

Oil Spill Trajectory Model

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ABSTRACT. The growing activities in the field of oil production and transportation in the Gulf of Suez, Red Sea increased the probability of accidental oil spill. The behaviour and pathways of the likely spilled oil depend on several environmental parameters. At the NIOF, a model was established to simulate the behaviour of the oil spill in marine environment. This model uses the general transport model, taking in consideration the effect of various physical processes on the oil spill and the changes that may occur during its movement on the surface of the sea. The movement of the spilled oil depends on wind speed and direction, tidal and residual water currents. Turbulent dispersion is an important mechanism influencing the horizontal spreading of the spill. The model simulates the movement of the spilled oil, the time lapsed before it touches the beach and its trajectory during the journey to the beach are calculated. The computer software is written in PASCAL. The model is useful for oil combating operation.

Introduction

Oil spill accidents can happen almost anywhere and at any time. There is no miracle cure and a major spill from a tanker or platforms will nearly always result in contamination of shorelines unless winds and currents carry the oil out to sea where it can dissipate and degrade naturally.

Even the best of planning and application of the most modern safety techniques can not ensure that accidental oil spills will not occur, it then becomes necessary to develop technical information required to determine management tools which provide decision makers with the technical information required to evaluate the environmental risks associated with the development of oil reserves, and to assess and ameliorate the environmental impacts of oil spills. An oil spill trajectory model should be a principal component of this management systems.

The objective of this model is to track and predict the fate of the oil during its movement in the marine environments. The model is adopted and modified for application in the Gulf of Suez.

Theoretical Bases of Simulation Model

The simulation model "TRACE" is based on the general transport equation of Ahlstrom (1975) :

$$\frac{\partial c}{\partial t} = - \bar{U} \cdot \Delta c + \Delta \cdot (K_h \Delta c) + \Phi \quad (1)$$

where :

c = mass concentration of oil,

\bar{U} = net advective current,

K_h = horizontal component of the combined dispersion coefficient, and

Φ = sources and sinks.

This equation is solved using the Discrete Parcel Random Walk Method of Ahlstrom (1975) in which the slick is assumed to consist of an ensemble of small discrete quantities of mass or parcels. Each of these parcels is assumed to move independently of the others in the ensemble with the mass concentration of oil being depicted by the number of parcels in a given area. According to equation (1), the motion of each parcel consists of advective and dispersive components. The transport of the slick parcel due to the net advective current is simulated using a Lagrangian approach, while that due to the turbulent dispersive component is simulated using the Homogenous Markov Random Walk Process.

In general, the processes included in "TRACE" model are advection, dispersion and spreading, and

weathering of an oil spill. In the following sections, a description of the procedure used to quantify each of these processes will be given :

I. Advection

The advection of an oil parcel is typified the vectorial sum of the wind-induced surface current, the tidally-induced surface current, and the residual current.

a. Wind-Induced Surface Current

According to Madsen (1977), the steady-state surface wind drift current \bar{U} is computed from the equation :

$$\bar{U} = \frac{U_*}{k} \left[\frac{\pi}{2} + i(-1.15 + \ln 30 l / k_s) \right] \quad (2)$$

where :

- u_* = friction velocity,
- k = Von Karmen constant,
- l = depth of frictional influence, and
- k_s = equivalent sand roughness of the sea surface.

The friction velocity u_* is given by Ruggles (1970) as :

$$u_* = 0.04 (\rho_a / \rho_w)^{1/2} W \quad (3)$$

where ρ_a and ρ_w are the air and water densities, and W is the wind speed. The depth of the frictional surface is given by Madsen (1977) as follows :

$$l = 3.66 W / \sin \psi \quad (4)$$

where ψ is the latitude of the spill location.

b. Tidal-Induced Surface Current

Tidal currents result primarily from the gravitational interactions of Earth, Moon and Sun. These currents are usually significant only near coastlines, or in restricted and shallow water areas.

The velocity vector of the base directional field at node (i, j) will be referred to as $(V_h)_{ij}$. The amplitude of the tidal flow is restricted to oscillate along the fixed directions established by the base directional field. The prediction of the amplitude of the tidal current oscillations was made as follows :

The tide stage function can be approximated well by :

$$y = [(h_n - h_{n-1})/2][1 - \cos(\pi(t - t_{n-1})/(t_n - t_{n-1}))] + h_{n-1} \quad (5)$$

where

$$y = \text{tidal stage,}$$

h_{n-1}, h_n = successive tidal stage maxima or minima,

t_{n-1}, t_n = successive times that correspond to the occurrence of h_{n-1} and h_n , and

t = the current time; $t_{n-1} \leq t < t_n$.

