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The Movement of Effluent From the City of Miami Sewage Ocean Outfall

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PREFACE

The Sea Grant Colleges Program was created in 1966 to stimulate research, instruction, and extension of knowledge of marine resources of the United States. In 1969, the Sea Grant Program was established at the University of Miami.

The outstanding success of the Land Grant Colleges Program, which in 100 years has brought the United States to its current superior position in agricultural production, helped initiate the Sea Grant concept. This concept has three primary objectives: to promote excellence in education and training, in research, and in information services in sea related university activities. These activities include the areas of science, law, social science, engineering, and business. It is believed the successful accomplishment of these objectives will result in practical contributions to marine oriented industries and government and will, in addition, protect and preserve the environment for the benefit of all.

With these objectives, this series of Sea Grant Technical Bulletins is intended to convey useful studies quickly to the marine communities interested in resource development without awaiting more formal publication.

While the responsibility for administration of the Sea Grant Program rests with the National Oceanic and Atmospheric Administration of the Department of Commerce, the responsibility for financing the Program is shared by Federal, industrial, and University contribution. This study, The Movement of Effluent From the City of Miami Sewage Ocean Outfall, is published as a part of the Sea Grant Program and was made possible by Sea Grant projects in Physical Oceanography directed by Dr. Thomas N. Lee.

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b_{GC}	width of Government Cut
b_{NC}	width of Norris Cut
h	depth
h_{GC}	depth of Government Cut
h_{NC}	depth of Norris Cut
t_t	travel time
u	velocity in X direction
v	velocity in Y direction
M	flow rate per unit width (=V x h)
Q	volumetric flow rate
Q_{GC}	volumetric flow rate for Government Cut
Q_{BC}	volumetric flow rate for Bear Cut
Q_{NC}	volumetric flow rate for Norris Cut
Q_O	volumetric flow rate for outfall
Q_R	volumetric flow rate ratio
S_A	particle path distance in coastal waters
S_B	particle path distance in inlet
S_X	particle displacement in X direction
S_Y	particle displacement in Y direction
V	uniform flow velocity
V_A	particle velocity in coastal waters
V_B	particle velocity in inlet
X	horizontal Cartesian coordinate, positive east
X_{BC}	location of Bear Cut along X-axis
X_{GC}	location of Government Cut along X-axis
X_{NC}	location of Norris Cut along X-axis

X_O	location of outfall along X-axis
X_P	location of effluent particle along X-axis
Y	horizontal Cartesian coordinate, positive north
Y_{BC}	location of Bear Cut along Y-axis
Y_{GC}	location of Government Cut along Y-axis
Y_{NC}	location of Norris Cut along Y-axis
Y_O	location of outfall along Y-axis
Y_P	location of effluent particle along Y-axis
α	angle between V and X-axis
β	angle between radial lines of sink or source and Y-axis
Δt	time interval
θ	angle between V and Y-axis
Ψ	stream function
Ψ_{BC}	stream function for Bear Cut
Ψ_{FC}	stream function for effects of Florida Current
Ψ_{GC}	stream function for Government Cut
Ψ_{NC}	stream function for Norris Cut
Ψ_O	stream function for outfall
Ψ_T	total stream function
Ψ_{WI}	stream function for wind-induced current

PREFACE

As this society becomes more awakened to its responsibility to itself and the environment of which it is part, an awareness develops regarding past indiscretions and present practices that have had visible effects on the environment. This is as it should be, for coupled with actions aimed at correction, these indiscretions become valuable lessons for the maturing of man.

One of these indiscretions has been the use and placement of ocean outfalls for removal of treated and untreated wastewater from coastal areas. The intent of this thesis is to supply information that can be used as an aid for the establishment of criteria governing the use of ocean outfalls in general, and in particular, the city of Miami's ocean outfall.

INTRODUCTION

Concern about the location of the city of Miami's ocean outfall has existed for some time. This concern has fluctuated with each new piece of information. This paper is the latest attempt to determine whether the concern is well founded.

Background Information

The City of Miami Sewage Treatment Plant at Virginia Key and its ocean outfall disposal system have been operating since 1956. Aerial photographs taken by the National Coast and Geodetic Survey in 1962 (photograph nos. 62-S(C)820 through 62-S(C)822) coincidentally contain a good view of the sewage outfall effluent (see Plate 1). The photographs show the effluent plume heading for the Norris Cut inlet, a condition which might be suspected of not meeting

PLATE 1

Undyed effluent heading NNW and entering Norris Cut (top of photo) the water quality standards for bathing waters in Norris Cut and possibly northern Biscayne Bay.

It is not known whether these photographs were seen by the Miami city administrators; however, much time passed before any action was taken with respect to the outfall. In this interval, a great amount of work was done and knowledge gathered on other ocean outfalls. An extremely enlightening and applicable three year study was started in 1967 in a neighboring area. Florida Ocean Sciences Institute did an extensive study on the Pompano Beach ocean outfall (Lee, et al., 1971). This work uncovered some impressive facts that helped precipitate action in Miami. It was found that during the majority of the year, "the effluent will rise to the surface forming a 'boil' and then move horizontally with the resultant surface current forming a 'plume'... The predominance of onshore winds produces a shoreward component in the resultant surface currents. This causes the outfall plume to travel at some angle toward shore, depending on the relative strength of the wind and the longshore velocities induced by the Florida Current." It was also noted that east-west meanderings of the Florida Current and spin-off eddies produced by it generate "large fluctuations in speed and direction of coastal currents," which at times reinforce onshore movement of the plume. This report stated that the intersection of the plume with bathing beaches was predictable and noted the need to study and improve ocean outfalls in southeastern Florida. Recognizing this need, the federal government, through the Environmental Protection Agency (EPA), began an investigation of waste disposal in southeast Florida.

The result is a fairly comprehensive report in the form of an environmental impact statement entitled "Ocean Outfalls and Other Methods of Treated Wastewater Disposal in Southeast Florida." This report states that "ocean outfalls are considered (by the EPA) an interim solution to total wastewater disposal until reuse and reclamation methods are identified, developed, and implemented." Cited among disadvantages of use of ocean outfalls were the destruction of reefs during construction of pipelines and a rendering of portions of recreational waters "aesthetically unpleasing as well as potentially hazardous, from a public health standpoint, for water contact activities."

The city of Miami started an investigation of its outfall discharge in early 1971. Its intent was to gather evidence of possible inlet and bay contamination with sewage effluent and to determine if a need existed to extend the outfall pipeline. Several groups were asked to do some quick studies. The United States Geological Survey did a one day dye study and found the plume entering Norris Cut. The National Oceanic and Atmospheric Administration (NOAA) did dye studies on two separate days, using rhodamine WT dye and a fluorometer (Mayer, 1972). Traces of dye were found in Norris Cut on the first day and in Bear Cut on the second day. A one day study was done by the University of Miami (Lee and Teytaud, 1971). They also used a dye tracer and found the plume heading for Government Cut. All of these studies were done on flood tide. A correlation between the wind direction and the presence of dye in a particular inlet seemed to be observable. With a northerly wind, dye was found in Bear Cut; and during a southerly wind, dye was measured in Norris Cut or Government Cut. These investigations were not extensive, but evidence of onshore drift of sewage effluent from the Miami Sewage Treatment Plant now existed.

Statement of Objectives

The objective of this study has been to trace, with a fair degree of accuracy and confidence, the path taken by the effluent from the Miami Sewage Treatment Plant when it leaves the outfall pipe in the Atlantic coastal waters. This was done by use of a simple but representative mathematical model and a varied field project.

It was hoped that this work could be used to establish whether a need existed for modifying the present ocean outfall system. On July 1, 1971, the Florida Air and Water Pollution Control Board handed down a federal order to the city of Miami to extend its ocean outfall pipeline (Willits, 1972). The results of this study can now be used to justify the upcoming modification expenditures and to help determine the proper location for the discharge point. The city's present proposed outfall pipeline extension would put the pipeline terminus some 2.9 n.m. (17,500 feet) east of Virginia Key in 90 feet of water (see Fig. 1). This work will make a judgment and a recommendation on this proposed location.

Description of Area

The sewage treatment plant on Virginia Key serves "fifty-five percent of the year round population of Miami" (Sloan, 1966). The plant, rated as a secondary treatment complex, makes use of a modified

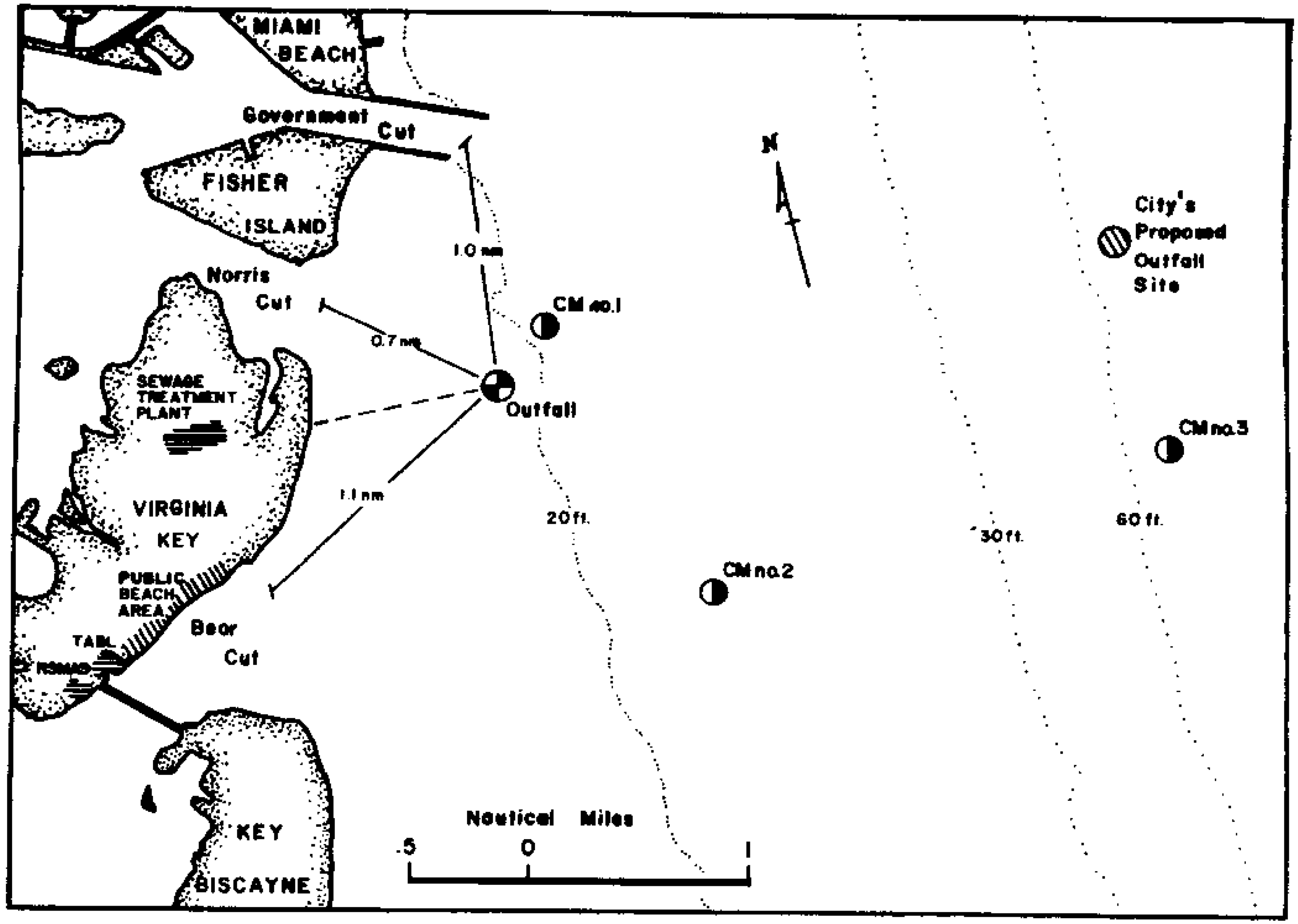

FIGURE 1

Study Area

activated sludge system for organic matter removal, settling tanks for settleable solids removal, and chlorination for bacteria kill (Dinn, 1971). The present plant effluent discharge rate is approximately 57 million gallons per day (m.g.d.)(Backmeyer, 1972). This rate will increase in the near future, for it is planned to pump the wastewater from Miami Beach to the Virginia Key plant for treatment and disposal (Willits, 1972). This will produce a combined discharge rate of approximately 85 m.g.d.

The plant effluent is discharged into the coastal waters off Virginia Key via a 4,500 foot long, 90 inch in diameter pipeline (Hyperion Engineers, 1957)(see Fig. 1). The effluent is emitted from three outlets in approximately 17 feet of water. Two outlets must be oriented close to each other for the effluent, being less dense than the surrounding waters, rises to the surface forming only two boils. Since the separation distance is small (approximately 100 feet), the two boils rapidly combine and henceforth will be referred to as a single boil. This boil is constantly present due to the shallow water depths at the point of discharge. The boil then becomes a plume as the surface currents move the effluent horizontally. Hence, a plume is constantly present and free to be moved about by the existing surface currents.

The ocean end of the outfall pipe is in close proximity to three inlets: 1.1 nautical miles from the mouth of Bear Cut, 1 nautical mile from the mouth of Government Cut and only .7 nautical miles from the mouth of Norris Cut (see Fig. 1). These inlets form part of the water link between the Atlantic Ocean and Biscayne Bay.

Some difficulty was encountered when attempting to find a meaningful value for the synoptic tidal volumes through these inlets. The standard data used for studies in the north Biscayne Bay area has been the work of Minkin (1949) and Hela (1957)(both used current meter data from inlets). Volumetric data gathered by McGuiness (1967), who used vertical profiled current meter data, showed some variance in values from Minkin's and Hela's data. This difference was due mostly to the construction of the Dodge Island complex and the associated dredge and fill operations, which occurred after Minkin and Hela made their measurements. It was decided that McGuiness' data for flood tide volume was more representative for Government Cut and Norris Cut than Minkin's or Hela's.

This decision was made with the aid of a volumetric flow rate ratio (Q_R), derived from Manning's formula (Dronkers, 1964). The ratio was established between the average physical dimensions (width = b, depth = h) of Government Cut (G.C.) and Norris Cut (N.C.), assuming an equal hydraulic gradient and roughness at each inlet. Hence,

$$Q_R = \frac{b_{G.C.} \ (h_{G.C.})^{5/3}}{b_{N.C.} \ (h_{N.C.})^{5/3}} . \qquad 1)$$

This ratio was used only as a rough means of assistance in determining the flow rate values best to use. Being applied in this capacity, the limitations of the ratio were deemed acceptable, those being: 1) $b \to \infty$ for R (the wetted perimeter), in Manning's formula, to be replaced by h, and 2) Norris Cut has a tidal range which is large with respect to h. Recognizing this, the ratio was then compared to the Q_R's obtained from the flow measurements made by Hela (1957), Minkin (1949), and McGuiness (1967) in Government

Cut and Norris Cut. The volumetric flow rate ratio formed from the McGuiness data showed the best agreement with Eq. 1) and these data were, therefore, deemed most acceptable.

The flood tide volume for Bear Cut was measured by Marine Acoustical Services (1966). These measured volumes were adjusted to the same tidal range as measured during the McGuiness experiment, in order to have equivalent tidal forcing. The values for the flood tide volume of the three inlets are listed in Table 1.

The tidal flow through the nearby inlets, fluctuations of the Florida Current, and local wind forcing all have a marked effect on the current in the study area. The semidiurnal ebb and flood of the flow through the inlets influence the water motion at the outfall outlet location due to the combined effect of the large flow rates and the close proximity of the inlets to the outfall terminus.

The Florida Current is the portion of the Gulf Stream which runs along the east coast of Florida in a northerly direction. The Continental Shelf extends some three miles east of the outfall outlet; hence, the area around the outfall does not experience the full force of the Current but only a fringe portion of it. This contribution to the overall forces working on the effluent plume is highly unpredictable due to the random nature of the perturbations in the western region of the Florida Current. The current exhibits large fluctuations in its speed and direction which are partially due to tidal modulations and east-west meandering (Düing, 1973). The east-west meandering brings the western edge of the Florida Current further from or nearer to the outfall.

Another confusing characteristic of the Florida Current is its ability to generate spin-off eddies. Lee (1972) observed spin-off

TABLE 1

Tidal Volumes and Flow Rates Through Inlets (Flood Tide)

Location	Flood Tide Volume	Adjusted Flood Tide Volume (tidal amp.=2.1 ft)	Average*** Volumetric Flow Rate, Q
Government Cut	926×10^6 ft^3*	926×10^6 ft^3	41.5×10^3 ft^3/sec
Norris Cut	335×10^6 ft^3*	276×10^6 ft^3	14.2×10^3 ft^3/sec
Bear Cut	$895 \times 10^6 ft^3$**	895×10^6 ft^3	40.0×10^3 ft^3/sec

*McGuiness, 1967

**Marine Acoustical Services, 1966

***Over half a tidal cycle

eddies in the coastal waters off Boca Raton and Pompano Beach, Florida. These eddies are formed in the west side of the Florida Current, travel to the north through the coastal waters, and rotate in a counter-clockwise direction. Therefore, water between the coast and the west side of the Florida Current can experience currents to the west, south, and east at intervals during the passage of these eddies. However, at the location of the Miami outfall discharge, the effect of Florida Current meanders and spin-off eddies is reduced by the shallow depths and increased shelf width. It is believed that in these shallow waters, tide and wind forcing is of greater importance in producing the observed currents.

Strong support for this belief is evident in data generated by a NOAA current meter, C.M. #1, which was located near the outfall terminus, seven feet below the surface (see Fig. 1). These data are displayed in Fig. 2a, a progressive vector diagram of a six day current record (sampling rate was every 10 minutes) from C.M. #1. The inlet effects, which are seen to be strongly evident, are filtered out by a 17 hour low pass filter and the result is a much cleaner progressive vector diagram, shown in Fig. 2b. The corresponding wind record, measured at Miami Beach, is shown as Fig. 2c. What is readily observable is the distinct dependency of the current direction on the wind direction. Shown in a comparison of Figs. 2b and 2c is the rapid response of the shallow water to the passing of a classical clockwise weather frontal system (cold front) resulting in an abrupt reversal of the water column. With the range of resolution of the filtered data (6 hour resolution), there appears to be no phase phase lag between the wind and the currents (Mayer, 1973).

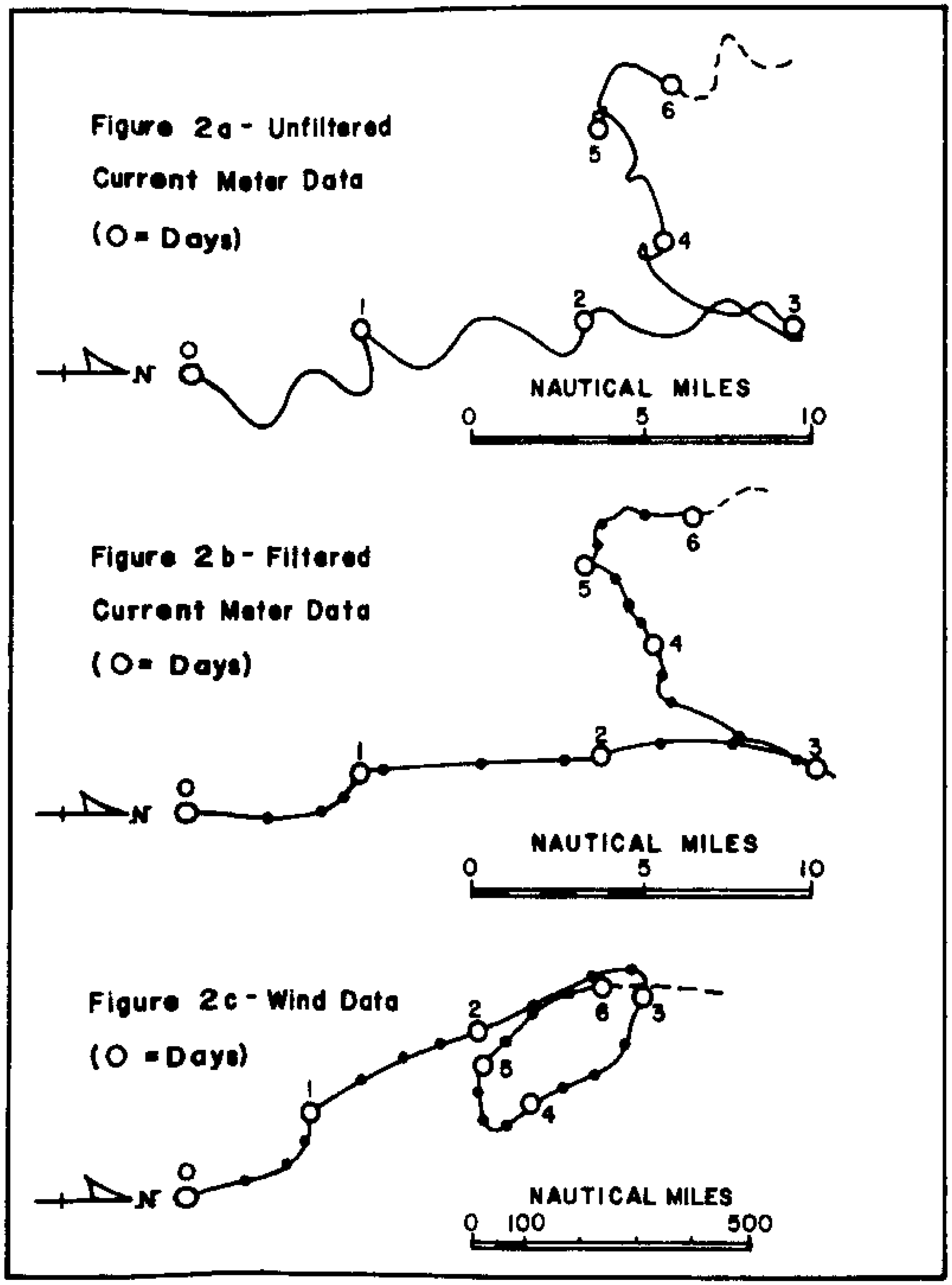

FIGURE 2

Comparative progressive vector diagrams for current and wind directions in study area

The record starts with the wind and current heading in a northerly direction. On the third day the winds cycled in a clockwise direction producing a strong southerly component. The current is seen to cycle in a similar manner at this time and also develops a strong southerly component. For two days the current had a definite onshore direction. After the fifth day the winds cycled back toward the north and the current direction is seen to respond immediately. A 73 day record made at C.M. #2 (see Fig. 1) by NOAA also repeatedly exhibited this correlation.

