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Numerical Simulation of Oil Spill Behavior in the Persian Gulf

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ABSTRACT: The aim of this research is to simulate oil spill behavior in the Persian Gulf due to the wind and tidal currents. This is achieved by coding an oil spill mathematical model consisting of several major sub-models including hydrodynamic model, oil slick dynamic model and oil weathering model. The base of all of them is Eulerian approach and they are coupled together to simulate spill incident in the Persian Gulf. The hydrodynamic model provided to simulate the tidal current is based on two dimensional depth averaged equations of shallow water discretized by finite volume method that is applied on rectangular structured mesh. The tidal current in the Gulf is made by imposing tidal fluctuation to the main open boundary at the Hormuz Strait. This model verification is carried out by comparison the resultant predictions of model with the available measured data and it shows a good agreement. Oil slick transport on the sea surface is simulated by an advection-diffusion model. Also, the most effective natural processes on oil fate and their effect on oil properties are estimated by an oil weathering model. Then, a test case including analytical solution is chosen to ensure the model capability on oil spill simulation. Finally, the model is implemented for a spillage event in the Persian Gulf. By explanation of the presented results, oil fate, the slick transport and other predicted data are demonstrated. The results show the model capability on modelling of an oil spill incident in marine environment.

Key words: Mathematical Modelling, Hydrodynamic Model, Oil Slick transport, Oil Weathering Processes

INTRODUCTION

Industrial growth has been accompanied by imposed environmental risks all around the world (Piccini *et al.,* 2012; Sadatipour *et al.,* 2012; Daniel and Prabhakara Rao, 2012; Afandizadeh *et al.,* 2012; Dimitrov *et al.,* 2012;Soltani *et al.,* 2012; Rahman and Al-Malack, 2012; Najafi and Afrazeh, 2011; Mwegoha *et al.,* 2011; Belkhiri *et al.,* 2011; Hallare *et al.,* 2011; Haruna *et al.,* 2011; Zou *et al.,* 2011; Lalevic *et al.,* 2011; Ajibola and Ladipo, 2011; Kavian *et al.,* 2011; Trogl and Benediktova, 2011; Sekman *et al.,* 2011). Because of the growing industrialization, the need for oil exploration and transportation is increased so, the risks of oil spill accidents are high. A major oil spill can cause long term and irrecoverable damages to the aquatic environment (Epstein and Selber, 2002). In this regards, the Persian Gulf is one of the most hazardous areas because there are a lot of on-shore and off-shore oil fields of Iran and Arabian countries in this area and Hormuz Strait is a strategic international path to transport the oil productions. Hence, in recent decades, several researchers have studied the transport and fate of oil spills in this region (Al-Rabeh *et al.,* 2000; Sabbagh *et al.,* 2007; Elhakeem *et al.,* 2007; Nagheeby and Kolahdoozan, 2010). After spillage, oil slick spreads over the water surface due to a balance between several forces, such as inertia, wind, wave, surface current, etc. At this stage, a number of natural processes take place, which change the volume and the properties of the spilled oil. These natural processes are a combination of complex physical, chemical and biological processes such as spreading, evaporation, water-in-oil emulsification, oil-in-water dispersion, etc. that is called as oil weathering processes (API, 1999). In real events, considering the area affected by the pollution, the numerical models can be a powerful tool on response action decision-making. The most important results of the numerical modelling are prediction of the slick path, oil fate, oil weathering profiles and the oil volume in each phases (slick, water and air) under dominant environmental conditions. (Reed *et al.,* 1999).

Oil spill models have been presented by either Eulerian or Lagrangian approaches. Using Lagrangian

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*Corresponding author E-mail: aghajanloo@ut.ac.ir models, the oil slick divided to a large number of small particles which are advected by surface current velocity obtained by Eulerian hydrodynamics and diffused accidently. In this method physical and chemical properties must be introduced for each particle (Wang *et al.*, 2008; Perianez, 2007 and Chao *et al.*, 2001). But in real incident, to increase the simulation accuracy, the water quality or pollution models need to be coupled with hydrodynamic models. In Eulerian models, a set of equations compatible with hydrodynamic equation are presented. Therefore, in this study the Eulerian methods is used to simulate the oil slick transport (Garcia-Martinez and Flores-Tovar, 1999; Paladino and Maliska, 2000; Tkalich *et al.*, 2003 and Tkalich, 2006).

In this study, a numerical model is presented to predict oil spill behavior by coupling several major sub-models. A hydrodynamic sub-model has been provided based on the depth average hydrodynamic equations on structured finite volumes. To solve the resulted equations, the alternating direction implicit (ADI) is used. The capabilities of model for simulating the flow pattern in simple and complex geometry have been tested. An oil slick dynamic sub-model based on advection-diffusion equation is applied to predict the oil slick transport. Also, the rates of oil mass losses due to natural process (evaporation, vertical dispersion, emulsification and dissolution) are estimated by an oil weathering model in each time step. Finally, the performance of this modeling system is presented for a virtual oil spill in the Persian Gulf.

MATERIALS & METHODS

The mathematical Hydrodynamic model is based on two-dimensional (2D) shallow water equations (SWE). The most important point is the smallness of the vertical velocity component in comparison with the horizontal ones and the hydrostatic distribution of pressure. The depth averaged shallow water equations are as follows:

$$\frac{\partial \xi}{\partial t}+\frac{\partial (u_i h)}{\partial x_i}+\frac{\partial (u_j h)}{\partial x_j}=\frac{\partial z}{\partial t} \qquad (1)$$

$$\frac{\partial (u_i h)}{\partial t}+\frac{\partial}{\partial x_i}\left(u_i^{2} h\right)+\frac{\partial}{\partial x_j}\left(u_i u_j h\right)=-gh\frac{\partial \xi}{\partial x_i}+\frac{\partial}{\partial x_i}\left(\upsilon_t\frac{\partial (u_i h)}{\partial x_i}\right)+\frac{\partial}{\partial x_j}\left(\upsilon_t\frac{\partial (u_i h)}{\partial x_j}\right)-\frac{\tau_{bi}}{\rho_w}+\frac{\tau_{si}}{\rho_w}\pm f_{ci} \qquad (2)$$

Where, ξ, h and z are water surface elevation, flow depth and bed elevation, respectively ($\xi = h + z$); i and j are coordinate directions ($i \neq j = 1,2$); u is surface current velocity; g is gravitational acceleration, υ_t is eddy viscosity coefficient; f_c is Coriolis forces due to earth rotation; τ_b and τ_s are bed friction and wind stresses terms and ρ_w is water density.

To solve the governing equations numerically, finite volume method has been used for spatial discretization and forward finite difference has been deployed for temporal discretization. The difference terms are expressed on a staggered grid in x-y space as shown in Fig. 1.

