SEWAGE DISPOSAL IN FALMOUTH, MASSACHUSETTS

II. PREDICTED EFFECT OF THE PROPOSED OUTFALL[1]

Dean F. Bumpus, Senior Scientist; W. Redwood Wright, Assistant Scientist and Ralph F. Vaccaro, Associate Scientist[2]

Abstract

The proposed addition of nearly 4 million gallons per day of effluent, from a secondary sewage treatment plant in Falmouth, to Vineyard Sound off Nobska Point is evaluated by means of current measurements, dilution estimates, and potential stimulation of phytoplankton growth. In terms of current usage no impairment of the water quality is indicated.

Introduction

The Whitman & Howard report[1] to the Town of Falmouth recommended a sea outfall (off Juniper Point, near the entrance to Woods Hole Passage) for its domestic sewage system. From inspection of the U.S. Coast and Geodetic Survey Charts and current data, it appeared likely that an outfall off Nobska Point would offer superior dilution and mixing and would minimize the chances of the effluent being carried into Buzzards Bay, the harbors and estuaries, or onto the beaches of the Town. No place east of Nobska Point along the Falmouth shore offered comparable tidal dilution and dispersion. On this basis, studies were concentrated on the area off Nobska Point (Fig. 1) to answer the following questions.

1. How far offshore should an outfall be located to minimize the return of effluent to the harbors and estuaries and beaches of Falmouth, and to avoid its entrainment in the current through Woods Hole Passage?

2. What dilution of the effluent would be expected as a result of the volumes of water moving past Nobska Point?

3. What effect would be expected upon the ecological cycle of Vineyard and Nantucket Sounds from the added phosphorous, nitrogen and carbon, the principal fertilizing elements in sewage?

Vineyard and Nantucket Sounds form a long shallow embayment lying south of Cape Cod and the Elizabeth Islands and north of Nantucket and Martha's Vineyard, see USC&GS charts 1209 and 1210. They open to the east into the Gulf of Maine, to the west into the Atlantic Ocean, and to the north in the western part through "holes" into Buzzards Bay. Semidiurnal tidal currents sweep forth and back through the sounds at speeds varying from nil (for only a

[1] This is the second of three papers relating to the main subject. It is identified as Contribution No. 2700 of the Woods Hole Oceanographic Institution.

[2] All, Woods Hole Oceanographic Institution, Woods Hole, Mass.

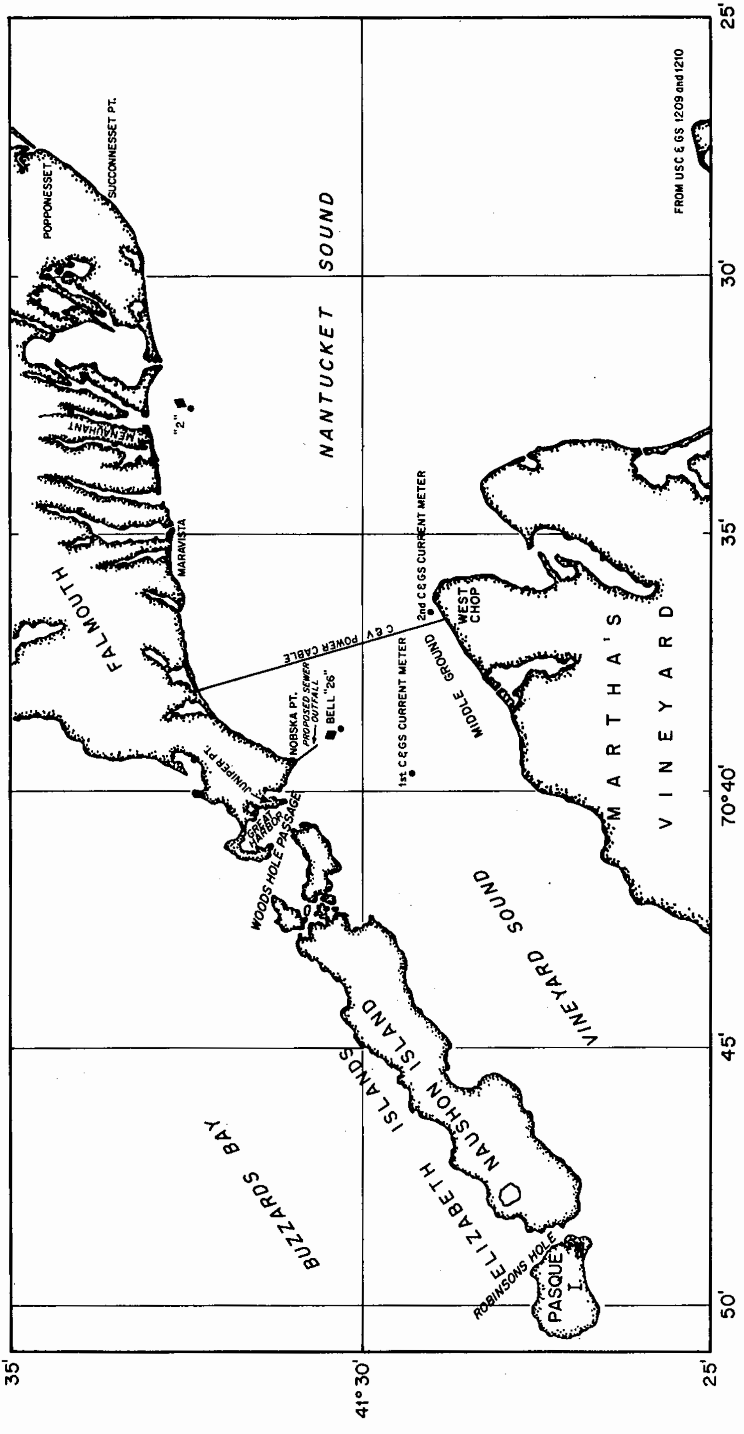

Figure 1. Chart of Vineyard and Nantucket Sounds showing places and objects mentioned in the text.

few minutes) to over three knots.[2] The tidal rise and fall averages about three feet at each end of the sounds but only 1.5 feet near Woods Hole, attributed by Redfield[3] to the interference of the tidal waves entering the sounds from the opposite ends. A further peculiar characteristic is the unequal duration of flow in opposite directions in the Woods Hole Passage. The eastward current duration exceeds the westward current duration by about two hours.

