A TECHNIQUE FOR FORECASTING SPILLED OIL TRANSPORT IN BAYS

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ABSTRACT

An AFOS-based computer model for predicting the motion of oil is described and applied to a historical spill. In this model, a surface oil slick is simulated by a set of drifting particles. Each drifter moves at a velocity which is the sum of a wind drift, a tidal current, and a random current that simulates diffusion. The wind drift is downwind at 3% of the wind speed. Drifters will beach when they cross a shoreline, and may re-enter the water if the winds are offshore. The program requires the location of the spill, a wind forecast, and some data on the tidal currents. The output is a series of maps showing the positions of floating and beached oil.

A hindcast was made of the spill of 1.1 million gallons of crude oil in San Francisco Bay in 1971. Data on the oil distribution and currents in the bay are readily available. Several computer runs were made, and the oil behavior during the first 26 hours is discussed. In general, changes in the position of the main mass of petroleum on the water were correctly forecasted. However, the model underforecasted the intensity of oil beaching, even when the model was modified to increase beaching by enhanced diffusion. The author concludes that gravitational spreading, which is not included in the model, may have been important.

1. INTRODUCTION

In the early hours of January 18, 1971 two fully-loaded oil tankers, the Arizona Standard and the Oregon Standard collided in heavy fog under the Golden Gate Bridge (2, 3). The oil spill which followed, the worst in San Francisco history, contaminated miles of shoreline, including parts of Sausalito and the beaches of the Presidio, and eventually triggered a Congressional investigation.

In situations such as this, National Weather Service forecasters may be called upon to supply projections of winds or oil behavior, especially in the short term before a distantly-located response team can be activated. A computer simulation model, OILSPILL (4), has been written in the Techniques Development Laboratory to assist forecasters. This Automation of Field Observations and Services (AFOS) applications program tracks the motion of oil on the open sea or inside bays where winds, and often tidal currents, are primarily responsible for transporting the oil.

We have used the OILSPILL program to simulate the behavior of oil during the San Francisco event to demonstrate the method's application and to reveal problems and insights in oil spill forecasting. The San Francisco spill had many features usually not encountered, making it both very difficult to predict and very instructive to simulate. Some of these features are the importance of tidal currents, the presence of islands and complex geography, the rapid release of a large amount of petroleum, the motion of the oil source point, and the difficulty of forecasting winds inside a bay. Data on the local tidal currents and observations of the areas of oil coverage were quite good. Wind information is not so complete, however, and its shortcomings demonstrate the importance of having both site-specific forecasts and observations by trained meteorologists.

Many of OILSPILL's features will be described in the following sections, but the reader is referred to (4) for more details. This technique is also quite different from that used by the Composite Oil Spill Model for Operational Services (COSMOS) program (5). In COSMOS, the two-dimensional, vertically averaged fluid equations are solved by a finite-difference method to get oil motion over the continental shelf area. A separate numerical model for the wind- and tidally-driven currents is also included. The computer code, designed to run on NOAA's IBM 360/195, proved to be much too large and complicated to run on the AFOS computer. OILSPILL employs greatly simplified physics and requires less core and running time.

2. OUTLINE OF THE SIMULATION MODEL

OILSPILL was designed to run on the AFOS Data General S/230 computer with a forecaster providing input data such as wind forecasts and water current data. The dynamics of oil motion, which are in fact quite complex, are simplified here in the trajectory method so they can be run on the S/230. The resulting equations cannot be expected to simulate oil behavior perfectly, but rather to show general oil motion tendencies. The output of the computer program is a series of maps which include a coastline for reference and show the areas of oil coverage. This output is produced on the AFOS paper plotter.

Basically, the motion of oil is simulated as the downstream advection of drifting particles or drifters. Each drifter represents a finite volume of oil resulting from an (assumed) uniform rate of release at the spill site. The drifters move at a velocity which equals the sum of the local wind drift and other currents, and has the general form

$$\vec{U} = c\vec{V} + \vec{W}_t + \vec{W}_r + \vec{W}_b + \vec{W}_w , \qquad (1)$$

where U is the oil velocity, and the terms on the right side are (in general order of importance) the wind drift ($c\vec{V}$), the tidal current ($\vec{W}_t$), the random current ($\vec{W}_r$), the background current ($\vec{W}_b$), and the wave drift ($\vec{W}_w$).