An approximate functional form for describing the tidal current can be derived by differentiating equation (5)

$$Y^l = \frac{\pi/2[(h_n - h_{n-1})/(t_n - t_{n-1})]}{\sin[(\pi(t - t_{n-1}))/(t_n - t_{n-1})]} \quad (6)$$

Equation (6) is an appropriate functional form, but it has to be adjusted to be applicable at all locations in the study area. To do this, it was first assumed that the actual current magnitude at a point (p) within the system at a given time is proportional to the relative magnitude predicted by equation (6)

$$V_p = K_p Y^l \quad (7)$$

This scalar relationship can be generalized to a vector function that is valid at all nodes in the system. Then :

$$\bar{V}_{ij} = K_p Y^l (\bar{V}_n)_{ij} \quad (8)$$

where $(\bar{V}_n)_{ij}$ represents a normalized base directional vector, and V_p is the actual current magnitude.

To calculate the value of K_p , the correlation between the maximum observed tidal current for a given tidal period and the tidal range at point (p) is calculated. If a linear fit of the data of the form

$$V_m = C_j (h_n - h_{n-1}) \quad (9)$$

where

V_m = the maximum observed velocity during a tidal cycle, and

C_j = tidal velocity correlation constant.

From the above equations, it follows that

$$C_j (h_n - h_{n-1}) = K_p (\pi/2) [(h_n - h_{n-1})/(t_n - t_{n-1})] \quad (10)$$

$$K_p = (2/\pi) C_j (t_n - t_{n-1}) \quad (11)$$

$$\bar{V}_{ij} = [(2/\pi) C_j (t_n - t_{n-1})][(\pi/2)(h_n - h_{n-1})/(t_n - t_{n-1})] \quad (12)$$

$$\sin[\pi(t - t_{n-1})/(t_n - t_{n-1})](\bar{V}_n)_{ij}$$

from which

$$\bar{V}_{ij} = [C_j (h_n - h_{n-1}) \sin(\pi(t - t_{n-1})/(t_n - t_{n-1}))](\bar{V}_n)_{ij} \quad (13)$$

Equation (13) allows the prediction of the tidal current at any time and at any nodal location.

c. Residual Surface Current

This current includes large-scale geostrophic cur-

rents, currents resulting from freshwater runoff, and any other current of persistent nature with respect to tidal and wind drift flows.

II. Dispersion

The dispersive component of the motion of an oil parcel on the water surface is the sum of the contributions from turbulence and physical spreading. Turbulent dispersion is due to the fact that the parcel is subject to turbulence-induced, Brownian-like random motions (Ahlstrom, 1975). From statistical considerations, it can be shown that the root mean square distance (d) moved by a given parcel during time (t) is given by

$$d = R_1 [6(D_x + D_y) t]^{1/2} \quad (14)$$

where R_1 is a random number ($0 < R_1 < 1$), and D_x and D_y are the x and y components of the turbulent dispersion coefficient. D_x and D_y are computed from the following equations (Quetin and Derouville, 1986).

$$D_x = 5.93 HU^* \quad (15)$$

$$D_y = 0.23 HU^* \quad (16)$$

$$U^* = [(\sqrt{g}) \bar{V} H^{5/6}] / kH \quad (17)$$

where

H = depth of water,

V = mean current speed, and

k = Strickler coefficient of frictional resistance.

U^* = frictional velocity.

The direction of the dispersive step is given by

$$\theta = R_2 (2\pi) \quad (18)$$

where R_2 is a random number ($0 < R_2 < 1$).

The contribution to the dispersion of an oil parcel due to physical spreading is assumed to be effective only during the initial stages of spill. The duration of this effect is determined by the time t_{\max} taken for an oil spill to reach its maximum spread. For $t < t_{\max}$, the physical spreading dispersion coefficient D_p is given by Venkatesh (1988) as follows:

$$D_p = 0.407 n^{0.268} (m^2/sec) \quad (19)$$

where n is the quantity of oil in a parcel in m^3 . For $t < t_{\max}$, D_p is added to each of D_x and D_y before the distance is computed.

III. Surface Tension Spreading

The spreading of oil on the water takes place through three regimes; inertial, viscous and tension

(Fay, 1969). When the oil is assumed to be spreading in a circular manner, the radius r_{\max} at maximum spread is given by the dimensional relationship

$$\pi r_{\max}^2 = A = 10^5 V^{0.75} \quad (20)$$

where

r_{\max} = maximum radius in (m),

A = area in m^2 , and

V = volume of oil in the parcel in m^3 .