This relationship is mathematically anticipated from Ekman's treatment of pure drift currents in finite depth (Neumann and Pierson, 1966). Ekman's work predicts that the angle between the wind and the surface current in water depths of 17 feet is approximately 3.4° (clockwise) or roughly aligned in the same direction.

The field work also consistently demonstrated that the surface currents in the vicinity of the outfall were strongly influenced by the wind. The orientation of the surface plume was repeatedly aligned with the wind direction until the plume came within range of the inlet tidal motion. At this point, the combined forces began observably working on the plume. If the plume was close enough to the inlet to overcome the wind-driven current, it was brought into the inlet. If not, the wind-driven current carried the plume past the inlet.

A survey was made of the daily wind data gathered at Miami International Airport for the year of 1971. It was found that the wind direction had a westward or onshore component 77% of the time. Therefore, for a major portion of the year, the surface waters in the study area have a wind-induced current which encourages onshore movement and possible entry into the inlets and bay.

Data gathered from the NOAA current meters in the area (C.M.'s #1 and #2) show that a typical current velocity is approximately .35 k to the north when the wind is out of the south (Mayer, 1973). As the winds reversed direction to come out of the north, the currents exhibit a similar speed toward the south. Therefore, .35 k will be used later in the mathematical model as a representative current speed.

KINEMATIC MODEL

The unique juxtaposition of the outfall and the three inlets of Government Cut, Norris Cut, and Bear Cut suggested that the use of a kinematic, source-sink model would be a convenient method for obtaining a mathematical prediction for the effluent's motion once it leaves the outfall pipe. The physical situation lends itself well to the use of a stream function, Ψ, representation.

The concept of stream functions follows directly from a solution to the continuity equation for steady, incompressible flow,

$$\frac{\partial(hu)}{\partial X} + \frac{\partial(hv)}{\partial Y} = 0.$$

The average over-depth velocity components, u and v, are in the X and Y directions respectively, with X positive to the east and Y positive to the north. Depth is denoted by h.

The stream function, Ψ, can then be defined as

$$\frac{1}{h}\frac{\partial\Psi}{\partial Y} = -u$$
$$\frac{1}{h}\frac{\partial\Psi}{\partial X} = v. \qquad 2)$$

Streamlines can be identified with lines representing constant values of the stream functions. It can also be shown that a vectorial combination of two-dimensional, incompressible flow fields can be accomplished by addition of their stream functions (Owczarek, 1968). In this case, the individual flow fields to be considered are a) the tidal flow through each inlet, b) the offshore currents generated by the wind and the Florida Current, and c) the outfall itself. Therefore, to obtain the resultant flow pattern in the study area, the following relationship describing the total stream function, Ψ_T, was derived:

$$\Psi_T = \Psi_{BC} + \Psi_{NC} + \Psi_{GC} + \Psi_{WI} + \Psi_{FC} + \Psi_O. \qquad 3)$$

This expression is a linear combination of the stream functions of all the major forcing factors on the flow in the study area. The tidal flow through the inlets is represented by Ψ_{BC} for Bear Cut, Ψ_{NC} for Norris Cut, and Ψ_{GC} for Government Cut. The effects of wind-induced currents and the entrainment by the Florida Current are represented by Ψ_{WI} and Ψ_{FC} respectively. The outfall itself is represented by Ψ_O.

During flood tide, the inlets are depicted as two-dimensional sinks and the outfall is depicted as a two-dimensional source. A two-dimensional sink is defined as a line into which the fluid flows radially inward at a uniform rate. The stream function equation for a sink (Owczarek, 1968) is:

$$\Psi_{sink} = -\frac{Q}{2\pi}\beta \qquad 4)$$

where Q is the volumetric flow rate and β is the angle in radians between the Y-axis and the radial lines of the sink.

The inlets are not true sinks since they draw fluid in through an arc of only 180°. To account for this, the stream function expression was doubled. The outfall, therefore, "views" a more accurate flow situation with the full flood volume entering the inlets on the "ocean side." This gives:

$$\Psi_{inlet} = -\frac{Q}{\pi}\beta. \qquad 5)$$

A two-dimensional source is defined as a line from which the fluid flows radially outward at a uniform rate. Its stream function equation is:

$$\Psi_{source} = \frac{Q}{2\pi}\beta. \qquad 6)$$

Therefore, the stream function expressions for the inlets during flood tide and the outfall are:

$$\begin{aligned} \Psi_{BC} &= -\frac{Q_{BC}}{\pi}\beta \\ \Psi_{NC} &= -\frac{Q_{NC}}{\pi}\beta \\ \Psi_{GC} &= -\frac{Q_{GC}}{\pi}\beta \\ \Psi_{O} &= \frac{Q_{O}}{2\pi}\beta. \end{aligned} \qquad 7)$$

Wind-induced currents and currents entrained by the Florida Current can be jointly depicted as a uniform flow. The stream function expression for a uniform flow (Owczarek, 1968), which implies constant depth, is:

$$\Psi_{UF} = VhX \sin\alpha - VhY \cos\alpha \qquad 8)$$

where V is the average over-depth velocity which is assumed to be constant over the flow field and α is the angle between V and the X-axis. This equation is adjusted to accomodate the use of compass readings to form:

$$\Psi_{UF} = VhX \cos\theta - VhY \sin\theta \qquad 9)$$

where θ is the angle between V and the Y-axis. Letting M = Vh and substituting this into Eq. 9) gives:

$$\Psi_{UF} = MX \cos\theta - MY \sin\theta. \qquad 10)$$

The total stream function (Eq. 3)) now becomes the combination of Eqs. 7) and 10):

$$\Psi_T = -\frac{Q_{BC}}{\pi}\beta - \frac{Q_{NC}}{\pi}\beta - \frac{Q_{GC}}{\pi}\beta + \frac{Q_O}{2\pi}\beta + MX\cos\theta - MY\sin\theta. \qquad 11)$$

This equation then describes an idealized model of the study area. The model is that of a constant depth, borderless (no shore) basin with three sinks and one source in it. The constant water depth assumed is 17 feet (the depth at the outfall), when actually the bottom slopes from 17 feet at the outfall terminus to as shallow as 1 and 2 feet at places near the inlets. The ideal fluid (i.e., nonviscous, irrotational) flows through the system at a uniform and constant rate. A constant tidal flow through the inlets is another simplification since the actual flow varies sinusoidally with time. The model is a compromise. Simplicity was maintained by avoiding complicating boundaries which, as will be demonstrated in the comparitive analysis section, did not detract from the model's ability to produce meaningful results.

The values used in Eq. 11) for the inlet volumetric flow rates (see Table 2) were computed by permitting the inlet's flood tide volumes of Table 1 to enter the inlets at a constant rate for the full flood cycle. Therefore, the kinematic model represents the flow into the inlets as constant (a square wave) where in actuality the flow is more sinusoidal.

TABLE 2

Constants for Eq. 11

$Q_{BC} = 40.0 \times 10^3\ ft^3/sec$

$Q_{NC} = 14.2 \times 10^3\ ft^3/sec$

$Q_{GC} = 41.5 \times 10^3\ ft^3/sec$

$Q_O = 2.1 \times 10^3\ ft^3/sec$

M = a) 0 ft^2/sec (Case 1)

b) 10.13 ft^2/sec (Case 2)

The volumetric flow rate for the outfall was computed from the average yearly discharge rate of 57 m.g.d. and was considered constant over the flood tide period. The value for M (for use in Case 2 in Fig. 4) was computed using a constant current speed of .35 k which has been shown as a representative value for the area, and a constant depth of 17 feet.

In order to plot the total stream function, an idealized map of the study area was created with the Y-axis of the coordinate system corresponding to the north direction. For simplicity, all the inlets were assumed to be located in a straight line. This minor alteration of the actual coastline (Fig. 3) adds greatly to the simplification of the model's solution and detracts little from its overall accuracy. Equation 11) was then solved by systematically plotting each of its six components. The two cases solved are pictorially presented as Figs. 3 and 4. Figure 3 (Case 1) shows the flow pattern generated by only the three inlets flooding and the outfall; i.e., M = 0. Figure 4 (Case 2) shows the flow pattern for a northward uniform flow of .35 k in conjunction with the three inlets flooding and the outfall.

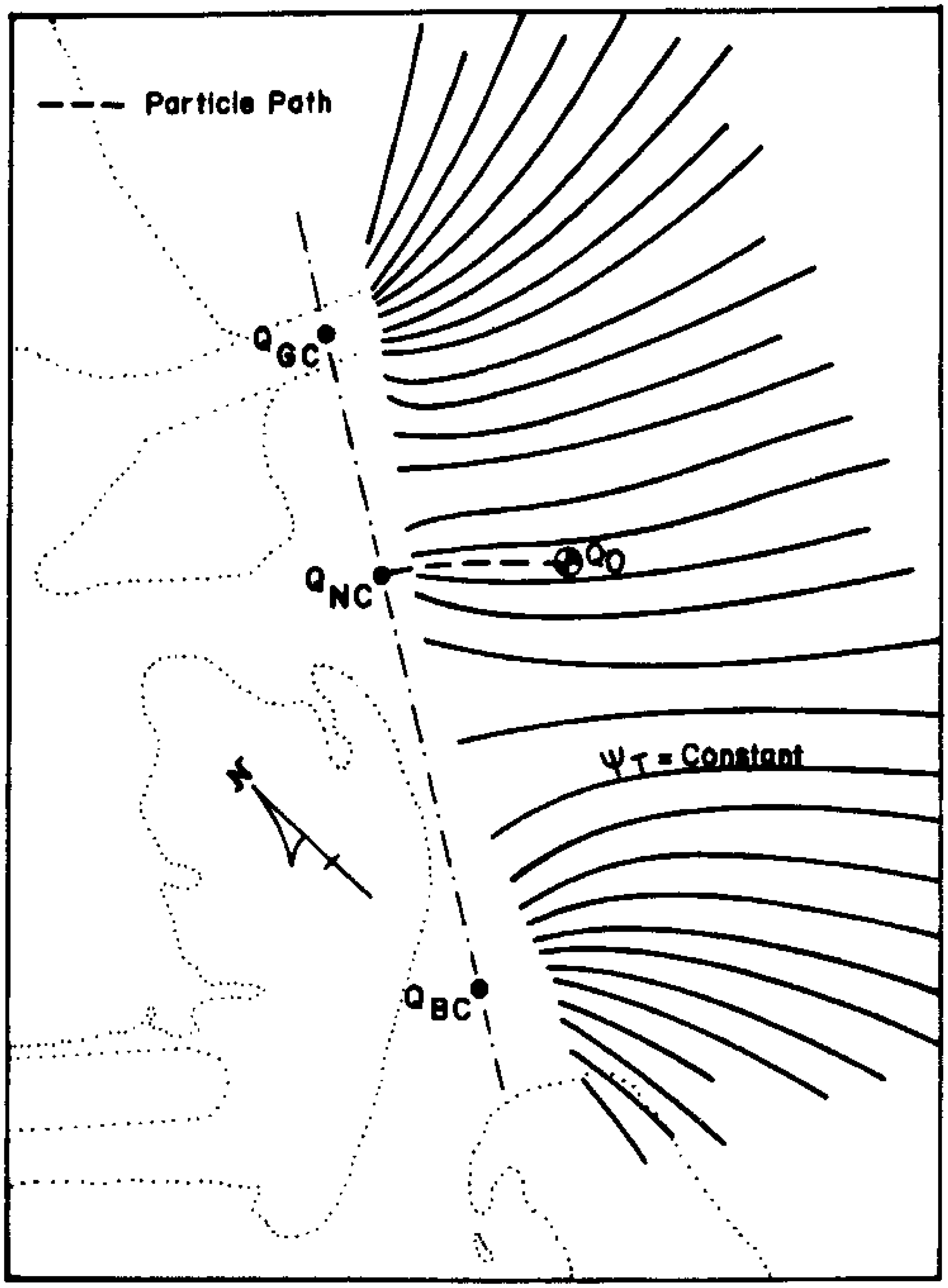

FIGURE 3

Flow pattern generated by three inlets (flooding) and outfall

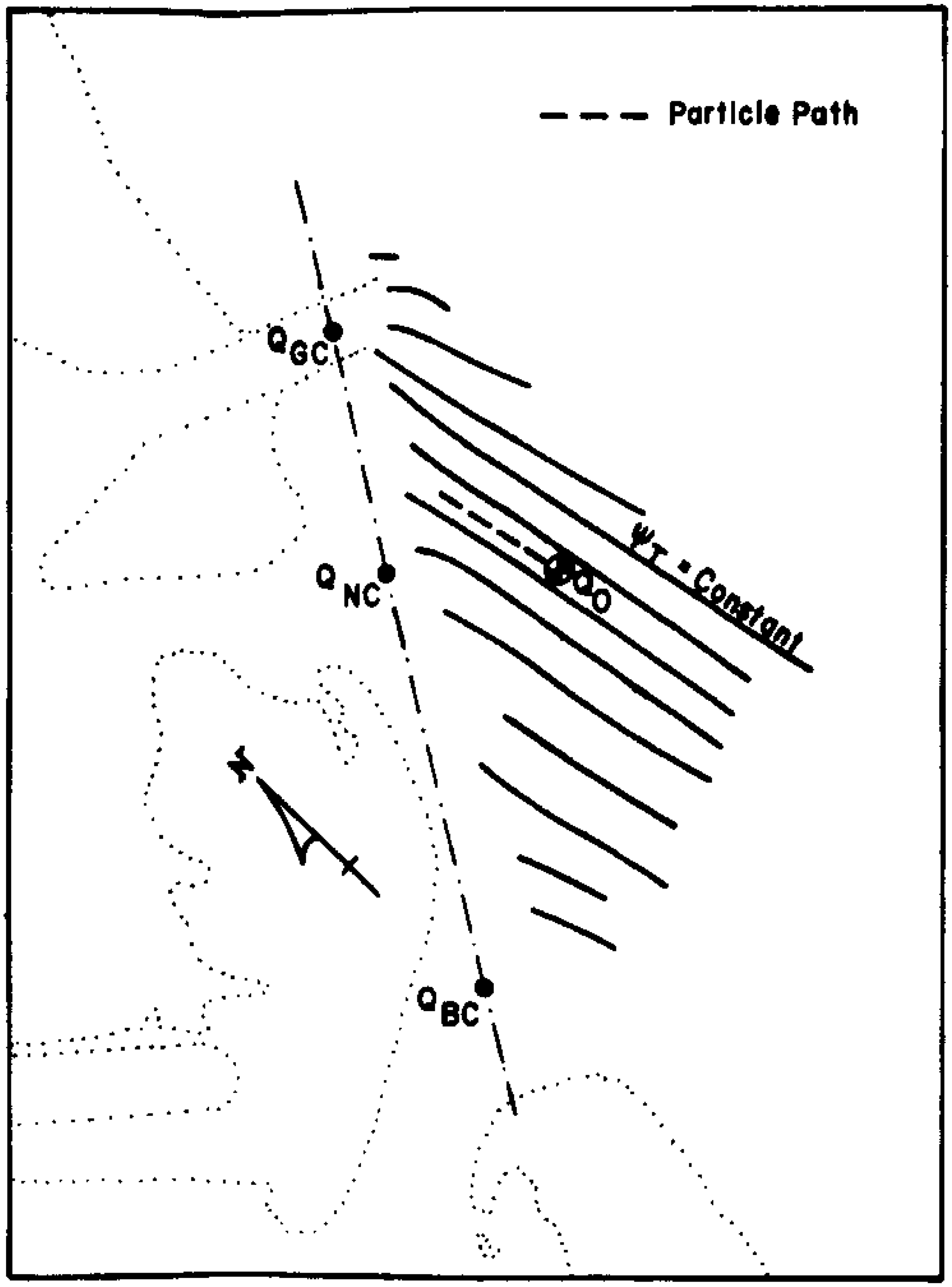

FIGURE 4

Flow pattern generated by three inlets (flooding), outfall, and .35 k uniform north flow

The comparitive strength of the drawing force of the inlets is readily observable in Fig. 3. The streamline spacing is a direct measure of the flow rates. The tighter the streamline pattern, the greater the flow rate. Therefore, the larger flow rate, and hence, the greater influence of Government Cut and Bear Cut compared to Norris Cut, is quite noticeable.

With the addition of the northward .35 k uniform current (see Fig. 4), the streamline pattern alters greatly. It is clearly evident that the coastal currents have a pronounced effect on the flow pattern. The streamlines follow a near northerly direction at the outfall as a result of the northerly coastal current. As the flow approaches the coast, the streamlines become distorted toward the west due to the sink effect of the nearby inlet. A similar flow pattern would exist for a southerly current due to the location of Bear Cut.

EFFLUENT PARTICLE MOVEMENT

The kinematic model gives an understanding of the spatial distribution of the flow in the study area. However, augmenting temporal information is necessary for a more complete understanding of effluent movement. Therefore, efforts were made to follow a particle of effluent in space and time after it surfaces at the outfall terminus. This was done by applying Eq. 2) directly to the streamlines generated by the kinematic model in Figs. 3 and 4. With this relationship, two points on the streamline will yield the velocity components (u, v) along the streamline. The particle is assumed to flow as the surface current; therefore, u and v are the components of the particle's velocity in the X and Y directions, respectively. By selecting a time interval (Δt) small enough to minimize inaccuracies incurred by the curvature of the streamline, these velocities can yield particle displacements (S) in the X and Y directions, using:

$$S_X = \int u dt \approx u(\Delta t)$$
$$S_Y = \int v dt \approx v(\Delta t). \qquad 12)$$

Therefore, the particle's path can be charted by registering its displacements after each time interval. The path is then known both in space and time.

This technique was used for Cases 1 and 2 with the first interation taken on an effluent particle at the outfall. The particle's progress was charted for each Δt. The results of this iterative process are shown in Figs. 3 and 4 as dashed lines. These calculations predict that an effluent particle will cover almost half the distance between its origin, the outfall, and Government Cut in one hour when the inlets are flooding and a .35 k northward coastal current exists (Case 2). When no uniform flow is present (Case 1), the effluent particle will enter Norris Cut in approximately four-and-one half hours.

It can then be stated that the effluent emanating from the ocean outfall is within the area of influence of the nearby inlets. When conditions exist as presented in Cases 1 and 2, the effluent can predictably enter the inlets.

The results obtained from the kinematic model and the effluent particle tracing were interesting and supplied impetus for the expansion of the project. However, the limitations of plotting stream functions for solving this problem became obvious early. The procedure was found to be very lengthy and tedious. New data and mathematical errors usually required a complete repetition of the stream function plots which took much time to generate. The data input was restricted to use of a square wave tidal cycle, and inherent weaknesses in the plotting technique did not permit the particle to be traced to the shoreline or into the inlets. The combination of these limitations and the desire to test additional cases lead to the generation of a computerized version of the stream function model.

PARTICLE TRAJECTORY COMPUTER PROGRAM

The techniques and equations used in the kinematic model and the effluent particle tracing were adapted to form a computer program. This program will essentially repeat what was previously done by hand but at a higher degree of accuracy and with a great deal more flexibility.

The reference system was converted to a Cartesian coordinate system. The reference axis is oriented such that positive Y is to the north and positive X is to the east. The origin of the axis system is located such that the coordinates of the inlets are as depicted in Fig. 5. Equation 11) is now rewritten for this system as:

$$\begin{aligned}\Psi_T = &- \frac{Q_{BC}}{\pi} \text{ arc tan } \frac{(X_P - X_{BC})}{(Y_P - Y_{BC})} - \frac{Q_{NC}}{\pi} \text{ arc tan } \frac{(X_P - X_{NC})}{(Y_P - Y_{NC})} \\ &- \frac{Q_{GC}}{\pi} \text{ arc tan } \frac{(X_P - X_{GC})}{(Y_P - Y_{GC})} + \frac{Q_0}{2\pi} \text{ arc tan } \frac{(X_P - X_0)}{(Y_P - Y_0)} \qquad 13) \\ &+ MX_P \cos\theta - MY_P \sin\theta.\end{aligned}$$

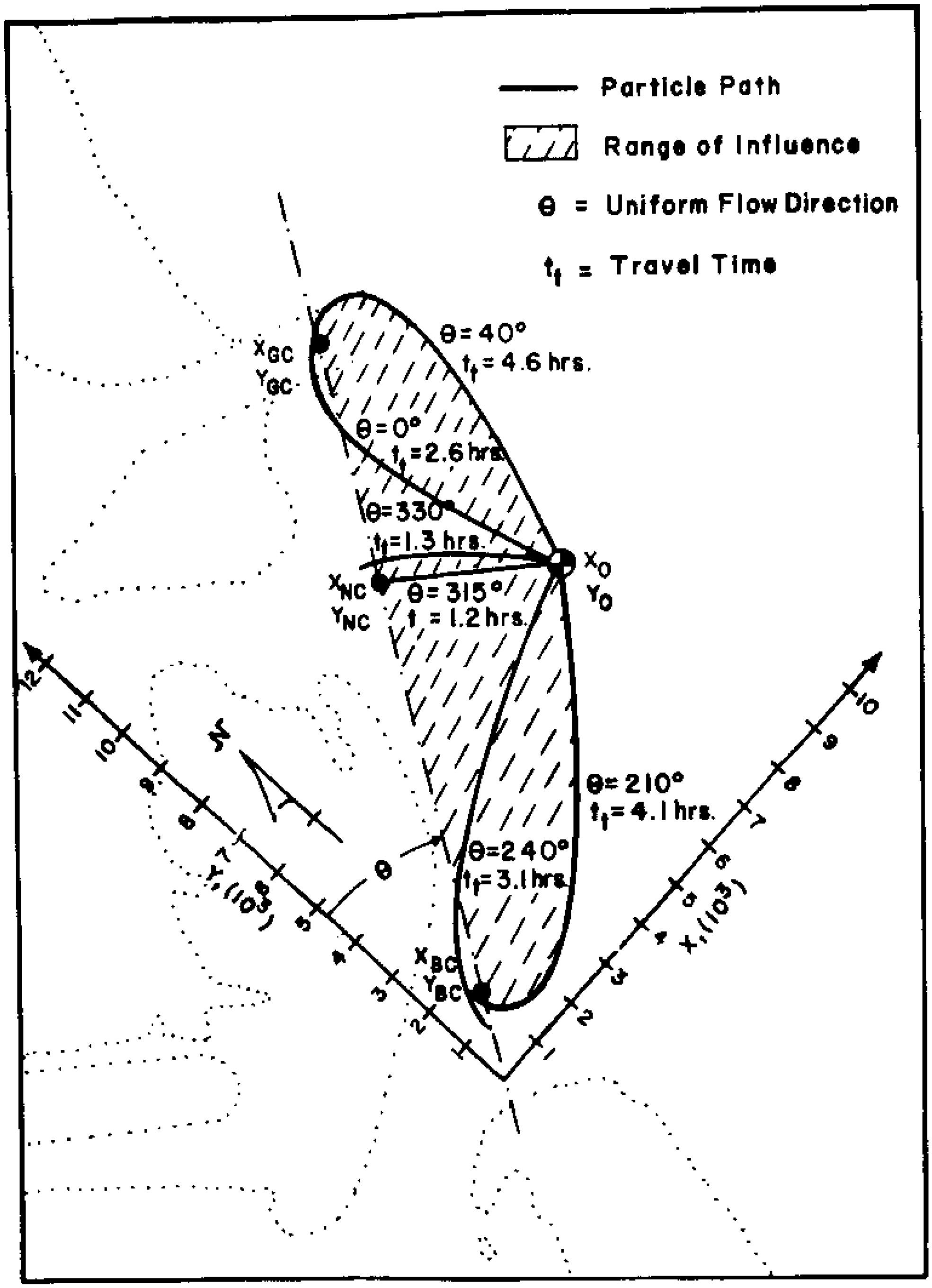

FIGURE 5

Predicted effluent particle trajectories

The inlet outfall locations are fixed with X_{BC} and Y_{BC} for Bear Cut, X_{NC} and Y_{NC} for Norris Cut, X_{GC} and Y_{GC} for Government Cut, and X_O and Y_O for the outfall. These are illustrated on Fig. 5. X_P and Y_P are the coordinates for the particle's location.

