Development and Application of Accurate Oil Spill Model for the Persian Gulf

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Abstract: This paper presents the results of simulating oil spillage trajectory in the Persian Gulf by using the GH limiter. The GH limiter has been used for the first time with unique formulation. All the numerical solution dispersion errors (typical of second-order methods and above) can be diminished by limiters. GH limiter minimizes all the dispersion errors, even the under-shoots. A distinguished difference of this new limiter with other limiters is diminishing the errors without altering or reducing the maximum value of pollution. It is tested against other limiters to show the high precision of GH. The model has been applied to simulate the oil spill accident in the Al-Ahmadi located south of Kuwait in Persian Gulf and its performance were further validated against documented events of Al-Ahmadi historical oil spill crisis in the Gulf. A comparison of numerical results with the observed data shows good conformity.

Key word: Oil spill, Oil pollution on the sea, Numerical models, spread of oil slick, Weathering, Hydrodynamic Modelling, Ghiassi - Heydariha Limiter, Persian Gulf

INTRODUCTION

Shipping is responsible for an estimated 568,000 tons of oil entering the marine environment annually (Johanston et al., 1998). Since the 1950s many foreign scholars had discussed the computational method of extending scope of oil slick, while in the domestic region this job was started from the 1980s (Fay, 1969; Xin, 1984). Large numbers of related experimentations on diffusion, spread and extend of oil slick was done. It was concluded to extend formula considering the role of diffusion, spread and decay (Zhou-hu, 1992; Aravamudan, 1984) and also focus on relationship among oil, water and wave (Liu et al., 1998, Zhou-hu, 2001). The Oil spill numerical modeling was developed on the basis of hydrodynamic modeling, and it is primarily applied to actual projects (Lehr et al., 1981). This article uses the theory of hydrodynamic mathematical model, oil slick extending, and spread and diffusion model, establishing the mathematical modeling of oil spill behavior and fate on the sea with the consideration of spread, diffusion, drifting and attenuation of oil slick influenced by evaporation and emulsification factors. A simpler model that only represents the most important physical processes may provide equally accurate results when some of the input data is unknown or uncertain. By representing only the dominant processes and having the appropriate input data for them avoids that the results of not well-characterized secondary processes may spoil the quality of the output data (Sebastia, 2007). In the last three decades, many investigators have studied the transport and fate processes of oil spills based on the trajectory method (Mackay et al., 1980; Huang, 1983; Shen et al., 1990; Shen and Yapa, 1988; Yapa et al., 1994; Spaulding, 1995; Lonin, 1999; Chao et al., 2001; Nazir et al., 2008; Heydariha and Ghiassi, 2010). Rather than numerical methods, some other statistical or intelligence based techniques are also developed and applied for predicting marine parameters. Baruque et al. (2010) proposed a CBR based scheme to predict oil slick movement and Malekmohamadi et al. (2008) developed an AAN based method to forecast wind induced wave characteristics.

2 Physical And Chemical Processes Of Oil Spill

Figure 1 shows a sketch of the important transport and weathering processes that affect oil spreading following a spill (Rasmussen, 1985). The main mechanisms which govern the fate of oil slick in marine are spreading, evaporation, dispersion, emulsification, sedimentation and biodegradation. They are understood with different levels of confidence and can be described by mathematical models, partially based and calibrated on empirical results. The nature of the different mechanisms will be reviewed. Figure 2 shows that a particle spending a higher proportion of time in the surface layers is advected further due to the effects of the wind and waves. It is important to note that the advection forces are independent of each other so that the wind and waves can act in the direction same or opposite to the tide. (Wang et al., 2008)

2.1. Evaporation:

Evaporation accounts for the largest loss in oil volume during the early stages of the slick transformation. It is mainly a function of wind speed (at 10 m above water surface), spill area, surface temperature and initial vapor pressure of oil among other parameters. In the present study, the following formulation is used to
calculate the rate of oil evaporated, proposed by Mackay (1980) and modified by others (Mackay et al., 1980a; Mackay et al., 1980b; API 1999)

\[ F = \left( \frac{1}{c} \right) \left[ \ln(P_0) + \ln \left( \frac{C K E t}{P_0} \right) \right] \]  

where \( E = K E \) is the "evaporative exposure" term, that varies with time and environmental conditions;

\[ K E = K_M \times A \times V_M / (R \times T \times V_0) \]

in which \( K_M = 0.0025 \times U_{\text{wind}}^{0.78} \) is the mass transfer coefficient (m/s); \( U_{\text{wind}} \) is the wind speed (m/s); \( A \) is the spill area in (m\(^2\)); \( V_M \) is the molar volume (m\(^3\)/mol); \( R \) is the gas constant equal to \( 82.06 \times 10^{-6} \) (atm.m\(^3\)/mol/K); \( T \) is surface temperature of the oil (K) that is generally close to the ambient air temperature \( T_E \) in K, and \( V_0 \) is the initial spill volume (m\(^3\)). (Mackay et al., 1980a)