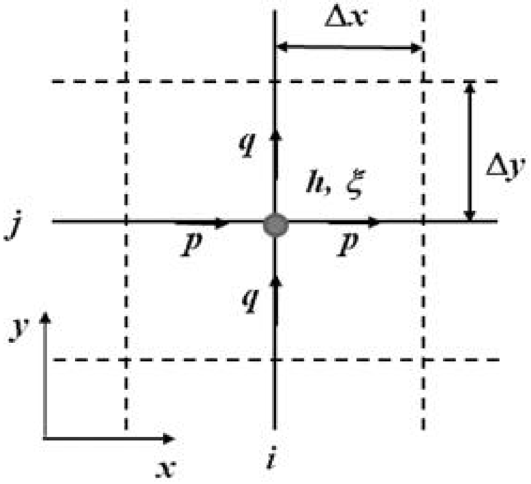

Fig. 1. Difference grid in x-y space

In order to solve 2D equations in two directions (*x* and *y*), the Alternative Direction Implicit (ADI) method is used that has been used extensively to solve SWEs due to its high stability domain and significant balance between computational cost and accuracy. This solving method may reduce the complexity of equations to a reasonable extent (Kim and Lee, 1994; Abbot and Minns, 1997; Nagheeby and Kolahdoozan, 2010). Because of the variations of existing terms in the governing equations, to achieve an acceptable and appropriate solution the Time-Splitting technique was chosen. By this way, all terms will be solved through a separate method and could be different from others. Hence, it gives the ability to solve different terms by a suitable and perfect method (Namin, 2004). To solve the transport equation in finite volume methods, a two-order accuracy method, the Fromm scheme, has been applied to solve the advection terms (Fromm, 1968) and the semi-implicit approach is used to compute the diffusion term. General types of boundary conditions are applied in this model; the input, output and wall boundary conditions.

The verification of current hydrodynamic model was carried out with several case studies. Results were compared with available analytical solution or laboratory measurements. The results show the capabilities of this model for simulating the flow pattern in simple and complex geometry. The detailed of this hydrodynamic model including governing equations, solution techniques and verification tests is presented in authors' previous works (Aghajanloo *et al.*, 2011). The most classical spreading equations were developed by Fay (1971), Hoult (1972), Mackay et al. (1980) and Lehr et al. (1984). They proposed models based on semi-empirical or analytical equations. Nowadays, an oil slick dynamics model can afford to routinely use such accurate and physically relevant formulation like the Navier–Stokes equations (Stolzenbach *et al.*, 1977; Warluzel and Benque, 1981). The oil dynamics in the aquatic environment could be expressed by the following equation.

$$\frac{\partial h_s}{\partial t}+\frac{\partial}{\partial x_i}\left(h_s v_j\right)-\frac{\partial}{\partial x_i}\left(D_s\frac{\partial h_s}{\partial x_i}\right)=\pm Q_s \qquad (3)$$

Where, h_s is the oil slick thickness; D_s is the slick spreading function ($D_s = g{h_s}^2\left(\left(\rho_w-\rho_o\right)\rho_o\right)/\left(f\rho_w\right)$); ρ_o is oil density; f is oil-water interface friction and Q_s is source/sink term. The oil drifting velocity component v_j ($v_j = u_j + \tau_j / f$) is computed using the shear stresses $\tau_j \approx 0.03U_j$ due to the wind velocity U_j in x and y directions (Tkalich *et al.*, 2003; Tkalich, 2006). The selected techniques to solve the equations of this model are similar to hydrodynamic model.

The most effective processes of oil weathering in the first days of spillage are evaporation, vertical dispersion, water-in-oil emulsification and dissolution that are mentioned in most oil spills models (Wang *et al.*, 2008; Tkalich, 2006; Nagheeby and Kolahdoozan, 2010). All of these processes are time dependent but the relative contribution of each process varies during the spill period. The modeling of these processes has some complexities about formulization of them and collection of the input data (Reed *et al.*, 1999). As emergency events of oil spill occurs, there isn't any ideal condition for field measurements and data collection. Hence, unfortunately, there is a significant lack of data on oil spill modeling.

To develop the oil weathering model for current study, the semi-empirical equations introduced by previous researches and their ability to predict the weathering processes are demonstrated. By comparison between the results of these equations and available laboratory measured data and analytical solution, the more suitable equations were selected. The detailed of the oil weathering model of this study has been explained in our recent paper (Aghajanloo and Pirooz, 2011). The weathering processes of current research are listed as:

The highest contribution of oil mass losses during the first days of spillage is relevant to evaporation (Sebastiao and Soares, 1995; Riazi and Edalat, 1996). In this paper, to estimate the evaporation rate (F_E), the analytical equation of Stiver and Mackay (1984) is used as follows:

$$F_E = \ln\left[1 + B\left(\frac{T_G}{T_E}\right)\left(\frac{K_E \cdot A_S \cdot t}{V_0}\right)\exp\left(A - B\frac{T_B}{T_E}\right)\right]\left[\frac{T_E}{BT_G}\right] \qquad (4)$$

Where, K_E is mass transfer coefficient ($K_E = 2.5\times10^{-3}\times U_{wind}^{0.78}$), U_{wind} is the wind speed, A_S is spilled oil area; V_0 is initial volume of spilled oil, t is time; T_E is environmental temperature ($^\circ K$); T_B is initial boiling point ($^\circ K$); T_G is the gradient line of T_B and T_E; A and B are constants derived from distillation data.

The water turbulence tears off droplet of oil and entrains them forming an oil-in-water emulsion. In this study, the following equation is used to compute the dispersion rate (Mackay *et al.*, 1980; Reed, 1989):

$$D = \frac{0.11(U_{wind}+1)^2}{(1+50\mu^{1/2}h_s S_t)} \tag{5}$$

Where, D is dispersion rate per hour, μ is the dynamic viscosity of oil and S_t is the interface tension of oil–water in ($dyne/cm$).

The formation of water-in-oil emulsion reduces the rate of other weathering processes and is the main reason for the persistence of light and medium crude oils on the sea surface (Spaulding *et al.*, 1994; NOAA, 1995). In this paper, the change in water content is expressed by equation of Mackay et al. (1980) as:

$$\frac{dF_{wc}}{dt} = K_{wc}(U_{wind}+1)^2\left(\frac{1-F_{wc}}{OC}\right) \tag{6}$$

Where, F_{wc} is the water content, K_{wc} is the emulsification coefficient that is equal to 2×10^{-6} for light oil and 4.5×10^{-6} for heavy oil, OC is equal to 0.7 for light oil and 1.15 for heavy oil (Rasmusen, 1985; Reed *et al.*, 1988).

The dissolution rate is much smaller than other processes under the same conditions. So, its effect on mass transfer may be neglected but the toxic components of dissolved products are an important process to be taken into consideration (Kuiper and Van Den Brink, 1987). The proposed equation of Riazi and Edalat (1996) for the rate of dissolution (F_{dis}) is used in this study:

$$F_{dis} = 1-\exp(-Q^{dis}\cdot t) \tag{7}$$

$$Q^{dis} = \left(\frac{K^{dis}}{y}\right)\cdot\left(\frac{C_s}{\rho_m}\right) \tag{8}$$

$$K^{dis} = 0.035\left(\frac{uL}{\nu}\right)^{0.8}\left(\frac{u}{D_v}\right)^{0.33}\left(\frac{D_v}{L}\right) \tag{9}$$

Where, K^{dis} is the mass transfer coefficient; ν is the kinematic viscosity of seawater; D_v is the diffusion coefficient of oil in water and L is the square root of surface area A.

The following equations are applied to predict the oil properties changed due to the weathering processes, specially evaporation and emulsion, in each time step (Mooney, 1951, Mackay *et al.*, 1980, Perry, 1992):

$$\mu = \mu_{ref}\exp\left(C_{E1}F_E + \frac{C_{wc1}F_{wc}}{(1-C_{wc2}F_{wc})}\right) \tag{10}$$

$$\rho_o = F_{wc}\rho_w + (1-F_{wc})(\rho_{ref}+C_{E2}F_E) \tag{11}$$

Where, μ_{ref} and ρ_{ref} is the viscosity and density of fresh oil at reference temperature T_{ref}. The constants C_{E1}, C_{wc1} and C_{wc2} are assigned values by the user based on the general oil type and C_{E2} is an experimental coefficient obtained in laboratory for each oil.