The current flowing easterly immediately off Nobska Point includes a branch from Woods Hole Passage which joins the flow from Vineyard Sound. When the current flows to the west, a portion passes through Woods Hole Passage (and Great Harbor) and the remainder travels down Vineyard Sound. We needed to ascertain the offshore extent of the separation between the Woods Hole flow and the flow to the westward south of the Elizabeth Islands. We wished also to determine the length of the tidal excursion in order to compare the projected volume of treated sewer effluent with the amount of sea water available for mixing during the tidal cycle. It was also desirable to estimate the exchange rate, i.e. how much new sea water is added to the system to replace that leaving the area within a given period of time.

Data Available

The anticipated average summertime outflow from the proposed secondary treatment plant, including a possible extension to East Falmouth, is estimated by the engineers at 3.7 million gallons per day, which is about 14 thousand m^3/day or 7 thousand m^3 per tidal cycle.

The proposed system is for domestic sewage only; no storm sewers or industrial wastes are included. Suspended solids and biochemical oxygen demand (BOD) would be 85% to 95% removed. The principal pollutants therefore are the nutrients, phosphorous and nitrogen. Their presence in large quantities could lead to overfertilization of the waters, with harmful effects on the resident plant and animal life. The anticipated concentration of these substances in the effluent are 30 mg/1 of phosphorous as phosphate, equivalent to 10 thousand mg/m^3 of PO_4-P and 40 thousand mg/m^3 of nitrogen (letter from Whitman & Howard to Bumpus, April 10, 1969). The dissolved carbon content should be about 40 thousand $gram/m^3$. The background concentration of these nutrients in the coastal waters adjacent to Vineyard Sound ranges from 25 mg/m^3 of PO_4-P and 140 mg/m^3 of nitrogen in winter to 6.2 mg/m^3 of PO_4-P and 7 mg/m^3 of nitrogen in the summer.[4] The dissolved organic carbon varies from 1000 mg/m^3 in the summer to 2300 mg/m^3 in the winter. (Menzel, personal communication)

The area and mean-low-water volumes of the two sounds were calculated by dividing USC&GS charts 1209 and 1210 into small rectangles at 2½ minutes of latitude and longitude and then determining the average depth of each rectangle or fraction thereof between lines connecting Gay Head to Cuttyhunk and Monomoy to Great Point, Nantucket. Using 70°40'W as the boundary separating the sounds, the results were:

	Area (km^2)	Volume (km^3)
Vineyard Sound	189.2	3.31
Nantucket Sound	1538.4	13.68
Totals	1727.6	16.99

On this basis the average depth at mean low water is 17.5 m (57.4 ft) in Vineyard Sound and 8.9 m (29.2 ft) in Nantucket Sound.

Mangelsdorf[5] measured the flow between Juniper Point and Nonamesset Island with a stationary salt bridge. He found a westward transport of 11 million m^3 per tidal cycle and an eastward transport of 27 million m^3 per tidal cycle, which means a total flow of 38 million m^3 per tidal cycle and a net flow to the eastward, into the Sound, of 16 million m^3 per cycle.

The tidal flow in the sound between Nobska Point and Middle Ground Shoal is about 4000 million m^3 per tidal cycle – 100 times that through the Woods Hole Passage – as estimated from the tidal current and bathymetric charts of the USC&GS. The estimate was refined somewhat with current meter records obtained by the USC&GS over a 15-day period in the summer of 1966. One instrument was at 15 feet in a water depth of 81 feet about 1.6 miles south of Nobska Point. The record showed an average peak velocity of 2.18 knots on the flood (east tide) and 2.36 knots on the ebb. As the velocity curve approximated a sine curve, the mean speed can be estimated at $2/\pi$ times the peak, or 1.45 knots. Applying this speed to a cross section area of the sound, from Nobska to Middle Ground Shoal, gives a total flow per tidal cycle of 2800 million m^3. The record also indicated a net westerly flow of 0.13 knots, equivalent to a net westerly transport of about 250 million m^3/tidal cycle. A second meter, located between Middle Ground and West Chop, showed a net easterly velocity of 0.60 knots. Applying this to the cross section area between Middle Ground and West Chop gives a net easterly transport of 75 million m^3/tidal cycle in that part of the sound. These results are tabulated in Table 1. It should be recognized that using observations made at one point in a tidal current to determine the transport through an entire section is not very reliable, except to give a gross idea of the magnitude of flow.

Experiments Conducted

Initially, we set out drogued buoys (ballasted Chlorox bottles with pilot chutes attached with 12 feet of cord) at intervals along a line between Nobska Point and buoy "26" at various phases of the tide, and observed their departures from the points of release by fixing their position from time to time through

Table 1. Vineyard Sound Transport Estimates

Method	Location	Date	Mean Speed (kts)	Cross Section Area (m^2)	Total Transport per tidal cycle ($\times 10^6$ m^3)	Net Speed (kts)	Net Transport per tidal cycle ($\times 10^6$ m^3)
US C & GS current meter	41°29′18″N 70°39′38″W	21 Aug–4 Sept 1966	1.45	86,500[1]	2800	0.13 W	250 W
US C & GS current meter	41°29′00″N 70°36′30″W	26 Jul–9 Aug 1966		5,700[2]	170[3]	0.60 E	75 E
Cape & Vineyard[4] Electric Co. cable	Falmouth beach to West Chop	summer – 1969	2	92,000	4200	0.1 E	200 E
Geodyne current meter	41°30′43″N[5] 70°39′05″W	26 Nov–10 Dec 1969	1.15			0.06 E	

[1] Nobska Point to Middle Ground Shoal
[2] Middle Ground Shoal to West Chop
[3] Calculated by integrating velocity curves
[4] See page 260
[5] At proposed site for outfall

horizontal sextant angles on known landmarks. Drift bottles and occasionally sea-bed drifters were released with the drogue buoys to help determine residual drift and dispersion. These experiments were conducted on 2 and 9 July and 11 August 1969. We were favored with calm to light winds during all of the above experiments.

Corollary to our experiments with drifting equipment, the use of a spare electric power cable extending from Falmouth shore, near the intersection of Oyster Pond Road and Surf Drive, across the Sound to West Chop on Martha's Vineyard was permitted the Woods Hole Oceanographic Institution, courtesy of the Cape and Vineyard Electric Co. This cable was used to measure the variations in the electric field generated by the tidal currents flowing through that section of Vineyard Sound, after the electromagnetic method of von Arx[6], Wertheim[7], and Trites and MacGregor[8]. This information, when integrated, also informs us of the net flow. A summer fellow, Reinhard Flick, under the guidance of Dr. Thomas Sanford, conducted these observations.

An effort to determine the net flow past Nobska Point was conducted in the autumn through the good offices of Paul F. Smith of the Geodyne Corporation and the Woods Hole Oceanographic Institution Buoy Group in which a self-recording meter was moored for two weeks in November-December, 1969.

