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RESULTS OF OCEAN DIFFUSION AND BIOLOGICAL STUDIES OF THE HOLLYWOOD, FLORIDA, OCEAN OUTFALL

John D. Crane, et al

Hollywood, Florida

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by

John D. Crane
Richard H. Jones
Environmental Science and Engineering, Inc.
Gainesville, Florida 32604

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Project Officer

Edmond P. Lomasney
U.S. Environmental Protection Agency
Region IV
Atlanta, Georgia 30309

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16. ABSTRACT

Full-scale diffusion experiments were conducted to estimate coliform bacteria concentration patterns of sewage effluent from two ocean outfalls located at Pompano Beach and Hollywood, Florida. The experiments consisted of two parts: turbulent diffusion of sewage effluent, and natural die-off of coliform bacteria. Further studies were conducted before, during, and after construction of the Hollywood, Florida, ocean outfall to determine the outfall's effect on ocean ecology. For the majority of the diffusion experiments, Rhodamine dye was injected at a continuous rate into the sewage at the sewage treatment plants. The data indicated that, for the travel times of interest, initial dye concentrations can be reduced by a factor as high as 1,000. Experimental determinations of coliform die-off rates indicated that during the summer months the natural die-off is approximately two orders of magnitude greater than that during the winter. The biological studies consisted of qualitative and quantitative evaluations of the microscopic algae and protozoa of the surface waters and the ocean floor to a distance of about two miles from shore. Detectable effects of the Hollywood outfall were confined to a very small mixing zone in the immediate vicinity of the outfall outlet in which a reduction of plankton was observed. Phytoplankton increase, which would be expected from nutrient enrichment, was not observed to occur as a result of the Hollywood outfall in the areas surveyed. The studies provide no indication that sewage release through the Hollywood outfall had any significant effect on aquatic ecology.

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ABSTRACT

Full scale diffusion experiments were conducted between August, 1968, and January, 1970, to estimate coliform bacteria concentration patterns of sewage effluent from two ocean outfalls located at Pompano Beach and Hollywood, Florida. The experiments consisted of two parts; turbulent diffusion of sewage effluent, and natural die-off of coliform bacteria. Further studies were conducted before, during, and after construction of the Hollywood, Florida, ocean outfall to determine the outfall's effect on ocean ecology.

For the majority of the diffusion experiments, Rhodamine dye was injected at a continuous rate into the sewage at the sewage treatment plants. The data indicated that, for the travel times of interest, initial dye concentrations can be reduced by a factor as high as 1,000.

Experimental determinations of coliform die-off rates indicated that during the summer months the natural die-off is approximately two orders of magnitude greater than that during the winter.

An empirical model was developed to predict downstream concentration patterns. This model can be used to aid in the design of similar outfalls on the Florida southeast coast.

The biological studies consisted of qualitative and quantitative evaluations of the microscopic algae and protozoa of the surface waters and the ocean floor to a distance of about two miles from shore.

Detectable effects of the Hollywood outfall were confined to a very small mixing zone in the immediate vicinity of the outfall outlet in which a reduction of plankton was observed. Phytoplankton increase, which would be expected from nutrient enrichment, was not observed to occur as a result of the Hollywood outfall in the areas surveyed.

Sludge deposits did not occur at the outlets of the Hollywood outfall as had previously been reported at other outfalls. This was due to the fact that Hollywood provided primary sewage treatment while the other outfalls reportedly had released raw sewage.

The studies provide no indication that sewage release through the Hollywood outfall has thus far had any significant effect on aquatic ecology.

This report was submitted in fulfillment of Project Number 57(R1)-01-68 under the partial sponsorship of the Office of Research and Development, Environmental Protection Agency.

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ACKNOWLEDGEMENTS

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Environmental Science and Engineering, Inc., of Gainesville, Florida, was responsible for the overall technical aspects of the grant under the direction of Dr. Richard H. Jones, Dr. Hugh D. Putnam, Dr. John B. Koogler, Mr. John D. Crane, Mr. Marvin Hamlin, and Mr. Robert Maxwell, who participated heavily in the research effort.

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SECTION I

CONCLUSIONS

Ocean Outfall Diffusion Studies

1. Sewage concentration patterns are influenced by wind magnitude and direction, tidal action, and currents resulting from the Florida Current. Of these factors, the Florida Current is by far the most influential.

2. Fecal coliform concentrations are dependent on ocean temperature as well as solar radiation. The 90 percent mortality times for coliform bacteria are estimated to be 7.4 hours in the winter and 1.5 hours in the summer.

3. The worst possible conditions for beach contamination occur in the winter when a toward - shore current is accompanied by a toward - shore wind. It is estimated that sewage plumes directed toward the shore occur less than two percent of the time.

4. Initial peak dilutions of the sewage in rising to the surface of the ocean is approximately 80 to 1 for the 30-inch Pompano outfall and approximately 30 to 1 for the 60-inch Hollywood outfall.

5. The surface concentration of sewage is approximately inversely proportional to downstream distance for well-defined plumes. For meandering and shore-directed plumes, the surface concentration varies approximately to the negative 1.3 power with distance.

6. The theoretical reduction of coliform bacteria from the Hollywood outfall mouth to the shore in a shore-directed plume is approximately 4,000 to 1.

7. The possibility of beach water coliform contamination caused by the Hollywood outfall is at the present time extremely remote.

Biological Studies

Marine plankton off the coast of Hollywood, Florida, showed no significant changes as a result of the construction and utilization of a sewage outfall. Some reduction of organism concentrations in the sewage boil was observed; however, this effect was limited to the small mixing zone in the immediate vicinity of the sewage release and was not considered significant.

A similar lack of change was observed in the ocean bottom biota at Hollywood. However, ocean bottom cores at Pompano Beach and Delray Beach indicated an increase of organisms associated with raw sewage, as well as a decreased concentration of dissolved oxygen. It was concluded that the degree of treatment received by the sewage at Hollywood was adequate to prevent the accumulation of sewage solids. Outlet conditions at Hollywood were such that not only were solids not deposited, but the bottom was scoured by the sewage discharge.

In general, populations of organisms increased toward the shore both at Hollywood and at other locations studied. This was indicative of increased enrichment near the shore. The bulk of this nutrient enrichment is probably a result of land runoff and drainage canal discharge rather than ocean outfalls.

These studies have provided no indication of detrimental effects to the ocean ecology as a result of the Hollywood outfall.

SECTION II

RECOMMENDATIONS

A comprehensive study of the diffusion and dispersion characteristics of each existing ocean outfall on the Florida southeast coast should be conducted, and investigations should be made, prior to construction of any future outfalls.

The diffusion characteristics and potential health hazards from microorganisms entering the ocean from the intracoastal waterway should be investigated.

A critical review is recommended of all available data on winds and currents for the area to determine if a definite correlation exists between wind direction and speed and surface currents. This information could then be used to forecast possible incidence of onshore (west) currents and the westerly component of normal north - south currents.

A study of the in situ survival patterns of known human pathogens in the marine environment should be made. This study should include organisms such as Salmonella and Staphylococcus, as well as mammalian viruses. Further, it should compare concentrations of these pathogens with coliform counts drawn simultaneously in order that a relationship of numbers of each might be developed.

It is recommended that each ocean outfall to be constructed in the future be considered on its own merits and that an ecological survey be conducted for each such outfall.

Qualitative and quantitative ecological studies should be complimented by certain parameters in order than any biological changes may be explained. These parameters should include nutrient analyses, dispersion studies, current patterns, and solids deposition.

SECTION III

INTRODUCTION

Population increases in the United States are placing more and more pressure on existing natural resources. Because of its tourist industry, Florida has a special interest in keeping its rivers, lakes, and beaches free from pollution. Florida's lower east coast, from Palm Beach to the Florida Keys, has unique waste disposal problems not found in other parts of Florida. This highly urbanized area, a strip about 10 miles wide, is bounded on the east by the Atlantic Ocean and on the west by the Everglades. Fear of polluting the Everglades has prohibited the discharge of wastewater, no matter how well it is treated, to the west. Fear of polluting groundwater supplies has prevented deep well injection of wastewater. The logical place for disposal of wastewater has been, therefore, the Atlantic Ocean. Increases in population have caused the installation of numerous ocean outfalls along this coast with little or no knowledge available concerning their effects on the ocean ecology.

Table 1 lists the ocean outfalls on Florida's lower east coast at the time of the studies. Figure 1 shows their location. The slope of the Continental Shelf at the point of discharge of most of the outfalls (90 foot depth) is one to twenty. It can be seen that only three of the outfalls were discharging wastes which received any type of treatment, and two of these were receiving only primary treatment. Until recently, state pollution control agencies have set no treatment design criteria for ocean disposal, therefore, little or no treatment had been provided at the time of this study.

Winds and tides are the forces which normally control the water movement on a continental shelf; however, there are two aspects of the southeastern Florida coast which cause wind and tide to lose more of their significance. These aspects are the narrowness of the continental shelf (1 - 1.5 miles in width) and the proximity of the Florida Current. The Florida Current passing within a few miles of Hollywood and Pompano with speeds up to 5 knots creates substantial eddies which spin off toward the shore. As a result, the Florida Current is the major force behind the near-shore circulation which in turn disperses ocean deposited wastes. Figure C1 in the Appendix shows an infrared satellite photograph of the Gulf Stream passing by the Florida coast. The infrared satellite photograph in Figure C2 shows massive eddies being projected off the Gulf Stream.

In 1968, as a result of the increasing number of ocean outfalls and the lack of knowledge concerning their effects, the Environmental Protection Agency funded a grant to the City of Hollywood, Florida, to demonstrate new sewage treatment methods at its wastewater

TABLE 1

OCEAN OUTFALLS ON FLORIDA'S LOWER EAST COAST

City	Date Approved	Diameter (inches)	Length (feet)	Discharge Depth (feet)	Capacity MGD Design	1969 Flow	Treatment
Miami Beach	1937	36	7,000	40	40	30	None
Key West	1952	24	4,570	33	11.5	5	None
Miami	1954	90	4,600	16	47	41	*M.A.S.
Palm Beach	1956	30	5,790	90	15	3	Comminution
Lake Worth	1957	30	5,200	90	13	3	Comminution
Delray Beach	1963	30	5,100	90	15	2	Comminution
Pompano Beach	1963	30	7,400	90	17	2.7	Comminution
North Miami	1964	36	10,000	60	15	7	Primary
Boca Raton	1966	36	5,500	90	8	0.0	Comminution
Hollywood	1968	60	9,700	90	40	13	Primary

*Modified Activated Sludge.

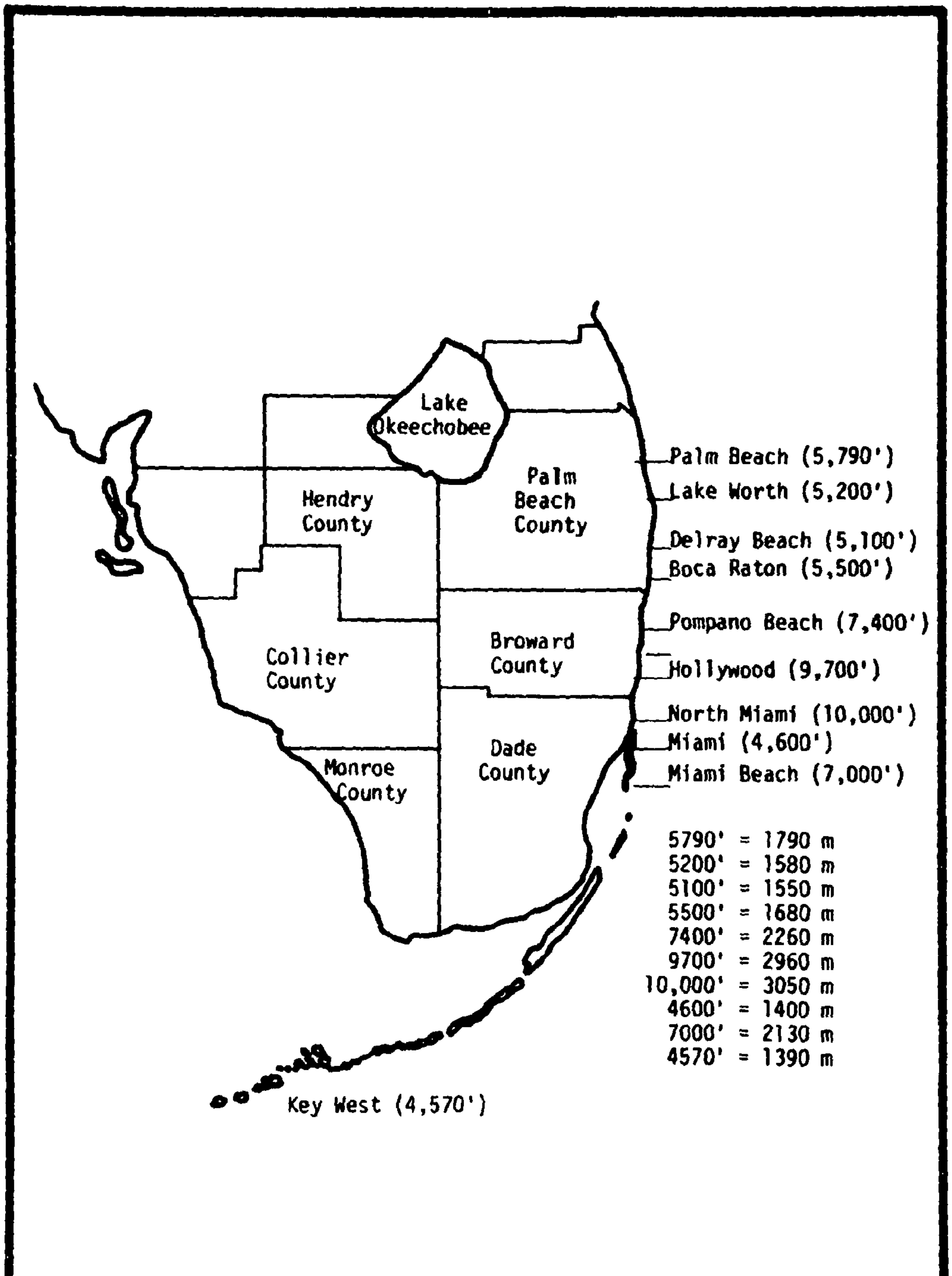


FIGURE 1

OUTFALLS OF THE SOUTHEAST FLORIDA COAST

treatment plant. Environmental Engineering, Inc. of Gainesville, Florida, was contracted to perform the necessary research work. A portion of this grant was to determine the effects of Hollywood's proposed ocean outfall on the local ecology and to develop and test a mathematical model for predicting diffusion from the new Hollywood ocean outfall.

Ocean Outfall Diffusion Studies

The Pompano Beach outfall, located 7,500 feet offshore and 90 feet below the surface, was studied prior to construction of the Hollywood outfall in order to predict the sewage field concentration that would result from the latter outfall. Pompano Beach, as shown in Figure 1, is about 15 miles north of Hollywood. At the time of these experiments (1968), the 30-inch diameter outfall at Pompano was discharging approximately 3,000 GPM of sewage.

In the spring of 1969, the first 5,000 feet of the Hollywood outfall was finished, and utilization of this portion began with the discharge of raw sewage while construction of the remaining section continued. This discharge through this 60-inch diameter outfall was approximately 10,000 GPM when dispersion studies were conducted in May.

In the fall of 1969, the Hollywood outfall was completed to 9,700 feet and the discharge of primary treated sewage began. Final diffusion studies were conducted at the Hollywood outfall in December, 1969.

Biological Studies

The Hollywood aquatic studies were coincident with a more extensive study completed in 1970 by Florida Atlantic Ocean Sciences, Inc., and the latter study provided much of the background for this report. The FAOSI Study included work at the Delray Beach and Pompano Beach outfalls, the proposed Boca Raton outfall, and the discharge area of the Hillsborough inlet. Access to the original data for all that work was available for this report.

Biological studies were conducted before, during, and after construction of the Hollywood outfall. Figure 2 shows the sampling schedule as well as the progress of outfall construction.

The Hollywood outfall was constructed on a sandy slope, barren of sediment and growths. A mature reef exists from 2,500 to 3,000 feet from shore. The slope continues beyond the reef until, at about 4,500 feet, another small reef is encountered. A third, large reef exists at 8,500 feet and rises from a depth of 55 to 40 feet. Beyond the third reef a sharp drop-off marks the edge of the continental shelf. The Hollywood outfall discharges at 9,700 feet in 90 feet of water as shown in Figure 3.

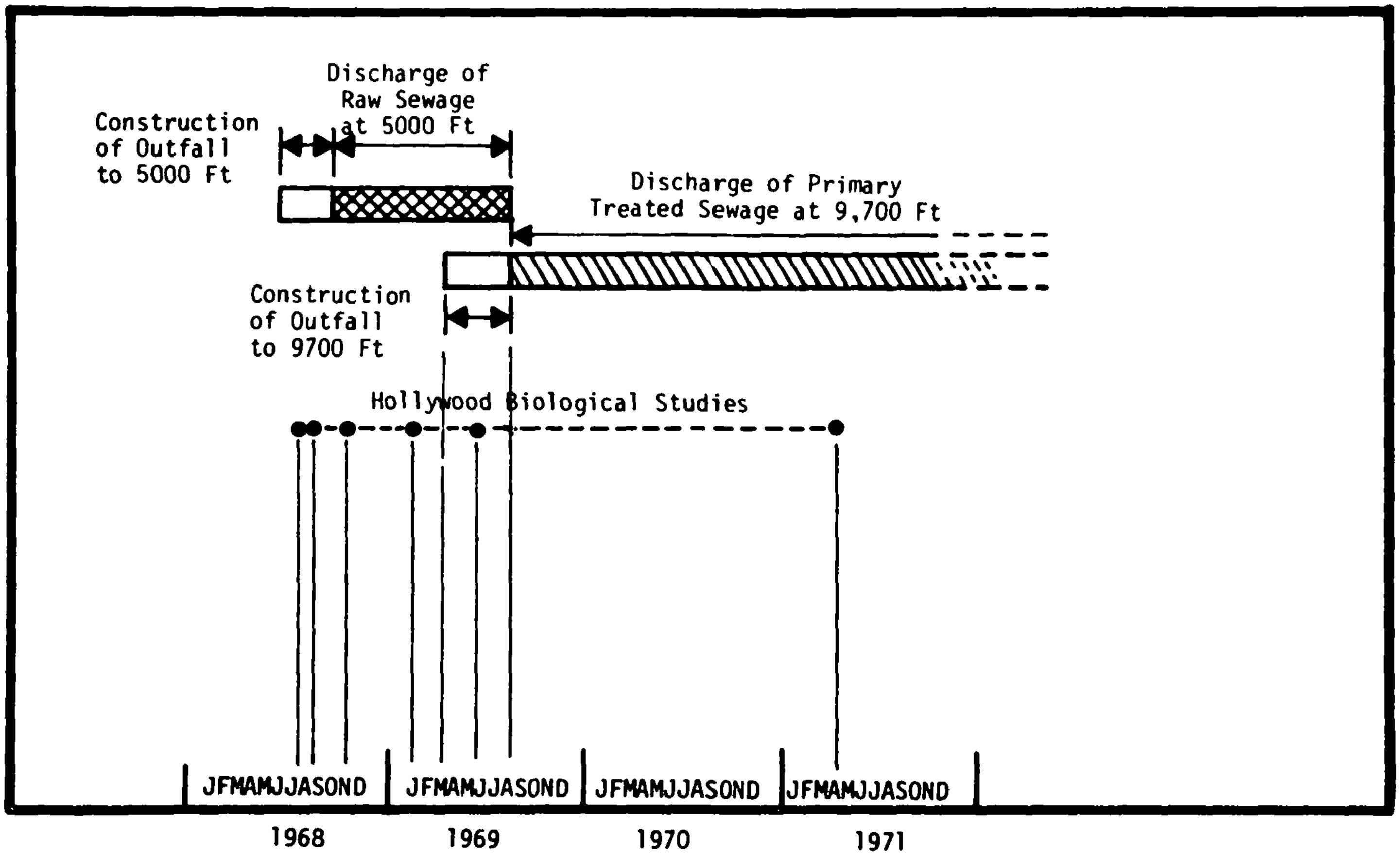


FIGURE 2: STUDY AND CONSTRUCTION SCHEDULE

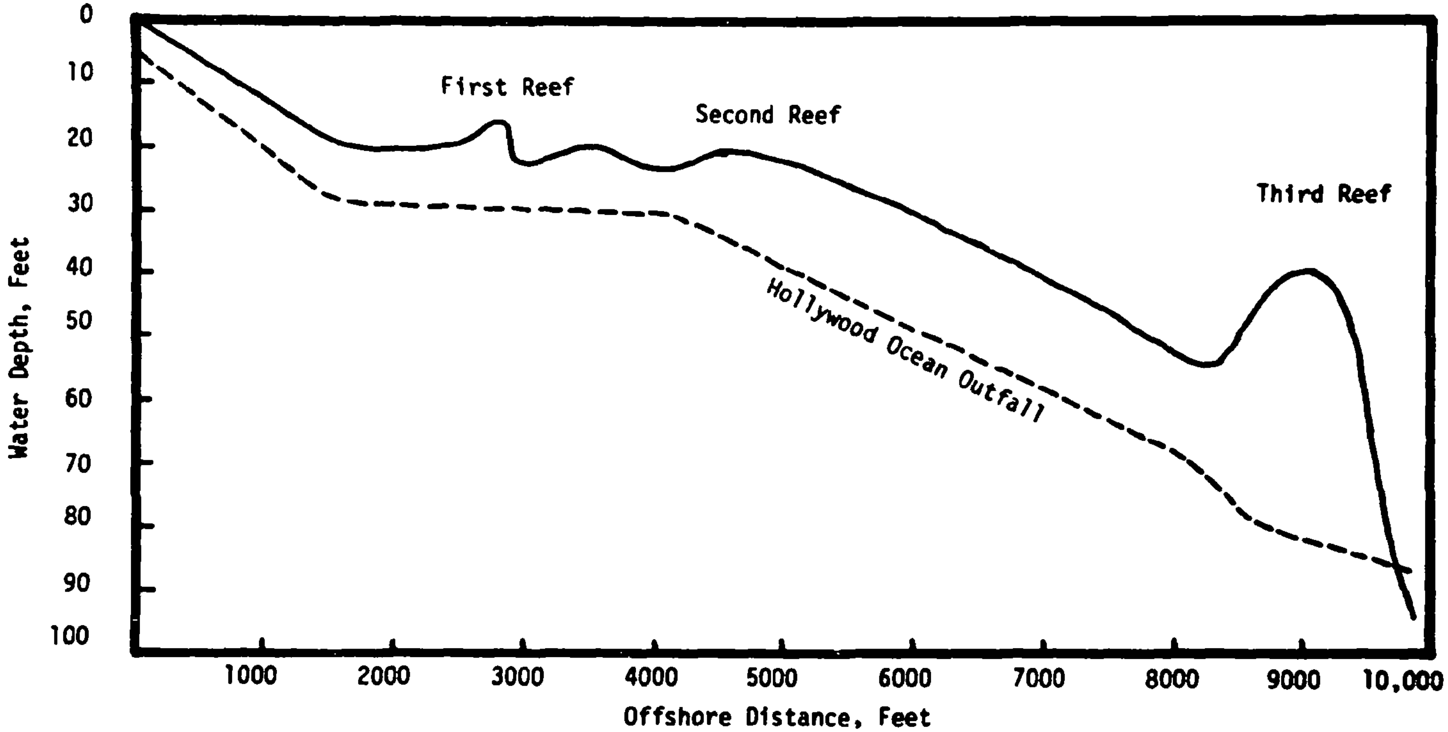


FIGURE 3: PROFILE OF OCEAN FLOOR OFF HOLLYWOOD, FLORIDA

SECTION IV

OCEAN DIFFUSION STUDIES: INVESTIGATIVE METHODS AND CONSTRAINTS

The most important criteria relating to water quality are those pertaining to bacteriological conditions. Prior to an ocean outfall installation, it is necessary to have reliable population estimates of coliforms within the sewage field as a function of travel time or distance from the source outlet. In other words, to meet water quality standards, it is necessary to know beforehand the initial composition of the waste; the physical, chemical, and biological characteristics of the water; and the extent to which diffusion of the waste is achieved.

Dye Studies

To obtain the information necessary to predict sewage field concentrations, fluorescent dyes (Rhodamine-B and Rhodamine-WT) were used as tracers. The dye was released at a constant and continuous rate directly into the sewage at either the Pompano Beach lift station or at the Hollywood sewage treatment plant. During each experiment the release time was about five to six hours. Once the resulting dye-plume had been visually established, repetitive traverses of the plume were made at numerous downstream locations (located by shore-positioned transits) to obtain the dye-plume concentrations. The data were then analyzed and the results were used to predict actual sewage field concentrations. Current speed and direction were measured periodically during each experiment with free drifting current crosses (drogues) whigh were observed from the transit stations. Vertical distributions of temperature and salinity were determined with a Beckman RS5-3 salinometer for some of the experiments. Also, current meter data were made available by personnel of the Florida Ocean Sciences Institute who were conducting near-shore circulation studies in the nearby area.

The dye-plume sampler consisted of a length of one-inch galvanized pipe containing a section of plastic tubing. The tubing was checked to insure that it neither contributed to the reading nor retained any dye by absorption. Attached to the intake end of the tubing was a strainer section which was oriented in the direction of flow. The sampler, rigidly attached to the back of a 31-foot motor launch, permitting sampling of the dye-plume down to seven feet below the water surface. The sampler was attached to the inlet of the fluorometer by another section of flexible tubing. The fluorometer outlet was connected to a constant flow pump and the discharge from the pump was directed overboard. The fluorescence measurements were recorded continuously.