The wind drift is taken to be a simple fraction (c) of the wind velocity, $\vec{V}$, and to be in the same direction. Data on the drift fraction are scarce and show a lot of scatter (Fig. 1), but a value of 0.030 was chosen for this study. Observations show that the oil tends to drift slightly to the right of the wind direction by a small angle (5°-10°), but we shall ignore this small deviation for this study.

OILSPILL uses data on the tidal flood current direction, speed, and time of maximum strength at the spill site and at other stations, if available. This type of data is available for San Francisco Bay from both the National Ocean Service's (NOS's) Tidal Current Tables (6) and from the Tidal Current Charts (7). When one or more extra tidal current stations are added, OILSPILL creates a two-dimensional field of current vectors by interpolating values between data points. It uses a weighted mean of the north and east components of the flood current, with the weighting function dependent on the inverse-square of the distance to the data point.

The random current accounts for the effects of atmospheric and oceanic turbulent diffusion, and is idealized as a small velocity of constant magnitude, q, and a variable direction. Random walk theory (8) shows that q is related to the two-dimensional diffusion coefficient, D, in the following way:

$$D = \frac{1}{2M} q^2 , \qquad (2)$$

where M is the number of walks, or steps, per unit time.

The background current is taken to be constant over the area of interest, and is used to simulate semi-permanent features such as the Gulf Stream. The wave drift is usually small, and since it is not well understood, is neglected here.

Forecasters frequently want to know how large an area will be covered by a given volume of oil. Any finite amount of oil will tend to spread out more or less uniformly over a calm water surface under the force of gravity. Since our model simulates drifting point masses, we don't explicitly include oil spreading. Several equations from the literature, however, will help to estimate the area which a point mass may cover. By assuming a circular oil mass of constant thickness, Blokker (9) formulated the slick radius, R, as

$$R = 0.5 \ (\frac{24}{\pi} \ \frac{(S_w - S_o)}{S_w}) \ S_o KQt)^{1/3} \qquad (3)$$

where S_w and S_o are the specific gravities of water and oil, respectively; K, a constant depending on oil type; Q, the oil volume; and t, the time after the oil enters the water. Fay (10) performed a dimensional analysis of the forces involved in the spreading and postulated the existence of three regimes.

The first regime involves inertial forces, and its duration is short. During the second, gravity is the dominant force, and the radius can be expressed as

$$R = 1.45 \ (\frac{S_w - S_o}{S_w} \ gQ^2 t^3 \nu^{-1/2})^{1/6} . \qquad (4)$$

where g is the gravitational acceleration and ν, the kinematic viscosity of water. The third regime, dominated by surface tension, predicts even faster expansion. Table 1 shows representative values of the radius predicted by each formula for various oil volumes and times. For the range of values chosen, Fay's equation predicts radii an order of magnitude larger than Blokker's.

For an actual spill, the most important forecast is where the oil will come ashore. OILSPILL predicts this when it advects the oil toward the coastline. When currents carry the oil into the shoreline, a check is performed and the oil is "beached" (i.e., stopped from motion) if the sum of wind drift and the random current (without water currents) is sufficient to carry it onto the shore. Beached oil is checked every hour, and the oil will refloat, under favorable winds, with a probability based on the residence time half-life. The half-life is defined as the time interval over which half the beached drifters will refloat, given that the winds are continually offshore.

Beside oil advection, there are several other features of OILSPILL worth noting. Coastal geography is included in the data package; the program automatically draws the shoreline and islands. This geography

is needed for calculating the beaching of oil. The weathering of oil is simulated by randomly removing a fraction of all drifters; the probability of removal is based on the petroleum type and its half-life. The oil spill source point is allowed to move, simulating drifting with the currents or cruising at a predetermined heading.

Because of model simplicity and computer storage limitations, a number of important effects cannot be simulated. The biggest drawback results from the representation of a two-dimensional continuum of oil on the sea surface as an ensemble of drifting points. Oil spreading due to gravity and surface tension effects is therefore prevented, and diffusion and weathering can only be roughly approximated. Also, the wind field is assumed to be constant over the area of simulation, so the channeling effects of land features are not included. And finally, the tidal current phase is, by assumption, constant at all locations--an extreme simplification of actual tidal flow.