This equation then expresses the total stream function at a point (particle's location). Taking the derivatives of Eq. 13) with respect to X and Y (see Eq. 2) yields:

$$u = M \sin\theta - \frac{Q_{BC}(X_P-X_{BC})}{\pi[(Y_P-Y_{BC})^2 + (X_P-X_{BC})^2]} - \frac{Q_{NC}(X_P-X_{NC})}{\pi[(Y_P-Y_{NC})^2 + (X_P-X_{NC})^2]} - \frac{Q_{GC}(X_P-X_{GC})}{\pi[(Y_P-Y_{GC})^2 + (X_P-X_{GC})^2]} + \frac{Q_O(X_P-X_O)}{2\pi[(Y_P-Y_O)^2 + (X_P-X_O)^2]},$$

$$v = M \cos\theta - \frac{Q_{BC}(Y_P-Y_{BC})}{\pi[(Y_P-Y_{BC})^2 + (X_P-X_{BC})^2]} - \frac{Q_{NC}(Y_P-Y_{NC})}{\pi[(Y_P-Y_{NC})^2 + (X_P-X_{NC})^2]} - \frac{Q_{GC}(Y_P-Y_{GC})}{\pi[(Y_P-Y_{GC})^2 + (X_P-X_{GC})^2]} + \frac{Q_O(Y_P-Y_O)}{2\pi[(Y_P-Y_O)^2 + (X_P-X_O)^2]}. \qquad 14)$$

Particle trajectories were computed by solving for the displacements (S_X, S_Y) with Eqs. 12) and 14) using an iterative technique and then summing these displacements with time. A time interval (Δt) of 10 minutes was found to produce fairly smooth trajectories. With this interval it took 37 iterations to cover the complete flood tide cycle (6.2 hours).

Some representative particle trajectories are plotted on Fig. 5. These plots were generated by placing the particle displacements at every 10 minutes as predicted by the computer program on the reference system. The result is a pictorial representation of a particle's trajectory originating at the outfall and, in the cases illustrated, traversing its way toward one of the inlets. Numerous cases have been run using the values for the volumetric flow rates (Q's) and the uniform flow velocity (M for Case 2) listed in Table 2. The uniform direction angle θ was varied in each case. By varying θ every 5 degrees, a range of influence was found. This range of influence represents the range of angles over which the uniform flow can vary and still bring the effluent within the influence of, and thereby entry into, one of the inlets. It was found that with a uniform flow velocity of .35 k, the range of influence is between 210° and 40° (Fig. 5).

There is no rigid boundary (shoreline) in the program; hence, the traces curve around the representative inlets in some of the trajectories. The particle travel time (t_t) from the outfall to the inlet is measured at the closest position of the trajectory to the inlet. The travel times for all of the particle trajectories in the range of influence are less than the flood tide time of 6.2 hours. Therefore, the effluent has sufficient time to get to and enter the inlets before the tide shifts to ebb. In fact, if a typical inlet current speed of 1 k over a 1 nautical mile distance between ocean and bay is considered, there is sufficient time for the effluent particles to reach the bay before the tide shifts.

MODEL EVALUATION

Dye tracing experiments were undertaken to obtain field data for use in evaluating the model's ability to accurately determine the effluent's trajectory and thereby determine the validity of the predictions. Six experiments were conducted over a six day period.

Five of the experiments used fluorescein dye as a tracer, and the remaining was conducted with rhodamine WT.

These dye studies of the effluent supplied detailed, tangible evidence of the effluent's path and destination. They also afforded the opportunity to collect chemical and biological samples which will be discussed later on in this paper. These experiments were timed in an attempt to observe the effects of the flood tide on the effluent. Therefore, the daily activities started at the beginning of flood tide.

The prime observational and sampling platform for all experiments was a 22 foot Aqua-sport with twin 50 h.p. outboard engines.

<u>Fluorescein Dye Experiments</u>

Fluorescein dye was used as a means of tagging the surface movements of the effluent. The dye, obtained in powder form, was mixed in quart jars the day before each experiment. It was found that a mixture of approximately one-third pound of dye for one gallon of water gave a solution that, when poured into the outfall boil, produced a suitable dye patch for visual tracking.

To mark the effluent, one quart of this dye solution was poured into the boil at the start of each experiment. On several experiments, this was repeated such that more than one patch was generated. The subsequent dye patch(es) was then followed by boat. The greenish yellow fluorescence of fluorescein happens to fall in the region of maximum sensitivity of the eye (Turner, 1968). Hence, this dye was a good choice for following visually. The dye could be seen for approximately one-half mile. Depending on diffusing and mixing conditions, it could be followed for one-half to three-quarters of a mile before it became too difficult to distinguish from the surrounding waters. The course of the patch was registered by taking sextant sightings at spaced time intervals on three known shore locations. When the patch diffused to the point where it was difficult to observe, it was seeded by pouring approximately one-half pint of the dye solution on the most concentrated portion of the plume. The operation of marking the plume, following the patch, sighting its location, and seeding the fading patch when necessary was continued until the end of the test day. When more than one was started at the boil, the task became one of repeatedly sighting each patch in order to trace the separate paths.

The sightings for location were recorded as stations. Both the sextants' readings and the time were entered in the record. These stations were also used as the points where many chemical and biological samples were taken.

Wind measurements were made by a recording anemometer located on the roof of the Tropical Atlantic Biological Laboratory (TABL) (see Fig. 1). These data are presented in Table 3.

Fluorescein dye proved to be a most convenient and economical way to trace the surface and, hence, the effluent plume. The dye traces made on several different days are presented as Figs. 6 through 9. On all these traces the strong dependency of the dye plume direction on the wind direction is consistently evident. On April 3, 1972 (see Fig. 6), the wind had a southeasterly direction as did the initial dye plume. The dye plume is seen to have turned toward Bear Cut as it came within the influence of the Cut. Two dye patches were established on this day. The variance of the two

TABLE 3

Wind Data* for Days of Dye Survey

Date	Time	Wind Direction (°)	Wind Speed (mph)
3 April 1972 experiment started 0700 (EST)	0500	340	8
	0600	340	9
	0700	340	8
	0800	350	9
	0900	350	8
4 April 1972 experiment started 0724 (EST)	0500	115	9
	0600	90	<8
	0700	105	9
	0800	100	10
	0900	100	10
5 April 1972 experiment started 0745 (EST)	0600	105	<8
	0700	90	<8
	0800	50	<8
	0900	105	<8
	1000	90	<8
	1100	100	<8
	1200	150	<8
6 April 1972 experiment started 0705 (EST)	0500	310	<8
	0600	305	<8
	0700	310	<8
	0800	320	8
	0900	310	8
	1000	320	9
	1100	315	8
7 April 1972 experiment started 0815 (EST)	0600	150	<8
	0700	140	<8
	0800	150	<8
	0900	210	<8
	1000	200	<8
	1100	200	8
	1200	145	8
	1300	150	9
5 May 1972 experiment started 0950 (DST)	0800	320	4
	0900	320	4
	1000	340	2
	1100	360	3
	1200	30	4
	1300	40	8
	1400	35	9
	1500	60	9
	1600	50	9

*Data from anemometer and vane at TABL

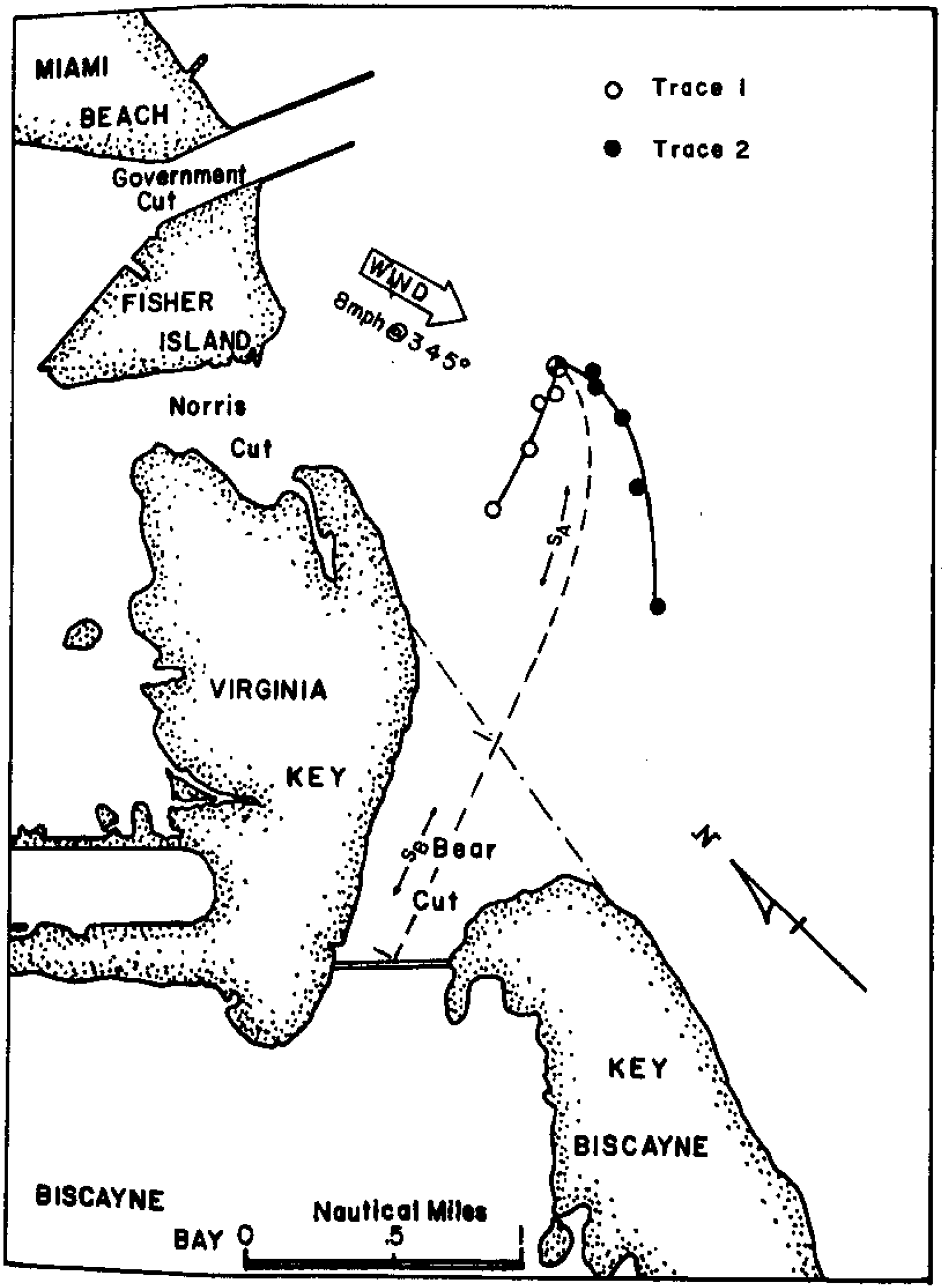

FIGURE 6

Dye survey for April 3, 1972

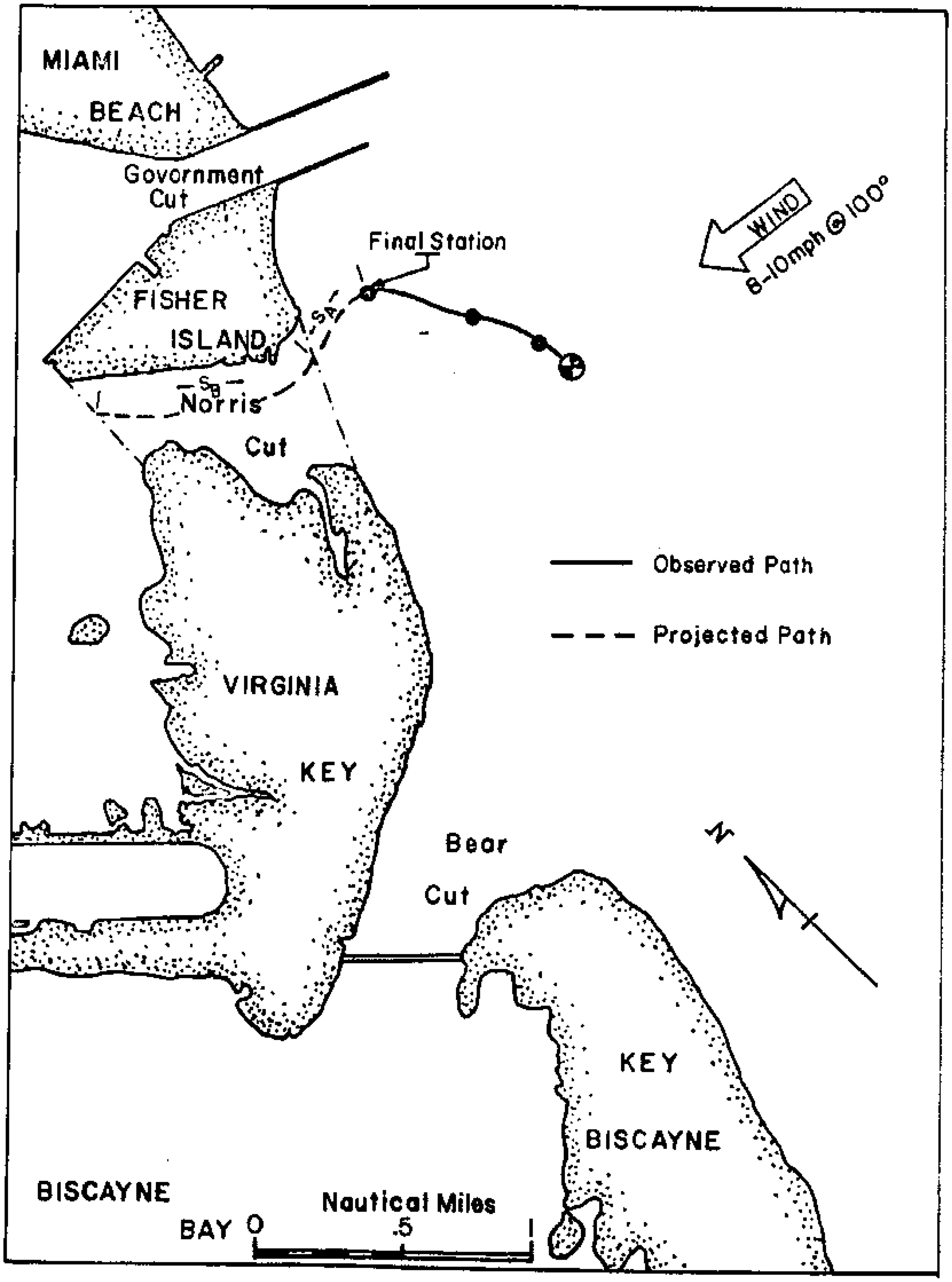

FIGURE 7

Dye survey for April 4, 1972

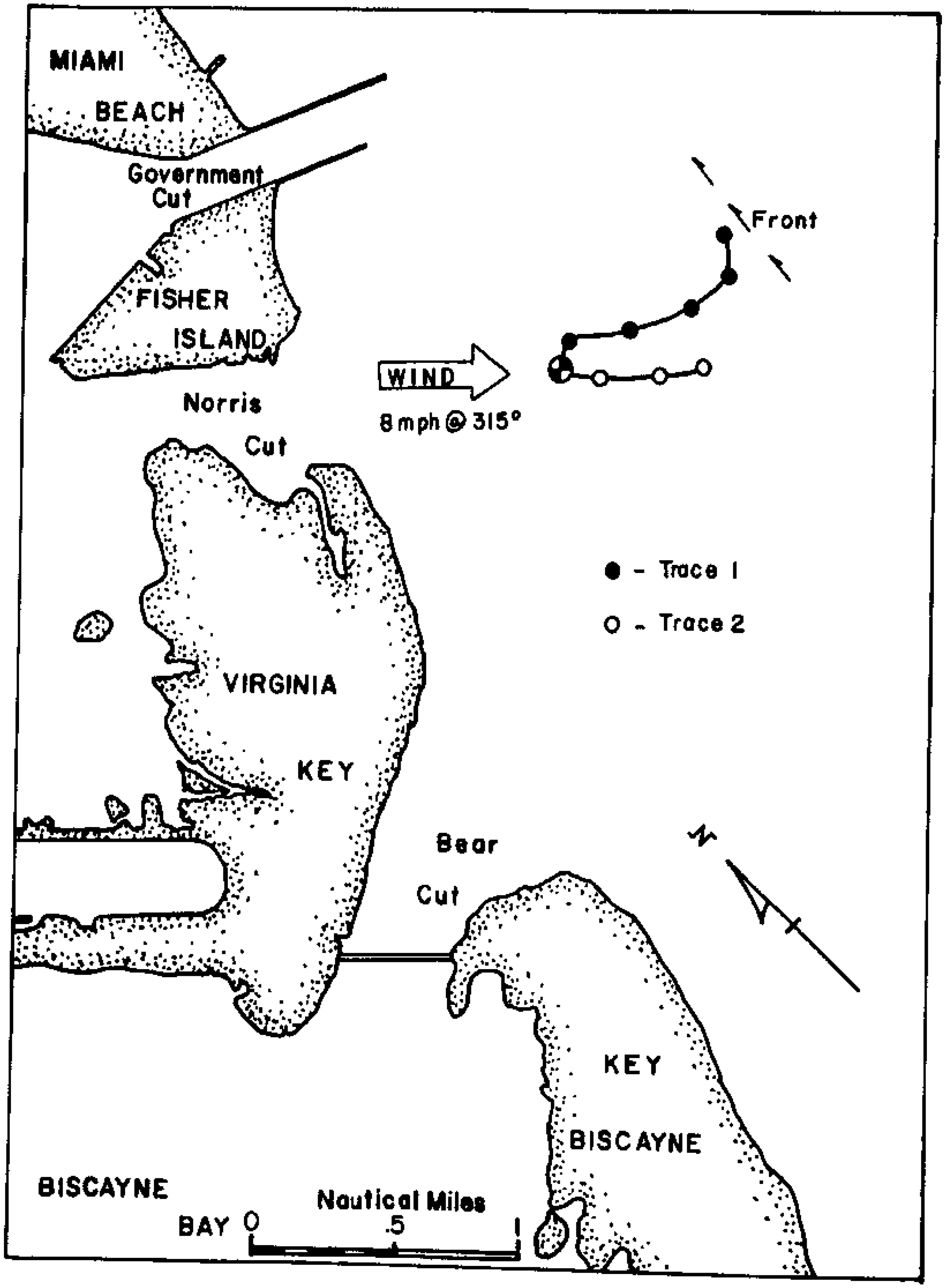

FIGURE 8

Dye survey for April 6, 1972

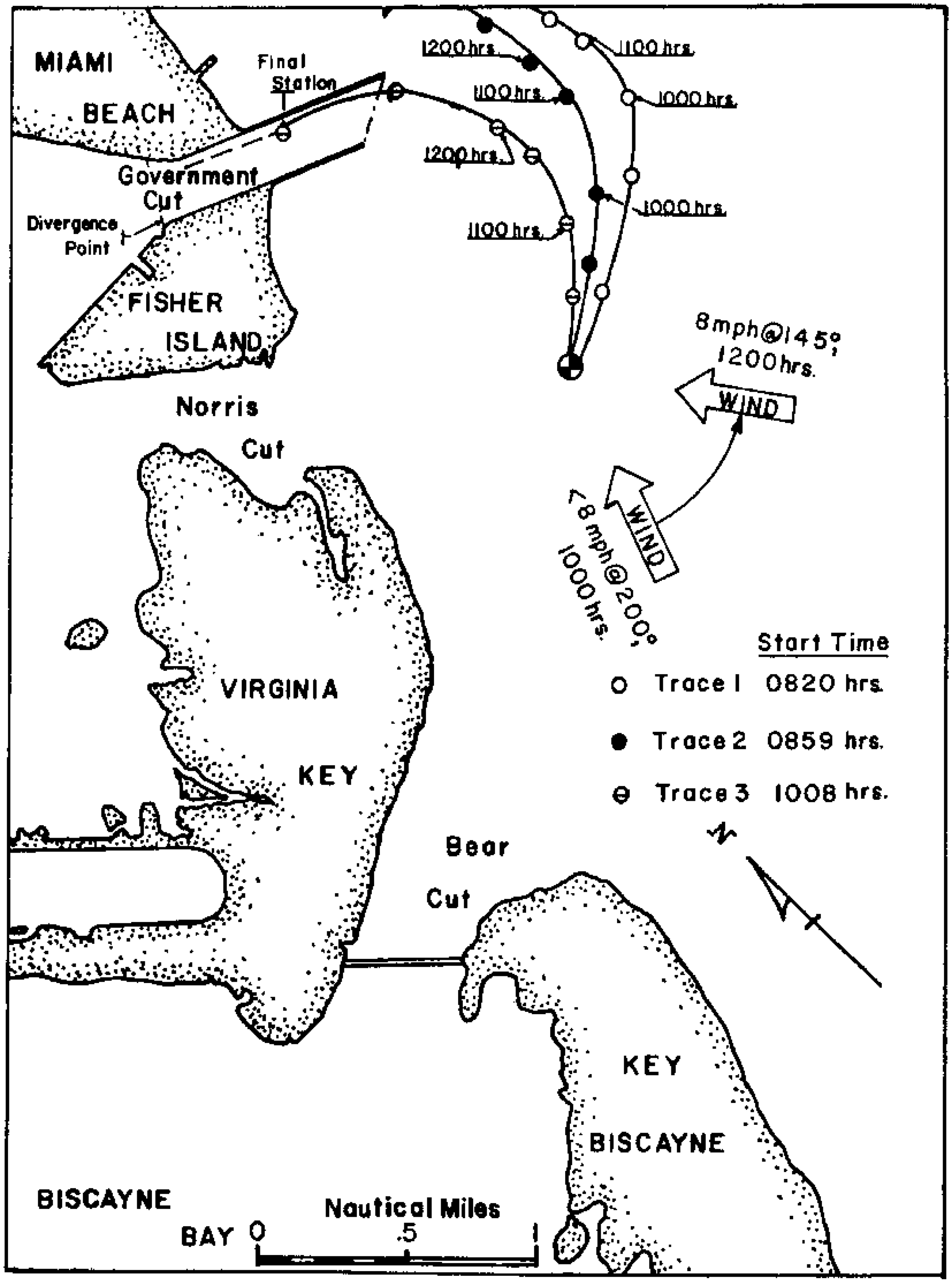

FIGURE 9

Dye survey for April 7, 1972

separate dye traces is a result of the interaction of the outfall, considered as a source, with a uniform flow. Initially the dye moves radially from the center of the source (boil) until the strength of the radial flow decreases in magnitude in comparison to the prevailing current. At this point, the dye patch will follow the current.

