Oil Spill Risk Simulation Model

By Jen-Men Lo,[1] Member, ASCE

Abstract: This paper presents a simulation numerical model that can generate an oil-risk map for a given area. The map shows monthly and yearly probabilities of oil-slick presence for each grid area. The probability computation procedure includes the oil-slick movement at each time stage until it completes the given time interval. An example was presented to generate the Kuwait oil-spill risk map by using the simulation model. The results of the oil-spill risk map can be used to determine the relative sensitivities of coastal sections where oil-slick occurrence are most probable. The decision maker can use this information for strategic planning in environmental protection and for selecting sites for seawater intakes, fish farms, and coastal recreation areas. The model simulates a spill's location, size, and associated movement based on statistical data. Horizontal wind vector components are simulated using a Markovian time series model based on local wind statistics. The simulation of the slick's movement includes the mechanisms of spreading and drift by wind and currents.

Introduction

Oil spills are a major environmental concern in coastal regions. The movement of the associated oil slicks can cause the shutdown of power and desalination plants, cutting off supplies of fresh water and electrical power, and can pollute the coastal environment and damage marine life.

An oil slick on the sea's surface is driven by winds, waves, and currents. Most oil-slick models consider the oil-slick movement a primarily deterministic mechanism. These models are useful for hindcasting spill movement and, sometimes, provide an insight into how oil spreads under a prescribed set of environmental conditions. When it comes to the problem of forecasting, however, oil-slick movement should be statistically simulated.

Tayfun and Wang (1973) employed a Monte Carlo simulation technique to study oil-slick drift under random winds. The method was used to forecast oil-slick movement statistically. However, this particular approach generates only the surface wind statistically and requires initial location and size of the spill as input parameters; in other words, the model generates conditional probabilities.

Stewart and Leschine (1986) discussed methods of oil-spill risk assessment, such as direct projection (*Proposed* 1979), regression models (*Oil Spill* 1978), probability models (Devanney and Stewart 1974a,b), and simulation models (Keith et al. 1977). These were developed to analyze spill frequencies and size and can be used to predict spill risk associated with oil terminals and oil tankers. However, none considers the oil-slick movement.

The model in the present study can statistically simulate location, size, and movement of an oil slick. Therefore, it can be used for strategic planning in environmental protection and for selecting sites for seawater intakes, fish farms, and coastal recreation areas.

[1]Cupertino, CA; formerly, Res. Sci., Kuwait Inst. for Sci. Res., Envir. and Earth Sci. Div., Hydr. and Coast. Engrg. Dept., P.O. Box 24885, 13109 Safat, Kuwait.

Note. Discussion open until October 1, 1991. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on January 2, 1990. This paper is part of the ***Journal of Waterway, Port, Coastal, and Ocean Engineering***, Vol. 117, No. 3, May/June, 1991. ©ASCE, ISSN 0733-950X/91/0003-0285/$1.00 + $.15 per page. Paper No. 25851.

J. Waterway, Port, Coastal, Ocean Eng., 1991, 117(3): 285-300

Risk-Map Simulation Model

An oil-spill risk map shows the probability of the presence of an oil slick within a given area based on repeated trials. For a typical trial, the model predicts the movement of a slick using six steps:

1. Simulating the oil spill's location based on the probability associated with the locations of oil-spill occurrences.
2. Simulating the spill size, based on the probability associated with the size of oil spills at a given location.
3. Selecting the initial time step at which the spill occurs, assuming the initial time step to be uniformly distributed over the dominant tidal cycle.
4. Determining the tidal current patterns that follow the initial time step.
5. Simulating the horizontal wind velocity components using a time-series model.
6. Simulating the processes of oil-slick drift and spread at each time step.

For each trial, the model first determines the location, size, and initial time of the spill and then predicts the movement at subsequent times, based on steps 4, 5, and 6. In this manner, the positions of the oil slick at each time step were determined for each trial until the final time step was reached. Consequently, the percentage risk of oil-slick occurrence for each given area can be calculated, and the oil-spill risk map follows accordingly. As would be expected, the more trials made, the more reliable the results will be.

Simulating Oil-Spill Location and Size

In each trial, two variables must be dealt with: the spill's location and its size. These cannot be predicted with certainty but may be described by using probabilities. But can one assign these probabilities? Devanney and Steward (1974a,b) suggest that spill size is approximated by a gamma distribution, the parameters of which are determined from historical data. Since such sta-

TABLE 1. Size Distribution of Oil Spill Accidents in Kuwait's Territorial Waters (except Shuwaikh and Doha Ports), 1979–1985

	Number of Spills by Volume of Oil (Barrels)												
Location (1)	<5 (2)	5–<10 (3)	10–<15 (4)	15–<20 (5)	20–<25 (6)	25–<30 (7)	30–<35 (8)	35–<40 (9)	40–<45 (10)	45–<50 (11)	50–<55 (12)	>100 (13)	Total (14)
Messilah Beach	—	—	—	1	—	—	—	—	—	—	—	—	1
Al-Ahmadi North Pier	42	8	4	1	1	1	—	—	—	—	—	1	58
Al-Ahmadi South Pier	37	8	4	1	1	—	—	—	—	—	1	2[a]	54
Sea Island	11	5	1	—	1	1	—	—	—	—	—	1	20
Shuaiba	36	3	2	—	—	—	—	—	—	—	1	—	42
Mina Abdullah	10	2	1	2	—	—	1	—	1	—	—	—	17
Mina Az-Zour	3	—	—	—	—	—	—	—	—	1	—	—	4
Kubbar Island	2	—	—	—	—	—	—	—	—	—	—	—	2
Total	141	26	12	5	3	2	1	—	1	1	2	4	198

[a]One accident on December 20, 1982, released 130,000 barrels of oil.

