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تطوير نموذج التتابعية العددية لانسكابات النفط البحرية

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الخلاصة

تم تطوير نموذج عددي اسمه «B-Oil» استنادا إلى حل المعادلات التفاضلية الجزئية للتدفق وملوثات الامتزاج لاعادة تتبع البقع النفطية في المناطق البحرية الكويتية ومياه الخليج العربي [السالم والبنا، 2015]. واقترن هذا النموذج مع نموذج KGulf وهو نموذج عددي هيدروديناميكي [السالم، 2012] ، الذي يمد نموذج B-Oil بالمعلومات عن حركة المياه السطحية. تم اعتماد خوارزمية لاغرانج لتتبع مصدر الانسكابات النفطية، وتم تطبيق تقنية إحصائية مونتي كارلو للتعرف على السير العشوائي في خوارزمية لاغرانج. تم التحقق من فاعلية التقنية عن طريق تطبيقها على ثلاثة حوادث النفطية السابقة التي وقعت في منطقة الخليج العربي ووثقت في المنشورات العلمية. وقد عمل النموذج على نحو كاف في توقع مصدر التسرب النفطي، وقد تحققت دقة عالية للنتائج خاصة عندما تكون المسافة بين مصدر التسرب النفطي والموقع المنتقل اليه أقصر مقارنة مع مسافات أكبر. ويعزى ذلك أساسا إلى قلة تمثيل للتيارات البحر السطحية في النموذج حيث تم استخدام متوسط سرعة الرياح. ومع ذلك، بإجراء عدد اختبارات أكبر، والذي بدوره يزيد من وقت النموذج الحسابي قد تبين تحسن في تنبؤات النموذج. وبقول ذلك، فإن امكانات وحساسية النموذج تم اختبارها عن طريق تطبيق عدة سيناريوهات عددية واختبار أهمية المتغيرات العددية على النموذج. يمكن استخدام هذه التكنولوجيات على أساس الوقت الحقيقي للتنبؤ بمصدر حدوث التسرب للنفط (أو أي مجسمات عائمة تتبع ميكانيكا لاغرانج في حركتها) مما يساعد صناع القرار في الاستجابة في الوقت المناسب لحوادث التسرب النفطي في المناطق البحرية او أي حادث طارئ.

Development of a backtracking numerical model for offshore oil spills

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ABSTRACT

A numerical model named 'B-Oil' is developed, based on the solution of the governing partial differential equations of flow and immiscible pollutants to backtrack oil slick incidents in both Kuwaiti offshore regions and the Arabian Gulf waters.The model was coupled with the KGulf Model, a hydrodynamic numerical model,which supplies the necessary 2-D flow fields of the surface waters. The Lagrangian discrete parcel algorithm was adopted to backtrack oil spills, and the Monte Carlo statistical technique was applied to overcome the random walks in the Lagrangian discrete parcel algorithm. The adopted technique was investigated with three previous oil incidents, documented in literature, which occurred in the Arabian Gulf. The model performed adequately in predicting the source of the oil spill, with general higher accuracy, when the distance between the transported and original oil spill locations were shorter, compared with larger distances. This was mainly attributed to the lack of representation of surface flow fields, particularly rising from the application of the average wind conditions. However, conducting larger test numbers, that in principal increases the computational times, have shown to improve the model predictions. Having said that, limitations and sensitivity of the model was addressed by means of numerical scenarios and testing the significance of effective numerical parameters. Such technologies could be used on a real-time basis to predict the source of an oil spill (or any floating matter following lagrangian mechanics) that helps decision makers in responding on timely basis to oil spill accidents in the offshore regions.

Keywords: Arabian Gulf; backtrack; hydrodynamics; oil spill.

INTRODUCTION

Large quantities of oil are transported world-wide to meet increasing human demands, particularly near the regions of developing countries such as the Arabian Gulf, hereafter called 'the Gulf'. This involves the extraction, storage, and transportation of oil through oceans and seas (Vanem et al., 2008). The countries bordering the Gulf produce more than 20% of the total global oil production (Facey, 2008), most of which is transported through this water body, as shown in Figure 1. Oil spills always have a harmful impact on the marine environment in both the short and long term, as explained by Guzman et al. (1991) and Peterson et al. (2003), respectively. Henceforth, it has been advised that all countries should establish a contingency plan to prepare for and respond sensibly in a timely manner to any accidental or intentional oil spill in their marine environment (Al-Salem & Al-Banna, 2015). Therefore, prediction of the fate, transport and tracking of oil spills is an important tool and can play a key role in decision making with regard to oil spill incidents. Practically speaking, this task is complex, because the spread of oil spills is governed by physical, chemical and biological processes that influence the oil patch at various spatial and temporal intervals. Numerical models have been widely used for predicting oil spill advection and dispersion (Reed et al., 1999) in the marine system, both in surface waters, as in Wang et al., (2005), and throughout varying levels of depth (i.e., 3-dimensional), as in Chao et al. (2001) and Wang et al. (2008). Oil spill models vary in type; for example, deterministic or trajectory models that allow for spatial and temporal predictions of oil slicks, whereas stochastic models, based on probability, are used to estimate the probability of where a given oil spill might travel after different periods of time (Mazurekand Smolarek, 2013). However, minimal efforts have been aimed at backtracking oil spills, or what are traditionally called mysterious spills (Breivik et al., 2012). Backtrack modeling of oil spills aim at predicting the original location (source) of a particular oil patch at a given time and location. This is considered as a vital tool in environments, where oil spills and illegal waste discharge are likely to occur, as it would provide managerial and legal guidance for decision makers. Previously, reverse-time models of passive tracers have been widely used to track near-shore sources of harmful materials to their origins (Havens et al., 2009). However, backtracking of particles is established due to the complexity of this task. In principle, a trajectory model could be run in reverse, if the horizontal forcing fields are adequately non-divergent and the object's properties remain in a linear state (Breivik et al., 2012). However, this rarely occurs for oil spills, because such spills undergo various physical and chemical processes.

The main aim of this paper is to present the development of a simple oil spill backtracking model that has a short running time and low computational cost. Achieving these objectives involves utilizing a simple algorithm that allows the concept to be applied as a smartphone application. Such development is crucial for the management and decision making in a region that relies heavily on oil production and transportation for national income, and experience both accidental and illegal discharges, such as the Gulf countries (Nour El-Din & Abdel-Moati, 2001; Naser, 2013]. Hereafter, development of the backtrack oil spill model 'B-Oil' is addressed and detailed. In addition, the efficiency of the algorithms are tested and verified using three previous oil spill incidents that occurred in Gulf waters. Finally, explanations of limitations of the model are given.

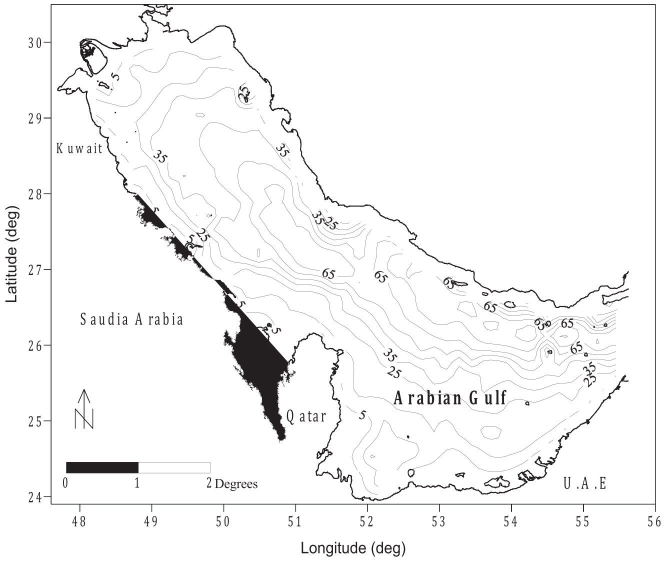

Fig.1. Arabian Gulf, including its location and bathymetric characteristics

METHODOLOGY

Prior to modeling the transport and dispersion of typical oil spill processes in estuarine and coastal waters, the hydrodynamic characteristics of the flow fields, such as water elevations and velocity components, must be predicted. In the current study, these characteristics are predicted by the hydrodynamic model named ‘KGulf’, which solves the governing hydrodynamic equations, details of which are included in Al-Salem (2012). Having said that, the KGulf model was successfully validated and widely used previously for studying the dynamics of the Gulf, as in Alosairi et al.(2011). For the purpose of the current study, a coarse numerical grid is utilized throughout the Gulf, whereas a relatively finer grid is used for the Kuwaiti territorial waters. At each grid point, the model provides the tidal elevations, especially, the tidal and wind-induced currents. Following this, the hydrodynamic model results are used as an input to the B-Oil model to predict source of the oil spill.