A brief dye experiment by two graduate students was conducted in August 1970 in order to determine the rate of diffusion at the surface.

Results

1. Flow across a section off Nobska Point at various phases of the tide.

Diagrams of the results of a dozen sets of drogue releases on a section between Nobska Point and buoy "26" are shown in Figure 2. The diagrams are related to the time of Slack, Flood Begins or Slack, Ebb Begins at Pollock Rip Lightship. Inspection of the diagrams reveals a general tendency for the east flowing current within ¼ mile of Nobska to run nearly parallel with the shore line, whereas drogues released farther off-shore were diverted slightly off-shore by the shoal immediately east of Nobska Point. At certain stages of the west flowing current, drogues released within ¼ mile of Nobska Point were carried into Woods Hole Passage, whereas these released farther off-shore headed westerly past the Elizabeth Islands. Thus to avoid direct flow toward the beaches or into Woods Hole Passage, the outfall should extend more than ¼ mile off Nobska Point.

Normalization of the drogue speed data reveals that the average speed of the current increases with distance off-shore, approaching a plateau at 0.3 miles (Figure 3). In comparing the time when the tide turned at 0.1, 0.2, 0.3 and 0.4 miles off Nobska, it is noted that the west flowing tide turns to the east about ½

Figure 2. Drift of drogue buoys away from the offing of Nobska Point at various times during the tidal cycle, related to tidal time at Pollock Rip Lightship.

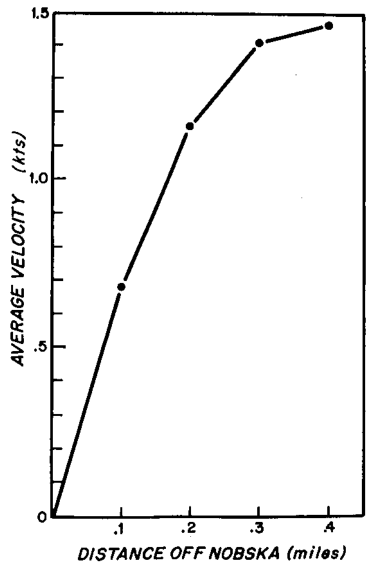

Figure 3. Average velocity of current off Nobska Point relative to distance offshore.

hour later inshore than offshore and that the east flowing tide turns west about an hour earlier inshore (Figure 4). It is further interesting to note that the volume of water flowing eastward increased with distance offshore (Table 2).

Table 2. Comparison of the Relative Volume of East and West Flow at Various Distances off Nobska

Distance off	Volume East	Volume West
0.1 mile	24%	76%
0.2	45%	55%
0.3	53%	47%
0.4	63%	37%

An echo sounder profile of the section from Nobska to Bell "26" (Fig. 5) showed a maximum depth of 28 m (91 ft) about 700 yards offshore. It thus appears that minimum return to shores, harbors and estuaries, coupled with maximum dilution and minimum length of outfall pipe, could be achieved at a distance of 0.375 miles south of Nobska Point (700 yards 141° T) from Nobska Lighthouse in 90 feet of water.

2. The length of a tidal excursion

Drogues were set out on three occasions at the time the tide was turning from one direction to the other, in order to ascertain how far a parcel of water

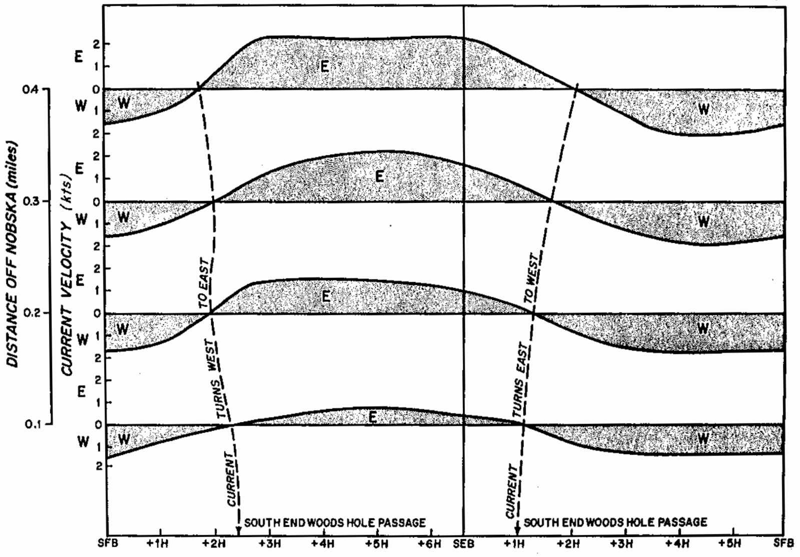

Figure 4. Diagram of the tidal flow at various distances off Nobska Point relative to tidal time at Pollock Rip Lightship.

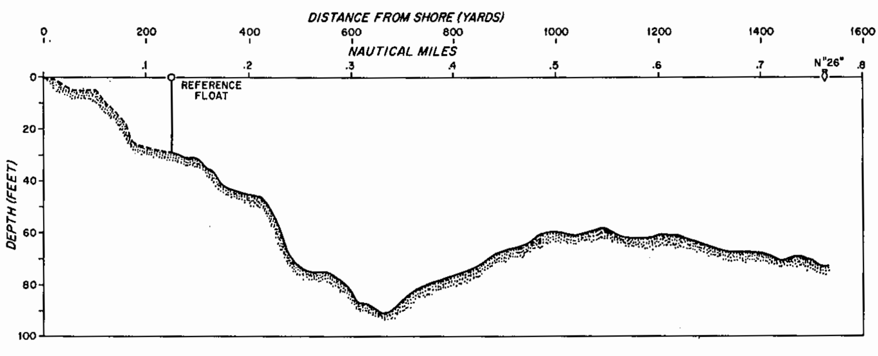

Figure 5. Bottom Profile, Nobska Point to Bell "26" azimuth 164°M. Position of reference float 41° 30′ 51″ N; 70° 39′ 11″ W. Depths seaward of reference float from echo-sounder run, 1355 – 1402, 15 July, '69. Depths inshore of reference float from C & GS chart #348.

may travel before it stops and begins to flow in the opposite direction. The experiment on July 2 (Figure 6) commenced shortly after 8 A.M. as the tide was turning east. The drogue released at a distance of 0.05 mile off Nobska Point went aground by the sign under Nobska warning of a Cable Crossing. The drogue launched 0.12 mile offshore tended toward the Falmouth shore and was eventually recovered off Maravista, undoubtedly after it had commenced to move westerly. The other three drogues launched at 0.20, 0.28 and 0.35 miles off Nobska drifted over 8 miles (14.8 km) in six hours to a point about one mile off Succonnesset Point. This experiment was conducted at the time of spring tide, hence the distance travelled may have been greater than average.

