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A TECHNIQUE FOR PREDICTING THE MOVEMENT OF OIL SPILLS IN NEW YORK HARBOR

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16. Abstract

Through experiments which were conducted it is apparent that the major factors involved in the transport of an oil slick in New York Bay are winds, tides and fresh water flow from the Hudson River. Computations have been made which quantify the effect of each of these factors on the movement of an oil slick. Quantification of each effect results in a simple method of forecasting the movement of an oil slick within the harbor. In addition, a method of predicting the boundaries within which a slick is most likely to move is presented.

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1.0 INTRODUCTION

Congress, on 3 April 1970, enacted the Water Quality Improvement Act. This Act directed the Coast Guard to prescribe methods and procedures for the removal and prevention of discharge of oil "into or upon the navigable waters of the United States, adjoining shorelines, or into or upon the waters of the contiguous zone." A method of predicting the movement of an oil spill could enhance substantially the Coast Guard's ability to carry out its duties as directed by the Water Quality Control Improvement Act. Used in a harbor, a reliable prodictive method would enable the Captain of the Port to forecast, under any weather conditions, the movement of an oil spill. The forecast would enable COTP to direct the proper placement of booms and deploy cleanup teams as rapidly as possible.

To obtain experimental data local oceanographic and meteorologic factors were measured in Upper New York Bay during the period 20 March to 25 April 1973. The experiments were designed to determine the advection of surface water in the Bay. When good correlation between oceanographic and meteorologic factors and surface advection can be found, a guide for predicting the movement of oil spills can be developed.

This report will indicate the experimental procedures, instrumentation and results of the experiments in Upper New York Bay. The feasibility of preparing a predictive guide for the movement of oil spills based on the experimental data will be discussed.

In addition, this report presents an analysis of oil spills occurring in Upper New York Bay and Kill Van Kull based upon data for calendar years 1971 and 1972. Regional priorities are established based on oil spill frequency within the Upper Bay. The names and locations of oil and petrochemical handling facilities are indicated. The priorities assigned to the regions show the approximate order in which monitoring devices should be deployed if surveillance systems to detect oil spills are made available.

2.0 NEW YORK HARBOR EXPERIMENTS

2.1 Instrumentation

Specially constructed, anchored surface current probes were used to collect surface current speed and direction data. These probes, which may be air dropped or boat launched, are tubular in shape and house an anchor which is attached to the probe by 150 feet of line. Upon contact with the water a special vinyl cover is dissolved releasing a free-floating cap and the anchor. After a short period of time, the current will cause the cap to drift away from the anchored float. By measuring the distance the cap has drifted from the float and the elapsed time of the drift, the speed of the surface current is easily computed. The direction of drift is obtained by taking bearings on a known landmark, in this case the Statue of Liberty. The same procedure is used when the probes are air deployed from helicopters. Both the cap and anchored float release dye for visual location from the boat or aircraft. Also, aerial photographs can be taken, and from these the speed and direction of drift can be determined.

Other instrumentation included hand-held anemometers for obtaining wind speed and direction data; water temperature and salinity monitoring systems; flowmeter-speedometers to obtain the speed of the boat. Accuracies of all measurements were acceptable, except for salinity values. The salinity sensor was found to be out of calibration, and therefore salinity values can be considered as relative values only.

2.2 Methods

Using two fast boats with two or three scientist/technicians aboard each boat, ten stations (Figure 1) were occupied frequently during the period 20 March to 25 April 1973. A summary of these operations is given in Table 1. Near synoptic measurements of surface currents, wind speed and direction, water temperature, and salinity were made at each station. One boat collected the data at the five northern stations (N1-N5) and the other boat collected the data at the five southern stations (S1-S5). Measurements were made at approximately the same time of day at each station. This timing interval provided measurements for many differing tides and winds.

Upon arrival at the first station, a surface current probe was released. As soon as the cap began its separation from the anchored float, timing of the drift commenced. After a period of time, when the cap had drifted some distance away from the anchored probe, the boat began a run from the fixed float to the cap. Upon arrival at the cap, the time of drift of the cap from initial release was recorded, as well as the elapsed time of the boat run between fixed float and cap. For every station the boat was run at about 1200 rpm while towing flowmeter-speedometers. These flowmeter-speedometers measured the speed of the boat run between anchored float and cap. The speed of the boat was then multiplied by the time of the boat run to compute the distance the cap had drifted from the probe. This distance was then divided by the total cap drift time to yield surface current speed. The direction of drift, as well as the salinity, water temperature and wind speed data were recorded. The boat then proceeded to occupy the next station.

2.3 Special Observations

On 22 March surface advection observations were conducted at four stations on Newtown Creek, from Greenpoint, Brooklyn, to Lenden Hill, Brooklyn, at the request of the COTP. This shore area is a proposed site for liquid natural gas facilities. Advection patterns in the surface layer would be useful if a spill from these proposed facilities ever occurred. Although no detailed description of the advection patterns can be determined from one day's data, the surface movement was downwind for stations within the creek. One station at the mouth of the creek appeared to be controlled by tidal flow. Further data would be necessary, however, to describe accurately the surface advection in the creek for all wind and tide conditions.

On 28 March a helicopter was used to measure surface current speed and direction for two stations in the outer bay and stations S4 and N4. These measurements of surface advection are given in Table 2. The starting time of each helicopter run between anchored probe and drifting cap is also

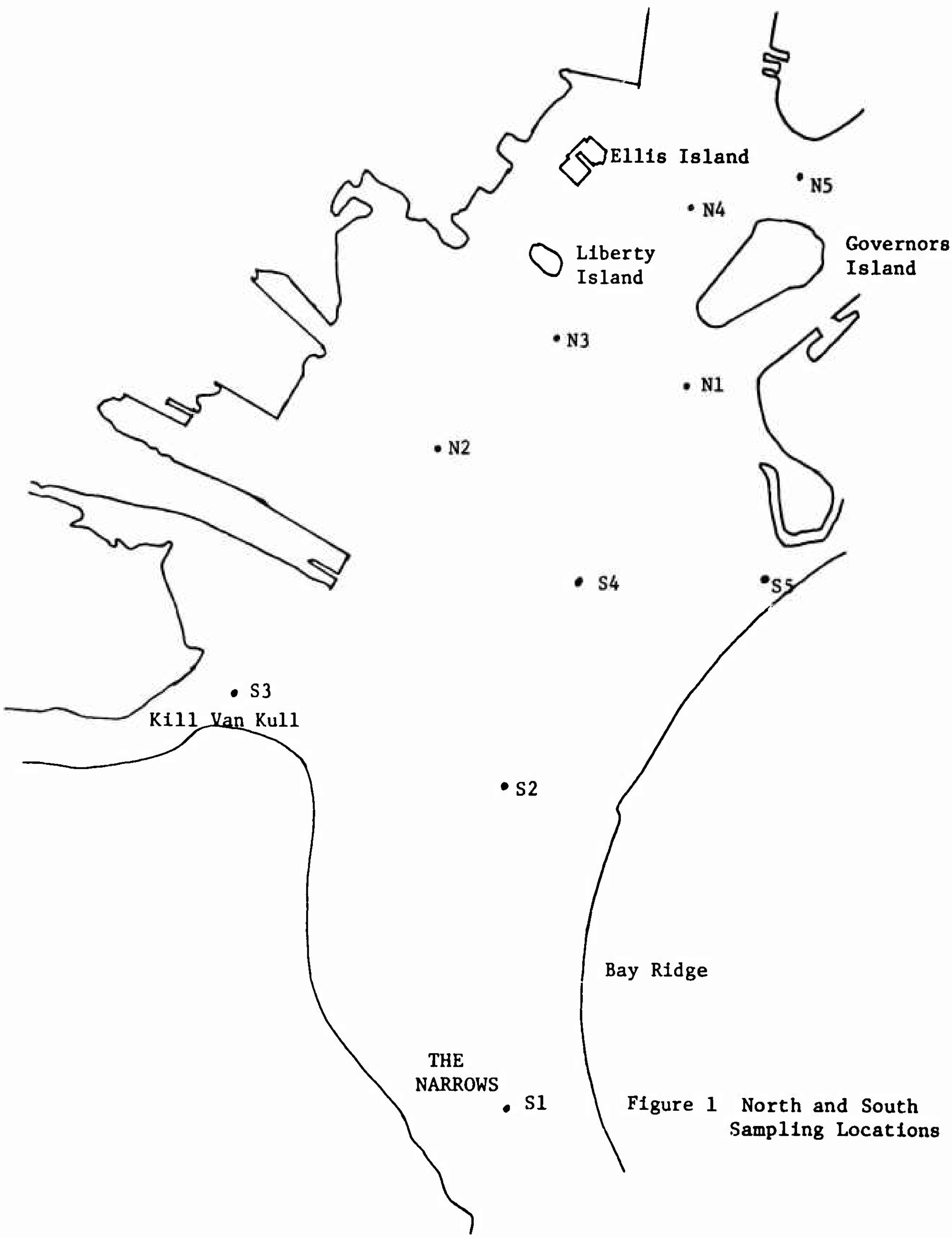


Figure 1 North and South Sampling Locations

Table 1. Number of Stations with Usable Data.

DATE	NORTH	SOUTH
20 March 73	3	4
21 March 73	5	5
22 March 73	Newtown Creek 4	
23 March 73	Secured - High Winds	
26 March 73	None - No Boat	5
27 March 73	4	5
28 March 73	5	5 (Plus 4 from helicopter)
29 March 73	5	5
30 March 73	5	5
2 April 73	5	5
3 April 73	5	5 (No salinities)
4 April 73	5	5
5 April 73	Secured - High Winds	
6 April 73	5	5
9 April 73	5	5
10 April 73	5	5
11 April 73	Secured - High Winds	
12 April 73	5	5
13 April 73	5	5
16 April 73	5	5
17 April 73	5	5
18 April 73	5	5
19 April 73	5	5
20 April 73	5	5
23 April 73	5	5 (No salinities)
24 April 73	No boats available	
25 April 73	5	5
26 April 73	Secured - High Winds	
27 April 73	Secured - High Winds	

Table 2. Helicopter Stations.

Date: 28 March 1973

	BUOY "N""A" OUTER BAY	GONG BUOY #3 OUTER BAY	S4	N4
TIME	0950	1010	1030	1035
SURFACE CURRENT SPEED (Kts)	0.47	0.77	0.89	1.21
PREDICTED TIDAL CURRENT SPEED (Kts)	Weak	0.2	0.85	1.10
SURFACE CURRENT DIRECTION (°T)	098	049	200	179
PREDICTED SURFACE CURRENT DIRECTION (°T)	---	030	199	190

shown in Table 2. This time was used to determine the predicted tidal current speed and direction from the Tidal Current Charts of New York Harbor and the Tide Tables - East Coast of North and South America (1973).

A comparison of results of boat versus helicopter measurements may be made for station S4 because the measurements were made at approximately the same time. Agreement is excellent; the computed boat values for current speed and direction were 0.89 kts and 200° T, while the computed helicopter values were 0.85 kts and 199° T.

2.4 Data Presentation and Preliminary Analysis

Tables 17 through 26 (Appendix B) summarize oceanographic and meteorological observations for stations S1-S5 and N1-N5. Preliminary analysis of the data at station N1 indicates that a predictive scheme for surface advection cannot be formulated from tidal predictions alone. Winds and fresh water flow must be taken into account.

By use of the Tidal Charts (New York Harbor) and the Tide Tables (East Coast of North and South America (1973)), the daily tidal speed and direction for station N1 were predicted from the time of the field measurements of surface current speed and direction. The absolute value of the difference between measured surface current speed and direction and predicted tidal current speed and direction was determined for each day of observations. These daily values were added and the sum was divided by the number of days of observations to calculate the average absolute value of daily difference between predicted tidal speed and measured surface speed. This value was 0.86 kts. The average absolute value of daily difference between predicted tidal current direction and measured current direction was 46.0°.

Thus, on any given day the tidal prediction values should vary from the actual conditions in the bay by an average of 0.86 kts and 46.0°. Because the measured speed at station N1 varied between 0 and 2 kts during the period of observations, the use of tidal information alone would lead to substantial errors in predicting the advection of surface water in New York Bay.

Because tidal predictions alone do not give viable results, a comparison between measured values and combined tidal, wind and fresh water values was attempted. A simple vectorial addition of tidal current, wind drift and fresh water run-off was used. The most difficult vector to measure is that due to fresh water flow emanating from the Hudson River.

The wind drift vector was computed by multiplying the wind speed times 0.035, a commonly used factor. This gives the speed of the wind-induced surface current. This value of 0.035 is tentative pending further research. However, it is expected that the actual value used will be this value or one very close to it. The direction of the wind drift vector was downwind of the measured wind for observations at station N1. For station N1 there were 11 days when it appeared that a fresh water vector factor should be applied.

A new predicted current speed and direction for each day of observations was found using the resultant vector from the combined tidal current, wind drift and fresh water vectors. The new predicted current speed and direction were compared with the measured values in the same manner as when the tidal values alone were compared. The average absolute value of daily difference between predicted speed and measured speed is 0.53 kts compared with the previous value of 0.86 kts. The average absolute value of daily difference between predicted direction and measured direction is 31.0° compared with the previous value of 46.0°. Thus, it is evident that wind-induced current and fresh water flow must be used in any predictive scheme formulated. Using these tentative results, it also appears that a first order predictive scheme will be possible by using tide, wind and fresh water data.

2.5 Data Correction

Surface current speed values (Tables 17-26) had been incorrectly computed because the time interval used was the total time from initial release of the probe to the time the boat passed the drifting cap. The time that should have been used was the time from initial release of the probe to the time the boat passed the anchored float. The method used to compute the corrected speed values is presented in Appendix A.

For all southern stations surface current speeds given in Tables 22-26 after 26 March must be increased by 0.25 kts. All northern stations given in Tables 17-21 after 21 March must be increased by 0.24 kts.

3.0 FACTORS DETERMINING THE MOVEMENT OF OIL SPILLS

3.1 Data Analysis

The experiment which measured the advection of surface water in Upper New York Bay is presented in Section 1.0 of this report. The measured values of surface advection observed in this experiment in New York are compared with the predicted values caused by tide alone and predicted values caused by tide, wind and fresh water flow combined (Table 3). The correlation between tidal prediction of surface current and measured surface current is poor in every case. However, when wind and fresh water flow are included in predicting surface movement, the correlation between predicted and measured surface current is significantly improved. Thus, for any predictive technique all three components must be considered.

Exact correlation between observed and predicted movement would have been ideal, but there are several reasons why this was not the case. First, the wind speed measured during the experiment was not an average hourly value; rather, it was an instantaneous value observed during the movement of the floating cap. Average hourly values of wind speed will give better results for the component of movement due to the wind. Second, the movement of surface water in New York was observed for each station for a period of several minutes. It is very difficult to predict the tidal component of surface flow at any given instant in time from tidal charts. The values given in the tidal charts are average hourly values, not instantaneous values, Finally, there are

Table 3. Comparison of Predicted Currents and Measured Currents.

Station	Difference between measured surface current and predicted tidal current		Difference between measured surface current and predicted surface current due to tide, wind and fresh water flow	
	Speed (Kts)	Direction (Degrees)	Speed (Kts)	Direction (Degrees)
N1	0.86	46	0.53	31
N2	0.35	57	0.35	33
N3	0.67	41	0.32	32
N4	0.63	51	0.40	52
N5	0.47	38	0.37	27
S1	0.59	43	0.51	17
S2	0.96	68	0.41	32
S3	0.53	57	0.43	38
S4	0.72	55	0.51	28
S5	0.44	60	0.37	49

certain unpredictable phenomena, such as eddies and shear zones, which may have affected the observed surface movement in New York Harbor. Eddy motion effects seem to be particularly evident at the inshore stations. These stations show the worst correlation between predicted movement and actual movement.

In spite of the possible errors noted above, correlation between predicted movement and observed surface movement is sufficient to indicate that a predictive movement technique can be formulated using the three major components involved in surface advection. This can be seen from a statistical analysis of the data listed in Tables 17-26. Of the 210 observations of surface movement made, 57 percent of the predicted speeds were within 0.4 knots of the measured speeds, and 73 percent of the predicted directions were within 40 degrees of the measured directions.

3.2 Wind and Wave Effects

An empirical value for wind drift was not obtainable from the data collected in New York. However, previous research by various investigators indicates that slicks will drift at 3 to 5 percent of the local wind speed. A value of 3.5 percent is recommended[1] for a predictive technique for New York Harbor. This value can be refined, if necessary, from future observations of the movement of oil spills within New York Harbor.

The relationship between wind peed and wave-induced drift is quite complex. Researchers, as yet, have not quantified this effect. However, it appears this effect will be quite small in comparison to the three major components. Also, wave formation in New York Harbor is generally not significant. Therefore, it is recommended that wave-induced surface movement be ignored for the present time.

3.3 Fresh Water Flow Effects - Empirical Observations

The fresh water discharge of the Hudson River has a significant effect on surface current velocities in Upper New York Bay. Two different approaches are presented in order to quantify this parameter. The first is an empirical approach based on the data obtained in New York. The second is a theoretical approach which is used to verify the results obtained empirically.

The United States Geological Survey maintains a continuous recording gauge at Green Island, N.Y., upstream from the Troy Lock and Dam. The variation in river height, and hence river flow, should propagate downstream at the speed of a long gravity wave. Therefore, the flow at any given time at Green Island should affect surface velocity in New York within 24 hours of that time. Observed surface velocities in New York Bay verify this assumption. On 6 April, for example, the predicted tidal flow for station N1 was 1.40 knots flooding. The observed condition was 0.21 knots ebbing. This large variation between predicted and observed surface current could only be accounted for by a large fresh water discharge occurring on 5 April at Green Island. Table 4 gives the average daily flow rates for Green Island for the period 15 March 1972 to 25 April 1973. It can be seen from Table 4 that the average daily flow for 5 April was an extremely high value of 82,000 cfs. This effect of fresh water flow on surface velocity is observed at the other stations taken on 6 April.

