U} = K_t \vec{U}_{tide} + K_w(z).(\vec{U}_{wind} + \vec{U}_{wave}) \tag{6}$$

U_{wind} and U_{wave} are velocities of wind and wave. The (U_{wind} + U_{wave}) are calculated based on the wind velocity in 10-meter height over the water surface. Thus, total velocity can measured as follows:

$$\vec{U} = K_t \vec{U}_{tide} + K_w(z).\vec{U}_{wind-10m} \tag{7}$$

which U_{tide} is integral velocity of depth-current, K_t is horizontal water current that is equal to 1 in the Persian Gulf, and $K_w(z)$ is determined by Equation (8).

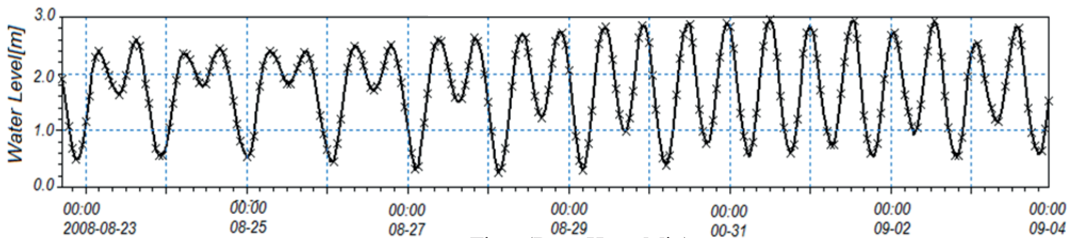
$$K_w(z) = K_w^*(1-\frac{3z}{h}).(1-\frac{z}{h}) \ , \quad 0 \le z \le h \tag{8}$$

which h is depth of water, z is the vertical distance from the water surface, and K_w^* is the wind drift factor with the value of 0.026. Wind direction is given in degrees and measured clockwise from true North to where the wind is blowing from.

3. Results and Discussion

The modeling was conducted in the Persian Gulf with an open boundary of Hormuz Strait. The results have been divided in two parts. The first part shows the hydrodynamical results, contains of water surface velocity and water level fluctuations in Assaluyeh. The second part represents the effects of wind and tide on oil spill diffusion. The water level fluctuations in Hengam Island where is closest to the Hormuz Strait are shown in Figure 1. Two parameters, wind speed and wind direction in Assaluyeh port (Figure 2 and Figure 3) were inserted to the model as boundary conditions The hydrodynamical results were compared with the experimental data achieved from buoys and flow-meters of Ports and Maritime Organization (PMO). The data of water level variations and current velocity were modeled in the area (Figure 4 and Figure 5).

Hengam Water Level, 2008



Time (Date-Hour-Min)

Figure 1. Water level variations in Hengam Island, 2008

Assaluye Port, Wind Speed, 2008

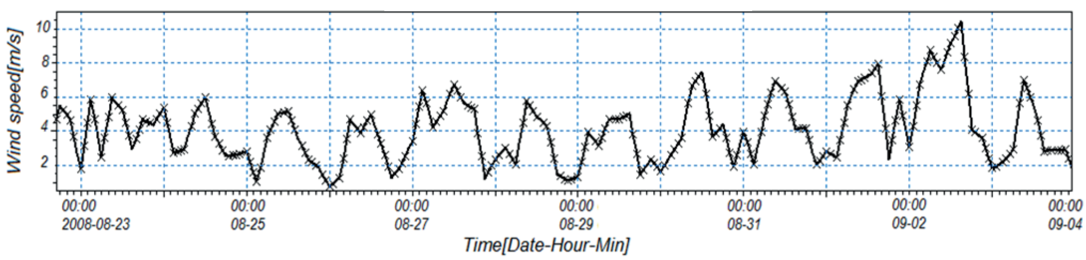
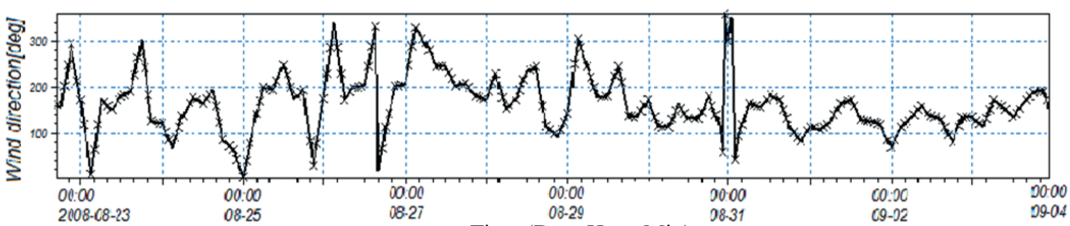