An estimate of the particle travel time (t_t) from the outfall to Bear Cut was made using the equation:

$$t_t = \frac{S_A}{V_A} + \frac{S_B}{V_B} \qquad 15)$$

where S_A = particle path distance from the outfall to the mouth of Bear Cut,

V_A = particle velocity from the outfall to the mouth of Bear Cut,

S_B = particle path distance from the mouth of Bear Cut to the Bear Cut bridge, and

V_B = particle velocity from the mouth of Bear Cut to the Bear Cut bridge

as seen in Fig. 6. V_A is the mean of the two dye patch velocities. The value used for V_B was that of the mean velocity over an average flood cycle. This average flood cycle was derived from several weeks of data gathered by the University of Miami in 1971. S_A and S_B are measured along the projected path. Equation 15) estimates that the effluent reached the Bear Cut bridge in approximately 3.5 hours. Since this is well within the time duration of the flood cycle, the effluent not only entered Bear Cut but also had enough time to enter Biscayne Bay. This finding and those to follow give strength to the belief that the effluent and its constituents enter the bay. Measurements presented later on will help establish these constituents qualitatively and quantitatively.

On April 4, 1972, the winds were out of the east. The plume's trajectory displayed a westerly component in response to this wind. It also had a northern component (see Fig. 7). This northern component is probably due in part to the wind set-up at the coast due to the presence of a shoreline and shallows. Equation 15) was modified; it now reads:

$$t_t = \frac{S_A}{V_A} + \frac{S_B}{V_B} + 1.9 \text{ hours} \tag{16}$$

where S_A and V_A are measured from the final station to the mouth of Norris Cut. The value for V_A was measured at this station using a drift bottle. S_B and V_B are measured from the mouth of Norris Cut to the entrance of the cut into Biscayne Bay. V_B is a mean velocity over an average flood cycle which was measured by McGuiness (1968). Again S_A and S_B are measured along the projected path (see Fig. 7). The dye took 1.9 hours to travel from the outfall to the final station. Hence, the estimated travel time of the effluent from the outfall to Biscayne Bay was found to be 3.75 hours.

On April 6, 1972, an offshore wind moved the plume eastward until it intersected a discontinuity in water properties (color, clarity, current speed, etc.) associated with what appeared to be an extreme westward location of the Florida Current surface front. After entering this frontal region, the dye was rapidly carried to the north (see Fig. 8).

From the data gathered on April 7, 1972, a comparative time analysis between the wind and the progression of the dye plumes clearly shows the rapid nature of the wind response for shallow waters. The wind altered its speed and direction during this experiment in which three traces were formed (see Fig. 9). Trace 1 was started at 0820 hours and moved out from the boil in an ENE direction. The wind at this time was southerly at less than 8 m.p.h. Between 1000 and 1100 hours, the wind speed increased from the SSW; and Trace 1 responded by shifting to align itself with the wind. As the dye plume proceeded further downstream, it continued to shift, probably in response to the flooding of Government Cut. When the wind direction changed between 1100 and 1200, Trace 1 was unaffected--most likely because it was already moving in the general direction of the wind and had gained enough momentum to shoot past Government Cut.

Trace 2 was started at 0859 and moved out from the outfall in an ENE direction. As the wind increased in speed, Trace 2 aligned itself with the wind direction. When the wind direction changed, the dye plume shifted again and followed a similar pattern as Trace 1.

Trace 3 was started at 1008 and proceeded to follow an ENE direction while it was close to the outfall. As the wind changed direction, Trace 3 turned toward the north and headed for Government Cut. As it neared the cut, the dye plume increased in speed and was carried into Government Cut with the flood current. It took 2 hours and 35 minutes (2.6 hours) for the dye to reach the mouth of Government Cut from the outfall. It is estimated that the effluent reached the divergence point of the cut (see Fig. 9) 3.3 hours after surfacing in the boil. This data again points out that the effluent's behavior is strongly affected by the tides through the cuts, the prevailing coastal current, and, in particular, the wind speed and direction.

Fluorometric Measurements

On May 5, 1972, rhodamine WT dye and a Turner fluorometer were used to follow and map the effluent plume. On this day, a joint effort by the University of Miami (U/M), NOAA, and the Environmental Protection Agency (EPA) produced conclusive evidence of the entry of the sewage plant effluent into Biscayne Bay.

A 30 gallon drum of 20% solution rhodamine WT dye (0.2 rhodamine WT and 0.8 ethylene glycol alcohol, density 1.2) was situated such that its contents could be pumped into the plant effluent just before final chlorination and entry into the outfall pipe. The pump was started at 0845 and the dyed effluent surfaced at 0950. This time was chosen to be close to the start of flood tide in the inlets. The predicted time of slack water between ebb and flood tide in Government Cut on May 5, 1972, was 0953. The dye was pumped into the system continuously for six hours. During fluorometric measurements, this rate of input was 3.4 gallons per hour (g.p.h.). In this manner, the plant effluent was tagged for the full flood tide.

The same boat and pumping system, as will be described for the salinity-temperature measurements (see Fig. 11), was used for the fluorometry runs, with the sensor and recorder now being the fluorometer and a Rustrak recorder, respectively. The fluorometer was fitted with a continuous-flow door which received sample water constantly from the probe via hosing and pump. The fluorometer's measurements, in the form of 0-1 milliamp signals, were recorded on the Rustrak chart recorder.

The fluorometer used in the experiment was a G. K. Turner Model III, which can measure concentrations as low as 0.01 parts per billion (p.p.b.). Reference light aperature settings of 1x, 3x, 10x, and 30x were used to detect concentrations ranging from 0.01 to 30 p.p.b. The instrument was calibrated before and after the experiment. The fluorometer showed no drift with the aperature setting most used during the test day (aperature setting 10x was used for concentrations of 0.2 - 3 p.p.b.). The other aperatures showed a maximum variance of 6%. All of the measurements showed the instrument's response to be near linear through each aperature setting.

Some three-and-one-half hours after the dye had initially surfaced, the dye plume was judged to be well established in a quasi-stable state. Repetitive traverses, marked with sextant positioning, were then made across the axis of the plume at numerous downstream locations (see Fig. 10). The chart from the Rustrak recorder was then referred to a calibration chart to determine concentration values.

Water samples were taken at areas of high dye concentration for analysis in the laboratory. These concentrations were too high to be measured in the field and, therefore, were diluted in order to register on the fluorometer. Some were taken at a plant station along the pipe just as they left shore. These samples were used to determine the initial dilution or dilution from the plant to the boil. Other samples were taken in the boil to complete the contouring picture.

After the dye plume had been mapped with the repetitive traverses, the boat was docked at the Rosenstiel School of Marine and Atmospheric Science (RSMAS) (see Fig. 1). The fluorometer and the recorder were

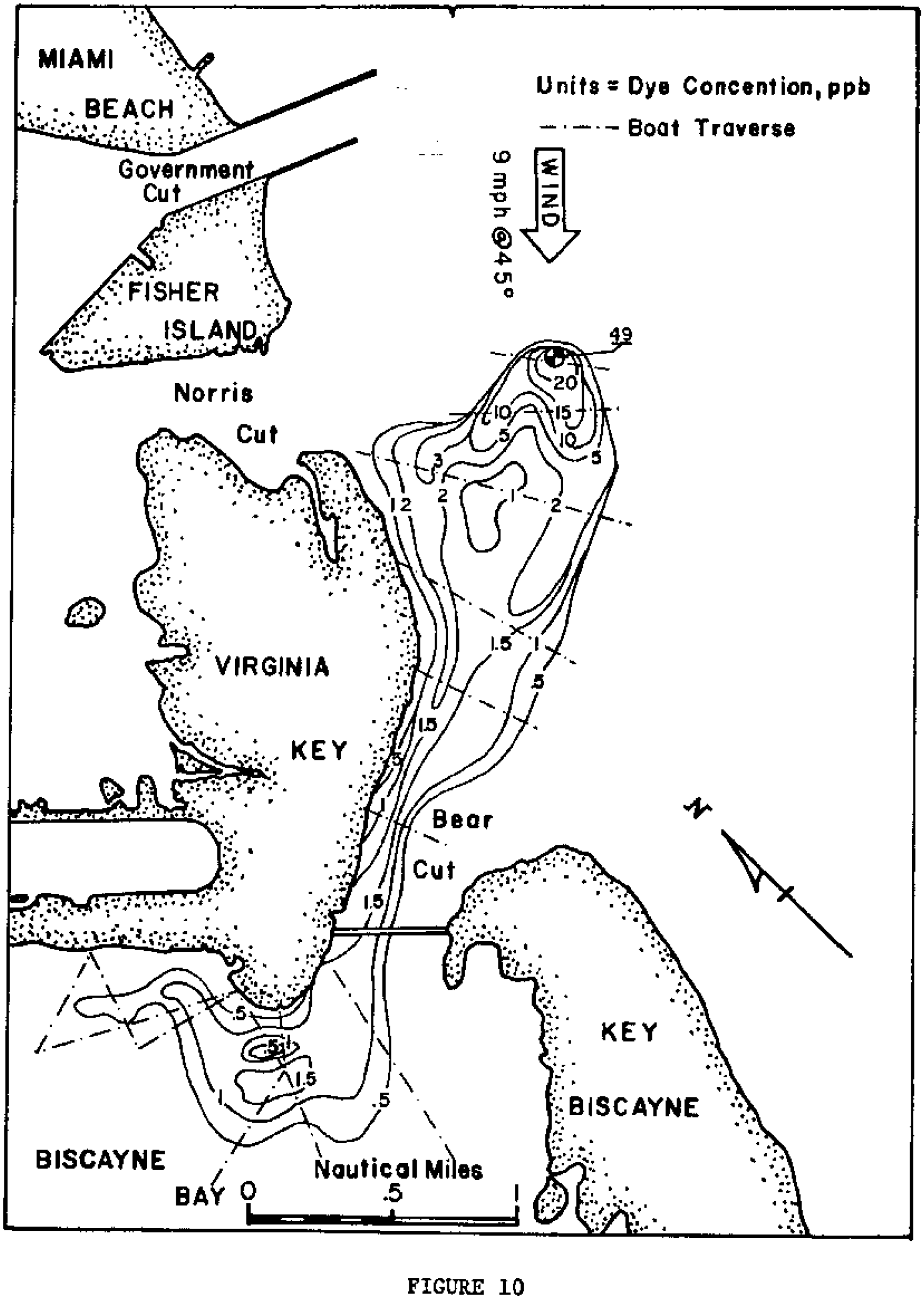

FIGURE 10

Dye survey for May 5, 1972

left in operation in order to monitor the exodus of the dye on ebb tide and observe whether any dye reentered the inlet on the following flood tide. The data generated by this experiment will be presented in the water quality analysis section of this paper.

The continuous reading, flow-through fluorometer produced data that was highly conducive to contour plotting. Figure 10 gives an extremely clear, graphic presentation of the effluent plume. In addition, the fluorometer readings have a quantitative validity when used to represent effluent concentrations since the dye thoroughly tags the effluent.

Wind influence was again found to be important to the initial direction of the plume. During this experiment, the wind was out of the northeast at 8-9 m.p.h. Figure 10 shows the dye plume headed toward the southwest aligned with the wind. This brought the dye plume into the influence of the tidal flood currents of Bear Cut. Hence, the dye plume was carried through Bear Cut and into Biscayne Bay.

The leading edge of the dye plume was observed to reach the bridge 3 hours and 17 minutes (3.28 hours) after it surfaced at the outfall. The current speed measured at Bear Cut bridge with a drift bottle was found to be approximately 1.65 k. This would carry the dye into Biscayne Bay 3 hours and 35 minutes (3.58 hours) after surfacing. From these measurements, it is projected that the dyed effluent reached the mouth of the inlet (ocean side) 2 hours and 54 minutes (2.9 hours) after surfacing.

The dye concentration in the boil had an average value of 49 p.p.b. This high concentration is seen to diminish rapidly near the boil (e.g., 60% in the first 400 feet). After leaving the initial mixing zone of the boil, the concentration contours became longitudinally oriented along the axis of plume travel. The contour lines are analogous to the equipotentials of a source in a uniform flow.

It is seen that the bay received a high concentration of 1.5 p.p.b. With the boil's average reading of 49 p.p.b., this would give a horizontal dilution of 32.7 to 1. Samples taken in the sewage plant just before entry into the outfall pipeline had an average concentration of 405 p.p.b. Therefore, the vertical or initial dilution is computed to be 8.3 to 1; and the overall dilution from the plant to the bay is 270 to 1.

Samples taken for inorganic phosphate content at the plant and in the boil gave a vertical dilution ratio of 10 to 1, which is in good agreement with the ratio achieved with dye.

Comparative Analysis

Data gathered in the field during these dye experiments were inserted into the particle trajectory computer program, and the results of each method were compared. Surface current measurements were obtained near the outfall by use of a drift bottle. These values were used as uniform flow values (coastal current) in the computer program (used Q values as listed in Table 2). These measurements will deviate somewhat from the true uniform flow since 1) the inlet tidal forces did exert their influence in the area of measurement, and 2) the drift bottle had some sail area. However, the sail area was small, and the effects of the inlets were minimal in the measurement area. Therefore, the measurements are a close representation of the uniform flow.

Table 4 lists the results of the particle trajectory program runs using field data gathered on the days that dye was followed entering Government Cut (April 7, 1972) and Bear Cut (May 5, 1972) and also the day it was traced approaching Norris Cut (April 4, 1972.) It is observable from a comparison of the results of the field and computer work presented that the computer model was able to duplicate the field findings quite well. The Bear Cut computer prediction had the largest difference (13.2%) from the field data in travel time to the inlets.

This good agreement establishes confidence in the model. From these results, it is seen that the assumptions and modifications made for simplicity did not interfere with the program's ability to produce meaningful and accurate predictions. In fact, attempts made to insert a sinusoidal sink rate (Q) and a sloping bottom failed to improve on the results displayed in Table 4.

WATER QUALITY ANALYSIS

During the dye tracing experiments, numerous parameters were measured in and out of the plume. These measurements served not only to trace the plume but also to determine some of the sewage treatment plant's input to the coastal and bay waters. These waters are classified as Class III by the state of Florida. Class III waters are those which are to be used for recreational purposes, including such body contact activities as swimming and water skiing, and for the maintenance of a well-balanced fish and wildlife population (Rules of Department of Pollution Control, Chap. 17-3). The state has established quality standards to be met to maintain these waters as Class III. One standard states that the coliform bacteria

TABLE 4

Comparison of Field and Computer Results

	Field Measurements			Computer Results	
Entry	Current Speed**	Current Direction**	Measured Travel Time*	Predicted Travel Time	% Difference
Bear Cut	.31 k	225°	2 hr. 54 min***	3 hr. 17 min.	13.2%
Government Cut	.36 k	20°	2 hr. 35 min.	2 hr. 45 min	6.5%
Norris Cut	.13 k	330°	2 hr. 24 min.	2 hr. 20 min.	2.8%

*Travel time measured between outfall and mouth of inlet

**Measured near outfall

***Projected from measurements

group shall not exceed 1,000 per 100 ml on a monthly average, nor exceed 1,000 per 100 ml on 20% of monthly samples, nor exceed 2,400 per 100 ml on any one day (Rules, Dept. of Pollution Control, Chap. 17-3). This standard will be referred to when discussing coliform bacteria measurements made. Another standard establishes a maximum level on the turbidity of these waters. The particulate matter adds directly to the turbidity of the waters. Nutrients encourage algal growth which in turn increases the turbidity.

The great number of parameters measured denotes an attempt to make the most efficient use of the boat time available. They also supplied the author with a wide range for familiarization with sewage outfalls in general. The data gathered is not extensive in any particular parameter but offers a broad area for study and understanding of ocean outfalls of this type.

Salinity and Temperature

The effluent of the treatment plant is less saline and warmer than the coastal waters. Samples taken at the treatment plant showed the effluent to have a salinity of 2 $^{o}/oo$ while coastal waters were generally 35.8 $^{o}/oo$. Temperature measurements at the boil were usually 0.8^{o}C above ambient.

Continuous measurements were made of these parameters in the study area with a Bissett-Berman Thermosalinograph Model 6600-T. This instrument consists of a control unit and a remote sensor. The control unit contains an adjustable speed chart recorder that provides a graphic record of salinity and temperature. The remote sensor measures salinity by a conductivity cell, which is temperature-compensated to an accuracy of ±0.15 $^{o}/oo$ on the ranges used. The remote sensor also contains the temperature probe which is accurate to ±0.1^{o}C.

The thermosalinograph was installed on a 22 foot Aqua-sport motorboat. The boat was specially fitted to accommodate a hydrodynamically shaped sampling probe that is affixed to the hull. The probe is connected to the remote sensor via hosing and a 12 volt (7 amp. maximum) pump (see Fig. 11). In this manner the remote sensor is constantly supplied with seawater at a rate of 5 gallons per minute. The salinity and temperature of the water are measured and then the sampled water is pumped over the side of the boat in this constant flowing system. The measurements are fed into the control unit and recorded on the chart recorder.

With the sampling probe one foot below the surface, the boat traversed the plume generated by the outfall and tagged by the dye. The stations and time were marked on the chart paper at the beginning and end of each traverse to give a distance/time relationship for computing the boat speed. With this information, horizontal (surface) contours for salinity and temperature could be drawn.

Temperature proved to be a poor means of following the effluent plume. The temperature difference existent between the boil and coastal waters disappears rapidly as the effluent mixes with the coastal waters. No temperature signature was found in the plume at a distance greater than approximately 600 feet from the boil. Salinity was found to be a better means of locating the effluent plume. A typical salinity contouring plot is presented in Fig. 12. This figure was generated from data gathered on April 3, 1972. The lowest reading in the boil was 29.6 $^{o}/oo$. Background salinity on this day was