In this research, to simulate oil spill behavior in marine environment, a numerical model has been developed. The model consists of three sub-models namely hydrodynamic model, slick dynamic model and oil weathering model. In each time interval, the hydrodynamic sub-model computes the marine situation and surface currents velocities. 2D governing equations of tidal currents are solved using the finite volume method on the structured staggered grid system and the resulted algebraic expressions are solved by the ADI technique. The results of this stage are applied for the slick dynamic sub-model. To increase the compatibility with the hydrodynamic sub-model, the Eulerian approach is used to predict the slick transport on the sea surface. In each time step, the rates of mass losses from oil slick and the changes of spilled oil due to natural weathering processes are estimated by oil weathering sub-model. The verification of each sub-model was done and cited in literature (Aghajanloo and Pirooz, 2011; Aghajanloo *et al.*, 2011). This model coding has been done in Visual Fortran language

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RESULTS & DISCUSSION

The analytical simulation of oil spill in an open channel is chosen to validate the current model results. This case study is a channel, 20m long and 10m width in that the surface current velocity along the longitudinal axis of the channel is assumed, $u = 0.1\,m/s$. Table 1 presents the modelling conditions of this case study. The released of Statfjord crude oil is assumed in a single grid point at *y*=5*m*. The physical characteristics of this petroleum component are presented in Table 2 (Nazir *et al.*, 2008). The surface concentration of oil can be evaluated by an analytical equation as (Kang, 1998):

$$S(x, y, t) = \frac{M}{H4\pi t\sqrt{D_x D_y}} \exp\left(-\frac{(y - y_0)^2}{4D_y t}\right) \exp\left(-\frac{(x - ut)^2}{4D_x t}\right) \tag{12}$$

Where: M is the total mass of oil (*kg*), D_x and D_y are dispersion coefficients (m^2/s). Fig. 2 presents the comparison of the quantative results of numerical model with analytical solution in the centerline of channel. Also, Fig. 3 shows the slick transport along the channel. The results show the current model ability to simulate the oil spillage in open channel.

Current oil spill model is run for a virtual incident in the Persian Gulf to indicate its capability to use in a real marine environment. Persian Gulf is located on the southern part of Iran and it is a semi-closed water body (Fig. 4). The Hormuz Strait is the major inflow boundary of this area which has a width of 56 *km* and connects the Persian Gulf via the Gulf of Oman to the northern Indian Ocean. The Gulf approximately occupies 1000×250 *km* area.

For accurate simulation of the hydrodynamic flow behavior, the geometrical characteristics of study area must be introduced to model. Therefore, the model covers the area by a structured rectangular mesh with grid size ($\Delta x = \Delta y = 2\ km$), including 58417 nodes and 57401 elements (Fig. 5). Because of a variety range of bed elevation in the Persian Gulf, a high accuracy 3D bathymetry map has been provided (Fig. 6). Table 3 presents the other modelling conditions of this real case.

The tidal current in the Gulf is made by imposing tidal fluctuation to the main open boundary at Hengam Island, Hormuz Strait (26°39'N 55°53'E). The required data for water surface fluctuations in certain period of time are available and plotted in Fig. 7 from 2002/10/01 to 2002/10/12. After providing the model input data, it could be applied to simulate the tidal current. To evaluate the model output, a check point has been chosen and the results of numerical model have been compared with observed data. This point is Assaluyeh Port, in the northern coastline of the Gulf (27°30'N 52°36'E). The comparison between predicted results and measured data are presented in Fig. 8 and they show good agreement between them. Fig. 9 shows the predicted water surface elevation several hours after simulation start time.

There is no available data in terms of oil transport in the region for calibrating the model. Therefore only the model applicability is demonstrated here. To simulate an oil spill event, a virtual instantaneous release of Statfjord crude oil is assumed to be occurred in a position close to Assaluyeh Port. It is assumed that the oil spill is occurred four days after starting the hydrodynamic model. This time allows the model to reach a stability solution of current components. Fig. 10 shows the initial location of oil spill and slick path during the time. From this Fig. observed that the path of oil slick is diverted to the coastlines. The wind direction is an effective parameter on slick diversion