A G. K. Turner, Model 111, fluorometer with a high volume continuous-flow door and a 0-1 ma Rustrak chart recorder were used to obtain the dye-plume concentrations. Source light aperture settings enabled the detection of concentrations covering the range 0.1 - 10 ppb (parts of dye per billion parts of sea water mixture by volume). The fluorometer was calibrated prior to each set of experiments by checking the fluorescence of standard dilutions of the dye in fresh sea water.

Coliform Bacteria Studies

Coliform survival in sea water was estimated for the first die-off studies by preparing sewage-sea water dilutions of 1:20 or 1:100 (1 part of sewage plus 19 or 99 parts sea water, respectively) in polyethylene bags. The bags were floated so that conditions of temperature, turbulence, and sunlight would approach those actually found in the discharged sewage. Trials extended for six hours during which time, at regular intervals, two 300 ml. portions from each container were collected in sterile BOD bottles and immediately processed for coliform detection by the membrane filtration (MF) technique. Each sample was replicated up to three times and counts were made following a 24-hour incubation period.

Gaussian Distribution Model

A generalized Gaussian distribution model for predicting concentrations from a continuous point source was used. Many theoretical and empirical models for predicting the concentration field have been investigated in the past (1-11). In general, concentration reductions, perhaps as high as a factor of 1,000 for travel times of about five hours or more, can be expected due to initial dilution of the waste in rising to the surface and subsequent diffusion. Rawn (12) reports that greater dilution can be achieved by the proper design of outfall diffuser sections. According to Tibby (13), natural die-off of bacteria and subsequent sedimentation will further reduce concentrations by a factor of about ten.

It is assumed herein that all settleable solids have been removed during primary treatment and that the lighter density sewage rises to the water surface almost directly above the point of discharge and forms a boil. In reality this does not always happen. To obtain a mathematical expression for the boil or volume source, a "virtual point source" (having the same strength as the volume source) is assumed to be located upstream at a distance X_0 from the center of the volume source.

Assuming a two dimensional Gaussian distribution of concentration having standard deviations S_y, S_z in the lateral (cross-stream) and vertical directions, respectively, the mean concentration $\overline{N}(x,y,z)$ at any point downstream from a continuous point source located in a field of homogeneous turbulence is given by Pasquill (10),

$$\overline{N}(x,y,z) = \frac{Q}{\pi \, \bar{u} \, S_y S_z} \exp\left[-1/2 \, (y/S_y)^2 - 1/2 \, (z/S_z)^2\right] \qquad \ldots (1)$$

where Q is the amount of pollutant released per unit time corrected to include the effects of pollutant decay; $\bar{u}$ is the mean current speed within the sewage field. It is further assumed that complete reflection at the water surface takes place as the lighter density sewage rises to the surface, analogous to fluids in the Sutton diffusion equation.

The plume standard deviations (having units of length) are functions of the diffusion time or distance from the source and are estimated from the dye-plume concentration data. For example, in the lateral direction, S_y is determined by the relation

$$S_y = \left[\frac{1}{\Sigma N_j} \Sigma N_j y_j^2 - \left(\frac{1}{\Sigma N_j} N_j y_j\right)^2\right]^{1/2} \qquad \ldots(2)$$

where N_j = dye concentration at lateral distance y_j measured from a reference position.

The vertical standard deviation S_z can be determined in a similar way only if vertical concentration profiles are obtained. Having estimates of S_y, S_z at several downstream locations, functional forms for S_y, S_z can be determined using regression techniques.

Plume Standard Deviations

Theory (14) indicates that for a field of homogeneous turbulence, S_y and S_z grow linearly with distance at first and then approach a one-half power growth with distance from the source. The theoretical expressions for small and large travel times are given (for the lateral direction) by

(a) $S_y^2 = \overline{v^2}\, t^2$ for small t,

(b) $S_y^2 = 2\overline{v^2}\, t_L t$ for large t,

where $\overline{v^2}$ is the rms value of the turbulent velocity fluctuations in the lateral direction, and t_L is the Lagrangian time-scale of turbulence for that direction. No theoretical expression exists for intermediate travel times. To use the equations it is necessary to have a record of the instantaneous lateral velocity component. This information was not obtained. Furthermore, the turbulence field is not homogeneous, at least in the vertical direction, and empirical forms for S_y, S_z were chosen to allow for the effects of stability and shear. Appropriate expressions for S_y, S_z for the single outlet outfall investigated are given by

$$S_y = S_{y_0} [1 + X/X_0]^m \qquad \ldots(3)$$

$$S_z = S_{z_0} [1 + X/X_0]^n \qquad \ldots(4)$$

where X_0 is the distance upstream from the center of the "boil" to the location if a virtual point source having strength Q and S_{y_0}, S_{z_0} are the standard deviations of the plume (boil) at X = o. Equations 1, 3, and 4 then constitute the diffusion model for estimating downstream concentrations of sewage effluent from an ocean outfall having a single outlet.

The initial dimensions at the surface of the rising sewage field are given by 4.3 S_{y_0} and 2.15 S_{z_0} if it is assumed that the concentration at the edges of the boil is defined as one-tenth the peak concentration at the boil center at the surface. The parameters X_0, S_{y_0}, S_{z_0}, m, and n are found by fitting Equations 3 and 4 to the dye-plume traverse data.

Diffusion Coefficient

Lateral and vertical components of the eddy diffusivity tensor (turbulent diffusion coefficient) can be determined from the profiles of dye concentration. For homogeneous turbulence, the lateral component of the eddy diffusivity for mass transport, K_y, is related to the standard deviation of concentration by

$$K_y = 1/2 \; \frac{\partial S_y^{\;2}}{\partial \; t} \; . \qquad ...(5)$$

From the theoretical relations stated earlier for S_y, it is apparent that K_y grows linearly with diffusion time at first and eventually approaches a constant asymptotic value proportional to the time-scale of turbulence. When two or more good cross sections of the plume are available, eddy diffusivity can be calculated by the relation

$$K_y = \frac{\bar{u}}{2} \; . \; \frac{\Delta S_y^{\;2}}{\Delta \; x} \qquad ...(6)$$

where u is the current speed and Δ represents a finite increment. If accurate estimates of $S_y{}^2$ and Δx cannot be obtained, then K_y can be estimated by

$$K_y = \frac{\bar{u}}{2} \; \frac{(S_y - S_{y_0})^2}{x} \; . \qquad ...(7)$$

Pollutant release rate

Assuming a first-order decay rate function for coliform bacteria, the effective pollutant release rate Q is given by

$$Q = Q_0 \; . \; \exp[-kt] \qquad ...(8)$$

where Q_0 = sewage release rate,

k = coliform die-off factor,
and t = pollutant travel time.

The die-off factor k is determined by fitting the equation

$$(MF)_t = (MF)_0 . \exp [-kt] \quad ...(9)$$

to the die-off data, where $(MF)_0$ is the initial coliform count at time zero.

Diffusion Model

The Gaussian distribution for homogeneous turbulence is a solution to the classical turbulent diffusion equation where $\bar{N}(x,y,z)$ is an estimable average concentration and the diffusion coefficients are related to the plume standard deviations as in Equation 5. $\bar{N}(x,y,z)$ is determined by averaging a large number of instantaneous concentration fields, $\bar{N}(x,y,z)$, all obtained under identical external conditions. In reality, $\bar{N}(x,y,z)$ is very difficult and costly to determine and can be approximated by a time-mean concentration field obtained with fixed position samples. However, in oceanic diffusion, the determination of the time-mean concentration field is also difficult and costly.

It is reasonable to assume, if current speed and hence turbulence level remain fairly constant with time, that $N(x,y,z)$, the instantaneous concentration field which is sampled here, does not differ significantly over a short time period from $\bar{N}(x,y,z)$. Equation 1 then is assumed to be applicable to instantaneous concentration fields as well, but only during the finite time interval that current speed and turbulence level remain constant.

The diffusion model used here and assumed to be applicable to single outlet ocean outfalls where the sewage rises to the surface and forms a "boil" is given (from equations 1, 3, 4, 8) by

$$\frac{N}{N_j} = \frac{\exp [-kt]}{D_p} . [1+X/X_0]^{-(m+n)} . \exp[-1/2(y/S_y)^2-1/2(z/S_z)^2] \quad ...(10)$$

where N = concentration at any point (x,y,z),

N_j = initial concentration in outfall pipe,

D_p = peak dilution in rising to the surface

$= N_i/N_p$

$= \pi\bar{u}\, S_{y_o} S_{z_o}/Q_o$, . . .(11)

and N_p - peak concentration at point (0,0,0),

The average dilution ($D_a = N_i/N_a$, where N_a is the average concentration in the boil) is related to the peak dilution by

$$D_a = 2.47 D_p. \quad . . .(12)$$

Equations 3 and 10 (with k = o and y = z = o) are plotted in Figures 4 and 5 with four values of the exponent (m + n).

Figures 4 and 5 illustrate that surface concentrations close to the boil $x/x_o < 1$ are practically unaffected by the plume growth rate which is a function of turbulence level. The predominant variable at close distances to the boil is the size of the boil itself which is related to the initial dilution, D_p, which in turn is dependent on sewage/sea water density difference, water temperature profile or stability, current speed, current vector profile, discharge port conditions, and water depth. At large downstream distances, $X/X_o > 10$, the initial "boil" size loses its effect on axial concentration and the plume grows with distance as would an equivalent point source.

The surface layer is an extremely complex system of motions having a wide range of scales. In some instances (perhaps most instances) advective effects are more crucial than turbulence effects. On windy days, however, turbulence will be generated both by shear of the wind-driven currents and by thermal instability due to surface cooling. For deep waters, on-shore surface currents will be deflected towards the right (looking at the shore) when the wind is blowing towards the shore. For shallow waters, the effects of bottom friction are felt at the surface with the result that on-shore currents will be deflected southward with a NE wind and northward with a SE wind. Theoretically, the worst situation occurs with NE winds in which case the surface currents

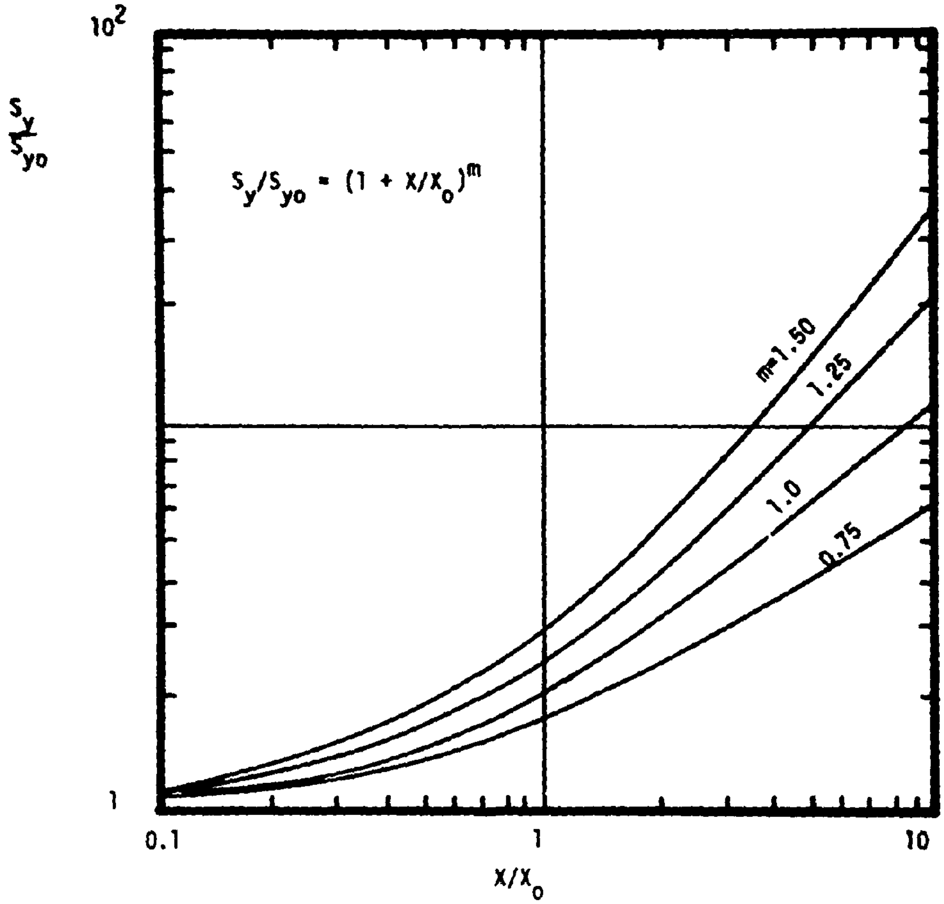


FIGURE 4 - LATERAL STANDARD DEVIATION VS. DISTANCE DIFFUSION MODEL

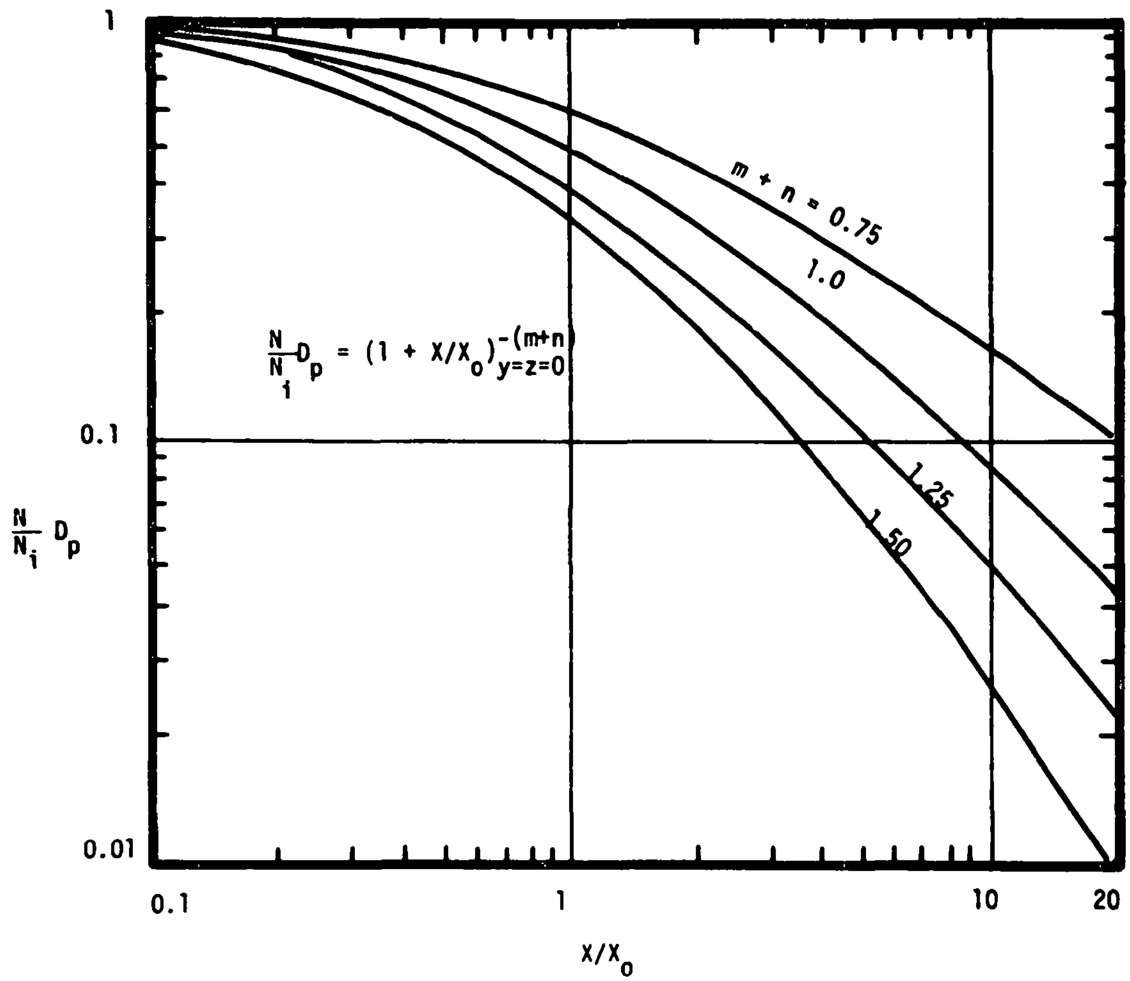


FIGURE 5 - SURFACE AXIAL CONCENTRATION VS. DISTANCE DIFFUSION MODEL

are subjected to a spiral motion changing from clockwise to counter-clockwise moving shoreward from deep to shallower water. The effect of strong winds on the surface sewage-field then, is to disrupt the plume making analytical analysis very difficult. With light winds, or with winds blowing parallel to the existing current direction, the sewage plume would be near symmetrical and analytical models can be utilized.

Another important effect of strong cross current winds is that the sewage will be mixed deeper on the windward side of the plume causing a marked skewness of lateral concentrations. Also, striations (streaks) or separations develop in the plume during the initial stages of diffusion and these are amplified with time. The resulting sewage-field pattern will have one or more concentration peaks at any cross section.

The structure beneath the surface is even more complex. To correctly consider vertical diffusion, a knowledge of the differences in the complexity of the structure at various levels is essential. In general, the dispersion varies from layer to layer and the presence of internal waves and horizontal shear gradients have a direct effect on vertical diffusion. Even in the absence of surface effects, sufficient turbulence may be generated by the presence of internal waves and horizontal shear gradients so as to disperse the sewage in the vertical direction. This effect becomes more pronounced downstream since the initial buoyancy of the sewage is rapidly decaying with travel time as the sewage field becomes more dilute.

Extensive field investigations would then appear to be the most effective source of estimating sewage-field concentrations. The combined interplay of empirical and analytical studies should provide reliable pollution forecasting procedures.

SECTION V

RESULTS OF STUDIES

This section contains a description of the results of each of the four diffusion studies and of the various aquatic studies conducted over the three-year period from July 1968 to July 1971. A discussion of the results is contained in Section VI.

Ocean Diffusion Studies

A general description of the oceanographic and meteorological conditions existing at the time of each of the thirteen experiments is presented in Table 2. The letters "P" and "H" preceding the experiment numbers signify the Pompano and Hollywood outfalls, respectively.

Pompano Studies, August 1968. Six experiments involving the release and subsequent sampling of tracer dye were conducted at the Pompano outfall in August, 1968. The water temperature was approximately 85°F for all of the experiments and a vertical temperature gradient of approximately -0.1°F per 5 feet was observed.

Little information concerning a diffusion model can be obtained from experiments P2 and P4 because of the very low current speed. The dye-plume during experiment P2 was first observed to be in a northeasterly direction, then southwardly with the tide-line shortly before low tide. Two hours later the dye-plume was heading southwest. In spite of the erratic current pattern, the dye field was continuously sampled. Because of the extreme calm conditions encountered during experiment P4, no downstream traverses were made. However, the "boil" appeared intermittently and several traverses were made to determine the dilution of the rising sewage-dye mixture between the month of the outfall and the surface.

Experiment P6 initially offered great promise of meaningful data concerning diffusion modeling. An extremely well defined plume, as shown in Figure C3, was observed to be moving directly north at the beginning of the traverses approximately 2 1/2 hours after the start of release. Several traverse were made downstream to approximately 3000 feet from the source. However, the plume was very narrow and plume width (hence, values of S_y) could not be determined to a sufficient degree of accuracy from the shore-based transit stations. Traverses were then made at approximately 6000 feet from the source and here it was observed that the plume had split-up into at least three sections covering a width of approximately 3000 feet. At 15,000 feet downstream from the source, the lateral spread of the dye-plume sections was at least 5000 feet. The reasons for the plume break-up are attributed to a 20 foot slick-line which moved in-shore and crossed the plume as well as striations which undoubtedly had developed in the direction of the 10 know wind which was at an angle with the plume axis.

TABLE 2

OCEANOGRAPHIC AND METEOROLOGICAL CONDITIONS DURING DIFFUSION STUDIES

Exp.	Date	Wind		Current		Sea	Tide*	Remarks
		Knots	From	Knots	From	Ft.		Plume Behavior
P1	8/06/68	8	NE	0.3	SSE	2	L	Slightly meandering
P2	8/07/68	12	NE	0.1	-	1	L	No definite plume
P3	8/08/68	8	E	0.3	SSE	2	L	Partly submerged
P4	8/12/68	8	SE	0.1	-	calm	H	No definite plume
P5	8/14/68	12	SE	1.4	S	4	H	Meandering
P6	8/15/68	10	SE	0.6	SE	3	H	Extremely narrow plume
P7	12/10/68	15	NE	0.4	NE	5	HL	Bent towards shore
P8	12/17/68	10	N	0.55	N	2	L	Partly submerged
P9	12/17/68	5	N	0.4	NNE	2	H	Well defined
P10	12/18/68	12	NE	0.6	N	4	L	Well defined
H1	5/20/69	5	NE	0.6	SE	2	L	Bent towards shore
H2	12/11/69	15	NW	0.3	N	1-2	L	No definite plume
H3	12/12/69	20	N	0.35	N	1-2	L	Well defined

*Either low (L) or high (H) tide occurred during experiment of approximately 4 hours duration.

As mentioned earlier, experiments P1, P3, and P5 were used in a diffusion model study. Experiment P3 offers more realistic data, since the dye was completely mixed with the sewage field. For this experiment, dye concentrations were also obtained in the outfall pipe. Divers positioned the dye sampler in the pipe outlet, and the concentration of the dye in the dye-sewage mixture was determined by diluting the samples and running them through the fluorometer. The divers observed that the plume rose nearly vertically for approximately 10 feet above the mouth of the outfall then the plume sharply leveled off, traveling at a slight upward angle to the water surface where a "boil" formed. The dye-concentration within the "boil" was 4.81 ppb. This corresponds to an initial dilution due to rising of 92:1 for the conditions existing during experiment P3. An increase in release rate will cause a corresponding decrease in dilution. The observed reduction then, is valid only when one sewage pump is on line (approximately 2600 GPM) as was the case for experiment P3. Results of coliform counts are presented in Table 3.

Pompano Studies, December, 1968. Four successful tracer-dye studies were conducted at Pompano during December, 1968. A 30 percent rhodamine dye solution was continuously released at a constant rate directly into the sewage at the Pompano Beach lift station. The sewage flow rate was approximately 2600 GPM through the 7200 foot length of 24-inch diameter outfall pipe. It was observed that the sewage-dye mixture surfaced approximately 100 minutes after the start of the dye injection. Once the sewage-dye plume had become established, repetitive traverses of the plume were made. Coliform die-off studies were also conducted and the combined effects of natural die-off and dilution of the sewage plume are presented.

Because of the extremely high coliform die-off rates observed during the summer studies at Pompano, the worst situation concerning pollution was expected to occur during the winter. Figure 6 shows the approximate positions of the plume center-lines for both the summer and winter dye experiments. The worst of these, from a pollution standpoint, is the winter experiment, Number P7. This is obvious since the plume centerline is the closest to the shore-line. However, winter experiment Number P9 had the highest center-line concentration. Both of these plumes are presented in Figure 7. The western boundary or edge of each plume is located at a distance of 2.15 S_y from the plume center-line and the concentration at a point on the plume edge is 10 percent of the centerline concentration adjacent to that point. In Figure 7, plume-edge concentrations are shown at 2000 foot intervals. The concentrations, MPN/100 ml, are per 1000 GPM of sewage discharged and die-off has been considered. Wind directions are also shown. These two plumes are indicative of the phenomena which take place. In one case, the wind is along the plume axis and the resulting narrow plume has relatively high concentrations. For the other case, the wind is strong and towards the shore causing the plume to bend in the direction of the wind. This spiral action promotes widening of the plume and relatively low concentrations result. Should this latter situation (strong on-shore winds) persist for several hours, there is little doubt that a pollution hazard could exist provided the sewage discharge rate was of the magnitude of 10,000 GPM or more.