The initial Vapor pressure \( P_0 \) in atmosphere at the temperature \( T_E \) is

\[ \ln(P_0) = 10.6(1 - T_0 / T_E) \]

where \( T_0 \) is the initial boiling point in K. The constant \( C \) can be determined by the relationship \( T_E C = \text{const.} \)

\[ C = 1158.9 \times API^{-1.1435} \]

\[ T_0 = 542.6 - 30.275 \times API + 1.565 \times API^2 - 0.03439 \times API^3 + 0.0002604 \times API^4 \]

A comparison of oil properties for a variety of crude oil and refined oil products is shown in table 1. All numbered persistence data are based on the relative persistence of the product in the environment, devided by the least persistent oil product (gasoline). The data of the table are adapted from (Curl and O’Donnel, 1997; Gilfillan, 1993; API, 1990; Markarian et al., 1993).

Fig. 1: Schematic description of oil spill processes (Shen and Yapa, 1988)

Fig. 2: Diagram of different forces act on particle advection (Corps, 2002).
Table 1: Characteristics of different oil types

<table>
<thead>
<tr>
<th>Product</th>
<th>Specific Gravity</th>
<th>API Gravity</th>
<th>Boiling Point (°F) Range</th>
<th>Relative Persistence</th>
<th>Pour Point (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>0.74 to 0.73</td>
<td>62 to 9</td>
<td>302 to 104</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Jet Fuel (JP-4)</td>
<td>0.80 to 0.75</td>
<td>56.7 to 44.3</td>
<td>518 to 203</td>
<td>-2</td>
<td>-</td>
</tr>
<tr>
<td>Kerosene</td>
<td>0.88 to 0.80</td>
<td>43 to 29</td>
<td>572 to 392</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Fuel Oil No. 2 (Diesel)</td>
<td>0.88</td>
<td>29</td>
<td>365 to 93</td>
<td>8</td>
<td>20</td>
</tr>
<tr>
<td>Lube Oil (Crankcase)</td>
<td>0.87</td>
<td>29</td>
<td>822 to 710</td>
<td>55</td>
<td>-35</td>
</tr>
<tr>
<td>Kuwait Light Crude Oil</td>
<td>0.85</td>
<td>37.8</td>
<td>-</td>
<td>320</td>
<td>-50</td>
</tr>
<tr>
<td>Fuel Oil No. 6 (Bunker)</td>
<td>0.97 to 0.96</td>
<td>18.5 to 10</td>
<td>826 to 615</td>
<td>400</td>
<td>60</td>
</tr>
<tr>
<td>North Slope Crude Oil</td>
<td>0.89</td>
<td>35 to 17.5</td>
<td>-</td>
<td>450</td>
<td>-</td>
</tr>
<tr>
<td>San Ardo (CA) Crude Oil</td>
<td>0.99</td>
<td>17.5 to 5</td>
<td>-</td>
<td>590</td>
<td>80</td>
</tr>
<tr>
<td>Residual Asphalt</td>
<td>-</td>
<td>10&gt;</td>
<td>752&lt;</td>
<td>1600</td>
<td>-</td>
</tr>
</tbody>
</table>

2.2. Emulsification:

The rate of emulsification increases when sea state rises. Emulsification can be described by (K.J. Farrell and A.M. Cawley, 1996):

\[
\frac{dY_w}{dt} = k_d (1 + U_s)^2 (1 - \frac{Y_w}{Y_w^f})
\]

where \(Y_w\) is fractional water content, \(Y_w^f\) is the final fractional water content (= 0.8), \(k_d\) is an empirical coefficient (=5.4×10^{-6}), \(U_s=3.5\% \times \text{Wind Speed}\) which is chosen to be dependent on wind speed. According to Fingas (1994), the viscosity of the oil changes from a few hundred cSt to about 50,000 cSt. This changes a liquid product to a heavy, semi-solid-like material (McLean and Kilpatrick 1997a, McLean and Kilpatrick 1997b). The National Research Council (2003) found that evaporation and spreading slow down due to emulsification; a preliminary experimental study by Ross and Buist (1995) found that oil evaporation is reduced when oil is mixed with water to form a stable water-in-oil emulsion. By increasing water content, evaporation rate decreases, as shown in Figure 3.