The computer program has been developed over several years and has been tested with data from several large oil spill events. The events, chosen because they had sufficient data, are the Torrey Canyon tanker grounding oil near the southwest coast of England in 1967; the Chevron oil drilling platform fire and spill off the Mississippi Delta in 1970; the Argo Merchant tanker grounding and breakup near Nantucket Island in 1976; the Amoco Cadiz tanker grounding off the Brittany coast of France in 1978; and the Burmah Agate tanker collision near Galveston, Texas in 1979.

Hindcasts of oil motion with OILSPILL show that useful results can be obtained in spite of the model's simplifications. We now proceed to a case study of the San Francisco spill of 1971.

3. THE SAN FRANCISCO BAY SPILL

At approximately 0141 PST on January 18, 1971, the outbound oil tanker Oregon Standard was struck portside by the incoming tanker Arizona Standard, and the two vessels, locked together, drifted on the flood tide toward Angel Island. The Oregon Standard began leaking its cargo of nearly 4.3 million gallons of heavy bunker fuel almost immediately, and within a few hours approximately 1.1 million gallons had spilled out (2). The drifting ships eventually came to rest a thousand yards off the south shore of Angel Island. During this time the winds were light, and visibility was extremely low due to the fog, which lifted at approximately 1030 PST (3). All leaking had stopped by the late afternoon.

One reason this spill was chosen was that the data are fairly complete, especially winds, tidal currents, and areas of oil coverage. Maps showing the location of oil, based on ship reports and U.S. Coast Guard overflights, are given in (3) for three times on January 18 and once each day on the following three days. We have used observed winds from an offshore ship at 30° 45' N, 122° 41' W; winds from the Coast Guard base on Yerba Buena Island (3) are also known. Strengths and times of occurrence of tidal flood and ebb currents for the Golden Gate are found in the NOS Tidal Current Tables. Values for January 18 and 19, 1971 are given in Table 2.

The local current pattern is depicted on the NOS Tidal Current Chart for San Francisco Bay (7). A copy of the chart for flood conditions at the Golden Gate appears in Fig. 2.

About 30 computer simulations of the San Francisco spill were made. In general, results improved markedly as more tidal data stations were added. Several simulations were carried out to test for the influence of specific variables on oil beaching, which, for this event, is somewhat underpredicted by our model. As a result, we modified the beaching routine by adding a random current to the wind drift when bringing oil ashore, rather than using wind drift alone. This modification increased the beaching frequency somewhat, but not as much as did an increased diffusion coefficient.

The diffusion coefficient employed was larger than that used in previous studies. For previous oil spills, we got satisfactory results with $D = 100$ ft^2/s. Here the use of $D = 500$ ft^2/s improved the simulation of the beaching of oil as it exited the bay on the first ebb tide. Gravity-induced spreading was neglected in this model, and it's likely that high diffusion was necessary to compensate for its absence. Spreading by gravity forces is most likely to be important during the first few hours of a spill when the oil is thickest.

Most of the other input values were fairly standard. We assumed a drift fraction of 0.030 and the type of petroleum to be conservative, i.e., it would not lose any mass by weathering. The beach residence time half-life was taken to be 15 hours.

The source motion used during the study requires further explanation. After the two ships collided, they drifted under the action of wind and current toward Angel Island. Tests of the drifting algorithm, with the source moving at 100% of the tidal current plus either 0% or 3% of the wind, showed the source moving, unrealistically, up into Richardson Bay. The probable rea-

son is that some of the details of the tidal current field have not been retained in our simplified model. The source motion was therefore modeled as a powered move with two segments: first the ships headed 52° (true) at 2.0 kt for 54 minutes, then headed 52° (true) at 1.0 kt for 54 minutes.

The base map drawn for the spill is shown in Fig. 3. The collision site appears near the center of the rectangular area, and the grounding site is denoted by a '$'. Locations of additional tidal current stations are denoted by the symbol 'X'. In other maps (Figs. 4-6), positions of floating oil are denoted by a number ('0', '1', '2', etc.). The number 0 means that from 1 to 3 drifters occupy the grid, the number 1 means that from 4 to 6 drifters occupy the grid, and so on. The symbol '@' indicates that one or more drifters are beached in the grid.

The time period we simulated began on 0000 GMT on January 18, and proceeded for 26 hours. Data on oil coverage for January 19-21 are less detailed so that period was not simulated. Oil release was begun at hour 10 (0200 PST) and discontinued after 5 hours. The computer run, which simulates the motion of 165 drifters, took about 12 minutes. Descriptions of oil coverage and model results for three different times is discussed below.