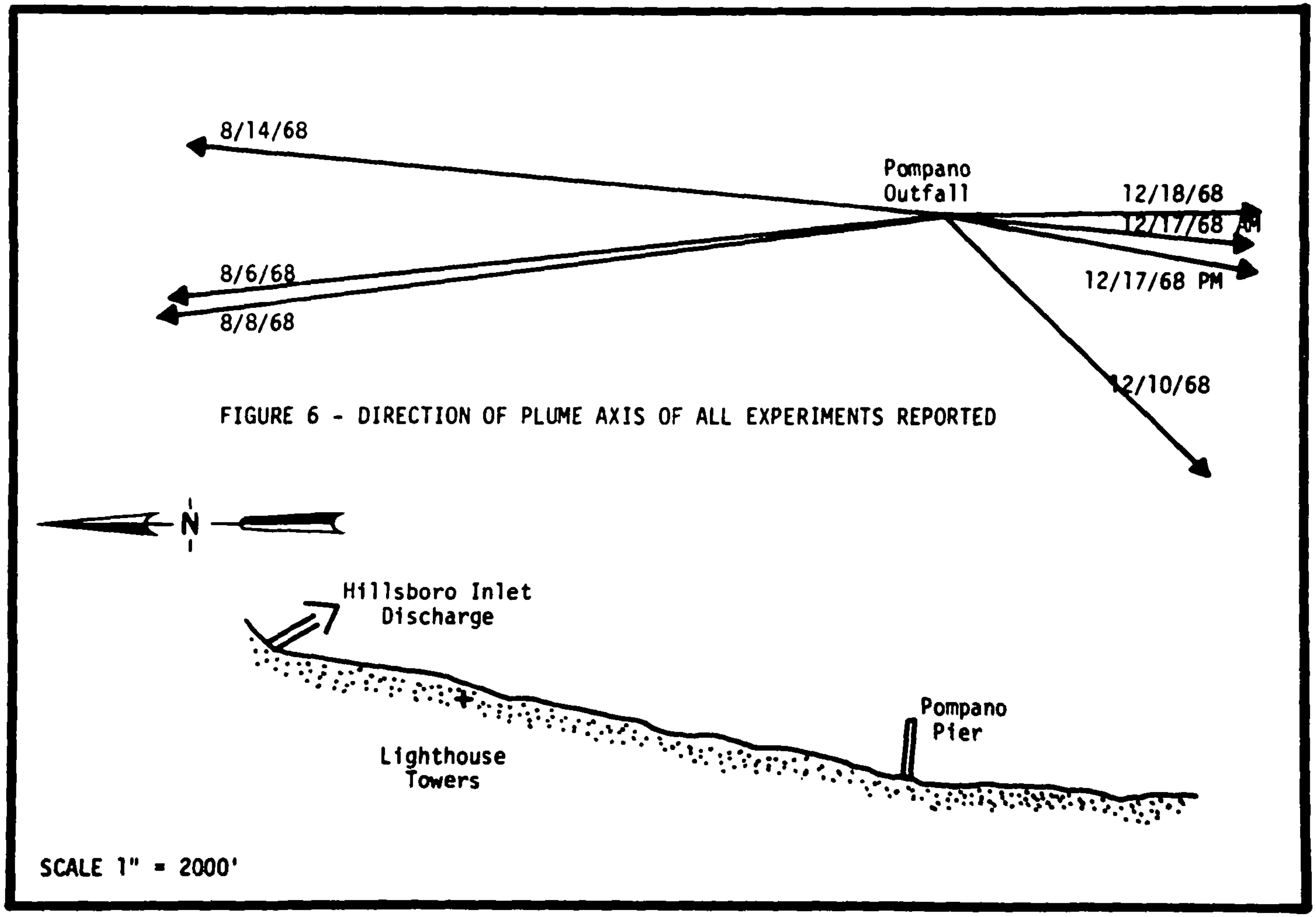
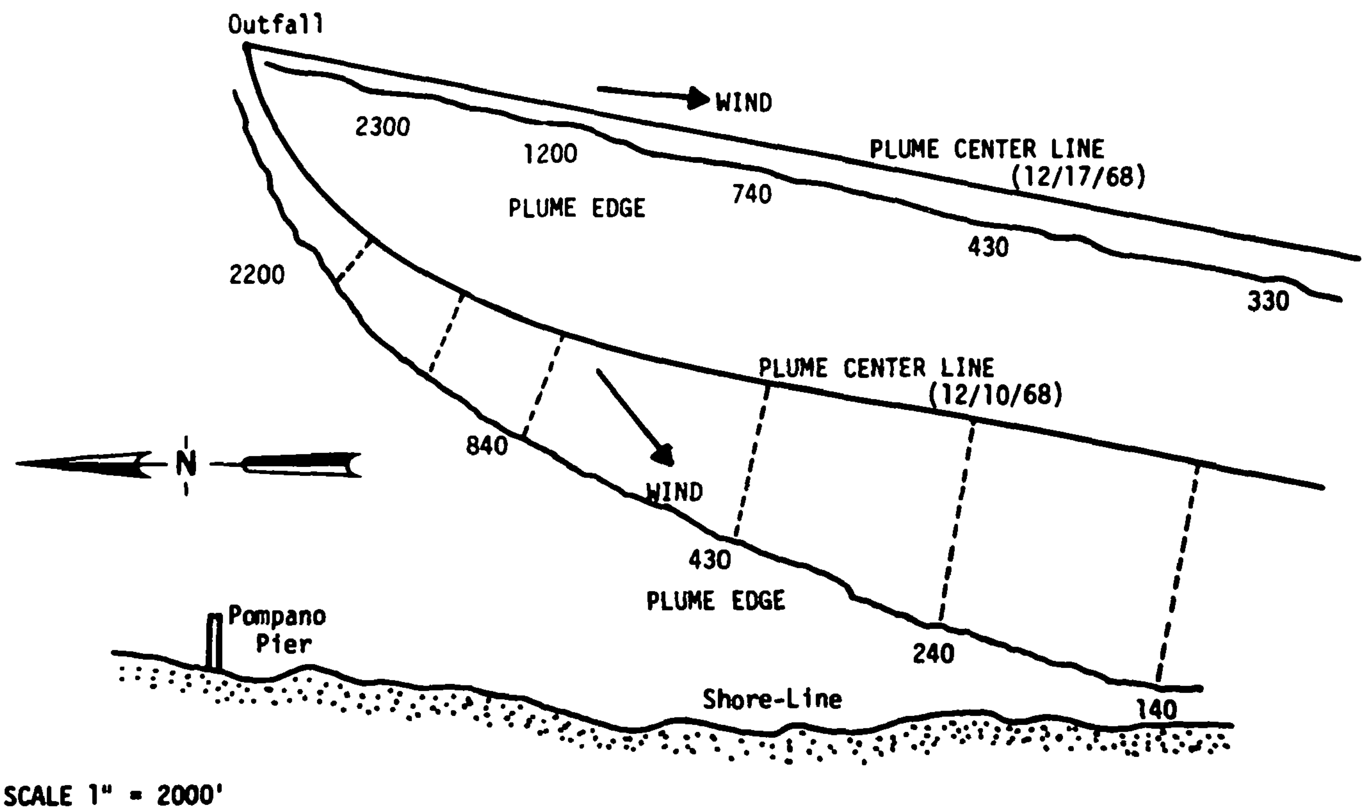


FIGURE 6 - DIRECTION OF PLUME AXIS OF ALL EXPERIMENTS REPORTED

FIGURE 7 - COLIFORM CONCENTRATION (MPN/100 ML/1000 GPM) ALONG WESTERN EDGE OF SEWAGE PLUME AT 2000' INTERVALS. EXPERIMENTS P1 AND P5. (COLIFORM DIE-OFF CONSIDERED.)



Includes dilution

TABLE 3

COLIFORM DIE-OFF DATA
POMPANO BEACH, FLORIDA

Trial 1. August 7, 1968	Trial 2. September 4, 1968
<u>Zero time</u>	<u>Zero time</u>
2×10^6 Coliforms/100 ml.	19×10^5 Coliforms/100 ml.
<u>1 hour</u>	<u>1 hour</u>
61×10^4 Coliforms/100 ml., Sample #1	30×10^4 Coliforms/100 ml., Sample #1
71×10^4 Coliforms/100 ml., Sample #2	40×10^4 Coliforms/100 ml., Sample #2
<u>3 hour</u>	<u>2 hour</u>
25×10^3 Coliforms/100 ml., Sample #1	29×10^3 Coliforms/100 ml., Sample #1
16×10^3 Coliforms/100 ml., Sample #2	16×10^3 Coliforms/100 ml., Sample #2
<u>6 hour</u>	<u>4 hour</u>
15×10^2 Coliforms/100 ml., Only Sample	24×10^2 Coliforms/100 ml., Sample #1
	50×10^2 Coliforms/100 ml., Sample #2
Water temperature - 85°F average.	<u>6 hour</u>
	7×10^2 Coliforms/100 ml., Sample #1
	15×10^2 Coliforms/100 ml., Sample #2
	Values for samples #1 and #2 represent averages of three determinations each sample.
	Water temperature - 89°F average.
	Salinity - 33.54%.

Profiles of measured dye-concentrations and the fitted Gaussian distributions presented in Appendix A show that the data can be represented reasonably well by a Gaussian distribution, particularly if wind and current are in the same direction. This is evidenced by experiments P7 and P8. On the other hand, when the wind cuts across the plume, the dye (and the sewage) will be mixed deeper on the windward side of the plume, resulting in a skewness of the concentration distribution. This situation is illustrated in Appendix A by experiment P10.

Hollywood Study, May, 1969. One successful experiment was conducted at the Hollywood outfall in May, 1969, at which time the outfall had been temporarily terminated at about 5000 feet offshore. The sewage flow was approximately 10,000 GPM through the 60-inch outfall pipe. The dye was first observed at the terminus about 205 minutes from the time it was first introduced into the lift station. The terminus itself was oriented such that the effluent was discharged straight upward through a 48-inch port.

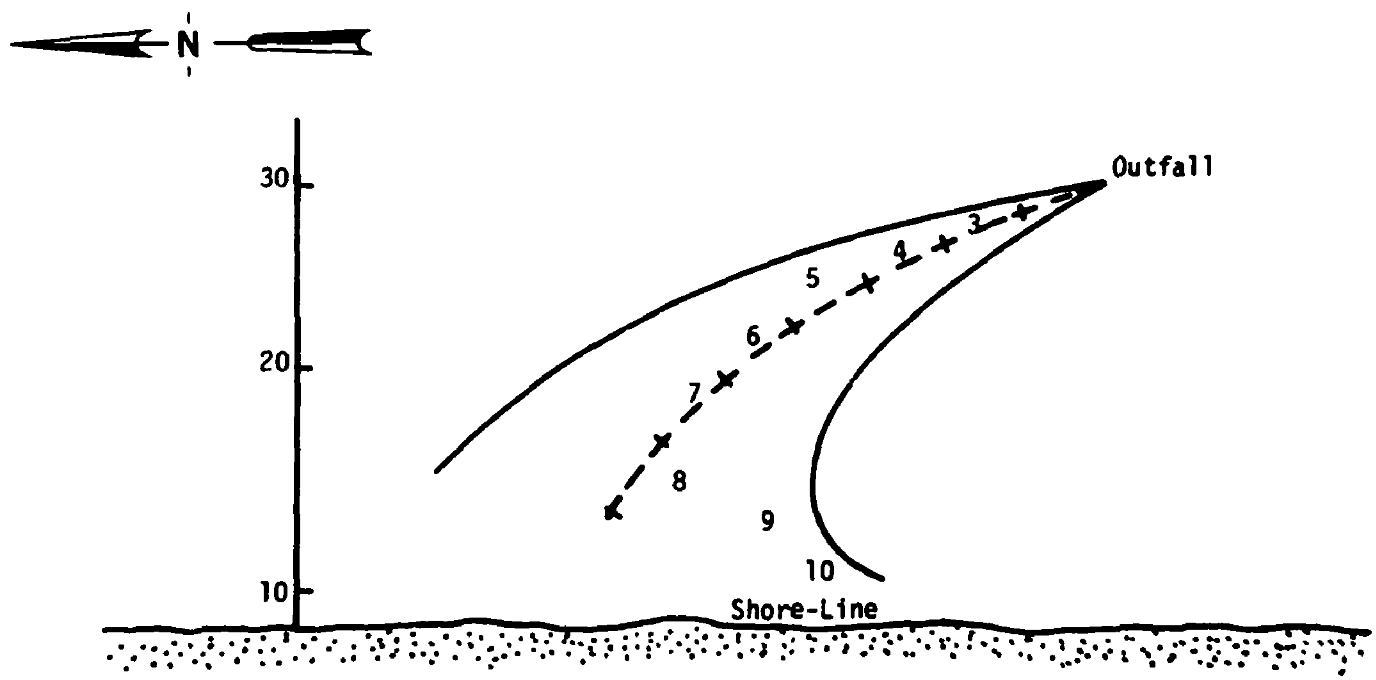
The plume headed west-northwest from the boil toward the shore as shown by Figure 8. Traverses were made after the plume was established and aerial photography was also used to define the plume (Figure C4). Divers sampled the end of the pipe for rhodamine concentration, salinity, temperature, and coliforms. These data are presented in Tables 4-6. Coliform samples were collected concurrently with the rhodamine on various locations, with dilution and plating being accomplished within five minutes of collection. Locations of sampling points are shown in Figure 8. The resulting coliform counts are contained in Table 6. Dye was released again on the following day; however, the oceanographic conditions were such that a large spiral was formed which had no distinct axis. One part of this plume split off and headed ashore. It could be followed visually about one-third of the distance to the shoreline. No fluorometry was done.

It was obvious that an unfavorable situation had been investigated wherein the sewage plume was directed toward the shore where it presented a possible pollution hazard. However, it was assumed that the increased sewage travel time and initial dilution and dispersion resulting from the extension of the outfall to its full length would prevent such an unfavorable situation.

The data used for estimating the plume standard deviations were obtained within the first 4200 feet of plume. Beyond this distance, the plume lost its identity because of the southerly drift of the near shore waters. The center-line concentration was reduced by a factor of approximately 15 during the first 4200 feet of travel. Combining diffusion and initial dilution then, the overall reduction in center-line (peak) concentration at a distance of 4200 feet downstream (approximately 1 1/2 hours travel time) is 150:1. Beyond 4200 feet, the data are practically meaningless because

FIGURE 8 - SEWAGE-DYE PLUME PATTERN
HOLLYWOOD, FLORIDA MAY 20, 1959

- LOCATION OF POINTS SAMPLED FOR
COLIFORM COUNTS



SCALE 1" = 2000'

TABLE 4

CONCENTRATION DATA

Experiment 1, May 20, 1969

DYE PLUME

1. Dye Release Rate, 3.24 lb/hr
2. Calculated Initial Dye Concentration, 720 ppb at outlet
3. Measured Initial Dye Concentration, 510 ppb at outlet
4. Peak Dye Concentration at Boil 70 ppb
5. Peak Initial Dilution = 7.3:1 (Based on Item 3)
   10.3:1 (Based on Item 2)
6. Lateral Standard Deviation, $S_y = S_{yo}(1 + X/X_o)^{1.29}$
7. Vertical Standard Deviation, $S_z = S_{zo}$
8. X_o = 600 Ft., S_{yo} = 21 Ft., S_{zo} = 3 Ft.
9. Boil Width, 4.3 S_{yo} = 90 Ft.

SEWAGE PLUME

1. Sewage Release Rate, $Q = 1200\ Ft^3\ min^{-1}$
2. Measured Initial Coliform Count, $N_i = 2 \times 10^6$/100 ml at outlet
3. Average Coliform Count at Boil, $N_a = 4 \times 10^4$/100 ml
4. Average Initial Dilution = 50:1
5. Calculated Average Initial Dilution, $7.8\bar{u}\ S_{yo}S_{zo}/Q$ = 25:1
6. Calculated Peak Initial Dilution, $\pi\bar{u}\ S_{yo}S_{zo}/Q$ = 10:1
7. Surface Concentration Model, $N/N_i = 0.1\ (1 + X/X_o)^{-1.29}\ \exp-[y^2/2Sy^2]$

TABLE 5

COLIFORM COUNTS AT BOIL, HOLLYWOOD OUTFALL

Date	Coliforms/100 ml	Previous 24-hr. Rain
3/27/69	4.2×10^4	0.69"
4/03/69	1.3×10^6	0
4/11/69	4.3×10^5	0.13"
4/21/69	2.1×10^7	0
4/30/69	4.7×10^7	0
5/15/69	2.9×10^5	0.45"

TABLE 6

COLIFORM COUNTS

Experiment 1, May 20, 1969

	Grab Sample* Location	Coliforms/100 ml
1	(boil)	4×10^4
2	(outfall outlet)	2×10^6
3	(7 ft.)	6×10^4
4	(2 ft.)	6.6×10^3
5	(2 ft.)	2×10^3
6	(2 ft.)	23
7	(2 ft.)	33
8	(2 ft.)	37
9	(2 ft.)	38
10	(2 ft.)	43

*See Figure 6.

of the slowly shifting current which had spread the plume in most directions. The grab samples taken at locations 6-10 (Figure 8), for example, show lower than expected counts since they were most likely taken in the southern edge of the sewage field. Also, the travel time of these samples cannot be estimated, hence, die-off cannot be properly accounted for. For meaningful coliform concentration results, it is necessary to know the travel time of the sample taken.

In all, the overall reduction in coliform concentration was observed to be 1000:1 after approximately 1 1/2 hours of travel at a distance of 3000 feet from the shore-line.

Hollywood Studies, December, 1969. During December, 1969, two experiments (H2 and H3) were conducted at the Hollywood outfall which had recently been extended to 9700 feet. A 20 percent Rhodamine-WT dye solution was continuously released at a constant rate into the sewage at the Hollywood lift plant. The sewage flow rate was approximately 1300 cubic feet per minute through the 60-inch outfall.

On December 11, the current direction changed practically a full 360 degrees during experiment H2 with the result that no sewage-dye plume was available for sampling. However, a good estimate of initial dilution of the sewage-dye plume in rising to the surface as well as *in situ* coliform counts were determined.

The second experiment, H3, on December 12, was successful in that a well defined plume was available for sampling. The results of both experiments are presented in Tables 7-11.

As was the case for the majority of all diffusion studies, the water temperature was relatively constant with depth (see Table 11); therefore, some degree of diffusion in the vertical direction was expected. A plume did not develop for experiment H2 although an average current speed of 0.3 knots was obtained. The plume was directed toward the south in experiment H3 at an average speed of 0.35 knots and the plume was found to grow in the lateral direction to almost the first power with distance from the boil. The actual calculated value was 0.996. Sampling in the vertical direction was not done because of time limitations.

In addition to the two diffusion studies, coliform die-off trials were conducted on December 9. Two mixtures of sewage and sea water were prepared in 20 gallon pails which were floated in the inlet water near the Florida Ocean Sciences Institute's laboratory. Subsequent coliform counts were made to determine the effects of direct sunlight on coliform die-off. One of the pails was covered while the other was exposed. The die-off results presented in Figure 9 are not in agreement with those found in the earlier studies. In fact, they were found to be at least one order of magnitude greater than those previously found. However, the coliform reduction in one container relative to that in the other clearly shows that for the travel times of interest (about four hours) a further reduction of ten to one will occur during conditions of clear, sunny skies (exposed container) as opposed to overcast conditions (covered container). This would also imply that nighttime coliform reductions are less than those occurring during daylight hours.

TABLE 7

COLIFORM COUNTS AND LOCATION
(Hollywood Outfall)

Date	Sample Location	Water Depth	Coliforms /100 ml	Dye Concentration
		(ft.)	(MF)	(ppt)
12/11/69	Sewage plant	-	60×10^6	260.*
Experiment H2	Outfall outlet	90	20×10^6	310.
	At boil	4	13×10^5	10.4
	At boil	4	14×10^5	8.1
	At boil	3	16×10^5	5.1
	At boil	2	18×10^5	6.9
	400 ft. N of boil	6	35×10^4	0.96
	900 ft. E of boil	2	74×10^4	3.4
	2000 ft. NE of boil	3	35×10^4	0.43
12/12/69	Sewage plant	-	NA	540.*
Experiment H3	At boil	3	50×10^4	9.3
	At boil	3	30×10^4	6.2
	1500 ft. S of boil	3	9×10^4	1.7

*Since these values are not in agreement, initial concentrations of dye determined by sampling at sewage plant may be in error.

TABLE 8

CONCENTRATION DATA

DYE PLUME	Experiment H1 12/11/69	 H2 12/12/69
1. Dye Release Rate, lb/hr	1.62	1.88
2. Calculated Initial Concentration, ppb*	350	385
3. Measured Initial Concentration, ppb	310	NA
4. Peak Concentration at Boil, ppb	12.0	12.4
5. Peak Initial Dilution, D_p	26:1	31:1 (Est.)
6. Lateral Standard Deviation	NA	$S_y/S_{yo}=(1+X/X_o)^{1.00}$
7. Vertical Standard Deviation	NA	NA
8. X_o, S_{yo}, S_{zo} (ft)	-	800, 124, NA
9. Boil Width, 4.3 S_{yo} (ft)	-	530
10. Calculated, S_{zo} (ft)**	-	2.9

SEWAGE PLUME	H1 12/11/69	H2 12/12/69
1. Sewage Release Rate, Q, $ft.^3$ $min.^{-1}$	1300 (Est.)	1300 (Est.)
2. Initial Coliform Count, MF/100 ml***	40×10^6	NA
3. Peak Coliform Count at Boil	18×10^5	40×10^4
4. Peak Initial Dilution, D_p	22:1	-

*Ratio of dye release rate to sewage release rate.

***Average of counts taken at sewage plant and at outfall outlet.

**Calculated from $\pi \bar{u} S_{yo} S_{zo}/Q = D_p$.

TABLE 9

FLUOROMETER CALIBRATION

Scale Setting	Scale Factor (ppb per chart division)
1X	2.35
3X	0.86
10X	0.31
30X	0.071

TABLE 10

DESCRIPTION OF EXPERIMENTS*

Experiment Number	Date	Dye Release (20%) Amount(lbs)	Dye Release (20%) Time(min)	Current Knots	Waves Ft.	Wind Knots	Sky %Clear
H1	12/11/69	48.4	359	0.3	1-2	NW15	80
H2	12/12/69	62.7	400	0.35	1-2	N20	80

*Conducted approximately 3 hours after high tide.

TABLE 11

WATER TEMPERATURE, SALINITY PROFILE
(Near Hollywood Outfall)

Location	Temperature °C		Salinity %	
	H1 12/11/69	H2 12/12/69	H1 12/11/69	H2 12/12/69
Surface	23.55	23.85	35.75	33.59
10 ft.	23.64	23.85	35.85	33.57
30 ft.	23.65	23.90	35.86	33.63
50 ft.	23.84	23.81	36.00	33.67
80 ft.	24.00	23.88	36.18	33.45

Biological Studies

Initial Hollywood Study, July, 1968. The first study conducted at Hollywood, prior to outfall construction, was a transect in which nine samples were collected. Table D1 in the Appendix shows the composition of the plankton in the top two feet of water. There were a total of 42 species, a relatively small number. Three of these, indicated by asterisks, are provisional names assigned by the investigators so that the organisms might be referred to in the future. These results were similar to previous Pompano studies in that the numbers showed a tendency to decrease with increasing distance from shore.

Two cores, from the 15-foot depth inshore, were found to be fine sand with no evidence of silt. Table D2 in the Appendix contains a list of the species found. The number of organisms is quite small for an interface sample, and the lack of ciliates--both of the species listed could be from the plankton--is quite puzzling.

There were small numbers of *Euglena sp.* in the cores, and this may be a significant organism in that this was the first record of *Euglena* for the Florida waters. Its previous appearances in Great South Bay in New York and in South San Francisco Bay had been preceded by organic pollution.

The numbers of organisms in the catch from four tows off Hollywood are shown in Table D3 in the Appendix. In each case, these were the organisms strained from a column of water, eight inches in diameter and about 100 feet long, with a volume of about 150 liters. Using these figures, there would have been very few organisms *per liter*. In this case, as in previous studies at Boca Raton, the population shown by towing was very small. Total numbers were not added because of size diversity and because the net was not calibrated. The data from two Gulf Stream tows and one inshore tow are presented in Table D4 in the Appendix. The dominant group in both cases was Dinoflagellata. *Actinaria* were numerous but no Radiolaria were found. The total number of organisms was again quite small.

Hollywood Study, August 1968. A set of transect samples out to the 10,000 foot point were analyzed on August 31, 1968. The results are presented in Table D5 in the Appendix. It was similar to the July set in that it showed few species--39--and few numbers per ml of raw water. The numbers per ml, the lowest ever recorded for the coastal area of southeastern Florida, indicated a very low nutrient level. A set of cores from 10, 54, and 60 foot depths was examined on August 30, 1968. A list of the organisms found is shown in Table D6 in the Appendix. A rather surprisingly large number of species (110) was secured. Ciliates were particularly plentiful with more than 39 being identified. Whatever the overlying water lacked in nutrients, the bottom did not. The organisms were not only widely varied in the interface but were also very numerous.

Hollywood and Boca Raton Studies, October 1968. Samples were taken at 1000 foot intervals from the beach out nearly to the Florida Current at Hollywood. Table D7 in the Appendix shows the species and numbers per ml found in eight samples. More than 65 species occurred in the plankton and some samples had relatively high numbers per ml. Most of the plankton consisted of diatoms. There were many species of dinoflagellates but relatively few cells. This bloom of mixed diatoms produced a considerably higher population than had been observed in the August study, but still not high enough to cause discoloration of the water. The higher population probably represents a more nutrient-rich water.

This set of transect samples had the highest population per ml of all previously recorded from Boca Raton to Hollywood. While three species of diatoms were primarily responsible for the high population, the populations of other species were also high.

Several cores were taken from Hollywood and Boca Raton. Table D8 in the Appendix lists the organisms from rather moderate depths at Boca Raton and Table A9 lists those from lesser to moderate depths at Hollywood.

There was a rather frequently occurring species list for all interfaces, but there were also organisms which rarely occurred. It is felt that the depths of water involved (50 to 90 feet) were not critical for chlorophyll containing organisms. Also, for many species, an interface within two or three feet of the surface yielded as many organisms as one at 90 feet. Nevertheless, there were some species which seemed restricted to the deeper water.

The interface at Boca Raton was a rather tough crust. Red patches, due to filamentous blue green algae and especially to the three species of Lyngbya listed, were apparent even without magnification. These cores also contained a large number of colorless Euglenids, a relatively small number of diatom species, and a large number of ciliate species. There were five species, denoted in the table by "p.n." and an asterisk, which the investigators have failed to find in available literature and which are believed to be new.

The Hollywood cores (Table D9) were from water containing fine debris and somewhat lowered visibility. The smaller number of species was not explicable. There were fewer Euglenids and ciliates than in the cores taken at Boca Raton, and, due to the softer crust, much fewer numbers of Lyngbya. This blue-green algae apparently has a prominent role in crust building due to its persistent and tough sheaths. This is not the case with the filamentous sulfur bacteria which were abundant at Hollywood.