![Fig. 3: Relationships between the evaporation and the water content of oil emulsion (Ross and Buist, 1995)](image)

2.3. Dissolution:

Dissolution is an important process from the point of view of possible biological harm, although it only accounts for a negligible fraction of the mass balance of the oil. It is a function of oil slick area, dissolution mass transferability and oil solubility in water. The present study uses the method of Cohen et al. (1980) and Huang and Montastero (1982). In this method the total dissolution rate \(N\) is calculated by

\[
N = KA\cdot S_0
\]

where \(K = 0.01 \text{ m/hr}\) and \(S_0 = 30 \text{ g/m}^3\).

2.4. Shoreline Deposition:

The vulnerability of a rocky shoreline to oiling depends on its topography and composition as well as its position. At one extreme, a vertical rock wall on a wave exposed coast is likely to remain unoiled if an oil slick is held back by the action of the reflected waves. At the other extreme, a gradually sloping boulder shore in a calm backwater of a sheltered inlet can trap enormous amounts of oil which may penetrate deep down through the substratum. The complex patterns of water movement close to rocky coasts also tend to concentrate oil in certain areas. Some shores are well known to act as natural collection sites for litter and detached algae and oil is carried there in the same way. On exposed coasts these sites are usually boulder/cobble beaches at the backs of bays or gullies which act as traps for the oil. As on all types of shoreline, most of the oil is concentrated along the high tide mark while the lower parts are often untouched. Oil tends not to remain on wet rock or algae but is likely to stick firmly if the rock is dry.
The present model simulates the shoreline deposition through an exponential decay function similar to that of the half-life method (Torgirimson, 1980). The volume of oil remaining on the shoreline is related to its original volume by:

\[ V_2 = V_1 e^{-k(t_2 - t_1)} \]  

(5)

where \( V_1 \) and \( V_2 \) are the volumes of oil on the shoreline at times \( t_1 \) and \( t_2 \), respectively. The decay constant \( k \) is expressed as \( k = [-\ln (1/2)]/\lambda \). In which \( \lambda \) is the half life. (Shen and Yapa, 1989-1990). Table 2 presents the halflife for different types of shorelines along with their vulnerability indices.

<table>
<thead>
<tr>
<th>Shoreline descriptor</th>
<th>Half-life (h)</th>
<th>Vulnerability index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposed headland</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Wave-cut platform</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Pocket beach</td>
<td>24</td>
<td>3</td>
</tr>
<tr>
<td>Sand beach</td>
<td>24</td>
<td>4</td>
</tr>
<tr>
<td>Sand and gravel beach</td>
<td>24</td>
<td>5</td>
</tr>
<tr>
<td>Sand and cobble beach</td>
<td>8760</td>
<td>6</td>
</tr>
<tr>
<td>Exposed tide flats</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Sheltered rock shore</td>
<td>8760</td>
<td>8</td>
</tr>
<tr>
<td>Sheltered tide flat</td>
<td>8760</td>
<td>9</td>
</tr>
<tr>
<td>Sheltered marsh</td>
<td>8760</td>
<td>10</td>
</tr>
<tr>
<td>Land</td>
<td>8760</td>
<td>0</td>
</tr>
</tbody>
</table>

3 Governing Equation and Solution Scheme
3.1. Convection-Diffusion Equation:

To simulate oil droplets transport in the water column, the advection-diffusion equation is used:

\[ \frac{\partial C}{\partial t} + \nabla (C(\overline{u}_x + \tau / f)) = \nabla (E_s \nabla C) + R_k \]  

(6)

where \( C \) is the concentration of the oil droplets in the water column; \( \overline{u}_x \) is the horizontal velocity; \( E_s \) is the horizontal turbulent diffusion coefficient; \( R_k \) is the oil kinetics term. At the interface of oil slick and water layer, where oil-slick mixing layer is appeared, the oil mass exchange is calculated according to the following kinetic (Tkalich 2001a, Tkalich 2001b):
\[ R_h = \frac{\delta_t}{Z_m}(C_{\text{max}} - C) + \frac{\nu}{Z_m}(C_{\text{min}} - C) \quad (7) \]

where \( C_{\text{max}} = h_0 \rho_0 / Z_m \) is the maximal possible concentration of the oil droplets; \( h_0 \) is the initial oil slick thickness in the unit surface area; \( C_{\text{min}} \) is the concentration of small droplets, which are not able to resurface due to small buoyancy and excessive downward mixing force; \( \delta_t \) is the rate of the slick dispersion because of the wave breaking (is a function of the wind speed or height of the respective breaking waves); \( b_s \) is the evaporation rate.