Similarly, drogues were launched on 9 July at the time of slack water and were followed as they moved westerly. The innermost drogue, launched at a distance of 0.25 mile off Nobska, eventually grounded off Witches Glen on Naushon, over 4 miles from its origin. The remainder, launched at 0.34, 0.55 and 0.66 miles off Nobska, travelled in company almost to Robinson's Hole, a distance of over 7 miles (13 km) in six hours.

A third excursion experiment was conducted on 11 August in which drogues were released in the offing of Bell "2" off Menauhant, just before the tide turned west, and were tracked for nearly six hours, actually until they had ceased westerly progress. This excursion was 4.5 miles (8.3 km) west.

The interesting points to note from this set of excursion experiments are:

a. Excursions from Nobska are on the order of 7-8 miles (13-14 km);
b. Return excursion from off Menauhant toward Nobska was substantially reduced, suggesting the net flow is toward the east.
c. With the exception of those drogues launched inshore of 0.25 mile off Nobska, all drogues drifted along together, being only slightly farther apart after 6 hours than they were initially.

3. *Drift Bottles*

Drift bottles were released with each drogue, and in some instances farther offshore out to buoy "26", in order to gain some insight into the extension of the drift beyond that defined by the drogue experiments. The drift bottles moved at a rate and direction comparable with the drogues. Of the 416 bottles released, 275 or 66% were recovered between West Dennis to the east and Cape Hatteras to the west. Those recovered were about equally distributed between east of the point of release along the north side of the Sound (32%), westward into Vineyard Sound to Rhode Island, New York and North Carolina (37%), and northward into Buzzards Bay (29%). Only 1% were recovered from Martha's Vineyard. When we break down the recoveries, relative to how far offshore they were launched and in what direction they eventually stranded (Table 3), we see that a high percentage of those released within ¼ mile off Nobska Point entered Buzzards Bay where the currents are weak; whereas beyond ¼ mile off Nobska the flow to Buzzards Bay was 25% or less.

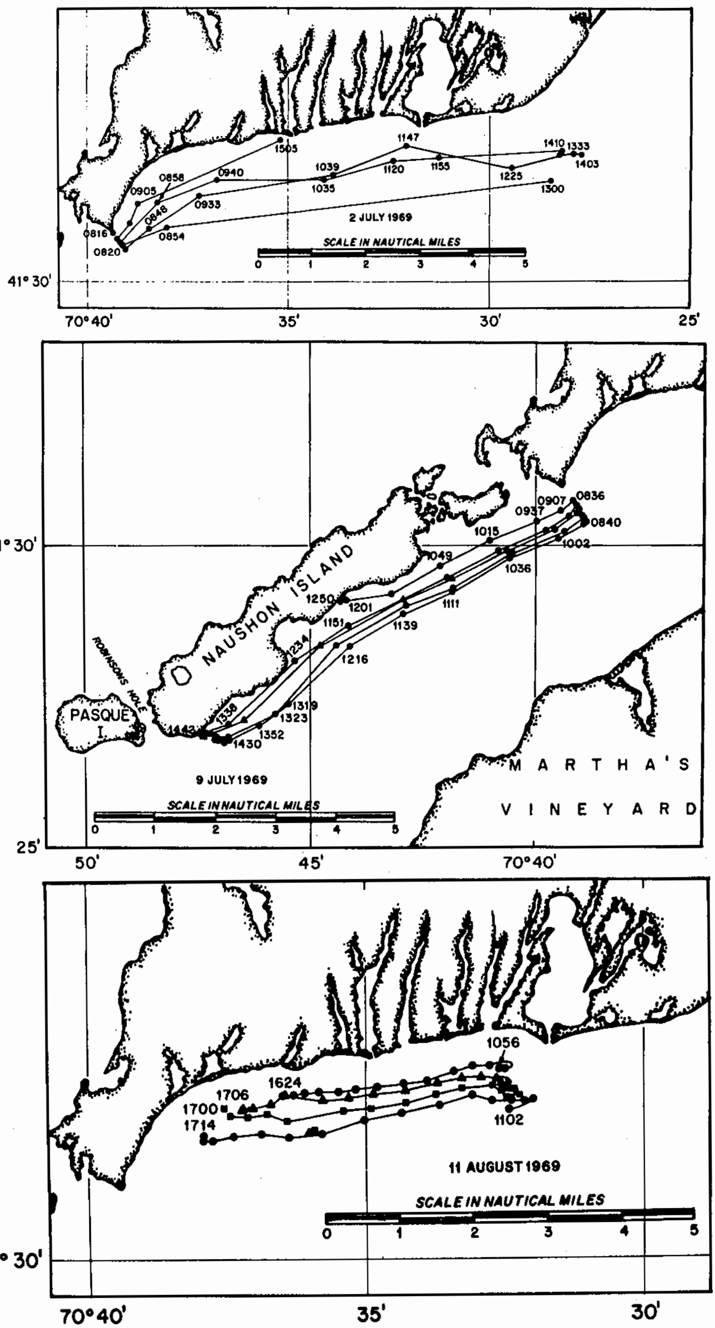

Figure 6. Drift of drogue buoys during the tidal excursion experiments.

Table 3. Percentage of Recovered Drift Bottles which Stranded Northerly, Easterly or Westerly Relative to Distance of Release off Nobska Point

Distance Offshore	N	E	W
0.00 – 0.25 mile	40	25	35
0.25 – 0.35	22	38	38
0.35 – 0.50	25	36	39
> 0.50	20	39	38

These returns show that, of those launched within ¼ mile off Nobska, 50% were recovered just over 4 miles from their point of release, whereas of those launched more than ¼ mile off Nobska, 50% were recovered within 6 miles of their origin. However, in view of our observations that bottles and drogues appear to drift together, we do not believe this means the bottles drifted directly to the beach where they stranded. Instead, they probably drifted back and forth for several tidal cycles. The north shore of the sound, east of Nobska, is a sandy shoreline well peopled in June, July and August; hence, there should be little or no delay in their recovery. Sixty-eight bottles were recovered here between 1 and 49 days after their release, of which 50% were recovered within 5 days. In contrast, the Elizabeth Islands present only patches of beach here and there, and as a whole are more sparsely peopled. Fifty-three bottles were found along the shore of the Elizabeth Islands between 0 and 65 days, of which 50% were recovered within 10 days.