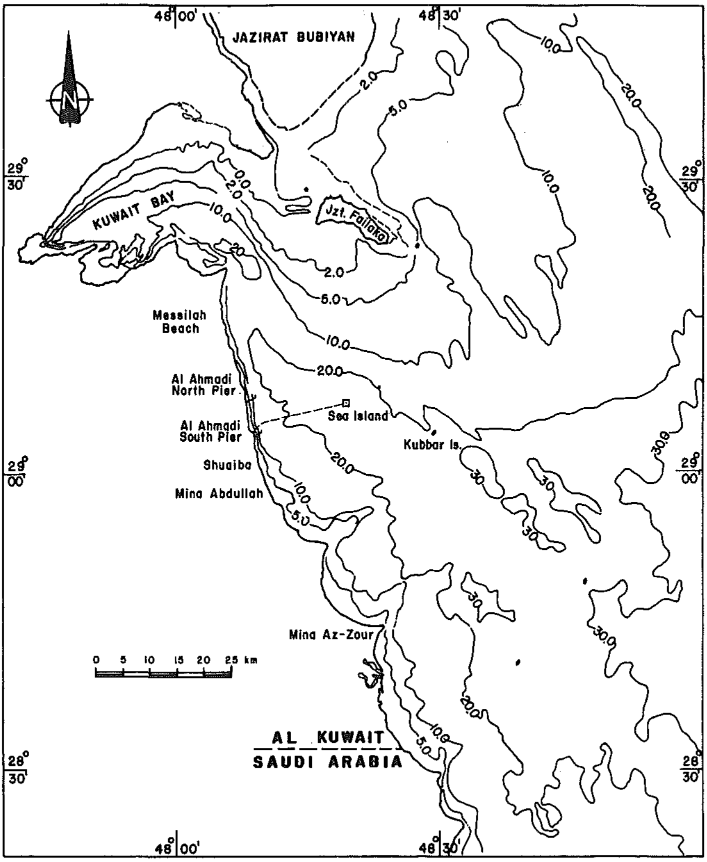

FIG. 1. Locations of Oil-Spill Accidents

tistics generally depend on sample size, the validity of this approach is open to question.

The risk-map numerical model here will take any probability function as defined by the user; in this study, however, the probability functions for the location and size of oil spills along Kuwait's coastline are based on historical data.

From 1979 to 1985, there were 198 recorded oil spills in Kuwait's territorial waters. Table 1 presents the number of such accidents and the resulting size distribution in barrels. Fig. 1 shows the locations of the accidents, mainly oil-loading terminals and ports.

The probability functions for the spill locations and sizes are estimated from the historical data, without resorting to any preconceived model for the underlying probability law. However, it is assumed that spill accidents occur independently in time and that the probability of simultaneous spill occurrences is negligible compared with that of single occurrence. Fig. 2 shows the estimated spill occurrence probabilities at each location based on field data. This forms the basis for the location simulation. The size of the spill

J. Waterway, Port, Coastal, Ocean Eng., 1991, 117(3): 285-300

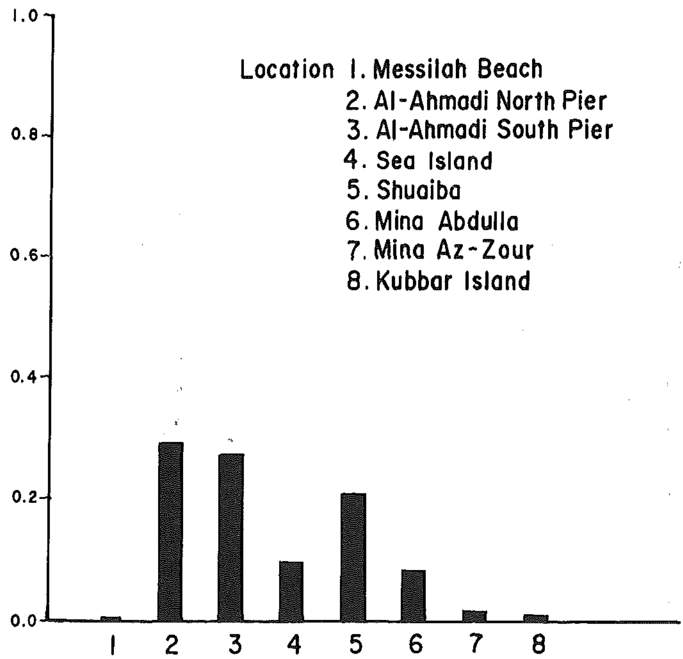

FIG. 2. Probabilities Associated with Locations of Oil-Spill Occurrences along Kuwait's Coastal Area

at each location is simulated similarly by using the probabilities associated with spill sizes at each location.

Simulating Tidal Currents

Because of the absence of comprehensive field measurements of tidal currents in areas such as the Kuwaiti waters, developing the appropriate numerical scheme for this purpose is one of the most difficult and controversial aspects associated with modeling transport processes in an ocean environment. The equations and boundary conditions governing hydrodynamic processes are nonlinear, and, therefore, analytical solutions are generally elusive. In the present case, tidal currents are simulated using a finite element model calibrated by field measurement and described in detail by Lo et al. (1985). Current velocity at each node was determined for each hour based on a typical tidal profile for a 25-hour period. The initial current was simulated to start any time within the 25-hour tidal cycle, assuming that the initial time is equally likely over the cycle.

Simulating Wind Components

Tayfun and Wang (1973) simulated wind speed and direction by assuming the two to be independent of each other. In the present case, wind speed and direction at each time step are considered to be statistically dependent on the wind speed and direction at the preceding time (Tayfun, unpublished report, 1983). On this basis, the wind vector is described in the form

$$\mathbf{W}(t) = \bar{\mathbf{W}} + \mathbf{W}'(t) \quad (1)$$

where $\mathbf{W}(t) = W_x\mathbf{i} + W_y\mathbf{j}$; W_x = x-component of wind velocity [easterly (+), westerly (−)]; W_y = y-component of wind velocity [northerly (+), southerly (−)]; $\bar{\mathbf{W}} = \bar{W}_x\mathbf{i} + \bar{W}_y\mathbf{j}$ = monthly mean wind vector; and $\mathbf{W}'(t) = W_x'\mathbf{i} + W_y'\mathbf{j}$ = time-varying component of $\mathbf{W}$.