Hour 0600: By 0600 on January 18, the oil had been leaking from the Oregon Standard for 4 hours. Passing ships reported a large area of oil contamination in the waters from the Marin Peninsula out to Angel Island (Figs. 4a and 4b). The original Coast Guard drawings (3) do not distinguish between areas of heavy and light coverage, but the model results show the thickest oil to be around the site of the leaking ship. Our model shows beached oil on Alcatraz Island and at Sausalito. The Coast Guard, while not specifically reporting any oil at these sites, mentions the presence of oil offshore of San Francisco's piers south of Alcatraz (3). While modeled and observed distributions are similar, it should be remembered that finding oil must have been difficult, to say the least, during those predawn hours in heavy fog.

Hour 1200: Shortly past noon the Coast Guard had finished its first overflight and reported oil coverage as shown in Fig. 5a. The time of the flight nearly coincides with the time of slack water after the ebb. The most prominent features of the oil distribution are the oil masses on the north and south shores of the Golden Gate, each with tails extending westward out to sea. Some oil apparently beached as it flowed past with the ebb tide. The computer map (Fig. 5b) shows an area of beached oil on the San Francisco shore at

Fort Point, but not the extensive contaminated area that was observed. The computer map also shows more beached oil on the Marin Peninsula, close the the areas actually hit. The Coast Guard reported a northerly breeze springing up at 1030 PST and concluded that this breeze was responsible for beaching oil at Fort Point.

The Coast Guard observed three separate streaks of oil, each aligned roughly parallel to the ebb current direction, just outside the bay's mouth. Streaking usually occurs because of winds, but here the tidal currents apparently created them. Our modeled output for hour 10 shows a single large diffuse patch of oil located offshore with no evidence of the streaky distribution. The fact that the patch lies further offshore than the streaks is probably due to the tidal current in the model being too strong in that region.

Three patches of oil were sighted very close to the location of the anchored ship, indicating that the Oregon Standard was still leaking some oil at this time. The two streaks to the north and west of the anchored ship seem to have come from points on the shore where oil had previously beached.

Our model has oil beaching on the north tip of Alcatraz Island. A large patch of oil is situated nearby (Fig. 5b), although we couldn't find reference to any beaching there.

Hour 1700: A late afternoon survey, toward the end of the flood tide, showed a continued presence of oil near the mouth of the bay, with large concentrations at Baker Beach and Fort Point (Fig. 6a). Our computer simulation also shows a large mass of oil near the bay entrance, especially the Baker Beach area. Our simulation also shows renewed oil beaching on the Marin Peninsula, although no heavy concentrations were reported at that time. Again, the simulation does not show the streakiness that was observed. Other areas where oil was sited, such as around Alcatraz, in the Racoon Straights, and near Sausalito, also have oil in the simulation.

4.   CONCLUSIONS OF THIS STUDY

Simulations of the 1971 San Francisco Bay oil spill have shown that the model can be applied in a real situation and how it can be useful to a forecaster. The model's results are highly dependent upon the accuracy of the input data, but most of these data should be easily obtainable during an actual spill.

The importance of good wind forecasts cannot be overstated. In this case, 3-hourly winds were used, and even more frequent

wind data may be necessary at times when oil passes a vulnerable location.

For example, we ran a test case with a 13 kt north wind at hour 1800 GMT, replacing the previously-used 13 kt ENE wind. As a result of this change, more oil was simulated to beach along the San Francisco shore.

Tidal currents were very important during this spill and reasonably good data were available on their characteristics. Improved results were obtained when additional data locations were used because the two-dimensional flow pattern was more accurately portrayed.

The fact that a relatively large diffusion coefficient was necessary indicates that gravity spreading should be explicitly included in future versions of this model. There are ways of estimating oil thickness per drifter, and since drifter separation is known, an estimate of the spreading ac-

celeration, based on the thickness gradient, could be made. High values for the diffusion coefficient would most likely be required during the early hours of a spill, and should become less necessary as the event continues.

In the model OILSPILL, even one drifter beaching is sufficient to be denoted on the map. In several cases for this spill, one simulated location of beached oil corresponded to a rather long stretch of actually contaminated coastline. This is because the model deals with drifting points, each of which has a lower probability of impacting a coastal segment than does the oil, distributed over a finite area, that it represents.