4. Sea-Bed Drifters

A sea-bed drifter is a "drift bottle" designed to drift along the bottom. It is a plastic disc with a 2-foot stem ballasted with a brass ferrule so it has slight negative buoyancy in sea water.[9] These were distributed at intervals along the section between Nobska Point and buoy "26". Of the 140 sea-bed drifters released, 45 were recovered; 40 drifted eastward, one went 2 miles to the west, one to Little Harbor, two to Wood Neck Beach in Sippewisset and one to Martha's Vineyard. Of those which went easterly, many stranded at Poponnesset. The average distance of strand was 7.8 miles from Nobska in 19 days. There were no significant differences in drift related to the off-shore distance of release.

5. Net Flow as Determined by Geomagnetic Electrokinetograph

The geomagnetic electrokinetograph measurements of Sanford and Flick during the summer of 1969 showed an easterly flow of 2200 million m^3 on the flood and a westerly flow of 2000 million m^3 on the ebb, for a net easterly flow of 200 million m^3 per tidal cycle, through the section from Surf Drive, Falmouth, to West Chop, Martha's Vineyard, in reasonable agreement with the results of the current meter calculations. The mean speed across the section was 2.0 knots.

6. Current Meter Record at Proposed Outfall Location

A self-recording current meter[10] was moored at a depth of 30 feet in 90 feet of water at 41° 30′43″N, 70°39′ 05″W (at the point of maximum depth between Nobska Point and Bell "26") for a 14-day interval, 26 November to 10 December 1969. The current ranged from 0.5 to 149.5 cm/sec (0 – 2.8 kt) with an average speed of 60 cm/sec (1.15 kt). The progressive vector diagram (Fig. 7) shows tidal excursions on the order of 13 km (7 miles) comparable to the evidence from the drogue experiments. The easterly current flowed toward 060°T at an average speed of 62 cm/sec for 6.28 hours, the westerly current flowed toward 234°T at an average speed of 45 cm/sec for 6.09 hours. The net flow was easterly at a rate of 1.45 km per tidal cycle, roughly 5% of the total flow, in good agreement with the 5% net easterly flow evidenced by the geomagnetic electrokinetograph measurements.

7. Dye Experiments

Two brief dye experiments were conducted in the summer of 1970 by two graduate students in the Woods Hole Oceanographic Institution–Massachusetts Institute of Technology Joint Program and were described in a typewritten report.[11] The experiments ran for about four hours each on both easterly and westerly tides. In each case Rhodamine B dye diluted to a specific gravity of 0.965 was released at the sea surface above the proposed outfall point. The spreading dye was photographed from the air and its concentration was determined in several samples taken by a small boat criss-crossing the plume. In addition, drogues were set out at various depths and tracked for the duration of the experiments.

Although too short to be conclusive, the dye experiments generally corroborated the results of the 1969 studies. For example, the drogues all stayed together and, on the easterly tide, both drogues and dye streak were diverted offshore by a shoal just east of the outfall point. The principal differences from the earlier experiments were (1) on the westward tide, with a southeast wind blowing, some of the dye came very close to the shore on Nonamesset Island and was carried into Woods Hole Passage, although most of it went down Vineyard Sound; and (2) the dye showed a good deal more horizontal dispersion, approximately 1 square nautical mile/hour (3.3 km^2/hr), than was evident in the drogue experiments.

Dilution and Dispersion

The degree of contamination to be expected from the sewage plant effluent cannot be estimated to better than an order of magnitude because of uncertainties about the degree of mixing with the waters of the sounds and the net transport of water through the sounds. It was concluded early in the

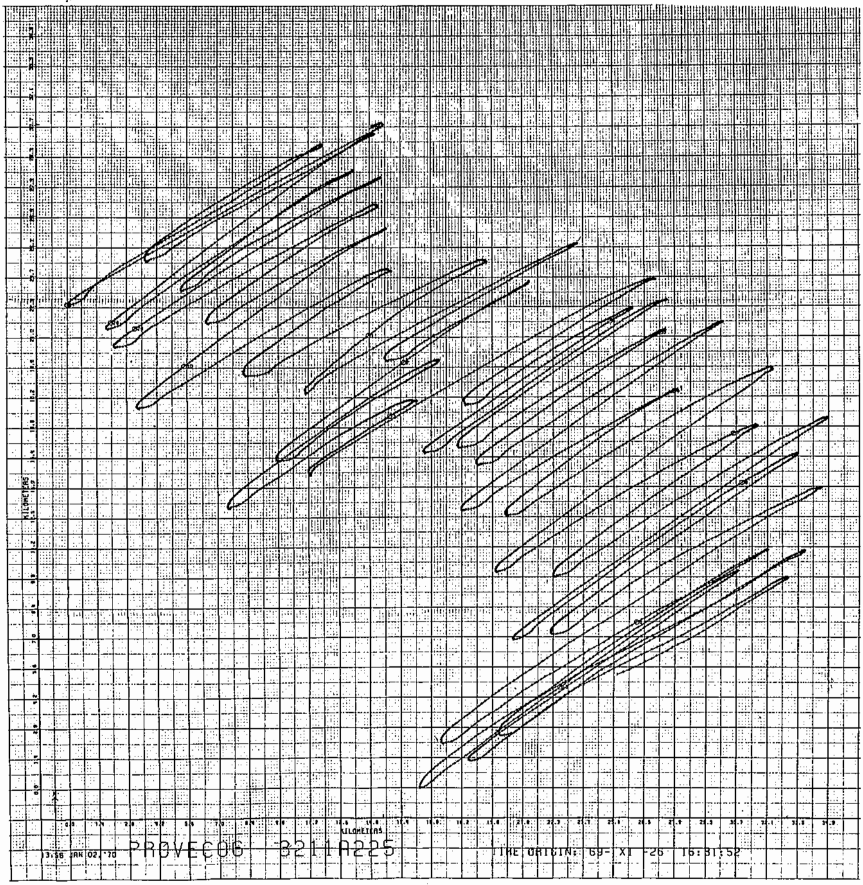

Figure 7. Progressive vector diagram of current meter data, 26 November to 10 December 1969 at 41° 30′ 43″N; 70° 39′ 05″W at 30′ in 90′ of water.

investigation that it would be fruitless to try to apply any refined theory to an area of strong reversing tidal currents. Instead, the emphasis has been on estimates based on the above measurements. We have tried to use conservative figures so that our results would be on the pessimistic side.

There are two fundamental and interrelated problems involved in predicting the concentration of pollutants from the sewer outfall: the rate of flushing and the mixing characteristics. The data in the previous sections permit calculation of the flushing rate by the methods of tidal exchange and net flow. Both methods assume complete mixing within the volume affected, and the first assumes, in addition, that the exchange of contaminated water for uncontaminated water at each change of the tide is a known quantity. Neither assumption is valid, of course, but reasonable approximations can presumably be made.