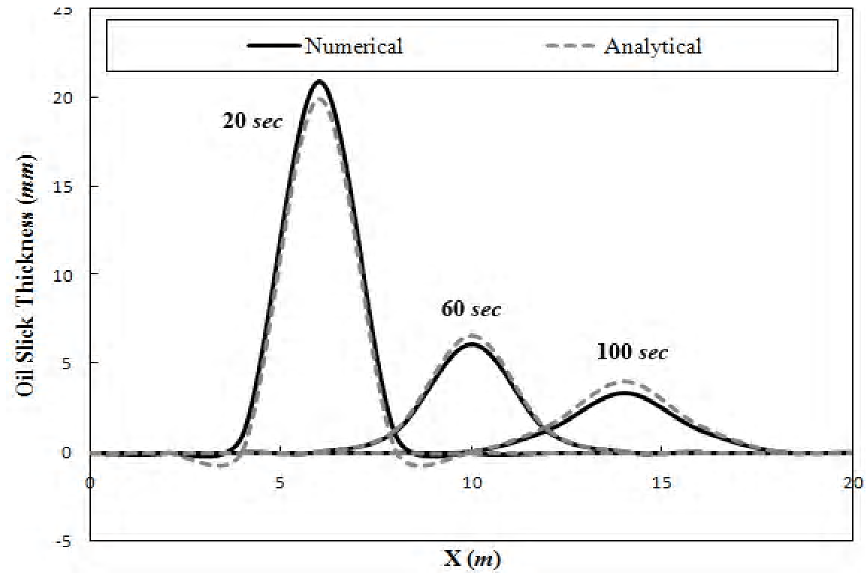

Fig. 2. Oil slick thickness at the channel centerline in different times

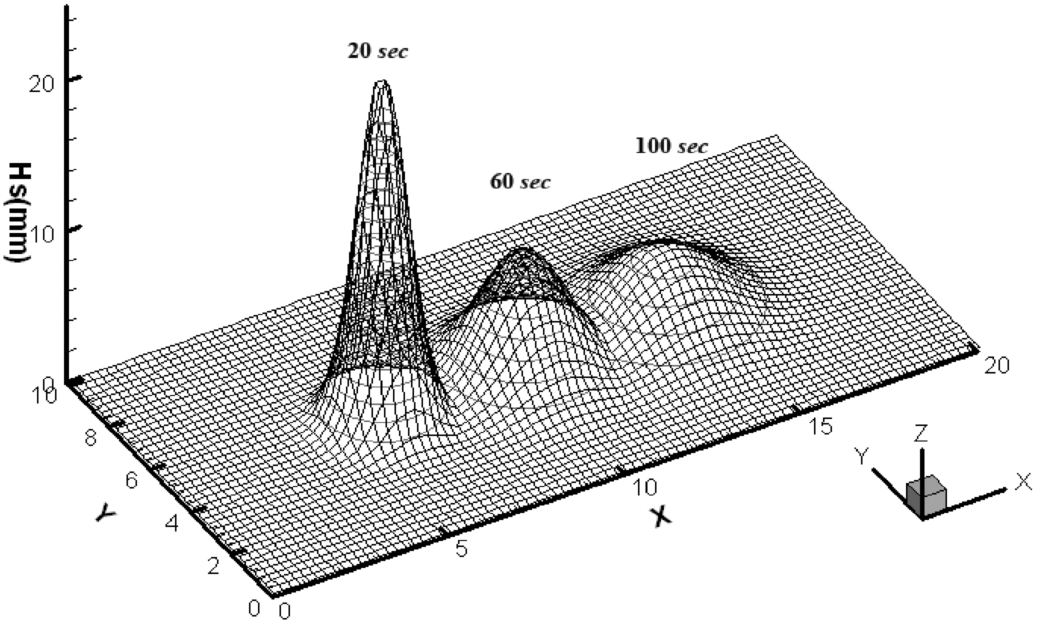

Fig. 3. Oil slick transport along the channel

Fig. 4. The modeling study area, Persian Gulf

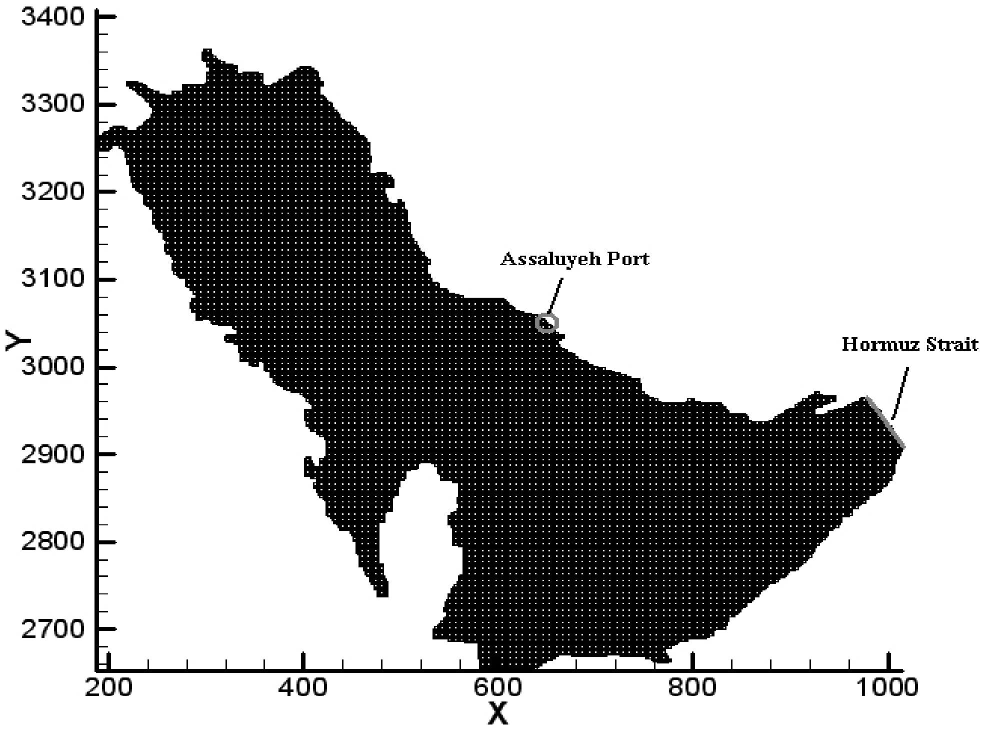

Fig. 5. The computational mesh of study area

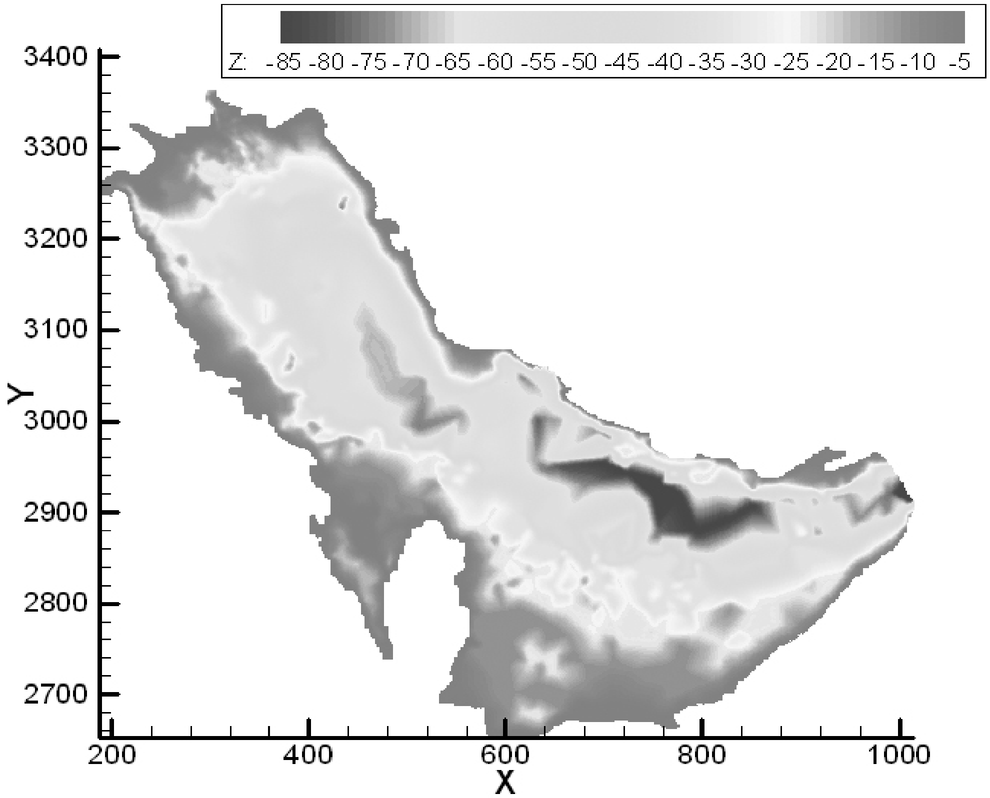

Fig. 6. The Bathymetry of study area

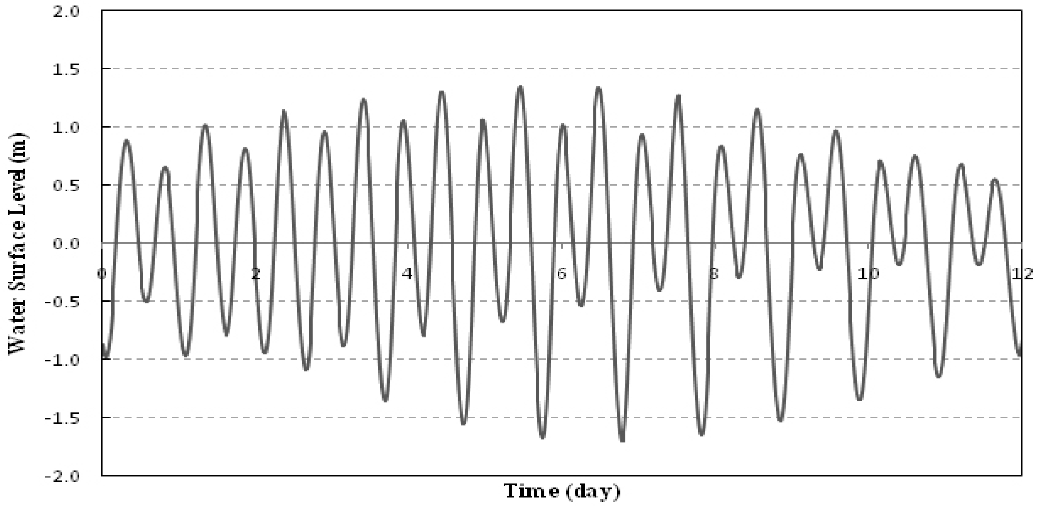

Fig. 7. Measured tidal fluctuation at Hengam Island, Hormuz Strait

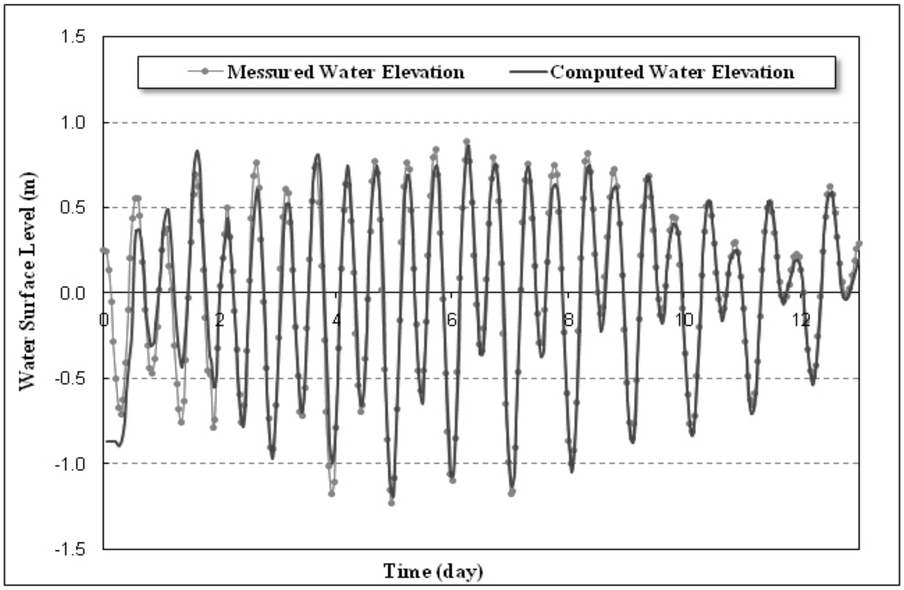

Fig. 8. The water surface elevations comparison at Assaluyeh Port

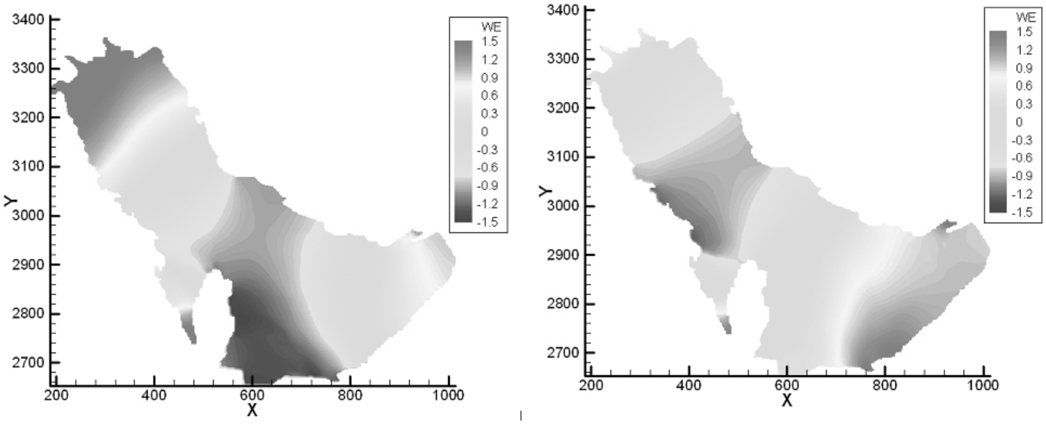

Fig. 9. Predicted water surface elevation by numerical model

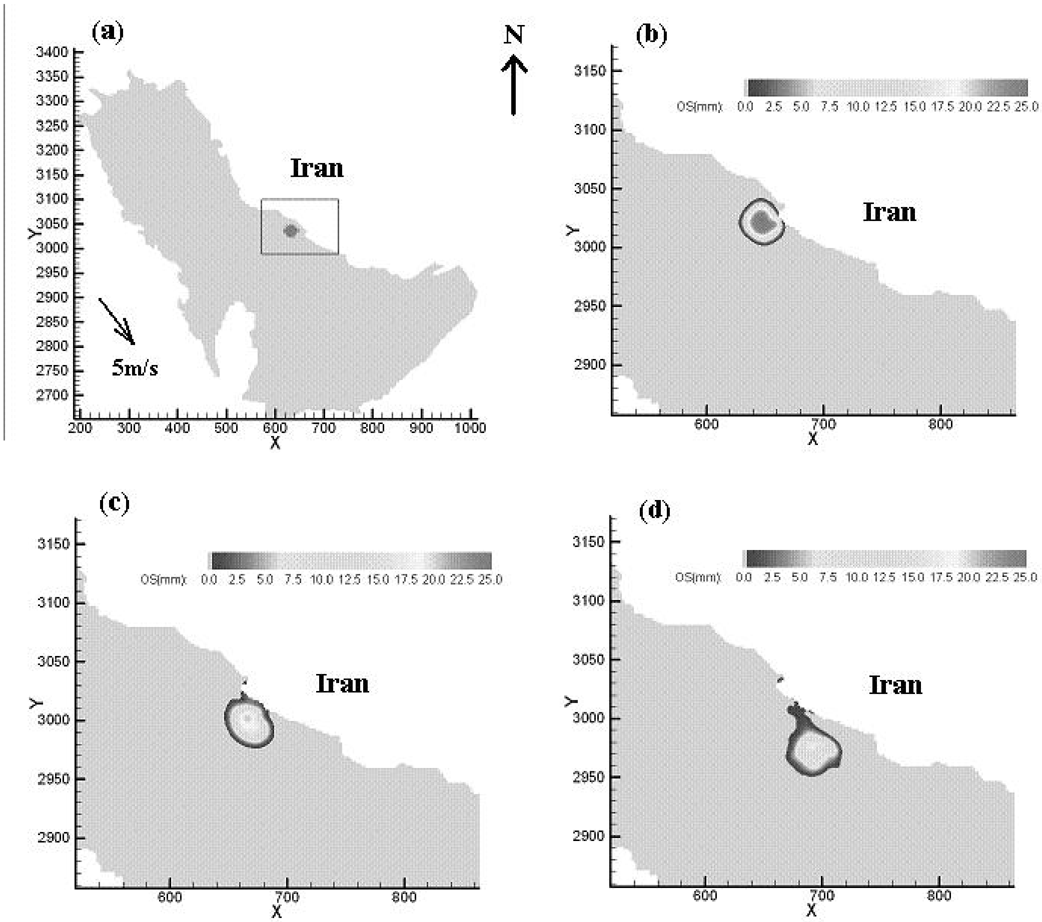

Fig. 10. The simulation results of oil slick transport during the time (a) initial (b) 1 day (c) 3 days (d) 5 days after spill

to the coastline and sensitive are, as well as tidal currents.

The changes of oil slick area (A_S) during the time are depend on the location of released, wind speed and blow direction, surface current velocity, type of oil, coastlines and islands adjacency, etc. The changes of normalized parameter of average slick thickness (h_S) are presented in Fig. 11. Hard decreasing of slick thickness in first hours is shown in this fig. This pattern occurs due to oil spreading on the sea surface and evaporation of major parts of petroleum production. Also, the changes of oil properties due to weathering process are computed by the model and their normalized parameters as shown in Fig. 12. The essential parts of these processes, especially evaporations and oil-in-water emulsification are happened in the first times of spillage. Therefore, the most portions of oil properties variations are occurred in this time. In this study, the changes of viscosity are significantly high, about 125 times larger than its initial value. Because of this increase, oil will be transformed to a high viscosity material and the rate of evaporation, slick transport become very slow.