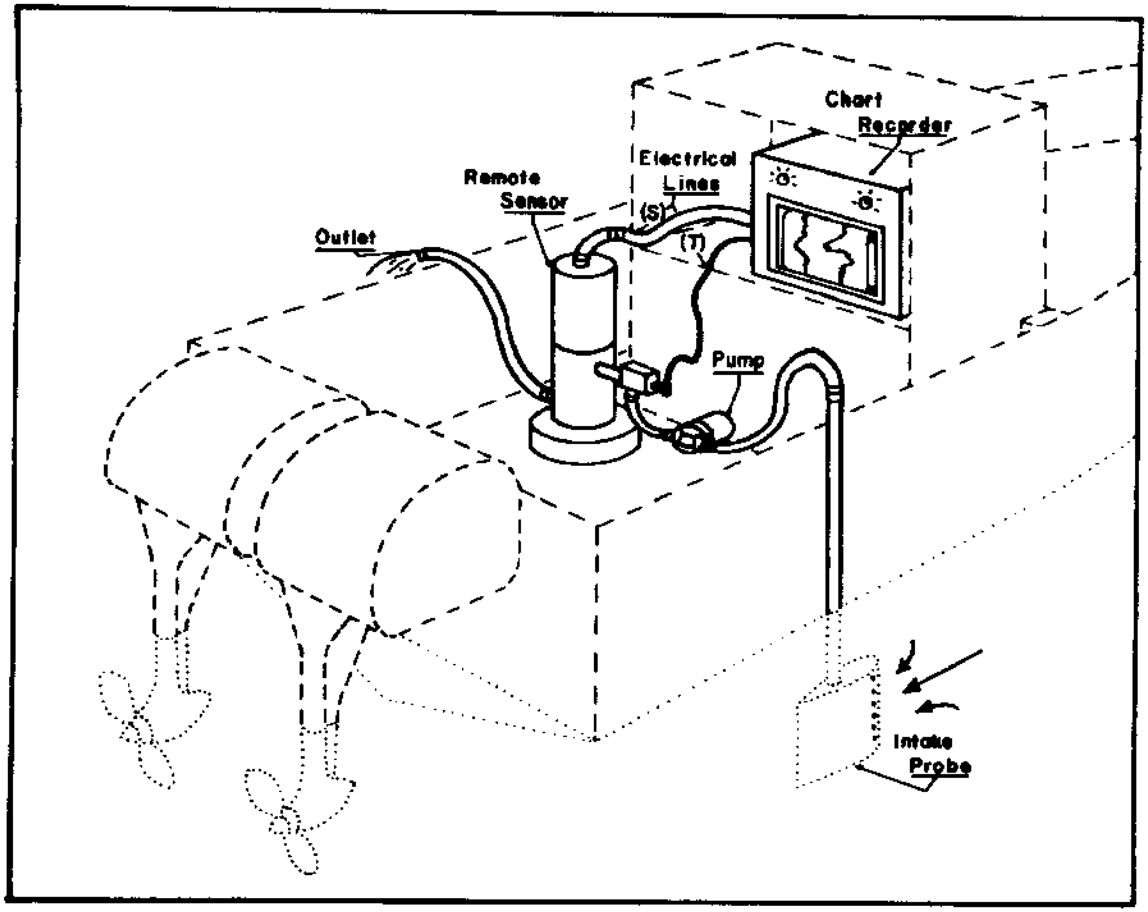

FIGURE 11

Arrangement for temperature and salinity measurements

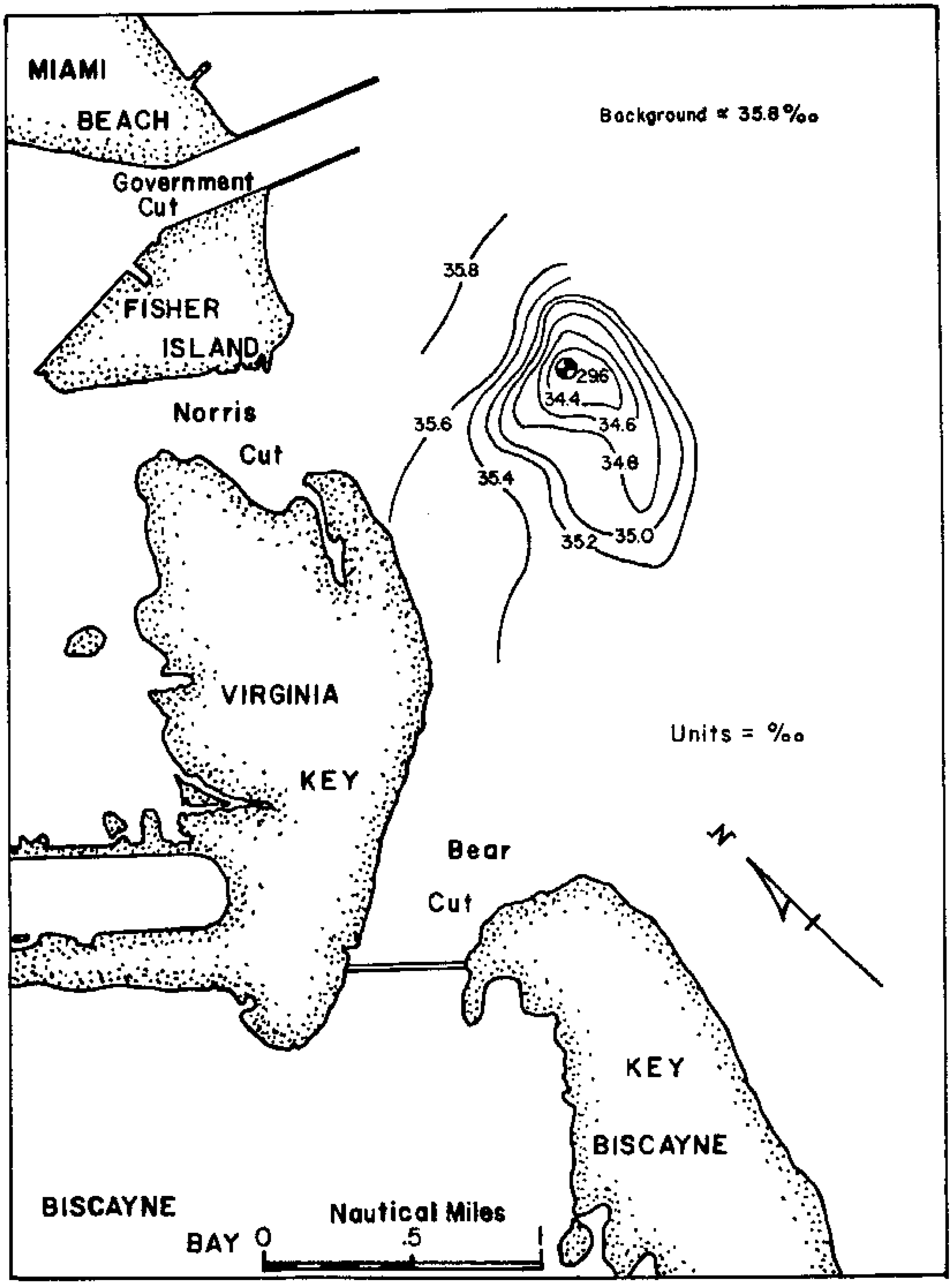

FIGURE 12

Salinity contours for April 3, 1972

35.8 $^{o}/oo$, giving a difference of 5.2 $^{o}/oo$. As the effluent is carried away from the outfall (compare with Fig. 6), the salinity increases due to the diffusion and mixing with the coastal waters. The less saline water of the outfall was still observable at a distance of 5,000 feet from the boil.

Particulate Matter

Sewage is high in organic and inorganic particulate matter. Even after treatment, the particulate content of the wastewater is discernably high. At stations along the axis of the plume, as marked by the fluorescein dye, water samples were taken to be used for particulate measurements. When collecting the samples, care was taken not to introduce particles from contact. The samples were collected in special bottles made of polycarbonate (PC). PC is a material to which particles will not adhere. Hence, with a slight agitation, all the particles in the bottle are in suspension for accurate particle measuring.

The sample bottles were returned to the laboratory, and their particle content was measured using a Coulter Counter Model T. The Coulter Counter contains a test cell that operates in such a way that sample water and electric current flow through a small orifice in the cell. When a particle from the sample water goes through the orifice, the electric circuitry sees this as an increase in resistance, which is proportional to the volume of the particle. In this way, the counter has a record of the volume and number of particles in the sample. A printer supplied with the unit prints out a record of the number of particles of particular size ranges and their volumes. The cumulative volume is the total volume of all the particles in one cubic centimeter of sample water. These readings were converted into concentrations--the units being parts per million (p.p.m.)

In these experiments, the particles measured ranged from 1 to 37 micron (mm x 10^{-3}) in diameter.

A representative day's data is presented in Fig. 13. This is compiled from water samples taken on April 6, 1972. It is observable that the particle content of the waters at increasing distances from the boil displayed a fairly consistent decreasing gradient (compare with Fig. 8). The boil produced a high reading of 4.5 p.p.m. which is 15 times higher than the lowest reading of the day (0.3 p.p.m. found in the waters seaward of the observed color line). At a distance of 4,800 feet along the plume's path, the reading was 1.0 p.p.m. or 22% of the boil value. This value is greater than 3 times the 0.3 p.p.m. value. Not all of this difference in generated by the presence of effluent since the coastal waters normally have a greater particulate volume than waters of Florida Current origin.

Aerial Photography

On May 5, 1972, an aircraft was used as an additional observational tool to map the surface effluent plume. The airplane personnel were in radio communication with the boat operations crew and flew at altitudes ranging from 2,000 to 4,500 feet.

The aerial survey included both color and infrared photography. Two 35 mm cameras with 28 mm f3.5 lens were used; one with a sky-light filter for kodachrome color, and one with a yellow filter for ektachrome infrared. The cameras were operated nearly simultaneously at uneven time intervals. The pictures were taken with the camera inside the aircraft, shooting through the side window as the plane rolled.

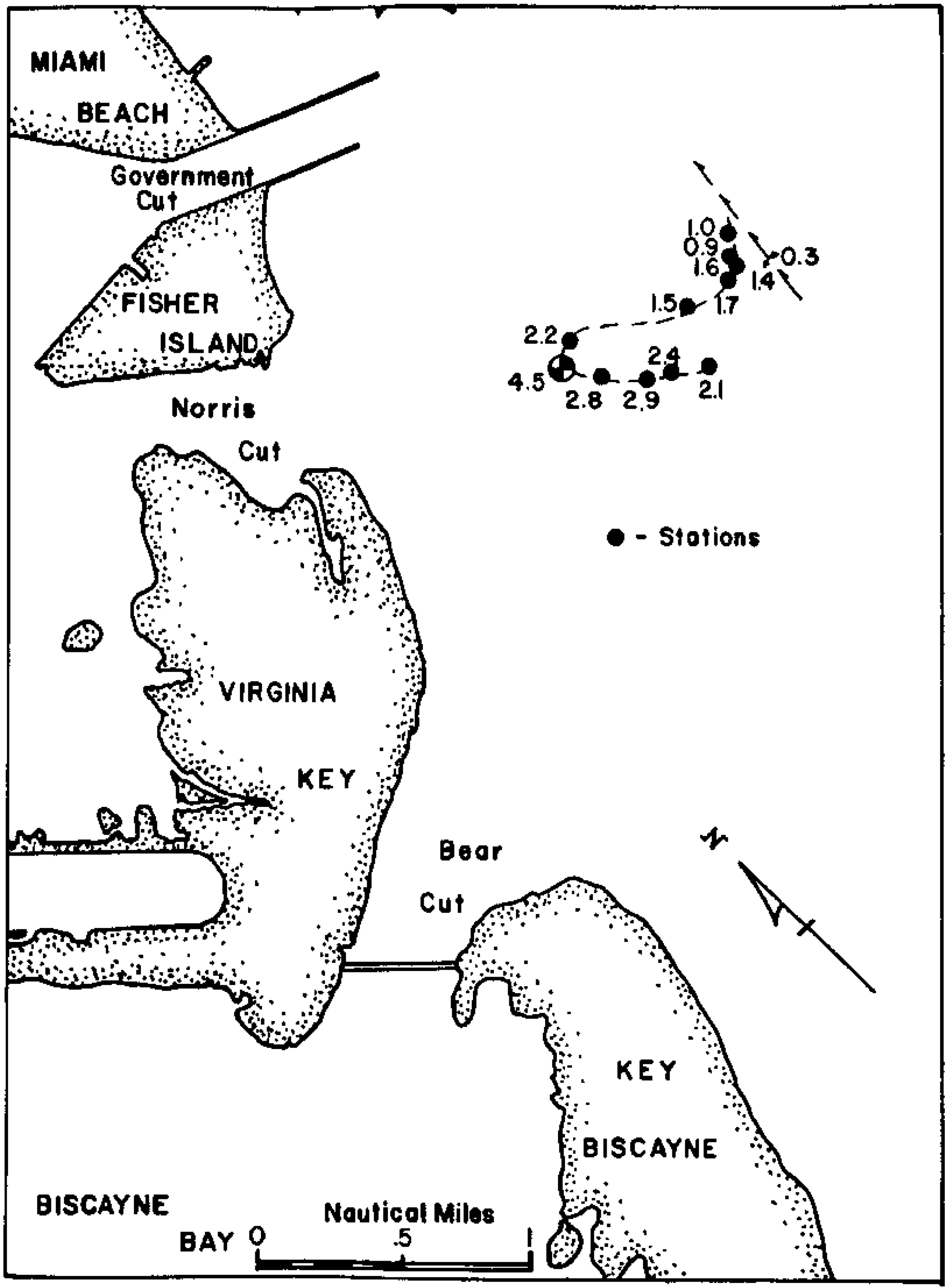

FIGURE 13

Particle measurements for April 6, 1972 (p.p.m.)

Plates 2 and 3 are photographs showing the red-dye (rhodamine WT dye) plume in its quasi-stable form eminating at the outfall and working its way into Bear Cut. For comparison, refer to Fig. 10. The contrast was not as sharp as hoped, but the photos afford some visual satisfaction of the day's activity. Infrared photos taken on this day possessed even less contrast than the color photos and, were therefore, of little value. Plate 2 was shot over the ocean looking west with Bear Cut to the left and Norris Cut to the right. Plates 3a and 3b were shot over Norris Cut at the same time. The view in 3a is toward the east with the outfall to the left. Plate 3b is looking south with Key Biscayne and Bear Cut bridge in the upper right corner. The double lobe shape seen in the dye plot (Fig. 10) is obvious here.

A fortuitous photo was produced when a NOAA geologist, Dr. G. Freeland, shot Plate 4 while flying over the study area in the Goodyear Blimp. The picture was taken looking north with Government Cut in the upper center of the photo.

Coliform Bacteria

"The coliform group of bacteria, which has its primary habitat in the intestinal tract of human beings, has long been the preferred indicator of fecal contamination of water and consequent possible presence of intestinal parasites or pathogens" (Fair, Geyer, and Okum, 1968). Hence, coliform measurements were undertaken 1) as indicators of water quality and 2) to help determine if pathogens could possibly reach the shore areas.

The coliform counts were made of water samples taken at the fluorometer outlet or over the side of the boat when the fluorometer was not in operation. The samples were kept on ice to minimize the

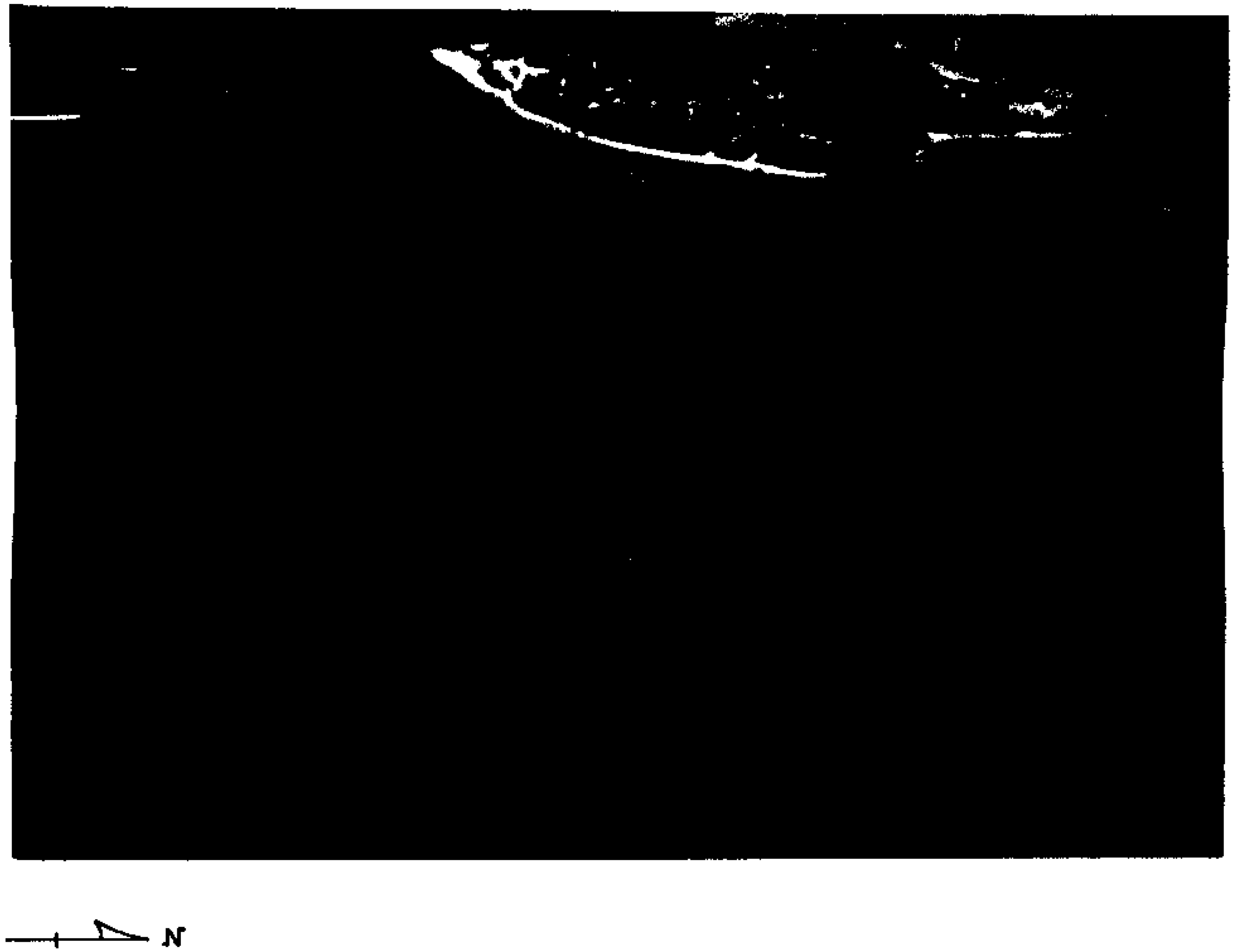

PLATE 2

Dyed effluent heading toward and entering Bear Cut (top left of photo; Norris Cut top right)

N

PLATE 3a

Dyed effluent heading toward...

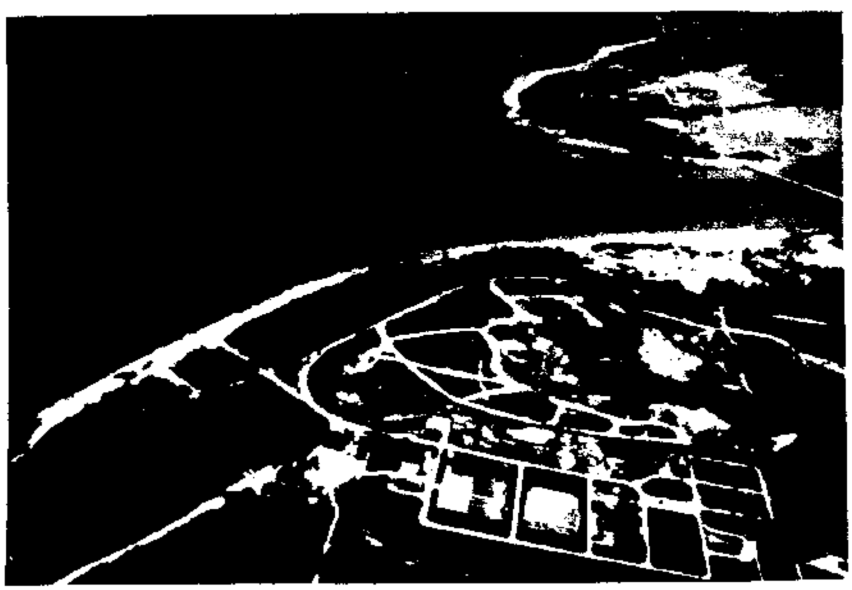

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PLATE 3b

...and entering Bear Cut; passing by public beach (right corner)

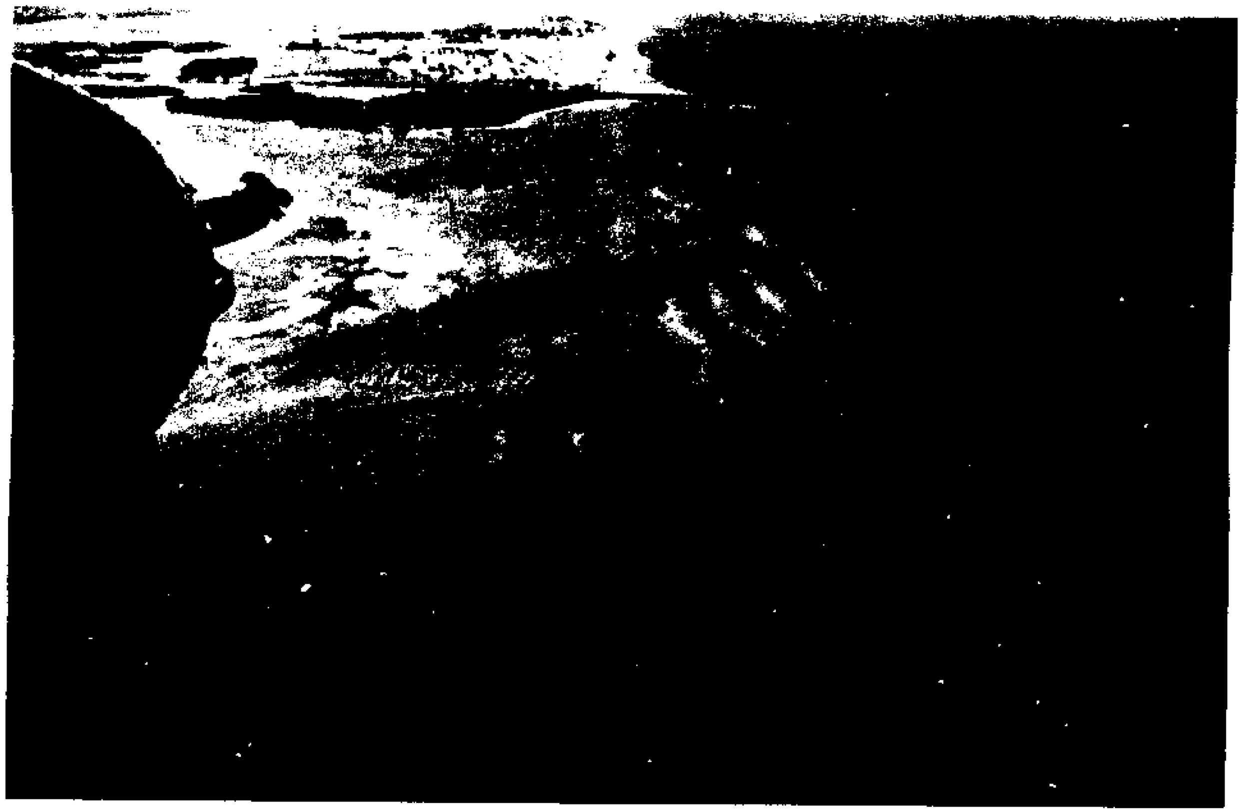

PLATE 4

Dyed effluent heading for Bear Cut (Miami Beach top center of photo)

bacteria die-off and/or reproduction while being returned to the laboratory for analysis (see Table 5).

On April 6, 1972, although only four samples were taken, the results, presented in Fig. 14, show a clearly decreasing gradient as the effluent moved off from the outfall (compare with Fig. 8). At the boil a count of 450 coliform per 100 ml was obtained. Some 3,600 feet from the boil a count of 95 coliforms per 100 ml or 21% of the boil reading, was still measurable.