There is evidence of some exchange in the drift bottle results. More than 28% of all the returns were from outside the sounds, either to the north in Buzzards Bay or to the west. If we consider only those bottles launched more than ¼ mile offshore, 25% of the recoveries were from outside the system and a third of those were from the west. Several tidal cycles are required, of course, to transport a float west from Nobska Point past Cuttyhunk, out of the sounds; the earliest return from beyond Cuttyhunk was 9 days.

Nearly complete vertical mixing, whether caused by wind stirring or by rapid flow over an undulating sea floor, can be assumed with some confidence; among the hundreds of bathythermograms in the W.H.O.I. files on the two sounds, only a handful of mid-summer observations show any thermal stratification. And, although the effluent will be warmer and less saline than the waters of the sounds, and hence, less dense, it will be introduced at the bottom of the sound, with downward diffusers on the outlet to encourage mixing, into water which is moving rapidly almost all the time. On the other hand, there is very little evidence of horizontal mixing except as provided by the dye experiments. Very little separation of drogues was observed on the three tidal excursion runs, except along the axis of flow at the beginning and end of the tidal cycle, when the inshore drogues changed direction earliest. The lack of vertical shear is shown by the surface drift bottles moving right along with the drogues at 12 feet depth. In one experiment comparing drogues at the surface and at 30 feet, the shallow drogues outdistanced the deep ones but only by about ten percent. Finally, the recovery of only 1 percent of the drift bottles on Martha's Vineyard argues that water flowing past Nobska keeps to the northern part of the sounds.

To allow for these mixing conditions it will be assumed in the following discussion that the mixing of effluent is restricted to one-tenth of the total volume of the sounds, and that one-tenth of the water entering the system on a change of tide is "new" water. We think these are conservative estimates; in combination they will predict concentrations 100 times greater than if mixing through the entire volume and 100% "new" water were assumed.

1. Tidal Exchange

The tidal exchange method is destribed by Ketchum[12] and applied in combination with tidal excursion data in Ketchum[13] for estuaries with river flow. He developed an expression for the quantity Q of river flow present in a given segment of an estuary after many tidal cycles, assuming complete mixing within the segment, as

$$Q = R/r$$

where R is the volume of river water introduced in a tidal cycle and r is the ratio between the intertidal volume (tidal prism) and the high tide volume of the segment. Because of the complications of large tidal excursions we will simply consider the entire sound as one segment.

Q becomes the amount of effluent in the sound after a steady state is reached. R is the effluent introduced during a tidal cycle (7 thousand cubic meters) and r = MP/(P+V) where M is the fraction of new water in the entering tide (0.1), P is the volume of the tidal prism and V is the mean low water volume of the system (17 cubic kilometers). Assuming a mean tidal rise of 0.7 m, P is 1.2 cubic kilometers, so that

$$r = \frac{0.1 \times 1.2 \text{ km}^3}{1.2 \text{ km}^3 + 17 \text{ km}^3} = \frac{1}{151}$$

Q then equals 151 R = 1057×10^3 m^3, or approximately one million cubic meters of effluent. If this quantity is mixed with 10% of the total volume of the sound, the dilution will be

$$\frac{1.7 \times 10^9 \text{ m}^3}{1 \times 10^6 \text{ m}^3} = 1700 \text{ sea water to 1 effluent}$$

The reciprocal of r, 151 cycles, is equivalent to residence time so it can be said that the effect of any unusual event, even discharge of untreated sewage, would be dissipated in less than three months.

2. Net Flow

A better estimate is probably that based on net flow, which represents the amount of uncontaminated water entering the system on each tidal cycle. When a steady state is reached, the ratio of sea water to effluent in the contaminated volume of the sound will be the same as the ratio of net flow per tidal cycle to the effluent introduced in a tidal cycle.

The net flow according to the cable measurements is about 200 million m^3 per cycle. If we apply the 10% assumption as before, we find that 7000 m^3 of effluent mixed with 20 million m^3 of sea water has a dilution of about 2850 to1.

3. *Immediate Mixing*

The foregoing applies to the general dispersion of effluent throughout the affected body of water, but the amount of contamination will, of course, be greater near the outfall.

We will assume that the sewage effluent is lighter than sea water and will be mixed by entrainment throughout the whole water column as it rises.

The absence of reliable information on mixing characteristics and the added complications of tidal fluctuations make it impossible to predict the effect accurately, but a minimum dilution figure can be established as follows:

Assume the effluent comes out of a diffuser 10 meters long at a depth of 28 meters at a rate of 14×10^3 m^3 per day. The current meter data, at the prospective outfall site, give evidence that the tidal flow past the outfall location amounts to 52 kilometers per day. Multiplying this rate of flow by the cross sectional area ($10\ m \times 28\ m = 28\ m^2$) = 14.6×10^6 m^3 of sea water to mix with the 14×10^3 m^3 of effluent, producing an initial dilution of 1000 m^3 of sea water for each cubic meter of effluent.

4. *Horizontal Diffusion*

Let us take the 1000 to 1 figure as a minimum estimate for immediate mixing as no allowance has been made for spreading of the effluent plume as it mixes upward through the water column. More important is horizontal diffusion as the effluent will be further diluted with two to ten times as much sea water within a few hours of discharge.

For example, the equations developed by Brooks[14] indicate that the contamination will spread to about three times its original width and the original dilution will be doubled by the time the effluent has been carried 1 km from the outfall. This sort of spreading was indicated by the dye experiments off Nobska Point, although quantitative data are not available.

Bowles et al [15] observed a continuous dye release in the English Channel in an area where the tidal heights and currents are somewhat greater than in our sounds. They found a minimum dilution of 4000 to 1 at slack water near the source. They also found a transverse eddy coefficient (k) of 10^4 cm^2/sec, and observed that the dye concentrations decreased downstream in inverse proportion to the square root of the distance. Their factor of proportionality, if applied to the Falmouth sewage effluent, would give a minimum dilution of 6000 to 1 a kilometer from the outfall. At one-quarter km from the source the concentration would be 3000 to 1; at 4 km it would be 12000 to 1.

Both the eddy coefficient of around 10^4 cm^2/sec and the inverse relationship with the square root of the distance are supported by other investigators. Ketchum and Ford[16] obtained k values from 2×10^3 to 7×10^3 cm^2/sec for pollutant discharges in the wake of a barge. Whipple[17] argues that the eddy coefficient in coastal waters should be of the order of UD where U is the tidal speed and D is the depth, which would give k of 10^5 cm^2/sec for a depth of 15 m and a speed of 1.15 knots. He also found that the plume width doubled in less than a kilometer and the dilution was quadrupled in 4 km. Bowden[18] tabulated k values ranging from 10^4 to 10^6 cm^2/sec in English coastal waters.