Monthly statistics on the x- and y-components of $\mathbf{W}'$ recorded at wind stations in Kuwait show that these components are correlated and that their joint distribution is approximated by the Gaussian law (Tayfun, unpublished report, 1983). On this basis, the time-ranging component is modeled as a normal Markovian process in the form

$$\mathbf{W}_n' = \alpha\mathbf{W}_{n-1}' + \mathbf{Z}_n \quad (2)$$

where $\mathbf{W}_n' = \mathbf{W}'(n\Delta t)$; Δt = time increment; and α = a scalar monthly constant given by

$$\alpha = \frac{\rho_{xx,1}\sigma_x^2 + \rho_{yy,1}\sigma_y^2}{\sigma_x^2 + \sigma_y^2} \le 1 \quad (3)$$

where σ_x, σ_y = standard deviations of W_x' and W_y', respectively; $\rho_{xx,1}$, $\rho_{yy,1}$ = auto-correlation coefficients of W_x' and W_y' corresponding to a time step of ±1 hour; $\rho_{xx,1} = \langle W_{x,n}'W_{x,n\pm1}'\rangle/\sigma_x^2$; $\rho_{yy,1} = \langle W_{y,n}'W_{y,n\pm1}'\rangle/\sigma_y^2$; $\langle\ \rangle$ = expected value of statistical average; and $\mathbf{Z}_n$ = a zero-mean random perturbation vector whose components are given by

$$(Z_x)_n = [(1 - \rho_{xy}^2)^{1/2}U_n + \rho_{xy}V_n]\sigma_{zx} \quad (4a)$$

$$(Z_y)_n = V_n\sigma_{zy} \quad (4b)$$

where U_n, V_n = zero-mean independent normal random variables, each with unit standard deviation; ρ_{xy} = the correlation coefficient of W_x' and W_y', and σ_{zx}, σ_{zy} = the standard deviations of Z_x and Z_y, respectively, given by

$$\rho_{xy} = \frac{\langle W_{x,n}'W_{y,n}'\rangle}{(\sigma_x\sigma_y)} \quad (4c)$$

$$\sigma_{zx} = \sqrt{1 - \alpha^2}\,\sigma_x \quad (5)$$

$$\sigma_{zy} = \sqrt{1 - \alpha^2}\,\sigma_y \quad (6)$$

The parameters required for the preceding model are presented in Table 2 and are based on the analysis of wind data recorded at Sea Island by the Kuwait Oil Company from January 1, 1977, to December 31, 1983. The station is located 15 km offshore, approximately midway along the Kuwaiti coastline; the anemometer is mounted 25 m above mean sea level. The recorded wind data were corrected for elevation to 10 m above mean sea level by applying the method recommended by the U.S. Army Corps of Engineers (*Shore* 1984).

Resio and Vincent (1977) suggested adjusting the over-water wind from the recorded data by considering both the location effects and the air-sea

TABLE 2. Statistical Parameters of Winds at Sea Island for 1977–1983

Month (1)	$\bar{W}_x$ (m/s) (2)	$\bar{W}_y$ (m/s) (3)	σ_x (m/s) (4)	σ_{zx} (5)	σ_y (m/s) (6)	σ_{zy} (7)	ρ_{xy} (8)	$\rho_{xx,1}$ (9)	$\rho_{yy,1}$ (10)	α (11)
January	0.88	−1.66	3.38	1.12	4.92	1.68	−0.51	0.87	0.91	0.90
February	0.66	−1.33	4.07	1.60	4.92	2.00	−0.53	0.91	0.91	0.91
March	−0.16	−0.42	3.92	1.57	4.34	1.74	−0.53	0.90	0.92	0.91
April	−0.22	−0.22	3.11	1.46	3.45	1.61	−0.05	0.91	0.91	0.91
May	0.60	−1.78	3.60	1.75	3.96	1.92	−0.38	0.84	0.89	0.87
June	3.00	−3.74	4.01	1.52	3.75	1.43	−0.46	0.92	0.92	0.92
July	2.63	−2.97	3.34	1.37	3.63	1.49	−0.43	0.90	0.92	0.91
August	2.68	−3.12	3.87	1.57	3.78	1.55	−0.38	0.91	0.91	0.91
September	0.89	−1.18	3.38	1.44	4.10	1.74	−0.27	0.87	0.92	0.90
October	0.61	−1.51	3.79	1.44	4.34	1.61	−0.40	0.92	0.93	0.93
November	0.49	−1.78	3.86	1.24	4.95	1.59	−0.54	0.92	0.96	0.95
December	1.63	−1.86	4.34	1.39	5.38	1.74	−0.56	0.93	0.95	0.95

temperature difference. Around Sea Island, there are no major topographic features of structures to affect the anemometer. The station is located offshore; therefore, there is no need for correction of onshore winds. Offshore wind may be adjusted based on wind speed and location; Resio and Vincent (1977) gave the relation of the offshore wind correction factor from the onland anemometers. There is no detailed information for the correction based on offshore wind stations. In the present study, offshore wind for the whole study area is assumed to be the same as that recorded at the Sea Island station. The air-sea temperature difference at the entrance of Kuwait Bay (west of Failaka Island, Fig. 1) was recorded by Dames and Moore (*Hydraulic* 1983), and the monthly average difference varies from −2.4° C to 8.3° C. The wind correction factor (Resio and Vincent 1977) for the air-sea temperature difference was introduced for this wind calculation.

Initial wind components can be chosen randomly from the joint distribution of the monthly data or the Markovian process can be initiated with the mean wind component values, allowing sufficient time for the transients to decay.