The thickness of the oil film is derived from

$$h_{\text{oil}} = V/A \quad (21)$$

The time taken for maximum spreading is given by

$$t_{\max} = [(r_{\max}^2 \rho_w^2 \nu_w) / k^4 \sigma^2]^{1/2} \quad (22)$$

where

ν_w = kinematic viscosity of water,

k = 2.3, and

σ = spreading coefficient for a specific type of oil.

For $t < t_{\max}$, the radius of an oil parcel is given by

$$r = \frac{r_{\max} \sqrt{\sigma}}{(\rho_w^2 \nu_w)^{0.25}} t^{0.75} \quad (23)$$

IV. Weathering Process

Evaporation

Evaporation is the process by which any substance is converted from a liquid state to become part of the surrounding atmosphere in the form of a vapor. In case of oil, the rate of evaporation depends on the volatility of various hydrocarbons constituents, temperature, wind and water turbulence, and the spreading rate of slicks.

The evaporative flux (E_f) is calculated using the following equation

$$E_f = \frac{k_e C_i P_i}{RT} \quad (24)$$

where

k_e = evaporative mass coefficient.

C_i = Concentration of i th component of oil.

P_i = Vapor pressure of the pure component at the temperature of the oil,

R = Universal gas constant, and

T = Air temperature above the oil slick.

Mackay and Mastugu (1973) defined K_e (in cm/sec) by

the relationship

$$K_e = 0.005 (W)^{0.78} \quad (25)$$

with the wind speed (W) specified in cm/sec.

Emulsification

Emulsification is the process by which one liquid is dispersed into another one in the form of small droplets. In the case of oil, the emulsion can be either oil in water or water in oil. To a great degree, emulsification is dependent on turbulent mixing in the water column caused by wave action. Mackay and Leinonen (1977) parameterized this process by a simple first-order expression given by

$$D = KV \quad (26)$$

where

D = Rate of emulsification,

K = Constant (per unit time), and

V = Volume of oil.

For k , the values of 15, 25, 35, and 45% were used by Mackay and Leinonen (1977) for sea states corresponding to wind speeds of < 4, 4-14, 14-25, and > 25 m/sec respectively. These values are also used in the present study. It is also assumed that only the non-volatile parts of the oil will be utilized in the formation of emulsions.

Application of the Simulated Model

The NIOF spill simulated model "trace" has been applied in the north central part of the Gulf of Suez under different environmental conditions. This model investigate the behaviour and movement of spilled oil from platform (lat: 29°10'48.4"N; Long.: 32°41'48.46"E) under the prevailing environmental conditions in Zaffarana area.

The input to the model included :

- 1 – Spill sizes and types.
- 2 – Meteorological and environmental data which comprised :

a) A time series of wind data measured at Suez meteorological station (29°56'N; 32°33'E). The duration of these data are 3 year (1989, 1990 and 1991) with time step equal to 1 hour. Generally about 36% of these data have velocity between 10 and 15 knots while about 31.117% is in the range between 5 and 10 knots and about 23.93% has velocity between 0 and 5 knots. On the other hand the most prevailing direction lies between 315 and 360° (52.64%) and between 0 and 45° (28.7% of the total data).

b) Recorded sea level data using Aanderra instruments collected by NIOF at Zafarana during the period November 1978 to October 1979.

c) The surface current measurements made by NIOF at Zafarana during the period November 1978 to October 1979 using Aanderra instruments too. From this data the maximum current speed was about 40 cm/sec and the minimum value is about 5 cm/sec while the current direction was mainly in SE direction.

The outputs of the model are statistically analyzed to defined the most probable contacted areas by oil spills. The thickness of the oil slick that may be contaminated on the shoreline is calculated. Also the thickness of oil film on the sea surface are calculated too. The following results are obtained :

– The beached areas by oil during winter season are scattered along the western coast of the Gulf of Suez as a result of variability in wind directions. Also, there is a possibility (3-7%) that the spill contacted the Eastern coast during winter season only. The Eastern Coast may be contacted by oil when SW winds prevail with relatively high wind speeds.

– The area between 29°5'24"N and 29°11'24"N and along the Western coast has the highest probabilities to be contacted by oil during spring (62.638 ± 0.9%), summer (73.19 ± 2.05%) and autumn (61.713 ± 5.5%).

– Sometimes, the spill contacted the beach before maximum spreading of the spill. This behavior is strong during July when NW winds prevail with relatively high speed.