For this study, the oil was taken to be conservative, or non-weathering. This gives a larger area of oil coverage than is likely to occur, but the model is less apt to miss areas of beached oil that may actually be present.

Method	Time (Hours)	Oil Volume (Thousands of gallons)				
		1	5	10	20	50
Blokker	1	0.1	0.1	0.1	0.1	0.2
	2	0.1	0.1	0.1	0.2	0.2
	5	0.1	0.1	0.2	0.2	0.3
	10	0.1	0.2	0.2	0.3	0.4
	20	0.1	0.2	0.3	0.4	0.5
	50	0.2	0.3	0.4	0.5	0.6
	100	0.2	0.4	0.5	0.6	0.8
	200	0.3	0.5	0.6	0.8	1.0
Fay	1	0.2	0.4	0.5	0.6	0.9
	2	0.3	0.6	0.7	0.9	1.2
	5	0.5	0.9	1.1	1.4	2.0
	10	0.7	1.3	1.6	2.0	2.8
	20	1.1	1.8	2.3	2.9	3.9
	50	1.7	2.9	3.6	4.5	6.2
	100	2.4	4.1	5.1	6.4	8.7
	200	3.4	5.7	7.2	9.1	12.3

Table 1. Radii in nautical miles of a circular oil slick of constant thickness calculated from the equations of Blokker (8) and Fay (9). The Blokker method, Eq. (5), is applied with the following values: $S_w = 1.02$, $S_o = 0.90$, and $K = 3 \times 10^4$ min^{-1}. The Fay method, Eq. (6), uses the same specific gravities, plus $g = 9.81$ m^2/s and $\nu = 1.0 \times 10^{-6}$ m^2/s.

Date	Time of Maximum (hour, minute)	Current Speed (kt) (F=flood, E=ebb)
18	0235	2.3 F
	0841	2.9 E
	1521	1.7 F
	2055	2.0 E
19	0321	2.0 F
	0932	3.1 E
	1629	1.8 F
	2152	1.6 E

Table 2. Tidal current floods and ebbs at the Golden Gate for January 18-19, 1971. Flood direction is given as 65°, ebb direction as 245°. Time is Pacific Standard.
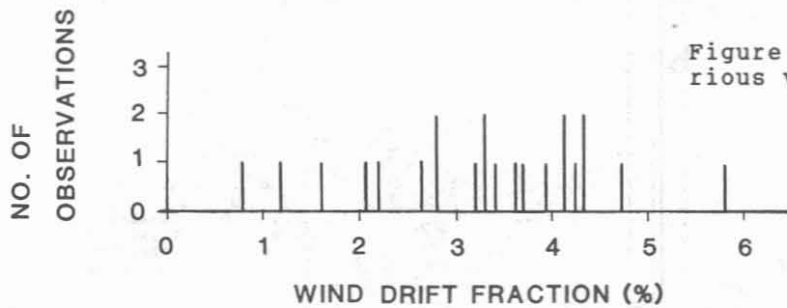
Figure 1. Frequency of observation for various values of the wind drift fraction.

Figure 2. Flood current vectors for the San Francisco Bay entrance for average tidal conditions (7). Speeds are in knots.
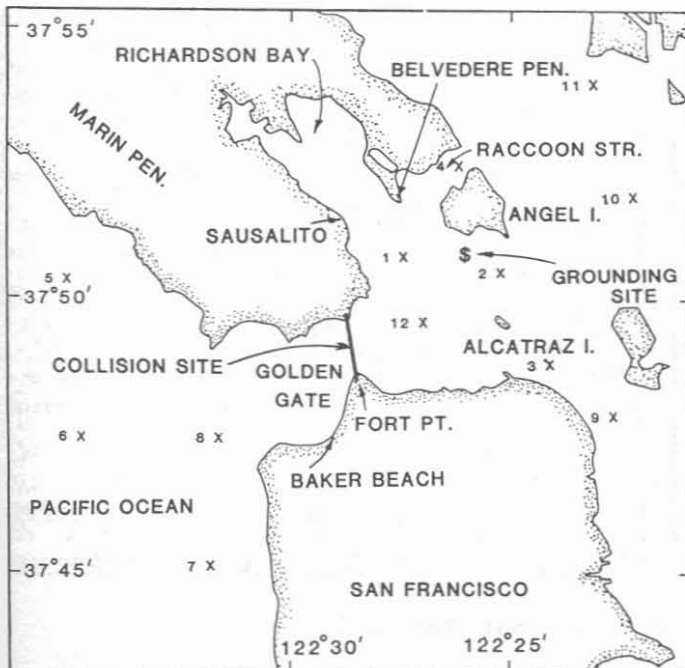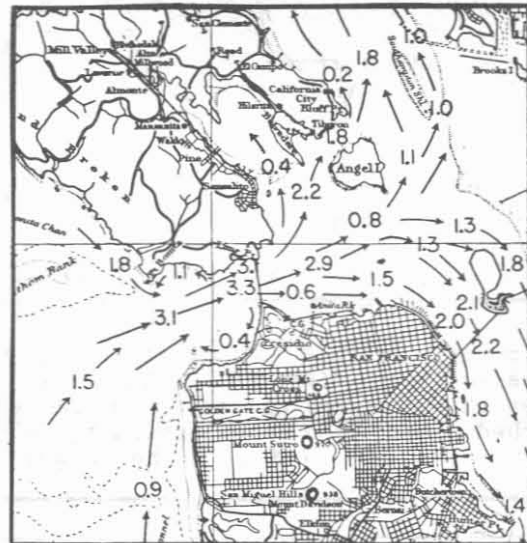