In addition, this same phenomenon is observed again on 4 April and 20 and 21 March following high water discharges at Green Island on the preceding days. Thus, for a predictive technique for oil spill movement, the average daily flow at Green Island for any given day will affect surface current speeds and directions in Upper New York Bay on the following day.

In order to obtain empirically the magnitude of the surface velocity caused by fresh water flow, it is assumed that the difference between the observed velocity and the predicted velocity from tide and wind considerations is caused by fresh water flow. Ten different average daily flow rates at Green Island were selected ranging in value between 20,000 cfs and 80,000 cfs (Table 5). For the day following these selected flow rates the difference between observed surface velocity and predicted surface velocity from tide and wind factors was found at stations N1, N3, N4, S1, S2, S3 and S4. These stations were selected because they are near the center of the bay and should receive the full velocity effects of the fresh water flow. For each day after a particular flow rate at Green Island, an average surface speed difference was found using the individual values of the stations indicated previously (Table 5). The data in Table 5 is shown graphically (Figure 2) as a line labelled "empirical." From this graph surface speed due to fresh water flow can be obtained from flow rate at Green Island. It must be remembered that to get a speed for any day the previous day's flow rate at Green Island must be used.

3.4 Fresh Water Flow Effects - Theoretical Considerations

The length of a salt wedge (Lo), as shown in Figure 3, can be determined theoretically[2] from the equation

$$\frac{Lo}{H} = 6.0 \left(\frac{V_\Delta H}{\nu}\right)^{1/4} \left(\frac{2V_r}{V_\Delta}\right)^{-5/2} , \qquad (1)$$

where Lo/H is the ratio of the length of the salt wedge to the depth of the river at the river mouth, ν is the kinematic viscosity of the liquid, V_r is the speed of the river at the initial point of the salt wedge, and V_Δ is defined as

$$V_\Delta = \sqrt{\frac{\Delta\rho}{\rho_m gH}}$$

Here, $\Delta\rho$ is the density difference between the salt water and the fresh water, ρ_m is the average density of the fresh and salt water, and g is the acceleration of gravity.

If the lengths of the salt wedges for the Hudson River are known for various flow rates at Green Island, then the speed of the river (V_r) can be computed from equation (1). The characteristics of the river[3] used for the calculations of river speed are given in Table 6. These values, once calculated, can be used to compute the speed of the surface layer (V_1) at the mouth of the Hudson River. This computation uses the equation of continuity

$$V_1 (H-h_{s1}) = V_r H.$$

Table 4. Daily Average Flow Rates at Green Island for the Period 15 March 1972 to 25 April 1972.

DATE	Q (cfs)	DATE	Q (cfs)	DATE	Q (cfs)
15 March	31,000	28 March	23,000	11 April	36,000
16 March	30,000	29 March	21,000	12 April	32,000
17 March	35,000	30 March	19,000	13 April	29,000
18 March	65,000	31 March	18,000	14 April	25,000
19 March	60,000	1 April	19,000	15 April	22,500
20 March	45,000	2 April	46,000	16 April	21,000
21 March	35,000	3 April	70,000	17 April	19,000
22 March	25,000	4 April	60,000	18 April	19,500
23 March	21,000	5 April	82,000	19 April	20,000
24 March	21,000	6 April	63,000	20 April	21,000
25 March	20,000	7 April	51,000	1 April	21,000
26 March	22,000	8 April	42,000	22 April	19,000
27 March	25,000	9 April	34,000	23 April	17,000
		10 April	32,000	24 April	18,500
				25 April	18,500

Table 5. Surface Speed in New York Caused by Flow Rate at Green Island

Q - Flow Rate (cfs)	Surface Speed
20,000	0.41
25,000	0.47
32,000	0.50
34,000	0.61
36,000	0.62
45,000	0.81
46,000	0.83
60,000	1.16
70,000	1.22
82,000	1.36

Table 6. Water Characteristics Used for Calculating River Speed.

Q - Green Island (cfs)	Lo (miles)	V_Δ (m/sec)	ν (m^2/sec)	H (m)
6,000	18	0.538	15.5×10^{-7}	13.72
12,000	22	0.538	15.5×10^{-7}	13.72
28,000	30	0.538	15.5×10^{-7}	13.72
36,000	40	0.538	15.5×10^{-7}	13.72

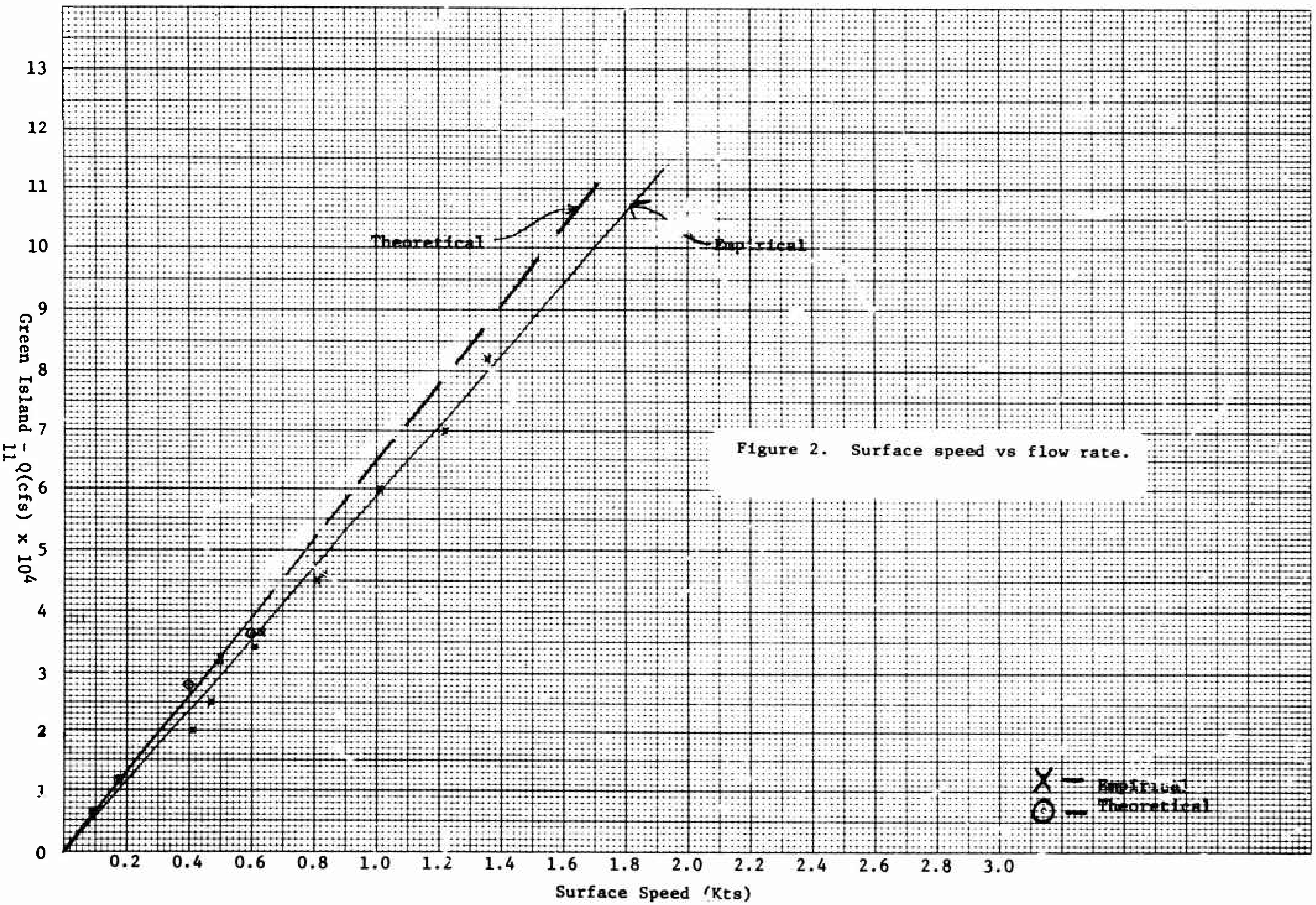


Figure 2. Surface speed vs flow rate.

Definition of Symbols

V_1 - Speed of the surface layer of the river, at the river mouth.
h_{s1} - Height of the salt wedge at the river mouth.
V_s - Speed of the salt water wedge.

SEE TEXT FOR DEFINITION OF OTHER SYMBOLS.

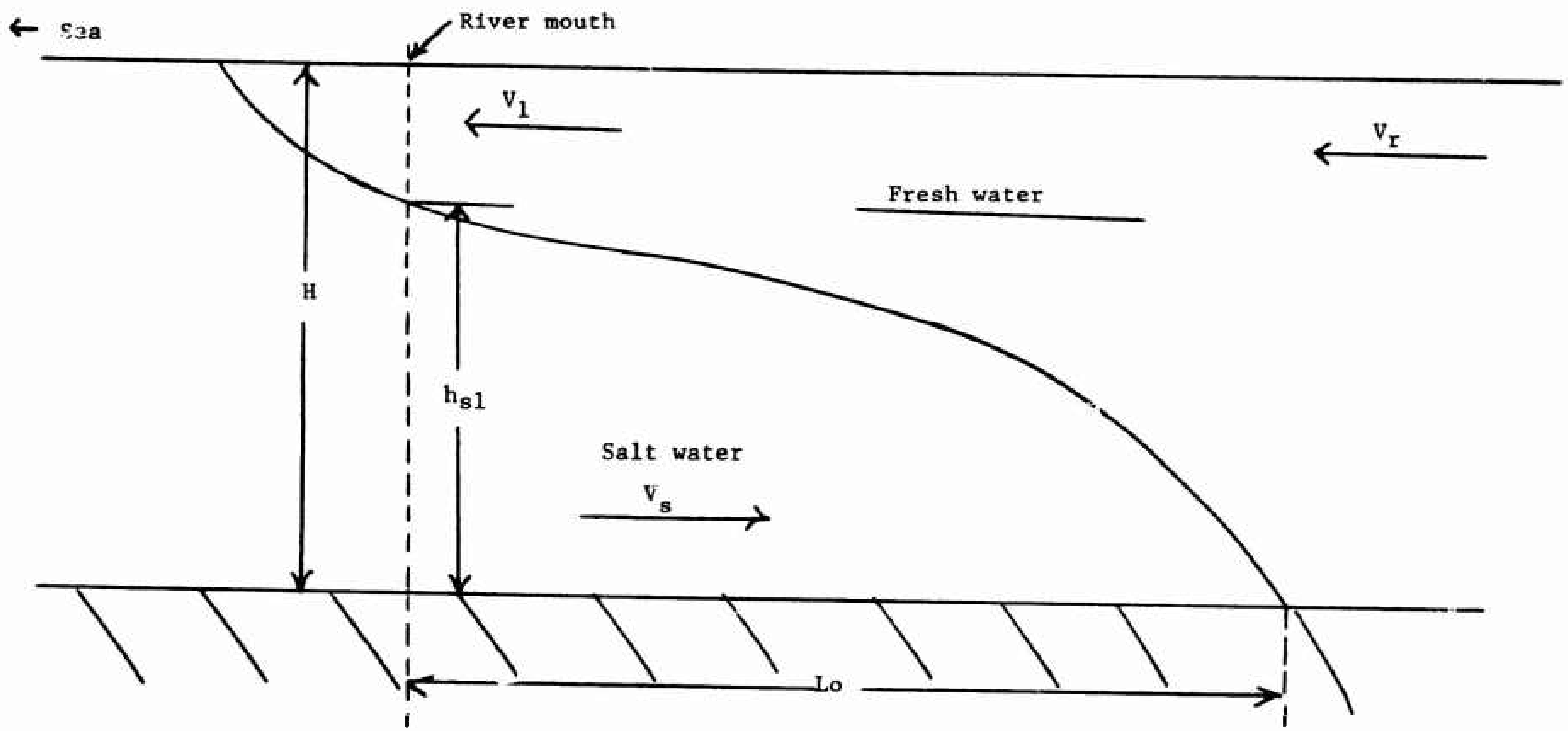


Figure 3. Simplified diagram of a salt-wedge estuary.

The computed values of surface speed (V_1) are shown graphically in Figure 2 as the "theoretical" line. The theoretical results compare favorably with the empirical results. Thus, the empirical observations are usable to predict surface speed in Upper New York Bay due to fresh water flow.

3.5 Boundaries Within Which Oil Slick Will Move

The boundaries within which an oil slick moves can be obtained from theoretical spreading rates for oil spills.[4,5] Should a release of oil occur, Figure 4 can be used to compute spill size. As the slick begins to move, the radial size of the slick perpendicular to the direction of movement will outline the boundaries within which the slick will move. The radial size of the slick for future positions can then be predicted in the same manner (Figure 5).

3.6 Verification of Predictive Technique

During the period 17-21 September 1973 surface current drifters were tracked in New York Harbor for periods of time ranging from 10 minutes to more than one hour. The location and movement of the drifters is shown in Figures 6-14. These drifters were made of cardboard one foot square. When soaked with water they became pliant and adhered to the contours of the water surface.

The data collected are shown in Table 7. Using the components of wind, tide and fresh water flow, predicted movements were computed for each drift and compared with the observed movements of the cardboard (Table 8). The correlation between observed and predicted movement is excellent. Of the 17 runs made, only one predicted direction varied more than twenty degrees from the observed direction. In 12 of the 17 runs, the predicted directions were within ten degrees of the observed directions.

The predicted distance travelled compared favorably to the observed distance travelled. The average percent difference between predicted and observed distance travelled is 25 percent. This appears to be too high a value for accurate predictions. However, a closer look at the data indicates that the 25 percent figure is misleading. Breaking the runs down on a time basis of 0-30 minutes, 30-60 minutes and runs greater than one hour gives a better perspective of predictive accuracy. For runs between 0 and 30 minutes the average percent difference between observed and predicted distance travelled is 31.8 percent; for runs between 30 and 60 minutes this difference is 18.8 percent; and for runs greater than 60 minutes the difference is 10 percent.

This same analysis can be done using distance travelled instead of time interval of the run. The average percent difference between observed and predicted distance travelled for drifts shorter than 500 yards is 36 percent; for drifts between 500 and 1000 yards this difference is 15.9 percent; and for drifts greater than 1000 yards the difference is 10 percent. Thus, for a predictive technique with a half-hourly or hourly time step, predictive movement should be within 15 percent of observed movement.

TABLE 7

DATA COLLECTED IN NEW YORK HARBOR SEPT. 17-21 1973

DATE	EXPERIMENT #	ELAPSED TIME OF EXPERIMENT	WIND VELOCITY (KTS)	WIND DIRECTION (0°T)	GREEN ISLAND DISCHARGE DATE	Q(cfs)
Sept. 17	01	0930-1001	9	020	Sept.10	4120
	02	1020-1058	10	055	11	4750
	03	1109-1129	11	230	12	5110
	04	1358-1426	6	205	13	1740
	05	1440-1510	7	225	14	1680
Sept. 18	06	0935-1002	8	200	15	2040
	07	1327-1400	6	250	16	1600
	08	1413-1525	7	230	17	7120
Sept. 19	09	0915-0925	3	000	18	5300
	10	0940-1005	10	355	19	3460
	11	0859-0909	8	045	20	3810
Sept. 20	12	0919-0925	8	065		
	13	0944-1008	6	245		
	14	1015-1037	7	250		
	15	1400-1510	9	275		
Sept. 21	16	0858-0930	8	025		
	17	0938-1025	7	345		

TABLE 8

COMPARISON OF PREDICTIVE AND OBSERVED MOVEMENT

DATE	EXPERIMENT #	DIRECTION OF MOVEMENT (°T) PRE.	DIRECTION OF MOVEMENT (°T) OBS.	DIFFERENCE BETWEEN PRE. AND OBS.	DISTANCE TRAVELED (YDS) PREDICTED	DISTANCE TRAVELED (YDS) OBSERVED	DIFFERENCE BETWEEN PRE. AND OBS.
Sept. 17	01	219	220	1R	303.8	567.1	263.3
	02	331	338	7R	729.1	648.1	81.0
	03	018	018	0L	688.6	688.6	-00.0
	04	331	333	2R	587.4	567.1	20.3
	05	264	267	3R	344.3	324.1	20.2
Sept. 18	06	359	002	3L	688.6	688.6	00.0
	07	028	030	2R	729.1	911.4	- 182.3
	08	031	037	6R	1174.7	1358.3	183.6
Sept. 19	09	223	205	18L	445.6	405.1	40.5
	10	049	035	14L	283.6	101.3	182.3
	11	228	228	0L	405.1	465.8	-60.7
Sept. 20	12	232	212	20L	364.6	526.6	-162.0
	13	064	069	5R	162.0	121.5	40.5
	14	065	071	6R	445.6	384.8	60.8
	15	021	022	1R	2774.8	2774.8	-00.0
Sept. 21	16	351	001	10L	202.5	162.0	40.5
	17	057	044	13L	425.3	445.6	-20.3