– The coastline extended between 29°5'30" and 29°10'00"N will be covered by oil **all over the year**. While the most contacted area by oil will lie in between 29°6'30" and 29°7'00"N. The spilled oil will contacted this area sometimes before maximum spreading and other time after maximum spreading.

Figure (1a-f) illustrates examples of the track of oil spill and expected covering area by oil. Also Table (1) summaries the result of trajectory models during the four seasons.

Reported field observation in the Gulf of Suez showed areas that are heavily polluted by oil spilled from offshore drilling and production platform at Zafarana. These areas (Fig. 2) are coincided with those occupying the higher probabilities of being polluted through the model.

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TABLE 1-a. Contacted areas with oil, its coverage area on the shore, extensions, thickness and average time taken to be beached during winter season.

Lat interval (°N)	Frequency (%)	Thickness of oil film (μ)	Thickness of slick along the coast (mm)	Average time (hour)
28.58 - 28.68	1.10	1.15	0.16	120.0
28.68 - 28.78	2.22	1.16	0.16	111.0
28.78 - 28.88	4.44	1.07	0.15	181.0
28.88 - 28.98	20.0	1.23	0.19	87.7
28.98 - 29.08	7.78	1.33	0.28	41.0
29.08 - 29.18	42.2	1.33	0.28	44.8
29.18 - 29.28	17.8	1.30	0.24	53.6
29.28 - 29.38	1.11	1.36	0.29	31.0
29.08 - 29.18 (Eastern coast)	1.11	1.29	0.24	55.0
29.18 - 29.29 (Eastern coast)	2.22	1.26	0.22	68.5

TABLE 1-b. Contacted areas with oil, its coverage area on the shore, extensions, thickness and average time taken to be beached during spring season.

Lat. interval (°N)	Frequency (%)	Thickness of oil film (μ)	Thickness of slick along the coast (mm)	Average time (hour)
28.78 - 28.88	2.20	1.30	0.24	
28.88 - 28.98	22.0	1.32	0.26	45.8
28.98 - 29.08	13.2	1.32	0.27	43.5
29.08 - 29.18	62.6	1.34	0.28	38.2

TABLE 1-c. Contacted areas with oil, its coverage area on the shore, extensions, thickness and average time taken to be beached during summer season.

Lat. interval (°N)	Frequency (%)	Thickness of oil film (μ)	Thickness of slick along the coast (mm)	Average time (hour)
28.88 - 28.98	16.3	1.32	0.26	46.0
28.98 - 29.08	12.0	1.32	0.26	43.8
29.08 - 29.18	71.7	1.37	0.31	29.79

TABLE 1-d. Contacted areas with oil, its coverage area on the shore, extensions, thickness and average time taken to be beached during autumn season.

Lat. interval (°N)	Frequency (%)	Thickness of oil film (μ)	Thickness of slick along the coast (mm)	Average time (hour)
28.88 - 28.98	10.2	1.28	0.23	60.0
28.98 - 29.08	19.3	1.23	0.20	84.6
29.08 - 29.18	69.3	1.31	0.26	74.4
29.18 - 29.28	1.14	1.34	0.28	39.0