3.2. Solution of Hydrodynamics Field:

A finite volume numerical model, CECAD-FSF, that had been developed by the author for solving the equations of fluid motion Cartesian coordinate system, is applied for flow modeling in the Persian Gulf. Staggered mesh is used to reduce the numerical oscillation. To solve the equations during the time, Alternative Direction Implicit (ADI) scheme is applied. In each time step, the flow surface level \( \xi \) and the velocity components (\( u, v \) and \( w \)) are calculated.

3.3. Solution of Advection-Diffusion Equation:

Three-dimensional advection-diffusion equation is discretized by applying the finite volume method in the Cartesian coordinate system and using the ADI scheme to solve it during the time. The solution scheme is second order accurate in space. Third-order upwind scheme is applied for spatial discretization of advective terms and second order central scheme is used for diffusive terms. The scheme is less diffusive compared to the first and second-order accurate schemes, if used for advective discretization.

4 Flux Limiter:

4.1. Limiter Implementation:

Flux limiters are used in high resolution schemes to avoid the spurious oscillations (wiggles) that would otherwise occur with high order spatial discretization schemes due to shocks, discontinuities or sharp changes in the solution domain. By using higher-order methods to achieve more accurate results we will face dispersion errors as it shown in figure 5. It’s typical for second and higher order methods.

![Fig. 5: Effects of dissipation and dispersion](image)

There are several types of limiters to capture and reduce oscillations around shock waves. The most applied limiters are MinMod, SuperBee and MC.

4.2. GH Limiter:

An effective limiter is proposed by the authors of this paper to apply for prohibiting oil concentration oscillation during oil spill simulation. This limiter uses data of 5 grids to reduce distortion around one grid. The Ghiassi-Heydariha Limiter can be defined as the following:
where a and b are slopes between grids \( (i-1) \approx (i) \) and \( (i) \approx (i+1) \) respectively. By using 3 points, it’s possible to achieve the acceptable accuracy which is shown in above figures.

4.3. Limiter verification:

The following three test problems are selected on the basis of simplicity and ease of reproducibility, and are intended to represent basic characteristics of behavior that might be encountered in practice. A given numerical scheme is considered successful if it is able to simulate all three test problems to within some desired level of performance; if a scheme fails one or more of the tests, it is deemed unsatisfactory no matter how accurately it simulates any one of the other tests. Performance is judged on the basis of a basic criterion: (1) total absolute error (ABSERROR) where \( \varepsilon \) is the local error at each node

\[
\varepsilon = \phi_{\text{computed}} - \phi_{\text{exact}} \tag{9}
\]

and (2) the WAVINESS or Total Variation of Error

\[
\omega = \sum_{i=1}^{N} |e_{i+1} - e_{i}| \tag{10}
\]

The first test profile follows that used by Sweby (1984), an isolated sine-squared wave of width 20Ax

\[
\phi_{t}(t=0) = \sin^{2}\left(\frac{\pi x}{20Ax}\right) \text{ for } 0 \leq x \leq 20Ax
\]

\[
= 0 \quad \text{otherwise} \tag{11}
\]

This function represents a relatively smooth profile with a continuously turning gradient and a single local maximum. In order to simulate practical situations, it is important to run the test problems over the same prescribed distance in all cases, irrespective of time-step (Courant number) or initial profile shape. In the tests described here, for example, the exact solutions advance by 80 mesh-widths. Two Courant numbers are used: \( c=0.05 \) (900 time steps), representing small \( \Delta t \); and a "moderate" value of \( c=0.5 \) (90 time steps). The 25-time-step simulation used by Sweby was not long enough to see significant differences between the methods studied, or to allow their gross deficiencies to develop (which are typically worse at small Courant numbers, for a fixed distance).

The second test profile is a unit step change in \( \phi \) over one mesh width. Initially, \( \phi = 0 \) everywhere to the right of a specified jump point all other points, including the upstream boundary, are set at 1.0. The unit step profile 10 is more fundamental than the isolated "square-wave", or box, used in some previous studies (e.g. Sweby used an isolated rectangular box of width 20Ax in addition to the isolated sine-squared function of the same width). The box profile, at best, merely gives twice as much information as the unit step. But for highly oscillatory methods, oscillations excited by the step-up interfere with those due to the step-down, and the resulting complex wave-pattern is not as enlightening as that of the simple step simulation. Basic test of monotonicity, a fundamental aspect of advective modeling. A "good" step simulation is one which monotonically resolves the step in a "small" number of mesh widths - the smaller the (monotonic) "numerical width," the better the method.