The Lagrangian discrete-parcel algorithm is used and the oil slick is viewed as a huge ensemble of small parcels (Figure 2) (Al-Salem & Al-Banna, 2015). The movement of each parcel is followed and recorded as a function of time, relative to a reference grid system fixed in space (Al-Salem & Al-Banna, 2015; Reddy, 1997; Shen & Yapa, 1988; Shen et al., 1987; Yapa & Chowdhary, 1989 and Yapa, 1994). In the Lagrangian discrete-parcel algorithm, the oil spill is divided into a large number of equal masses. These parcels are introduced into the system in the form of an instantaneous spill at a typical spill site (x,y) and time (t). Each parcel is then allowed to move with the drift velocity. That being said, the water speed sr and the wind speed w_r can be calculated from Equations (1) and (2), respectively. Where U_x and U_y are the velocity components in the x and y directions, respectively, and W_x and W_y are the wind components in the x and y directions.

$$s_r = \sqrt{U_x^2 + U_y^2} \text{and} \tag{1}$$

$$w_r = \sqrt{W_x^2 + W_y^2} \tag{2}$$

The drift velocity, u_i^t and v_r^t , of the oil spill accounts for the effects of both water currents and wind currents and can be calculated using Equations (3) and (4) for the x and y directions, respectively. Where W^d is the drifting speed due to wind, which typically varies from 2 to 4% of the wind speed (wr) (Schwartzberg, 1971) and Boufadel et al., 2014); 3% was used for the current study.

$$u_i^t = U_x + W_x^d \tag{3}$$

$$v_i^t = U_y + W_y^d \tag{4}$$

The component of the velocity due to dispersion of the oil slick is calculated by random walk analysis, as shown in Equations (5) and (6). The computation for oil parcels is calculated numerically by integrating the drift velocity at each time interval. For numerical accuracy, sub-time intervals are used for the advection of oil parcels. When the current field is known, then turbulence can be added as random walks Rnd ( ) that have, in general, a Gaussian distribution with dispersion that corresponds to turbulent activity. Therefore, for a particle i, the following hold:

$$dx_i = u(x_i, y_i, t)dt + Rnd_x(i) \tag{5}$$

$$dy_i = v(x_i, y_i, t)dt + Rnd_y(i) \tag{6}$$

Schwartzberg's experiments indicate that the drift has the same direction as the wind, but theoretical studies for wind-induced surface current, conducted by Ekman (1905), suggest that the direction of the drift velocity has a small deflection to the right or left of the wind direction. The Monte Carlo statistical technique can be applied to overcome this random walk in backtracking simulations of the Lagrangian discrete-parcel algorithm, as explained in Binder & Heermann (2010); (Al-Salem & Al-Banna, 2015). Using the Lagrangian discrete-parcel algorithm in a backward time series approach, the path of the center of the oil particles was simulated starting from a given location to track the probable origin of the spill for *N* tests as illustrated in Figure 2 (Al-Salem & Al-Banna, 2015). Then, all the probable locations were grouped in defined limits of D_x and D_y according to the total number of tests completed, to generate the final location probabilities as in Equation (7) and shown in Figure 2. Where, P_i is the probability of the particle location, *N* is the total number of simulated tests, *i* is the test number out of total tests *N*, D_x and D_y are the limits set for the difference in the locations *X* and *Y* for all simulated tests.

$$P_i = \frac{\sum\Big((abs\,(X_{i+1} - X_i) \leq D_x) and\, \big(abs\,(Y_{i+1} - Y_i) \leq D_y\big)\Big)}{N} \tag{7}$$

The algorithm in Equation (7) is coupled with KGulf, to yield the source of the oil spill, i.e., B-Oil. The user of the model must set the total number of tests that the model must undertake and the diameter of the area, where the probabilities may occur (in meters), i.e., D_x and D_y. Based on Equation (7), the probability distribution of the position of the oil is estimated by calculating the fraction of the central spill that could realistically reach various locations within selected time intervals, where it also depends on the number of tests, as shown in Figure 2. For example, if a probability of 50% is indicated at a particular location for 20 tests, then half of the tests (10) resulted in that location. The remaining would therefore have resulted in other locations. If probabilities overlap at a particular location, as shown in Figure 2, then the probability is accounted for in the first set of test results and not the second set. This modeling technique will be tested and verified in the following section.

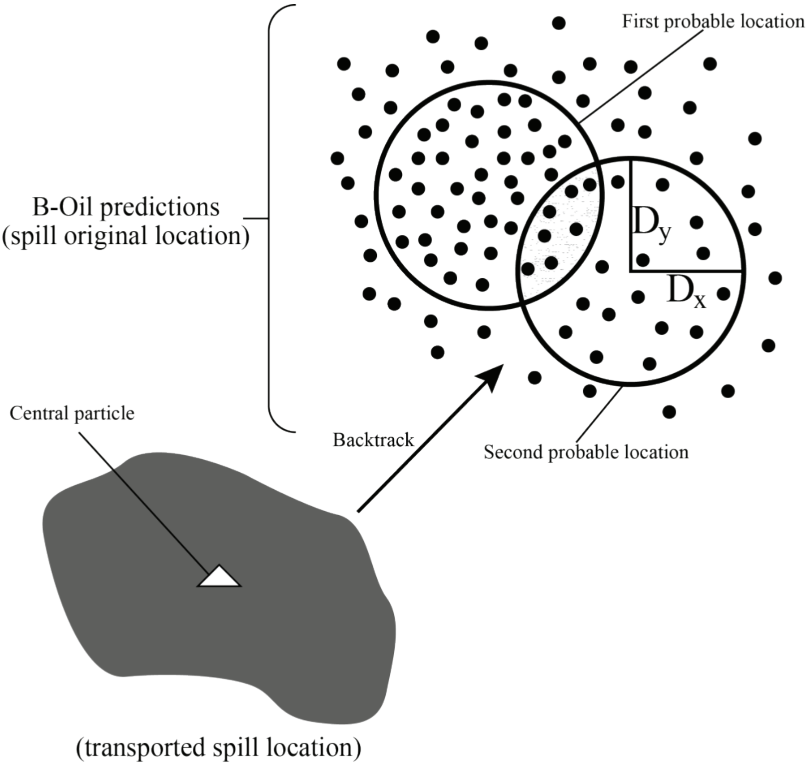

Fig. 2. B-Oil model illustrations

RESULTS AND DISCUSSION

In this section, the B-Oil model will be tested and validated using a previous oil spill that occurred in the Gulf, in which both the original location of the oil spill and its transported (sited) locations after a given time are known and have been previously documented in the literature (Al-Rabeh et al., 1992; Elhakeem et al., 2007; and Elshorbagy & Elhakeem, 2008). To assess the efficiency of B-Oil prediction techniques, three oil spill incidents were considered with varying distances between the original oil spill location and transported spill location. The Port of Shuaiba (Kuwait) oil spill incident is considered as a short-range prediction, with a distance of approximately 17 km, whereas the Al-Ahmadi (Kuwait) and Nowruz (Iran) oil spill incidents are assessed as intermediate and long-range predictions, with distances of approximately 100 and 400 km, respectively.