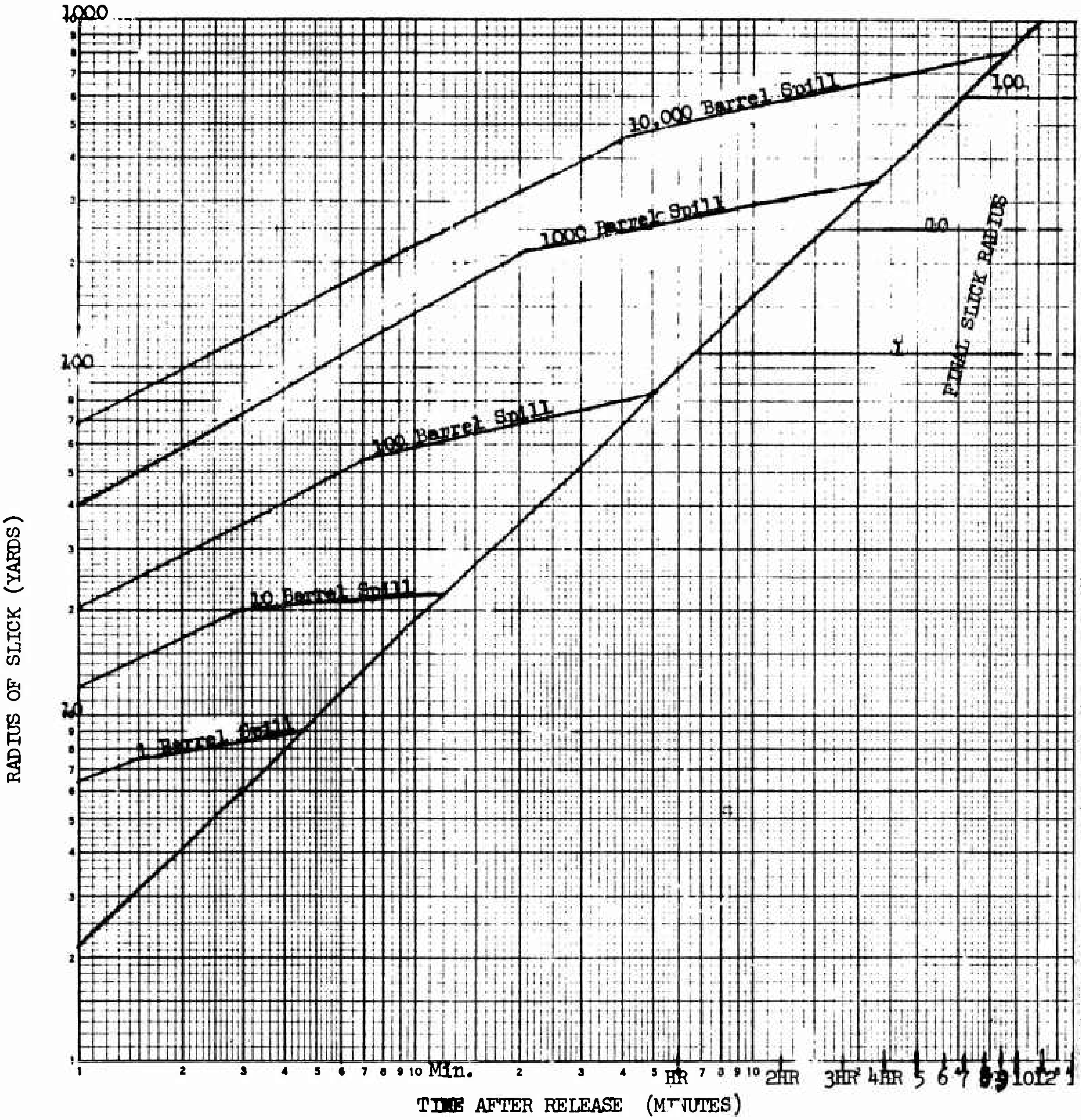


Figure 4. Slick Radius Versus Time for a Sudden Release.

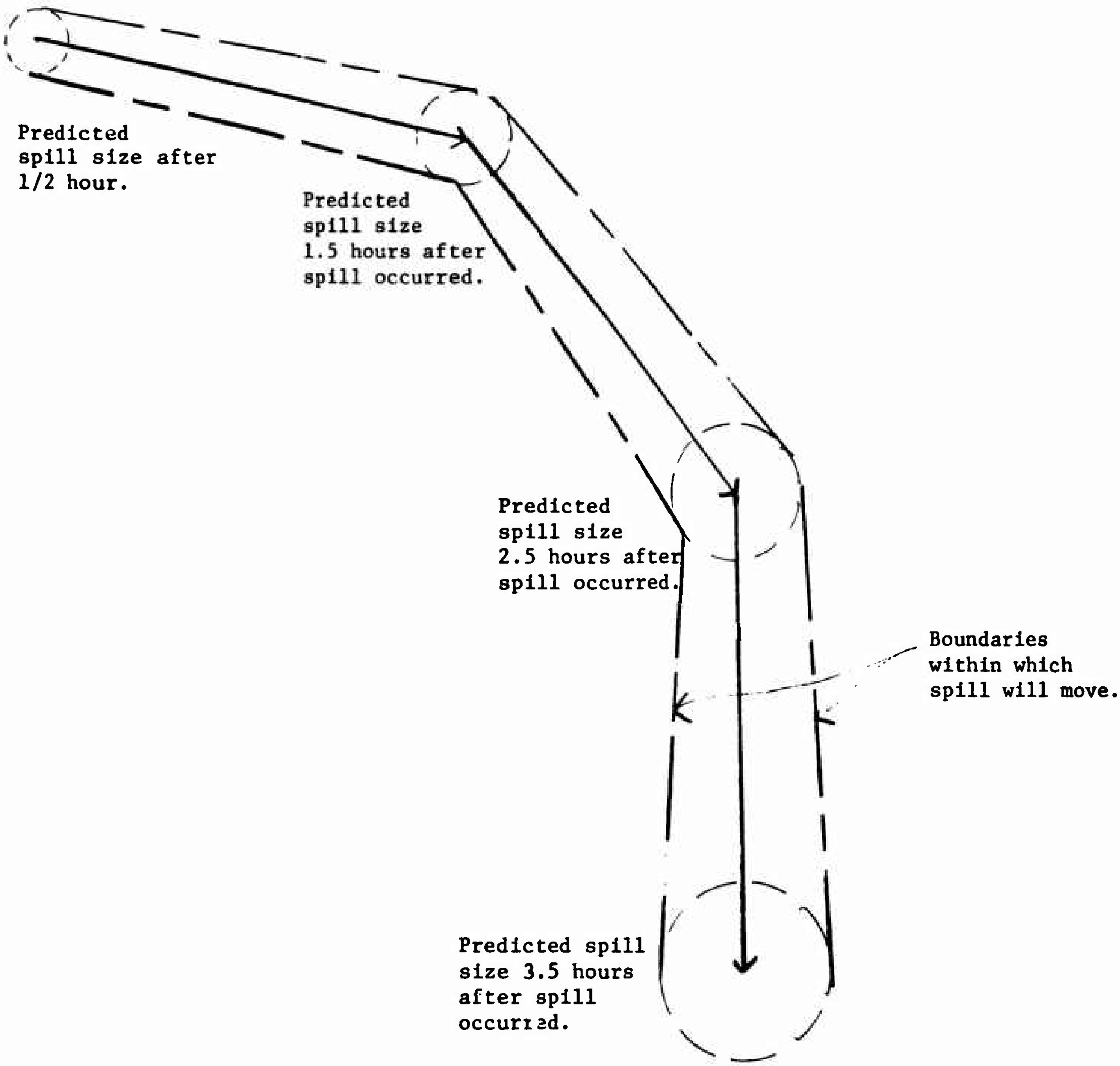


Figure 5. Spill boundaries for an oil spill (example).

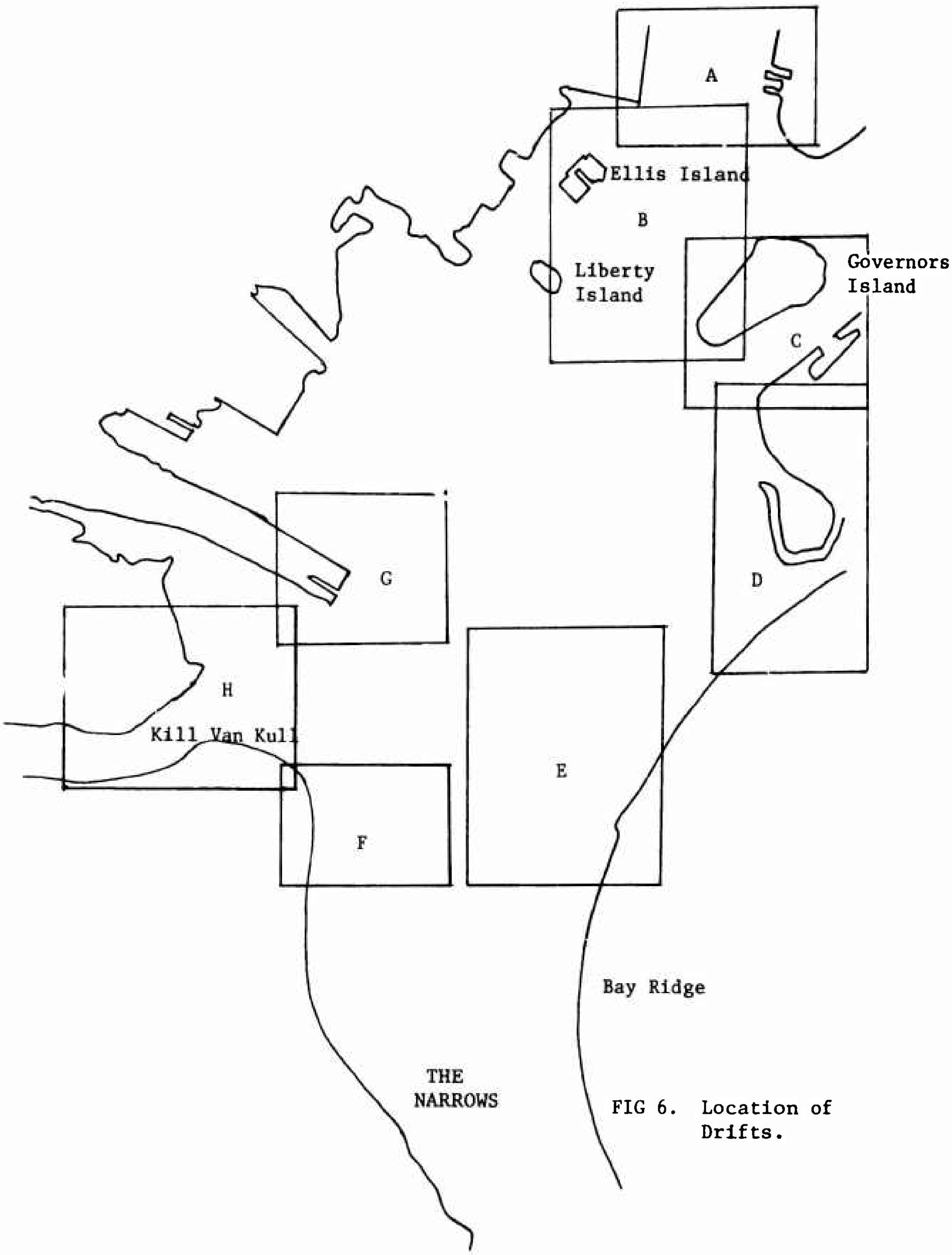
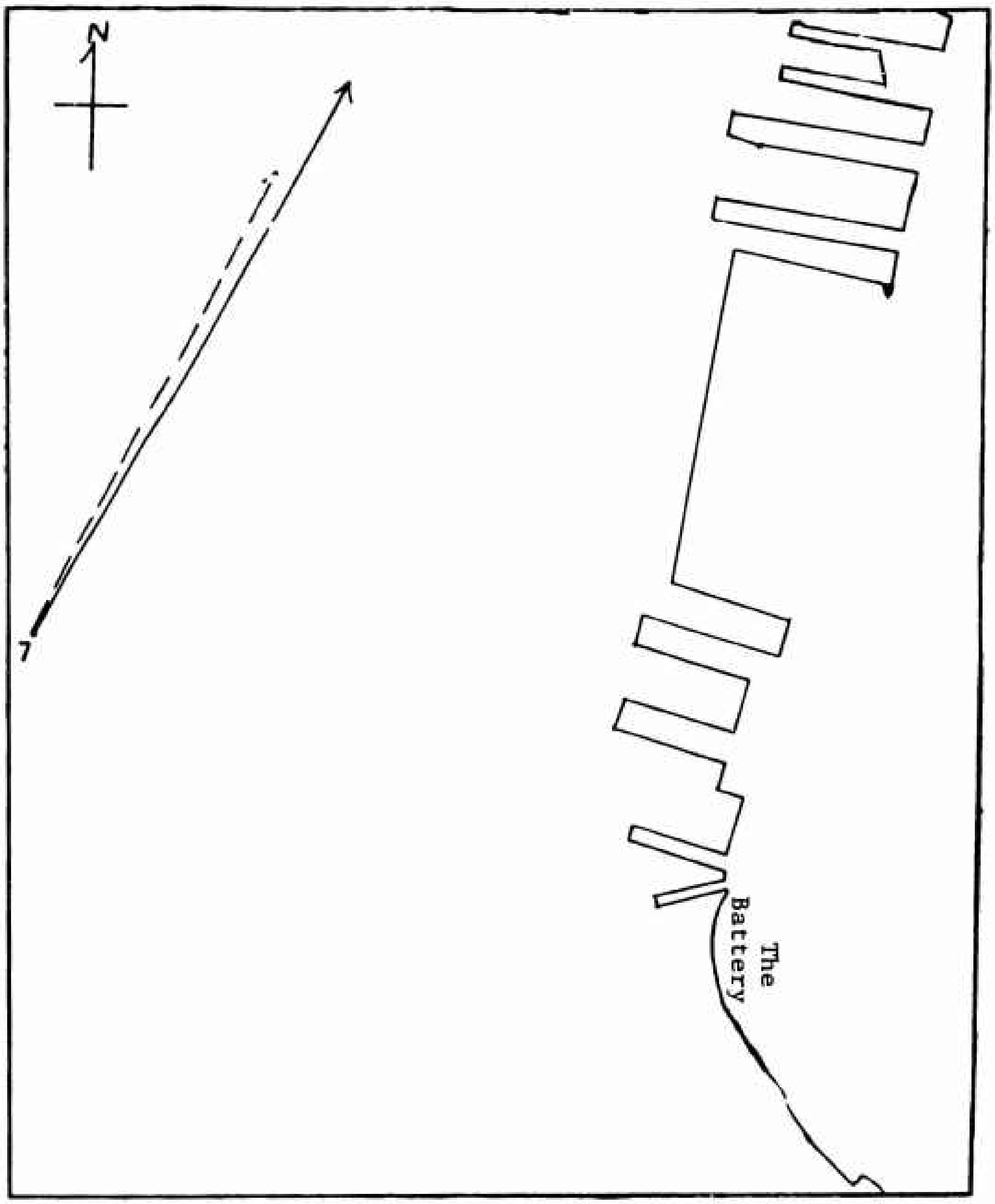


FIG 6. Location of Drifts.