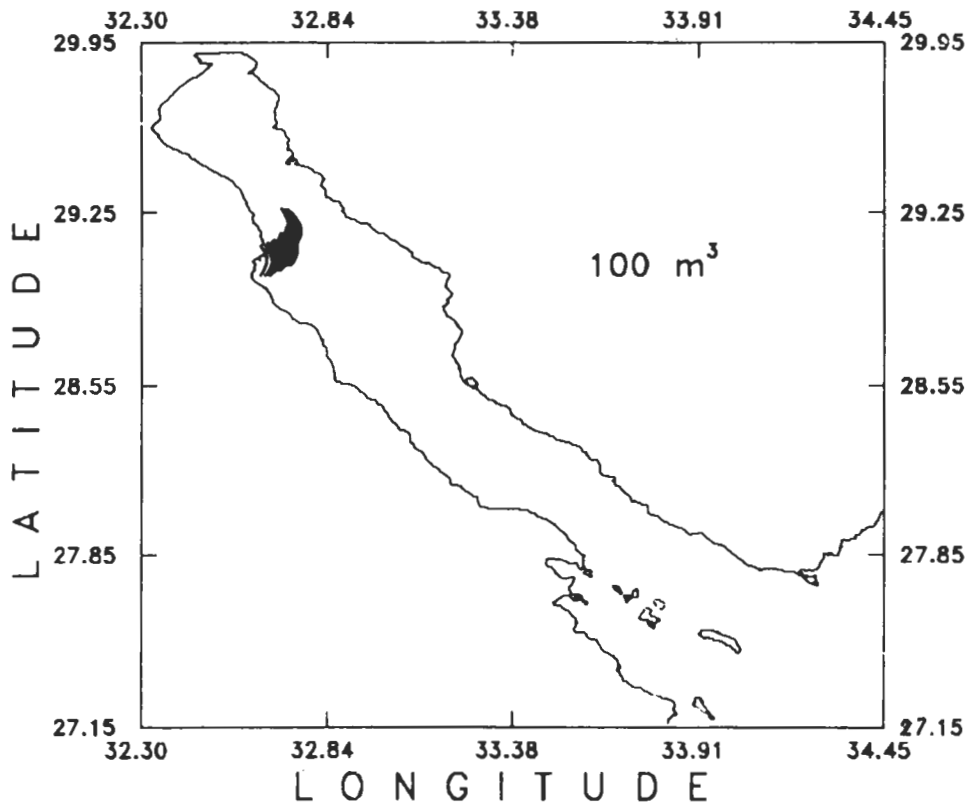


FIG. 1a. Expected covering area by oil on 31 January.

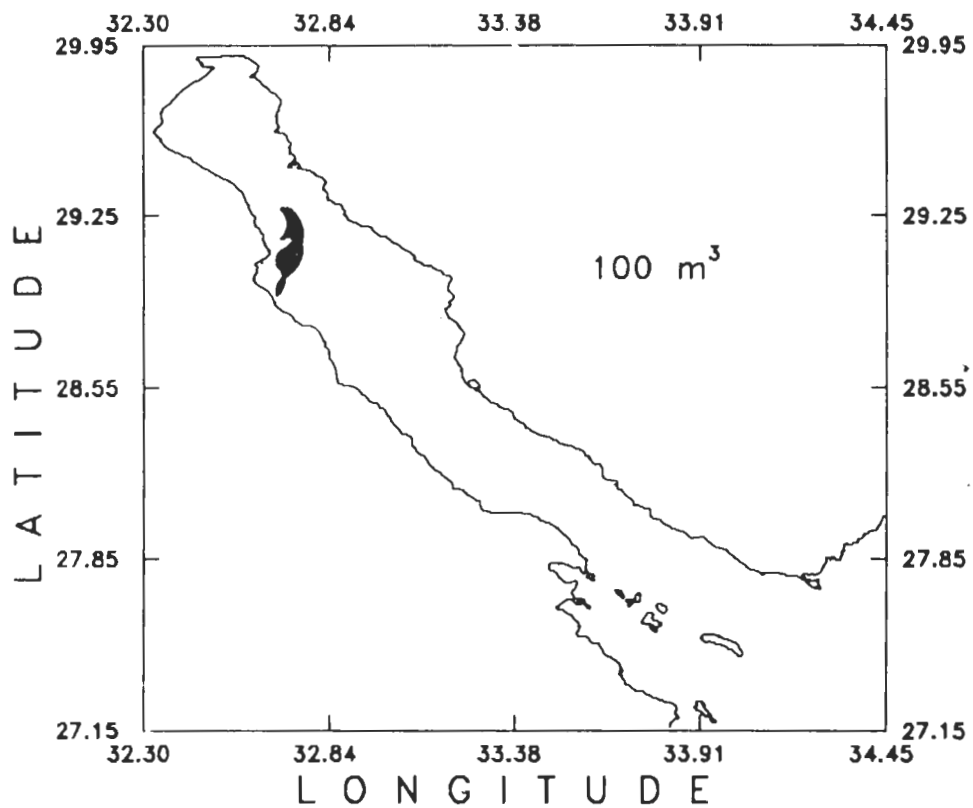


FIG. 1b. Expected covering area by oil on 27 March.