Curiously, even in cores taken at 30 feet, the blue-green algae were pink in color. Diatoms were abundant but ciliates were sparse. All species of ciliates observed were common. The Hollywood cores also contained three possibly new organisms.

Hollywood and Pompano Beach Studies, February and March 1969. Transects were analyzed at Pompano Beach and at Hollywood in February 1969 and at Pompano Beach in March. Slides left exposed for 48 hours were counted for each transect. A total of 17 cores were obtained, four in February from Hollywood and two in March from beyond the Pompano outfall at a depth of 150 feet.

Table D10 in the Appendix is a list of the species found in each of the three transects. It is quantitative in that it shows (1) the maximum number in any one of the samples at each of the three locations, (2) the total number of species for each sample, and (3) the number of samples which contained the species in the volume of water (100 ml) examined. Only 107 species were found and only about 20 of these were common to all three locations. Considering that 26 samples were examined, the diversity of species was not great. All major groups of plankton algae and protozoa were represented, but there were a predominance of diatoms and dinoflagellates along with a limited number of protozoa except for zooflagellates. The conditions represented are presumably of a highly mineralized continental shelf water but one low in nutrients.

As illustrated in Table D11, there was little difference between the results of the Hollywood transect and the results of the two at Pompano. There were no indications of blooms or of sewage enrichment, either in the vicinity of the outfalls or at any point along the transects.

All of the species listed in Table D10 are common in inshore waters. Some of them have not been located in available literature and may be new or undescribed species, but this is to be expected in the examination of so many samples.

Table D12 is a list, without numbers per ml, of an assemblage of suspended and swimming organisms taken in March, 1969, just above the Pompano cores. Half of these organisms did not occur in the 26 samples of Table D10. It was quite interesting that only seven of the 28 species were non-photosynthetic. All of the photosynthetic forms were motile and presumably healthy. According to the divers who took the samples, the light at this depth (150 feet) was good.

Many of the deep water species were also common in the interface of cores taken from depths of 60 to 100 feet but were extremely rare in surface plankton. Such species are apparently able to move a short distance above the interface but are normally bottom dwellers. If swept into suspension, they will attach to any solid substance with which they happen to come in contact. Four of the above species were commonly found in samples from moderate depths. Yet even the diatom, Asterionella kariana, which was found in very large numbers at moderate depths, was never observed in the surface plankton.

Table D13 in the Appendix is a list of species in four interface samples at Hollywood at depths of 30 to 80 feet, and those in six interface samples at depths of 90 to 150 feet at Pompano Beach and Delray Beach. Three of these, as indicated in the table, were taken directly beneath the sewer outfalls.

The ten samples of Table D13 should include the more common species for sandy bottoms at considerable depths. That an area of three or four square inches is far from inclusive of the whole species group is evident by comparing the total number of species, 143, for the ten cores with each individual core. Only one core approximated even half the total number of species. Virtually all of the samples were sand or sand-shell of varying degrees of coarseness and any organic matter present would have been interstitial. Nevertheless, organics were in sufficient quantities that substantial numbers of organisms could be present. Diatoms were usually most abundant. If it were possible to identify all of the diatoms and the other species as well, the total species number would substantially increase.

There were no sharp differences between the Hollywood cores and those from the other locations. There was some evidence that more organic matter was present in the Pompano-Delray cores; the comparable cores in columns 6, 9, and 10 reflected this by their larger number of species. This was to be expected since the Pompano Beach, Boca Raton, and Delray Beach ourfalls discharged raw sewage. Cores 5, 7, and 8 showed a decided effect of sewage by having large numbers of sulfur bacteria with an almost total reduction of diatoms. In fact, these cores had ciliates as the greatest number of species and greatest biomass.

A mound, about 15 inches high and three to four feet across, which had built up beneath the Pompano outfall during a period of minimal current action, was cored on March 17, 1969. It was found to be composed mostly of sand with some large granules which appeared to be a tarry material. Material from the mound was quite malodorous.

The mound material contained a high sulfur bacteria population of the genera Thiovulum, Thiothrix, and certain species of Beggiatoa. Free living bacteria were also abundant, as evidenced by both visual observation and by the biota present. The biota also included three or more species of worms in abundance (as many as six in a two inch core) and two or more copepods. One diatom, Navicula, was recorded. The remaining species were large ciliates. In general, the biota of the mound differed sharply from that of other areas tested.

Judging from the sulfur bacteria, the dominance of facultative ciliates, and the lack of photosynthetic organisms, conditions in the interface beneath the outfall were anaerobic.

Due to the apparent difference between the plankton in the Florida Current and that of the shelf water, these two areas were sampled extensively during the February-March study. Ten samples were taken on February 11, at the depths indicated in Table D14, using both a Clarke-Bumpus sampler and a water bottle. A No. 20 net was used as well as a centrifuge for nannoplankton. Two more surface towings, one in the Florida Current and one in shelf water, were made on February 14, again on March 18, and once again on March 20. Since the catches in the later samplings were quite similar to those for the first shown in Table D14, no tabulation is presented. However, a list of species different from those in Table D14 is presented in Table D15. The latter table provides an indication of the uniformity of the two locations.

Hollywood and Pompano Beach Studies, June 23-26, 1969

In the four days of field work on this occasion, transects were run from Pompano Beach to the Florida Current and from Hollywood well out into deep water. The transects were part of a routine check designed to take into account seasonal changes as well as any effects of the incoming sewage. The Hollywood outfall had begun discharging effluent at 5,000 feet the previous March and this was the first study conducted after that time.

The sediment-water interface was also studied at both locations, in the outfall area and some distance from it, in an effort to provide a more exact study of sewage effects on bottom organisms and also to determine how far from the outfall the zone of influence extended.

The first transect was run on June 23 from the beach to the Florida Current at Pompano Beach. This followed several days of high temperatures, minimum winds, and heavy rainfall. The sampling crew reported about 18 inches of cloudy water on the surface out to Station 7 with only the last three Stations being in clear water. Salinometer checks revealed the cloudy water to be quite brackish. Stations 8, 9, and 10 had normal Florida Current salinites.

Plankton was sparse. As shown by Table A16, a total of 42 species occurred in all Pompano samples. All three Florida Current samples contained a total of 16 species of which only seven also appeared in the shelf samples.

The shelf water was markedly richer in nutrients than the Florida Current water. A small centric diatom, *Cyclotella sp.*, occurred in bloom numbers at Stations 1 to 4. The diatom, *Skeletonema costatum*, was abundant. The population, while few in species, was generally more dense than is common in this area. This was especially true of the February numbers at both Pompano and Hollywood, and while total numbers in March (Table D10) were equally high, this was usually for one station, whereas the high numbers at Pompano in June extended through the six western stations.

However, both numbers per ml and the species list suggest that the water at these 16 Pompano Beach and Hollywood stations in June was poorly fertilized. No sewage effect was evident. This was probably due to the large dilution the sewage received in relative short distances after being discharged. Large numbers of *Cyclotella* at Pompano Beach Stations 1, 2, 3, and 4 were attributed either to outflow from the inlet or to plankton patchiness. The lack of occurrence of large numbers of other species at either location provided further evidence of no fertilizing effect from the sewer outfalls. Only 73 species or genera were recognized, 42 of them in the Pompano Beach transect and 51 in the Hollywood transect.

Table D17 is a breakdown of all organisms recognized in the interface material in four cores at and around the Pompano Beach outfall, and in four cores at and around the Hollywood outfall. The species list, a total of 121, was about as large as for previous cores. Conditions in the interface are generally conducive to a much more varied biota as long as sharply restrictive conditions do not prevail. There was a decided patchy effect, illustrated by 37 species being peculiar to Pompano Beach and 46 to Hollywood while only 34 were found in both. In the time it had been in operation (three months), the Hollywood outfall had not built up a mound of blackened material underneath the outfall opening like that observed at Pompano. The four Hollywood cores also showed no restrictive influences. In fact, the core beneath the outfall gave evidence of enrichment, having more species (65) than the three somewhat distant ones. Its diatom population was the richest in recognizable species of all eight cores. The Hollywood cores either showed no effect from the sewage outfall or showed some enrichment which increased the biota in the area.

The Pompano Beach outfall had at this time built up a mound of black debris of mostly sand which was gradually increasing in overall size but not greatly in height. Table D17 indicates that the interface within this area was non-productive and probably had a high oxygen demand. At any rate, practically the only organisms present were those tolerant of hydrogen sulfide and low dissolved oxygen. This is shown in Table D17, columns 1 and 2.

Because of the blackening and because there seems to be no life other than bacteria in the mound beneath the Pompano outfall, cores were taken at Delray Beach and Pompano Beach. These were sent to Dr. Parks of Florida Atlantic University for a determination of organic content. They were extruded from the tube an inch at a time, and each five gram aliquot was dried for 24 hours at 150°C, then heated for 19 hours at 500°C.

Table D18 shows the depth below the surface at which sample was taken, and the percent of volatile matter. At Delray, the percent of matter volatilized by ignition at 500°C, was 4.95 at the surface, i.e., within the top inch, and 3.58 at the eight inch depth. The greatest loss, 7.79 percent, was within the seven inch level. The core was evidently not long enough. The same was true for the nine inches of Pompano. At Pompano, however, the percent volatilized was much higher--20.45 within the top inch, 9.42 at the nine inch depth and 39.07 at the seven inch depth. Variations in amounts of volatile matter simply represent differences in rates of accumulation at different times.

Hollywood Studies, July 7, 8, 1971

The Hollywood outfall had been discharging primary treatment effluent at 9,700 feet from the shore for nearly a year at the time of these studies. The studies essentially involved examination of surface water in transect samples from the beach eastward into the Florida Current; examination of tows made with a Clark-Bumpus calibrated plankton net towed at various depths; and examination of the water-sediment interface and some incidental sampling. The water samples were centrifuged at about 2,000 rpm for three to four minutes and then decanted by suction. The catch was studied at 100 and 400 diameters by a drop method. The drop method was also used for net and interface samples which were taken by scuba divers at 30 to 150 feet with two inch plastic tubes. The tubes were jammed into the sediment and stoppered at both ends before being brought up.

The transect usually showed the plume reaching the surface as a boil. The outfalls were at or just beyond the third reef and in approximately 90 feet of water. Samples taken in the boil often showed a sharp drop in organism content and, at times, much sewage debris. A sewage odor was often evident. The water mass was, of course, different from ocean water but it very quickly became well mixed, and a short distance from where it reached the surface, was no longer detectable insofar as the plankton was concerned.

No biological effect of the Hollywood outfall was detectable more than a few feet from where the plume reached the surface, and no bottom effects were observed at all. This contrasted with the Pompano and Delray raw sewage outfalls for which almost half an acre showed effects at times.

Table D19 in the Appendix shows the number of species for all Stations and for each Station, and the number of cells at each Station on July 8, 1971. Comparison with previous reports on the Hollywood outfall, and for the Boca Raton-Pompano Beach area, shows that this transect was typical for a three-year period. The number of species was small for any given Station. Many species recurred time after time, and a typical list of shelf organisms and one for the Florida Current existed for the plankton. While a total list of species might eventually reach several hunderd, those of frequent recurrence would form a small portion of the list.

As usual, the bulk of species consisted of dinoflagellates and diatoms. If all species could have been identified, the species list would have been much longer. As it stands, the list represents the major plankton groups other than green euglenids and silicoflagellates.

The numbers per ml were quite low with some tendency to drop as samples were taken more seaward. These numbers represent a very poorly fertilized water. Station 6, west of the boil, had the highest number, but east of the boil the numbers dropped. Numbers were lowest in the boil area and many of these organisms were dead. There is no evidence that the sewage contributed either bacteria or chemicals as nutrient enrichment. Most of the organisms in the transects were photosynthetic and autotrophic.

Since copepods are sometimes abundant in this area and are able to escape the water sampling techniques, five tows were made with a No. 20 Wisconsin plankton net. No clogging was experienced when the net was towed for approximately 100 feet in shelf water. Some clogging occurred when the net was towed for 200 feet in the Florida Current. Table D20 shows the catches per liter. Certain organisms were not counted. These included the blue green algae Skujaella which clumps very badly in the net; Lyngbya sp., also a blue green; and the large dinoflagellates, Ceratium fusus and Ceratium massiliense. The latter tow occurred in some numbers, but not in sufficient numbers to be found in a 50 ml water sample.

Table D20 also shows the numbers per liter of 19 groups or categories of organisms which were counted. As expected, copepods outnumbered all others, being most abundant close to shore but decreasing abruptly a mile out. There was about a threefold increase as towing progressed through the boil, a sharp increase west of the plume, and a drop in the Florida Current east of the plume. These differences hardly reflect an influence of the sewage but rather the very patchy distribution or swarming of copepods.

Considering the size and "appetites" of copepods and the numbers of small plankton in Table D19, it might appear that the copepods have an inadequate food supply. However, if the figures in Table D19 are multiplied by 1,000 (the number of milliliters in a liter), it would seem that the food supply is ample.

What Table D20 does show is that within the boil area the net plankton is sharply reduced. In this mixing zone there is no fresh water group to replace the net planktons which have either been killed, swept out of the area, or have been able to escape from it. Many of these organisms are good swimmers, and a one hundred foot area is not necessarily a trap for them.

The Florida Current came far inshore during the July, 1971 studies. While its presence there was reflected in the kinds of organisms, as indicated by those at Station 5, the numbers are seen to be reduced in the Florida Current. There is no indication here or in Table D19 that this area is enriched by sewage contributions from Miami Beach or Dade County.

Four cores were taken with 2-inch plastic tubing north, east, south, and west of the outfall end, and an additional one was taken in sand beneath the outfall. There was some blackening in all five samples and all contained some silt except for the one beneath the conduit opening. The interface was qualitatively studied; time was not available for a quantitative study. Examination of the interfaces was difficult in that the sandiness of the material prevented a thin spread, allowing many of the organisms to move rapidly and be rarely in the open.

Table D21 shows the organisms found in the five cores taken July 7, 1971. It should be stated this is not a complete list of the reasons given above. But in the last five years many such cores have been examined and the species recurrence is very high. In deep water such as this, it is common to find a number of organisms not possible to identify from available literature.

The heaviest populations are found in a sand-silt interface. Even at 90 and 150 feet the shelf waters had sufficient clarity so that photosynthetic species are abundant. Thus diatoms of the genera Navicula and Mastogloia were dominant numerically with great frequency, although large ciliates usually dominated in biomass. The numbers of sulfur bacteria in this interface material indicated that the dissolved oxygen was low and hydrogen sulfide was present. Numbers and biomass of the ciliates indicated a large bacterial population.

Table D21 could be for any one or more of a very large number of cores taken in the Boca Raton-Hollywood area during the previous four years. The number of species for five cores, 59, was about what had been found previously. Also, the three cores with the coarsest sand, O, N, and W, had the fewest species. E had the most silt and the largest species list. However, any one of these cores had from five to ten unidentified ciliates and fully as many diatoms. These organisms were also typical and the species could have been reported many times over. The total populations appeared to be rather more sparse than usual, but this was an estimate and not a count. In short, there was nothing unusual about the Hollywood cores, whether compared to previous Hollywood or Pompano and Delray cores. The only unusual feature was a lack of an anaerobic mound such as had been observed at Pompano.

SECTION VI

DISCUSSION OF DIFFUSION STUDIES

A summary of the results of all of the diffusion studies is presented in Table 12. The column headings, with the exception of DF3, are explained in the text of this report. The quantity DF3 is the overall dilution factor (including initial dilution in rising to the surface) after three hours travel time from the boil.

The profiles of measured dye-concentrations and the fitted Gaussian distributions presented in Appendix A illustrate how well a Gaussian distribution fits the data. It can be concluded from these profiles, with reference to Table 2, that the data can be represented reasonably well by a Gaussian distribution provided the wind and current are in the same direction. This is evidenced by experiments P7, P9, and H3. On the other hand, experiments P3 and P8 illustrate the skewness of the concentration distribution resulting from wind cutting across the plume.

Figures 10, 11, and 12 are presented to indicate the magnitude of the variables S_y and N as well as to show the goodness of fit, or more appropriately, the lack of fit. Data obtained in experiment P6, a surface release, and in experiment P10, an outfall release, are presented for comparison. The behavior of S_y and N_{max} (axial concentration) for the outfall release is shown in Figures 10 and 11. Values of 1400 feet and 0.91 were determined for the variables X_0 and m, respectively. Estimates of S_z could not be obtained from the traverse data and N_{max} was found to vary with distance approximately to the negative one power. For the surface release experiment, shown in Figure 12, N_{max} was found to vary with distance raised to the negative 0.85 power. However, estimates of S_y could not be obtained because of the extremely narrow plume which developed. The surface release experiment involved the continuous release of dye at a fixed position at the water surface, and as observed in Figure 10, the dye concentrations are greater at the three foot depth than at the five foot depth. However, this is not necessarily true for an outfall release where the sewage-dye mixture rises to the surface and eventually forms a plume. It is seen from Figure 9 that the dye concentrations are not consistently greater near the surface. This situation occurs because the center-line of the rising plume is bent in the downstream direction and by the time the center-line (location of maximum concentration) reaches a point on the surface, lesser concentrated dye is already upstream of that point. This condition makes it quite difficult to obtain the vertical plume standard deviation, S_z, from the variable depth traverses.

The fitted lateral standard deviations and the surface axial concentrations are presented in Figures 13 and 14 for all of the experiments. Values

TABLE 12

SUMMARY OF RESULTS OF DIFFUSION EXPERIMENTS

EXP.	Plume Characteristics: Dimensions, ft.			Plume Characteristics: Exponents		Dye Plume: Concentration (ppb)		Dye Plume: Dilution		Sewage Plume: Concentration Coliforms/100 ml		Sewage Plume: Dilution	K_y
	X_o	S_{yo}	S_{zo}	m	m+n	N_i	N_p	D_p	DF3	N_i	N_p	D_p	ft^2sec^{-1}
P1	Surface Release			0.57	1.28	-	-	-	-	-	-	-	1
P2	Surface Release			-	-	-	-	-	-	-	-	-	-
P3	550	45	9	0.79	1.68	440	4.8	92:1	4800	-	-	-	4
P4	-	-	-	-	-	440*	4.6	95:1	-	-	-	-	-
P5	Surface Release			1.14	1.24	-	-	-	-	-	-	-	4
P6	Surface Release			-	0.85	-	-	-	-	-	-	-	-
P7	850	105	1.5**	0.98	1.20	500*	11.9	42:1	630	-	-	-	35
P8	150	26	9**	0.77	0.80	500*	6.2	80:1	2300	-	-	-	20
P9	2200	81	4.5**	0.61	1.0	500*	5.4	92:1	400	-	-	-	6
P10	1400	32	6**	0.91	1.0	500*	6.4	78:1	690	-	-	-	2
H1	600	21	3	1.29	1.29	510	70	7.3:1	330	$2x10^6$	$4x10^4$	50:1	41
H2	-	-	-	-	-	310	12.0	26:1	-	$4x10^7$	$1.8x10^6$	22:1	-
H3	800	124	3**	1.00	1.0	-	9.3	31:1*	280	-	$5x10^5$	-	46

**Calculated from diffusion model (includes initial dilution).

*Estimated (refer to original reference).