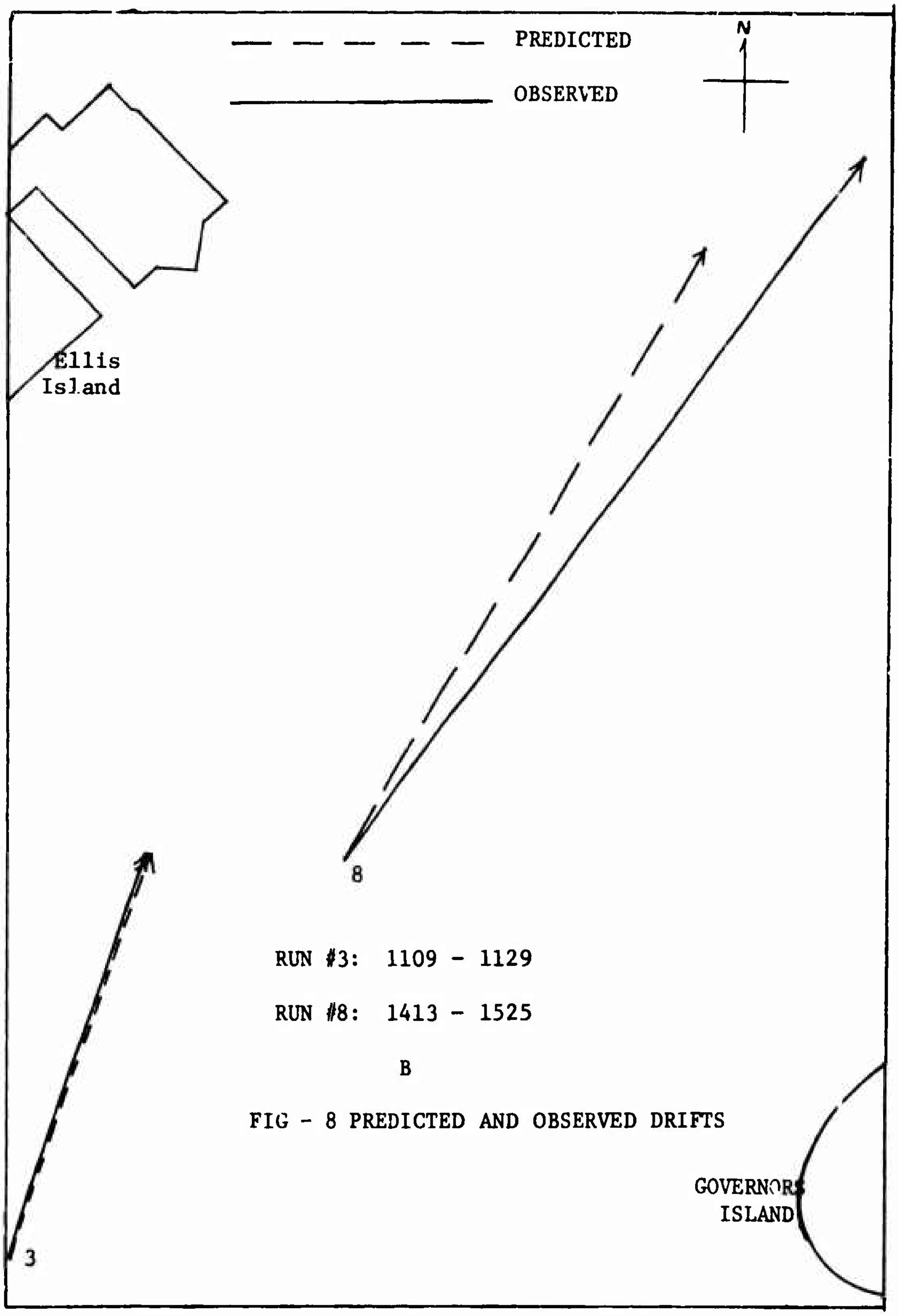
RUN #7: 1327 - 1400

FIG - 7 PREDICTED AND OBSERVED DRIFTS

A

— — — — PREDICTED

———— OBSERVED

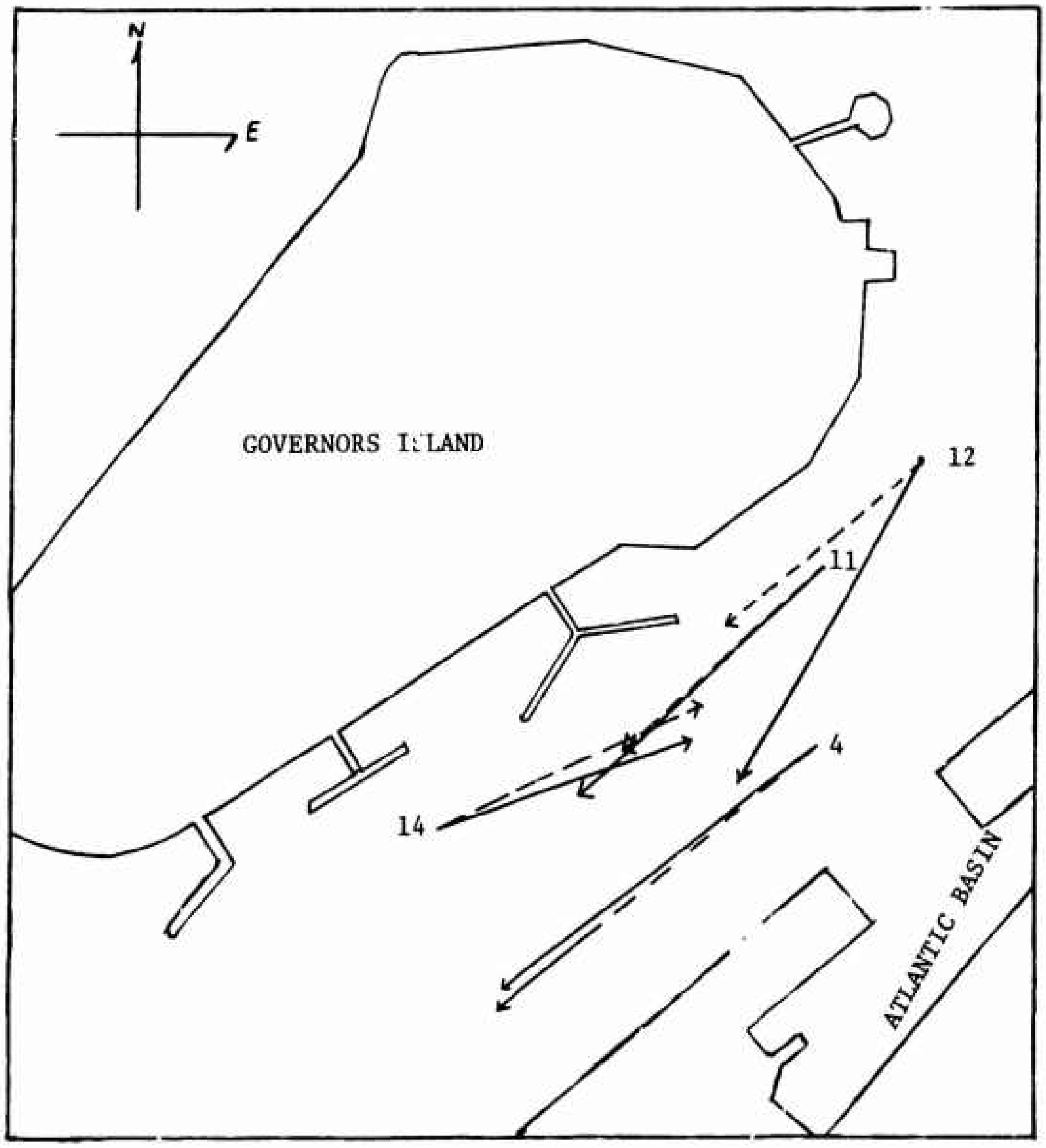


RUN #3: 1109 - 1129

RUN #8: 1413 - 1525

B

FIG - 8 PREDICTED AND OBSERVED DRIFTS



RUN #4: 1358 - 1426

RUN #11: 0859 - 0909

RUN #12: 0919 - 0925

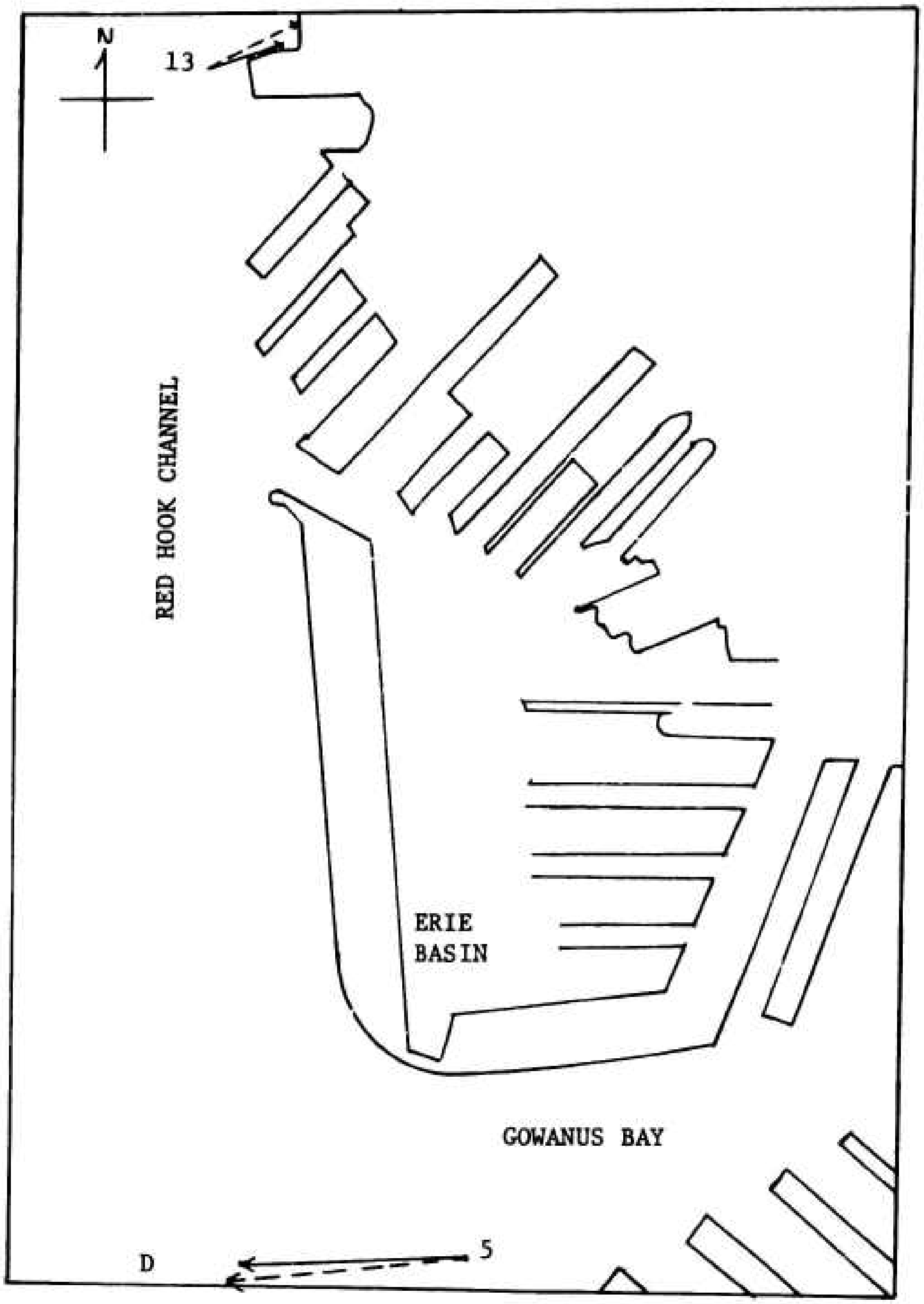
RUN #14: 1015 - 1037

— — — — PREDICTED

———— OBSERVED

C

FIG - 9 PREDICTED AND OBSERVED DR1FTS



RUN #5: 1440 - 1510

RUN #13: 0944 - 1008

— — — — — PREDICTED

———————— OBSERVED

FIG - 10 PREDICTED AND OBSERVED DRIFTS

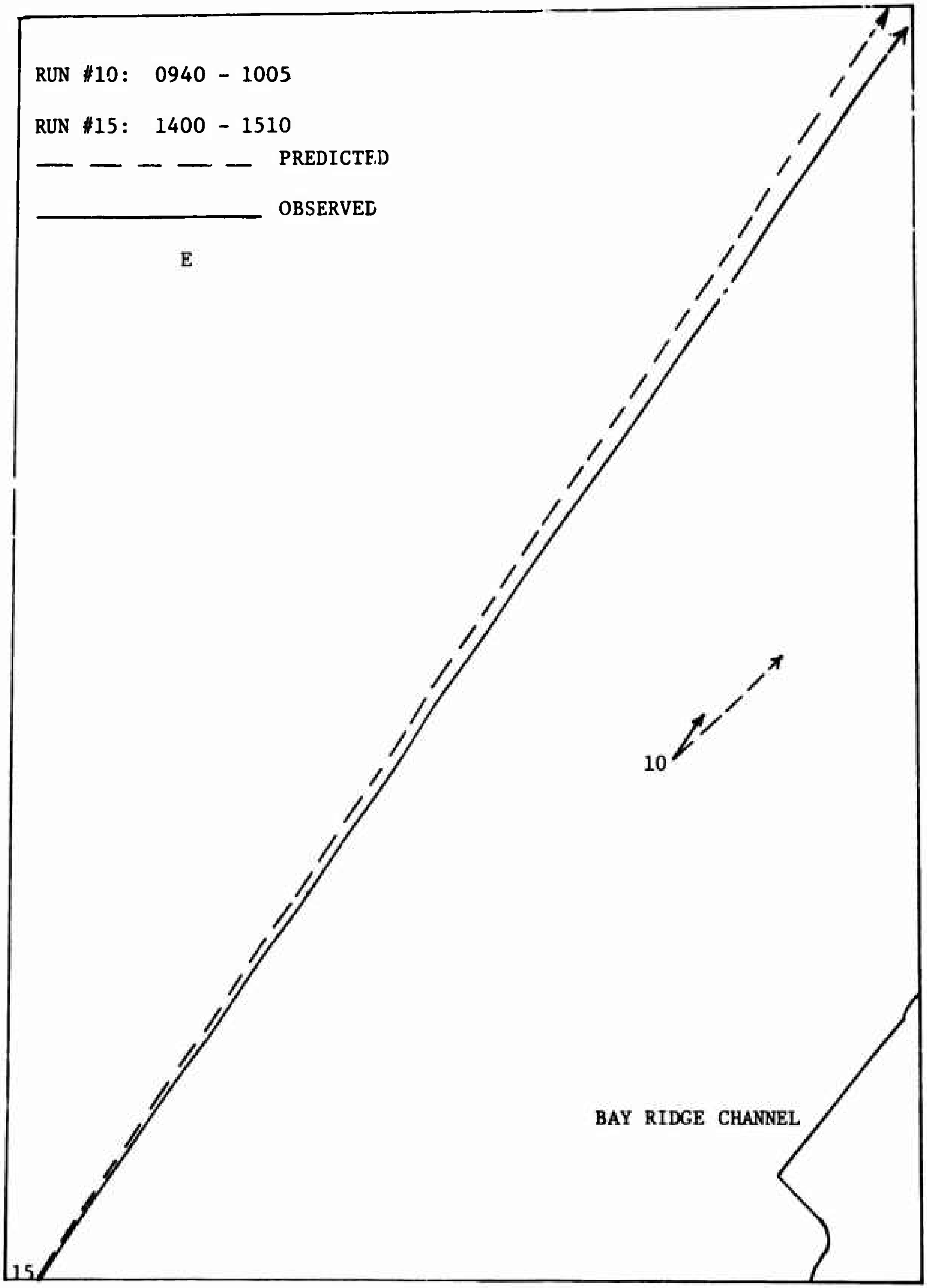
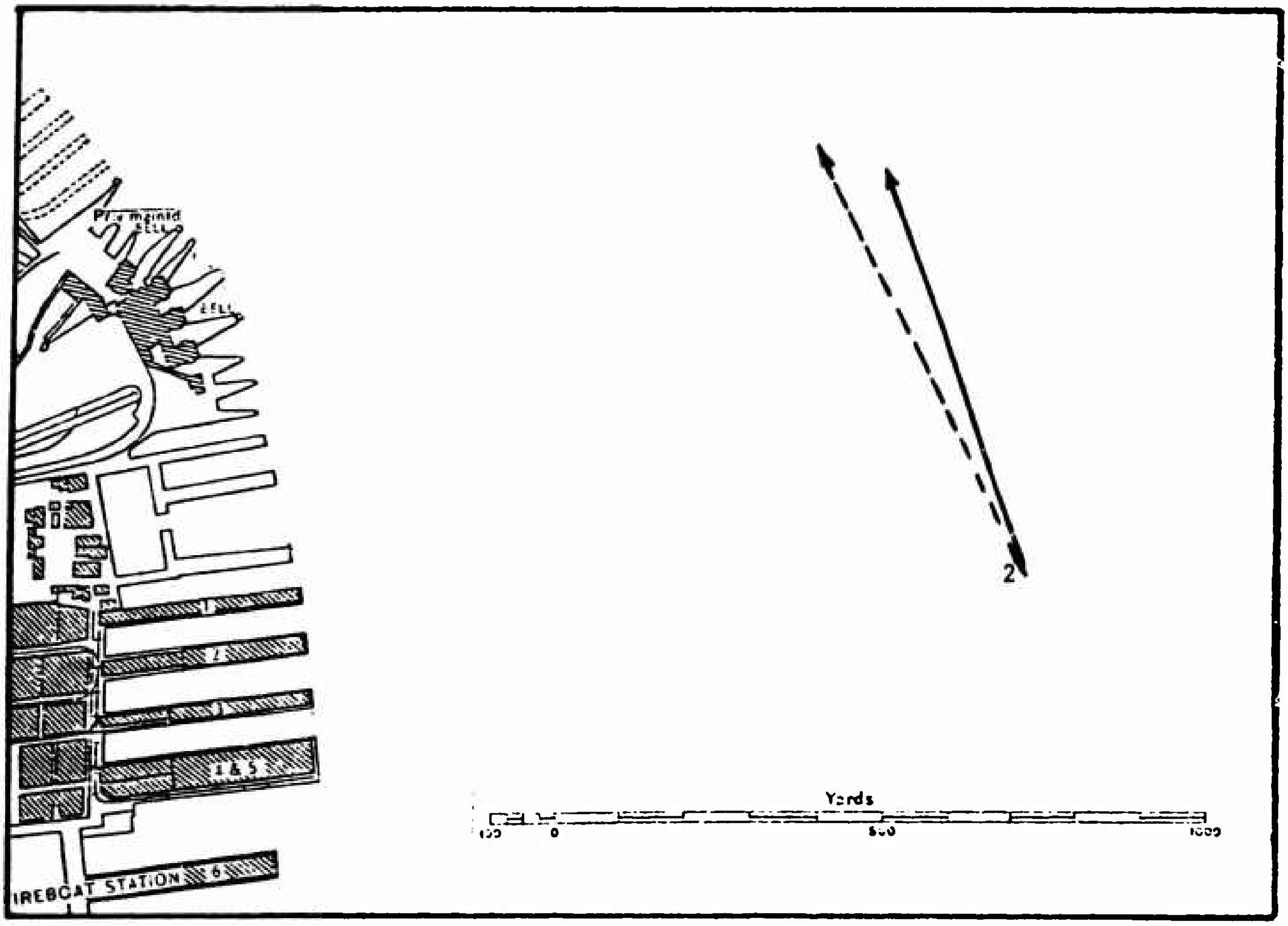