Figure 3. Base map for the San Francisco Bay spill. The symbol 'X' preceded by a number represents one of the 12 additional tidal current stations.

Figure 4. Spilled oil distribution for 18 January, hour 0600 PST. The left panel shows the observed oil distribution (cross-hatched area) and the grounding position of the tankers ('$'). The right panel shows the simulated distribution of surface oil for the same time ('O', '1', '2', etc. denote floating oil. '@' denotes beached oil).
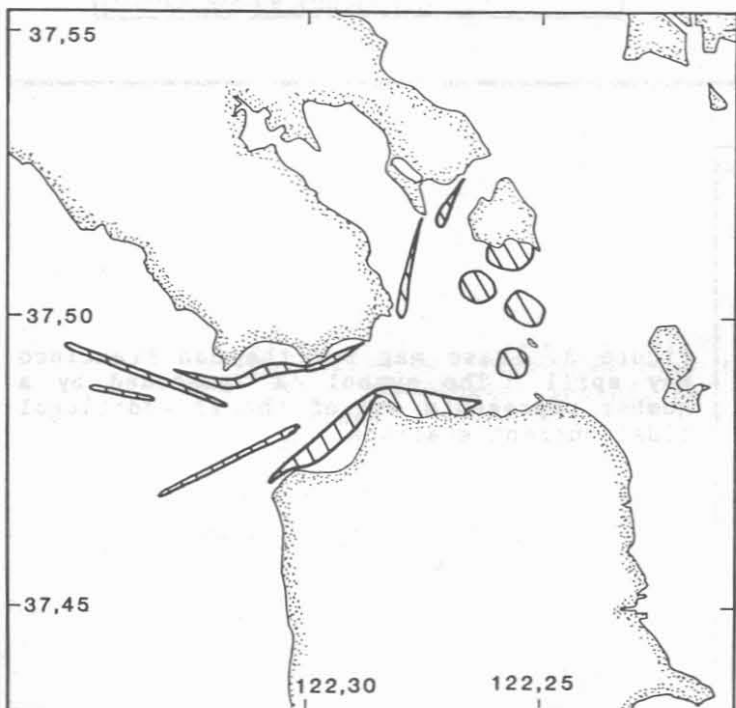