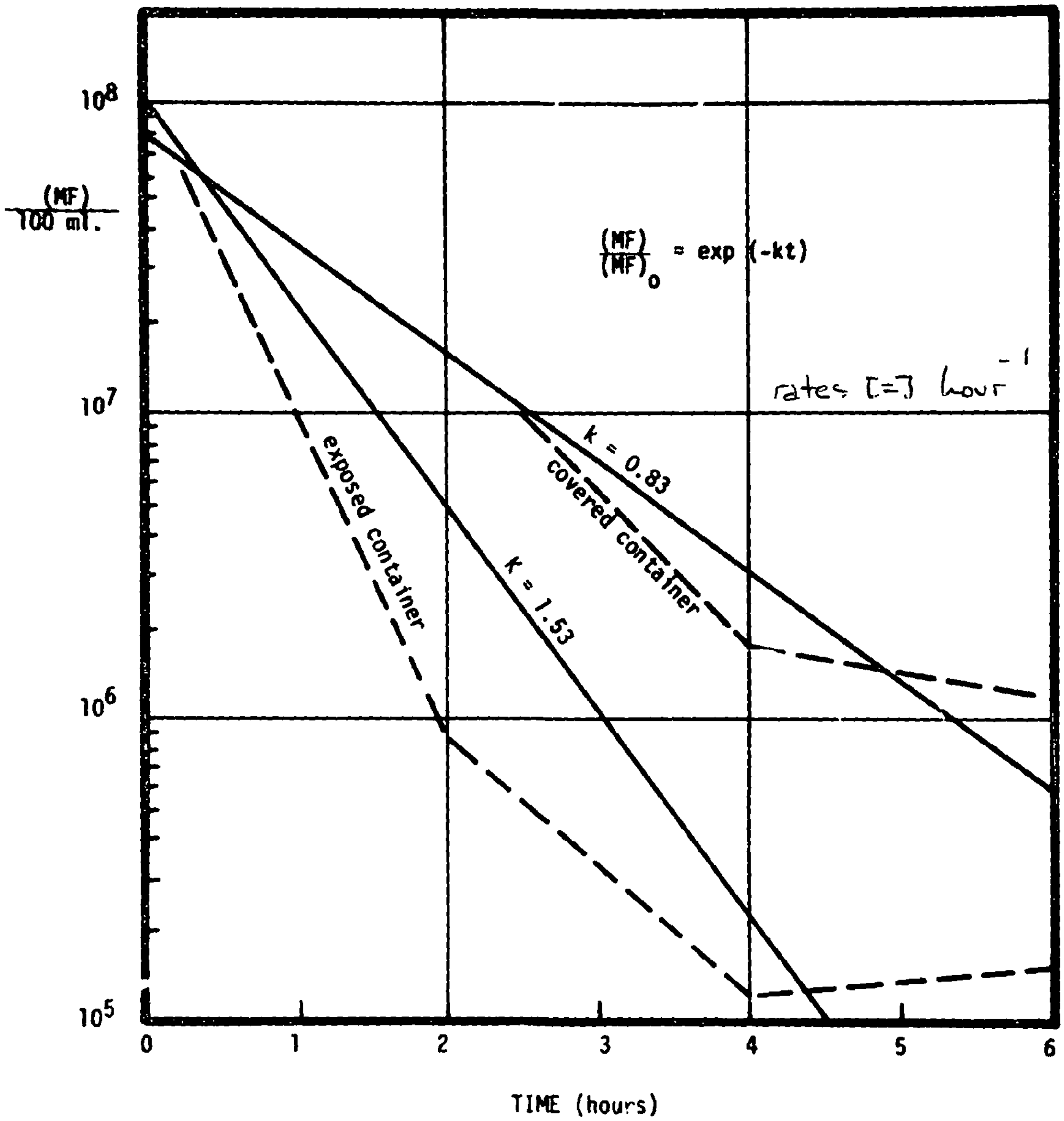


FIGURE 9 - COLIFORM DIE-OFF RATE
DECEMBER 9, 1969

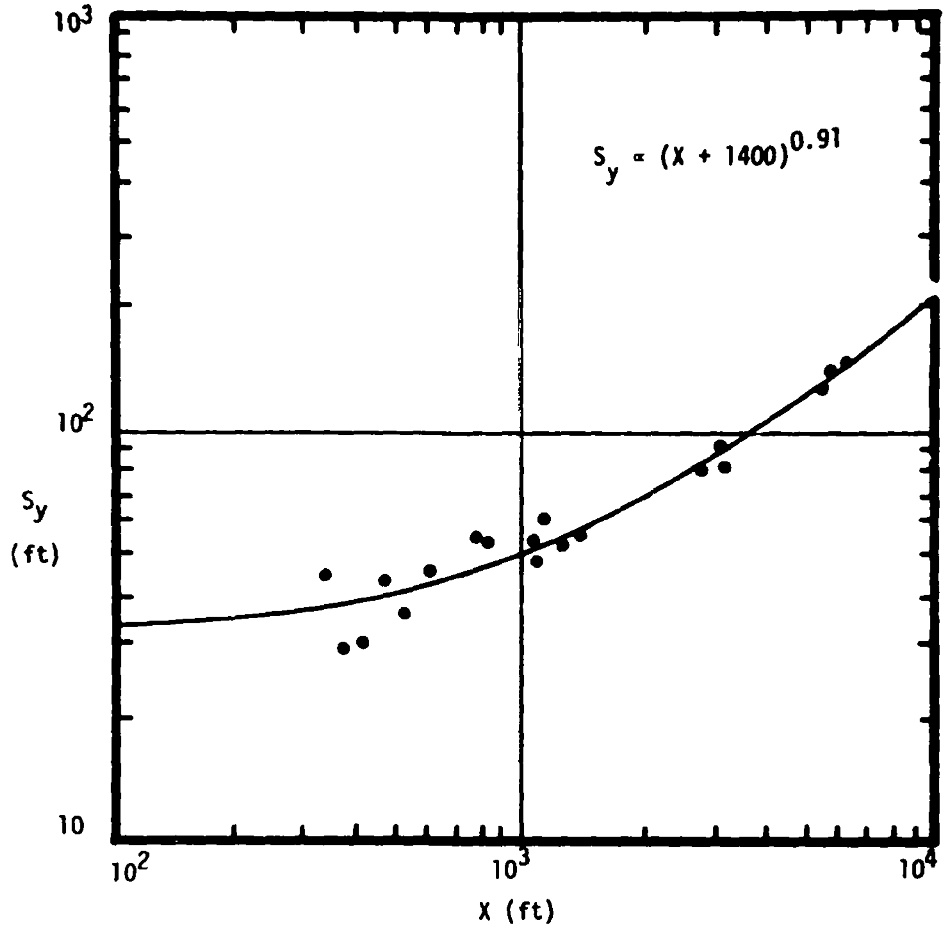


FIGURE 10 - LATERAL STANDARD DEVIATION VS. DISTANCE
DECEMBER 18, 1968 OUTFALL RELEASE

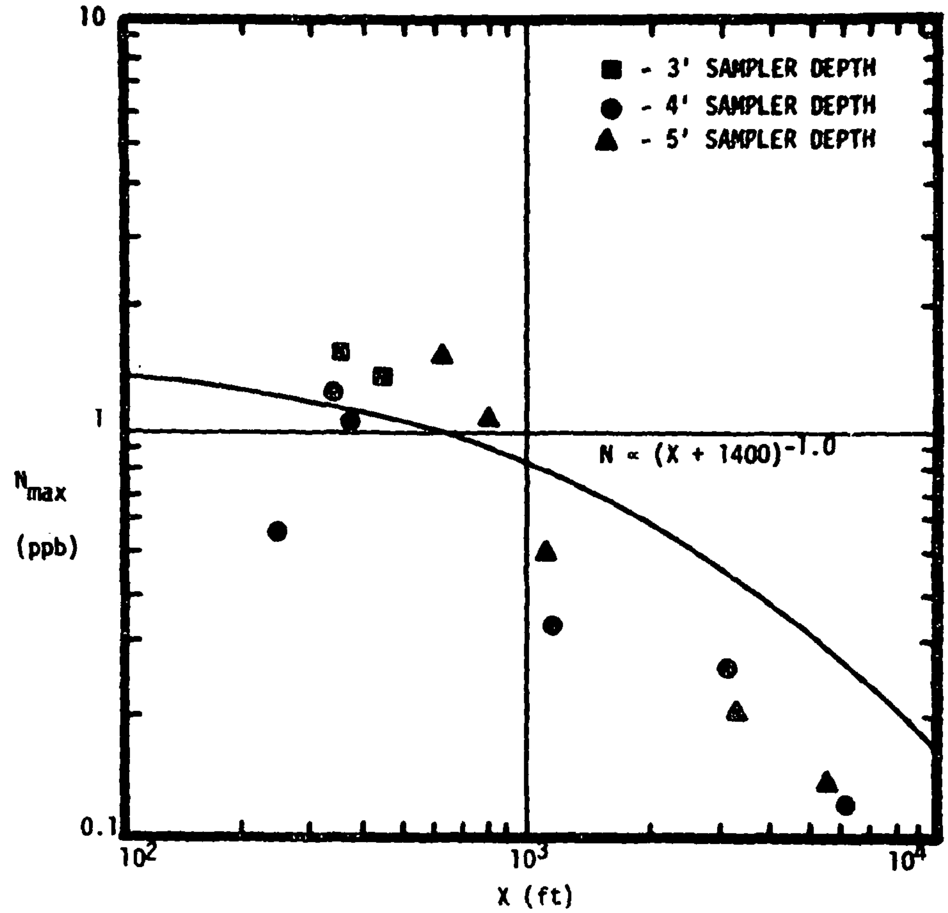


FIGURE 11 - AXIAL CONCENTRATION VS. DISTANCE
DECEMBER 18, 1968 OUTFALL RELEASE

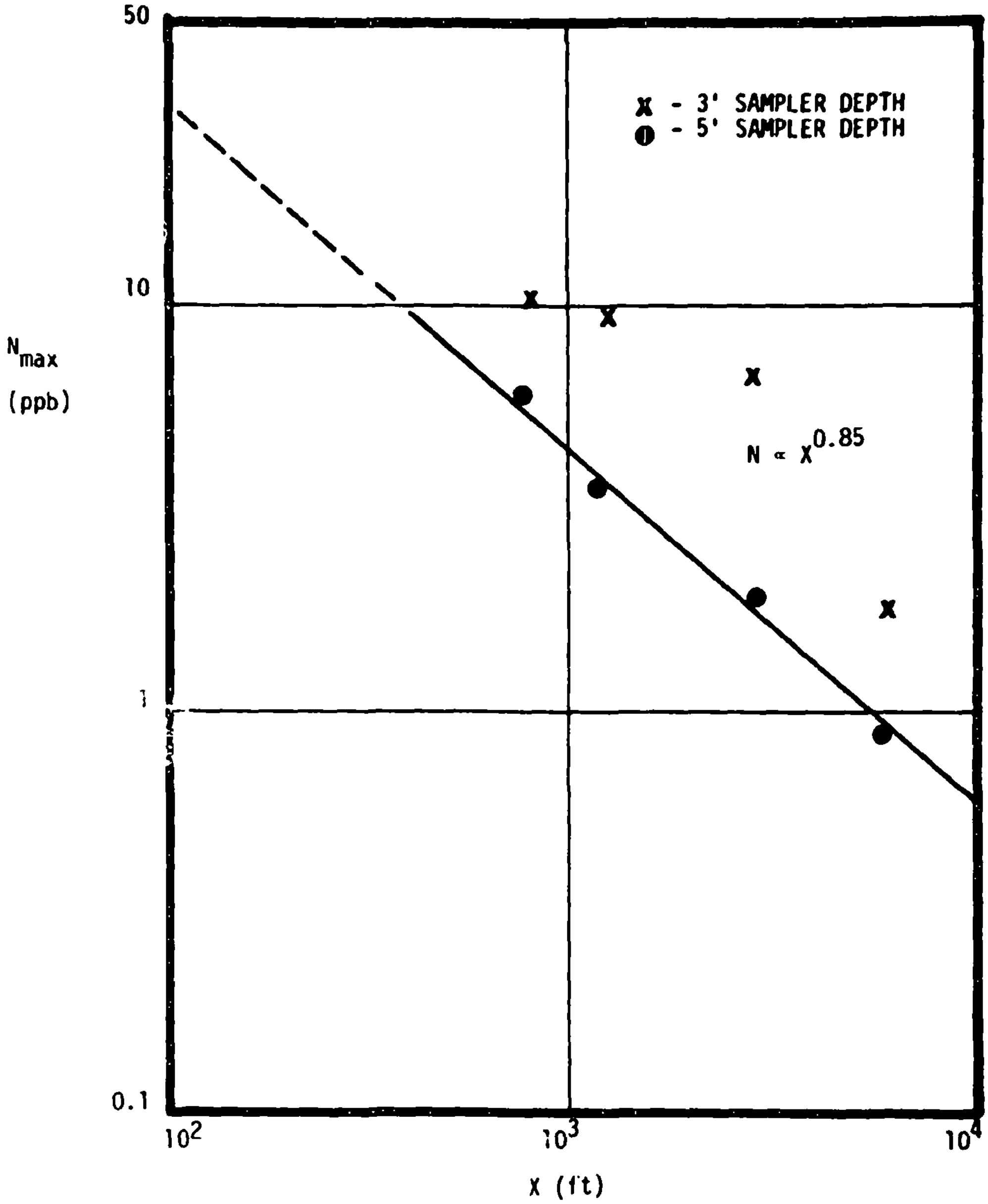


FIGURE 12. AXIAL CONCENTRATION VS. DISTANCE
AUGUST 15, 1968 SURFACE RELEASE

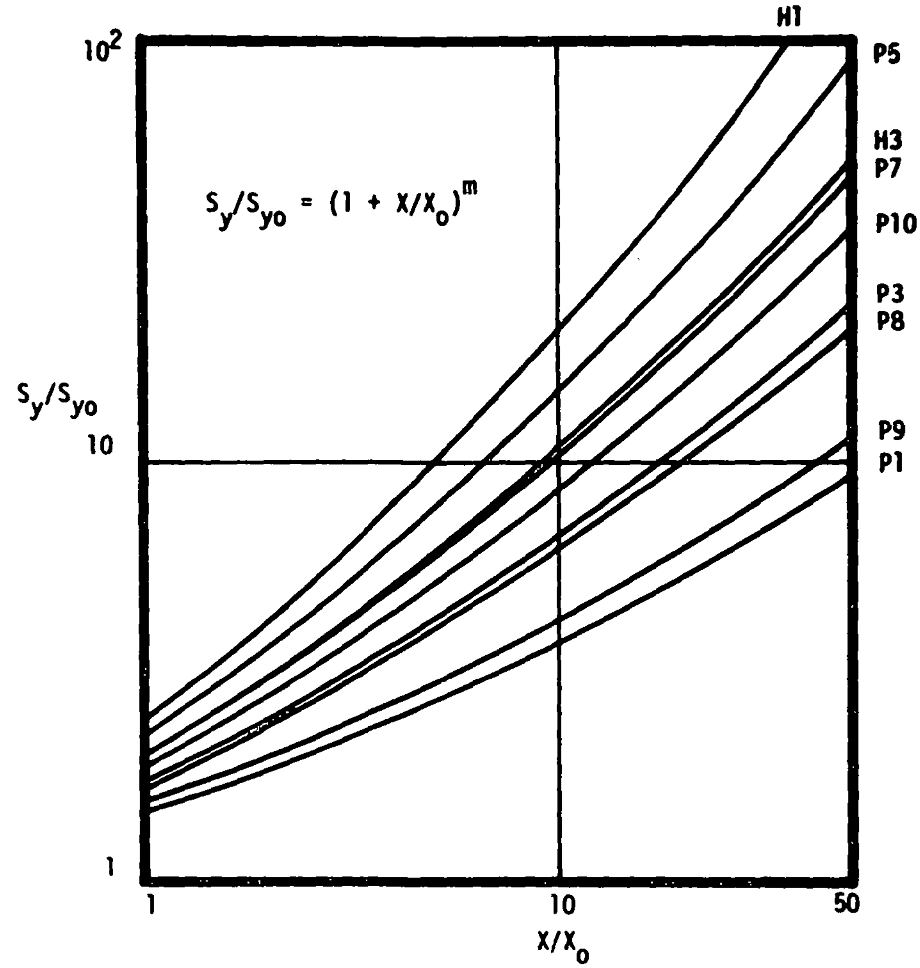


FIGURE 13 - LATERAL STANDARD DEVIATION VS. DISTANCE
FITTED EXPERIMENTAL RESULTS

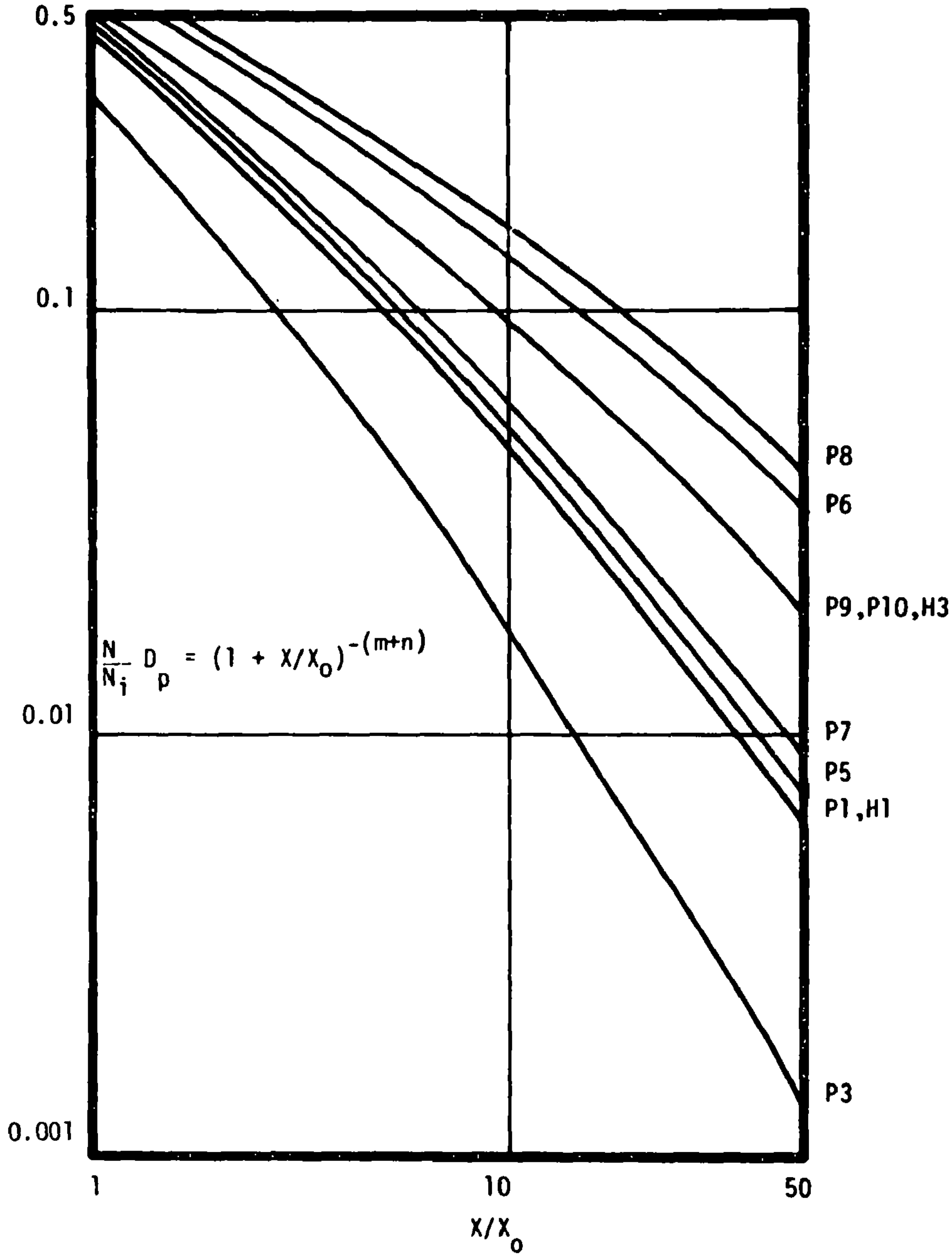


FIGURE 14 - SURFACE AXIAL CONCENTRATION VS. DISTANCE FITTED EXPERIMENTAL RESULTS. COLIFORM DIE-OFF NOT CONSIDERED.

of the quantities X_o, S_{yo}, m, m + n, N_i, and D_p are given in Table 12. Also, the raw data (N_{max}, S_y) are given in Appendix B. The variable X/X_o is equivalent to a time variable T/T_o where $T = X/\bar{u}$, $T_o = X_o/\bar{u}$. The only requirements for drawing the curves are values of the exponents m and m + n. Hence, the surface release experiments are also presented in Figures 13 and 14, although equations 3 and 10 (with y=z=o) are appropriate to the single outlet outfall release only, and not for a continuous release at the surface in which case equation 1 would be appropriate.

It is clearly evident from Figures 13 and 14 that there is considerable spread in the data. For example, at the Pompano outfall S_y/S_{yo} varies from 4.4 (experiment P9) to 10.3 (experiment P7) at X/X_o = 10. Also N/N_i varies from 0.2 (experiment P8) to 0.013 (experiment P7) at X/X_o = 10. For the Hollywood experiment of December 12, (experiment (H3), the values of S_y/S_{yo} and N/N_i at X/X_o = 10 were 11.0 and 29 X 10^{-4}, respectively. Large values of S_y/S_{yo} and low values of N/N_i are associated with low downstream concentrations. From the limited amount of data available, it would appear that surface concentrations are higher at the Hollywood outfall than surface concentrations at the Pompano outfall.

Considering only those plumes which were fairly well defined (experiments P8, P9, P10, and H3) the data can be approximated by the relations

$$S_y/S_{yo} = (1 + X/X_o)^{0.80} \qquad \text{. . . (13)}$$

$$D_p \; N/N_i = (1 + X/X_o)^{-1.0} \qquad \text{. . . (14)}$$

The exponent m is closer to 0.75 for the Pompano experiments. Average values of 1100 feet and 65 feet can be used for X_o and S_{yo}, respectively. For the Pompano runs the average value of S_{yo} is approximately 45 feet. Considering all of the Pompano experiments, the peak dilution D_p is approximately equal to 80, whereas for the Hollywood runs (H2,H3) the peak dilution is approximately equal to 30.

For those trials where the wind was blowing across the plume (P1, P3, and P5) or where the plume was heading towards shore (P7 and H1) the exponents m and m + n are greater than those given above for a well defined plume. The average values of m and m + n for experiments P1, P3, P5, P7, and H1 are approximately 1.0 and 1.3, respectively. Figures 4 and 5 can be used, with the approximate values of the exponents, to estimate plume widths and axial concentrations for the two types of plume behavior (well defined and either meandering or bent towards shore due to wind and current effects).

The results of the coliform die-off trials are presented in Figure 15. It is seen that during the summer, natural coliform die-off or mortality in the warm (85°F) Florida ocean shelf water is extremely rapid in comparison to that during December. The initial coliform counts for the undiluted sewage, $(MF)_o$, varied between 12 X 10^6 to 55 X 10^6 per 100 ml. Die-off

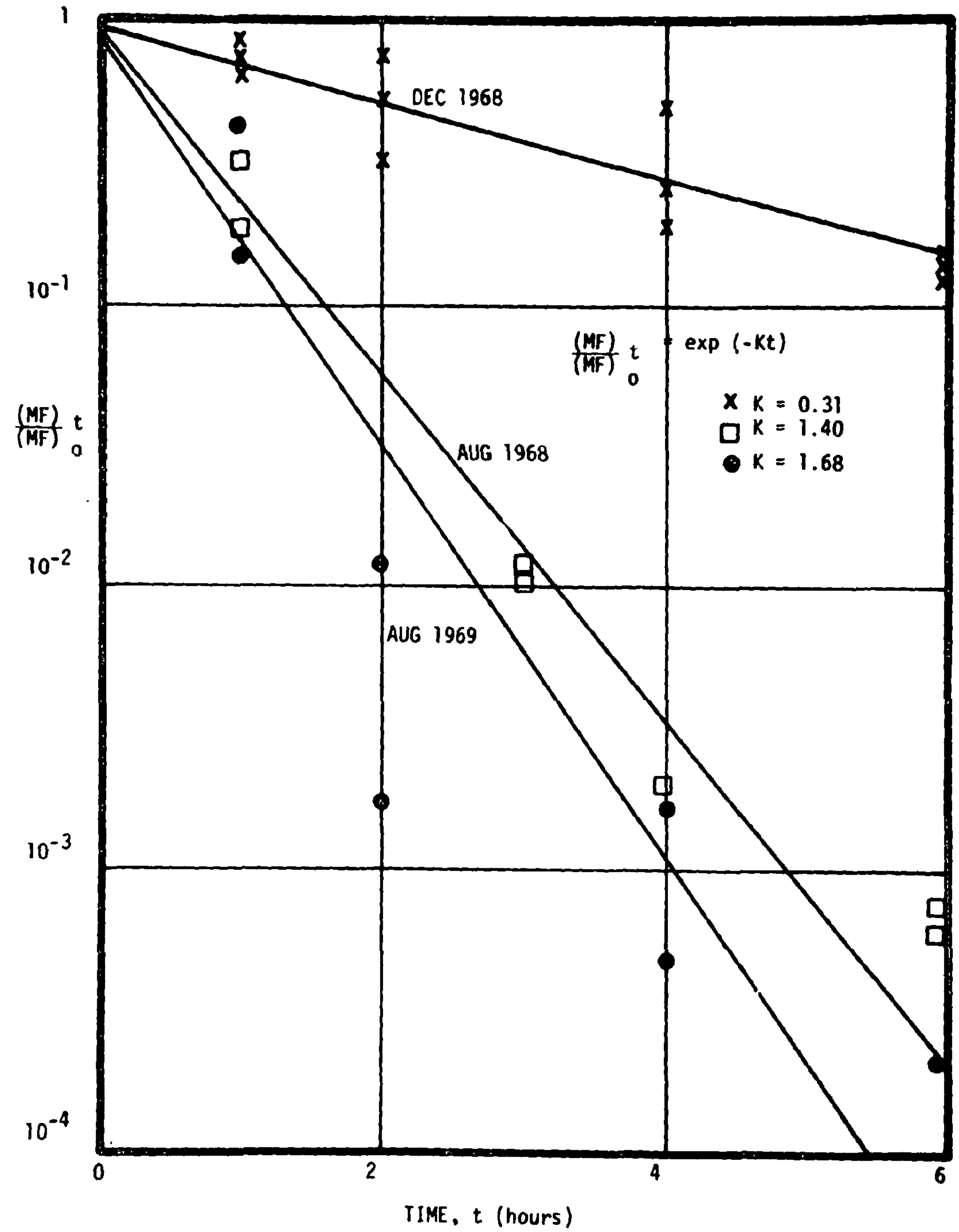


FIGURE 15 - TOTAL COLIFORM NATURAL DIE-OFF RESULTS

or mortality rate factors of k = 0.31 $hours^{-1}$ for the December, 1968 data and k = 1.40, 1.68 $hours^{-1}$ for the August, 1968 data, were determined by fitting equation (9) to the data. The fitted curves of Figure 14 corrected for natural die-off are shown in Figure 16. Die-off factors of k = 0.31 1.55 were used for the December and August experiments. These rates correspond to a 90 percent mortality time (t_{90}) of 7.4 hours for December and 1.5 hours for August. It should be pointed out that die-off results reported here do not include any reduction in coliforms that may occur because of sedimentation (6). Also because of the wide variations in coliform die-off rates reported here and in the published literature as well, the results presented in Figure 16 are an indication only as to what the surface concentrations would be if the die-off rates were as shown in Figure 15.

Of the 13 runs reported, nine were concerned with an outfall dye release of which three (P9, P10, and H3) were classified as a well defined plume. During these three experiments, both the wind and the current were practically in the same direction -- toward the south. The overall three-hour dilution factor, DF3, for P9 and P10 averaged about twice that for experiment H3. This is to be expected since the water depth to pipe diameter ratio at Hollywood is twice that at Pompano, while the sewage flow rates per unit pipe area are approximately the same, i.e., approximately 70 cfm per ft^2. Initial peak dilutions at Pompano averaged 80:1 while at Hollywood the initial peak dilution (at 10,000 feet; experiments H2 and H3) averaged approximately 30:1. Initial peak dilutions, as estimated from the analytical solutions of Fan and Brooks (7), for the simple case of a rising column in a homogeneous ocean are 50:1 and 20:1 for the Pompano and Hollywood outfalls, respectively. Cross-stream diffusion coefficients varied between 1 and 46 $ft^2\ sec^{-1}$ which are within the range expected for oceanic diffusion.