B-Oil model predictions for the port of Shuaiba (Kuwait) oil spill

An oil spill of 220 L was accidentally released into the northern Kuwaiti Sea at the port of Shuaiba, where large quantities of oil are transported, and spread at a depth of 17 m on Aug. 2, 2010, as illustrated in Figure 3. The Kuwait Institute for Scientific Research was involved in the incident investigation, in which the oil spill was transported 17-20 km north of the original oil spill location and the dominant wind conditions were blowing from the south, and to less extent from northwest, as shown in Figure 4. The B-Oil model was set to 143 h of total simulation time, 20 tests and 2000 m for Dx and Dy,. Having said that, the number of probabilities of the model in this case are 5 probable locations for the oil source (Figure 5). The wind data for this incident were applied to the model with a 1 h resolution. The results of B-Oil probabilities show excellent agreement with the observed oil location: the highest probability achieved by the model was 45%, which corresponds to 9 out of 20 tests and occurred at less than 1 km away from the original source of the spill, as shown in Figure 5 and Table 1. The percentage of the probability does not necessarily reflect the accuracy of the prediction. Table 1 illustrates that the location in scenario 5 yielded a probability of 5%, i.e., the lowest among all scenarios considered, yet this location was the second closest site to the actual source of the oil spill. This is attributed to the stochastic nature of the model, arising from the techniques explained in the previous section. Therefore, it is important to distinguish between the highest probability and the most accurate probability.

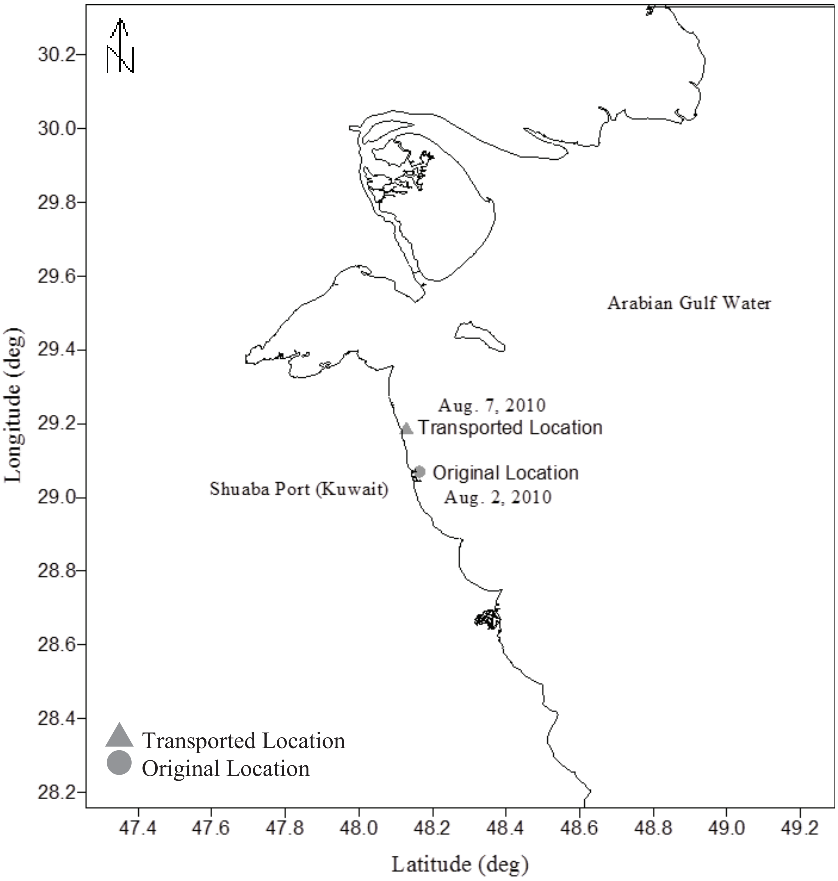

Fig. 3. Observed and transported locations for the port of Shuaiba (Kuwait) oil spill on Aug. 2, 2010

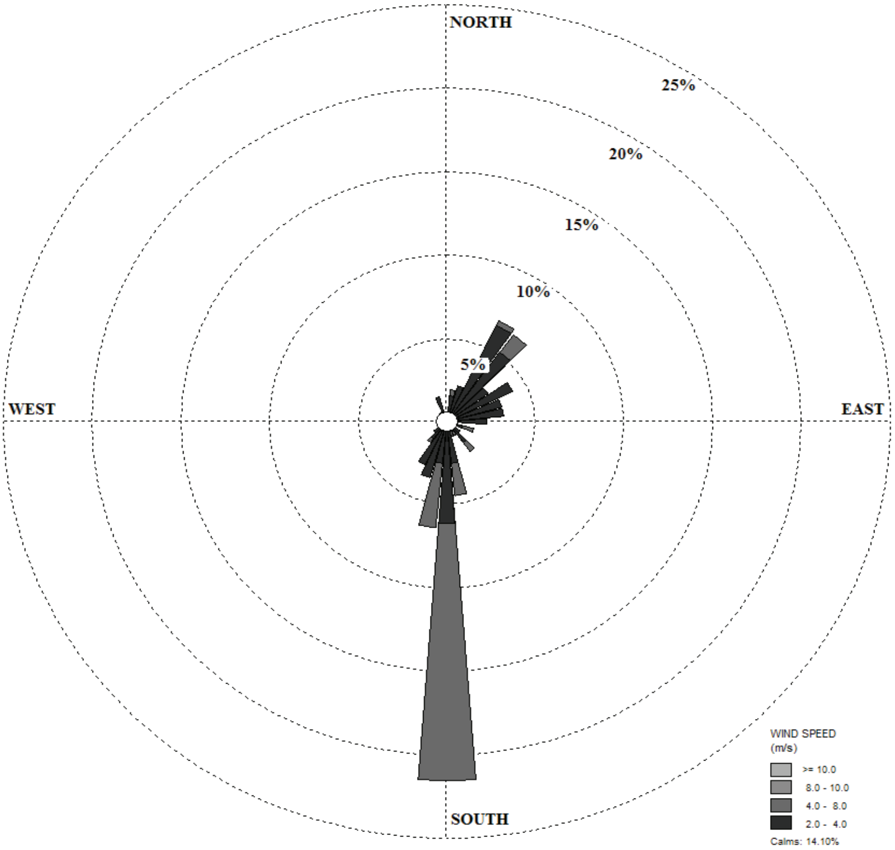

Fig. 4. Wind conditions during the port of Shuaiba (Kuwait) oil spill incident

Table 1. Observation summary of port of Shuaiba (Kuwait) oil spill sited on Aug. 7, 2010

Case	***Observation and Date***		***Location***	
	Longitude E (deg)		*Latitude N (deg)*	
	Original	Aug. 2, 2010	**48.1626**	**29.0716**
Port of Shuaiba Figure 5	***Transported***	Aug. 7, 2010	48.1287	29.1886