In connection with the experiment of May 5, 1972, the EPA set up their laboratory equipment for bacteria analysis on the dock at RSMAS. Several times during the day's experiment, samples were returned to the dock in order to minimize the time delay between collection and analysis. All samples so collected were millipore-filtered within two hours of collection. The results were both startling and informative. Both total and fecal coliforms were measured at seventeen stations at various times during the day (see Table 6). The furthest station where coliforms were measureable was 4,100 feet from the boil (see Fig. 15). At the time this measurement was made, the boil had a reading of 380 coliforms (total) per 100 ml and 46 coliforms (fecal) per 100 ml. Due to a dramatic decrease in coliforms observed before these measurements were made, this picture is not accurate or representative for the day. The first sample taken in the boil showed a fecal coliform count of approximately 102,000 coliforms per 100 ml (see Table 6). Three-quarters of an hour later, the fecal coliform count was down 50% to 55,000 coliforms per 100 ml. The next hour and 10 minutes saw a drastic drop to a coliform count of 46 coliform (fecal) per 100 ml. The final sample taken at

TABLE 5

Methods of Analysis Used by Different Contributing Laboratories

Laboratory	Total PO_4	Inorg. PO_4	NO_2-NO_3-N	Silicon	NH_3-N	Total Coliform	Fecal Coliform	Salinity
Environmental Protection Agency (EPA	Automated Single Reagent Method		Automated Cadmium Reduction Method	Technicon Auto-Analyzer Method and Modifications	Automated Thenolate Procedure	Milipore Membrane Standard Method	Milipore Membrane Standard Method	
University of Miami (U/M)		Standard Procedures-Greenfield and Kalber, 1954. Modified by Murphy and Riley, 1958				Milipore Membrane Standard Method	Milipore Membrane Standard Method	Beckman Induction Salinometer Model RS-7B
Dade County Pollution Control (DCPC)	Molybdenum Blue Method of Standard Methods					Multiple Tube Method with Lactose Broth	Multiple Tube Method with Lactose Broth	

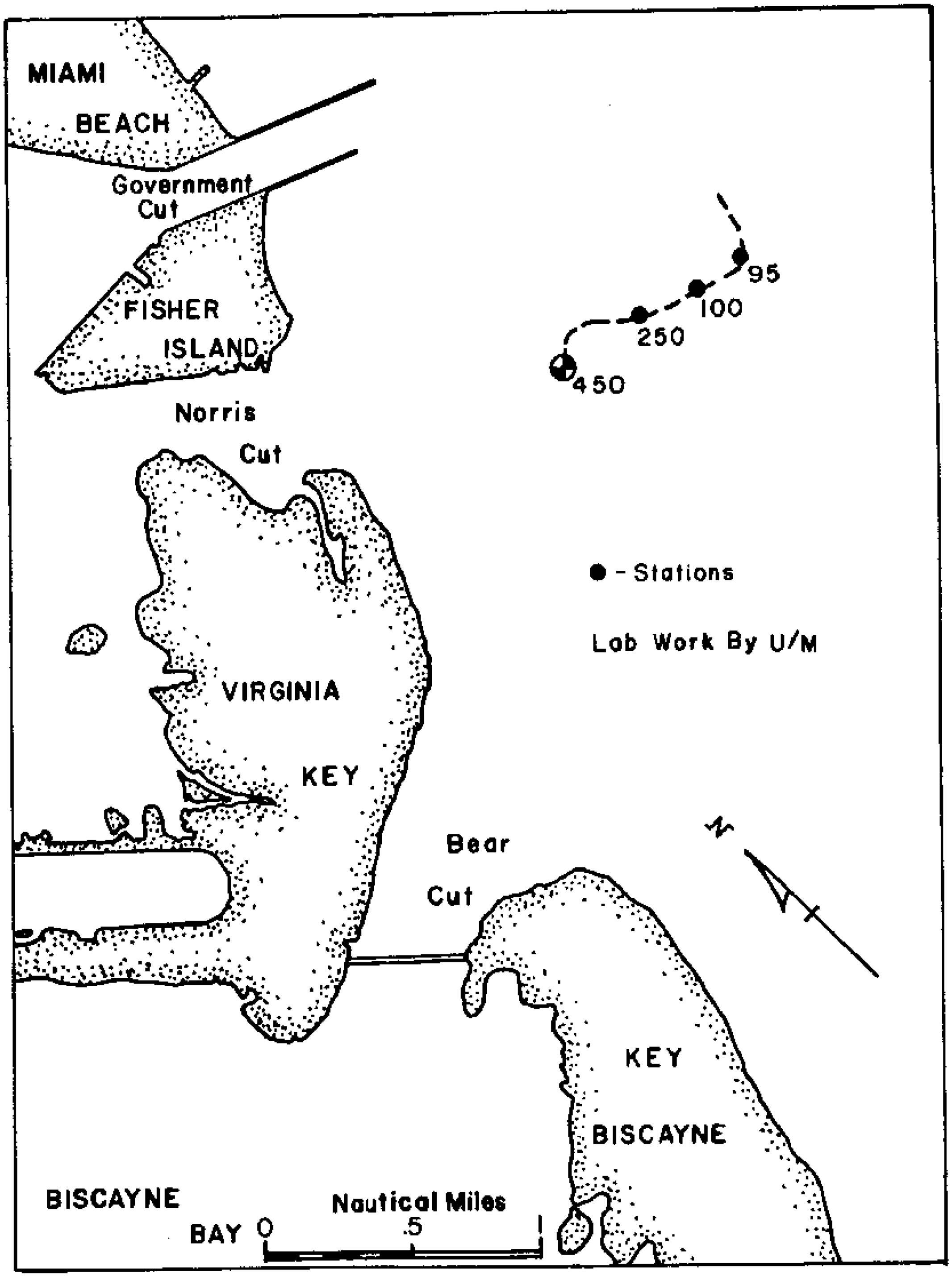

FIGURE 14

Coliform bacteria measurements for April 6, 1972
(total coliforms per 100 ml)

TABLE 6

Bacterial Sample Results for May 5, 1972

Station*	Total Coliform/100 ml	Fecal Coliform/100 ml	Time Collected
B-1 (Boil before dye)	>27,000	≈102,000	0925
A-1 (Background coastal)	<2	<2	0935
B-2 (Boil)	53,000	55,000	1010
S-3 (Boil)	380	46	1120
S-4	815	950	1148
S-4A	86	64	1151
S-5A	76	90	1157
S-5	116	144	1201
S-6 (Boil)	76	6	1330
S-7	8	<2	1338
S-8A	2	<2	1355
S-8	4	<2	1359
S-8 (Background)	<2	<2	1404
S-9	<2	<2	1407
S-10	<2	<2	1421
S-12	<2	2	1434
S-13	<2	2	1441
S-15	<2	<2	1521
S-16	<2	<2	1542
S-18	<2	<2	1605
Control	<1	<1	1745

*Stations located on Fig. 15

Lab work by EPA

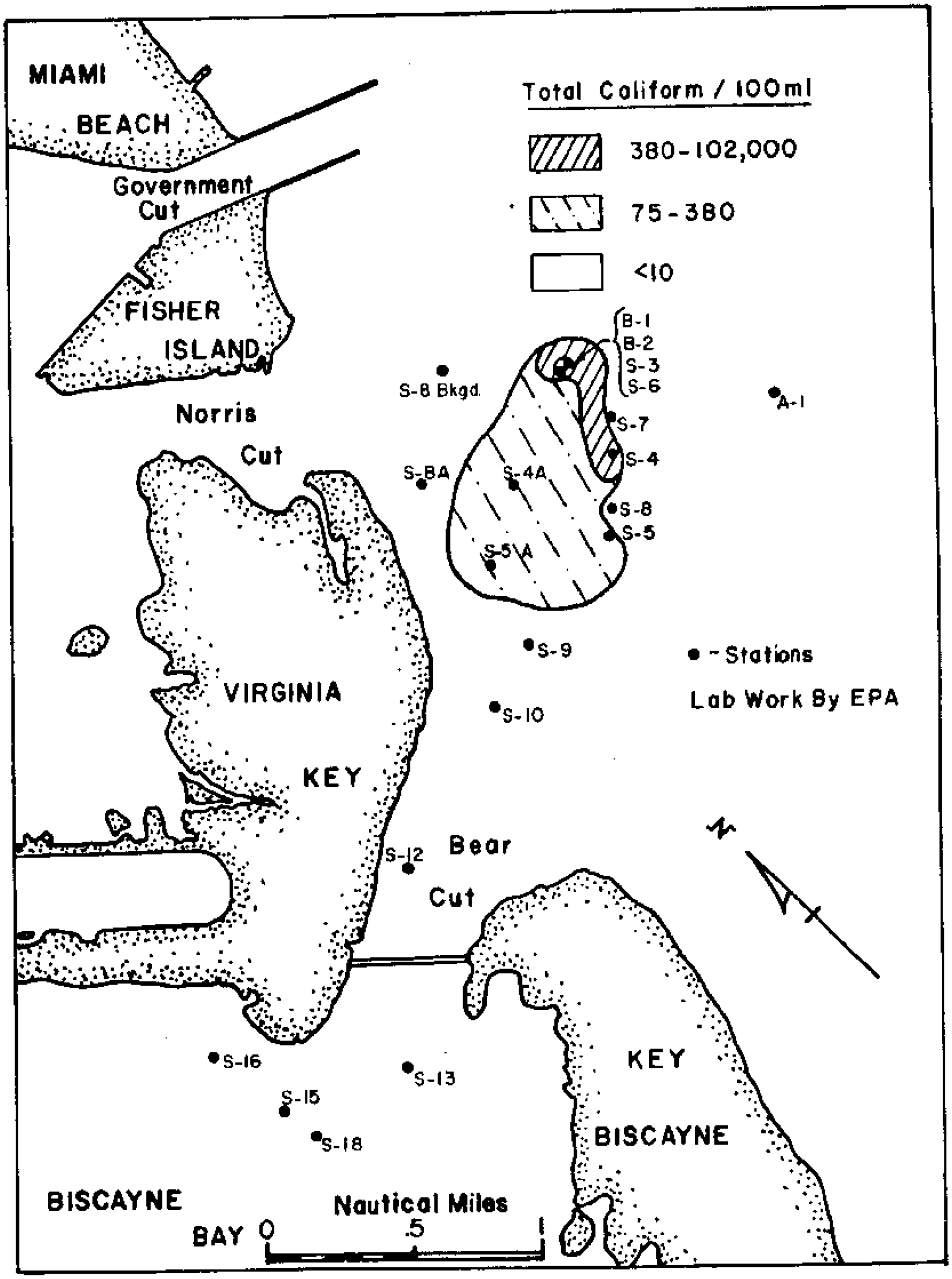

FIGURE 15

Coliform bacteria measurements for May 5, 1972 the boil produced a count of 6 coliform (fecal) per 100 ml. This tremendous decline in coliform bacteria measurable in the effluent is due to a substantial increase in chlorination at the plant during this period. The plant operator reported the rate of chlorination was increased beginning at the time the dye was added (EPA, 1973). This great variance in bacteria kill makes the data rather nebulous. However, an important fact should be noted here. The mass of water containing the high coliform counts emerged from the outfall pipe and moved on before the dye plume was established and traverses taken across it. Therefore, the water of high coliform content was never encountered again. However, it is feasible to calculate what the coliform count would have been had the water contaminated with the high number of coliform bacteria been sampled again off the beach. From fluorometer concentrations at the boil (49 p.p.b.) and on the beach (1.5 p.p.b.), it is seen that the reduction from the boil to the beach is 3.0×10^{-2}. This corresponds to a coliform count of 3,060/100 ml at the beach when the boil count is 102,000/100 ml as measured. If the winter value (water temp. = 75°F) of bacteria die-off derived by Putnam (Stewart, Putnam, Jones, and Lee, 1969) for southeast Florida coastal water is used, an additional reduction is obtained. This die-off equation is as follows:

$$(MPN)_T = (MPN)_O \cdot e^{-.31t} \qquad 17)$$

where MPN = most probable number of coliforms/100 ml,

T = total,

O = original, and

t = time in hours.

The die-off reduction is seen to be 3.9×10^{-1} and the total reduction is 1.17×10^{-2}. This indicates that the Virginia Key bathing waters contained bacteria counts of 1,190 qoliform per 100 ml or approximately 1.2 times the accepted water quality maximum (monthly average). Two points need to be mentioned here. The first is that the water quality standards are established with total coliform. The 102,000/100 ml boil count used is fecal coliform. However, the total coliform count should be higher than the fecal; therefore, calculations are on the conservative side. The second is that the value of 1,190 coliforms/ 100 ml does not exceed the 2,400 coliform/100 ml standard for any one day. It is not known how often this high count occurs in the boil; but from this work, it is believed that the appearance of effluent in the inlets and by the beaches is not infrequent. Therefore, a possibility exists, though probably slight, that the standard stating that 20% of the monthly samples must not be greater than 1,000 coliforms/ 100 ml might be exceeded.

If this high coliform count at the boil is considered as not just an incidental occurrence producing a bacterially high water slug, but existent for the time necessary for the plume to achieve its quasi-stable (approximately 3 to 4 hours) as depicted in Fig. 10, then the following calculations are possible. The distance between the outfall and the Bear Cut bridge is 1.8 nm, and the plume took 3.28 hours to traverse this distance; therefore, the average current speed is 0.55 k. Using this speed in conjunction with Eq. 17), bacteria die-off calculations were made. These numbers were used with the physical reduction due to dilution presented in Fig. 10, and the result is shown in Fig. 16. The area outlined in Fig. 16 contains coliform counts greater than or

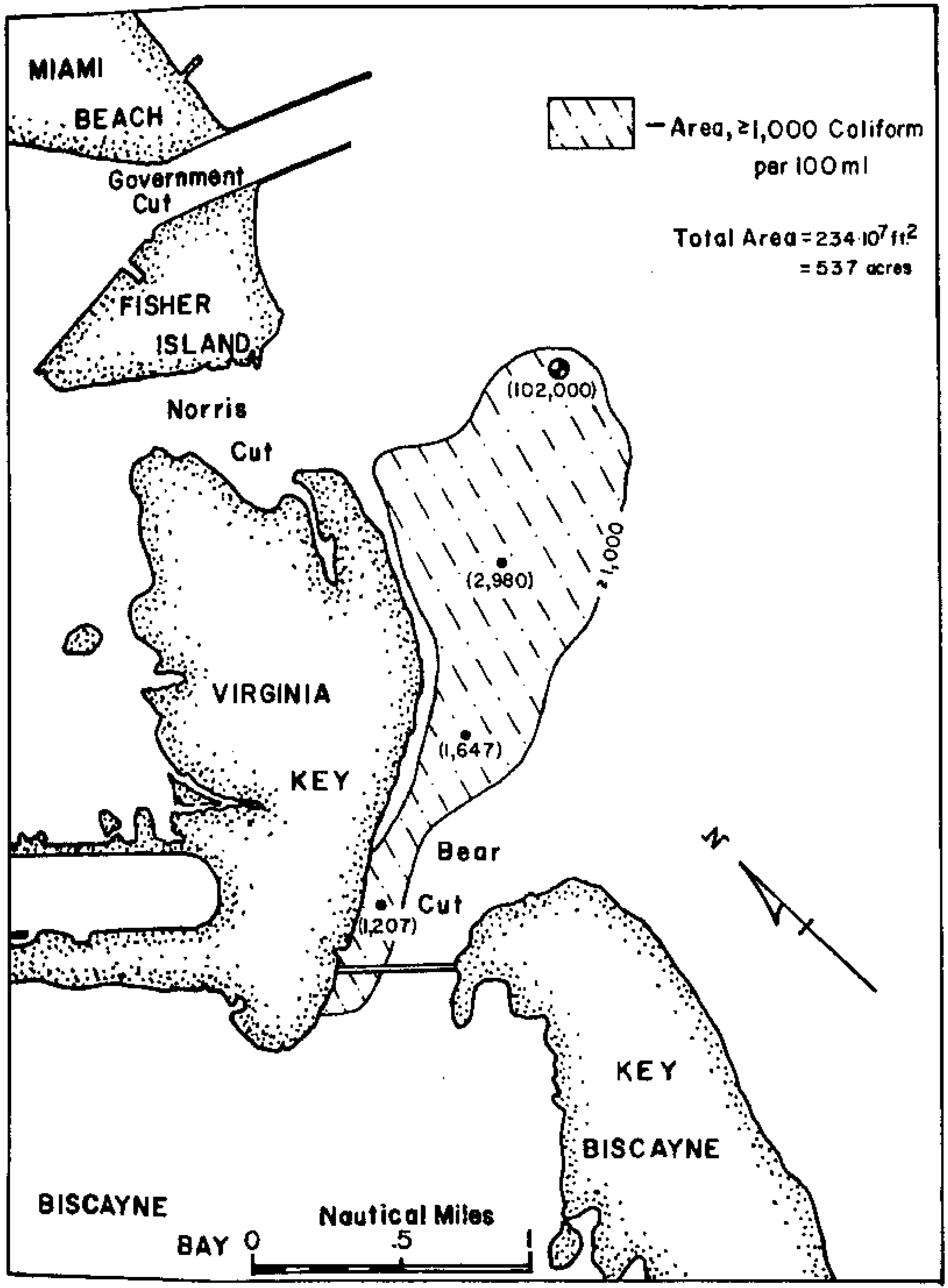

FIGURE 16

Calculated area containing ≥ 1,000 coliforms per 100 ml equal to 1,000/100 ml; the values within brackets are calculated coliform counts along the axis of the plume. Therefore, the outfall under the conditions stipulated would render this area, some 2.34 x $10^7 ft^2$ (537 acres), unacceptable for swimming or any other water contact activity if this occurred 20% of the monthly sampling time.

Some interesting observations can be made from the data gathered on May 5, 1972, when the sampling boat was docked with the operating fluorometer aboard. The record generated indicates that dyed effluent did exit the bay on ebb tide following its entry on the previous flood tide. Since this record was gathered at only one location, a quantitative value could not be placed on this flushed effluent. However, it can be postulated, that while a portion of the effluent will leave the bay, some will remain during ebb tide. This is produced by an asymmetry in the flow patterns between flood and ebb. The physical situation is such that the flooding coastal waters achieve high velocities (approximately 3 k) coming through this narrow inlet--Bear Cut. Upon entry into Biscayne Bay, these waters flow far into the bay. This jetting action carries these waters, and hence effluent, further into the bay than the less forceful ebbing waters can reach. During ebb tide, the bay waters are drawn more uniform radially into Bear Cut. The result of this asymmetry of flow patterns is that all the waters tainted with effluent that enter on flood tide do not exit on the ebbing tide. Therefore, effluent gets stranded in the bay.

Further data gathered in this experiment indicates that of the effluent that exits on ebb tide, a quantity of this returns on the following flood tide. At the point location of the fluorometer, some 28% of the reading taken on the ebb tide was measured on the returning flood tide. Hence, the Biscayne Bay-Bear Cut system possesses a cyclic mode which returns previously flushed waters to the bay. Dr. H. Gordon (1973) also has observed this occurrence and, based on 21 days of particulate data, estimates the percentage of return to be as high as 70 to 80%. This finding, coupled with the belief that contaminated flooding waters are stranded in the bay, foretells of a persistency on the part of the effluent-contaminated waters to remain in the vicinity of Bear Cut and Biscayne Bay. When one considers the ability of some bacteria and viruses to survive in seawater, e.g., 6 to 90 days for poliovirus (Gerba, 1972), the tendency for effluent-polluted waters to reside in the bay and cut over extended periods of time takes on added importance. It means that local bathers and area fauna are exposed to, and have a greater opportunity to be infected by, sewage-contaminated waters.

On three separate days, random bottom samples were taken in the study area and returned to the lab for bacteria analysis. These samples were taken by dragging a weighted sampling bucket over the bottom and also by using a small, one inch in diameter corer. The corer did not produce a useable core at all times due to the loose, sandy nature of the bottom. Therefore, the bucket became the main source of collection for the sediment samples. Again the samples were iced and returned to the laboratory (U/M) for analysis (see Table 5). Figure 17 shows the results of the coliform counts (coliforms/100 ml) made on all three days. The data reveals a distinct gradational decrease in the coliforms as one moves out from the outfall. This decrease is least pronounced toward the east. The high values to the east and low values to the west of the outfall

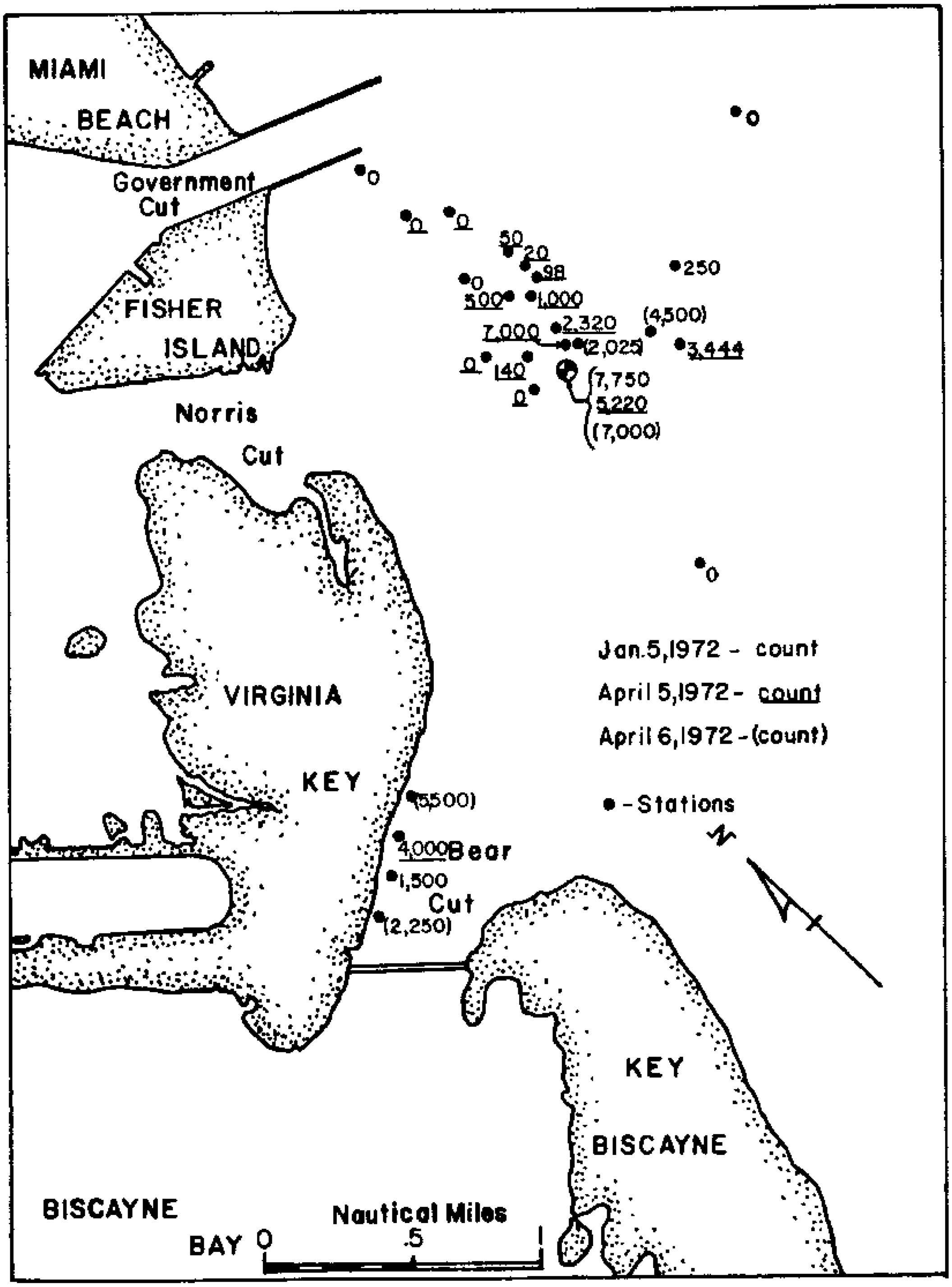

FIGURE 17

Coliform bacteria measurements of bottom samples
(total coliforms per 100 ml)

are probably demonstrative of the jetting action of the inlets. The combined jetting of Norris Cut and Bear Cut on ebb tide is in an easterly direction and would move the effluent plume toward the east where solid material could be deposited. The more detailed gradient observable to the north exhibits the possible value of a close grid survey. The coliform counts form a moderately consistent gradient for some 2,400 feet. If more stations had been taken, it is felt that the bottom coliforms might have given a view of the effluent plume's mean path. For example, more stations located to the near south of the outfall would have permitted a more definitive statement to be made about the northern gradient. It can only be said here that the effluent plume has a north component, but it is not possible to determine from these data if this is a preferential direction.