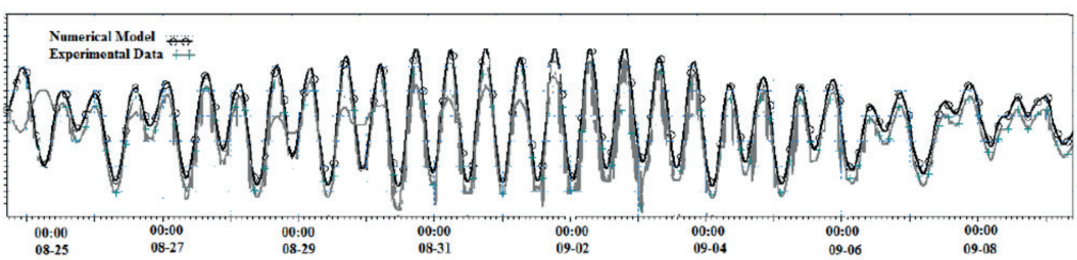
Figure 2. Wind speed (m/s) in Assaluyeh Port, 2008

Assaluye Port, Wind Direction, 2008



Time (Date-Hour-Min)

Figure 3. Wind direction in Assaluyeh Port, 2008



Time (Date-Hour-Min), 2008

Figure 4. Comparison between the study results and experimental data of water level fluctuations in Assaluyeh, 2008

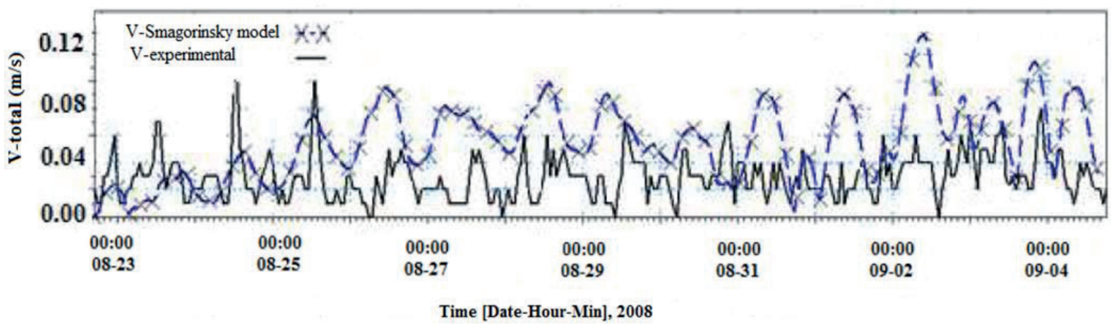


Figure 5. Comparison between the study results and experimental data of current velocity in Assaluyeh, 2008

To analyze the oil pollutions, the solubility, evaporation, emulsion and the remained amount of oil spill due to wind and tide variations are compared in the following sections.

3.1. Wind effects

The wind force is the most important factor that affects on physical and chemical variations of oil spill. To investigate the wind effects on the oil spill, two conditions were considered in the model; with wind and without wind. As is shown in Figure 6, in windy conditions, the evaporated oil considerably increased in the first day and then it got constant values. The modeled data in windy condition showed that the evaporation increased about 92% in comparison with the condition of without wind. Figure 7 indicates the periodic process of oil emulsion in water. This trend illustrates instability of the emulsion as well and when the wind blows, 69% enhancement of emulsion is evident.