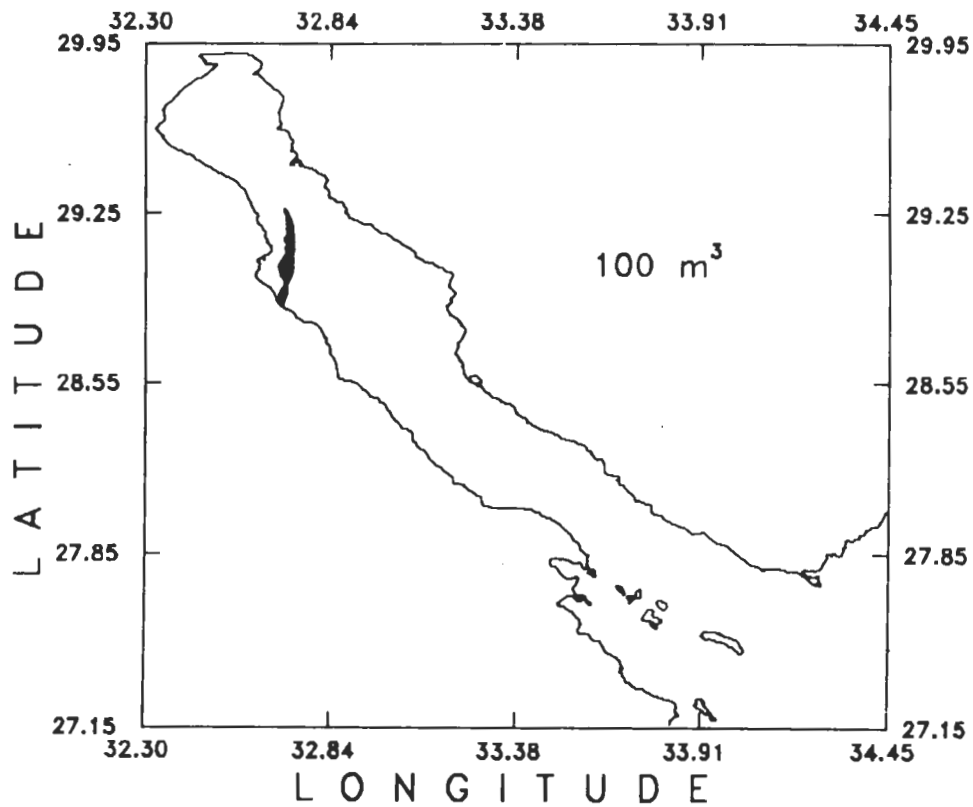


FIG. 1c. Expected covering area by oil on 14 May.

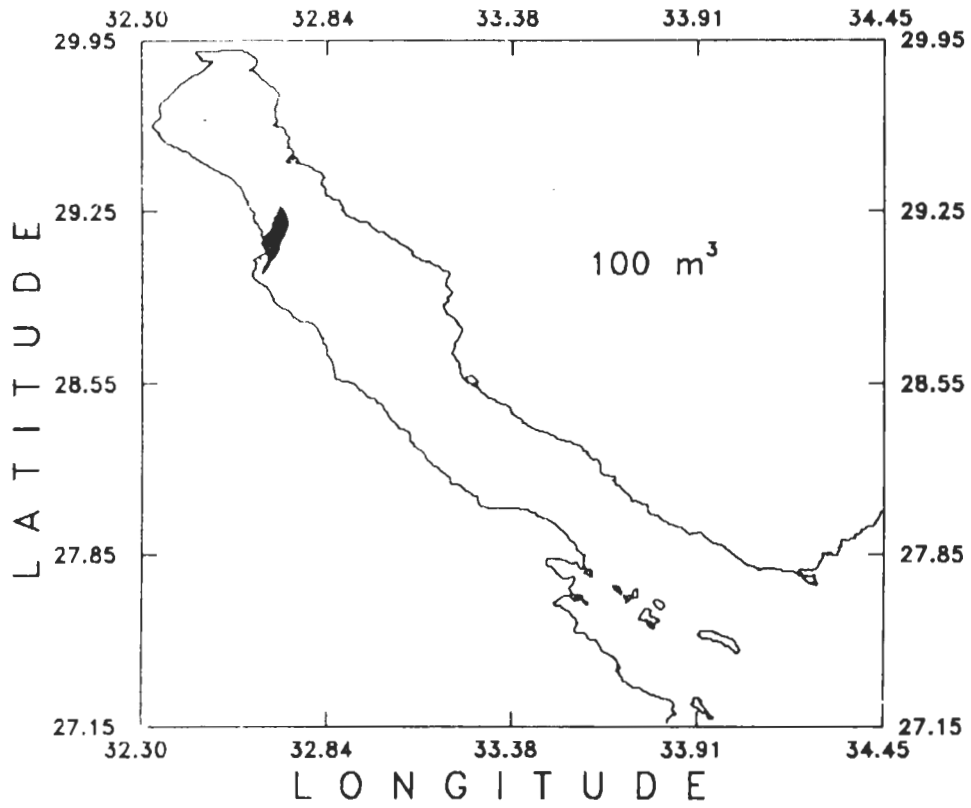


FIG. 1d. Expected covering area by oil on 11 July.