The eddy coefficient can be used with the following expression developed by Reid[19]:

> For the minimum dilution D_{min} at a distance x downstream from a continous point source S at a depth H in a uniform current of speed U:

$$D_{min} = \frac{2H\sqrt{2\pi kUx}}{S}$$

Thomas[20] uses the same expression without the factor 2 under the radical. For U = 60 cm/sec, H = 15 m and k = 10^4 cm/sec, Reid's expression gives a minimum dilution of more than 10000 to 1 at 1 km from the outfall.

To summarize the calculations above: initial mixing would be at least 1000:1; assuming the net flow through 10% of the cross section, the dilution would be 2850:1; or assuming the steady state tidal prism method the dilution would be 1700:1. Horizontal diffusion and mixing should increase the dilution several fold. For the calculation of the effect of nutrients on plant production in the next section we have chosen the conservative steady state dilution of 1700:1.

Effects of Nutrients on Plant Production

The effects of a sewer outfall on the ecology of the sounds will depend ultimately on the magnitude of change in those factors which regulate the biochemical cycle in those waters. Usually, the effects of both organic substances which are decomposed by bacterial activity and inorganic chemicals which stimulate the growth of marine plants must be considered. Here, however, the addition of plant nutrients would appear to be the more relevant consideration providing the outmoded Woods Hole outfall becomes inoperative. Calculations by Whitman & Howard predict an overall decrease in organic loading of the neighboring waters once effective secondary treatment is established.

All treated sewage effluents characteristically contain significant concentrations of phosphorus and nitrogen which can ultimately influence standing crops at all levels of the food chain. When excessive, such fertilization leads to an over-abundance of organic production having undesirable effects on water quality. On the other hand, a shortage of these same elements frequently limits the productivity of coastal waters.

The engineers have estimated that each cubic meter of effluent from the proposed plant will contain 10 grams of phosphorus, 40 grams of nitrogen and 40 grams of dissolved organic carbon. With a minimum dilution of 1700 to 1, the final concentrations to be added to those naturally present should not exceed 6.0 mg of phosphorus, 25 mg of nitrogen or 25 mg of carbon per cubic meter. We have studied the effect of this enrichment increase by evaluating its effect on the marine food chain at the primary production level, assuming complete utilization. The predicted changes in production are then compared to the natural biochemical variations known to occur under existing conditions.

Typically, the amounts of phosphorus and nitrogen in a representative phytoplankton cell vary according to cell size and the available concentration of nutrient elements outside the cell. Table 4 compares the elementary composition (in terms of phosphorus, nitrogen and carbon) for a small specie (*Cyclotella nana*) and a very large specie (*Thalassiosira fluviatalis*). From this information, the projected increase in cell numbers corresponding to a known increase in the concentration of a given nutrient element can be calculated as:

$$N = \frac{\Delta C}{C_1}$$

where N is the increase in cell numbers, ΔC the external change in nutrient concentration and C_1 the elementary content of an average cell. Thus the anticipated increase in phytoplankton numbers corresponding to a phosphorus and nitrogen increase of 6 and 25 mg per cubic meter respectively would be expected to range between 2 and 12 billion cells per cubic meter. How this increase compares to the normal population is included in the data shown in Table 5.

Table 4. Carbon, Nitrogen and Phosphorus Contents of Small and Large Marine Phytoplankters in Growing Culture[1]

	Mean Cell Volume (10^{-12} cm^3)	Elementary Composition ($mg \times 10^{-8}$ per cell) Phosphorus	Nitrogen	Carbon
Cyclotella nana	34	0.04-0.06	0.40-0.60	1.00-4.00
Thalassiosira fluviatalis	4000	0.20-0.40	2.00-4.00	10.0-20.00

[1]Personal communication, Dr. Louis Hobson of the Woods Hole Oceanographic Institution.

To evaluate other parameters useful to this analysis we have used certain previously established relations descriptive to the physiology and growth of marine phytoplankton. August studies in the Gulf of Maine[4] have shown that

Table 5. Maximum Variations[1] in Some Biochemical Parameters in Vineyard Sound and Predicted Changes Following Outfall Installation

	Pre-outfall Max	Pre-outfall Min	Potential Outfall Effluent Effect	Post-outfall Totals Max	Post-outfall Totals Min
Dissolved constituents mg/m^3					
Phosphorus	25	6	6	31	12
Nitrogen	140	7	25	165	32
Organic carbon	2300	1000	25	2325	1025
Particulate constituents mg/m^3					
Organic carbon	13690	200	(207)[2]	13897	407
Nitrogen	1650	20	25	1675	45
Phosphorus	(183)[3]	(4)[4]	6	189	10
Chlorophyll A	125	5	(3.0)[2]	128	8
Phytoplankton cell counts cells/m^3	25×10^9	1.0×10^9			
Phytoplankton estimates cells/m^3					
large cells			2×10^9	27×10^9	3×10^9
small cells			12×10^9	37×10^9	13×10^9
Dissolved oxygen as oxygen					
mg/m^3	10000	7200	−654[5]	9346	6546
ml/l	7.0	5.0	−0.46[5]	6.54	4.54

[1] Analysis compiled by Department of Marine Biology, W.H.O.I.

[2] Assuming all nitrogen and phosphorus from effluent is converted to plant cells at a C : N : Cl A ratio of 8.3 : 1.0 : 0.12

[3] Estimated from N : P ratio of 9 : 1, see text for April conditions in Gulf of Maine

[4] Estimated from N : P ratio of 5 : 1, see text for August conditions in Gulf of Maine

[5] Assumes complete oxidation of effluent organic carbon (25 mg/m^3) plus the expected increase in particulate carbon (207 mg/m^3) and allows 2.82 milligrams of oxygen for each milligram of carbon oxidized.

when the supply of plant nutrients in the surface water is at the annual minimum, the ratio (by weight) in the phytoplankton of nitrogen:phosphorus approximates 5:1. In April, however, with an excess of plant nutrients available, the same relation increases to about 9:1. Comparable observations from Vineyard Sound when the standing crop of phytoplankton was at the annual maximum showed that the ratio of carbon:nitrogen corresponds to 8.3:1. In combination with other direct analysis on the dissolved and suspended matter in Vineyard Sound water, the above ratios have been used to develop the information shown in Table 5 where the additive effect attributable to a functional outfall is superimposed on the seasonal conditions which now prevail in these waters.