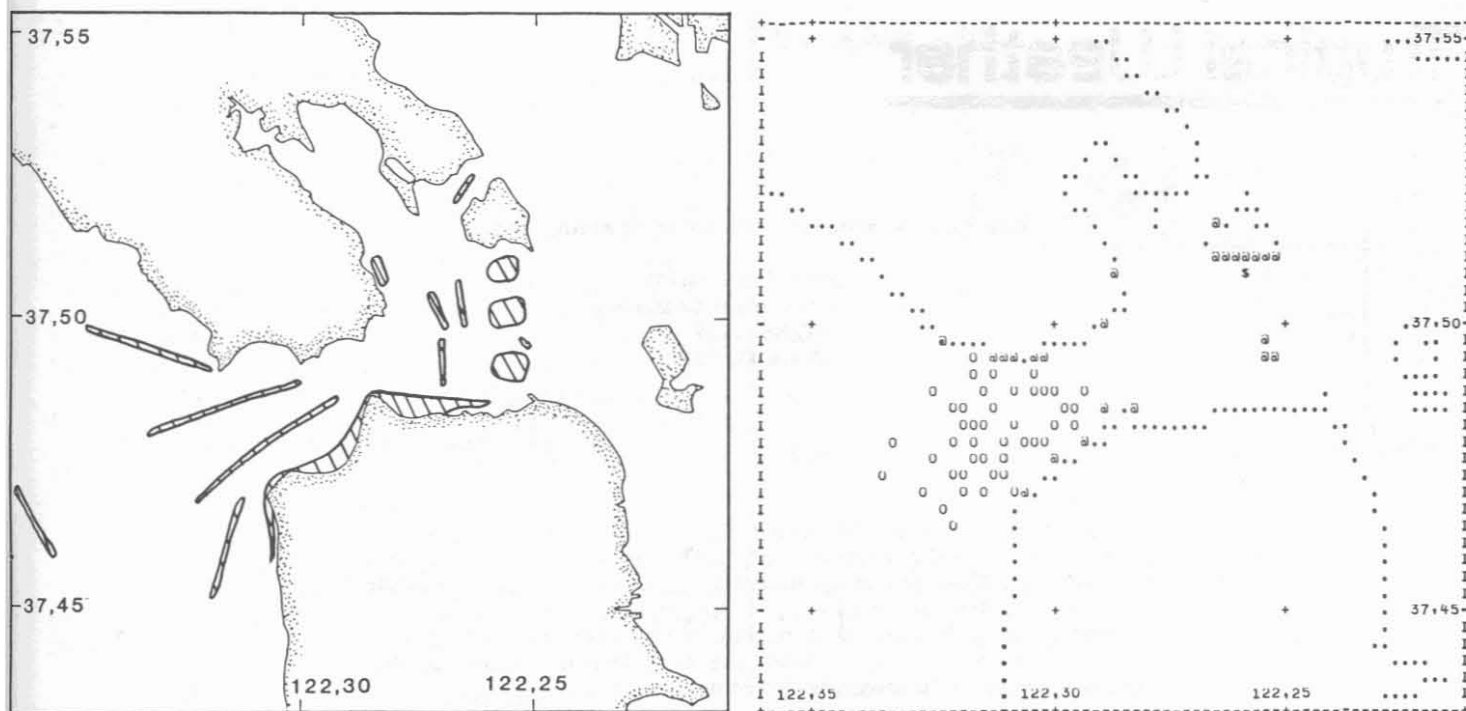Figure 5. Same as Fig. 4, but for hour 1200 PST.

Figure 6.   Same as Fig. 4, but for hour
1700 PST.

REFERENCES AND FOOTNOTES

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(2) Conomos, T. J., 1975: "Movement of spilled oil as predicted by estuarine nontidal drift." Limnology and Oceanography, v. 20 (2), pp. 159-173.

(3) U.S. Congress, 1971: "San Francisco Oil Spill," Hearings before a special subcommittee of the Committee on Merchant Marine and Fisheries, House of Representatives, Serial No. 92-3, 533 pp.

(4) Hess, K. W., 1983: "Simulation of Spilled Oil Behavior in Bays and Coastal Waters." NOAA Techniques Development Laboratory Computer Program TDL CP 83-2, National Weather Service, NOAA, U.S. Department of Commerce, 21 pp.

(5) Barrientos, C.S., and K. W. Hess, 1983: Ocean Oil Spill Concentration and Trajectory Forecast Project. Final Report to the Environmental Protection Agency under Interagency Agreement EPA-1AG-0693 (available from NTIS as PB84-114453).

(6) National Ocean Survey, 1983: "Tidal Current Tables 1984, Pacific Coast of North America and Asia," National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 260 pp.

(7) _____, 1973: "Tidal Current Charts -- San Francisco Bay." National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 12 pp.

(8) Csanady, G.T., 1972: "Turbulent Diffusion in the Environment." Reidel, Boston, pp. 248.

(9) Blokker, P. C., 1964: "Spreading and evaporation of petroleum products on water," Proceedings Fourth International Harbour Conference, Antwerp, Belgium, pp. 911-919.

(10) Fay, J.A., 1971: "Physical processes in the spread of oil on a water surface," Proceedings Joint Conference on Prevention and Control of Oil Spills, Washington, D.C., American Petroleum Institute, pp. 463-467.