High coliform counts were found in four sediment samples taken off Virginia Key Beach on all three days (see Fig. 17). They ranged from 1,500 to 5,500 coliforms per 100 ml. These measurements were all made in shallow water, approximately 100 to 200 feet from shore, along the public beach. These high levels of coliforms in the sediments indicate a public health hazard to bathers at Virginia Key Beach, especially if these organisms and others can be resuspended. It is not known if these high coliform counts are attributable to the outfall since there were no samples taken between the outfall terminus and Virginia Key Beach. The fact that the public beach uses septic tanks that were installed about eighteen years ago offers another possible explanation for the high values. Again more sample stations would have helped make the picture more definitive.

The above coliform sedimentary analysis must be tempered with the realization that a lack of knowledge concerning coliform growth in seawater sediments exists. This lack of knowledge clouds the exact meaning of the numbers. For example, it is not known whether the coliform counts made represent growing colonies of some longevity or short-term deposits. Hence, though the counts give an idea of the plume's path, it is not certain for what range of time this path is representative.

Nutrients

Sewage effluent contains considerable quantities of nutrients. Some typical values are presented in Table 7.

TABLE 7

Typical Values of Some Nutrients in Sewage Effluent*

	mg/l
Phosphorus as P	10.1
Ammonia Nitrogen as N	11.3
Nitrate-Nitrite Nitrogen as N	4.1
Silicon as Si	5.1

*Extracted from EPA, 1973

These nutrients were measured 1) to act as indicators of water quality and 2) to help determine the concentration of these nutrients in the effluent plume.

Water samples were collected during each experiment and returned to the laboratory for analysis. The analysis of the samples was done by three different laboratories. They are listed along with the method they used in Table 5. In the results, the separate laboratories will be acknowledged along with their contribution.

The principal macronutrients about which most is known, as is reflected in Table 7, are the various forms of phosphorus, nitrogen, and silicon. Phosphorus and nitrogen are basic ingredients for the growth of algae. Silicon is a nutrient material which is an essential part of the solid structure of silica flagellates, diatoms, and some radiolarians and sponges (EPA, 1973).

Phosphorus

Phosphorus was measured in two forms, total and inorganic phosphate. A comparison of all phosphate data taken throughout the experiments shows that the phosphate in the effluent was almost totally in the form of inorganic phosphate (approximately 94%). The average boil reading for all inorganic phosphate measurements was 340 μg/l. An interesting observation can be made when this figure is compared to the inorganic phosphate measurement of 1,066 μg/l made by Lee and Teytaud (1971) on February 5, 1971, at this outfall. The measurements indicate that the present effluent is only one-third as rich in phosphates as in February, 1971. The event that probably had the most to do with this large decline in one year's time was the adoption of county ordinance 71-31. This ordinance states that no detergent using phosphates will be sold in Dade County as of April 30, 1971.

Even with this major decrease in phosphate levels, the boil readings of inorganic phosphate over all experiments averaged 76 times higher than background. Figure 18 is a contoured representation of inorganic phosphate measurements made on April 7, 1972 (compare with Fig. 9). On this day the boil had an inorganic phosphate count of 276 μg/l, some 59 times greater than the background value. The furthest station from the outfall had a count of 17.4 μg/l or 3.7 times the

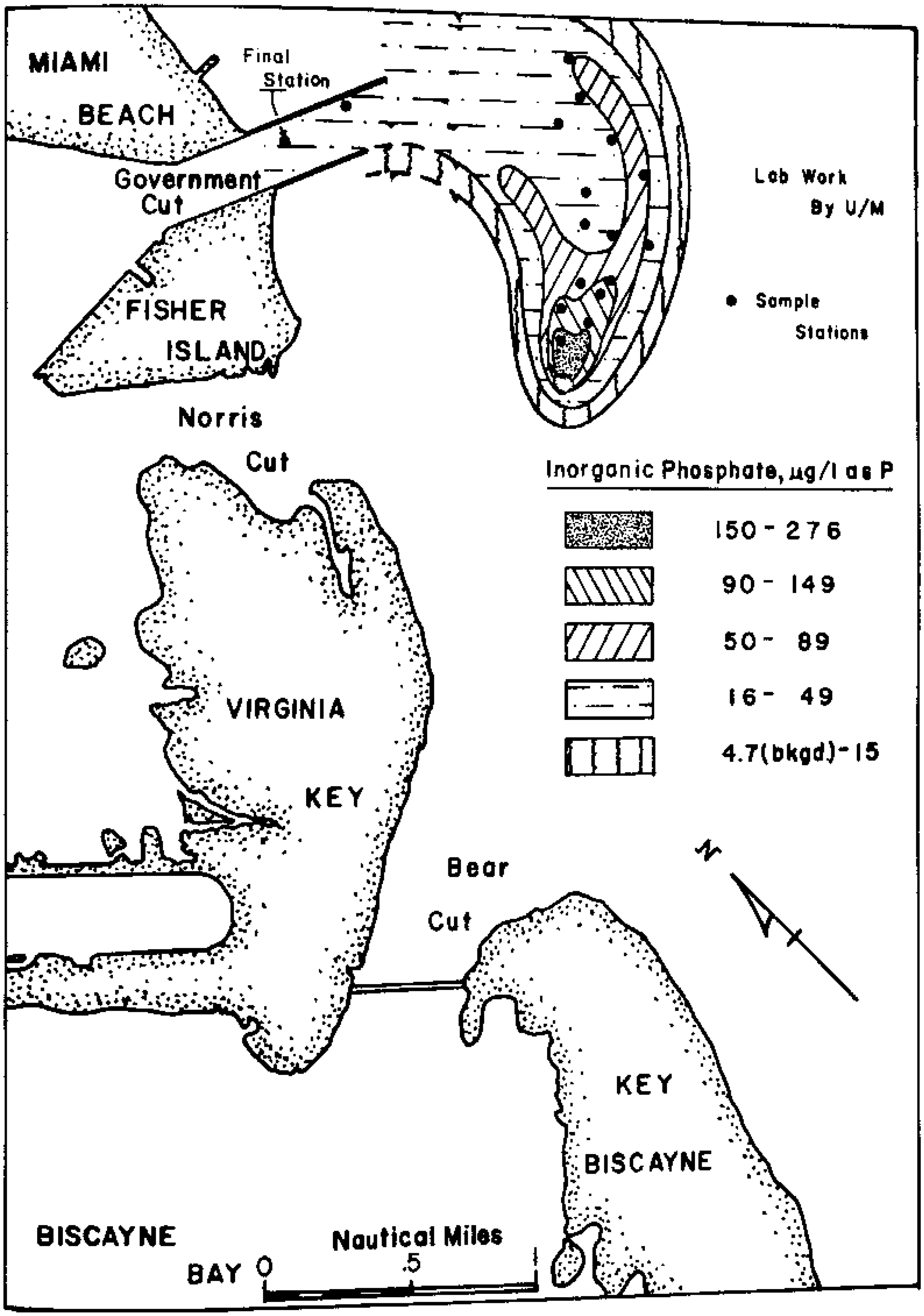

FIGURE 18

Inorganic phosphate contours for April 7, 1972 background value. The downstream reduction was therefore 16 to 1. Lee and Teytaud (1971) mentioned that mixing and diffusion with coastal waters, along with biological absorption by phytoplankton, are the major causes for this reduction. As was noticed with other measured parameters, a major portion of the reduction occurs in the near boil area. It is observable from Fig. 18 that within 1,200 feet of the boil the initial phosphate concentration is reduced by 63%.

The phosphate readings did not return to background in the plume as far as it was traced, which was 9,500 feet or greater than 1.5 nm. The plume entered Government Cut and carried with it the high phosphate levels into Biscayne Bay.

Nitrogen

Nitrogen was measured in two forms on May 5, 1972, as ammonia and as nitrate-nitrite. The nitrate-nitrite was low in the boil and became diluted to background levels within 2,500 feet in the plume. The average ammonia nitrogen concentration in the boil was 855 μg/l, some 170 times the background level. The ammonia nitrogen was measurably existent in the total dye plume as can be seen when comparing Fig. 10 (dye) and Fig. 19 (ammonia). The plume, upon entering Biscayne Bay, had a high reading of 45 μg/l which is nine times the background value for ammonia nitrogen. Figure 19 clearly depicts the ammonia nitrogen's entry into Biscayne Bay through Bear Cut after traveling approximately 2.5 nm. A similar picture is seen for silicon concentrations in the plume of May 5, 1972 (see Fig. 20).

Silicon

The boil displayed a silicon content of 665 μg/l or 70 times the background reading. The bay received concentrations of silicon 5.3

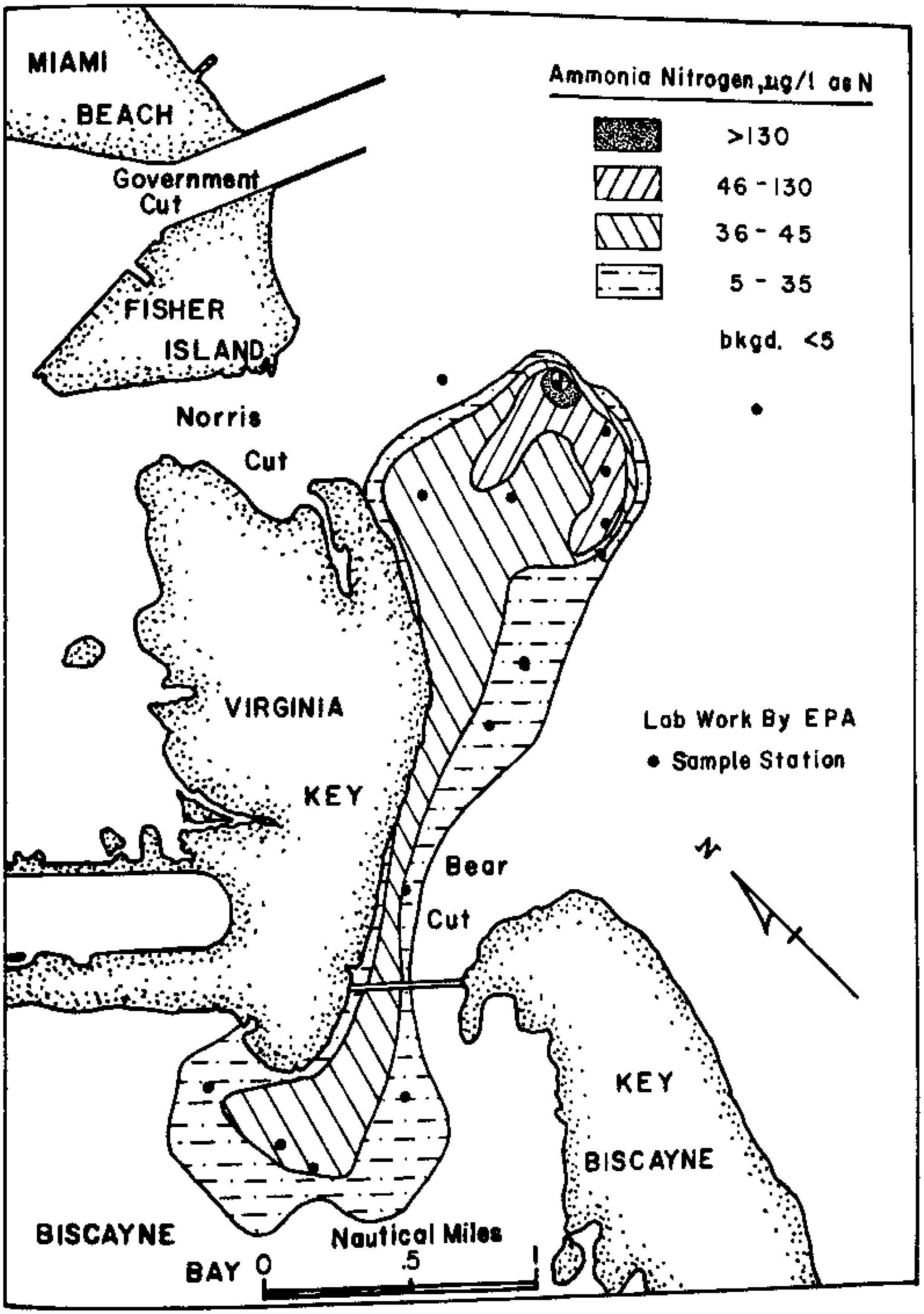

FIGURE 19

Ammonia nitrogen contours for May 5, 1972

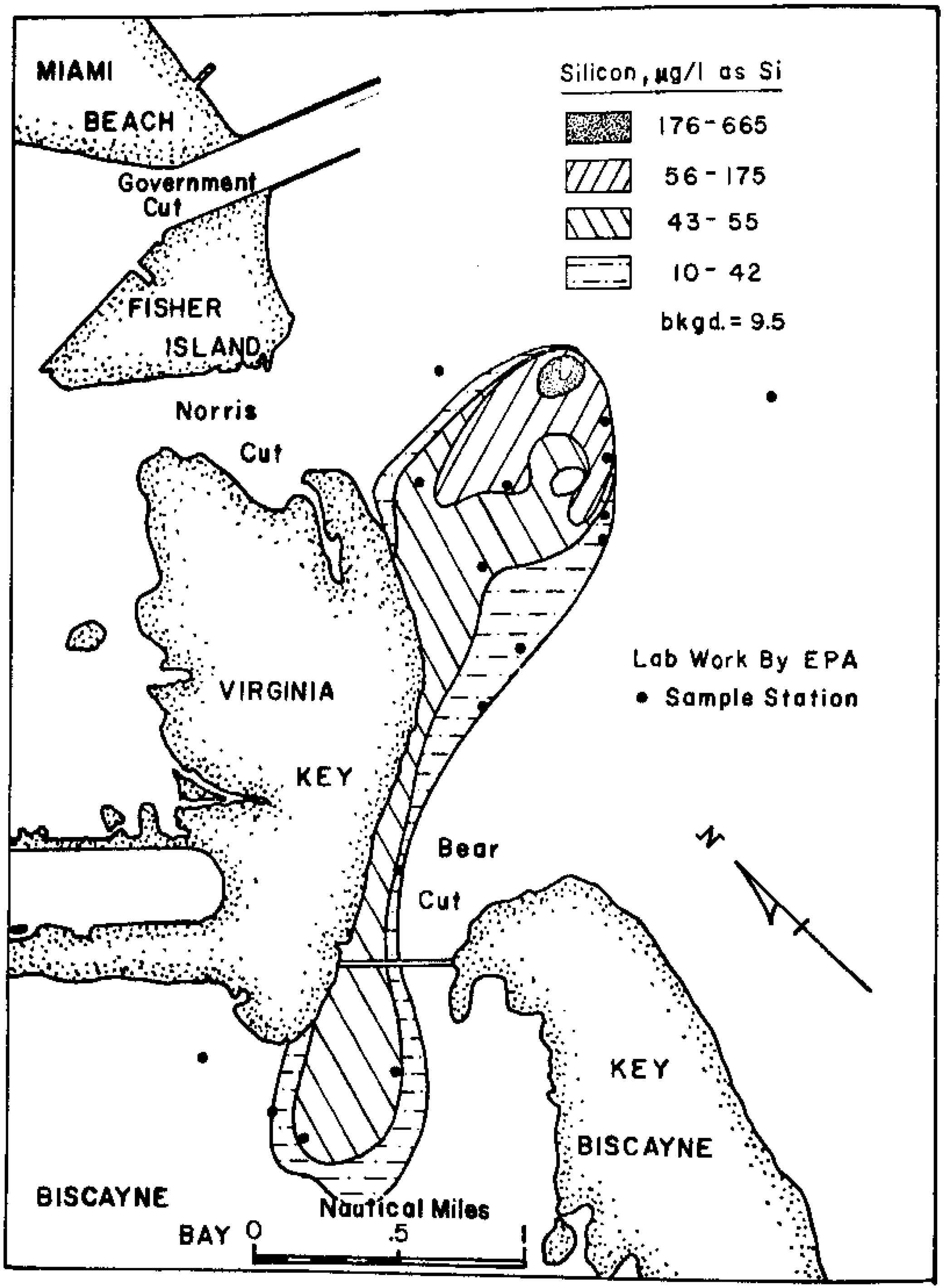

FIGURE 20

Silicon contours for May 5, 1972

times background levels. These nutrient plots pictorially establish the plume's entry into the bay. The nutrient measurements themselves unquestionably show the nutritional input the sewage outfall makes to Biscayne Bay.

A survey of the existent but limited data on nutrient levels of upper Biscayne Bay (near Rickenbacker Causeway) revealed large seasonal changes in phosphate, ranging from 0.00 μg/l to 22.32 μg/l and averaging about 6.82 μg/l (McNulty, 1966; Dade County Pollution Control, 1972). Ammonia measurements made in south Biscayne Bay averaged about 0.19 μg/l (U. S. Geological Survey, 1973). These ammonia measurements were made on only one day, localized in the southern bay, and, therefore, are not highly representative. No silicon data was found.

When comparing these figures with the plume readings, there is an indication that effluent's nutrients are contributive to the nutrient intake of the bay. Outfall plume phosphate and ammonia levels in the bay are 2.5 and 237 times the background bay readings, respectively. Considering that the effluent enters the bay 40% of the time, this contribution seems appreciable.

The bay effluent readings were also found to be greater than the highest readings that the U. S. Geological Survey (Freiberger, 1972) obtained in the two canals--the Miami River and the Coral Gables Canal--entering this upper bay area. Bay effluent phosphate levels were greater than 2 times and ammonia levels were greater than 15 times these canal readings. This finding emphasizes the significance of the outfall effluent on the overall nutritional level of the bay.

The ability of the Bear Cut-Biscayne Bay flow-patterns to strand effluent-tainted waters in the bay must again be considered in conjunction with nutrient levels. Some of the effluent waters which enter the bay will diffuse and mix with the bay waters and become one with them. The latest calculation on the residence time of Biscayne Bay waters (Gordon, 1973) is approximately 100 days. Hence, the nutrients brought into the bay in the effluent have quite sufficient time for biological uptake. The flow-patterns in the area and this high residency time indicate a situation where the nutrients are permitted to accumulate.

Therefore, it can be said that nutrients enter the bay from the city sewage outfall. Their concentrations are significantly higher than the normal bay levels. The consistency of this input makes their contribution appreciable. These effluent nutrient concentrations are greater than any other measured major input (i.e., the Miami River and the Coral Gables Canal) into the bay in the area under consideration. The flow-patterns in the bay-cut area can permit these nutrients to be taken up in the ecosystem where they accumulate.

PROPOSED OUTFALL EXTENSION

The city of Miami is under federal order to extend their ocean outfall pipeline. The extension that is planned by the city would put the outfall terminus some 2.9 nm (17,500 feet) east of Virginia Key in 90 feet of water (see Fig. 1). An attempt to estimate the effluent particle movement at this new location was undertaken.

With the established belief that the particle trajectory model produced reasonable predictions with the existent outfall location, the model was applied to the proposed outfall location. Due to the many simplifications incorporated in the model, the results will not be an exact representation. However, the results are considered meaningful when used as guidelines. Steps were taken to make the modification of the model as conservative as possible in hopes of producing results of some value,

The computer program for prediction of particle displacements was used in its original form. A new uniform depth and highly conservative values for the speed and direction of the uniform flow were inserted. A new depth of 26 feet (actual depth varies from 1 to 90 feet) was arrived at by taking a conservatively weighted average from standard bathymetric charts. For the uniform flow direction the worst cases were selected, those being a flow directly toward Norris Cut (compass reading 279°) and a flow toward Government Cut (compass reading 298°). These directions were coupled with a uniform current speed of 0.5 k. The proposed outfall terminus will be located in 90 feet of water, a location which strongly establishes the outfall in the edge of the Florida Current. A joint study by NOAA and U/M produced a three-week record in a location similar to the proposed outfall site (see C.M. #3, Fig. 1). This record, Fig. 21, shows the current to be consistently to the north with short excursions to the south. A westerly current of 0.5 k does not appear on the record. Therefore, it is felt that the speed and directions used are conservative to the point where they might occur only on brief occasions, such as at the start of a cyclonic eddy or during periods of strong onshore winds.

With the direction set at 279° the model predicts the effluent will enter Norris Cut in 4 hours and 45 minutes (see Fig. 22). The model predicts the effluent will enter Government Cut in 4 hours and 20 minutes when the direction is set at 298°. Therefore, on the rare occasions when the offshore currents come from the east, there is a possibility that the inlets could be reached by the effluent.