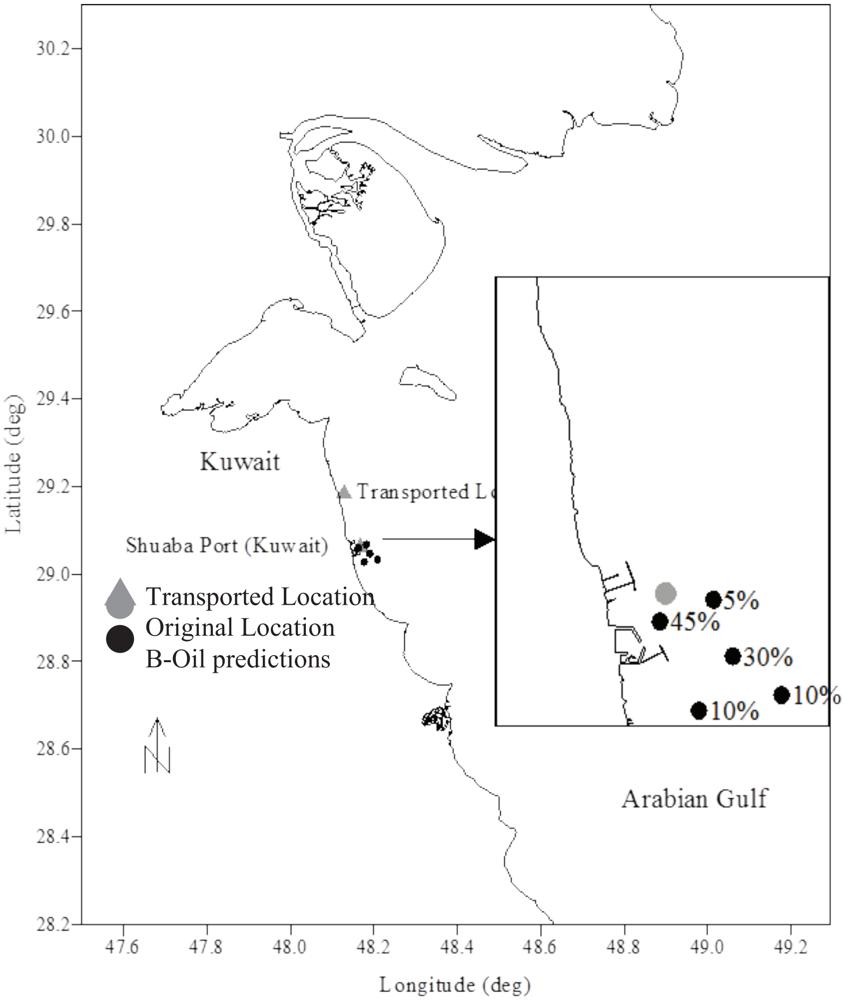

Fig. 5. Backtrack simulation for the port of Shuaiba (Kuwait) oil spill incident

B-Oil model predictions for the port of Al-Ahmadi (Kuwait) oil spill

The 1991 Middle East war resulted in deliberate oil spills in Kuwaiti coastal waters (Al-Abdali *et al*., 1996). The Al-Ahmadi oil spill started on Jan. 19, 1991 off the shore of the port of Al-Ahmadi, as shown in Figure 6. The oil spill was transported along the Arabian coast, with low quantities of oil dispersed toward the Iranian coast, as shown in Figure 6. This is mainly attributed to the dominant north-westerly winds and, to a lesser extent, the density-driven currents that played a key role in transporting the oil plume along the Arabian coast (Azam *et al*., 2006).The observed locations of the leading edge of the oil spill on Feb. 14 and Mar. 18, 1991 are concentrated near the island of Abu Ali (Saudi Arabia), at the northern region of the Kingdom of Bahrain, as shown in Figure 6 (Al-Rabeh et al., 1992; Elshorbagy & Elhakeem, 2008; Al-Salem & Al-Banna, 2015). For this incident, both observation dates were considered: Feb. 14, 1991 (Case A) and Mar. 18, 1991 (Case B), as detailed in Table 2. With regard to the B-Oil model settings, similar configurations were used as for the previous incident. Due to a lack of data, instead of applying a time-varying wind speed and direction, the dominant wind conditions were set as 20 km/h blowing from northwest for the entire simulated period. Considering the meteorological conditions of the Gulf region during this period, the wind speed and direction applied for this incident are assumed to be acceptable, given that similar conditions have been applied satisfactorily to predict the fate and transport of the Al-Ahmadi oil spill, as in Elhakeem et al. (2007) and Al-Rabeh et al. (1992). For Case A, the total simulated time was set to 625 h and the simulated test number to 20, while the Dx and Dy remained as 2000 m. The total number of scenarios was 13 due to the larger simulation time and distance, compared to the previous incident, and two locations reached 15%, i.e., 3 out of the 20 tests for each scenario, as shown in Figure7. However, most of the scenarios were placed within a 9-km radius of the origin of the spill; see Figure 7. In comparison, Case B, which is located 120 km away from Case A, B-Oil was set in similar manners to case A, but with a total simulated time of 1393 h. A total of 8 scenarios were predicted, as shown in Figure 8. In this case, the predicted origin distance increased; all of the scenarios were located along the Kuwaiti coastline and 20 km away from the origin, as shown in Figure 8. This indicates that the modeling results for Case B predict the origin of the oil spill less accurately than those for Case A; however, the source of oil spill region was well-defined.

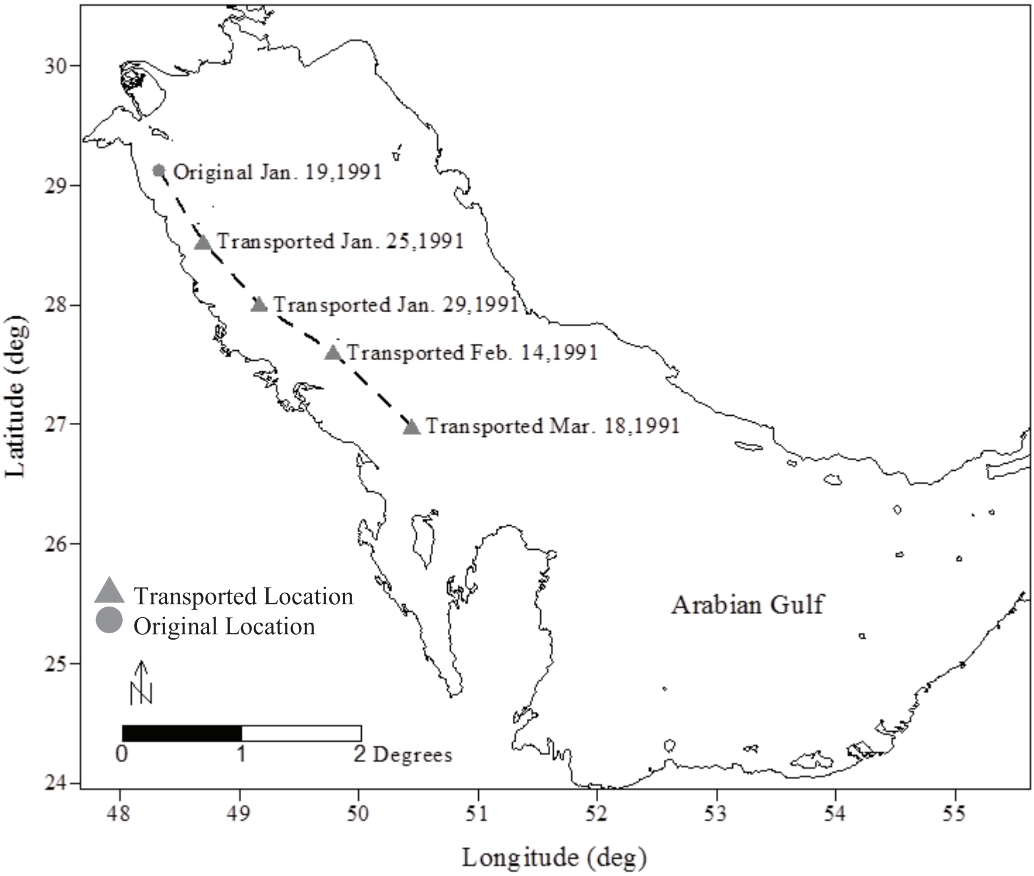

Fig. 6. Observed and transported locations of the Al-Ahmadi (Kuwait) oil spill on Jan. 19, 1991 (Elshorbagy & Elhakeem, 2008; Elhakeem et al., 2007; Al-Rabeh *et al*., 1992)

Table 2. Observations summary of the Al-Ahmadi (Kuwait) oil spill sited on (Cases A and B)

Cases	*Observations*		*Location* Longitude E (deg)	Latitude N (deg)
	Original	Jan. 19, 1991	**48.3333**	**29.1166**
(Case A) Figure 7	***Transported***	Feb. 14, 1991	49.7847	27.6058
(Case B) Figure 8	***Transported***	Mar. 18, 1991	50.5151	26.9151