The oil fate can be demonstrated by estimation of oil mass balances in three phases including air phase (the evaporated oil), water phase (the dissolved and dispersed oil in water column) and slick phase (remained oil) as shown in Fig. 13. In this study, after 5 days, about 38% of the total oil is lost by evaporation, 10% enters the water column (including dissolved and dispersed oil in water), 42% remains on the water surface. It is clear that, the mass balances of these phases depend on oil properties, environmental conditions (temperature, wind speed, etc.) and water characteristics (current velocity, turbulent energy, etc.). Throughout history several oil spill incidents have been reported in the Persian Gulf and the biggest of them was occurred in January 1991, nonetheless there is major leakages of available measured data about this case same as other incidents. Hereupon we have

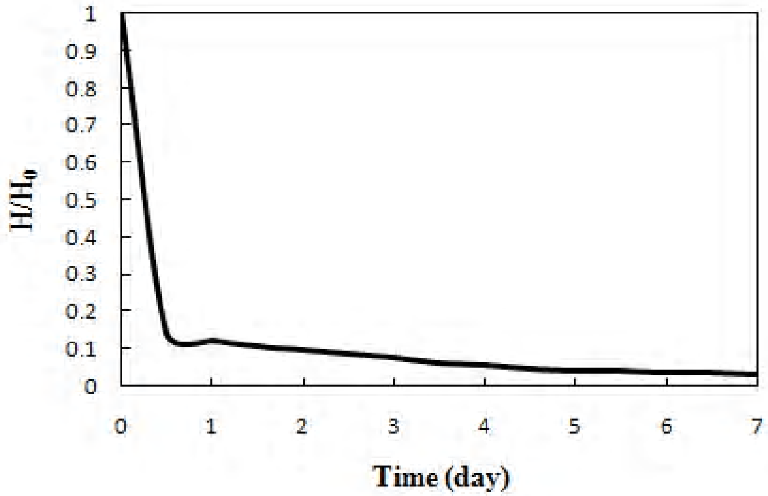

Fig. 11. Normalized parameter of average oil slick thickness

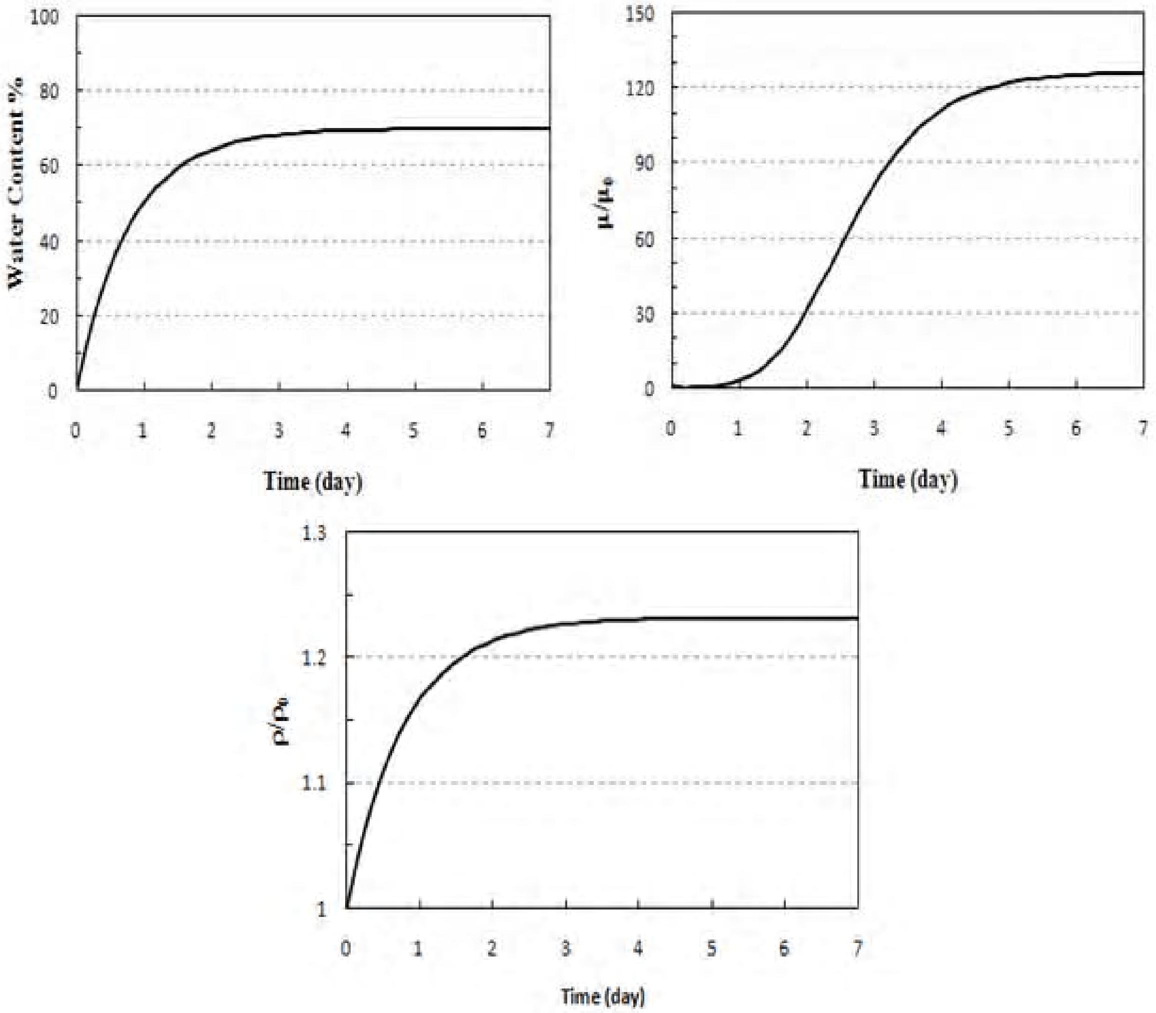

Fig. 12. Changes of oil properties (a) water content in oil-in-water emulsification, (b) dimensionless oil viscosity (c) dimensionless oil density

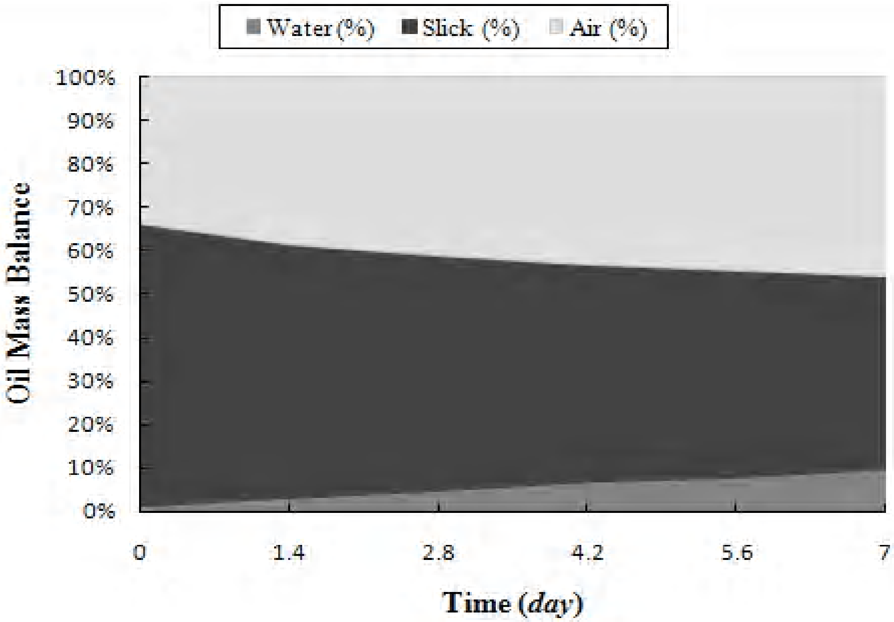

Fig. 13. The mass balance of each media due to oil weathering processes

principal difficulties to verify the results of our oil spill model and in this work we can only compare the predicted position of oil slick and its movement on the Gulf surface with available data.