Simulating Drift

Oil slicks on the sea's surface are influenced by currents, winds, waves, and the earth's rotation. Schwartzberg (1971) studied the combined influence of winds, waves, and currents and suggested that the drift speed due to wind was 3–4% of the wind speed 10 m above the sea surface. The combined drift movement is regarded as a simple vector sum of wind and current drift. Its general form is given by

$$\mathbf{U}_t = \mathbf{U}_w + K_c\mathbf{U}_c \quad (7)$$

where $\mathbf{U}_w$ = the velocity due to wind; $\mathbf{U}_c$ = the water current velocity (in the present study only the tidal current was considered); and K_c = a constant. Schwartzberg (1971) suggests that the value of K_c is 0.56, based on laboratory results. Lissauer (1980) obtained reasonably accurate movement predictions compared to field data by using a K_c value of 1. In this study, K_c

J. Waterway, Port, Coastal, Ocean Eng., 1991, 117(3): 285-300

was assumed to be 1, and this has been validated by two field trials in Kuwaiti territorial waters.

The equations for predicting the x- and y-coordinates of the center of the spill can be written as

$$L_x(t + \Delta t) = L_x(t) + [\mathbf{U}_t(t)]_x \Delta t \quad (8)$$

$$L_y(t + \Delta t) = L_y(t) + [\mathbf{U}_t(t)]_y \Delta t \quad (9)$$

where $L_x(t + \Delta t)$ = x-coordinate of the center of the slick at time $t + \Delta t$; $L_y(t + \Delta t)$ = y-coordinate of the center of the slick at time $t + \Delta t$; $L_x(t)$ = x-coordinate of the center of the slick at time t; $L_y(t)$ = y-coordinate of the center of the slick at time t; $\mathbf{U}_t(t)$ = the slick's drift velocity at time t; and Δt = time increment, defined by the operator.

The wind-induced oil-slick drift velocity $\mathbf{U}_w$ has the form

$$\mathbf{U}_w = 0.03[W \cos(\theta - \theta')\mathbf{i} + W \sin(\theta - \theta')\mathbf{j}] \quad (10)$$

where W = wind speed 10 m above the sea's surface; θ = wind direction; and θ' = deflection angle (Ekman 1905). Under steady state and shallow water conditions (Ekman 1905; Neumann 1968), the deflection angle is computed from

$$\theta' = \tan^{-1}\left[\frac{\sinh\left(2\pi \dfrac{d}{D}\right) - \sin\left(2\pi \dfrac{d}{D}\right)}{\sinh\left(2\pi \dfrac{d}{D}\right) + \sin\left(2\pi \dfrac{d}{D}\right)}\right] \quad (11)$$

where d = the local water depth; and D = the depth of frictional influence, given by

$$D = \pi\left(\frac{E}{\rho\omega \sin \phi}\right)^{1/2} \quad (12)$$

where E = the eddy viscosity coefficient in the upper strata of the oceans (E = 100 g/cm-s); ρ = the density of the seawater (ρ = 1.03 g/cm^3); ω = the earth's rotation speed ($\omega = 7.29 \times 10^5$ rad/s); ϕ = the local latitude, which for Kuwait City is 29° 22′ N.

The constant value of D = 52.5 m is assumed to be reasonably representative for the Kuwait coastal area.

Simulating Spread

The spread of oil on the water's surface has been studied by a number of researchers (Blokker 1964; Fay 1969, 1971; Hoult 1972; Mackay et al. 1980; Lehr et al. 1984a,b). Lehr et al. (1984a) did a series of test spills with spill sizes of 13 barrels of Arabian heavy crude oil and 20 and 51 barrels of Arabian light crude oil in the fall of 1982 in the Arabian Gulf. They found the oil-spread prediction using Blokker and Fay's formula to be much smaller than the field measurements. Later, Lehr et al. (1984b) formulated a modified Fay-type spread equation:

J. Waterway, Port, Coastal, Ocean Eng., 1991, 117(3): 285-300

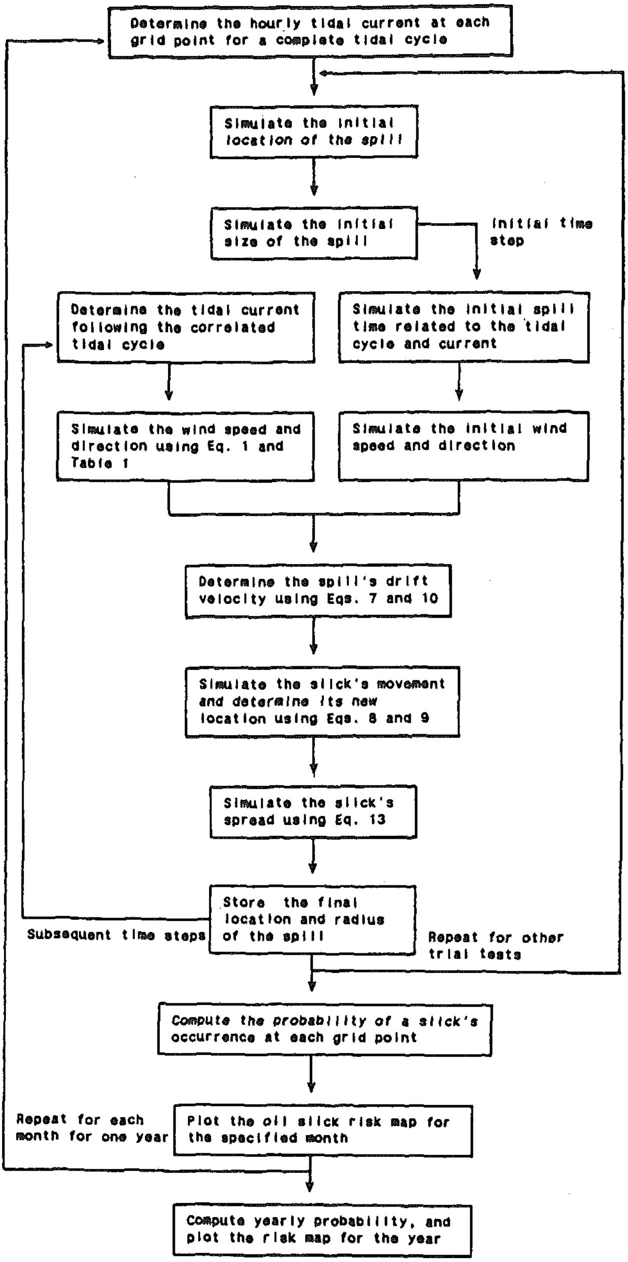

FIG. 3. Flowchart of Computational Procedure

$$A = 2{,}270\left(\frac{\Delta\rho}{\rho_o}\right)^{2/3} V^{2/3}t^{1/2} + 40\left(\frac{\Delta\rho}{\rho_o}\right)^{1/3} V^{1/3}W^{4/3}t \qquad (13)$$