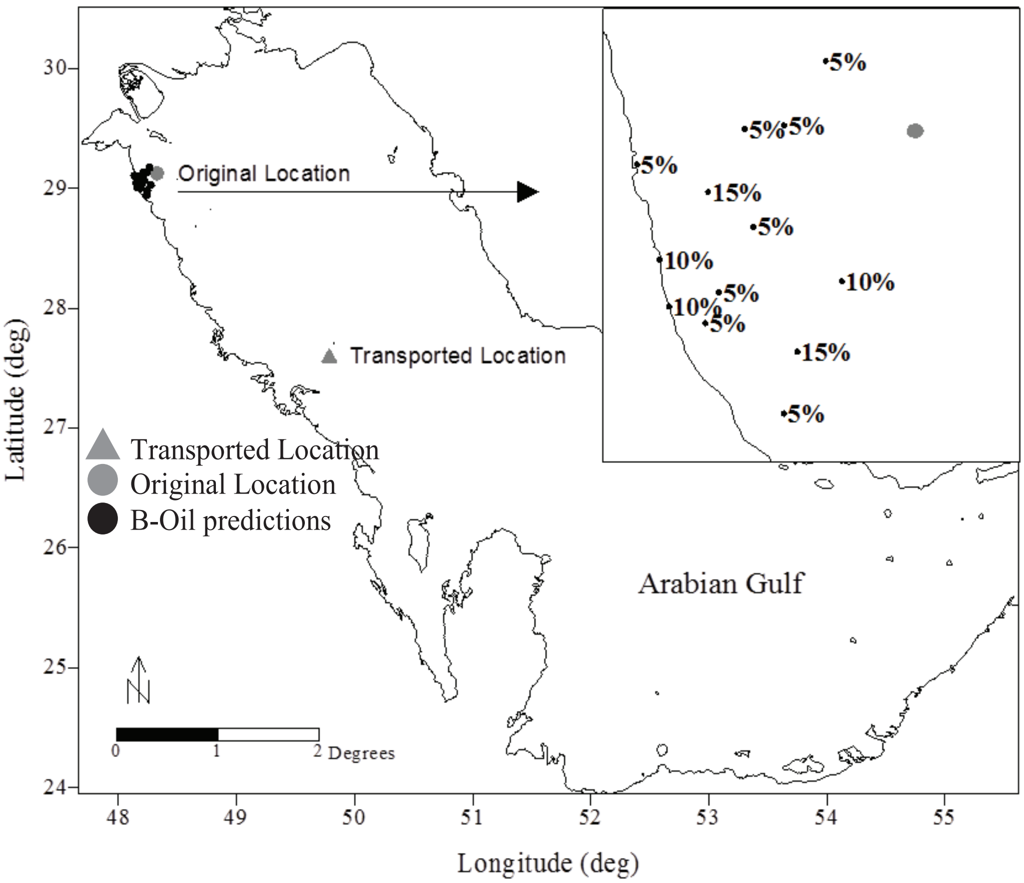

Fig.7. Backtrack simulation for the Al-Ahmadi (Kuwait) oil spill incident (Case A)

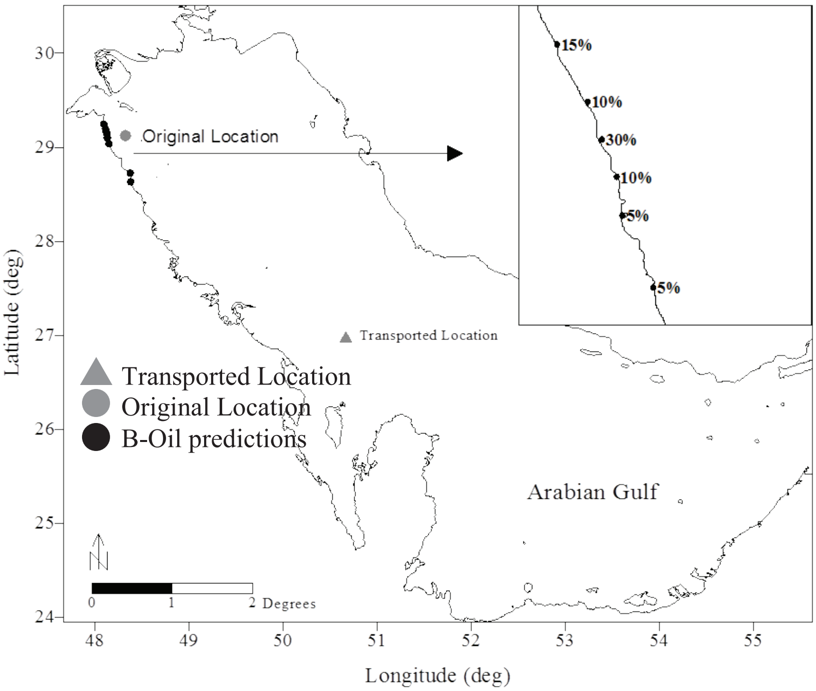

Fig. 8. Backtrack simulation for the Al-Ahmadi (Kuwait) oil spill incident (Case B)

In theory, dispersion and transport of a typical oil slick occurs in several phases. First, in the near field, the local turbulence mixes or stirs the effluent into the receiving water. Second, when the effluent develops in scale and reaches a scale comparable to the ambient velocity field, the mean velocity shear distorts the effluent cloud, as explained by Okely et al. (2010) and Alosairi et al. (2011). When the effluent expands further in scale, the residual current plays a key role in transporting the effluent (Lewis, 1997). This clearly means that the rate of dispersion and transport of effluent increases, as the length scale of a given area increases. This is due to the variation in flow characteristics that effluent may experience in an estuary (Alosairi *et al*., 2011). This variation may explain the differences between Case B and Case A given the lack of detailed velocity field representations in the KGulf model, particularly near the shore, where high dispersion may occur (Alosairi *et al*., 2011). Additionally, KGulf is an empirically derived model from tidal constituents that does not account for waves. Furthermore, a time-varying wind condition could significantly improve the velocity field representations and accordingly improve the predictions of B-Oil. In a previous study of the fate and transport of this particular oil spill, Al-Rabeh et al. (1992) showed that accurate meteorological effects are essential for accurate trajectory predictions. Although density-driven currents do affect the transport of oil spills except near the center of the Gulf (Al-Rabeh et al., 1992), the KGulf model is based on tidal currents and does not consider density-driven currents that may have pronounced influence on the results. Therefore discrepancy between the model results and the actual conditions may rise. For decision making, which is mainly focused on quick response and in the interest of low computational costs, the predictions of this incident in both cases are considered to be excellent. Logically, an increased number of tests would increase the accuracy of the predictions, but the computational cost would increase. In the following incident, the effect of increasing the number of tests on B-Oil performance will be examined.