During the Gulf War, major amounts of the Kuwait crude oil were released into the Persian Gulf from destroyed tankers, oil terminals and oil wells. The size of spilled oil is not known accurately owing to the hostilities at the time but there are several reports about it. In January and February 1991, approximately 8,000,000 barrels of oil spilled directly into the Gulf forming a 600 square mile of slick (NOAA, 1992).

In this stage, the 1991 Al-Ahmadi spill is modeled to ensure the model validity and the predicted positions of spilled oil by current model are compared with some observed data and predicted results of OILPOL model. The basic conditions of modelling are same as the virtual incident modelling in recent section, such as grid size, time step etc. The tidal current fluctuation at Hormuz Strait, over a 48 days period starting on 14 January, is used as hydrodynamic input data and an example of this is presented in Fig. 14 as water surface elevations. The wind above the oil slick was reported as north-west 20 knots (Al-Rabeh *et al.*, 1992). The spill rate of 12,500 barrels of Kuwait crude oil per hour is assumed over a ten days period starting at 00:00 hours on 19 January. The chemical and physical properties of Kuwait crude oil are presented in Table 4. In Fig. 15, oil slick positions predicted by current model are shown for several days after spill. As seen, the slick path is diverted to the south coastlines. Fig. 16 shows the distribution of the surface oil after 28 days on 18 February. To verify the results of model, some available data have been collected and shown in Figs 17-18. Fig. 17 presents the predicted position of oil slick on 18 February by OILPOL model (Al-Rabeh *et al.*, 2000) and the corresponding observed position is presented in Fig. 18. After analyzing the model output maps, a good agreement is seen between the predicted results by current model and other observed and predicted positions. In spite of the major leakage of sufficient data, the Figs are good evidence to ensure the model abilities.

CONCLUSION

In this work, a mathematical model is developed to simulate the oil spill behavior in real marine environment. The current oil spill model includes three major sub-models including: (a) the hydrodynamic model to simulate the tidal currents; (b) the oil slick dynamic model to simulate its transport on the sea surface and (c) the oil weathering model to predict the rates of oil losses due to natural processes and the changes of oil properties. The detailed characteristic of these sub-model were presented in recent works of authors (Aghajanloo and Pirooz, 2011, Aghajanloo *et al.*, 2011). The validation and verification of model is carried out by comparison the numerical results with analytical solution. The obtained results show the capability of the model in selected case study.

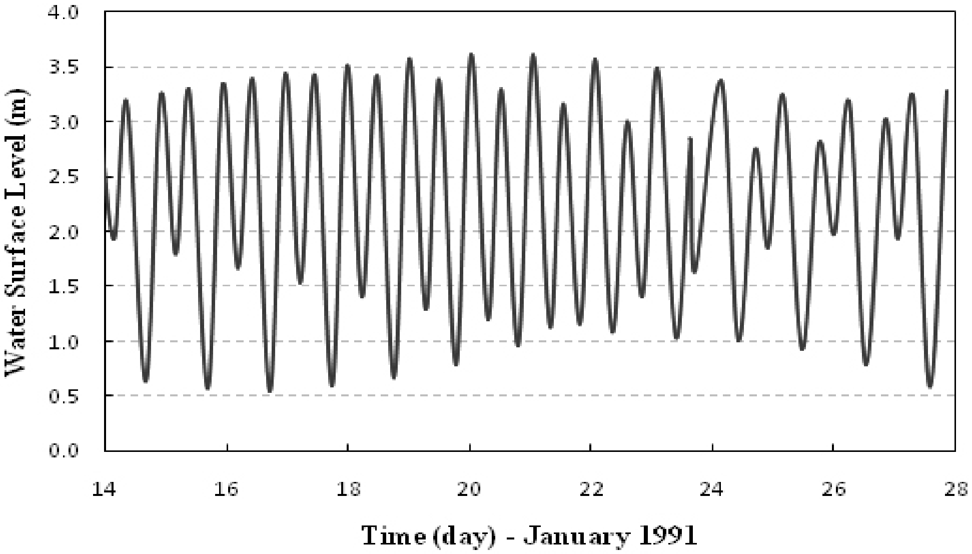

Fig. 14. Measured tidal fluctuation at Hormuz Strait

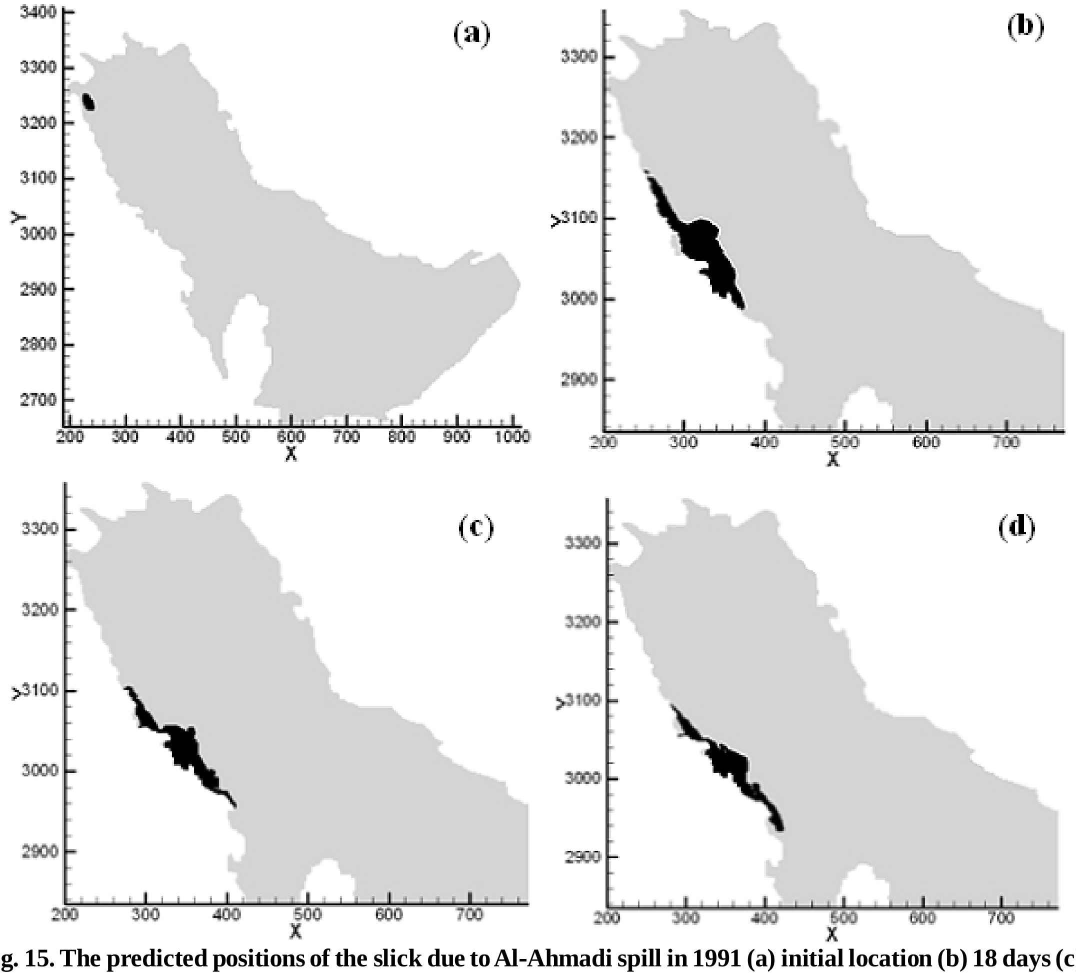

Fig. 15. The predicted positions of the slick due to Al-Ahmadi spill in 1991 (a) initial location (b) 18 days (c) 28 days (d) 35 days after spill