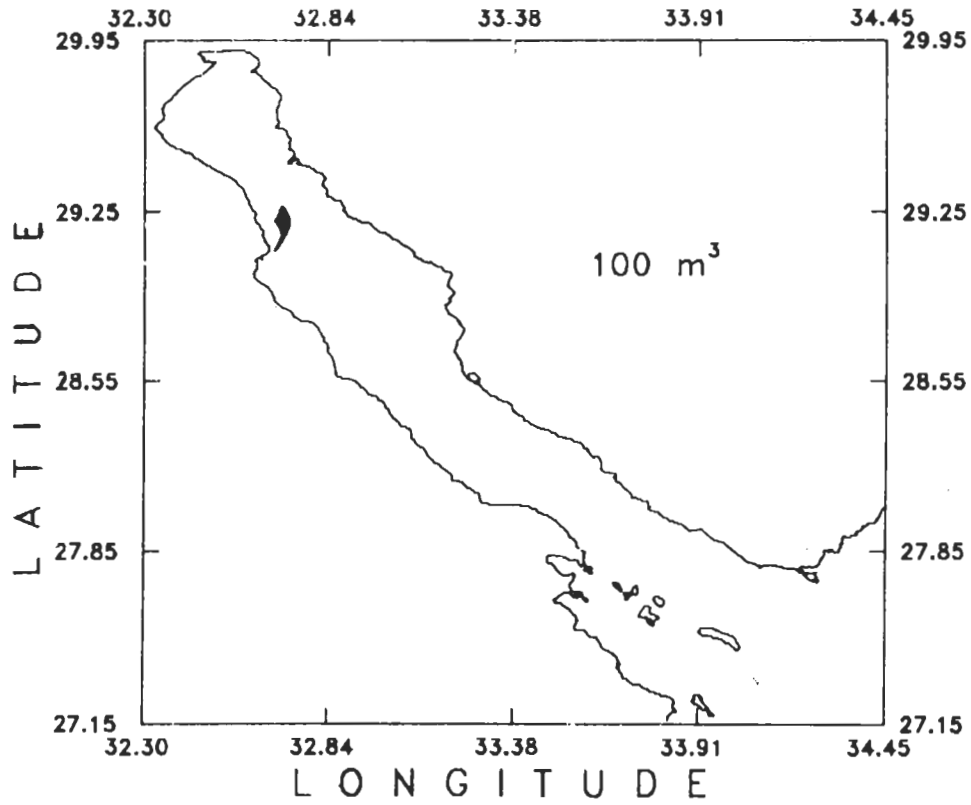


FIG. 1e. Expected covering area by oil on 11 September.