Model simulation of the Nowruz oil spill

In early 1983, a ship collided with a well platform in the offshore Iranian Nowruz oil field approximately 250 km north of Jubail, shown in Figure 9 (Al-Amirah, 1983). This collision caused the well to cease production of oil. On Feb. 27, 1983, during high winds and seas, the well blew out, causing a spill of 1,500 to 2,000 barrels of heavy crude oil per day. On Mar. 2, 1983, another two wells caught fire following a political conflict in the Nowruz oil field area. Figure 9 shows the progression of the oil spill on various dates. It is well documented that the residual currents, particularly in the surface waters, where the oil spill was concentrated, acted in counterclockwise direction in the upper Gulf region (El-Sabh & Murty, 1988; Al-Amirah, 1983 and Elshorbagy et al., 2006). These currents played a key role in transporting the oil slick toward the Arabian coastline. For the B-Oil investigations, three cases were considered for this incident.The observed locations and for the spills on Mar. 23, 1983 (Case C), Apr. 16, 1983 (Case D) and Apr. 25, 1983 (Case E) are given in Table3, respectively. Further details of the incident can be found in Al-Amirah (1983). Similar to the previous incident (Al-Ahmadi, Kuwait), a dominant wind condition was applied due to lack of data: the representative direction was set to blow from the northwest direction at a constant speed of 25 km/h. In addition, the B-Oil was set in similar manner to the previous incidents in terms of the Dx and Dy. However, for the total simulated time it was set to 577, 1153 and 1369 h for the Cases C, D, and E, respectively. In all cases for this incident, the B-Oil results had a high number of scenarios compared to the previous incidents, as well as more variation in the calculated probabilities than for the previous incidents, as shown in Figures 10, 11 and 12 for the Cases C, D and E, respectively. Here, where large number of tests would result in more accurate probabilities, but for the consistency and the assessment of the method purposes the test number remained the same in all incidents. However, this aspect of the method will be assessed in the upcoming section. Case C was the most accurate in predicting the source of the spill compared to Cases D and E, as shown in Figures 10, 11 and 12, respectively. The lack of accuracy in predicting the original location of the oil spill is proportional to the distance between the source of the oil spill and the observed locations. As an example, in Case C, the B-Oil predictions were approximately 12 km away from the actual source, whereas the distance increased to 40 and 60 km in Cases D and E, respectively. Again, this may arise from the flow field representations obtained from KGulf, most likely due to the assumption of constant northwest wind. Variations in wind, e.g., by applying a southeasterly wind, may assist in retarding and deflecting the flow regime at the surface layer and therefore provide more reliable probabilities.

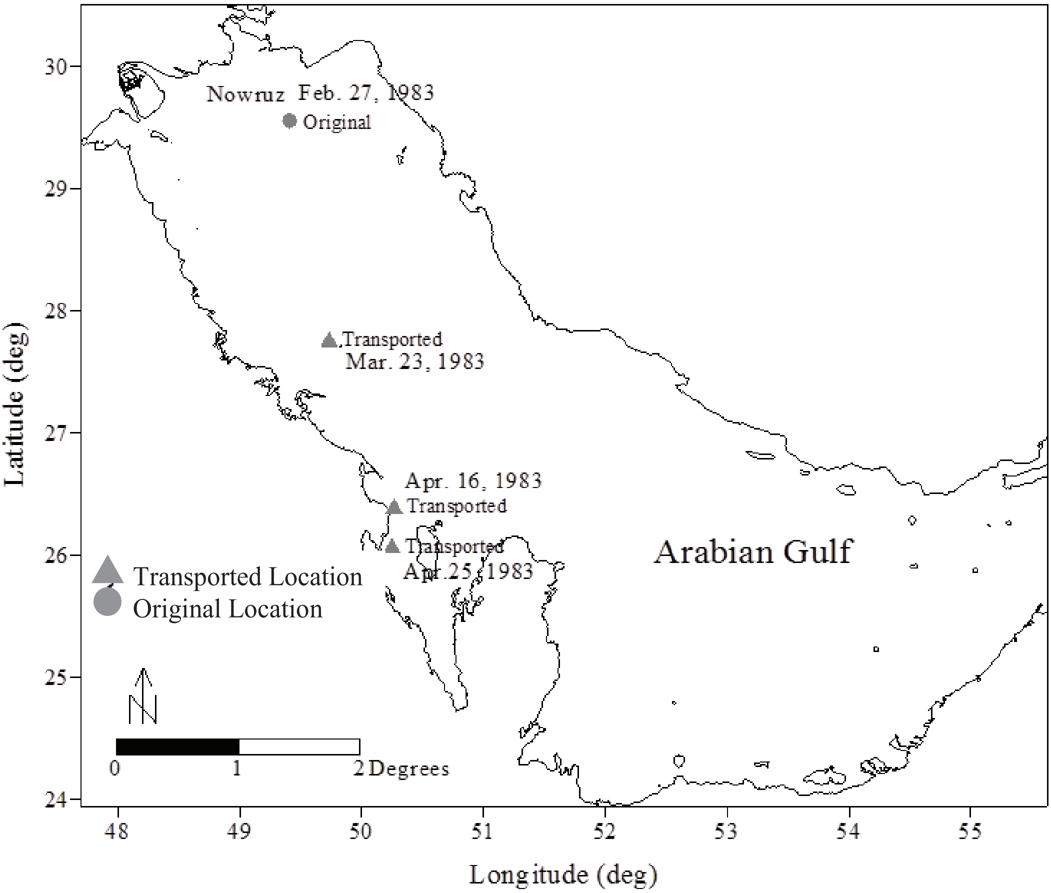

Fig. 9. Observed location of the Nowruz oil spill, Feb. 27, 1983 (Al-Amirah, 1983)

Table 3. B-Oil simulation summary of the Nowruz (Iran) oil spill sited on Mar. 23, 1983

Cases	***Observation and Date***		***Location*** Longitude E (deg)	Latitude N (deg
	Original	Feb. 27, 1983	**49.4166**	**29.5500**
(Case C) Figure 10	***Transported***	Mar. 23, 1983	49.7313	27.7702
(Case D) Figure 11	***Transported***	Apr. 16, 1983	50.2658	26.4005
(Case E) Figure 12	***Transported***	Apr. 25, 1983	50.2464	26.0770

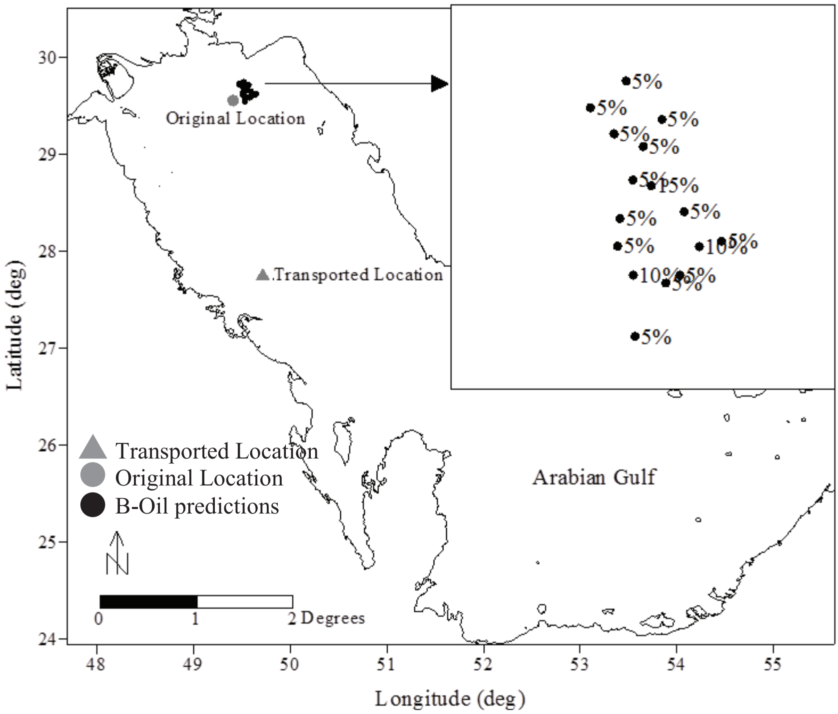

Fig.10. Backtrack simulation for the Nowruz (Iran) oil spill incident (Case C)