where A = the area of the slick in square meters; ρ_o = the density of the oil; $\Delta\rho$ = the density difference between water and oil; V = the initial volume of the slick; t = the time in minutes; and W = the wind speed in knots. This equation gives much better predictions than Blokker and Fay's formula; the predicted area includes both the thick (black) and thin (sheen) areas.

Eq. 13 was used to predict spreading. However, in the simulation, the shape of spread is assumed to be circular instead of elliptical, as recommended by Lehr et al. (1984b); therefore, the radius of spread can be determined from the area of spread.

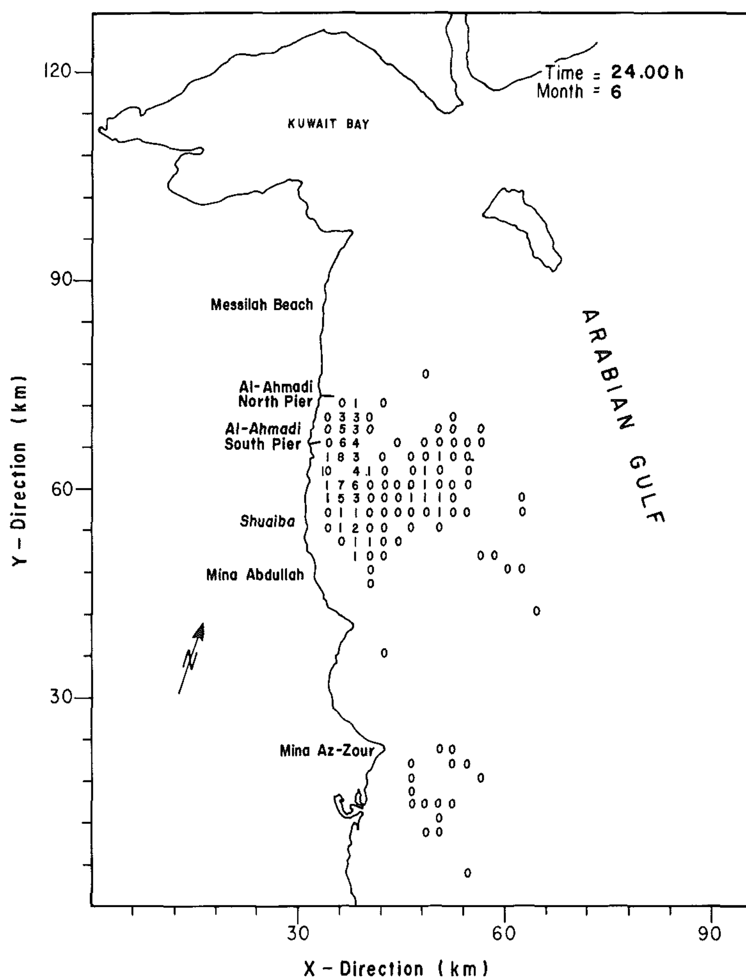

FIG. 4. Probability of Oil Slick Position in Kuwaiti Waters during June, 24 hours after Spill, for 1,000 Trials

J. Waterway, Port, Coastal, Ocean Eng., 1991, 117(3): 285-300

Kuwait Oil-Spill Risk Map

The oil-spill risk simulation model was applied to predict the probability of a slick's presence in Kuwaiti territorial waters. The position and area of oil-slick movement were recorded at each time step for each trial up to the final time step. This information was used later for determining the probability of the slick's presence at each grid point. The risk map can be simulated for any given oil-spill duration. In this study, durations of 24 and 48 hours were selected for demonstration, because most small spills (less than 100 barrels) can be cleaned within two days; the hourly time-step increment is used for all trials. The computational procedure is outlined in the flow chart shown in Fig. 3. The trials totaled 1,000; this number was decided by