On two occasions (P7 and H1), the plume was directed towards the shore; initially and eventually the plume oriented itself along the direction of the wind approximately parallel to the shore line. Grab samples were taken and coliform counts were made while tracking the towards-shore plume (experiment H1) with the result that coliform counts did not exceed 100 per 100 ml at distances less than 2000 feet from the shore line where the water depth is approximately 20 feet. (Experiment H1 was conducted when the Hollywood outfall was extended to only 5000 feet.) It is of interest to estimate the fraction of time a situation such as this would occur -- that is, a situation where the currents are directed towards the shore with fairly strong winds from the east. Currents are towards the west only seven percent of the time with average speeds of approximately 40 miles north of Hollywood, is presented in Figure 17. It is seen that for the year 1968, winds in excess of 13 mph were from the east approximately 20 percent of the time. If the two factors are independent, a rough estimate of the percentage of time that currents and winds are simultaneously in directions such that the plume could head towards the shore is given by 0.07 X0.20 = less than

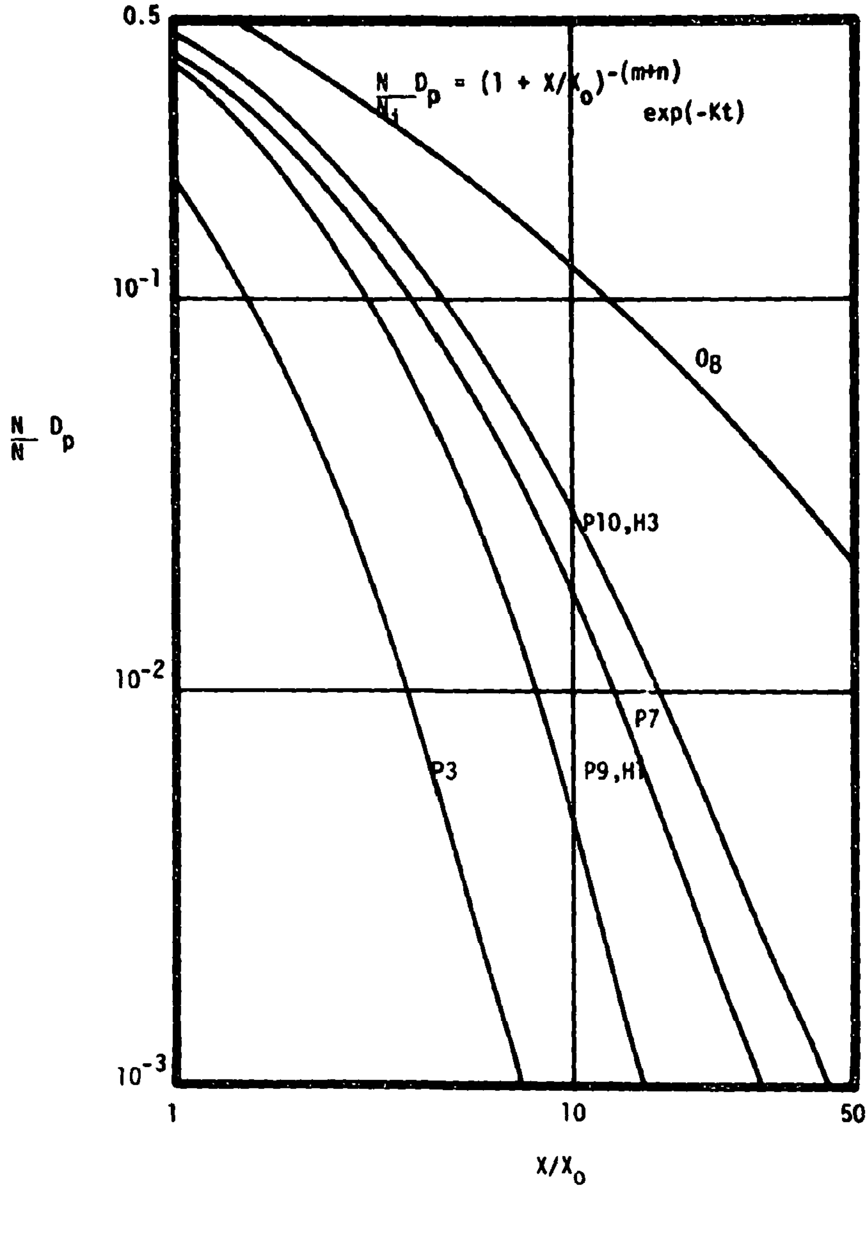


FIGURE 16 - SURFACE AXIAL CONCENTRATION VS. DISTANCE COLIFORM DIE-OFF RATE CONSIDERED

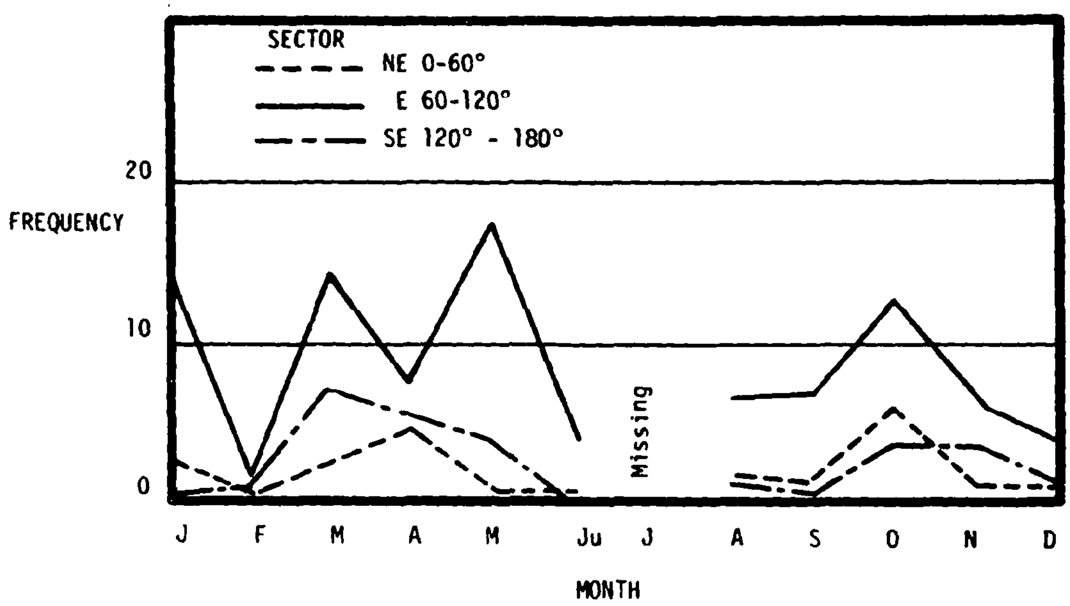


FIGURE 17 - PERCENTAGE OF TIME WIND SPEED GREATER THAN 13 MPH WITHIN A 60° SECTOR. DATA FROM WEST PALM BEACH AIRPORT 1968

two percent of the time. However, wind persistence data is not available and there is no indication as to how long a situation like this would occur.

Of the remaining four outfall dye release experiments, the plume was partly submerged on two occasions (P3 and P8) resulting in high values of the three hour overall dilution factor (DF3), causing little or no concern when related to possible beach contamination. On the other two occasions (P4 and H2), a plume did not form owing to the absence of a predominant current direction.

The remaining four experiments (P1, P2, P5, and P6) were surface dye release runs which were conducted to establish diffusion data, primarily in the lateral direction. These surface release experiments were terminated early in the program because of the limited amount of information obtained in comparison to the outfall release experiments.

Although only a limited number of experiments were conducted, a diffusion model based on the results can be formulated to predict sewage (coliform) concentrations downstream from the boil. The axial concentration at the surface is given by

$$\frac{N}{N_i} = \frac{4.2 \times 10^{-4}}{S_{yo}\, S_{zo}} \cdot \frac{Q_o}{\bar{u}} \cdot [1 + X/X_o]^{-(m+n)} \cdot \exp(-kx/\bar{u}) \qquad \ldots (15)$$

where N = concentration at the surface

N_i = initial concentration in the outfall pipe
Q_o = sewage release rate, GPM
$\bar{u}$ = mean current speed, knots
S_{yo}, S_{zo} = plume standard deviations at the location of the boil, feet.

The average values of the product S_{yo}, S_{zo} are 270 and 220 for the Pompano outfall and the Hollywood outfall, respectively. Using a conservative value of 210 and with x_o = 1100 feet = 0.208 miles and $m + n = 1.0$, the model for predicting downstream maximum surface concentrations from the Hollywood outfall (and Pompano outfall) is given by

$$\frac{N}{N_i} = 2 \times 10^{-6} \cdot \frac{Q_o}{\bar{u}} \; [1 + X/0.208]^{-1.0} \cdot \exp(-kx/\bar{u}) \qquad \ldots (16)$$

With plumes directed towards the shore, the exponent $m + n = 1.0$ would be replaced by $m + n = 1.3$ as mentioned earlier.

Using Equation 16, the following table presents reductions in concentration at various downstream locations for values of $\bar{u}$ = 0.3 knot = 0.346 miles/hour, $m + n = 1.0$, $m + n = 1.3$, $k = 0.31$ (winter die-off), $k = 1.55$ (summer die-off).

X miles	N(X = 0) / N(X) m + n = 1.0		N(X = 0) / N(X) m + n = 1.3	
	k = 0.31	k = 1.55	k = 0.31	k = 1.55
0	1	1	1	1
1	10	130	18	220
2	36	5.2×10^3	70	1.1×10^4
4	240	4.9×10^6	600	1.2×10^7

It is to be noted that the concentration reductions shown above are determined relative to the concentration at the boil and not to the initial concentrations in the pipe. From Equation 16 the initial concentration reduction is given by

$$\frac{N}{N_i} = \frac{1}{D_p} = 2 \times 10^{-6} \cdot \frac{Q_o}{\bar{u}} \qquad \ldots (17)$$

and

$$\frac{N}{N_i} \quad \frac{1}{80} \quad \text{at Pompano outfall}$$

$$\frac{1}{30} \quad \text{at Hollywood outfall}$$

The worst possible situation concerning beach contamination would be a plume directed towards the shore during the winter months (k = 0.31). Using an initial coliform count of $N_i = 10^7$/100 ml for primary treated sewage, $N_i = 10^3$/100 ml for secondary treated sewage, and an initial coliform reduction of N/N_i = 1/30, the maximum coliform counts at the surface according to the model are presented below.

X miles	N(X) (MF)/100 ml (for $N_i = 10^7$ / 100 ml)	N(X) (MF)/100 ml (for $N_i = 10^3$ / 100 ml)
0	30×10^4	30
1	20×10^3	2.0
2	4000	0.40
4	260	0.03

These are maximum (axial) concentrations. A further reduction by a factor of 10 would apply at the "edges" of the plume located at 2.15 S_y from the plume center-line. The exponent m in Equation 3 is given by

$m = 0.8$ and $m = 1.0$ for well-defined plumes and meandering or shore-directed plumes, respectively. Using an average value of 70 for S_{yo}, the plume half-widths are presented below.

X miles	Plume Half-Width, feet ($2.15\ S_y$)	
	$m = 0.80$	$m = 1.0$
0	150	150
1	600	870
2	1000	1600
4	1700	3000

As an example, the coliform concentration at the center-line of a shore-directed plume, during the winter months when $k = 0.31$, would be 4000 (MF) per 100 ml at a distance of 2 miles from the boil and only 400 (MF) per 100 ml at a distance of 1600 feet measured perpendicular from the center-line at the 2 mile location.

Based on the above results it is unlikely that beach contamination will occur at the present time. However, as the sewage release rate increases with increasing population, the possibility of excessive coliform counts occurring near the beach also increases.

AQUATIC STUDIES

The studies that were conducted at Hollywood and adjacent areas began eight months before outfall discharge began at 5,000 feet from shore at Hollywood and ended nearly a year after discharge began at 9,700 feet. Since the plankton in the transects at Hollywood showed no marked changes during the three-year period, the inference is that any detectable effects of the outfall are confined to a very small mixing zone and, apparently, to where the sewage reaches the surface. The number of species in the last transect were somewhat higher than on previous occasions before the 9,700 foot outfall was completed, but numbers per milliliter were low.

With the exception of transects in October,1968, transects from July, 1968, through July, 1971, indicated a nutrient deficient water supporting relatively few species of organisms and relatively low concentrations. There is little reason to believe that this paucity was due to anything other than a lack of nitrates and phosphates, especially since the inshore waters contained low numbers.

The October, 1968, transects, taken before discharge commenced at Hollywood, produced a record high population of organisms per milliliter. Although the high values were mainly caused by three species of diatoms, the population of all species were relatively high. The bloom of diatoms, and the accompanying general increase in populations, probably represented a rapid (and temporary) build-up of available phosphorus and nitrogen. It is highly possible that an enriched mass of water had moved into the area and remained there long enough (24-72 hours) for a bloom to occur. Neith transects taken a month earlier or those taken four months later indicate enrichment.

Core samples of the bottom were taken concurrently with the transects and generally corresponded to the results of the transects with the exception of cores taken in August, 1968. Transects on this date indicated a very low nutrient level in the water while cores indicated that the bottom had plentiful nutrients. The sharp difference between these cores and those of the preceding month is difficult to reconcile. A possible explanation is that a patchy distribution of organisms occurred; however, it is questionable as to how the interstitial biota might have moved about. It is also possible that the coarseness of the sand in the August cores might have allowed particulate matter to settle deeper into the cores. A personal equation might have been involved--it is much more difficult to obtain a good quantitative estimate of microorganisms in coarser sand.

But whatever the cause, the fact remains: the distribution of microbiota on the bottom off the coast of Hollywood in August, 1968, was patchy but abundant.

In general, comparison of bioassays of the Hollywood area conducted before sewage discharge (July and August, 1968 and February, 1969) with those conducted after discharge (January, 1969 and July, 1971) showed essentially no change in numbers or species types. It is true, and of course inevitable, that most salt water organisms trapped in the sewage plume or in the quite small mixing zone will be killed. Such organisms, however, are few in number and quickly reproducible; no irreplaceable damage is done.

Comparative bioassays of other outfalls along the Southeastern coast of Florida produced results similar to those at Hollywood--generally non-enriched water due to the enormous volume of water sweeping past the coast and providing dilution. However, bottom cores taken at the Pompano Beach and Delray Beach outfalls indicated a slightly higher organic content than did those taken at Hollywood. A significant effect of the Pompano and Delray outfalls was observed in the form of black, anaerobic mounds, no more than two feet high, oval in shape, and as much as 60 to 100 feet in length. The mounds, appearing at various times, were subject to current attrition and were not permanent. They appeared to be of coarse sand blackened by hydrogen sulfide. The danger, of course, exists under proper conditions, of such a mound building up into a large sludge bank over a period of time. The area could become a literal desert with disastrous affects on the local ecology.

As stated above, however, the mounds at Pompano and Delray Beach were of passing existence because of current action and presented no apparent problem.

The situation at the Hollywood outfall is just the opposite. In front of the conduit exit and in line with it is a row of six tall pilings. The strength of the outflow and the currents about the pilings have excavated an elongate oval pit about five feet deep (to hard bottom) and more than 40 feet long.

The fact that periodic sludge build-ups occurred at Pompano Beach and Delray Beach, but did not occur at Hollywood, is attributed to the fact that Pompano Beach and Delray Beach were discharging raw sewage. The primary treatment received by the Hollywood effluent was sufficient to remove most of the suspended solids from the sewage. The new state requirements of secondary treatment will eliminate sludge accumulation at all outfalls.

Since the incoming sewage contains orthophosphate mixes, some increase in phytoplankton might be expected. It is known from Tampa Bay, Great South Bay (New York), and Peconic Bay (New York) that treated sewage effluents increase the phytoplankton by one or two orders of magnitude. However, these bodies of water are estuaries with much smaller volumes of ocean water to acquire the nutrients. It might be concluded that the shelf water along the southeastern cost of Florida is well able at this time to dilute the incoming sewage to the point where the nutrients are still insufficient to produce high populations of plankton algae and protozoa.

An exact expression of the ecological conditions existing off the coast of Hollywood is practically an impossibility due to the extremely complex phenomena occurring at and below the water surface. The proximity of the Florida Current with its resulting eddies on the unique continental shelf creates near-shore water movements in three dimensions; at various times the current direction at a particular point may be north or south, toward shore or away from shore, and in different directions at various depths. Any particular sampling point may find water that has moved northward from the Miami outfall, southward from the Pompano Beach and Palm Beach outfalls, toward shore from the Florida Current, or outward from the local canal's outlets. Such was the case with the nutrient enrichment observed off the Hollywood coast in October, 1968. The enriched mass of water could only be observed; its origin could not be established.

The sandwiching of water flow, i.e., different layers of different qualities flowing different directions, was most clearly exemplified by the conditions off Pompano Beach on June 23, 1969. This condition is well known to divers in these coastal waters, but is not otherwise so obvious.

Several areas of this study have pointed out the need for accompanying chemical analyses for orthophosphate, nitrate, and carbon, as well as measurements of productivity. This work, then, rather than detecting effects of a general nature, detects minor highly localized effects and presents a general illustration of the microbiota of the continental shelf, the Florida Current, and the sediment-water interface. It is possible that as the population of southeastern Florida increases more sewage will be carried offshore. If so, this and similar studies will provide a background against which biotic changes may be detected.

SECTION VII

PUBLIC HEALTH IMPLICATIONS

Ocean disposal of domestic sewage along populated coastal areas can impair water quality in beach areas and create a health risk for swimmers when enteric microorganisms from the waste field are present in shore water. Monitoring these recreational areas for their bacteriological quality becomes a necessity for public health.

Indicator organisms traditionally non-pathogenic to man have been utilized as a criteria of water quality. Therefore, bacterial species and population size have been used as the yardstick to determine risk of infection from contact with shore water. The coliform group has been most frequently employed for this purpose although microbiologists have shown the usefulness of entercocci and fecal coliforms as additional microbial indicators.

Improved laboratory techniques have made possible the direct isolation of bacterial and viral pathogens from contaminated water. The procedures are, in many cases, elaborate and time consuming, but the data are useful especially when correlated with numbers and species of the intestinal microflora used as water quality indicators. Information of this kind has led to a reassessment of the overall coliform group as a valid indication of microbial pollution of surface water. The National Advisory Committee on Water Quality Criteria (4), for example, rejected the use of total coliforms as a water quality indicator in favor of fecal coliforms as the best overall group. The Committee also favored fecal streptococci as a supplement to fecal coliforms in determining quality both in marine and fresh water used for primary contact sports.

There has been a continuing need for information regarding the correlation between Salmonella, enteric viruses and the concentrations of indicator organisms. Slanetz and his co-workers have stated that the absence of coliforms or fecal streptococci in 100 ml samples or seawater may not insure the absence of pathogens in shellfish (15). Clarke, et. al. (3), state that the relative enteric virus density to coliform density in human feces is about 15 virus units for every 10^6 coliforms. They further estimate 0.15 to 1.5 virus units per 100 ml of polluted surface water.

Intestinal organisms will survive in natural waters for varying lengths of time depending on a variety of factors all of which are not presently known. Both pathogens and non-pathogens appear to remain viable longer at low temperatures. Elevated temperatures as found in the summer along the Florida coast bring about an interplay of factors which decrease survival of bacteria and viruses. The correlation of temperature and survival of microorganisms in natural water has been documented many times in the literature. Clarke, et al., found that Coxsackie A_2 virus survived 61 days in sewage held at 8°C and only 41 days at 20°C. These workers observed similar effects in river water using Poliovirus I, Echo 12, and Coxsackie 9. In all cases, they observed longer virus survival in treated clean water or in grossly polluted water. Liu, et al.(8), working with Poliovirus I in filtered seawater found that 50 percent of the virus was lost in five days and 90 percent in nine days at temperatures of 22°C. No tests were made at a lower temperature. Other studies relating to virus survival by Metcalf and Stiles (9) using three viruses (Poliovirus I, Echovirus 6, and Coxsackievirus B3) show a temperature dependence during exposure in estuarine water. In all cases, enteric virus survival in summer was about one-half that during the winter.

Probably the most significant problem in eventually determining the risk of infection from swimming water containing bacterial or viral pathogens is a lack of good basic epidemiological data on transmission of disease agents in natural waters. Virus levels for the most part will be low in bathing areas and the incidence of infection among bathers will be difficult to determine. This is particularly so as Berg (16) states (detection is observed by the concomitant and subsequent, higher frequency spread by the direct personal contact route, and by the relatively low incidence of readily associated overt disease that accompanies such infections." As yet, there is virtually no good information regarding minimal infective doses of virus for man although Plotkin and Katz (17) have found that one TCD_{50} of Fox strain Poliovirus 3 may be infective for infants. It is fairly obvious that until reliable and rapid techniques are developed for quantitative viral detection in seawater and our knowledge improves on amounts of virus that can cause infection in man (a rather formidable task) viral standards for recreational water can be only guess work.

Diffusion and die-off studies show that relatively few coliform organisms will be present in inshore waters. However, survival of enteric organisms is considerably longer in winter and the probability of bacterial or viral pathogens reaching the beach areas during this time of year is maximal. In addition, Berg (16) and England, et al. (5), have shown that removal of virus in sewage depends to a large extent on the wastewater treatment process. Activated sludge is the most efficient. Laboratory tests have shown 99 percent removal in 45 minutes by this method, where as little virus removal occurs in sewage given primary treatment. Trickling filters also do not remove virus to any great extent.

It might be expected then that outfalls discharging raw waste into the marine environment may be a greater hazard to beach areas than those whose effluent is properly treated to reduce pathogens.

Applying the data of Clarke, et al., (15 virus units to 10^6 coliforms) and using an overall reduction in sewage concentrations of 2000:1 (assuming no die-off), the maximum expected concentration in shore water would be one virus unit per liter. These conditions would apply when the plume was directed toward beach areas. During the winter tourist season, the lower east coast is heavily populated. The Bureau of Economic Research at the University of Florida estimates the population of Dade County, as of July 1, 1968, at 1,139,500. The 1967 data of the Florida Development Commission show tourists traveling by automobile to Miami, Miami Beach, and Ft. Lauderdale to approximate 2,600,000. The resulting increase of domestic waste places an additional microbial burden into these coastal waters. Since bacterial die-off is less under low temperatures, the probability of microbial pathogens reaching and persisiting in shore water would be greatest at this time of the year. The potential public health hazard is obvious.

Presently, beach water contamination from sewage outfalls is remote. The highest coliform count (MPN) of 20 stations along shoreline under surveillance by the Dade County Health Department was 23/100 ml in a period extending from March through October, 1969. As population increases over the next decade, water used for recreational purposes will contain greater microbial burdens. This decline in water quality may be a significant factor in human infections transmitted through the aquatic environment.

Along the lower Florida east coast, those responsible for water quality on beaches must face the fact that sewage outfalls will be discharging increasing quantities of waste a short distance offshore. Hence, beach contamination is a distinct possibility.

SECTION VIII

RELATIONSHIP OF OCEAN OUTFALLS TO TOTAL OCEANIC POLLUTION OFF THE SOUTHEASTERN FLORIDA COAST

The Atlantic Ocean off of Palm Beach, Broward, and Dade Counties in southeastern Florida receives pollution primarily from two sources: (1) municipal and industrial wastewater discharged directly into the ocean via outfalls, and (2) the discharge of numerous canals draining the Everglades. The drainage canals, in addition to being recipients of domestic wastes, transport significant quantities of pesticides, herbicides, minerals, and nutrients. In order to prepare an adequate evaluation of the ecological effects of ocean sewage outfalls, it becomes necessary to consider the relation of the outfalls to the overall scope of pollution.

Drainage canals form a complex network across southeastern Florida. Primary canals drain water from the Everglades for the purposes of regional flood control and agricultural utilization and convey it to outlets on the coast. Secondary canals, connected to the primary canals, have the function of local flood control. Control structures in the primary canals prevent the movement of seawater upstream and maintain freshwater reservoirs during the dry season in order to prevent saltwater intrusion into the Biscayne Aquifer.

The discharge of the canals is affected considerably by seasonal rainfall. The low flow during the dry season is mainly due to ground-water inflow; therefore, the canals tend to have fairly high concentrations of dissolved minerals and to be alkaline. In the rainy season the dissolved minerals are low and the water is slightly acidic.

For the purposes of this discussion, the six primary canals within Broward County, Florida, are compared with the two sewage outfalls, Hollywood and Pompano Beach, of that county. Figure 18 shows the layout of the canals, the location of the various sampling points, and the locations of the outfalls.

Table 13 shows the nutrient content of the canal water at the sampling points. These results are derived from data reported by the United States Geological Survey.

It would be expected that as the canals approach the coast and pass through urbanized areas, their nturient concentrations would increase as a result of increased sewage and urban runoff. The results of Table 13 indicate that increased nutrient contents are experienced. The increase is illustrated by Figure 19 which shows relatively little change in nitrate plus nitrite nitrogen and total phosphorus between site 39 (more than 20 miles inland)