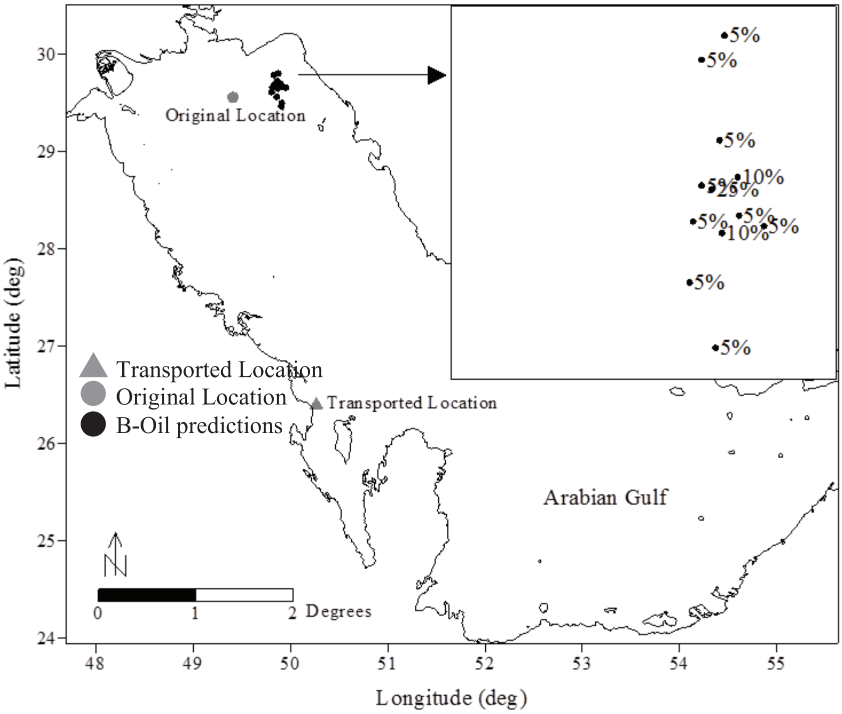

Fig. 11. Backtrack simulation for the Nowruz (Iran) oil spill incident (Case D)

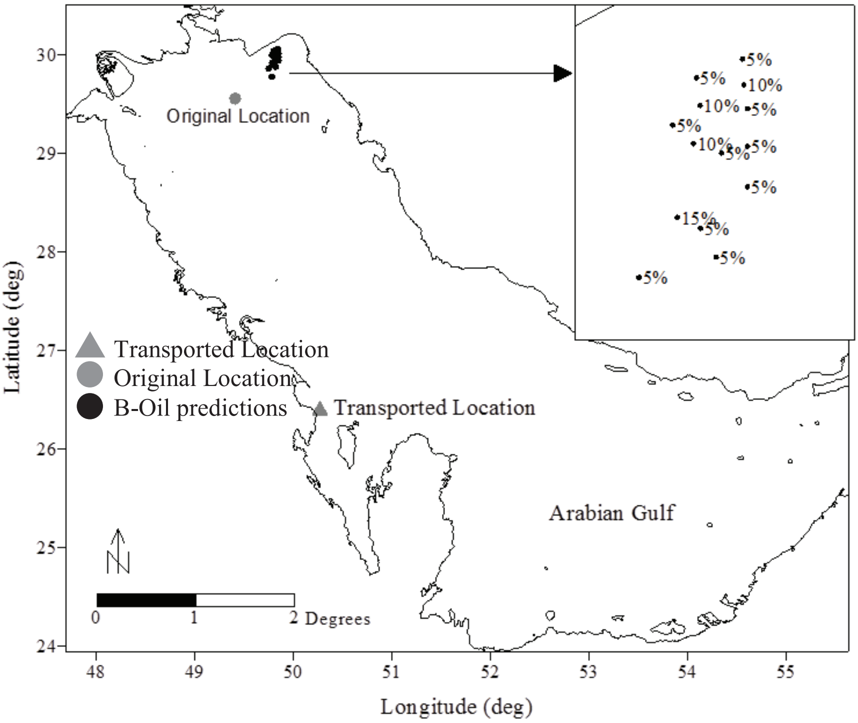

Fig. 12. Backtrack simulation for the Nowruz (Iran) oil spill incident (Case E)

To assess the limitations of the model, it is important to conduct a sensitivity analysis on various parameters of the model. The Shuaiba (Kuwait) and Nowruz (Iran) 'Case C' oil spill incidents were considered for this analysis due to the variability of the incident conditions and input parameters. Two factors were considered to assess the behavior of B-Oil: the number of tests and the distance limits Dx and Dy. The number of tests was increased to 20, 40, 60, 80 and 100 tests, and the other parameters remained the same. Similarly, to assess the effect of distance limits, Dx and Dy were reduced to 1,700, 1,300, 900, 500, 300 and 100 m, and the remaining parameters were held constant except for the number of tests, which was increased to 50 tests for all analyses. In both cases, the distance to the origin for each condition was calculated, and the B-Oil results were compared as shown in Figures 13 A and B for variations in the number of tests and in Figures 14 A and B for variations in distance limits. The 'Distance to origin' is defined as the distance between the predicted and the actual oil locations. In Figures 13 A and B, the scenario with the probability nearest to the origin was considered, not the scenario with the highest probability. In contrast, in Figures 14 A and B, the scenarios with the highest probabilities were considered, not those nearest to the origin. This choice was made to indicate the effects of both parameters considered in the analysis, since the first is related to the number of tests and the later is related to the distance limits.

As shown in Figure 13, increasing the number of the tests reduced the distance to the origin; in other words, the accuracy of the B-Oil prediction increased in both incidents. Logically speaking, an increased number of tests would result in a high number of scenarios, which are close to the origin. Although the model results followed similar trends in both incidents, the predictions of the model for the Nowruz incident were relatively more responsive to the increase of the number of tests which have improved the results. This is mainly attributed to the uncertainties of the model which were explained previously. The larger the distance the more uncertainties will rise and therefore additional tests would improve the results.

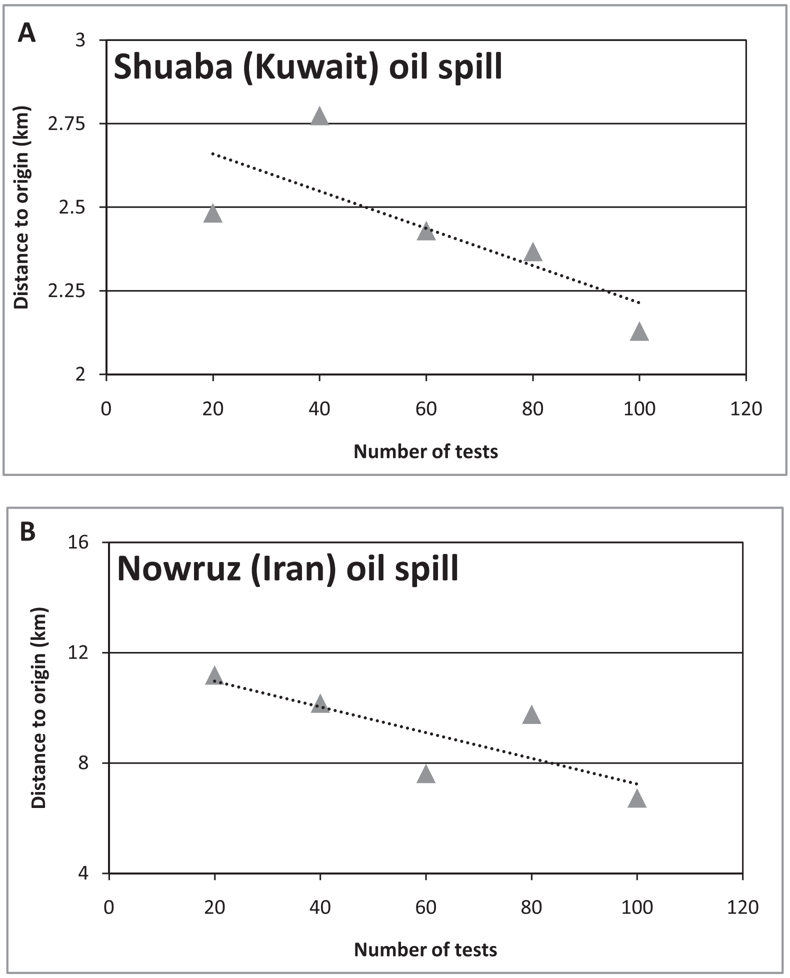

Fig. 13. Effect of the number of tests on model predictions for the AShuaiba oil spill; BNowruz oil spill

Changes in the distance limits Dx and Dy yielded similar effects to the 'Number of tests' but in the opposite manner, as shown in Figures 14 A and B. Due to the larger degree of error in the Nowruz incident compared to the Shuaiba incident, the improvements in the model predictions are more pronounced in the Nowruz case, as shown in Figure 14 B. Reducing the distance limits resulted in high probabilities near the source, compared with the probabilities obtained for large distance limits. Therefore, distance limits effects the probability at the regions near the original location of the spill.