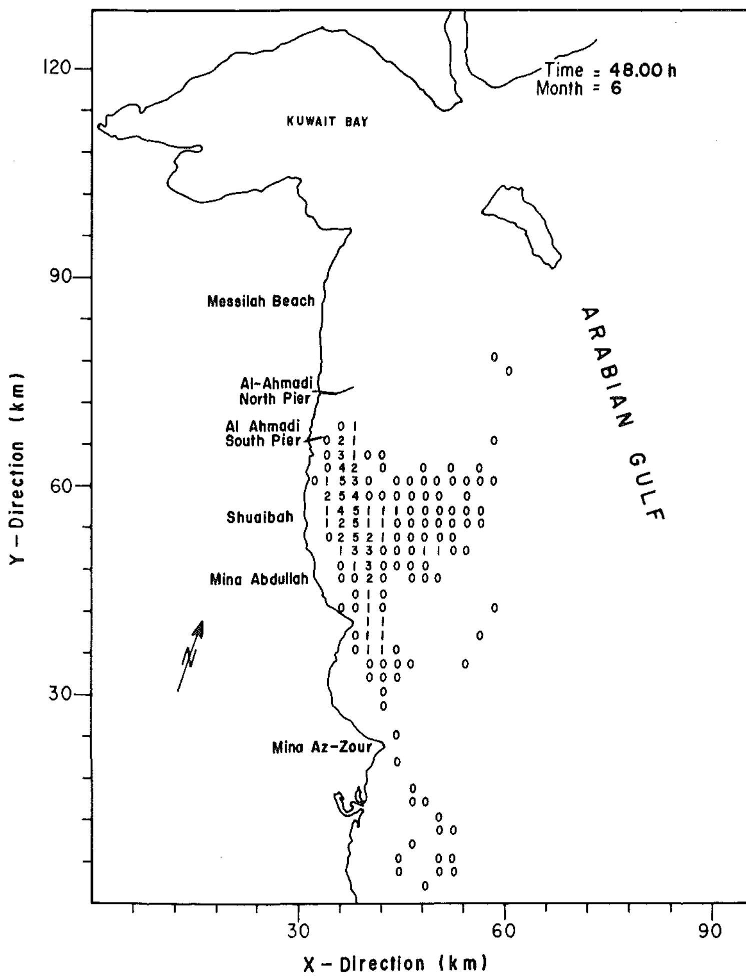

FIG. 5. Probability of Oil-Slick Position in Kuwaiti Waters during June, 48 hours after Spill, for 1,000 Trials

J. Waterway, Port, Coastal, Ocean Eng., 1991, 117(3): 285-300

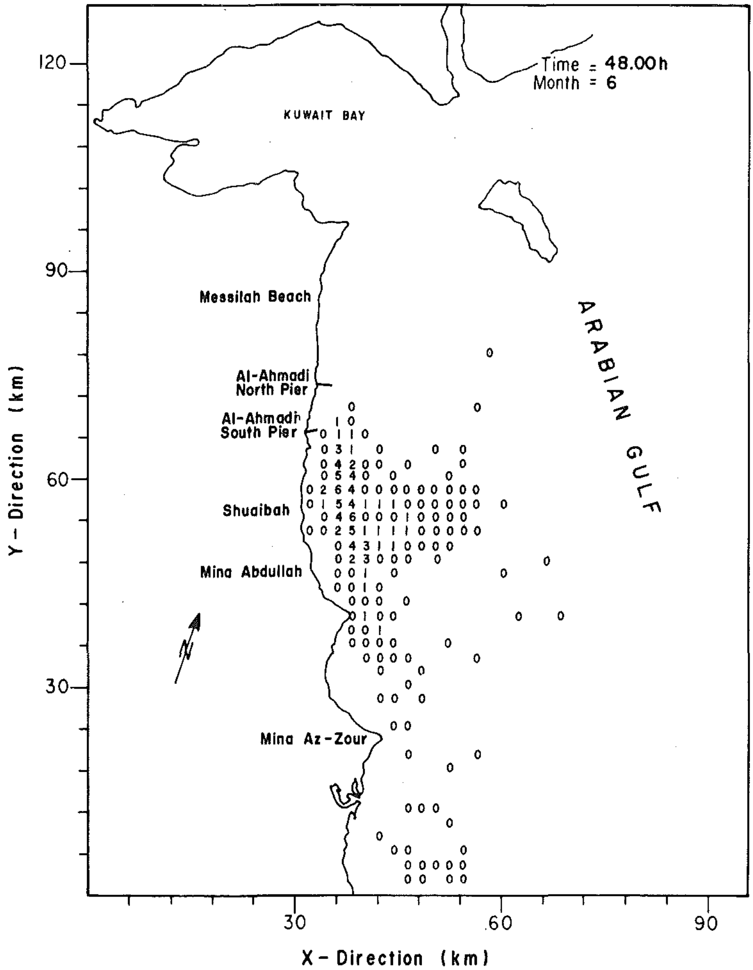

FIG. 6. Probability of Oil-Slick Position in Kuwaiti Waters during June, 48 hours after Spill, for 1,500 Trials

a sensitivity test with various trial numbers.

The model output gives the probability of oil slick-locations in a grid size of 1 × 1 km. Figs. 4 and 5 show Kuwait oil-spill risk maps of 24 and 48 hours for June. The numbers in the figures represent the probabilities (in percent) that the slick will be at the respective locations; 0 signifies a probability greater than 0 but less than 1%. For areas without numbers, the probability is 0.

Fig. 6 shows the Kuwait oil-spill risk map for 48 hours in June for 1,500 trial tests. A comparison between Figs. 5 and 6 shows the results to be approximately the same; thus, it was considered unnecessary to increase the number of trials beyond 1,000 in this case.