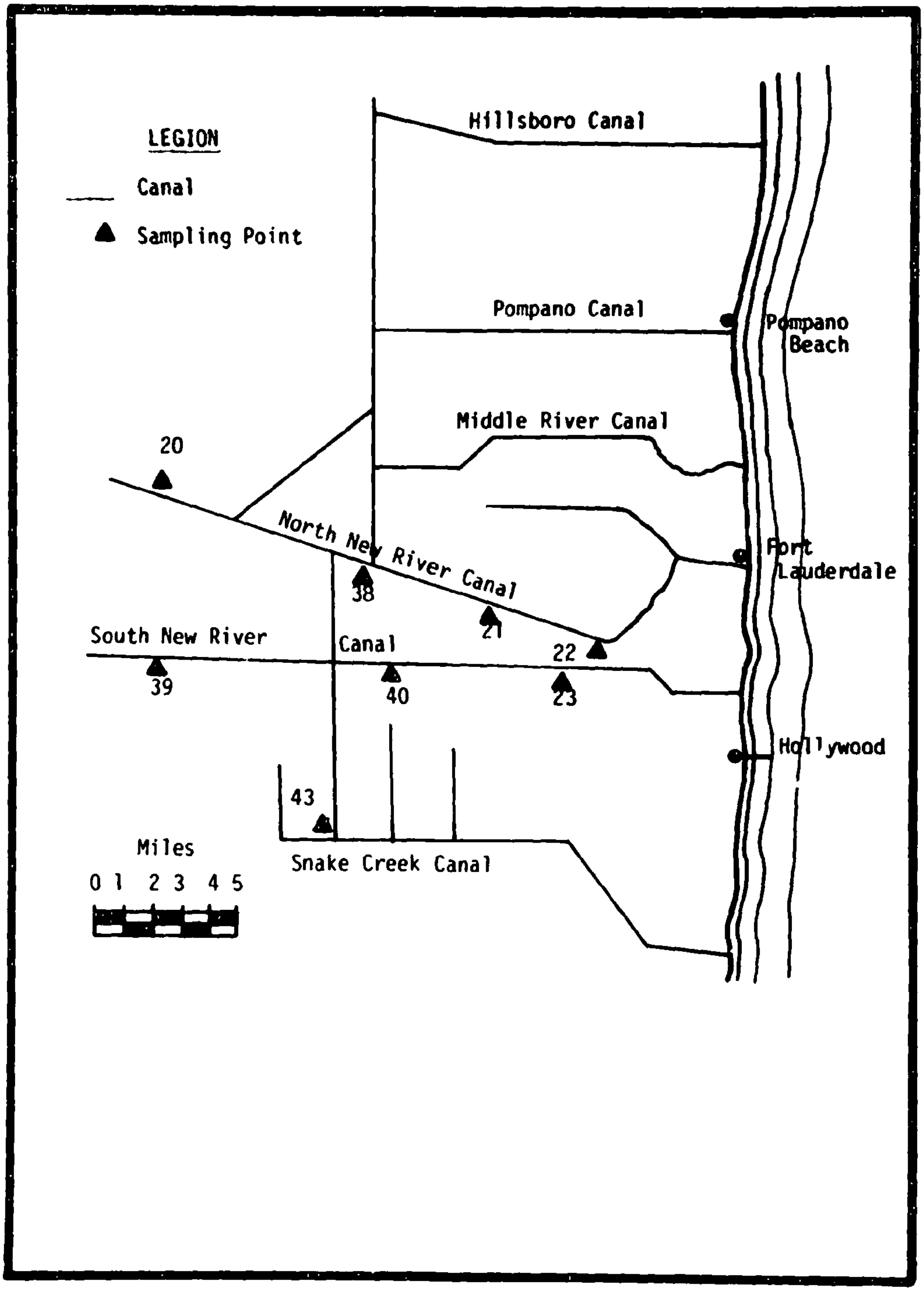


FIGURE 18

PRIMARY CANAL SYSTEM OF BROWARD COUNTY, FLORIDA

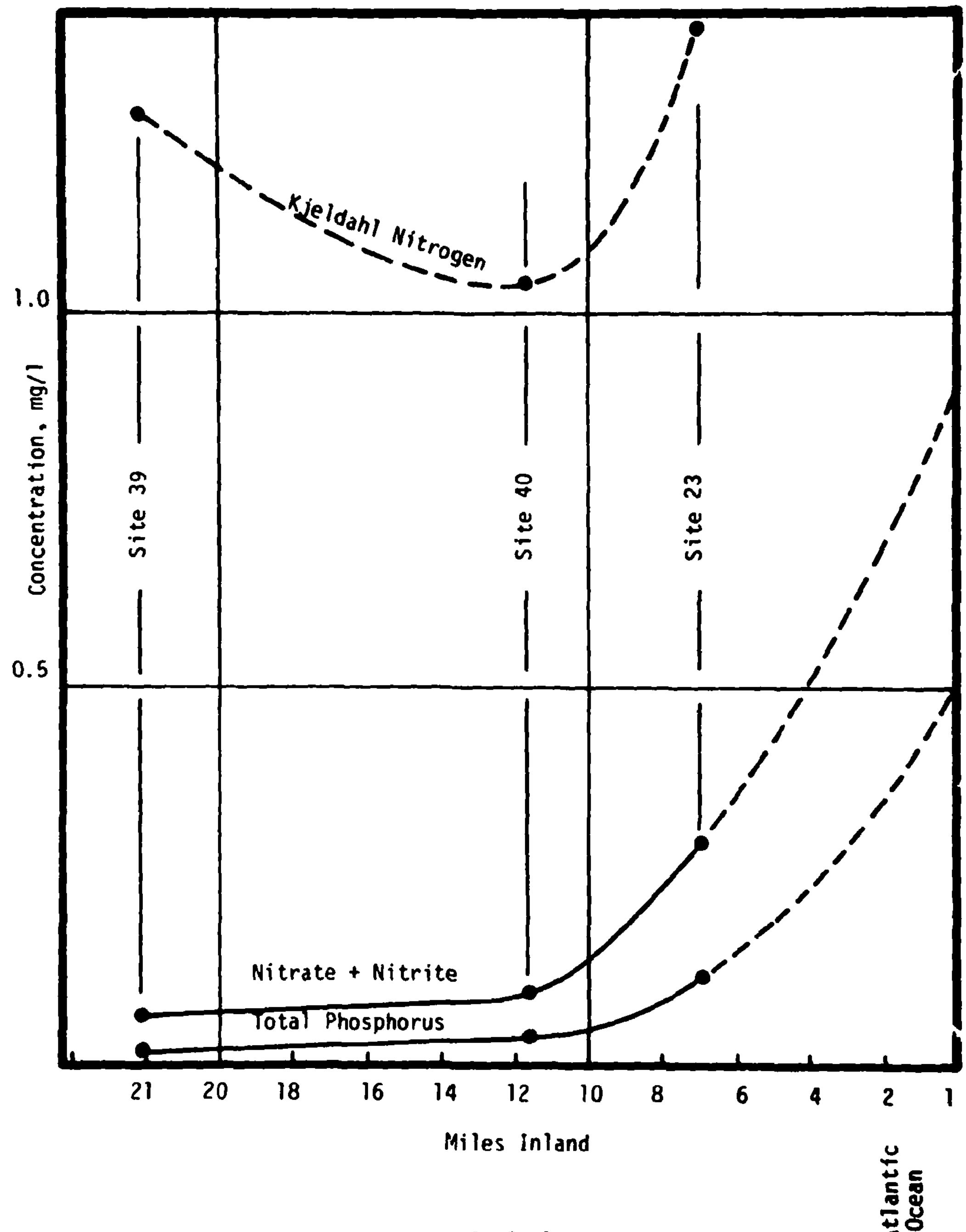


FIGURE 19

NUTRIENT CONCENTRATIONS IN SOUTH NEW RIVER CANAL, BROWARD COUNTY, FLORIDA

TABLE 13 NUTRIENT CONCENTRATIONS AT SELECTED TEST SITES IN THREE PRIMARY DRAINAGE CANALS, BROWARD COUNTY, FLORIDA

SITE NO.	Nitrate + Nitrite mg/l as N	Samples From/To	No. of Samples	Total Phosphorus mg/l as P	Samples From/To	No. of Samples	Kjeldahl Nitrogen mg/l as N	Samples From/To	No. of Samples
20	0.08	3-69/9-71	24	.005	3-69/9-71	24	1.35	3-69/4-71	5
21	0.18	10-68/9-71	23	.006	10-68/9-71	23	1.08	10-68/4-71	6
22	0.25	2-69/9-71	22	.14	2-69/9-71	23	0.67	6-69/4-71	4
23	0.26	10-68/9-71	25	.09	10-69/4-71	25	1.35	10-68/4-71	6
38	0.08	9-70/4-71	3	0.01	9-70/4-71	3	1.18	9-70/4-71	3
39	0.06	2-70/9-71	21	0.01	2-70/9-71	21	1.26	9-70/4-71	3
40	0.08	9-70/4-71	3	0.02	9-70/4-71	3	1.02	9-70/4-71	3
43	0.10	9-70/9-71	18	0.01	9-70/9-71	21	0.95	9-70/4-71	3

and site 40 (more than 10 miles inland). However, as the canal enters the urbanized area, increases of about 225 percent and 350 percent are observed for nitrate plus nitrate nitrogen and total phosphorus, respectively, between sites 40 and 23. A 34 percent increase of kjeldahl nitrogen is observed between the last two sites; however, there are few data available. It must be noted that site 23 is approximately seven miles inland. If it were to be assumed that the rates of increase observed between sites 40 and 23 were to continue between site 23 and the mouth of the canal, the nitrate plus nitrite concentration would increase to over 0.5 mg/l and the total phosphorus concentration would increase to over 0.2 mg/l.

Using data for site 23 on the South New River Canal and site 22 on the North New River Canal, comparable nutrients levels are assumed for the other canals at equivalent distances (five to seven miles) inland. These values are shown in Table 14. The total nutrient load transported by the canals at that distance inland is nearly 10,000 pounds per day. All indications are that this figure would be considerably higher by the time the canals actually discharge into the ocean.

Broward County has two ocean outfalls at Pompano Beach and at Hollywood. Table 15 shows the nutrient concentrations and loads for the effluents of the two outfalls. The data are based on analyses conducted on the Hollywood effluent and corresponding estimates for the Pompano effluent. As indicated in Table 15, the total nutrient load of the sewage effluents is nearly 3,000 lbs/day. A comparison of this figure with the primary drainage canals indicates that the nutrient contribution of the ocean outfalls of Broward County is less than one-third of the nutrient loads of the county's primary canals five to seven miles inland.

If the increase of nutrients from the inland points to the coastal discharge is considered, and if additional pollution sources such as direct urban runoff on the coast, water craft wastes, and industrial wastes are taken into account, the nutrient contributions of the ocean outfalls become almost insignificant.

TABLE 14 NUTRIENT CONCENTRATIONS AND LOADS IN SIX PRIMARY DRAINAGE CANALS (APPROXIMATELY FIVE TO SEVEN MILES INLAND), BROWARD COUNTY, FLORIDA

	Flow, MGD 1969 Water Year	$NO_2 + NO_3$ mg/l	$NO_2 + NO_3$ lb/day	TP mg/l	TP lb/day	KN mg/l	KN lb/day
North New River Canal	172	0.25	359	0.14	201	0.67	961
South New River Canal	163	0.26	353	0.09	122	1.35	1835
Snake Creek Canal	300	0.25*	626	0.1*	250	1.0*	2502
Hillsboro Canal	202	0.25*	421	0.1*	168	1.0*	1684
Pompano Canal	18.5	0.25*	39	0.1*	15	1.0*	154
Middle River Canal	20.2	0.25*	42	0.1*	17	1.0*	168
TOTAL DISCHARGE	876		1840		773		7304

*estimated

TABLE 15 NUTRIENT CONCENTRATIONS AND LOADS FOR POMPANO BEACH AND HOLLYWOOD OCEAN OUTFALL EFFLUENTS

	1969 Flow MGD	Nitrite + Nitrate		TP		KN	
		mg/l	lb/day	mg/l	lb/day	mg/l	lb/day
Pompano Beach	2.7	0.2*	4.5	7.0*	158	20*	450
Hollywood	13	0.3	32.5	3.6	390	18	1992
						Total Nutrients = 2987 lb/day	

*estimated

SECTION IX

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SECTION XI

GLOSSARY OF TERMS AND ABBREVIATIONS

Aerobic - Requiring, or not destroyed by, free elemental oxygen.

Algae - Primitive plants, one or many celled, usually aquatic, and capable of elaborating their foodstuffs by photosynthesis.

Anaerobic - Requiring, or not destroyed by, the absence of air or free elemental oxygen.

Annelids - Aquatic earthworms, leeches, and polychaetes.

Amoeboid Protozoa - Single celled organisms of Phylum Protozoa and Class Sarcodina. Move by pseudopodia (streaming) movements and temporary extensions of cell.

Autotrophic - Utilizing inorganic compounds as carbon sources.

Bacteria - A group of universally distributed, rigid, essentially unicellular microscopic organisms lacking chlorophyll. They are usually considered as plants.

Bioassay - A method of determining toxic effects of wastewater by observing changes in biological activity.

Biomass - An accumulation, growth, or colony of living organisms.

Biota - Animal and plant life, or fauna and flora, of a water body.

Bloom - A rapid increase of plant population, usually algae, caused by an environmental change.

Blue green algae - Division Cyanophyta. Pigments not localized in definite chromatophores. Nucleus lacks nucleolus and nuclear membrane always present in freshwater plankton catches.

Boil - A rise in a water surface caused by the turbulent upward flow of water.

Chloromonadida - Order of widespread grass-green algae.

Chlorophyceae - Class of green algae.

Chrysophyceae - Class of golden-brown algae; microscopic motile cells. Phylum Chrysophyta (yellow-green or golden-brown algae).

Ciliates - Class of protozoa possessing cilia (tiny hairs) used for locomotion.

Coccolithophora - Free swimming algae of Division Chrysophyta. Surrounded by an envelope embedded with numerous small calcareous discs (coccoliths).

Coliform - Bacteria, including the genera Escherichia and Aerobacter, of the family Enterobacteriaceae whose presence is taken to indicate fecal pollution.

Copepoda - A subclass of Crustacea composing a large portion of zooplankton and universally distributed in plankton and in benthic and littoral regions. They are usually less than 2.0 mm long and exist as both parasitic and free-living forms.

Core - A small cylindrical sample of earth produced by a core drill.

Diatoms - Unicellular microscopic aquatic organisms with a box-like structure consisting principally of silica.

Dinoflagellates - Brownish, chiefly marine, algae, of the Phylum Pyrrophyta, containing two external flagellum.

Ecology - The relationship between organisms and their environment.

Empirical Model - A description, in mathematical terms, of observed data.

Entercocci - A group of cocci having its normal habitat in the intestines of man or animals.

Euglenida - Colorless flagellate algae order, Division Euglenophyta. Naked free swimming cells with 1, 2, or 3 flagella.

Euglenids - See Euglenophyceae.

Euglenophyceae - Phylum of algae; grass-green, unicellular, motile; lacking cell wall; common name Euglenoids or Euglenids.

Facultative - The ability to adapt to the presence or absence of oxygen.

Fecal Coliform - Coliform organisms which have their normal habitat in the intestines of man or animal.

Fecal Streptococci - A group of bacteria of the Entercocci group.

Fluorescent Dyes - Dyes which exhibit the phenomenon of fluorescense, i.e., absorb the energy of ultraviolet waves and emit it as visible waves of greater length.

Fluorometer - An instrument which measures the degree of fluorescense; therefore, measures indirectly the concentration of fluorescent dye.

Gallons Per Minute (GPM) - A measurement of flowrate in terms of volume per unit time.

Gaussian Distribution - A two parameter symmetric distribution of random occurrences. Also called a "normal distribution."

Genus - A group of very closely related species.

Gonyavlaxdigitale - Unicellular Dinoflagellate.

Green algae - Division Chlorophyta. Pigments in chromatophores. Filamentous and unicellular species. Both aquatic and terrestrial.

Gymnodinium - Unicellular Dinoflagellate.

Gyrodinium Pinge - Unicellular Dinoflagellate.

Interstitial - Consisting of or existing in small open spaces or pores.

Microbiota - Microscopic plants and animals.

Milliliter(s) (ml) - A measurement of volume.

Most Probable Number (MPN) - That number of organisms per unit volume that, in accordance with statistical theory, may be more likely than any other number to yield the observed test results. Expressed as density of organisms per 100 ml.

Nematode worms - Parasitic roundworms.

Nereid worms - Polychaete marine worms.

Ostracoda - An abundant and widely distributed subclass of Crustacea. Ostracoda resemble minature (less than one mm) mussels.

Outfall - A conduit that receives wastewater from a collecting system or treatment plant and carries it to a point of final discharge, the point of discharge.

Pathogens - Disease-producing microorganisms.

Photosynthesis - The creation of complex organic materials from carbon dioxide, water, and inorganic salts, with sunlight as the source of energy and with the aid of a catalyst such as chlorophyll.

Photosynthetic organisms - Organisms that obtain their energy for growth from light from photosynthesis.

Phytoplankton - Collective term for the plants and plant-like organisms present in plankton.

Plankton - The aggregate of passively floating, drafting, or weakly motile mostly microscopic organisms in a body of water, usually composed primarily of algae. A basic aquatic food source.

Primary treatment - The first major (sometimes the only) treatment in a wastewater treatment works, usually sedimentation. Primary treatment removes a substantial amount of suspended matter but little or nc colloidal and dissolved matter.

Protozoa - Small one-celled animals including amoebae, ciliates, and flagellants.

Rhizopoda - Group of protozoa.

Rotifer - A characteristically fresh water, microscopic, elongated, and cylindrical phylum possessing a corona (ciliated or funnel-shaped structure at the anterior end) and a mastax (specialized pharynx). Less than five percent of the species occur in marine or brackish waters.

Salinity - A measure of the concentration of dissolved mineral substances in water.

Salmonella - A common water pathogen; a bacterium.

Scyphozoans - Coelenterates, common marine jellyfish.

Species - One kind of organism; a subdivision of a genus.

Staphylococcus - A common enteric bacteria, some forms of which are pathogenic.

Sulfur bacteria - Bacteria capable of using dissolved sulfur compounds in their growth. Common bacteria of domestic sewage.

Thigmotropic - Existing within pores; under cover.

Volvocales - Family of motile, unicellular, or colonial with various shapes except that colonies are never filamentous; Class Chlorophyceae (grass-green algae), Phylum Chlorophyta (green algae).

Zooflagellata - Animal-like forms of protozoa (as opposed to phytoflagellates) having no chlorophyll and thus receiving nourishment by the ingestion of plants and animals.

CFM - Cubic feet per minute (Ft^3Min^{-1}) - A measurement of flow rate in terms of volume per unit time.

D_a - Average dilution in boil.

D_p - Peak dilution in boil.

DF3 - Three hour overall dilution factor in plume.

k - Natural die-off factor for coliform bacteria.

K_y - Turbulent diffusion coefficient in cross-stream direction.

(MF) - Coliform counts determined by Milipore Filter technique.

N - Instantaneous concentration in plume.

$\bar{N}$ - Time-mean concentration in plume.

N_a - Average concentration in boil.

N_i - Initial concentration in outfall pipe.

N_p - Peak concentration in boil.

PPB - Parts per billion.

PPM - Parts per million.

Q - Equivalent source strength on sewage release rate corrected for decay.

Q_o - Initial source strength or sewage release rate.

RPM - Revolutions per minute.

S_y - Standard deviation of concentration in cross-stream direction.

S_z - Standard deviation of concentration in vertical direction.

S_{y_o} - Initial plume standard deviation in cross-stream direction at boil.

S_{z_o} - Initial plume standard deviation in vertical direction at boil.

t - Diffusion time or travel time from boil.

t_l - Lagrangian time-scale of turbulence.

$\bar{u}$ - Mean current speed.

x - Downstream distance measured from boil.

y - Cross-stream distance measured from plume axis.

X_o - Upstream distance from boil to location of virtual point source of equal strength.

SECTION XII

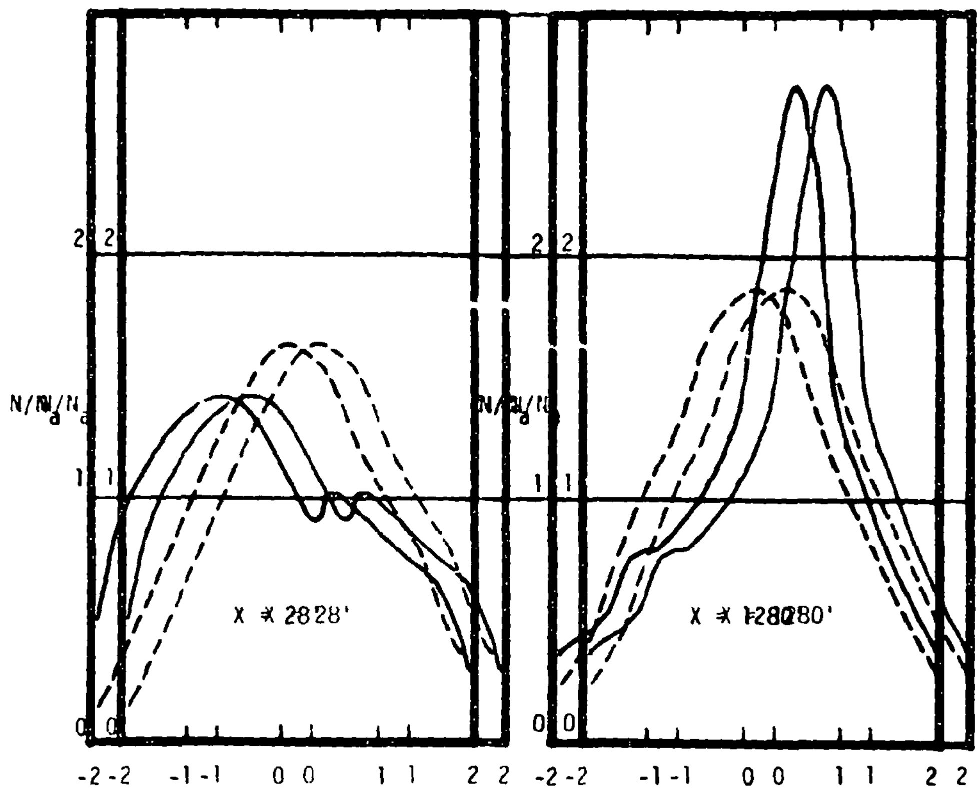
APPENDICES

A. COMPARISON OF DYE PLUME CROSS-SECTIONS WITH FITTED GAUSSIAN DISTRIBUTIONS

B. MEASURED PEAK (AXIAL) DYE CONCENTRATIONS AND CROSS-CURRENT (LATERAL) PLUME STANDARD DEVIATIONS

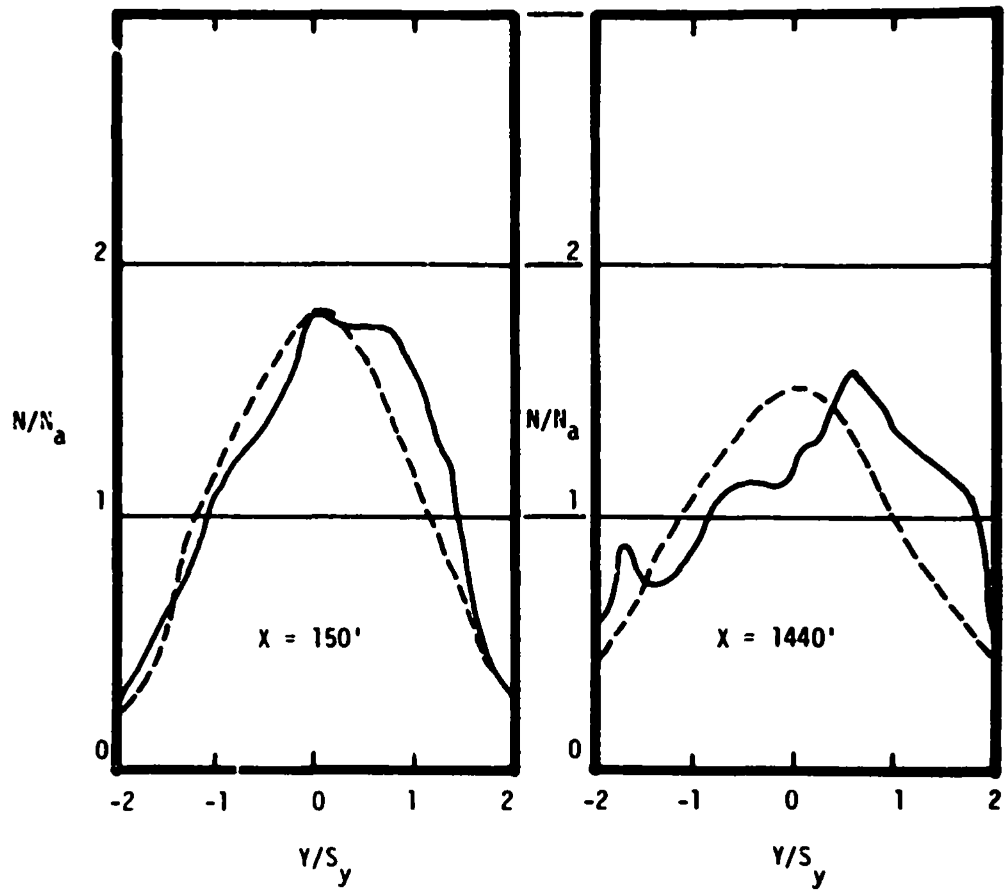
C. PHOTOGRAPHS

D. AQUATIC STUDY DATA



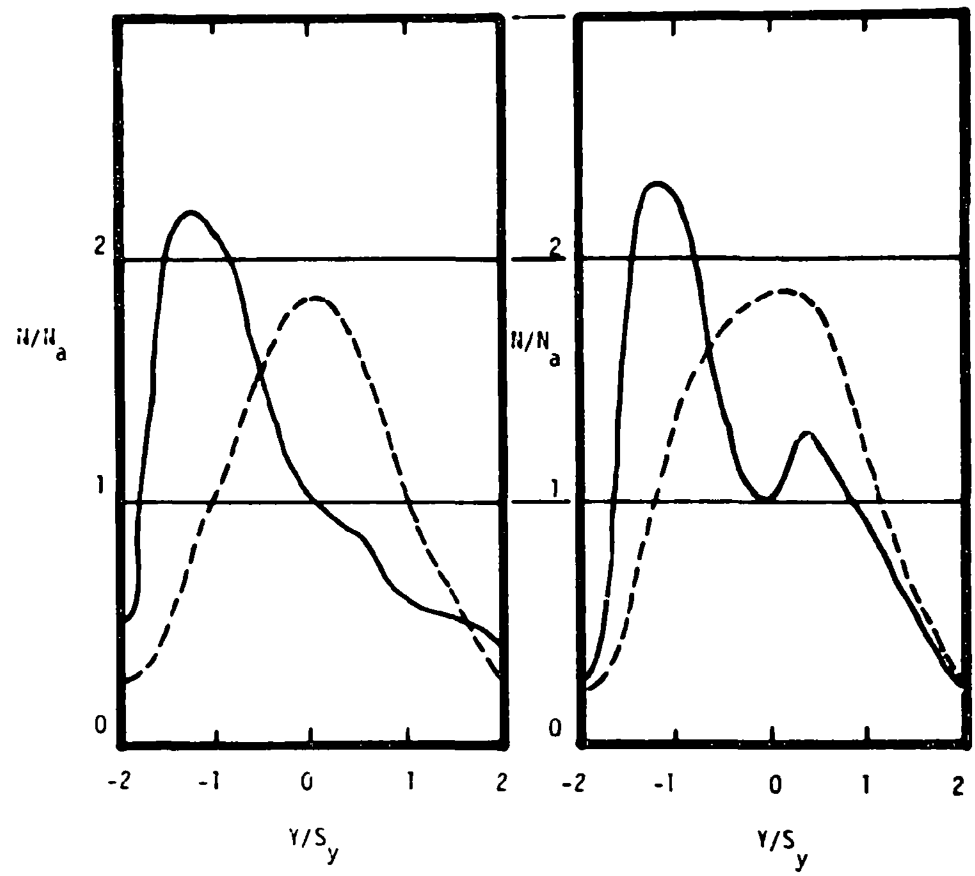
AUGUST 8, 1968

FIGURE A1 COMPARISON OF DYE PLUME CROSS-SECTIONS WITH FITTED GAUSSIAN DISTRIBUTIONS
POMPANO STUDY, AUGUST 8, 1968 (EXPERIMENT 3)



DECEMBER 10, 1968

FIGURE A2 - COMPARISON OF DYE PLUME CROSS-SECTIONS WITH FITTED GAUSSIAN DISTRIBUTIONS
POMPANO STUDY, DECEMBER 10, 1968 (EXPERIMENT P7)



DECEMBER 17, 1968 (am)

FIGURE A3 - COMPARISON OF DYE PLUME CROSS-SECTIONS WITH FITTED GAUSSIAN DISTRIBUTIONS
POMPANO STUDY, DECEMBER 17, 1968 (EXPERIMENT P8)