FIG - 11 PREDICTED AND OBSERVED DRIFTS



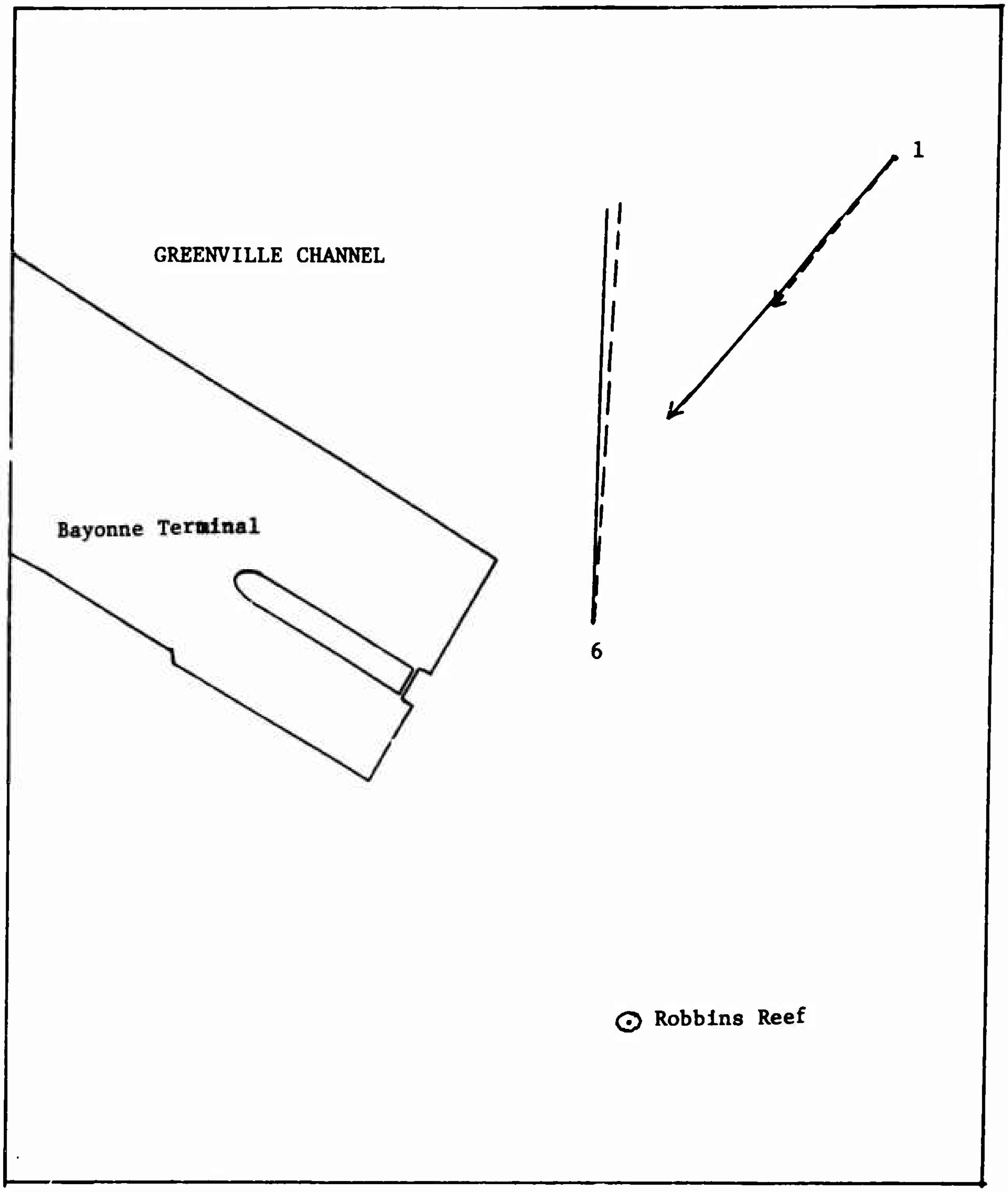
RUN #2: 1020 - 1058

F

PREDICTED

OBSERVED

FIG -12 PREDICTED AND OBSERVED DRIFTS



RUN #1: 0930 - 1001

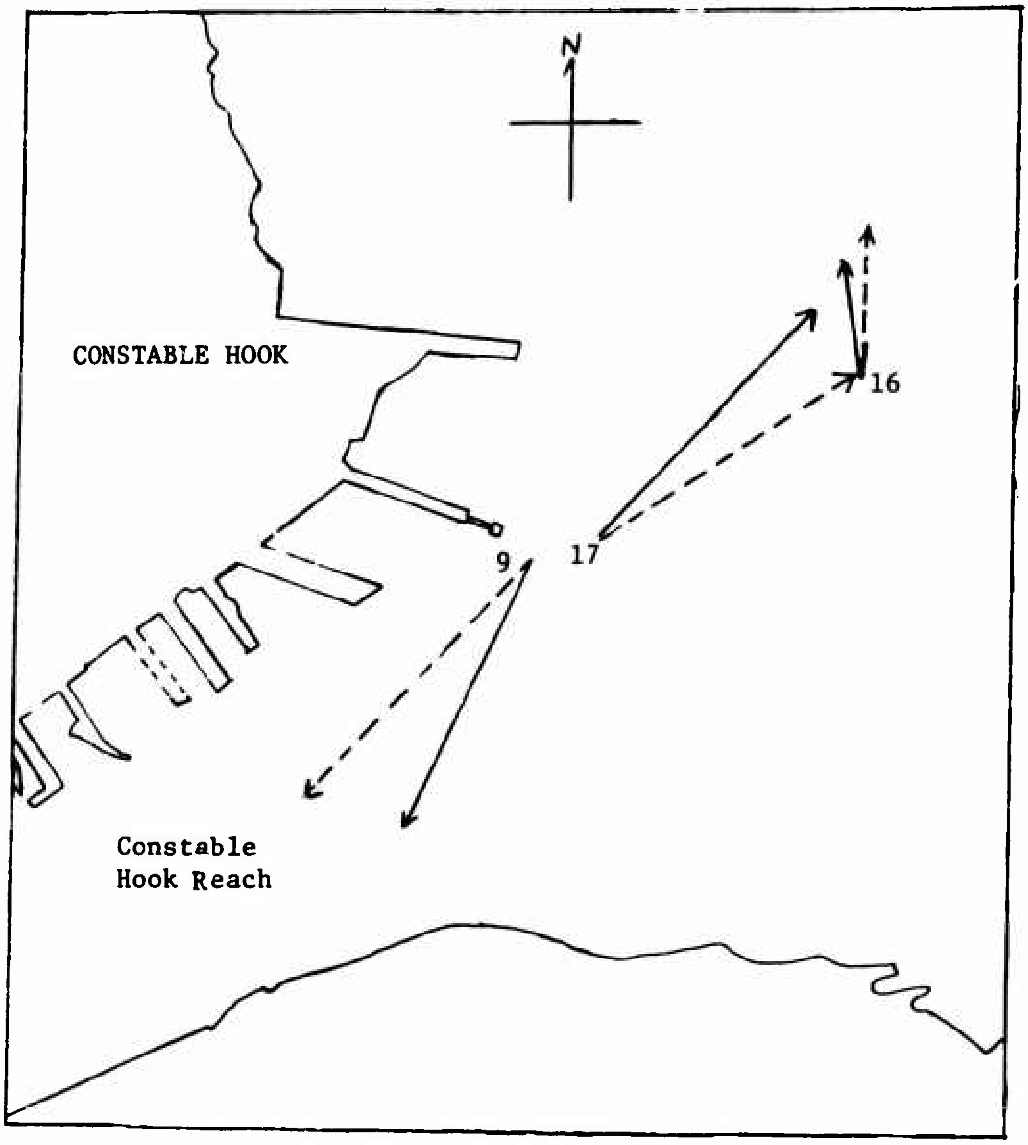
RUN #6: 0935 - 1002

PREDICTED

OBSERVED

G

FIG - 13 PREDICTED AND OBSERVED DRIFTS



RUN #9: 0915 - 0925

RUN #16: 0858 - 0930

RUN #17: 0938 - 1025

— — — — PREDICTED

———— OBSERVED

H

FIG - 14 PREDICTED AND OBSERVED DRIFTS

On 10 December 1973, one additional tracking test was conducted. The purpose of this test was to determine whether or not accurate predictions of the movement of an oil spill could be made for periods in excess of two hours. The results of this test, shown in Figure 15, demonstrate that the movement of an oil spill can be predicted accurately for periods of several hours, in this case 3-1/2 hours.

This tracking test also verified the need for using river runoff and wind drift for predicting the movement of an oil spill in estuaries. The river flow increased the speed of the ebb current by 0.28 knots. Had this factor not been included, the predicted southerly movement of the oil spill would have been far short of the observed movement. In addition, the wind factor played an important part in the prediction. When the tide turned, the observed movement was to the north. The tidal current charts indicate that the movement should have been into Kill Van Kull. It was the wind which prevented this movement into the Kill. By adding the wind factor the prediction compared favorably with the observed movement.

The circles on the track line of Figure 15 indicate the successive sizes of a 1000-barrel oil spill with respect to time of the initial spill. The boundaries within which a spill of this magnitude will move can be obtained as outlined in Section 3.5 of this report. If this is done, it can be seen that the predicted track line usually was contained within this boundary.

4.0 POTENTIAL OIL POLLUTION SITES - UPPER NEW YORK BAY

4.1 Data

Oil spill records have been accumulated for several years by the Dangerous Cargo Section of the Third U.S. Coast District. From these records lists of the reported petroleum spills in the Kill Van Kull and Upper New York Bay areas for 1971 and 1972 have been prepared (Tables 9-12). The causes and amounts of these spills are given in Table 13. The locations of these spills have been plotted for each of the two years (Figures 16 and 17). Numbers entered on Figures 16 and 17 indicate the number of spills in that particular area.

The United States Coast Guard has issued a report entitled, "Multi-Agency Oil and Hazardous Materials Pollution Contingency Plan for the New York Coastal Region." Extracted from the supplement to this report is a list of oil and petrochemical handling facilities in Upper New York Bay (Table 14) and a map showing the location of these facilities (Figure 18).

Other information presented includes an analysis of reasons for spillage and amount of spills (Tables 15 and 16).

4.2 Regional Priorities Based on Spill Records

It must be emphasized that the data presented are based on reported spills and therefore are probably biased because a region may have been designated with a lower priority as a result of unreported spills rather than a lack of them. On the other hand, areas of frequently reported oil spills (such as the Kill Van Kull area) show a high priority.

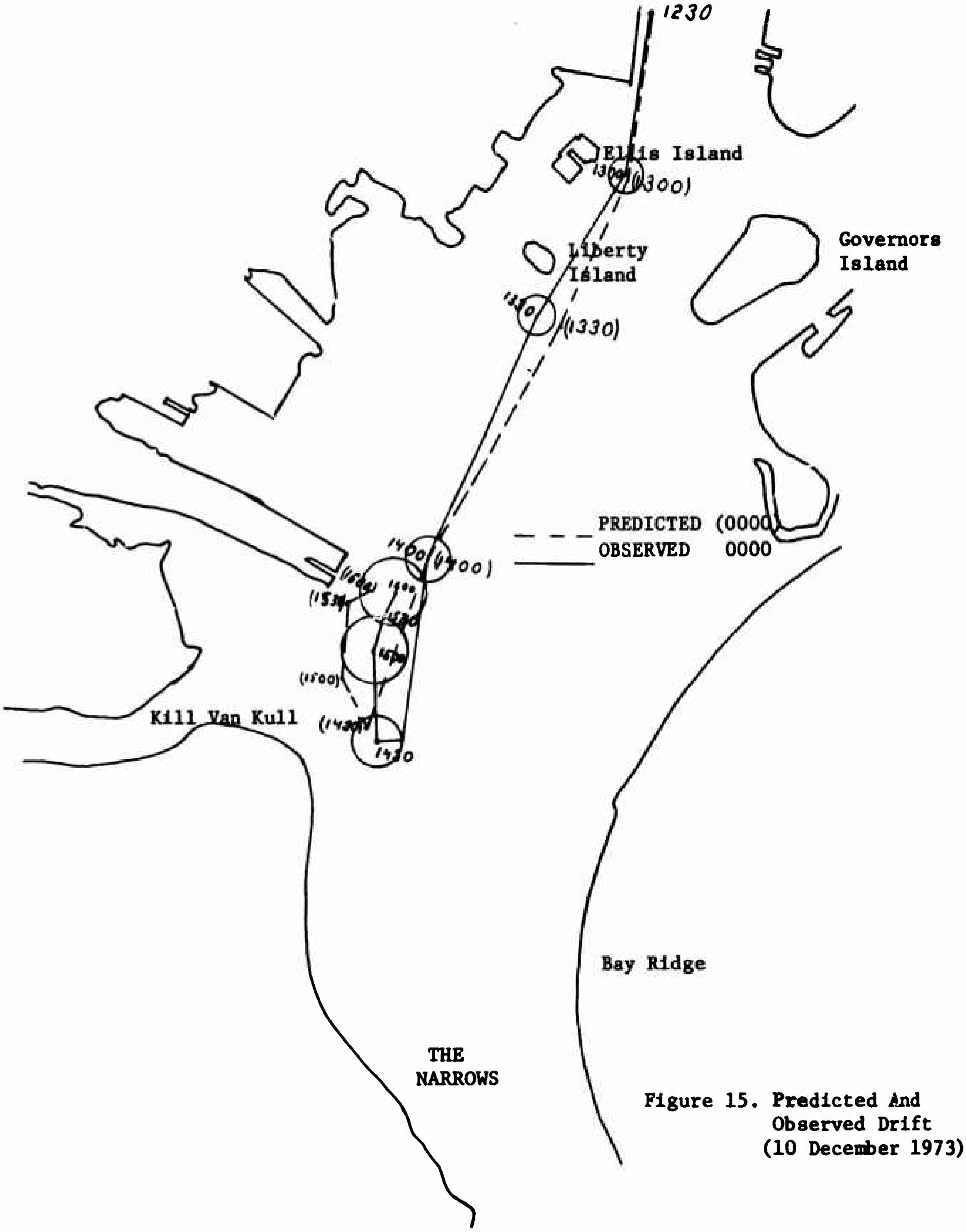


Figure 15. Predicted And Observed Drift (10 December 1973)

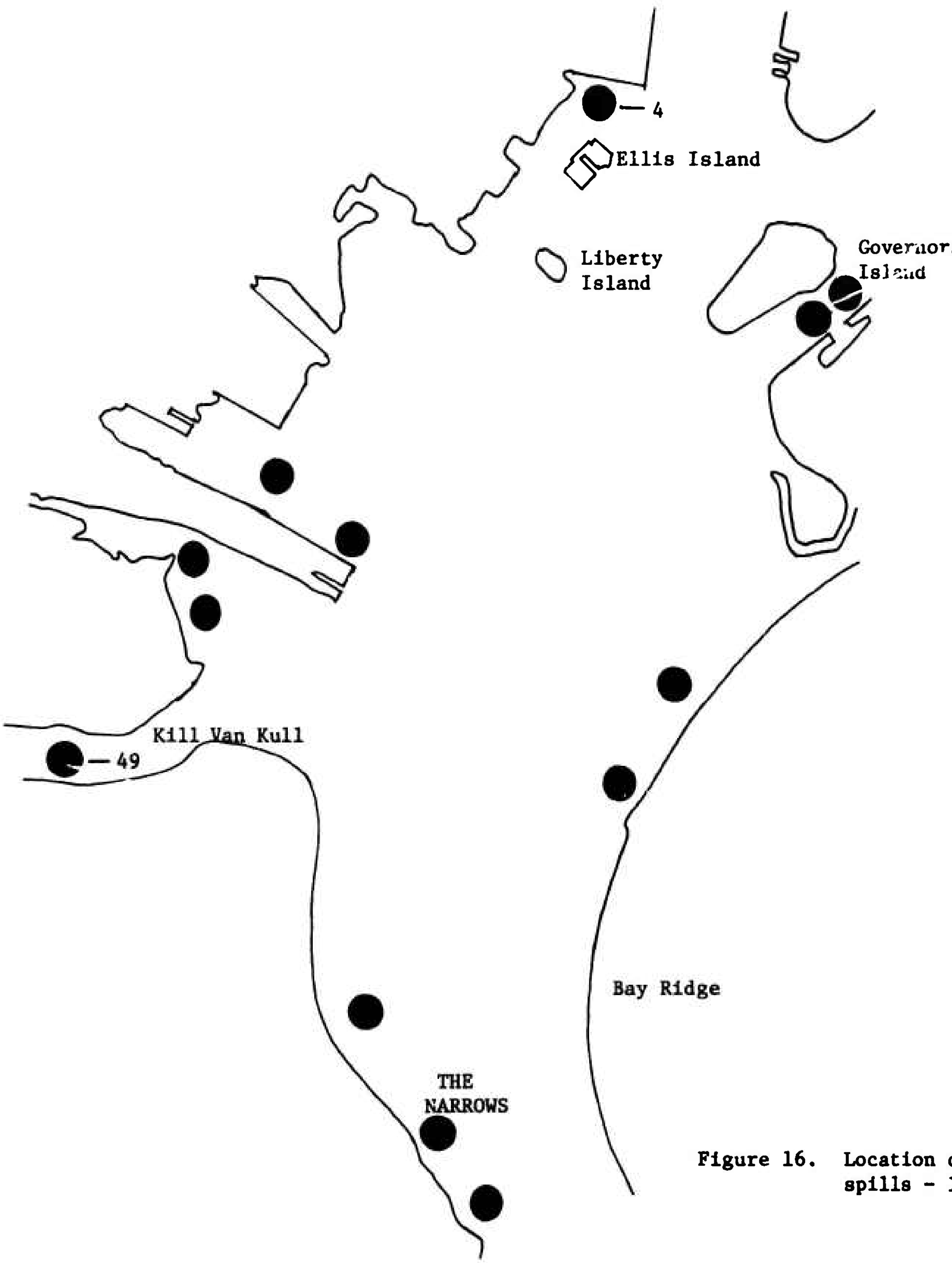


Figure 16. Location of oil spills - 1971.