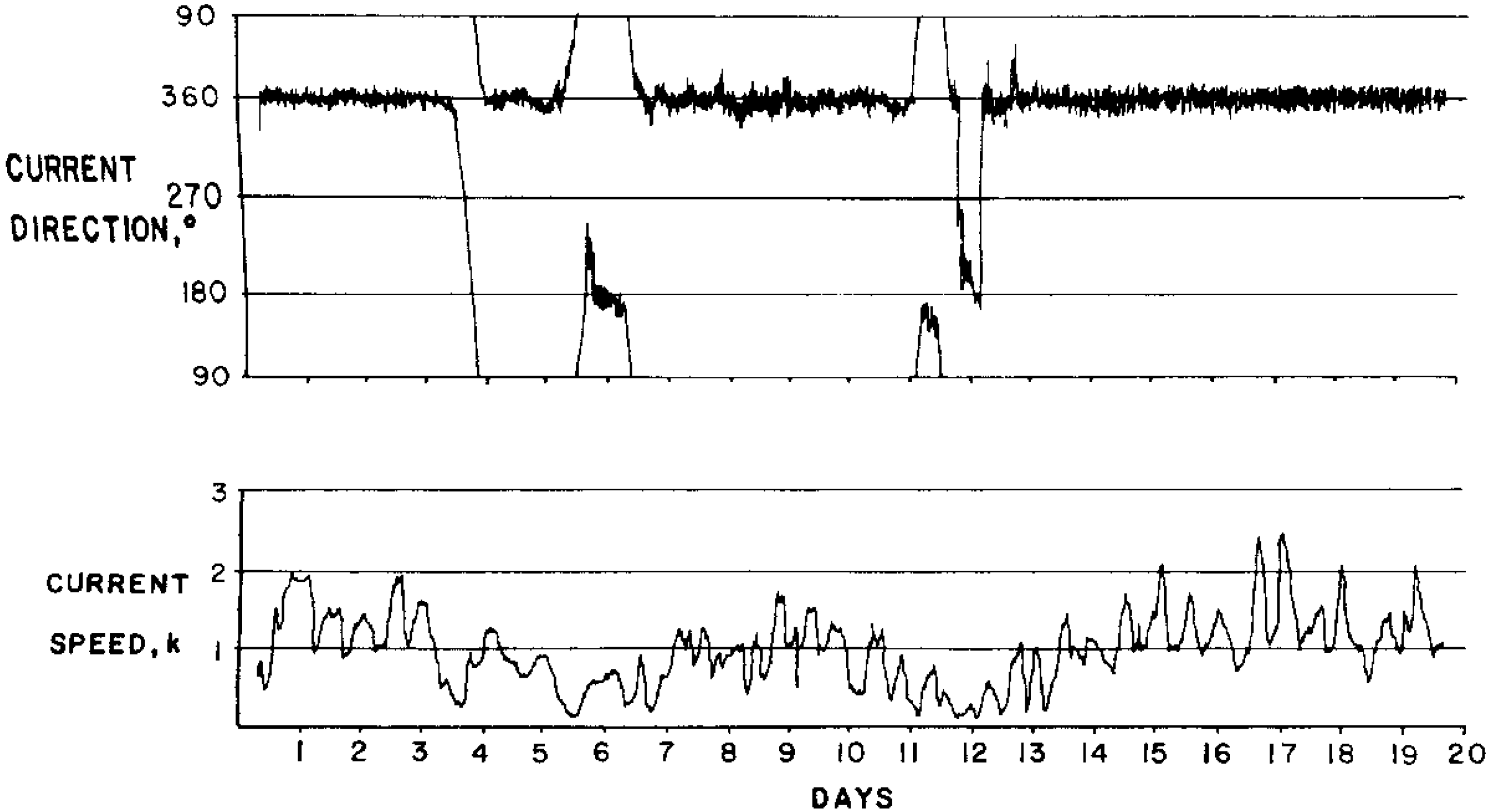

FIGURE 21

Current speed and direction at 90 foot isobath

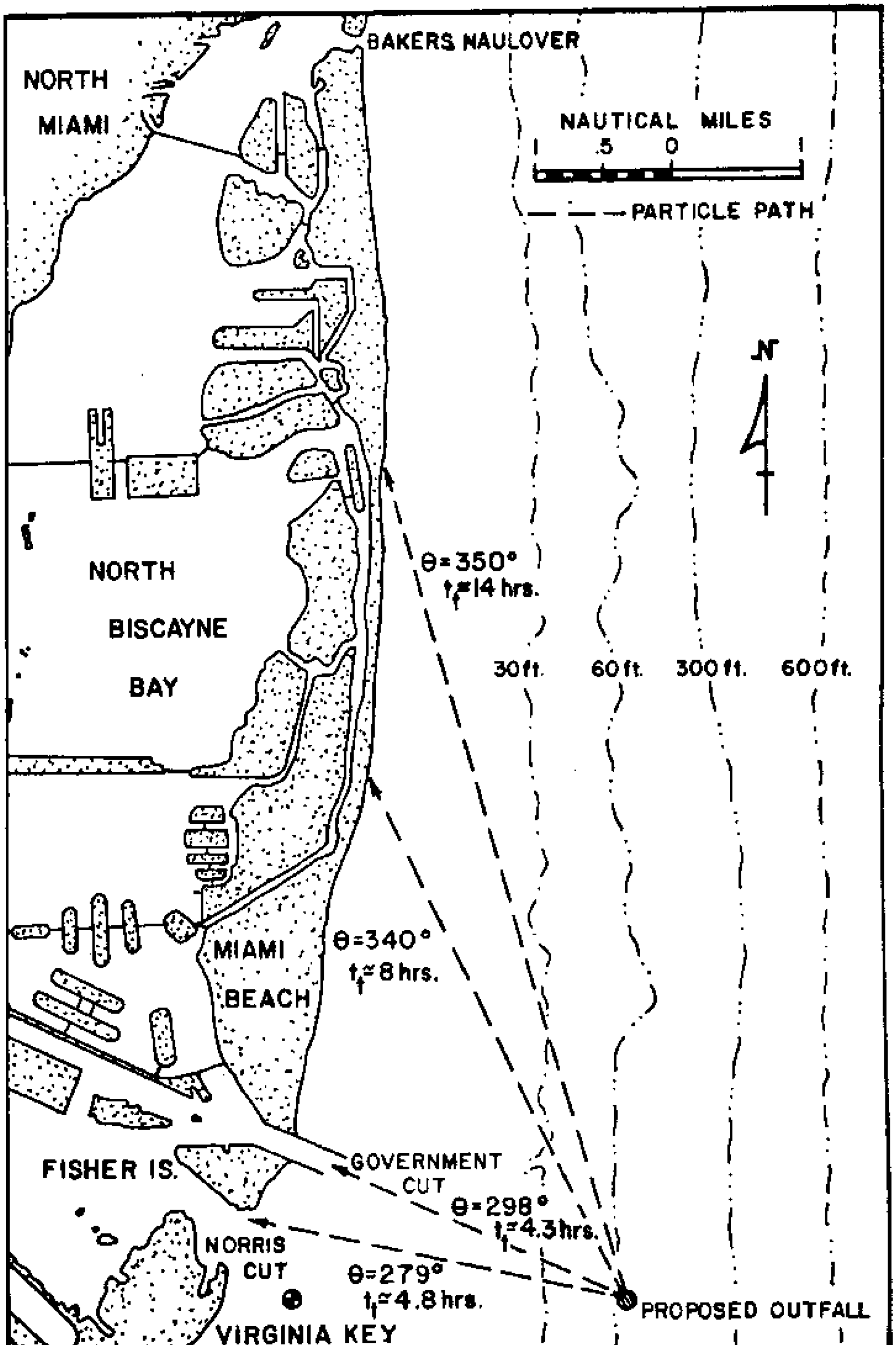

FIGURE 22

Predicted effluent particle trajectories
from city proposed outfall

If more common offshore current directions are used, the program predicts that the effluent will not enter the inlets but will reach the coast and beach areas to the north. For a current direction of 340°, the travel time is expected to be approximately 8 hours; for 350°, 14 hours. This foretells of the possible contamination of these areas with sewage effluent.

The speed of the northerly current at the proposed outfall site comes close to averaging about 1 k, with excursions to 2 k (see Fig. 21). Therefore, the 0.5 k speed used in the program is a conservative estimate for the outfall site but is probably a good estimate of the average speed over the distance from the proposed outfall to the northerly intersection points with the coast.

From the predictions made with this modified program, it is felt that the proposed ocean outfall will greatly reduce the incidence of effluent entering Biscayne Bay and impinging on bathing beaches south of Government Cut. However, the program also predicts the possible contamination of beach areas between Government Cut and Baker's Haulover (see Fig. 22) with waters containing active bacteria and viruses. It is therefore felt that the proposed outfall location is not an ideal location if the health and safety of Miami Beach bathers is to be considered.

A plan proposed by Lee and McGuire (1972), based on their work in southeast Florida, would place the outfall terminus at a deeper depth of 300 - 400 feet. This would require extending the planned extension only an extra 4,000 - 5,000 feet. Laying pipeline in these deeper depths will be more expensive, but the cost increases seem advisable since the Lee and McGuire outfall plan would alleviate the pollution hazard for the beaches north of the outfall. This plan will be described in more detail in the recommendations.

DISCUSSIONS AND CONCLUSIONS

The main objective of this project was to trace the path taken by the effluent of the Miami Sewage Treatment Plant once it leaves the outfall pipe in the coastal waters off Virginia Key. This was accomplished with accuracy and confidence, using both a mathematical model and a varied field program.

The mathematical model was a simplified representation of the study area, using a sink-source stream function format. This model was computer programmed to predict the trajectory of an effluent particle once it is emitted at the outfall for a full flood cycle. The program predicts that over the range of current direction angles of 210^{o} to 40^{o} (magnetic), the effluent will enter one of the three inlets in the study area and, consequently, the bay. It is strongly evident from this work and others, that the current direction in this shallow water study area is directly related and nearly aligned with wind direction. With this correlation, the model prediction, and the total wind record for 1971, it is believed that the effluent from the city's outfall enters an inlet and Biscayne Bay 40% of the time or 80% of the flood tides.

The model's ability to accurately duplicate field-obtained data established added confidence in its predictive capability. This confidence fostered an expansion of the model to enable particle trajectories to be made for the proposed outfall extension planned by the city. The predictions made with this modified model indicate that the new location for the outfall will greatly reduce the incidence of effluent entering Biscayne Bay. However, it also predicts that effluent will probably impinge on beach areas to the north of Government Cut with active bacteria and viruses.

In the field, the effluent was observed to be retained in the near shore areas off Virginia Key nearly constantly during flood tides. When the effluent was tagged with dye, it was traced entering Government Cut and Bear Cut on two separate days and approaching Norris Cut on another. Fluorometric data gathered on the day the plume entered Bear Cut definitely established the presence of the effluent in Biscayne Bay. The fluorometer also monitored a propensity on the part of a substantial portion of the flushed bay waters to return on the following flood tide. Dr. H. Gordon (1973) estimates that as much as 70 to 80% of the flooding waters of Bear Cut are returning after being flushed from the bay. These findings stimulate concern for the well being of Biscayne Bay and the public beaches in this area when one considers the nutritional, bacterial, and viral content of domestic wastewater and the hazardous potentials of these constituents. This concern prompts the following discussions.

Domestic wastewater is high in nutrients. This manifested itself in the concentrations of several nutrients measured in the effluent boil: ammonia nitrogen, 170 times the coastal background; inorganic phosphate, 76 times the coastal background; and silicon, 70 times the coastal background. These nutrients existed in the plume for a distance sufficient enough to enable them to enter Biscayne Bay. Measurements of ammonia nitrogen and silica were made in Biscayne Bay at levels 9 and 5.3 times coastal water background, respectively. Inorganic phosphate was measured entering Biscayne Bay at a level 3.7 times coastal water background.

The nutrient concentration levels introduced to the bay by the effluent were significantly higher than the normal bay levels and any canal input into this bay area. The consistency of the effluent nutrient input (40% of the time) makes this input noteworthy. A portion of the nutrient-ladened effluent will mix with bay waters and eventually be taken up in the ecosystem where accumulation of nutrients can occur during the 100 day residence time estimated for Biscayne Bay.

Nutrients are an integral part of the photosynthetic process of algae and other plant life. Certain amounts are necessary for a balanced system. However, if nutrient concentrations rise above the level needed for this balance, eutrophication of the water mass can ensue. This would entail excessive growth of algae and other plant life, depletion of dissolved oxygen, and other related problems (Ferguson, 1968). There can be situations where excessive nutrient inflow will have no significant effect on algae growth because some other factor, such as high turbidity or water color, may act to retard algae growth (Lund, 1969). However, it is believed that in upper Biscayne Bay one of the ingredients for possible eutrophication, at times, can exist; that is a high nutrient input into a water body with poor flushing characteristics. Therefore, it is felt that concern is warranted.

Domestic wastewater contains large numbers of bacteria and viruses. These organisms constitute a direct hazard to man through water contact when the wastewater is deposited in the ocean. An indirect hazard also exists since fish can transport human pathogens to areas far from sources of contamination; e.g., an ocean outfall (Clarke, Berg, Kabler, and Chang, 1964). Diseases such as typhoid fever, bacterial and viral enteritis, hepatitis, asiatic cholera, bacterial dysentery, and poliomyelitis can be transmitted to man by the water route (Gerba, 1972; EPA, 1973). Therefore, concern over the presence of waters containing domestic wastewater is warranted.

From this study, it is clear that Miami's wastewater spends much time in the coastal waters near shore and often makes its way into the inlets and the bay. On one day the effluent's presence was definitely established at the public beach areas on Virginia Key.

The bacterial and viral content of these contaminated waters as they contacted Virginia Beach is not clearly known. Measurements made off the bathing area showed low coliform readings (less than 2/100 ml). However, these measurements were made on a day when highly erratic readings were occurring at the effluent boil. Fecal coliform counts varied from 6 to approximately 102,000/100 ml denoting a highly ineffective chlorination system at the treatment plant. It has been calculated, taking into account the physical dilution and bacterial die-off in the area, that the high boil coliform count of 102,000/100 ml produced waters off the public beach area with 1.2 times the state's accepted water quality standard (monthly average). When the high readings are not considered as a short-term occurrence but are permitted to exist for 3 to 4 hours on flood tide, calculations foretell of the outfall rendering some $2.34 \times 10^7 ft^2$ or 537 acres of coastal, inlet, and beach waters unacceptable for water contact sports.

However, most of these calculations become purely academic when some recent findings are noted. "In the past the safety of water from pathogens has been determined by low coliform counts, but today it is realized that this does not always give us a true indication of the presence of bacterial pathogens and none on the presence of viruses" (Gerba, 1972). The original intent of the water quality standard of 1,000 coliforms per 100 ml was as a guide for action and gives no direct insight into pathogenic content (Carpenter, 1973). Methods and disinfection practices have evolved for coliform removal; the most common, chlorination, is used at the Miami Sewage Treatment Plan. However, there is evidence that some bacteria may be resistant to chlorination (Long and Bell, 1972). Also, chlorination of effluent at levels which significantly reduce numbers of coliforms does not affect viral content (Lund and Hedstrom, 1967). Therefore, it becomes clear that low coliform counts generated by chlorination do not necessarily mean the waters measured are safe or free of bacteria and viruses. Metcalf and Stiles (1968) measured poliovirus in oysters that were in waters that had coliform counts of 70/100 ml.

Even with the virucidal effects of seawater, survival time for poliovirus has been measured by numerous investigators as being anywhere from 6 to 90 days (Gerba, 1972). This would say that once viral agents are introduced into the system, they could survive for days, increasing their chance to infect a bather. This is particularly noteworthy considering the finding of the cyclical nature of contaminated waters near the Bear Cut Bridge and, hence, public beach areas.

It is therefore evident that the potential hazard of a treated sewage effluent cannot be accurately judged by coliform counts or chlorine residuals. Plant effluents contain bacteria and viruses that are deleterious to human health and in high enough levels to "warrant concern" (EPA, 1973). This concern must be intensified with the knowledge that seemingly none of the hospitals in the Miami area pretreat their wastewater before they insert it into the Miami sewer system. Therefore, it is submitted that a more logical criteria or standard for determining whether a hazard level has been reached is simply establishing the presence or existence of effluent in recreational waters. Effluent from the Miami Sewage Treatment Plant at times contaminates the Virginia Beach area. The hazard exists.

RECOMMENDATIONS

These recommendations follow from the conclusions and a concern for the health and well-being of the people and waters of Miami and neighboring areas. The present discharge location of the city of Miami's ocean outfall is completely unacceptable. The following is recommended:

1. Until major alterations are made on the Miami Sewage Treatment Plant, improved practices need be initiated at the plant itself. The The chlorination techniques used at the plant obviously fail to kill bacteria at a consistently high level and, therefore, need to be improved. This might only require increased monitoring. Possible improvements in removal of viruses might be initiated by use of coagulants such as $Al_2(SO_4)_3$, $Ca(OH)_2$, or $FeCl_3$ (Berg, 1971).

Hospitals in the area should consider some form of pretreatment prior to insertion of their wastewater into the Miami sewage system to remove bacteria and viruses. Chlorination and coagulants might be used, although water sterilization by heat might prove to be least expensive.

Use of Virginia Key beaches should be restricted until the danger of contaminated waters contacting the beach is removed. This recommendation might seem harsh, considering the lack of evidence that any individual has been infected while swimming here. However, Berg (1971) and Gerba (1972) point out that many viruses cause unapparent or latent infections which are difficult to recognize as being waterborne. These infected individuals may show no outward signs of disease but can act as carriers to infect others.

2. If the city of Miami is going to stay with the concept and use of ocean outfalls, it needs to consider the construction of one that will serve its people best. Plans have been drawn for an extension of the present pipe to move it to a depth of 90 feet. This is a depth being used by many of Miami's neighboring cities in southeast Florida. Work done on several of these outfalls by Lee and McGuire (1972) has yielded a concept for ocean outfall placement that takes advantage of the natural structure of the coastal and shelf waters in the area. In late spring and early summer, a seasonal thermocline exists across the shelf in depths less than 100 feet. However, this usually disappears in July. Lee and McGuire (1972) report that a more permanent thermocline exists below the 200 to 250 foot level most of the year (see Fig. 23). If the sewage effluent were released below the thermocline where it will mix and diffuse with surrounding waters, the chances of it surfacing would be greatly diminished.

It is recommended by Lee and McGuire that wastewater treatment plant effluents be discharged between 300 and 400 feet through diffusers. The diffusers obtain high initial dilutions of approximately 100:1 (EPA, 1973).

If this were done, the effluent would be emitted in waters of high velocity and below the thermocline. These natural oceanic features would then mix the rising effluent at depth and, at practically

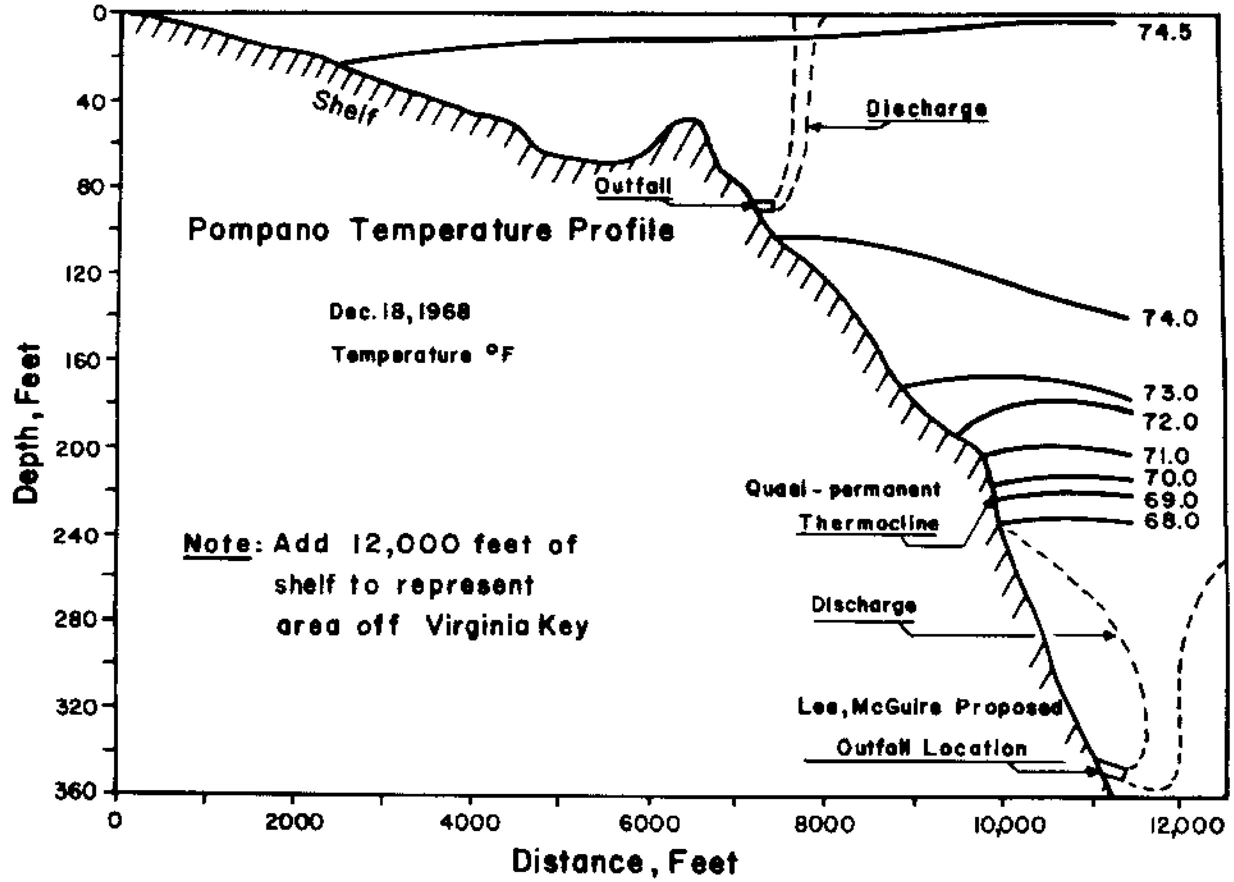

FIGURE 23

Typical temperature profile for shelf waters of southeast Florida all times, prevent the effluent from surfacing. If the effluent does not surface, it will not come under the influence of a possible wind-induced onshore current and, hence, will not be able to contaminate bathing areas. Predictions made on the city of Miami's proposed outfall extension to 90 feet show that when the effluent surfaces, Miami Beach and areas north could receive effluent-contaminated waters. Locating the discharge point below the thermocline would prevent that situation.

Even if the effluent should surface, the increases in dilution, distance from shore, and contact time with the bactericidal and virucidal properties of seawater will greatly lessen its potential danger to shore and beach areas.

In addition to the outfalls, treatment procedures should be increased at least to the state law requirements of 90% BOD removal (secondary treatment) for all ocean outfalls. Disinfection should be an integral part of this treatment. Both of these will help to remove pathogens (Gerba, 1972). The pathogens once in the water could infect man directly, on the rare occasions that effluent waters might reach recreational areas, and indirectly, by being transported by fish to these areas. The fauna itself can be harmed or made unsafe for consumption (Gerba, 1972).

It has been found that chlorinated effluents high in ammonia and organic matter can be detrimental to marine flora and fauna (EPA, 1973). It is recommended that studies be initiated in this area using Miami's effluent and treatment facility. It may be found that a different method of disinfection, for example, ozonation, might be best for the environment used for wastewater disposal.

3. In the Federal Water Pollution Control Act Amendments of 1972, a national goal was established for the elimination of discharging any pollutants by 1985. When this is coupled with the possible water shortage in south Florida, an alternate method to ocean disposal for handling wastewater seems called for. It is recommended that serious and energetic consideration be given to advanced waste treatment and water reuse systems. Present and planned treatment facilities should be prepared for eventual transfer to water reuse. Expediency calls for improved treatment and extended outfalls. Foresight calls for water recycling.

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