The unit step is also a The third test profile follows one used by Steven (Zalesak1987) that he attributes to B.E. McDonald. It consists of a semi-ellipse of width 2iw, initially centered at \( i_w \)

\[
\phi_{t}(t=0) = \sqrt{1-(i-i_w)^2/i_w^2} \text{ if } |i-i_w| \leq i_w
\]

\[
= 0 \quad \text{otherwise} \tag{12}
\]

This is a rigorous test in that an initial (leading) step change in gradient is followed by a region of continuously changing gradient and finally by a trailing step. Methods which are oscillation - free in the simple step simulation may generate significant waviness just behind the leading step or just ahead of the trailing step.

The test used here differs slightly from that used by Zalesak in being 20Ax wide to conform to Sweby's sine-squared profile, rather than 30Ax; this does not have any significant qualitative effect on results.
Fig. 6-A: Courant = 0.05  ABS(ERROR) = 0.47  Corrected ABSERROR = 0.39

Fig. 6-B: Courant = 0.05  ABS(ERROR) = 0.27  Corrected ABSERROR = 0.20

Fig. 6-C: Courant = 0.05  ABSERROR = 2.6  Corrected ABSERROR = 2.1
4.4. Comparison with MinMod:

The described GH limiter is compared with MinMod limiter to evaluate its efficiency, as illustrated in figures 7 to 9. Figure 7 shows the result of Fromm method for a simple test without applying any limiter (Warburton, 2005a). As can be seen, there are some oscillations on either side of discontinuity. After applying the MinMod limiter, due to its formulation, there won’t be any oscillations but the maximum value will be greatly reduced (figure 8).
Fig. 7: Fromm (central slope): Oscillations either side of discontinuity (Warburton 2005b)

Fig. 8: The MinMod limiter has clearly been activated at the turning point on the smooth part of the solution which is not desirable.

Fig. 9: The GH limiter functions very well

GH limiter is diminishing the errors without altering or reducing the maximum value of pollution like MINMOD (figure 9).
5 Oil spill in the Persian Gulf:
5.1. Hydrodynamic Data:
The developed 3D hydrodynamic model has been already applied and calibrated for the Persian Gulf to simulate the tidal currents in the Gulf. The location of Hormuz (and Larak) island at the Strait of Hormuz is suitable to represent the water level entering the Persian Gulf. Tidal elevations at different locations of the Persian Gulf are available. Computational domain for oil spill simulation is limited to the North West part of the Gulf as shown in figure 10. Computational results of the Persian Gulf were mixed with tidal constituents (i.e. water level) at Hormuz Island to generate the open boundary condition at the east side of the concerned domain. General flow pattern in the concerned domain is in agreement with several flow models in the north west of the Persian Gulf also velocities are of order of 15 cm/sec which is appropriate for this domain. (Elahi and Ashrafi, 1992)

![Figure 10: Transient spill in clockwise field of spring tide](image)

5.2. Wind Data:
For accurate oil spill modeling, the daily wind velocity need to be applied that, unfortunately, was not available for simulating Al-Ahmadi spill event. Al-Rabeh et al. (1992) used average effective monthly wind velocities values and directions in the Gulf. These values were used for summer and winter simulations (Table 3) but in the current modeling as suggested by Al-Rabeh (1994) Optimal values for wind deflection angle (γ) and wind drag coefficient (β) for the Gulf, 26.03° to the right of the wind direction and 0.031 were used.

<table>
<thead>
<tr>
<th>Season</th>
<th>Jan</th>
<th>Feb</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>Sept</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direction (°)</td>
<td>141.7</td>
<td>131.7</td>
<td>132.5</td>
<td>128.5</td>
<td>118.5</td>
<td>127.7</td>
<td>122.8</td>
<td>126.3</td>
<td>132.8</td>
<td>143.4</td>
<td>147.8</td>
<td>135.9</td>
<td>132.7</td>
</tr>
</tbody>
</table>
5.3. Previous Simulations:
Al-Ahmadi oil spill was occurred over the period of January–May 1991 in Kuwait in the upper part of the Persian Gulf and available information and sightings are reported by Al-Rabeh *et al.* (1992). Al-Rabeh stated that the volume of oil released may have been as large as $6 \times 10^6$ barrels. The oil type was medium Venezuelan and was mostly released at or near Mina Al-Ahmadi 25 km south of Kuwait city.