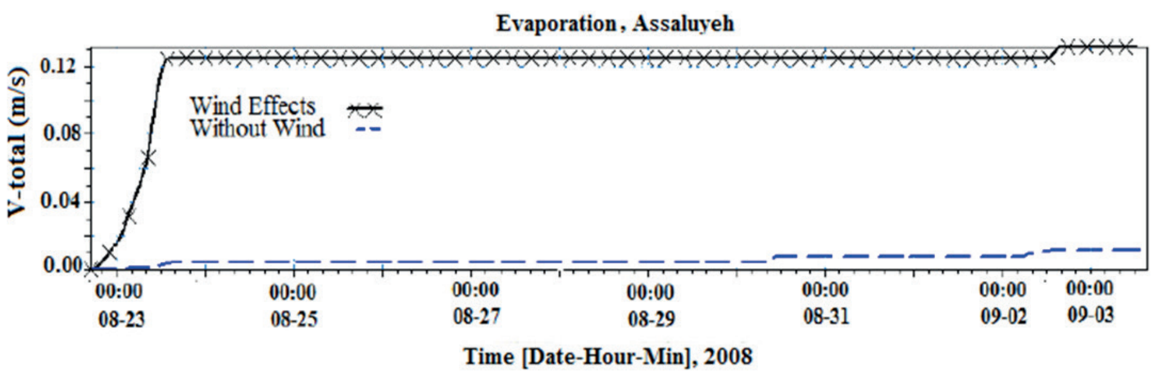


Figure 6. Wind effects on oil evaporation in Assaluyeh, 2008

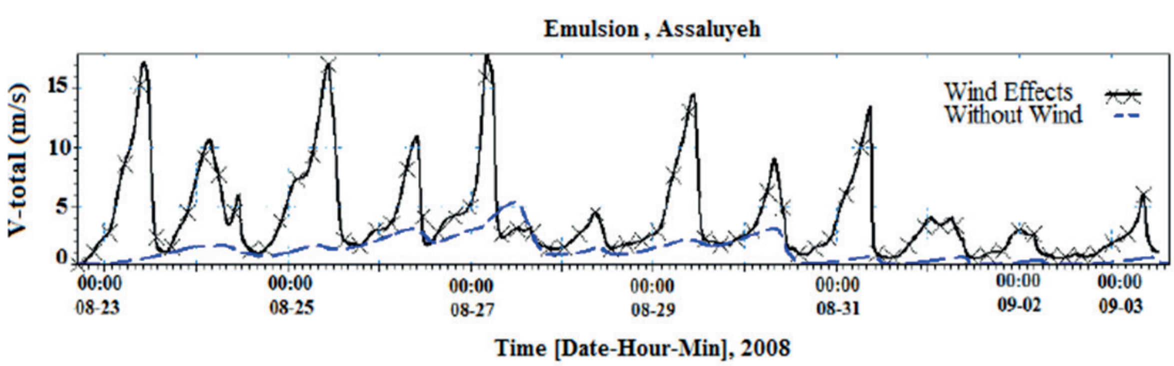


Figure 7. Wind effects on oil emulsion in Assaluyeh, 2008

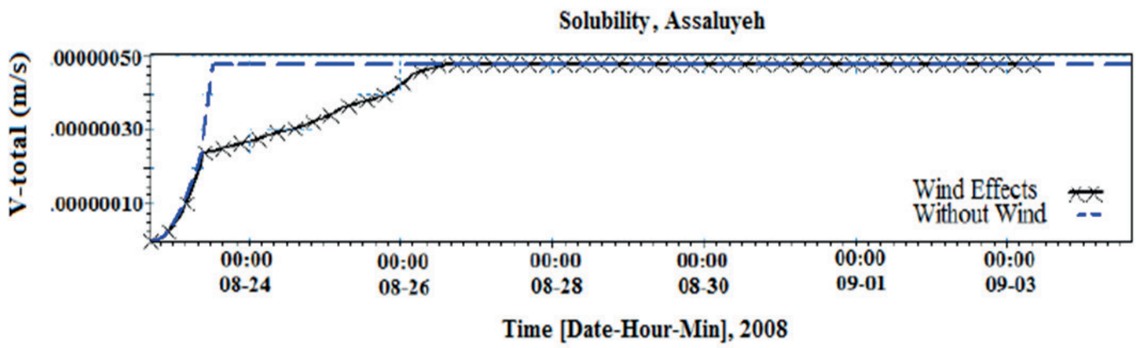


Figure 8. Wind effects on oil solubility in Assaluyeh, 2008

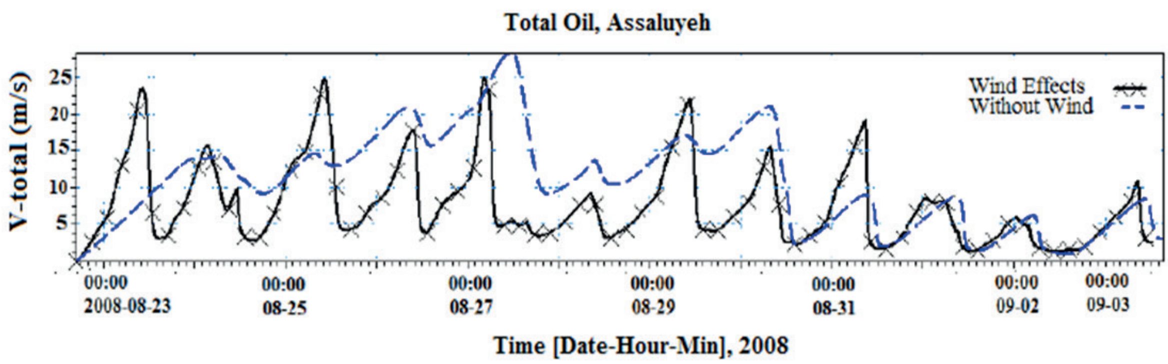


Figure 9. Wind effects on total oil spill in Assaluyeh, 2008

Figure 8 shows the solvability of oil in water. As is obvious in the figure, in contrast with the evaporation and emulsion, the oil solubility in water reduced in about 17%, and this means that the wind blowing could not