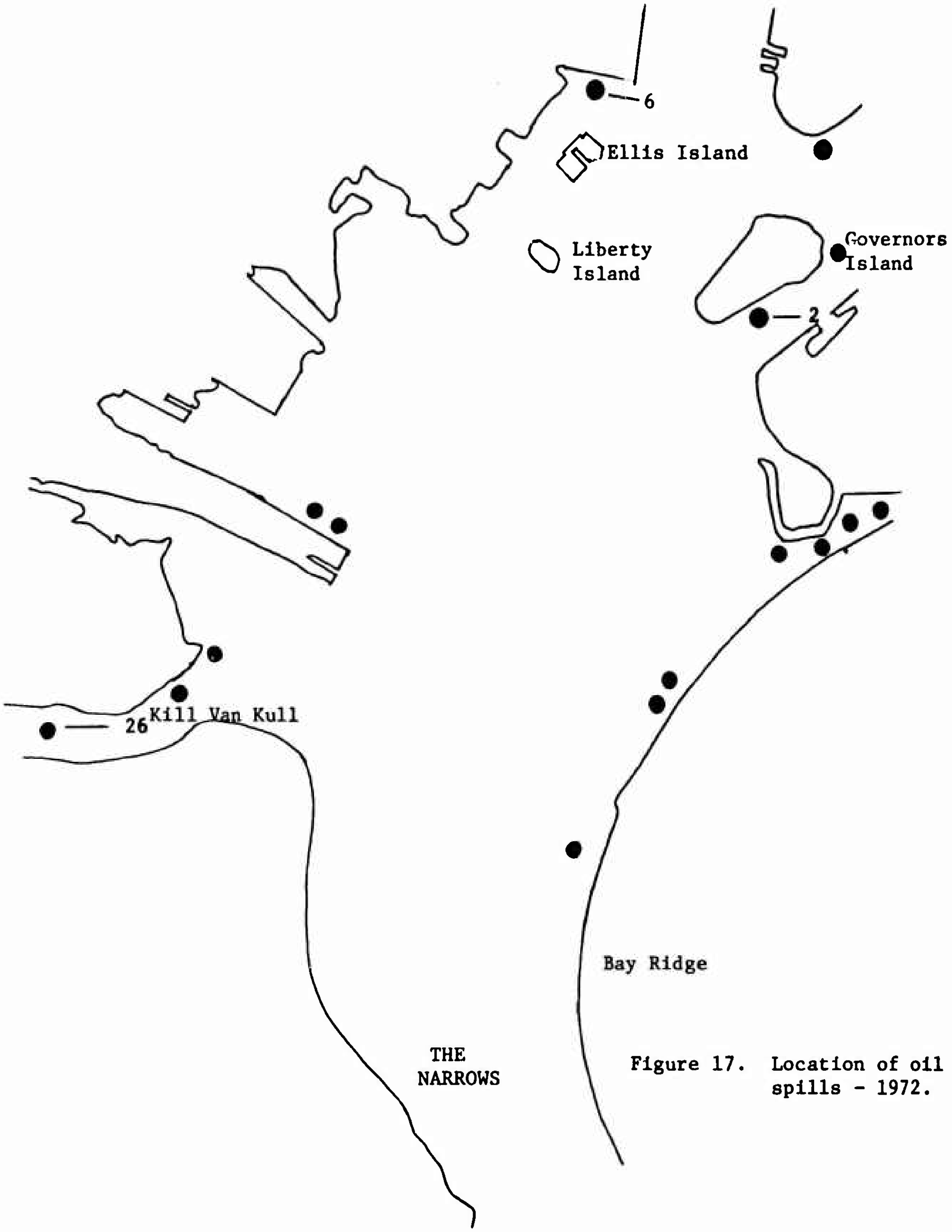


Figure 17. Location of oil spills - 1972.

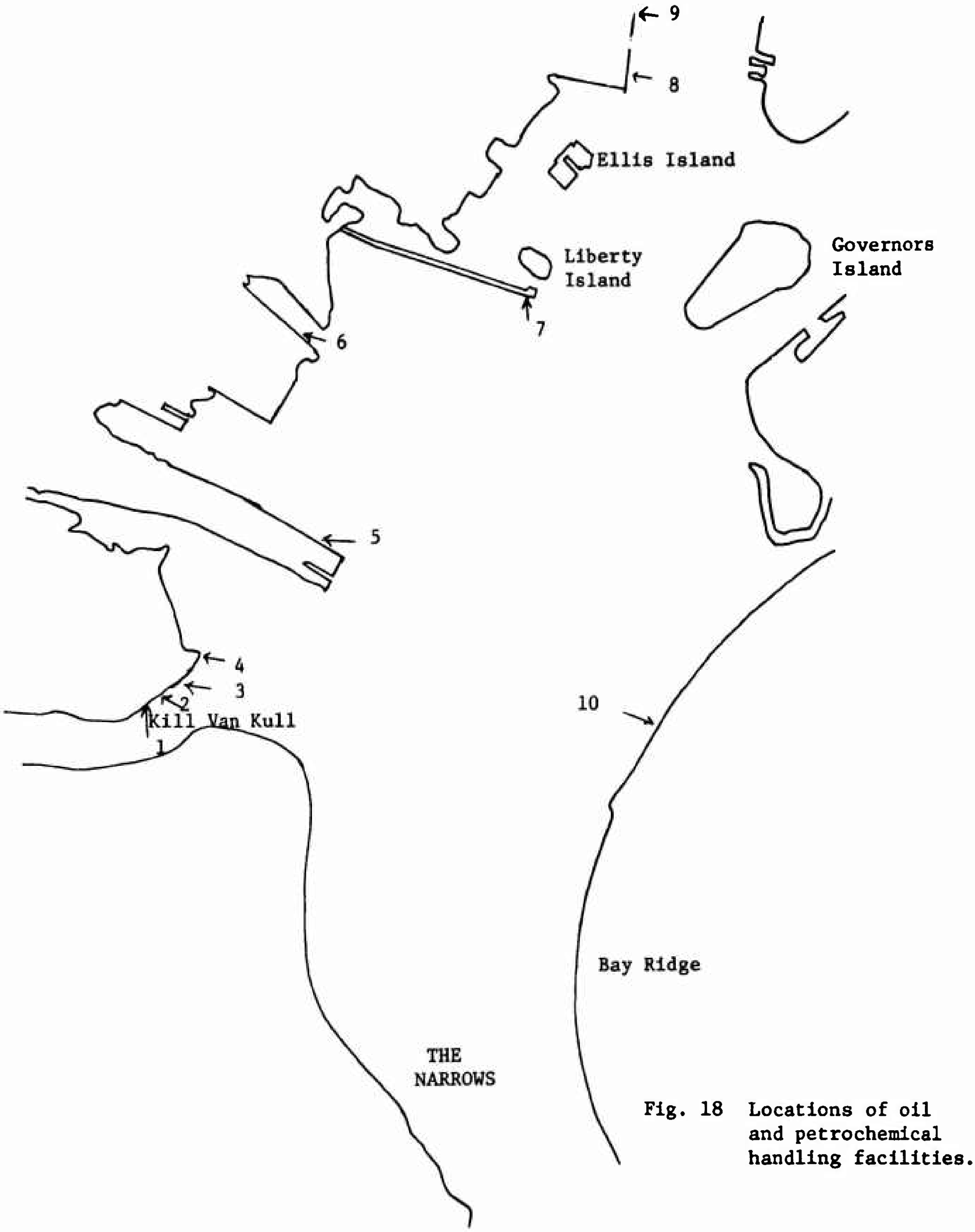


Fig. 18 Locations of oil and petrochemical handling facilities.

TABLE 9

REPORTED PETROLEUM SPILLS IN UPPER NEW YORK BAY - 1971

Facility or Vessel	Date	Cause 1	Cause 2	Amount
Eldorado Term.,Bayonne,N.J.	3 July 71	12	1	1
Esso Oil Co.,Edgewater,N.J.	8 Mar. 71	--	7	1
Kraft Containers Co.,Bayonne	22 June 71	10	5	1
Metropolitan Petro.Co.,Brooklyn	19 Jan. 71	1	5	8
Mobil Oil Terminal,42nd St.Brooklyn	28 Jan. 71	1	5	2
USNS Towle,MOT,Bayonne,N.J.	14 July 71	12	5	8
Royal Patrol,New Jersey	8 Feb. 71	10	1	1
Wellen Oil, Jersey City,N.J.	Jan. 71	--	-	1
Wellen Oil, Jersey City,N.J.	Feb. 71	9	1	-
Wellen Oil, Jersey City, N.J.	April 71	9	1	-
Wellen Oil, Jersey City, N.J.	June 71	11	5	1
Mobil Oil Term.,Staten Island,N.Y.	12 Sept. 71	2	1	2
Paragon Oil, Brooklyn,N.Y.	15 Jan. 71	2	2	1
Texaco, Brooklyn, N. Y.	1 April 71	9	-	1
Gulfport, Staten Island, N. Y.	5 Aug. 71	1,3	1	1

TABLE 10

REPORTED PETROLEUM SPILLS IN KILL VAN KULL - 1971

Facility or Vessel	Date	Cause 1	Cause 2	Amount
Bayonne Ind.,Bayonne,N.J.	29 Jan.71	9	1	1
Bayonne Ind.,Bayonne,N.J.	Feb.71	9	-	-
Bayonne Ind.,Bayonne,N.J.	Feb.71	-	-	-
Bayonne Ind.,Bayonne,N.J.	17 Apr.71	7	1	1
Bayonne Ind.,Bayonne,N.J.	Sept.71	11	-	-
Bayonne Ind.,Bayonne,N.J.	21 Oct.71	--	-	-
Bayonne Ind.,Bayonne,N.J.	9 Nov.71	9,11	-	2
Bayonne Ind.,Bayonne,N.J.	18 Nov.71	7,11	-	1
Bayonne Ind.,Bayonne,N.J.	21 Nov.71	13	-	1
Bayonne Ind.,Bayonne,N.J.	30 Nov.71	7	-	1
Bayonne Ind.,Bayonne,N.J.	10 Dec.71	13	-	1
Bayonne Ind.,Bayonne,N.J.	15 Dec.71	9,13	-	1
Bayonne Ind.,Bayonne,N.J.	30 Nov.71	9,11	-	1
Enjay Chem.Corp.,Bayonne,N.J.	31 Mar.71	7	2	1
Humble Oil, Bayonne,N.J.	3 Sept.71	1	1	1
Humble Oil, Bayonne,N.J.	22 Jan.71	2	1	3
Humble Oil, Bayonne,N.J.	23 Nov.71	7	1	1
Humble Oil, Bayonne,N.J.	30 July 71	1	1	2
Humble Oil, Bayonne,N.J.	12 Aug.71	2	1	4
Hess Oil Co.,Bayonne,N.J.	30 July 71	1	1	1
Howard Fuel Co.,Bayonne,N.J.	16 Nov.71	1	1	1
Howard Fuel Co.,Bayonne,N.J.	10 Dec.71	7	1	4
Rollins Terminal,Bayonne,N.J.	14 June 71	12	-	1
Rollins Terminal,Bayonne,N.J.	29 June 71	12	-	1
Rollins Terminal,Bayonne,N.J.	15 Sept.71	7	-	1
Rollins Terminal,Bayonne,N.J.	15 Oct.71	12	5	1
Rollins Terminal,Bayonne,N.J.	19 Oct.71	12	-	1
Rollins Terminal,Bayonne,N.J.	21 Oct.71	12	-	1
Rollins Terminal,Bayonne,N.J.	22 Nov.71	5	-	1
Texaco,Bayonne,N.J.	18 Nov.71	5	5	1
Texaco,Bayonne,N.J.	25 Apr.71	2	-	4
Texaco,Bayonne,N.J.	2 Dec.71	13	1	1
A.Gross,Inc.,Linden,N.J.	11 Feb.71	1	1	1
Mobil Oil Terminal,Staten Island	12 Sept.71	2	1	2
Port Mobile,Staten Island	5 Jan.71	9	-	2
Port Mobile,Staten Island	8 Feb.71	12	-	1
Port Mobile,Staten Island	10 Apr.71	7	-	1
Port Mobile,Staten Island	21 Apr.71	2	-	3
Port Mobile,Staten Island	4 Aug.71	7	-	2
Port Mobile,Staten Island	14 June 71	9	-	1
Port Mobile,Staten Island	20 July 71	9	-	1
Port Mobile,Staten Island	17 Sept.71	9	-	1
Port Mobile,Staten Island	7 Dec.71	13	-	1
Port Mobile,Staten Island	7 Dec.71	9	-	1
Port Mobile,Staten Island	7 Dec.71	9	-	1
Port Mobile,Staten Island	8 Dec.71	1	5	1
Shell Oil Co.,Seawarren,N.J.	17 June 71	1	5	1
Shell Oil Co.,Seawarren,N.J.	23 Dec.71	12	5	1
Shell Oil Co.,Seawarren,N.J.	30 Dec.71	7	-	1

TABLE 11

REPORTED PETROLEUM SPILLS IN UPPER NEW YORK BAY - 1972

FACILITY OR VESSEL	DATE	CAUSE 1	CAUSE 2	AMOUNT
Con. Edison,27 St.,Brooklyn,N.Y.	8 Mar.72	7	-	1
Esso,Constable Hook,N.J.	25 Mar.72	7	-	1
Esso,Constable Hook,N.J.	26 June 72	9	-	1
Esso,Freeman St.,Brooklyn,N.Y.	6 Apr.72	10	7	1
Mobile Oil Co., Brooklyn,N.Y.	31 Jan.72	1	-	1
Wellen Oil,Jersey City, N.J.	13 Jan.72	9	5	1
Wellen Oil, Jersey City,N.J.	7 Feb.72	9	5	1
Wellen Oil, Jersey City,N.J.	14 Feb.72	9	-	1
Wellen Oil, Jersey City,N.J.	13 Apr.72	9	-	1
Wellen Oil, Jersey City,N.J.	9 May 72	9	-	1
Wellen Oil, Jersey City,N.J.	20 Apr.72	9	-	1
Con.Edison,Gowanus Bay	15 Nov.72	-	-	5
Mystery, Upper Bay	17 Nov. 72	-	-	-
Datchogue Oil, Gowanus Canal	21 Nov.72	-	-	1
Governors Island, Yankee Pier	4 Dec.72	-	-	1
Governors Island, Yankee Pier	5 Dec.72	-	-	1
Mary Merry, Upper Bay	5 Dec.72	-	-	-
USS Huntington,MOT Bayonne	11 Dec.72	-	-	1
Unknown,Soyos West Bay Ridge	11 Dec.72	-	-	-
Con.Edison,59 St. Brooklyn	13 Dec.72	-	-	1
DD 781, MOT Bayonne, N.J.	14 Dec.72	-	-	1
Visllva Syoti,Pier 8, Brooklyn	20 Dec.72	-	-	1
Esso Bayonne,Constable Hook	29 Dec.72	-	-	1
Esso Bayonne,Constable Hook	29 Dec.72	-	-	1

TABLE 12

REPORTED PETROLEUM SPILLS IN KILL VAN KULL - 1972

FACILITY OR VESSEL	DATE	CAUSE 1	CAUSE 2	AMOUNT
Bayonne Ind.,Bayonne, N.J.	11 Feb.72	8	5	1
Bayonne Ind.,Bayonne, N. J.	11 Feb.72	8	-	1
Bayonne Ind.,Bayonne, N.J.	5 Apr.72	8	-	1
Bayonne Ind., Bayonne, N. J.	15 June 72	12	-	3
Bayonne Ind., Bayonne, N. J.	24 July 72	9	-	1
Bayonne Ind., Bayonne, N. J.	6 Aug. 72	9	-	1
Bayonne Ind., Bayonne, N. J.	12 Sept. 72	9	-	1
Humble Oil, Bayonne, N. J.	20 Aug. 72	7	1	1
Howard Fuel Co., Bayonne, N. J.	10 Apr.72	1	5	2
A. Gross, Inc.	10 Jan.72	7	-	1
A. Gross, Inc.	27 Jan.72	7	5	1
Port Mobile, Staten Island	27 Jan.72	9	-	1
Port Mobile, Staten Island	20 Feb.72	13	-	2
Port Mobile, Staten Island	9 Aug. 72	7	5	1
Port Mobile, Staten Island	7 Aug. 72	7	5	1
Port Mobile, Staten Island	7 Aug. 72	7	5	2
Port Mobile, Staten Island	9 Aug. 72	12	5	8
Port Mobile, Staten Island	30 Nov. 72	--	1	1
Standard Tank, Bayonne, N. J.	13 Nov. 72	--	1	-
Unknown, Kill Van Kull	21 Nov. 72	--	-	-
Bayonne Ind., Bayonne, N. J.	23 Nov. 72	--	1	2
Bayonne Ind., Bayonne, N. J.	29 Nov. 72	--	1	-
Bayonne Ind., Bayonne, N. J.	11 Dec. 72	13	1	1
Humble Oil, Bayonne, N. J.	12 Dec. 72	--	-	1
Unknown, Kill Van Kull	12 Dec. 72	--	-	-
Diana Moran, Texaco Bayonne	15 Dec. 72	--	-	-

TABLE 13

CAUSES AND AMOUNTS OF OIL SPILLS

Cause 1	Cause 2	Amount
1. Tank overflow	1. Facility	1. 1-5 bbls
2. Hose rupture	2. Vessel	2. 5-10 bbls
3. Grounding	3. Lack of communication	3. 10-50 bbls
4. Bilge pumping	4. Unqualified personnel	4. 50-100 bbls
5. Structural fault	5. Negligence	5. 100-200 bbls
6. Collision	6. Unplugged scuppers	6. 200-300 bbls
7. Broken equipment		7. 300-500 bbls
8. Missing drip pan		8. 500-1000 bbls
9. Seepage		9. Greater than 1000 bbls
10. Deliberate		
11. Boom leaking		
12. Over board Discharge		
13. Pipeline rupture		

TABLE 14

POTENTIAL POLLUTERS-UPPER NEW YORK BAY

Oil Handling	Petrochemical
1. Hess Oil and Chemical Corp.	1. Eldorado Terminals Corp.
2. Humble Oil and Refining Co.	
3. Constable Hookworks	
4. Bayonne Terminal	
5. Tankport Terminals Inc.	
6. Tankport Terminals Inc.	
7. McConnell Fuel Oil Co.	
8. Harborside Terminal Co., Inc.	
9. Whale Oil Co., Inc.	