Figs. 7 and 8 show Kuwait oil-spill risk maps for the year. The probability

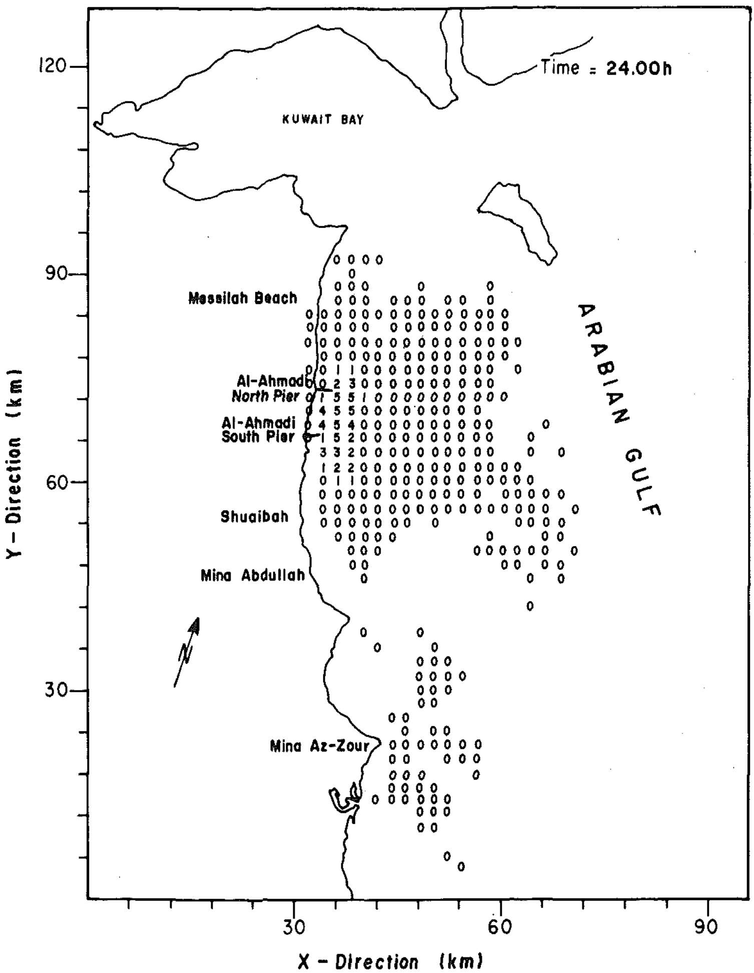

FIG. 7. Probability of Oil-Slick Position in Kuwaiti Waters, 24 hours after Spill, for One Year

is determined for the results from January to December; it represents 12,000 trials, i.e., 1,000 trials for each month.

The results of the Kuwait oil-spill risk map can be used to determine the relative sensitivities of coastal sections where oil-slick occurrence is the most probable. The decision-maker can use this information for future planning in coastal development, particularly for selecting sites for fish farms and seawater intakes.

Conclusions and Recommendations

An oil-spill risk simulation model that can be used to estimate the probability of oil-slick occurrence in a given area has been presented. Oil-spill

J. Waterway, Port, Coastal, Ocean Eng., 1991, 117(3): 285-300

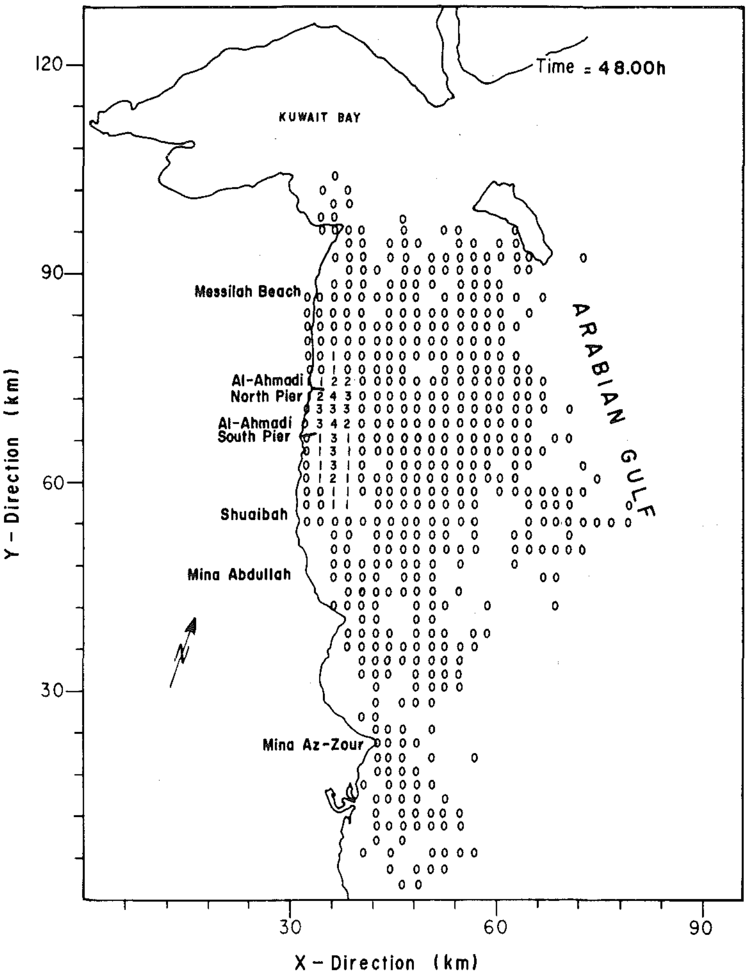

FIG. 8. Probability of Oil-Slick Position in Kuwaiti Waters, 48 hours after Spill, for One Year

location and size are simulated based on the associated probability functions derived from historical data. The relability of the probability function depends on the amount of the data; the more data, the better the prediction. Wind is simulated using a time-series model based on local wind statistics. The drift and spread of the oil-slick movement are included in the model.

An example was presented to generate the Kuwait oil-spill risk map by using the simulation model. The results of the model can provide regulating agencies with a guide for combating oil spills. It can be used as a first step toward constructing a risk map within an area of interest. Further study is needed to improve the model, specifically:

1. The probability function of spill location in the present approach was estimated from recorded data at locations where spills have occurred, but it ignores

the fact that the probability of oil-spill occurrence also depends on the type of activity at a location, e.g., the probability is higher at loading terminals than in commercial harbors. Therefore, a probability function based not only on location but also on activities in harbors, shipping routes, anchorage areas, oil-loading terminals, and oil pipelines is needed.

2. Similarly, the size of spill was simulated here based solely on data recorded at locations where spills have occurred. Again, however, the size of the spill depends mainly on the nature of the activities, e.g., the largest spills have been related to oil-loading terminals, oil pipelines, oil wells, and tankers. Therefore, a probability function related to the size of spills and based on activities rather than on location alone should be developed.

3. The probability functions of spill location and size are estimated based on historical data. However, since most oil-spill accidents involve human error, measures to correct, control, or eliminate them may significantly reduce the probability of future occurrence. In other words, the probability function of spill location and size must be modified to reflect experience gained in operating a particular facility.

Appendix. References

Blokker, P. C. (1964). "Spreading and evaporation of petroleum projects on water." *Proc., 9th Int. Harbor Conf.,* Antwerp, Belgium.

Devanney, J. W., and Stewart, R. J. (1974a). "Analysis of oil spill statistics." *MIT Sea Grant Program Report No. MITSG 74-20,* Massachusetts Institute of Technology, Cambridge, Mass.