too much change the solubility of oil in water. However, when the wind blew, the oil spill reduced in about 30% due to the increasing of evaporation and emulsion (Figure 9).

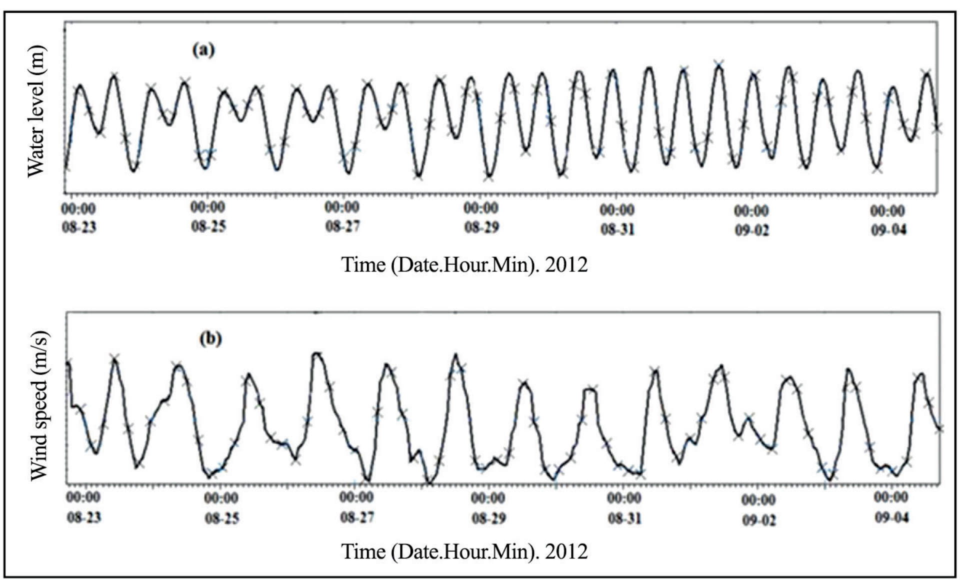


Figure 10. (a) Water level fluctuations in Hengam Island, 2012; (b) Wind speed in Assaluyeh port, 2012

3.2. Tide effects

To investigate the effects of tides on oil spill fate, the water level fluctuations near Hengam Island during two different years, 2008 and 2012 were exerted to the model. In addition, time series of wind speed in 2012 in Assaluyeh was applied as an input for the model (Figures 10a and 10b).