It can be seen in this table that the amount of phosphorus added by the proposed sewer represents a doubling of the natural summer concentration and about a 25 percent increase in the winter background level. For nitrogen the corresponding increased would be about 5 times the summer value and 18 percent over the winter value; the dissolved organic carbon changes would be negligible during both seasons.

The table indicates that these additions will have an effect on plant production in the sounds which will not exceed the normal seasonal variation. Any measurable increase in fertility would appear restricted to the summer months when the levels of standing crop are already depressed due to a lack of sufficient plant nutrients. Similarly, no untoward oxygen depletion is foreseen, the predicted maximum annual variation being from 4.54 to 6.54 ml/1 (6500 and 9300 mg/m^3) respectively for the summer and winter months. During the more productive seasons of the year these calculated changes can be expected to become progressively less significant in terms of the normal background situation until such time as the annual maximum in standing crop (spring bloom) begins to recede.

It should be emphasized that the above analysis presupposes an effluent entirely composed of domestic sewage which has undergone effective secondary treatment. Excessive amounts of organic carbon or toxic substances, such as heavy metals and nondegradable hydrocarbons which can be concentrated in marine organisms could cause deleterious effects and a significant departure from these predictions.

Conclusions

If the town should elect to dispose of its sewage effluent in the marine environment, a location off Nobska Point would be preferable to a proposed location off Juniper Point. The data indicate that the sewer outfall should be extended to a location 0.375 miles from Nobska Point where minimum return of the effluent to the beaches, harbors and estuaries of Falmouth would be achieved, where the tidal flow reaches maximum speeds, and where the depth of water is greatest to provide for maximum immediate dilution.

A steady state condition would be reached in 75 days when the sewage effluent would be diluted by a volume ranging from at least 1700-2800 parts of sea water for each part of effluent. Slightly higher concentrations could be expected in the immediate vicinity of the outfall pipe.

The concentrations of nutrients added to the sounds and ecological effects would be less than is experienced in the normal annual cycle.

There would be no impairment of the quality of the water.

Acknowledgement

We acknowledge with thanks advice and criticism from A.C. Redfield and B.H. Ketchum. This research was supported in part by N.I.H. Grant EC 00178.

References

1. Jones, R.T. "Report on Proposed Sewerage System for the Town of Falmouth, Massachusetts", Whitman & Howard, Inc., Dec. 1968, 84 pp and appendix.
2. U.S. Coast and Geodetic Survey. "Tidal Current Charts, Narragansett Bay to Nantucket Sound", U.S. Coast and Geodetic Survey Serial 628. Third ed., 1955, 12 p.
3. Redfield, A.C. "Interference Phenomena in the Tide of the Woods Hole Region", *Journal of Marine Research,* Vol. 12, 1953, pp. 121-139.
4. Vaccaro, R.F. "Available Nitrogen and Phosphorus and the Biochemical Cycle in the Atlantic off New England", *Journal of Marine Research,* Vol. 21, 1963, pp 284-301.
5. Mangelsdorf, P.C., Jr. "The World's Longest Salt Bridge", *Marine Sciences Instrumentation,* Vol. 1, 1963, pp 173-185.
6. von Arx, W.S. "An Electromagnetic Method for Measuring the Velocities from a Ship Underway", Papers in Physical Oceanography and Meteorology. Vol. II, No. 3, 1950, pp 1-62.
7. Wertheim, G.K. "Studies of the Electrical Potential Between Key West, Florida, and Havana, Cuba", Transactions of the American Geophysical Union. Vol. 35, No. 6, 1954, pp 872-882.
8. Trites, R.W. and MacGregor, D.G. "Flow of Water in the Passage of Passamaquoddy Bay Measured by Electromagnetic Method", *Journal of the Fisheries Research Board of Canada,* Vol. 19, No. 5, 1962, pp 895-919.
9. Lee, A.J., Bumpus, D.F., and Lauzier, L.M. "The Sea-Bed Drifter", International Commission for the Northwest Atlantic Fisheries Research Bulletin No. 2, 1965, pp 42-47.
10. Richardson, W.S., Stimson, P.B., and Wilkins, C.H. "Current Measurements from Moored Buoys", *Deep-Sea Research,* Vol. 10, No. 4, 1963, pp 369-388.
11. Charnews, D.J. and Jaffee, R.J. "Water Transport off Nobska Point by Dye Tracing", WHOI-MIT Joint Program, WHOI Department of Engineering, Aug. 1970, (unpublished m/s) 50 pp.
12. Ketchum, B.H. "Hydrographic Factors Involved in the Dispersion of Pollutants Introduced into Tidal Waters", *Journal of the Boston Society of Civil Engineers,* Vol. 37, 1950, pp 206-314.
13. Ketchum, B.H. "The Exchange of Fresh and Salt Waters in Tidal Estuaries", *Journal of Marine Research,* Vol. 10, 1951, pp 18-38.
14. Brooks, M.H. "Diffusion of Sewage Effluent in an Ocean Current", in Proceedings of 1st International Conference on Waste Disposal in the Marine Environment, E.A. Pearson, ed. Pergamon Press, 1960, pp 246-267.
15. Bowles, P., Burns, R.H., Hudswell, F., and Whipple, R.T.P. "Sea Disposal of Low Activity Effluent", Proceedings of 2nd International Conference on Peaceful Uses of Atomic Energy, United Nations, N.Y. Vol. 18, 1958, pp 376-389.
16. Ketchum, B.H. and Ford, W.L. "Rate of Dispersion in the Wake of a Barge at Sea", Transactions of the American Geophysical Union, Vol. 33, No. 5, 1952, pp 680-684.
17. Whipple, R.T.P. "Considerations on the Siting of Outfalls for the Sea Disposal of Radioactive Effluent in Tidal Waters", in *Advances in Water Pollution Research,* Vol. 3, E.A. Pearson, ed., Pergamon Press. 1964, pp 1-18.
18. Bowden, K.F. "The Mixing Processes in a Tidal Estuary", in *Advances in Water Pollution Research,* Vol. 3, E.A. Pearson, ed., 1964, pp 329-342.
19. Reid, R.O. "An Analysis of Dispersion of Radioactivity from Sources on the Sea Bed", (unpublished), cited in Radioactive Waste Disposal into Atlantic and Gulf Coastal Waters, NAS-NRC Publication No. 655. Washington, D.C., 1959, p 18 jj.
20. Thomas, R.H. "Marine Dilution and Inactivation of Sewage", in *Advances in Water Pollution Research,* Vol. 3, E.A. Pearson, ed., Pergamon Press, 1964, pp 57-76.