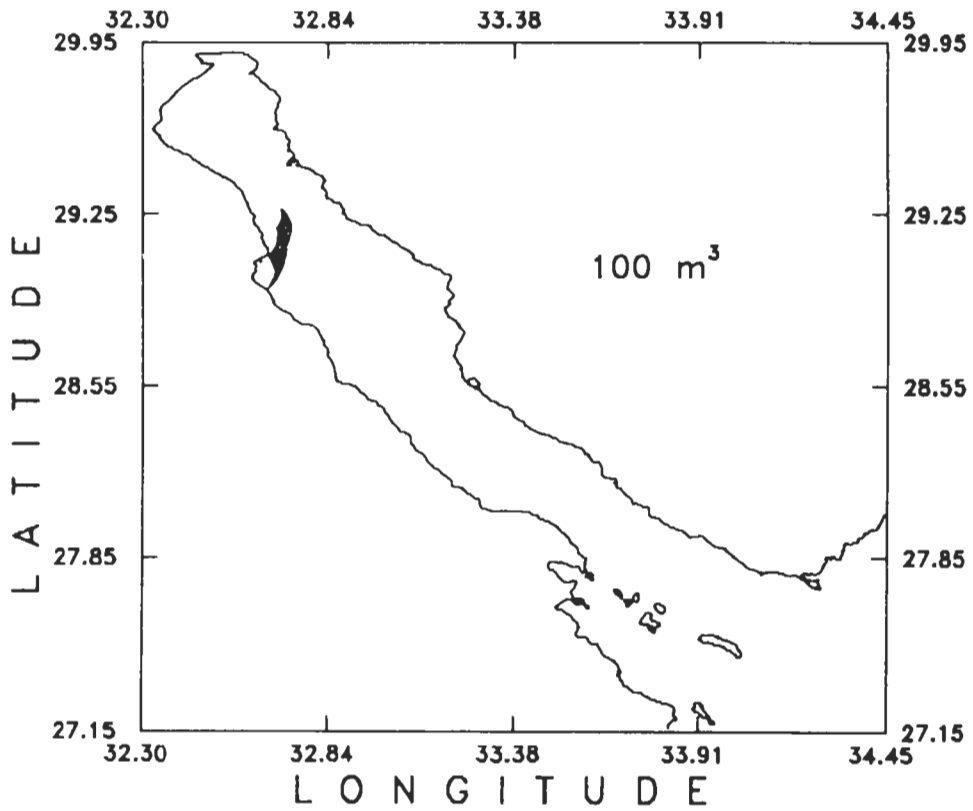


FIG. 1f. Expected covering area by oil on 3 November.

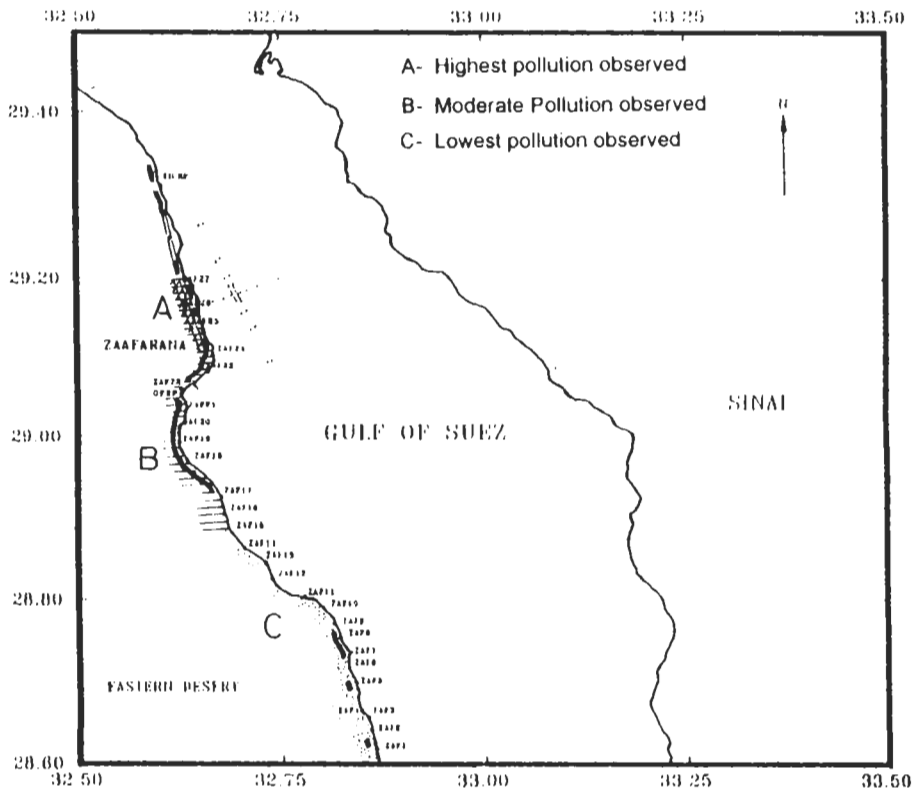


FIG. 2. Evaluation of oil pollution along the Gulf of Suez.

نمذجة رياضية للمسار المنحني لبقع زيت البترول

ابتسام السيد و سعيد غيث و على إبراهيم بلتاجي

المعهد القومي لعلوم البحار والمصائد ، الأسكندرية ، جمهورية مصر العربية

المستخلص: أدت زيادة النشاط في إنتاج البترول ونقله في خليج السويس إلى زيادة احتمالية وقوع حوادث بقع البترول. يعتمد مسار تلك البقع على العديد من العوامل البيئية مثل الرياح من حيث السرعة والاتجاه والتيارات البحرية وحركة المد والجزر. بناء على ذلك قام المعهد القومي لعلوم البحار والمصائد بإعداد نموذج رياضي مستخدماً لغة البسكال ليحاكى مسار تلك البقع الزيتية في البيئة البحرية وحساب الزمن الذي يمضي كى تصل تلك البقع إلى الشاطئ مع تحديد مكان وصولها إليه وسمك طبقة الزيت المتجمعة على الشاطئ. واعتمد هذا النموذج العام لانتقال البقع الزيتية واضعاً في الاعتبار تأثير معظم العوامل الطبيعية عليها والتغيرات التي تطرأ عليها نتيجة لحركة تلك البقع الزيتية في البيئة البحرية.