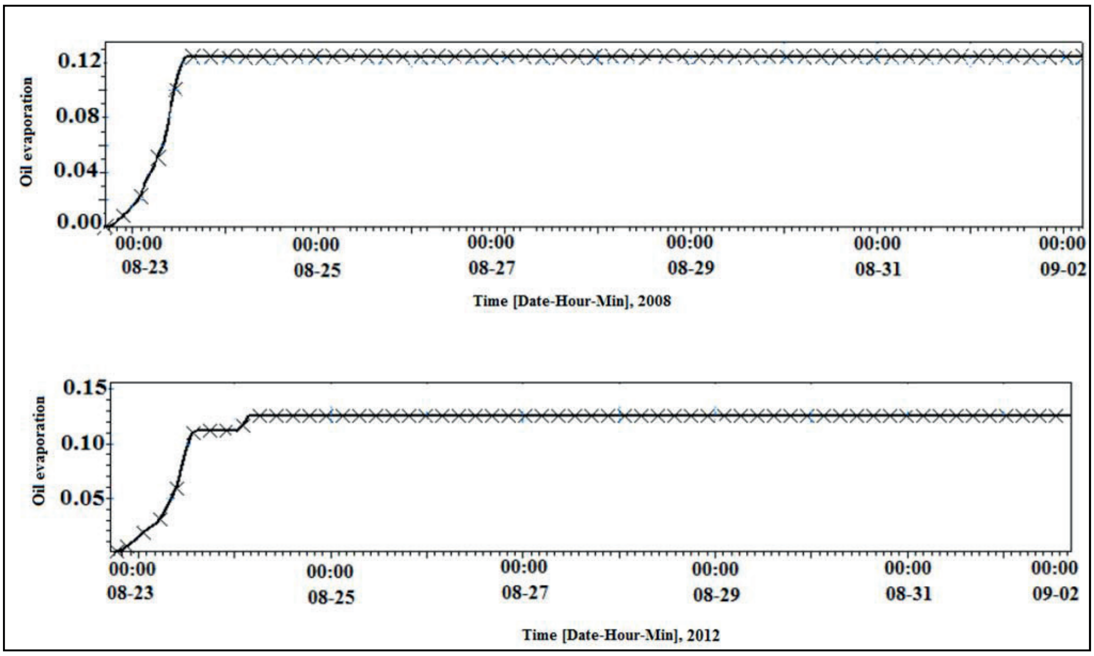


Figure 11. The effects of tidal currents on the oil evaporation Assaluyeh port in 2008 (up) and 2012 (down)

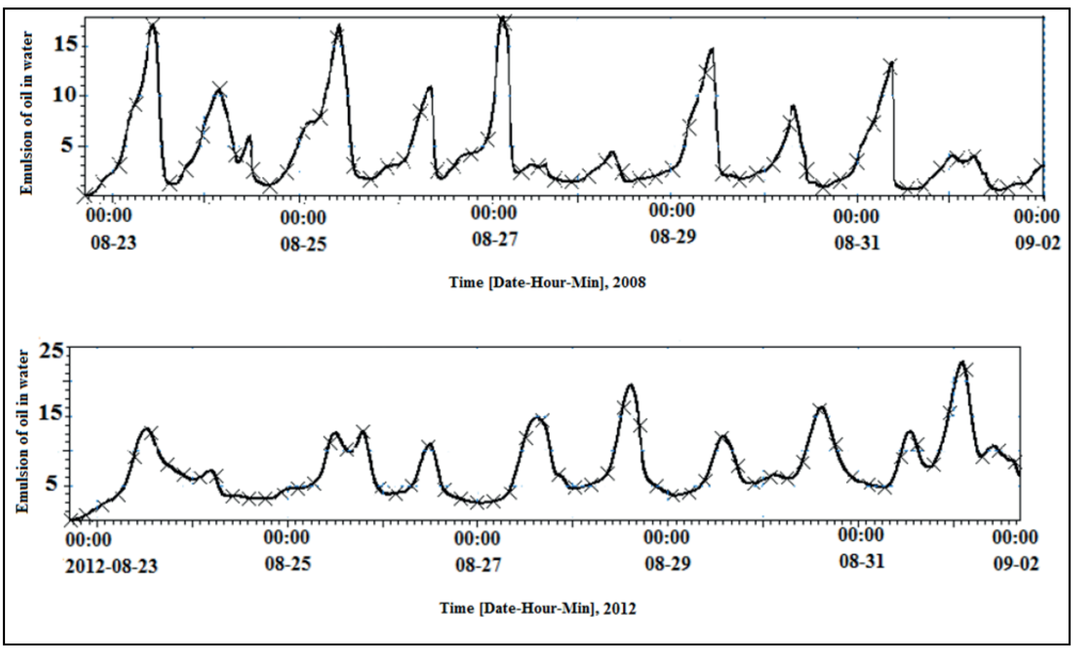


Figure 12. The effects of tidal currents on the oil emulsion in water Assaluyeh port in 2008 (up) and 2012 (down)