Results of three different models are compared in this paper. (a) Among several researchers who have described and simulated the occasion, the trajectory model (GULFSLIK II) applied in King Fahd University of Petroleum and Minerals (Al-Rabeh *et al.*, 1992) provided reasonably accurate predictions and have extensively documented the actual trajectory of the spill. (b) MIKE3-SA module solves the so-called Fokker-Planck equation for suspended oil substances by the Lagrangian Discrete Parcel Method (LDPM). (c) The current model, developed based on the mentioned scheme described in sections 3.2 and 3.3, is using the flow field produced from the previous hydrodynamic simulation typical to the validation setup as described in section 5.1.

All The models take into consideration the natural dispersion, evaporation, emulsification, and dissolution as the encountered weathering processes in the oil spill analysis. Figure 11 represents the actual and predicted trajectories of the oil spill over the period from January 19, 1991 to February 14, 1991.

5.4. Simulation Results:
To evaluate the slick trajectory, the slick leading edge advancement with time was derived from simulation results as reported in Table 4 along with the times recovered from the actual oil spill sighting and from the simulated KFUPM GULFSLIKII model at five stations along the Saudi coast.

The simulation results show that after the first week of the February, a non-prevailing southeastern wind front took place. This caused lowering the velocity magnitude of the northwestern wind in the region and the trajectory of the oil spill was reversed and delayed during the rest of February and March, when the net wind blow was in favor of the northwestern wind which again caused the spill to move slowly in the southeast direction. Relatively, a simulated trajectory similar to the actual trajectory plot is produced (Figure 11). The simulation results reveals that much more horizontal spreading took place during the holding conditions in the February as was typically noticed by Spaulding *et al.* (1993). The spill moved northwest due to the southeast wind front which caused the spill to impact the Saudi coast from latitude 28º40′ to 27º20′ from the period of February 11, to March 18, 1991. Al-Rabeh *et al.* (1992) reported that the oil spill impacted the Saudi shoreline from latitude 28º44′ to 27º. The MIKE3-SA and CURRENT MODEL results showed that the impacted region along the Saudi coast was almost similar to the actual condition. The extent of shoreline impact was less in the simulation than it was in real life. This is probably due to the difference in the wind data combination of magnitude, direction, and duration from the real data.

![Fig. 11: (a). Al-Ahmadi spill actual and predicted trajectory of leading edge as reported by Al-Rabeh *et al.* (1992) (b). Al-Ahmadi oil spill trajectory with speculated wind data (southeast wind front) using GULFSLIKII (c). Al-Ahmadi oil spill trajectory with speculated wind data (southeast wind front) using MIKE3-SA (Elhakeem2007) (d). Al-Ahmadi oil spill trajectory with speculated wind data (southeast wind front) using Current model](image-url)
Figure 12 shows the average thickness of the oil slick as a function of time. It can be observed that the oil slick thickness decreases rapidly during the first 5-6 h. This means that the first stage of spreading occurs within a short time. After the initial phase involving gravity, inertia, and viscous forces, the surface tension phase of spreading takes over and lasts for a longer time until the oil slick becomes unstable and breaks up (Chao et al., 2003).

![Thicknness of Oil Slick](image)

**Fig. 12:** Averaged thickness of oil slick

<table>
<thead>
<tr>
<th>Location</th>
<th>Date of actual oil sighting</th>
<th>Predicted date of impact using GULFSLICKII</th>
<th>Predicted date of impact using MIKE3</th>
<th>Predicted date of impact using CURRENT MODEL</th>
</tr>
</thead>
</table>

**Conclusion:**

Simulating results of oil slick transport and its fate on the Persian Gulf has been presented in this paper. The northwestern wind front effect started hindering the slick down-movement during the second week of February until the first week of March. Due to the sheer effect of the confronting wind fronts, this caused the slick to spread laterally and resulted in fragmenting the slick into smaller patches. The model takes into account major physical-chemical phenomena of oil slick. In order to achieve high accuracy, the GH flux limiter has successfully implemented to minimize errors. As shown earlier, three practical tests has been done to make sure the competency of this limiter and also its performance were further validated against famous Minmod limiter and the results have been shown. The model was able to correctly predict the slick center of gravity movement. The simulated results show that the model is useful for investigating the oil slick trajectory on the water surface.

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