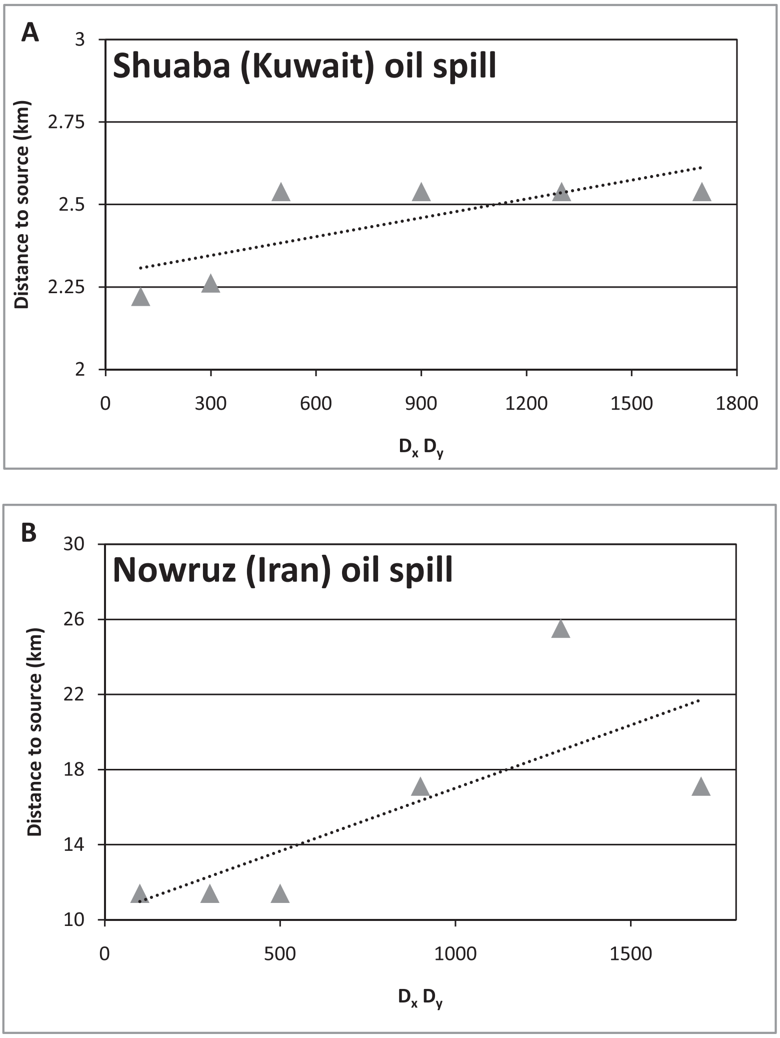

Fig. 14. Effect of Dx and Dy on model predictions for the A Shuaiba oil spill; B Nowruz oil spill

The assessment of the technique utilized to backtrack the oil spill, or in principle Lagrangian particles, using statistical approach have revealed that the accuracy of the predictions is case sensitive and can be improved by sensible consideration of the number of tests and distance limitations. Accurate representation of the velocity fields plays a key role in predicting the source of the oil spill. However, factors which are not considered in the approach such as mass of oil, evaporation, and biological effects raise the uncertainties. Considering such factors would improve the probabilities of the origin location of the spill, but on the other hand, it would be computationally expensive. Here, where factors such as number of tests and distance limitation should be well considered and can further improve the predictions with minimal computational cost. It is worth noting that trapping of oil spill in semi-enclosed embayments or near the coastline has not been considered in this study, since this adds an extra temporal dimension to the problem.

To clarify, the current development does not account for the trapping time that a typical spill would take before it has been transported to offshore regions. Perhaps this can be an area where further studies are needed to further develop the model to allow for trapping time.

Traditionally oil spills sources are known, particularly of large scale. However, in active coastal areas such as Kuwait, accidental and illegal oil spill occur very frequently and in varying quantities. With the advancement of technology, in particular the smartphones that has large memory capacity, and the simplicity of the methods explained previously, it can be adopted and used on smartphones to backtrack such incident. Coding Equation (7) with simple algorithm, in one hand, and using the navigation facilities of the smartphones, on the other hand, had enabled the model to be used on smartphone. This technique has already been developed on smartphone as an application by the first author of the manuscript and tested on mysterious oil spill incident occurred in the southern coast of Kuwait water. The time and transported location of the incident, in terms of longitude and latitude, of the incident were reported by the Kuwait Environmental Protection Agency (KEPA) which was used as input to the application on the smartphone. The number of the tests and the distance limits are also user defined. Other data such as hydrodynamics and wind is used from the KGulf application, which has already been published (Al-Salem, 2012) and available as a smartphone application. The B-Oil application was able to predict the location of the oil spill origin, which helped the KEPA and other governmental bodies to open investigation with the violated parties. Most advantageous, the results of the application can be sent directly to the concerned bodies via e-mail facilities in the smartphone, that would in turn enable concerned bodies, and possibly the society, to be involved in monitoring the coastal water and act on timely basis. Given large coverage of the navigation facilities in the smartphones, such technology can be used in other fields such as coast guard, coast rescue and KEPA boats to track any breach of law or even accidents that has a particle tracking nature.

CONCLUSION

In this study, different components of a system designed to calculate oil spill backtracking predictions are provided. The system includes a 2-D hydrodynamic model, KGulf, which is coupled to an oil spill backtrack trajectory model. The Lagrangian discrete-parcel algorithm was considered for the backtracking technique, and the Monte Carlo statistical technique was applied to overcome random walk in the backtracking simulation. The algorithm used for this purpose was explained, validated and assessed using three oil spill incidents that occurred in the Gulf. The incidents considered in this study cover various conditions that enabled assessment of the model behavior. The main conditions considered for model validation are the distance range between the spill and the transported location and the wind variability applied in the model. Given the relatively low-energy and high-salinity waters of the Gulf, particularly in shallow regions, it is likely that pollutants with relatively lower densities, such as oil, will remain in the top layer, where wind can affect further transport (Al-Rabeh et al., 1992 and Elhakeem et al., 2007). In relation to this, the coupled model B-Oil has shown that, it is crucial to consider variable wind conditions for accurate backtracking predictions. Discrepancies between model predictions and real values for the long range distance were mainly associated with the flow fields and wind conditions applied in the model. Having said that, the assessments considers that the observed data was well collected and documents in both space and time, and therefore, inaccurate recordings may logically results in disparity between the model and the observations. Wave effects were not considered in KGulf, and constant wind conditions were applied in two oil spill incidents. However, to increase the accuracy of the predictions, the distance range was reduced, while the number of tests was increased. This modification resulted in better predictions, but increased the computational cost slightly. Most importantly, the technique can be used well for crisis management strategies and decision-making, allowing for a quick response, given the time needed for a typical simulation, which is more rapid than the traditional oil spill models. Furthermore, the model can be used for other applications related to drifting surface objects or pollution, such as storm water runoff, industrial waste discharge and fish kill transport. The algorithm utilized for model development can be used for virtual monitoring, smartphone applications and online applications, as shown on the first author's website (http://www.hceatkuwait.net) (Al-Salem & Al-Banna, 2015). Finally, B-Oil is designed for offshore predictions, where particle trapping near the coastal region is not considered. The main challenge for further development of B-Oil is to consider the coastal interactions that occur during the time spent by particles in trapped regions before being released to offshore waters.

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