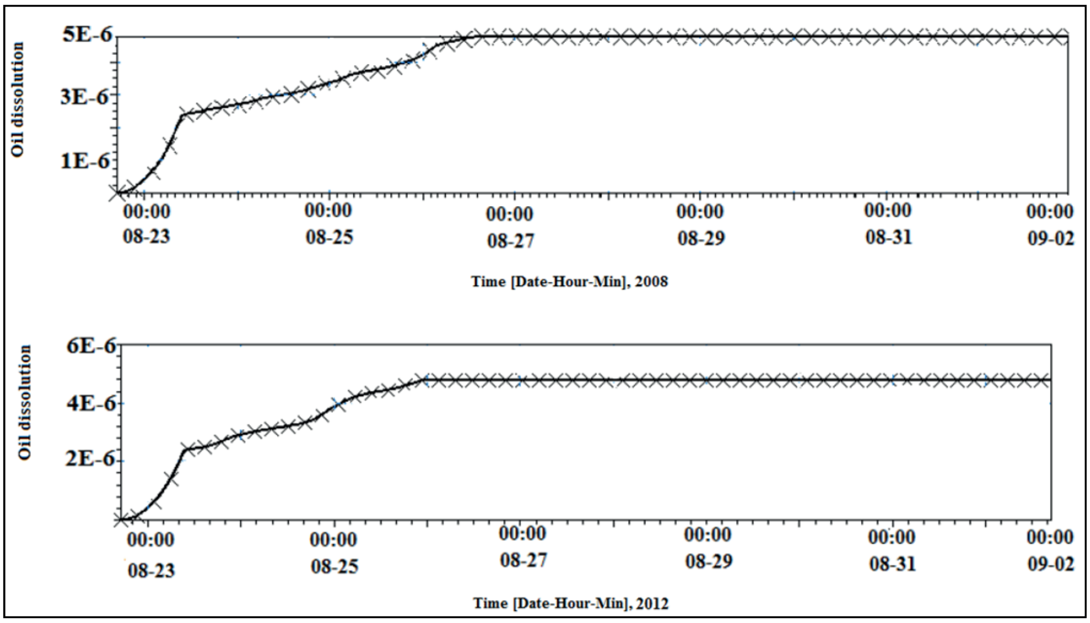


Figure 13. The effects of tidal currents on the oil dissolution Assaluyeh port in 2008 (up) and 2012 (down)

Furthermore, all oil spill destruction and reduction processes were analyzed. In Figure 11, the amounts of oil spill evaporation during the two years are compared. According to numerical results the values of evaporation showed about 8% enhancement. Moreover, the oil emulsion in water increased about 36% (Figure 12). This rising was due to relative increasing of water level fluctuations, caused more oil and water mixing and generating a stable emulsion in the area. As it is evident in the Figure 13, the solubility of oil in water had little change and could be negligible.