TABLE 15

REASONS FOR SPILLAGE

	1971		1972	
Reason	Number	%	Number	%
Tank Overflow	10	15.6	2	4.0
Hose Rupture	6	9.3	-	---
Grounding	1	1.6	-	---
Bilge Pumping	-	0.0	-	---
Structural Fault	2	3.1	-	---
Collision	-	0.0	-	---
Broken Equipment	9	14.1	8	16.0
Seepage	11	17.2	11	22.0
Boom Leak	5	7.8	--	----
Overboard Discharge	9	14.1	2	4.0
Pipeline Rupture	5	7.8	2	4.0
Other or Unknown	6	9.3	25	50.0
TOTALS:	64		50	

TABLE 16

AMOUNT OF SPILLS

	1971		1972	
Amount	Number	%	Number	%
1-5 bbls	44	68.8	37	74.0
5-10 bbls	7	10.9	3	6.0
10-50 bbls	2	3.1	1	2.0
50-100 bbls	3	4.5	-	---
100-200 bbls	-	---	1	2.0
200-300 bbls	-	---	-	---
300-500 bbls	-	---	-	---
500-1000 bbls	2	3.1	1	2.0
Greater Than 1000 bbls	-	---	-	---
Unknown	5	9.4	7	14.0
TOTALS:	64		50	

On the basis of the data presented in Tables 9-14 and Figures 16-18, five regions can be defined (Figure 19). Region 1 has been given Priority I for several reasons: First, the majority of oil spills (74%) occur within this region. Second, five of the ten listed oil handling facilities are located in this region. Finally, the potential for large volume spills is greatest in this region. Of the three reported spills of over 500 barrels, two occurred within Region 1.

Regions 2 and 3 are given Priority II. These regions cover the areas of lesser spill frequency in comparison to Region 1. Region 2 has two major oil handling facilities, and Region 3 has one. Within these two regions 16 percent of the reported spills occurred.

Regions 4 and 5 are given Priority III, the lowest priority. These two areas have the lowest percentage of spills in both numbers and volumes.

There are factors which can change the priorities given. Additional areas of oil and petrochemical handling facilities may be established. As noted before, only reported spills have been analyzed. Many unreported spills from ships occur in anchorage areas such as the one located in Region 4 off Staten Island. Finally, the entire bay is subject to large spills due to vessel collisions. This is particularly true of Region 4 in the Narrows area where tidal currents have the greatest velocity and maneuvering room is restricted. Because of the factors noted above, the priority assignments should be reviewed periodically and changed when necessary.

5.0 CONCLUSION

Oil slick trajectories in New York Harbor result mainly from the influence of tidal currents, wind-generated currents, and fresh water flow from the Hudson River. Experimental results indicate that a simple vector addition of these three components will yield reasonably accurate predictions of oil spill movement.

Tidal currents can be predicted from published information. This paper quantifies the components of movement caused by fresh water flow and wind through the use of empirical and theoretical considerations. In addition, a method of predicting the boundaries within which the slick will move is presented. This information can be used to prepare a predictive guide for the movement of oil spills in New York Harbor.

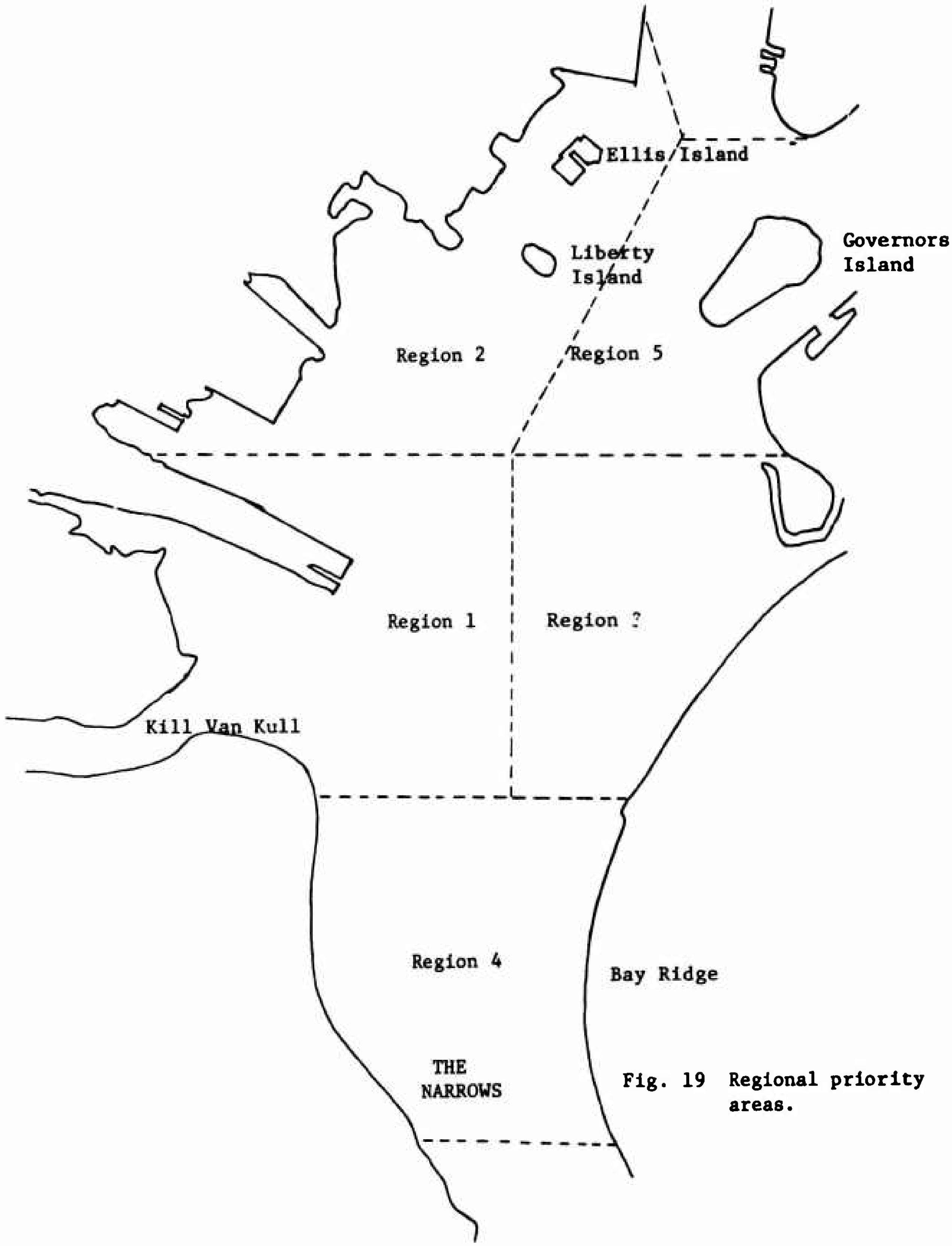


Fig. 19 Regional priority areas.

REFERENCES

1. Schwartzberg, H.G., "Spreading and Movement of Oil Spills," US Department of Commerce, Technical Report PB 192852, March 1970.

2. Keulegan, G.H., "The Mechanism of an Arrested Saline Wedge," Estuary and Coastline Hydrodynamics, A.T. Ippen (ed.), McGrawHill, New York, 1966.

3. Simmons, H.B., et al, "Hudson River Channel, New York and New Jersey Plans to Reduce Shoaling in Hudson River Channels and Adjacent Pier Slips," Technical Report No. 2694, US Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, September 1965.

4. Fay, J.A., and D.P. Hoult, "Physical Process in the Spread of Oil on a Water Surface," USCG R&D Report No. 714107/A1001, Contract No. DOT-CG-01,381A, July 1971.

5. Orthlieb, F.L., "Forecasting Oil Spill Behavior, A Preliminary Guide," USCG R&D Report No. 724107.1, July 1971.

APPENDIX A

Data Correction

Current data for several stations were incorrectly computed because the time interval used was measured to the boat's passage by the floating probe rather than to the moored probe. Several stations were taken where the elapsed time from initial release of the probe to boat passage past the anchored float, as well as past the floating cap, was recorded. These stations were used to correct those stations where the elapsed time between boat passage past the anchored float to the drifting cap was not recorded.

Boat speed can be computed by dividing the distance travelled by the time interval of the boat run from anchored float to drifting cap. This was done for those stations where the time interval was known. After computing the individual boat speeds an average boat speed was calculated from the individual station values. This average boat speed divided into the distance the cap moved gives the time of the boat run between anchored probe and drifting cap for those stations with missing data. This time was subtracted from the total time of cap drift from initial release to boat passage past the drifting cap to get a corrected time. This corrected time value was then used to compute the surface current speed. For each station the surface current speed computed using the average boat speed was compared to the known surface current speed using the actual speed of the boat. For the southern stations the average difference between these two speeds was ± 0.9 cm/sec. Since these values are relatively small, the computed average boat speed can be used for correcting surface current speeds.

Correcting surface current speeds for those stations where the time of the boat run between anchored float and drifting cap is not known was done by computing the times using the average boat speed. After the time values were found they were subtracted from the total time of cap drift from initial release to boat passage past the cap to get corrected time. This corrected time was then used to compute the surface current speed for each station. For each station the difference between this new speed and the incorrect speed previously computed was found. The average of these differences was then found and used as the factor for correcting surface current speeds.

APPENDIX B

EXPERIMENTAL DATA

TABLE 17

STATION N1 DATA

Month - Day	3-21	3-27	3-28	3-29	3-30	4-2	4-3	4-4
Time Boat Run Commenced	(0914)	(0904)	(0910)	(0910)	(0910)	(0857)	(0904)	(0855)
Surface Current Speed (kts)	0.79	1.68	2.41	1.03	0.47	0.14	0.46	0.48
Predicted Tidal Current Speed (kts)	1.08	1.10	1.3	1.20	1.00	0.10	0.33	0.90
Surface Current Direction (°T)	330	190	170	213	200	154	100	246
Predicted Tidal Current Direction (°T)	025	190	205	200	210	200	030	020
Wind Direction	025	000	035	185	070	015	275	090
Wind Speed (kts)	8	19	9	7	2	3	16	11
Surface Water Temperature (°c)	1.4	1.7	7.8	4.4	3.9	5.6	6.7	6.7
Salinity (°/₀₀)	13.5	12.0	11	7.0	15.5	15.0	14	12.5

Month - Day	4-6	4-9	4-10	4-12	4-13	4-16	4-17	4-18
Time Boat Run Commenced	(0920)	(0915)	(0850)	(1025)	(0906)	(0910)	(0900)	(0840)
Surface Current Speed (kts)	0.21	1.83	0.23	1.99	0.65	0.32	0.56	0.47
Predicted Tidal Current Speed (kts)	1.30	0.1	1.00	1.80	1.80	0.30	0.50	1.00
Surface Current Direction (°T)	135	185	130	194	098	170	073	008
Predicted Tidal Current Direction (°T)	030	190	190	200	200	200	010	020
Wind Direction	270	005	125	295	335	240	240	260
Wind Speed (kts)	18	6	6.5	11	9	7.0	7.5	4
Surface Water Temperature (°c)	6.1	5.6	5.6	3.3	3.3	6.1	6.1	8.3
Salinity (°/₀₀)	5.0	9.0	11	8.0	12.0	14.5	13.0	14.0

Month - Day	4-19	4-20	4-23	4-25
Time Boat Run Commenced	(0838)	(0845)	(0855)	(0950)
Surface Current Speed (kts)	0.30	0.40	1.01	1.67
Predicted Tidal Current Speed (kts)	1.00	0.88	0.30	0.10
Surface Current Direction (°T)	001	004	183	183
Predicted Tidal Current Direction (°T)	025	020	020	200
Wind Direction	105	035	250	350
Wind Speed (kts)	2	11	7	8
Surface Water Temperature (°c)	7.8	7.8	11.1	12.8
Salinity (°/₀₀)	13.0	13	8.5	7.2

TABLE 18

STATION N2 - DATA

Month - Day	3-20	3-21	3-27	3-28	3-29	3-30	4-2	4-3
Time Boat Run Commenced	(1507)	(0935)	(0917)	(0925)	(0922)	(0928)	(0915)	(0916)
Surface Current Speed (kts)	0.57	0.49	0.38	0.31	0.60	0.86	0.82	0.49
Predicted Tidal Current Speed (kts)	0.25	0.30	0.10	0.20	0.50	1.00	0.40	0.44
Surface Current Direction (°T)	140	250	200	200	170	202	180	170
Predicted Tidal Current Direction (°T)	170	020	190	200	190	200	200	200
Wind Direction	295	045	015	054	210	---	055	284
Wind Speed (kts)	8	5	17	7	6	Calm	3	14
Surface Water Temperature (°c)	3.3	2.5	4.4	4.4	3.9	5.6	5.6	6.1
Salinity (°/₀₀)	6.2	11.0	12.0	11.5	11.0	15.5	14.5	14.5

Month - Day	4-4	4-6	4-9	4-10	4-12	4-13	4-16	4-17
Time Boat Run Commenced	(0910)	(0939)	(0932)	(0930)	(1035)	(0940)	(0926)	(0920)
Surface Current Speed (kts)	0.18	0.71	1.01	0.36	0.22	0.69	0.48	0.67
Predicted Tidal Current Speed (kts)	0.20	0.20	0.1	0.40	0.30	0.80	0.30	Slack
Surface Current Direction (°T)	308	120	224	130	168	180	120	143
Predicted Tidal Current Direction (°T)	035	020	210	210	200	200	180	----
Wind Direction	090	287	355	255	275	285	250	265
Wind Speed (kts)	7	22	4	16	10	16	8	9.5
Surface Water Temperature (°c)	5.3	6.7	3.3	6.1	2.5	3.3	6.1	5.6
Salinity (°/₀₀)	12.0	8.0	7.0	8.0	9.5	10.0	14.5	14.0

Month - Day	4-18	4-19	4-20	4-23	4-25
Time Boat Run Commenced	(0905)	(0902)	(0900)	(0910)	(1010)
Surface Current Speed (kts)	0.43	0.26	0.28	0.21	2.40
Predicted Tidal Current Speed (kts)	0.40	0.40	0.32	0.10	0.10
Surface Current Direction (°T)	058	054	285	268	200
Predicted Tidal Current Direction (°T)	020	020	020	020	200
Wind Direction	247	195	045	253	035
Wind Speed (kts)	10	4	10.5	10	8
Surface Water Temperature (°c)	9.1	7.8	7.8	11.1	10.6
Salinity (°/₀₀)	14.1	13.0	11.0	10.5	11.0

TABLE 19

STATION N3 - DATA

Month - Day	3-20	3-21	3-27	3-28	3-29	3-30	4-2	4-3
Time Boat Run Commenced	(1533)	(1002)	(0938)	(0943)	(0930	(0944)	(0933)	(0927)
Surface Current Speed (kts)	2.62	0.11	1.6	0.89	0.52	1.28	0.29	0.47
Predicted Tidal Current Speed (kts)	1.00	0.20	0.70	0.70	0.60	1.10	0.40	0.33
Surface Current Direction (°T)	180	270	200	185	173	225	208	180
Predicted Tidal Current Direction (°T)	190	020	200	190	190	200	225	200
Wind Direction	278	043	023	048	163	072	023	275
Wind Speed (kts)	5	7	16	8	8	2	2	13
Surface Water Temperature (°c)	3.3	2.5	3.3	3.3	4.7	4.4	5.6	5.6
Salinity (°/₀₀)	---	11.5	8.0	11.5	10.5	9.0	14.5	14.0

Month - Day	4-4	4-6	4-9	4-10	4-12	4-13	4-16	4-17
Time Boat Run Commenced	(0928)	(0945)	(0945)	(0945)	(1048)	(0933)	(0945)	(0935)
Surface Current Speed (kts)	0.23	0.47	1.37	1.46	1.33	1.32	0.65	0.33
Predicted Tidal Current Speed (kts)	0.20	0.60	0.1	0.80	1.04	1.10	0.40	0.20
Surface Current Direction (°T)	329	125	214	170	199	180	200	132
Predicted Tidal Current Direction (°T)	020	020	010	190	190	190	190	190
Wind Direction	068	203	023	293	238	303	248	233
Wind Speed (kts)	14	18	6	13	9	10	10	4
Surface Water Temperature (°c)	5.0	5.0	3.3	5.6	3.9	2.2	6.1	5.6
Salinity (°/₀₀)	11.5	7	6.0	6.0	4.5	7.0	1.5	12.5

Month - Day	4-18	4-19	4-20	4-23	4-25
Time Boat Run Commenced	(0935)	(0916)	(0910)	(0920)	(1020)
Surface Current Speed (kts)	0.56	0.46	0.14	0.34	1.45
Predicted Tidal Current Speed (kts)	0.40	0.40	0.60	0.35	0
Surface Current Direction (°T)	048	018	298	224	189
Predicted Tidal Current Direction (°T)	020	020	020	020	---
Wind Direction	255	163	063	235	033
Wind Speed (kts)	8	3	17	7	7
Surface Water Temperature (°c)	9.4	7.8	7.8	11.7	10.6
Salinity (°/₀₀)	13.0	11.0	9.5	9.0	5.5

TABLE 20

STATION N4 - DATA

Month - Day	3-21	3-28	3-29	3-30	4-2	4-3	4-4	4-6
Time Boat Run Commenced	(1023)	(1001)	(0940)	(0954)	(0950)	(0940)	(0940)	(0955)
Surface Current Speed (kts)	0.46	1.91	1.1	0.98	0.56	0.71	0.18	0.83
Predicted Tidal Current Speed (kts)	1.30	1.50	1.3	1.40	0.50	0.77	1.30	1.00
Surface Current Direction (°T)	100	1.90	168	225	218	210	058	070
Predicted Tidal Current Direction (°T)	025	190	180	200	220	200	010	010
Wind Direction	038	053	208	108	012	291	128	308
Wind Speed (kts)	6	2.5	8	2	2	12	12	18
Surface Water Temperature (°c)	0.56	3.9	3.3	4.4	5.6	5.9	4.4	6.7
Salinity (°/oo)	12.0	8.5	6.0	8.0	12.0	13.0	12.0	6.0