Devanney, J. W., and Stewart, R. J. (1974b). "Bayesian analysis of oil spill statistics." *Marine Tech.,* 11, 365–382.

Ekman, V. W. (1905). "On the influence of Earth's rotation on ocean currents." *Arkiv for Matematik Astronomi Och Fysik,* 2, 1–53.

Fay, J. A. (1969). "The spread of oil slicks on a calm sea." *Oil on the sea,* D. P. Hoult, ed., Plenum Press, 53–63.

Fay, J. A. (1971). "Physical processes in the spread of oil on a water surface." *Proc., Joint Conf. on Prevention and Control of Oil Spills,* American Petroleum Institute, 463–467.

Hoult, D. P. (1972). "Oil spreading on the sea." *Ann. Rev. Fluid Mech.,* 341–368.

Hydraulic studies. (1983). Vol. III, Final report submitted by Dames and Moore, to the Ministry of Electricity and Water for Kuwait.

Keith, V. F., et al. (1977). "Real-time simulation of tanker operations for the trans-Alaska pipeline system," presented at the annual meeting of the Society of Naval Architects and Marine Engineers, New York, N.Y.

Lehr, W. J., et al. (1984a). *Empirical studies of the spreading of oil spills.* Water and Envir. Div., Res. Inst., Univ. of Petroleum and Minerals, Dhahran, Saudi Arabia.

Lehr, W. J., et al. (1984b). *A new technique to estimate initial spill size using a modified Fay-type spreading formula.* Water and Envir. Div., Res. Inst., Univ. of Petroleum and Minerals, Dhahran, Saudi Arabia.

Lissauer, I. M. (1980). "Forecasting the movement of oil spills." *Envir. Int.,* 3, 145–150.

Lo, J. M., et al. (1985). "Simulation of oil spill dynamics and risk analysis for Kuwait's coast." *Report No. KISR1692,* Kuwait Inst. for Scientific Res., Safat, Kuwait.

Mackay, D., Patterson, S., and Trudel, K. (1980). *A mathematical model of oil spill behavior.* Report for Environmental Control Directorate, Canada.

Neumann, G. (1968). "Major types of ocean currents." *Ocean currents.* Elsevier Publishing Co., Amsterdam, Netherlands, 178–191.

Oil spill risk analysis for the Federal northern tier pipeline environmental statement.

(1978). Prepared by Oceanographic Institute of Washington for the Bureau of Land Management, Washington, D.C.

The proposed oil refinery at Eastport, Maine—A preliminary oil spill risk assessment of marine operations. (1979). Prepared by Engineering Computer Opteconomics, Inc., for the Office of Habitat Protection, Nat. Marine Fisheries Services, Nat. Oceanographic and Atmospheric Admin.

Resio, D. T., and Vincent, C. L. (1977). "Estimation of winds over the Great Lakes." *J. Wtrwy., Port, Coast., and Oc. Div.*, ASCE, 103(2), 265.

Schwartzberg, H. G. (1971). "The movement of oil spills." *Proc. Joint Conf. on Preventing and Control of Oil Spills,* American Petroleum Institute, 489–494.

Stewart, T. R., and Leschine, T. M. (1986). "Judgement and analysis in oil risk assessment." *Risk Analysis,* 6(3).

Tayfun, M. A., and Wang, H. (1973). "Monte Carlo simulation of oil slick movements." *J. Wtrwy., Harb., and Coast. Engrg. Div.*, ASCE, 99, 309–324.

Shore protection manual. (1984). U.S. Army Corps of Engrs., Washington, D.C.

Appendix II. Notation

The following symbols are used in this paper:

A = area of spill;
D = depth of frictional influence;
d = local water depth;
E = eddy viscosity coefficient in upper strata of ocean;
K_c = constant for determining oil slick drift velocity due to current;
$L_x(t)$ = x-coordinate of center of oil slick at time t;
$L_y(t)$ = y-coordinate of center of oil slick at time t;
t = time;
$\mathbf{U}_c$ = current velocity;
U_n, V_n = zero-mean independent normal random variable at time step n;
$\mathbf{U}_t$ = oil slick drift velocity;
$\mathbf{U}_w$ = oil slick drift velocity due to wind;
V = initial volume of oil slick;
W = wind speed;
$\mathbf{W}(t)$ = wind vector;
$\bar{\mathbf{W}}$ = mean wind vector;
$\mathbf{W}'(t)$ = time-varying component of $\mathbf{W}$;
$\mathbf{W}'_n$ = time-varying component of $\mathbf{W}'(t)$ at time step n;
W_x = x, easterly (+) or westerly (−), component of wind velocity;
$W'_x(t)$ = time-varying component of $\mathbf{W}'(t)$ in x-direction;
W_y = y, northerly (+) or southerly (−), component of wind velocity;
$W'_y(t)$ = time-varying component of $\mathbf{W}'(t)$ in y-direction;
$\mathbf{Z}_n$ = zero-mean random perturbation vector at time step n;
$\mathbf{Z}_{x_n}$ = x-component of $\mathbf{Z}_n$;
$\mathbf{Z}_{y_n}$ = y-component of $\mathbf{Z}_n$;
α = scalar monthly constant for wind;
$\Delta\rho$ = density difference between water and oil;
θ = wind direction;
θ' = deflection angle;
ρ = density of seawater;
ρ_o = oil density;
ρ_{xy} = correlation coefficient of W'_x and W'_y;

$\rho_{xx,1}$ = auto-correlation coefficients of W'_x corresponding to time step of ± 1 hour;
$\rho_{yy,1}$ = auto-correlation coefficients of W'_y corresponding to time step of ± 1 hour;
σ_x = standard deviation of W'_x;
σ_y = standard deviation of W'_y;
σ_{zx} = standard deviation of Z_x;
σ_{zy} = standard deviation of Z_y;
ϕ = latitude; and
ω = earth rotation speed.

J. Waterway, Port, Coastal, Ocean Eng., 1991, 117(3): 285-300