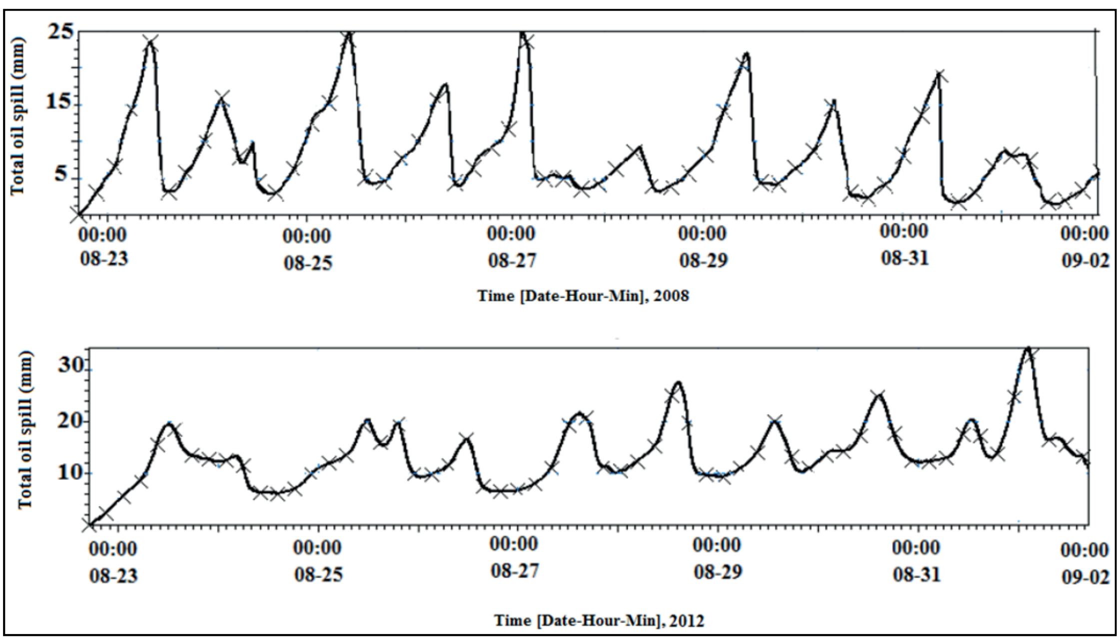


Figure 14. The effects of tidal currents on the total oil spill Assaluyeh port in 2008 (up) and 2012 (down)

The total oil spill over the water surface in 2012 showed an increasing of about 33% in comparison with its value in 2008. The rising oil spill in water surface was due to the increasing of oil emulsion in water and partly oil evaporation (Figure 14).

The oil spill fate was determined at the final stage of modeling (Figure 15). The figure indicates that oil spill moved toward the west and extended beside the shoreline. According to the measurements of latitude and longitude, the polluted area was about 62 km^2. The geographical map can show that the environmental pollution due to the oil reached near to the Kangan port and even it polluted all parts of the Siraf port. However, whatever happened in 2012 is obviously different. The diffusion of oil slick was toward Nayband Gulf and the polluted area was about 28 km^2.

According to the Figure 15, the oil spill extended in the south part of the Assaluyeh port, but the oil spill trapped in the Nayband Gulf and could not expanded much more, because the area is closed. Due to high density oil trapped in the Nayband Gulf, the cleaning costs increases and the wild life in the area is under dangerous. As a result, different factors had impact on the oil pollution expansion during the study period, which the most important factors were water level fluctuations, wind speed and wind direction.

Conclusion

In this paper, a three dimensional simulation was performed for an oil spill fate in the Persian Gulf. The results and analysis showed that the simulation could be applicable for prediction of the oil spill movement. At first, the solution of hydrodynamical equations of turbulent currents, wind field, and water level fluctuations in the area showed a reasonable adaption with Smagorinsky formula and experimental data, thus, a current pattern was determined in the Persian Gulf. Then, using the wind field, modeled pressure, the random steps method, and Fokker-Planck equation, the effects of different parameters such as wind and tides on this process was investigated. The results represented that the polluted area in 2008 was estimated about 62 km^2 that caused a considerable pollution in Siraf port and Kangan port. Furthermore, in 2012, the oil spill development was observed in the south of the Assaluyeh port which was evident of the pollutant water in Nayband Gulf in 30-km of Assaluyeh port.

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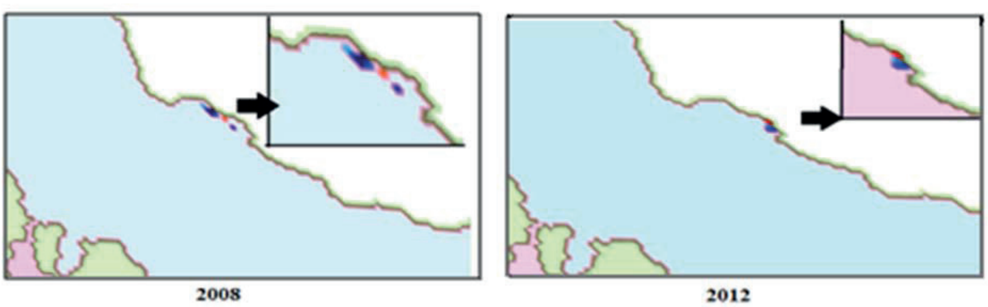

Figure 15. The expansion of oil spill during the study period; 2008 (left), and 2012 (right)

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