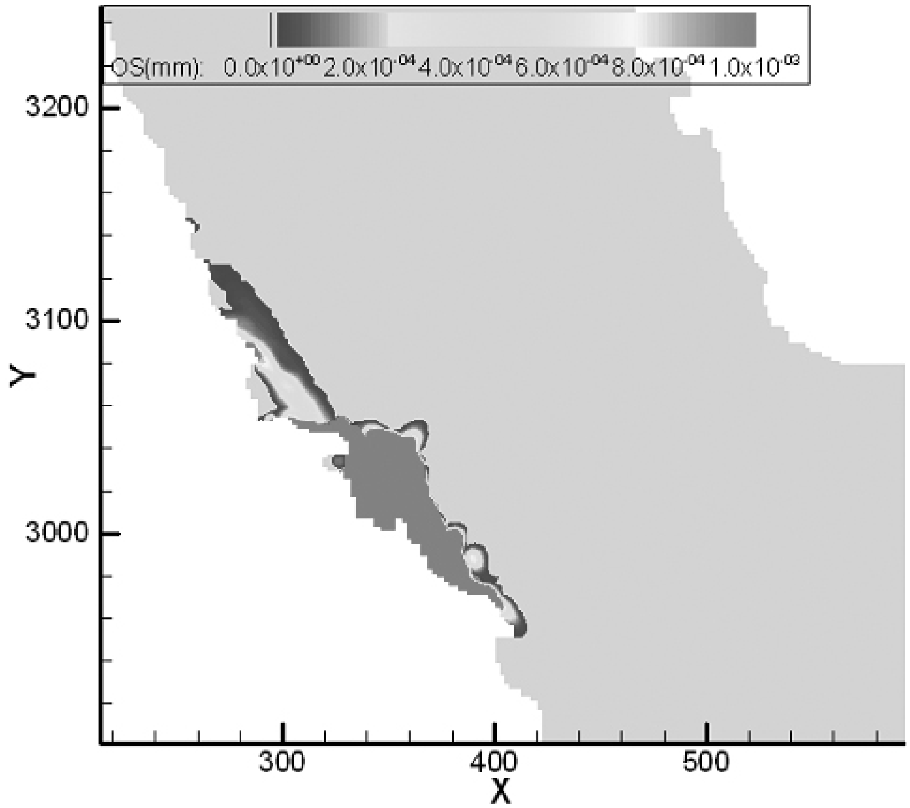

Fig. 16. The oil slick thickness map on 18 February (28 days after spill)

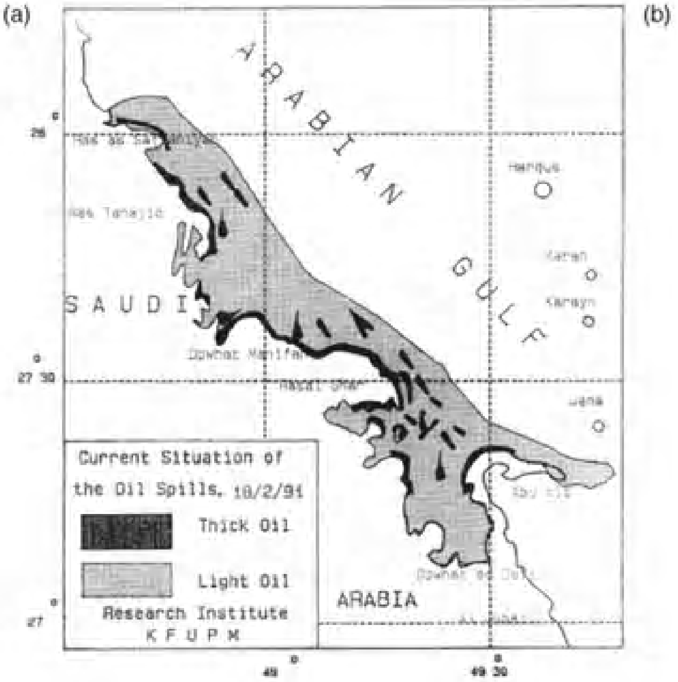

Fig. 17. Surface oil distribution of the Al-Ahmadi spill on 18 February 1991 predicted by OILPOL (Al-Rabeh *et al.*, 2000)

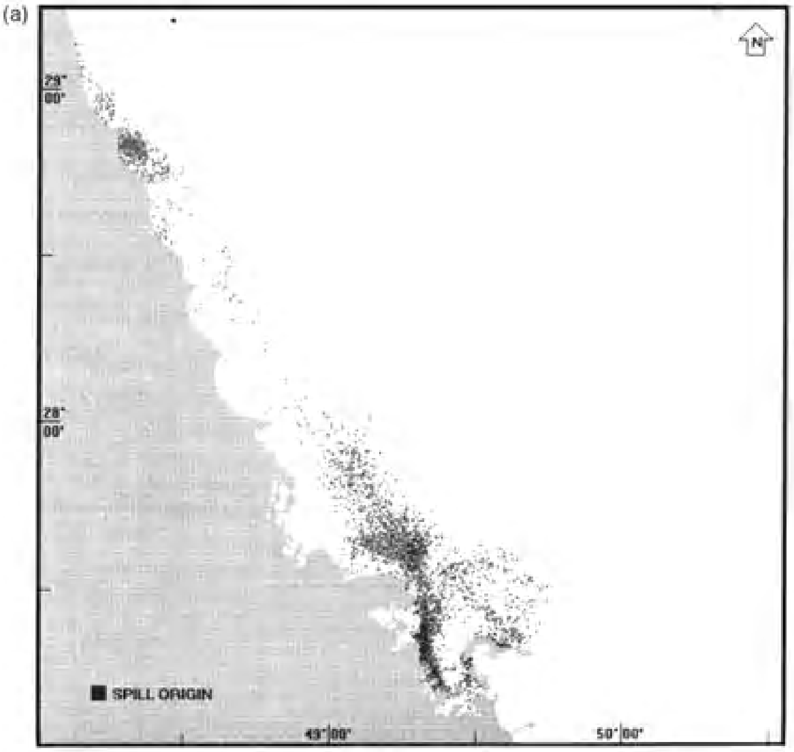

Fig. 18. Observed oil distribution of the Al-Ahmadi spill on 18 February 1991 (Al-Rabeh *et al.*, 2000)

Therefore, the model is run for a real marine environment, Persian Gulf and a virtual event is chosen to indicate the model capability in prediction of oil spill behavior in real field. Also, simulation of Al-Ahmadi spill is carried out to show the model ability to predict the accurate positions of oil slick during the time.

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