Month - Day	4-9	4-10	4-12	4-13	4-16	4-17	4-18	4-19
Time Boat Run Commenced	(1002)	(1000)	(1100)	(0949)	(1000)	(0950)	(0930)	(0929)
Surface Current Speed (kts)	1.85	1.15	0.67	1.10	0.65	0.18	0.18	0.51
Predicted Tidal Current Speed (kts)	0.50	1.30	1.80	2.00	0.50	weak	1.30	1.53
Surface Current Direction (°T)	194	170	194	178	200	115	054	043
Predicted Tidal Current Direction (°T)	185	190	190	210	190	---	010	020
Wind Direction	300	288	238	358	278	213	248	245
Wind Speed (kts)	6.0	9	10	13	5	1	4	3
Surface Water Temperature (°c)	6.1	3.3	4.4	3.3	7.8	5.6	8.9	6.7
Salinity (°/oo)	6.0	8.0	3.0	6.0	10.0	1.30	12.5	14.5

Month - Day	4-20	4-23	4-25
Time Boat Run Commenced	0918	(0930)	(1033)
Surface Current Speed (kts)	0.14	0.78	0.56
Predicted Tidal Current Speed (kts)	1.12	0	0.50
Surface Current Direction (°T)	172	328	135
Predicted Tidal Current Direction (°T)	020	---	190
Wind Direction	048	228	008
Wind Speed (kts)	15	5.5	9
Surface Water Temperature (°c)	7.2	11.0	10.6
Salinity (°/oo)	11	7.0	6.0

TABLE 21

STATION N5 - DATA

Month - Day	3-20	3-21	3-27	3-28	3-29	3-30	4-2	4-3
Time Boat Run Commenced	(1559)	(1040)	(1010)	(1012)	(0947)	(1050)	(1003)	(0946)
Surface Current Speed (kts)	0.27	0.46	0.83	1.09	0.96	0.94	1.09	0.34
Predicted Tidal Current Speed (kts)	1.30	0.60	0.40	1.00	1.00	1.30	1.30	0.30
Surface Current Direction (°T)	215	100	200	210	205	205	224	107
Predicted Tidal Current Direction (°T)	225	045	220	220	220	220	230	270
Wind Direction	280	065	025	040	295	120	065	288
Wind Speed (kts)	5	6	6	8	5	2	3	10
Surface Water Temperature (°c)	4.4	6.1	3.3	4.4	3.9	5.0	6.7	6.1
Salinity (°/₀₀)	12	14	18	12	17	15	18.0	14

Month - Day	4-4	4-6	4-9	4-10	4-12	4-13	4-16	4-17
Time Boat Run Commenced	(0955)	(1005)	(1015)	(1015)	(1118)	(1006)	(1008)	(0958)
Surface Current Speed (kts)	0.14	1.28	1.43	0.86	0.42	1.14	0.72	0.16
Predicted Tidal Current Speed (kts)	0.20	1.20	1.00	0.40	0.60	1.71	1.40	0.70
Surface Current Direction (°T)	318	060	093	090	219	202	140	070
Predicted Tidal Current Direction (°T)	030	030	090	090	220	220	250	213
Wind Direction	035	303	040	295	245	295	250	220
Wind Speed (kts)	18	18	7	15	9	15	7	3.5
Surface Water Temperature (°c)	6.1	5.6	3.3	5.8	4.5	3.3	8.3	6.7
Salinity (°/₀₀)	13.5	5	7.5	10	12.0	13.0	15	15

Month - Day	4-18	4-19	4-20	4-23	4-25
Time Boat Run Commenced	(0942)	(0942)	(0928)	(0940)	(1040)
Surface Current Speed (kts)	0.74	0.79	1.12	1.87	1.08
Predicted Tidal Current Speed (kts)	0.90	1.00	1.12	0.65	0.40
Surface Current Direction (°T)	103	058	064	098	083
Predicted Tidal Current Direction (°T)	090	040	040	090	090
Wind Direction	225	095	080	245	060
Wind Speed (kts)	6	2.5	10	8	5
Surface Water Temperature (°c)	8.9	6.7	6.7	11.1	10
Salinity (°/₀₀)	13.5	12	11	10	10

TABLE 22

STATION S1 - DATA

Month - Day	3-20	3-21	3-26	3-27	3-28	3-29	3-30	4-2
Time Boat Run Commenced	(1421)	(0920)	(1036)	(0910)	(0930)	(0908)	(0933)	(0904)
Surface Current Speed (kts)		1.12	1.08	1.70	1.05	1.00	1.03	0.36
Predicted Tidal Current Speed (kts)		1.40	0.55	0.90	1.05	1.38	1.54	0.40
Surface Current Direction (°T)		350	165	180	203	180	164	173
Predicted Tidal Current Direction (°T)		350	350	170	160	170	160	170
Wind Direction		042	000	350	073	177	128	348
Wind Speed (kts)		4	7	17.5	9	9	6	3
Surface Water Temperature (°c)	3.1	3.3	3.9	3.3	3.3	3.9	3.9	5.6
Salinity (°/..)	11.1	15.0		13.0	13.5	10.0	15.5	18.0

Month - Day	4-3	4-4	4-6	4-9	4-10	4-12	4-13	4-16
Time Boat Run Commenced	(0920)	(0911)	(1034)	(0917)	(0900)	(0906)	(0915)	(0906)
Surface Current Speed (kts)	0.80	0.71	0.61	0.67	1.22	0.93	1.27	0.72
Predicted Tidal Current Speed (kts)	0.40	1.10	1.30	Slack	1.10	1.92	1.98	0.70
Surface Current Direction (°T)	150	000	098	175	143	168	139	175
Predicted Tidal Current Direction (°T)	160	350	350	----	170	170	170	170
Wind Direction	253	083	253	358	223	283	307	223
Wind Speed (kts)	13	13	20	5.5	10	11	11.5	8
Surface Water Temperature (°c)	7.35	5.6	4.4	5.6	5.6	3.9	5.3	5.0
Salinity (°/..)		11	7.0	9.0	9.0	10.0	14.0	15.0

Month - Day	4-17	4-18	4-19	4-20	4-23	4-25
Time Boat Run Commenced	(0905)	(0858)	(0846)	(0856)	(0909)	(1000)
Surface Current Speed (kts)	0.30	1.42	0.85	0.31	0.70	0.51
Predicted Tidal Current Speed (kts)	0.50	1.35	1.62	1.60	0.65	Slack
Surface Current Direction (°T)	263	008	349	351	120	188
Predicted Tidal Current Direction (°T)	350	350	350	350	350	-----
Wind Direction	262	238	164	083	263	003
Wind Speed (kts)	7.5	8	7	12	10	8
Surface Water Temperature (°c)	8.9	6.7	10.6	7.8	11.7	9.4
Salinity (°/..)	17.0	17.0	17.0	17.0		12.0

TABLE 23

STATION S2 - DATA

Month - Day	3-20	3-21	3-26	3-27	3-28	3-29	3-30	4-2
Time Boat Run Commenced	(1521)	(0935)	(1100)	(0928)	(0945)	(0928)	(1000)	(0920)
Surface Current Speed (kts)	3.20	0.14	1.52	1.30	1.65	0.92	1.02	0.64
Predicted Tidal Current Speed (kts)	1.20	1.40	0.60	0.50	1.00	0.95	1.40	0.50
Surface Current Direction (°T)	180	000	185	180	178	184	180	168
Predicted Tidal Current Direction (°T)	200	010	000	180	190	190	190	190
Wind Direction	278	073	030	350	021	202	143	313
Wind Speed (kts)	14	6	9	17	4	7	2	2
Surface Water Temperature (°c)	3.3	3.3	3.3	3.3	2.2	3.9	4.4	5.6
Salinity (°/..)	8.5	12.5		11	11.5	10	14	17

Month - Day	4-3	4-4	4-6	4-9	4-10	4-12	4-13	4-16
Time Boat Run Commenced	(0935)	(0918)	(1046)	(0938)	(0912)	(0935)	(0930)	(0922)
Surface Current Speed (kts)	0.58	0.49	0.51	1.05	1.11	2.20	1.19	0.76
Predicted Tidal Current Speed (kts)	0.40	0.88	1.10	0.40	0.50	1.50	1.71	0.50
Surface Current Direction (°T)	132	260	123	180	118	199	178	118
Predicted Tidal Current Direction (°T)	190	350	010	020	190	190	190	190
Wind Direction	258	088	268	001	268	263	273	268
Wind Speed (kts)	14	9	22	6.5	17	9	16	13
Surface Water Temperature (°c)	7.3	4.40	3.3	5.6	5.6	1.7	5.6	5.0
Salinity (°/..)	---	12	8	9	9.0	8.0	7.0	14

Month - Day	4-17	4-18	4-19	4-20	4-23	4-25
Time Boat Run Commenced	(0920)	(0913)	(0905)	(0909)	(0925)	(1012)
Surface Current Speed (kts)	0.71	0.40	0.13	0.10	0.67	0.91
Predicted Tidal Current Speed (kts)	0.50	0.80	1.17	1.36	0.65	0.10
Surface Current Direction (°T)	108	059	009	273	180	203
Predicted Tidal Current Direction (°T)	010	000	010	010	000	350
Wind Direction	252	243	158	078	268	358
Wind Speed (kts)	11	7	7	9	10	9
Surface Water Temperature (°c)	7.2	6.7	10.0	7.78	11.7	1.03
Salinity (°/..)	16.5	14.0	13	16		13

TABLE 24

STATION S3 - DATA

Month - Day	3-20	3-21	3-26	3-27	3-28	3-29	3-30	4-2
Time Boat Run Commenced	(1543)	(0949)	(1114)	(0948)	(1001)	(0940)	(1010)	(0935)
Surface Current Speed (kts)	0.21	0.18	1.10	0.10	0.45	0.39	0.93	0.77
Predicted Tidal Current Speed (kts)	0.20	0.20	0.55	0.80	0.25	0.50	0.94	1.40
Surface Current Direction (°T)	230	120	270	190	106	293	110	146
Predicted Tidal Current Direction (°T)	250	270	270	270	100	090	100	110
Wind Direction	266	055	350	335	026	194	134	Calm
Wind Speed (kts)	20	5	7	12	5	5	14	----
Surface Water Temperature (°c)	3.9	1.1	3.9	4.4	3.9	3.6	5.6	5.0
Salinity (°/₀₀)	13	12		11.5	14.5	10.5	14	18

Month - Day	4-3	4-4	4-6	4-9	4-10	4-12	4-13	4-16
Time Boat Run Commenced	(1045)	(0930)	(1120)	(0952)	(0927)	(0950)	(0945)	(0940)
Surface Current Speed (kts)	0.93	0.19	1.13	0.85	0.43	0.82	1.04	1.40
Predicted Tidal Current Speed (kts)	1.76	0.80	0.80	1.00	0.64	0.60	1.00	1.40
Surface Current Direction (°T)	076	290	160	230	108	059	109	098
Predicted Tidal Current Direction(°T)	090	090	100	270	270	070	090	090
Wind Direction	276	090	296	330	286	282	244	241
Wind Speed (kts)	14	13	20	4	13	14	10.5	8
Surface Water Temperature (°c)	7.35	5.0	3.3	5.6	4.4	3.3	7.5	6.1
Salinity (°/₀₀)	14	12	10	8.2	8.0	8.5		12

Month - Day	4-17	4-18	4-19	4-20	4-23	4-25
Time Boat Run Commenced	(0939)	(0930)	(0915)	(0923)	(0938)	(1031)
Surface Current Speed (kts)	0.34	1.58	0.35	0.11	0.00	0.78
Predicted Tidal Current Speed (kts)	1.00	0.40	0.20	0.40	0.50	0.65
Surface Current Direction (°T)	068	083	029	284	----	248
Predicted Tidal Current Direction (°T)	090	090	270	270	270	270
Wind Direction	275	260	270	071	251	010
Wind Speed (kts)	9	8	4	7	13	9
Surface Water Temperature (°c)	8.9	6.7	7.8	7.8	11.0	10.6
Salinity (°/₀₀)	17.5	15	13.5	13		10.5

TABLE 25

STATION S4 - DATA

Month - Day	3-20	3-21	3-26	3-27	3-28	3-29	3-30	4-2
Time Boat Run Commenced	(1505)	(1006)	(1138)	(1000)	(1028)	(1000)	(1030)	(0945)
Surface Current Speed (kts)	2.69	0.28	1.15	1.30	0.65	1.20	1.20	0.47
Predicted Tidal Current Speed (kts)	1.70	1.20	0.65	0.70	0.55	0.90	1.40	0.70
Surface Current Direction (°T)	180	010	190	190	199	185	206	209
Predicted Tidal Current Direction (°T)	200	020	010	190	200	190	200	200
Wind Direction	269	044	020	350	009	179	120	Calm
Wind Speed (kts)	8	6	4	13	9	6	5	----
Surface Water Temperature (°c)	3.9	1.1	4.4	2.8	2.8	4.4	5.6	4.4
Salinity (°/₀₀)	12.5	12.0	10.0	11.0	14.0	9.0	12.0	19.5

Month - Day	4-3	4-4	4-6	4-9	4-10	4-12	4-13	4-16
Time Boat Run Commenced	(1108)	(0944)	(1134)	(1012)	(0938)	(1005)	(1000)	(0953)
Surface Current Speed (kts)	1.07	0.26	0.20	1.17	2.16	1.17	1.96	0.42
Predicted Tidal Current Speed (kts)	1.32	0.44	0.40	0.50	1.28	1.71	0.50	0.20
Surface Current Direction (°T)	170	260	123	180	199	188	175	132
Predicted Tidal Current Direction (°T)	200	020	020	010	200	200	200	200
Wind Direction	279	090	270	354	259	239	301	239
Wind Speed (kts)	10	17	18	3	15	16	9.5	6
Surface Water Temperature (°c)	7.6	4.4	4.4	6.1	4.4	2.5	7.5	5.6
Salinity (°/₀₀)		13	9.0	6.0	8.0	7.5		14.0

Month - Day	4-17	4-18	4-19	4-20	4-23	4-25
Time Boat Run Commenced	(0950)	(0945)	(0930)	(0946)	(0953)	(1047)
Surface Current Speed (kts)	0.17	0.35	0.52	0.27	0.58	1.69
Predicted Tidal Current Speed (kts)	0.60	0.60	1.08	1.28	0.50	0.10
Surface Current Direction (°T)	069	069	034	028	206	168
Predicted Tidal Current Direction (°T)	010	010	020	020	020	010
Wind Direction	291	224	Calm	069	244	009
Wind Speed (kts)	8	5	----	12	9	10
Surface Water Temperature (°c)	8.9	7.2	10.0	7.8	11.9	10.8
Salinity (°/₀₀)	15.5	14.0	13.5	15.0		8.9

TABLE 26

STATION S5 - DATA

Month - Day	3-20	3-21	3-26	3-27	3-28	3-29	3-30	4-2
Time Boat Run Commenced	(1624)	(1024)	(1153)	(1039)	(1039)	(1012)	(1050)	(0955)
Surface Current Speed (kts)	0.57	0.21	0.73	0.05	0.45	0.70	0.13	0.48
Predicted Tidal Current Speed (kts)	0.10	0.40	0.60	0.20	0.30	0.60	0.60	0.90
Surface Current Direction (°T)	050	135	050	330	225	325	316	225
Predicted Tidal Current Direction (°T)	180	010	020	000	215	200	200	200
Wind Direction	325	065	010	005	010	175	094	Calm
Wind Speed (kts)	11	3	10	14	10	5	4	----
Surface Water Temperature (°c)	3.9	1.7	3.9	2.8	3.3	4.4	5.6	4.4
Salinity (°/°°)	12.5	13	13	16	17	11.5	15	18

Month - Day	4-3	4-4	4-6	4-9	4-10	4-12	4-13	4-16
Time Boat Run Commenced	(1118)	(0952)	(1148)	(1035)	(0948)	(1013)	(1010)	(1008)
Surface Current Speed (kts)	0.86	0.62	0.50	0.71	0.73	0.47	0.37	0.68
Predicted Tidal Current Speed (kts)	1.50	0.20	0.10	0.80	0.10	0.72	1.35	1.00
Surface Current Direction (°T)	172	265	134	045	044	229	039	162
Predicted Tidal Current Direction (°T)	200	020	190	020	180	190	190	190
Wind Direction	305	051	245	005	295	255	355	255
Wind Speed (kts)	8	18	15	5.5	14	9	15	4
Surface Water Temperature (°c)	7.45	4.4	4.2	6.1	2.8	1.9	7.2	6.1
Salinity (°/°°)		0	8.0	11.0	13	8.5		13

Month - Day	4-17	4-18	4-19	4-20	4-23	4-25
Time Boat Run Commenced	(1005)	(0955)	(0940)	(0958)	(1005)	(1057)
Surface Current Speed (kts)	0.71	0.59	0.51	0.50	0.90	0.66
Predicted Tidal Current Speed (kts)	0.60	0.20	0.63	0.88	0.55	0.35
Surface Current Direction (°T)	158	119	039	358	050	038
Predicted Tidal Current Direction (°T)	190	020	000	000	020	000
Wind Direction	235	230	Calm	095	260	355
Wind Speed (kts)	7	3	----	12	8	9.5
Surface Water Temperature (°c)	9.4	8.3	11.1	7.2	11.6	11.7
Salinity (°/°°)	14	13.5	14.5	16		13.8