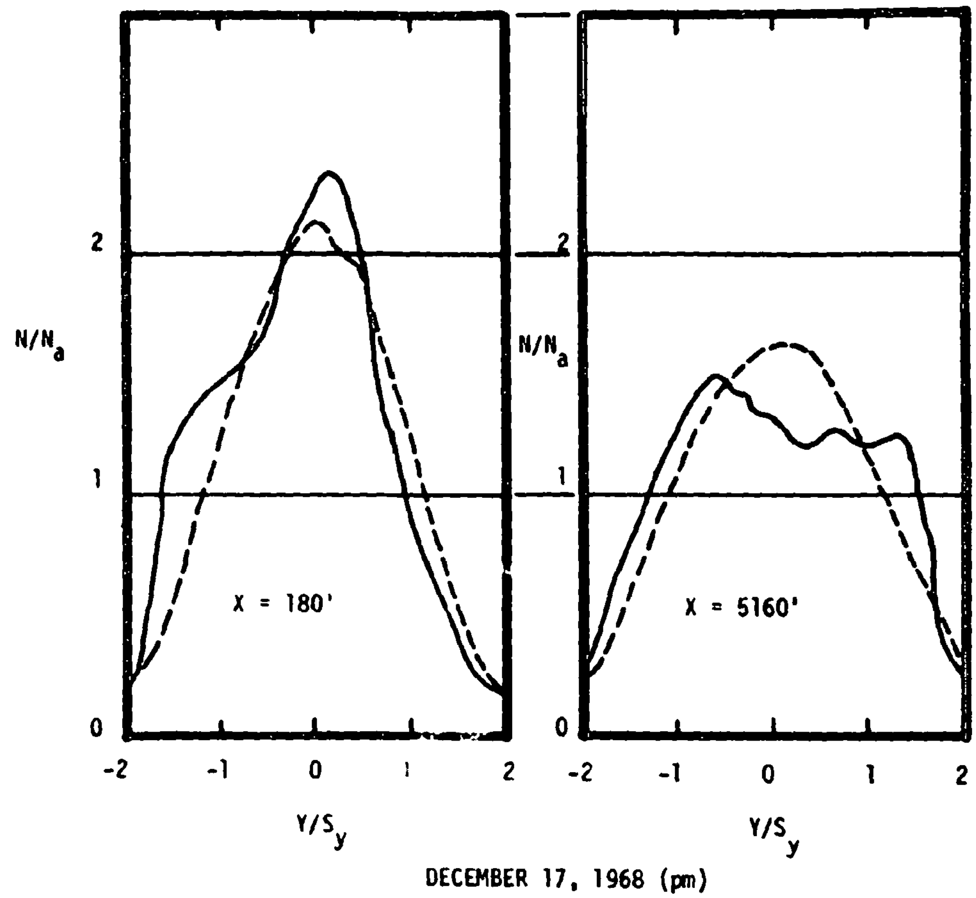


FIGURE A4 - COMPARISON OF DYE PLUME CROSS-SECTIONS WITH FITTED GAUSSIAN DISTRIBUTIONS
POMPANO STUDY, DECEMBER 17, 1968 (EXPERIMENT P9)

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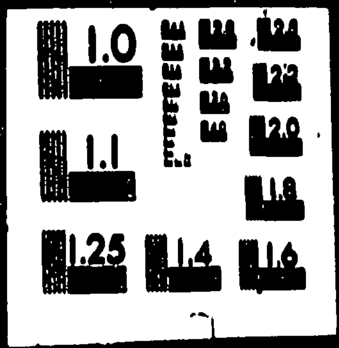


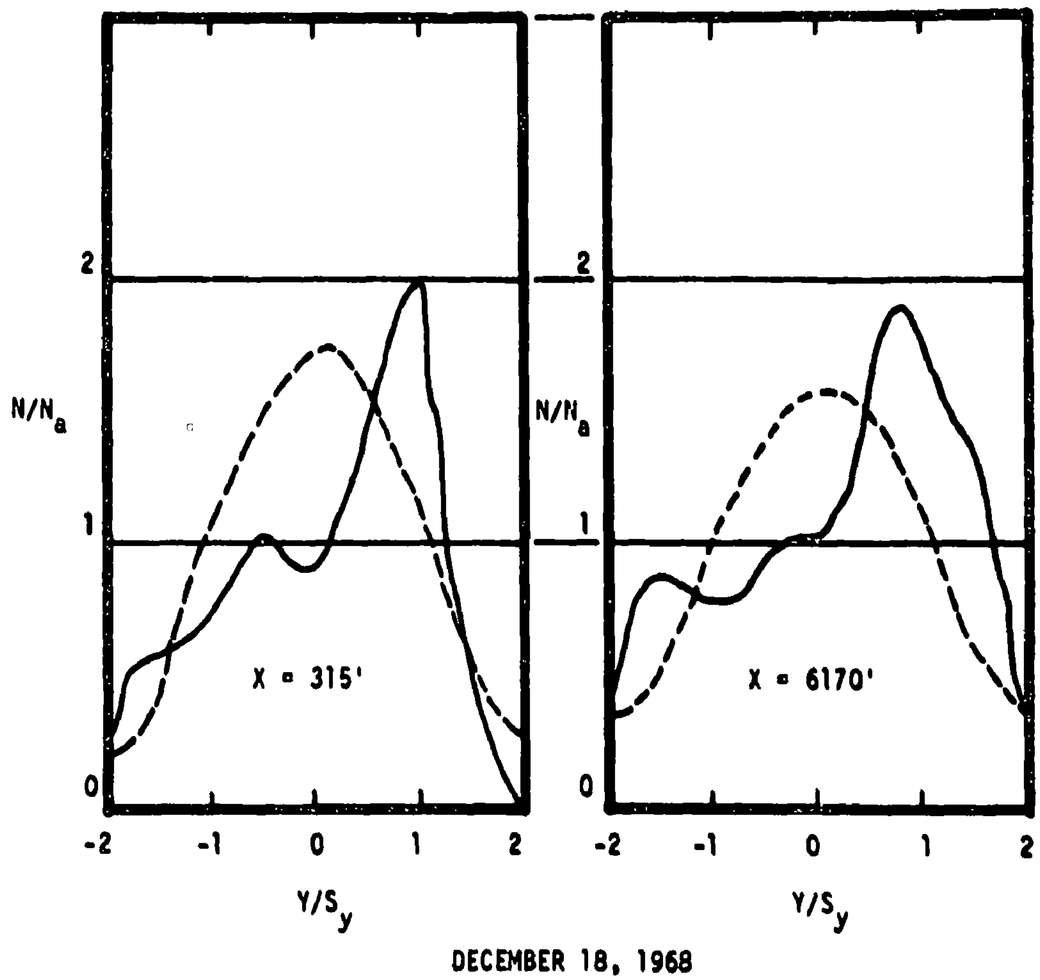
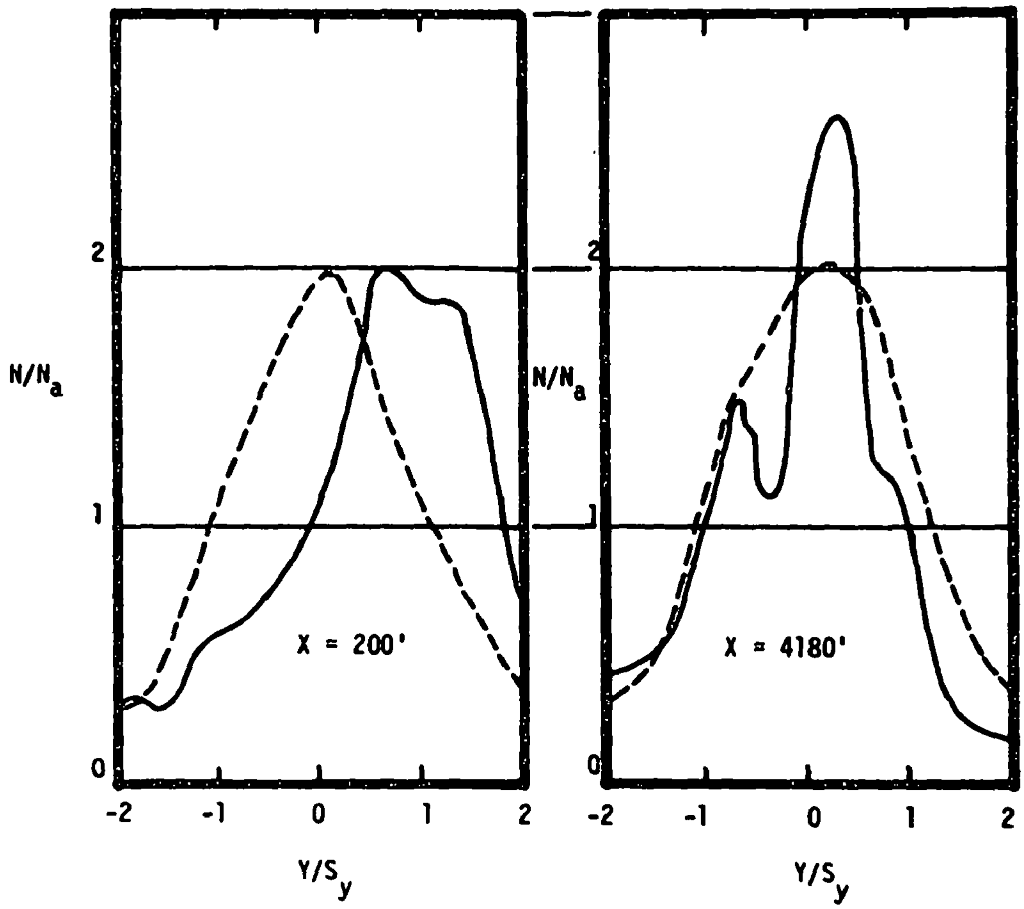
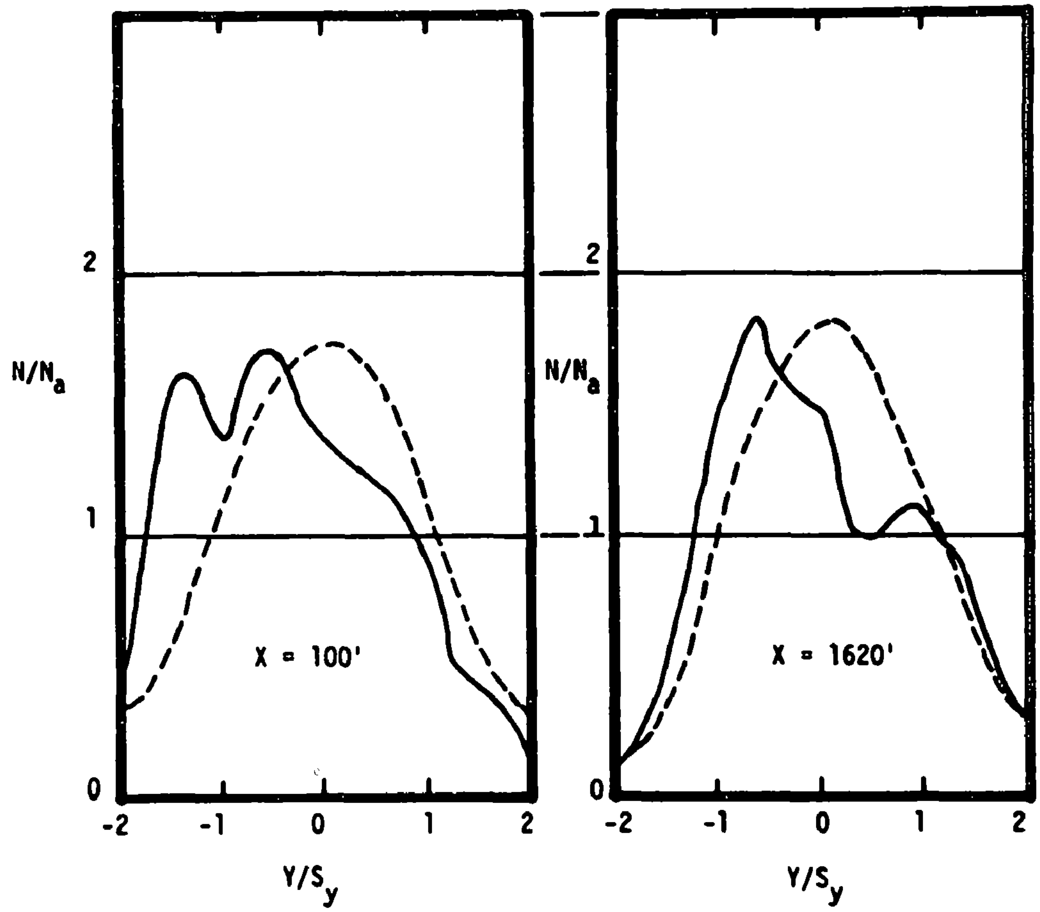


FIGURE A5 - COMPARISON OF DYE PLUME CROSS-SECTIONS WITH FITTED GAUSSIAN DISTRIBUTIONS
POMPANO STUDY, DECEMBER 18, 1968 (EXPERIMENT P10)



MAY 20, 1969

FIGURE A6 - COMPARISON OF DYE PLUME CROSS-SECTIONS WITH FITTED GAUSSIAN DISTRIBUTIONS
HOLLYWOOD STUDY, MAY 20, 1969 (EXPERIMENT H1)



DECEMBER 9, 1969

FIGURE A7 - COMPARISON OF DYE PLUME CROSS-SECTIONS WITH FITTED GAUSSIAN DISTRIBUTIONS
HOLLYWOOD STUDY, DECEMBER 9, 1969 (EXPERIMENT H2)

APPENDIX B

MEASURED PEAK (AXIAL) DYE CONCENTRATIONS AND CROSS CURRENT (LATERAL) PLUME STANDARD DEVIATIONS

TABLE B1 POMPANO STUDY, AUGUST 6, 1968 (EXPERIMENT P1)

Downstream Distance (ft)	Plume Standard Deviation, S_y (ft)	Maximum Concentration ppb Observed	Maximum Concentration ppb Fitted*	Sampler Depth (ft)
460	37	0.75	0.48	5
1430	53	2.65	2.07	5
1570	72	2.15	1.40	5
1840	70	1.10	0.92	5
5100	115	0.39	0.29	5
5170	94	0.29	0.25	5
8740	256	0.26	0.16	5

TABLE B2 POMPANO STUDY, AUGUST 8, 1968 (EXPERIMENT P3)

Downstream Distance (ft)	Plume Standard Deviation, S_y (ft)	Maximum Concentration ppb Observed	Maximum Concentration ppb Fitted*	Sampler Depth (ft)
130	51	4.86	4.81	3
130	47	2.59	2.75	3
230	51	2.56	2.28	3
30	53	4.33	4.80	6.5
130	59	4.01	3.61	6.5
540	81	2.05	1.84	4
1280	118	0.43	0.28	4

*Peak concentration determined on this table and on following tables by fitting to the plume traverse data a Gaussian distribution having the same area, mean, and standard deviation as the concentration profile.

TABLE B3 POMPANO STUDY, AUGUST 14, 1968 (EXPERIMENT P5)

Downstream Distance (ft)	Plume Standard Deviation, S_y (ft)	Maximum Concentration ppb Observed	Maximum Concentration ppb Fitted*	Sampler Depth (ft)
4950	36	0.73	0.60	5
5460	40	0.95	0.75	5
5360	49	1.22	1.06	3
5390	31	1.34	1.19	3
5430	35	1.04	0.90	3
5240	41	1.78	1.60	3
5260	47	1.80	1.72	3
5380	37	2.24	2.17	3
2910	15	2.67	2.17	3
2910	30	2.33	1.88	3
2830	30	2.00	1.63	3
2750	29	2.16	1.83	5
2640	18	2.69	2.58	5
2600	28	1.69	1.54	6.5
2610	26	1.15	1.11	6.5
7910	47	0.40	0.42	3
7910	107	1.12	0.85	3
8250	83	0.54	0.54	3
8120	93	0.72	0.58	3
8010	115	0.76	0.80	3
7950	113	0.67	0.59	5
7740	55	0.68	0.65	5
7870	73	0.74	0.59	6.5
7730	96	0.40	0.30	6.5

TABLE B4 POMPANO STUDY, DECEMBER 10, 1968 (EXPERIMENT P7)

Downstream Distance (ft)	Plume Standard Deviation, S_y (ft)	Maximum Concentration ppb Observed	Maximum Concentration ppb Fitted*	Sampler Depth (ft)
210	140	3.06	2.88	4
160	111	3.75	3.58	4
150	112	4.56	4.64	4
260	113	4.05	4.37	4
890	236	1.10	1.14	4
1440	283	0.92	0.95	4
1070	239	0.60	0.68	4
1400	230	0.60	0.68	4

TABLE B5 POMPANO STUDY, DECEMBER 17, 1968 (EXPERIMENT P8)

Downstream Distance (ft)	Plume Standard Deviation, S_y (ft)	Maximum Concentration ppb Observed	Maximum Concentration ppb Fitted*	Sampler Depth (ft)
190	59	2.40	1.76	4
100	33	1.26	1.37	4
170	37	1.05	1.08	4
110	41	0.87	0.80	4
160	44	0.64	0.56	4
150	46	0.49	0.54	4
400	90	0.25	0.25	4
610	84	0.49	0.40	7
990	118	2.13	1.95	2
330	50	1.30	1.21	2
80	37	2.75	2.09	2

TABLE B6 POMPANO STUDY, DECEMBER 17, 1968 (EXPERIMENT P9)

Downstream Distance (ft)	Plume Standard Deviation, S_y (ft)	Maximum Concentration ppb		Sampler Depth (ft)
		Observed	Fitted*	
620	100	1.69	1.36	2
660	95	1.13	1.18	2
550	87	1.80	1.47	2
600	116	1.66	1.49	4
580	124	1.60	1.52	4
570	75	1.95	1.53	4
600	96	1.70	1.39	6
600	94	1.70	1.33	6
640	76	1.18	1.33	6
990	91	1.30	1.41	6
1030	113	0.71	0.73	6
1050	107	0.82	0.83	4
1050	111	0.57	0.51	4
1100	102	0.47	0.42	2
1820	110	0.50	0.46	2
2820	158	0.11	0.13	2
2910	104	0.39	0.46	4
3770	145	0.18	0.14	6
3920	151	0.26	0.24	6
3950	112	0.26	0.29	4
4020	171	0.35	0.32	4
3990	171	0.34	0.20	4
4100	147	0.19	0.22	2
4980	188	0.15	0.12	2
5160	191	0.21	0.25	2

TABLE B7 POMPANO STUDY, DECEMBER 18, 1968 (EXPERIMENT P10)

Downstream Distance (ft)	Plume Standard Deviation, S_y (ft)	Maximum Concentration ppb		Sampler Depth (ft)
		Observed	Fitted*	
320	46	1.80	1.46	4
400	32	0.71	0.68	3
360	30	2.92	2.65	3
460	44	1.68	2.06	3
610	47	1.51	1.57	6
790	57	1.15	1.29	6
760	57	0.98	0.86	6
1050	54	0.66	0.57	6
1160	64	0.55	0.42	6
1070	50	0.50	0.40	4
1210	56	0.27	0.27	4
1390	57	0.28	0.25	2
2760	82	0.40	0.37	2
3030	94	0.30	0.36	4
3040	85	0.18	0.18	4
5410	132	0.17	0.14	6
5670	146	0.14	0.14	6
6170	154	0.13	0.11	4

TABLE B8 HOLLYWOOD STUDY, MAY 20, 1968 (EXPERIMENT H1)

Downstream Distance (ft)	Plume Standard Deviation, S_y (ft)	Maximum Concentration ppb		Sampler Depth (ft)
		Observed	Fitted*	
210	37	12.6	11.8	2
200	42	15.7	16.2	2
170	24	24.5	20.3	2
1150	47	8.40	7.30	2
1080	84	12.3	6.35	2
2260	121	2.80	2.76	2
2340	199	2.98	2.78	2
2440	123	3.21	2.51	2
3880	362	3.80	2.49	2
4180	381	4.22	3.18	2

TABLE B9 HOLLYWOOD STUDY, DECEMBER 12, 1969 (EXPERIMENT H3)

Downstream Distance (ft)	Plume Standard Deviation, S_y (ft)	Maximum Concentration ppb		Sampler Depth (ft)
		Observed	Fitted*	
100	136	6.82	7.45	3
900	304	2.63	3.00	3
700	220	2.94	3.36	3
1620	365	1.86	1.96	3
1580	353	1.86	1.97	3

APPENDIX C

PHOTOGRAPHS

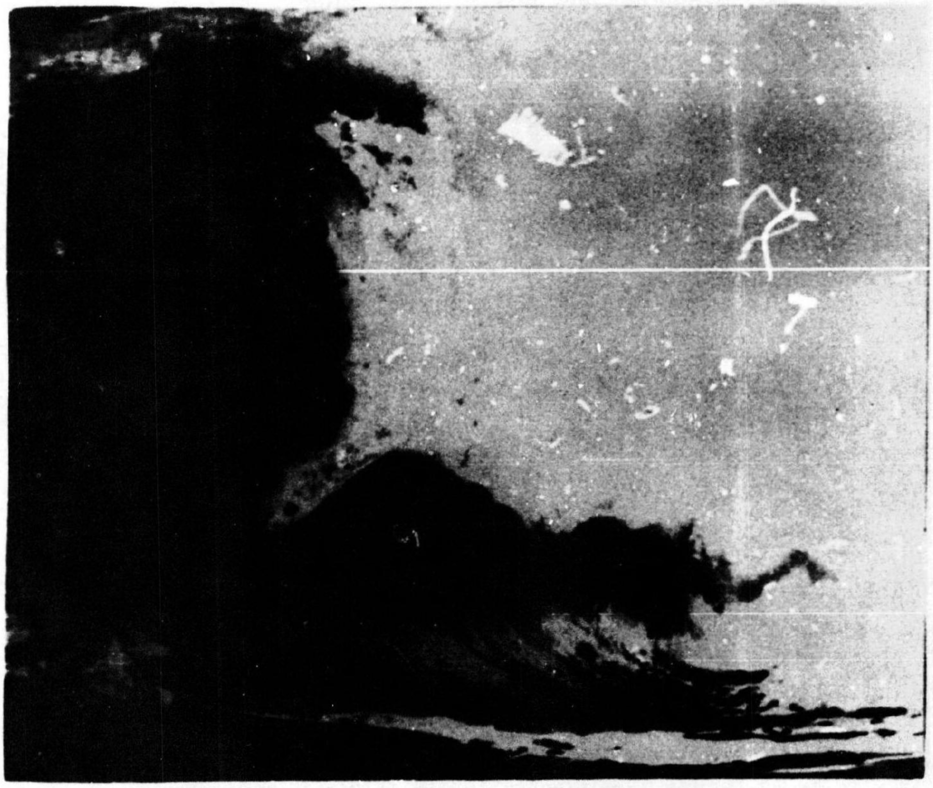


FIGURE C1 - THE GULF STREAM

FIGURE C2 - EDDIES OFF THE GULF STREAM

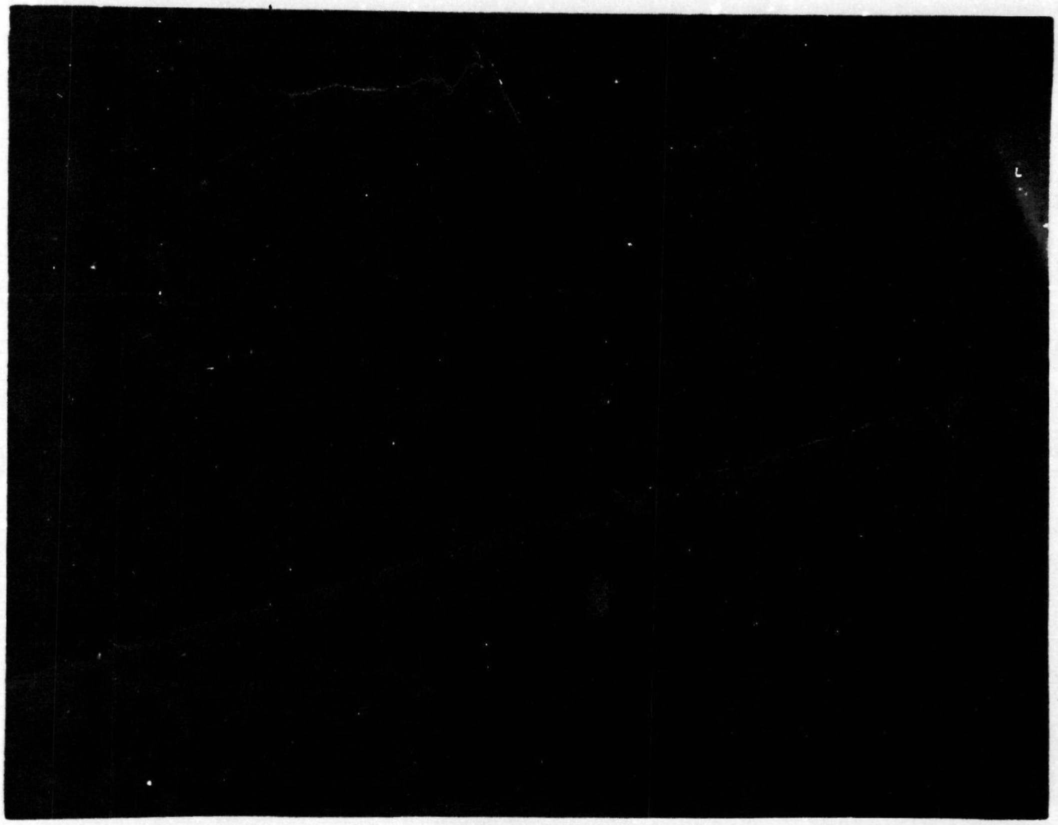


FIGURE C3 - DYE PLUME (EXPERIMENT P6)