

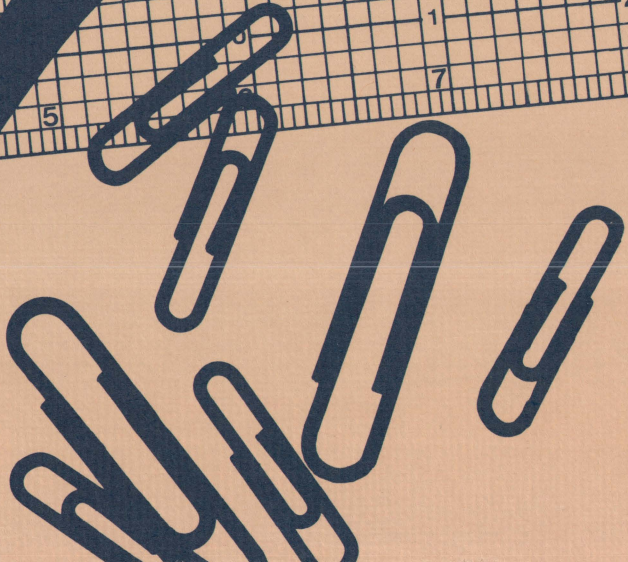
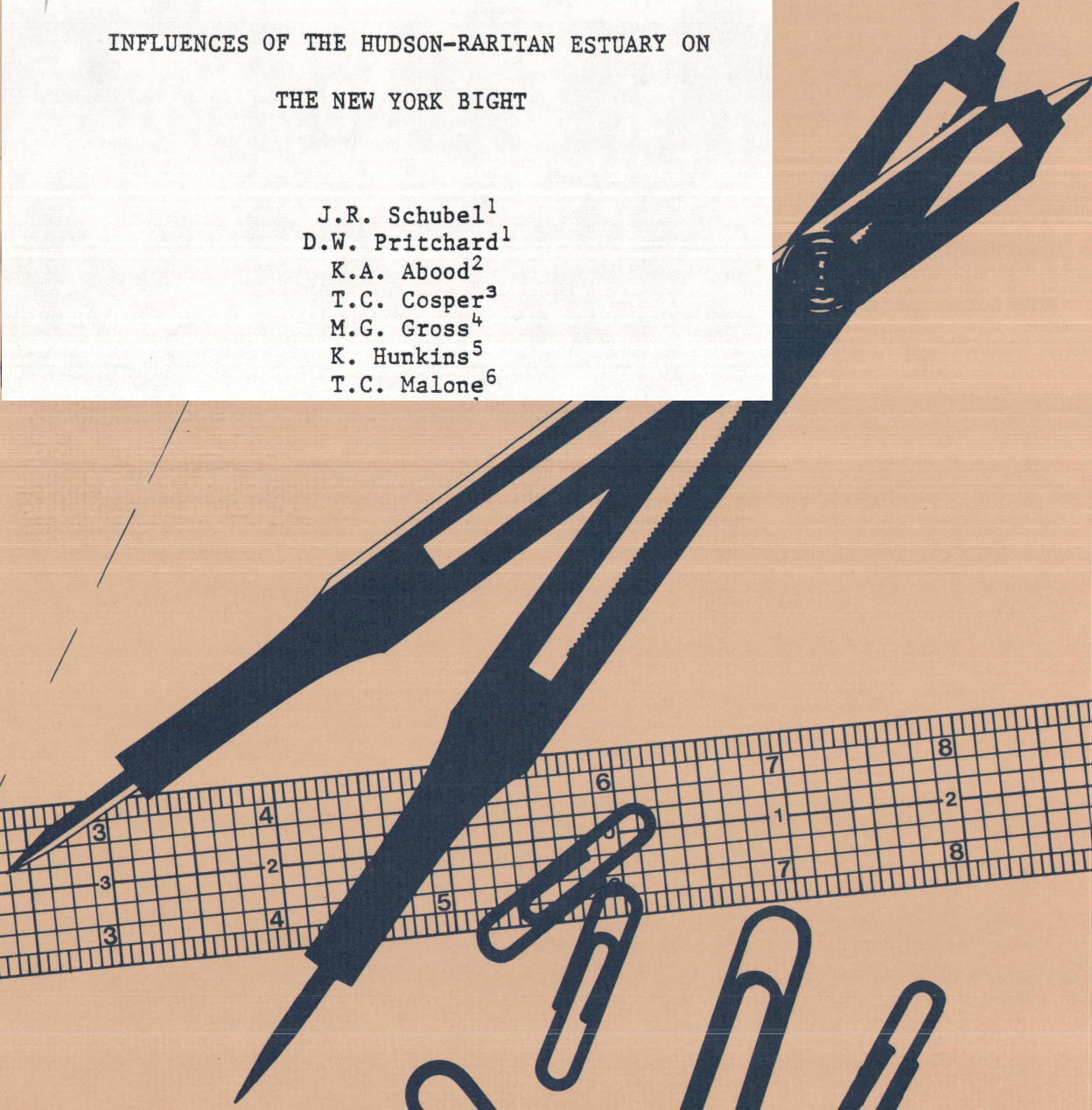
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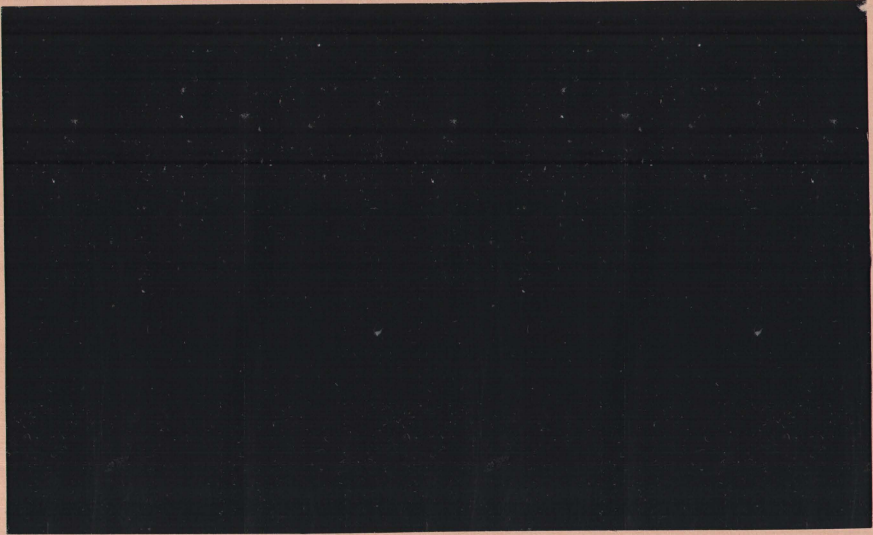
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INFLUENCES OF THE HUDSON-RARITAN ESTUARY ON
THE NEW YORK BIGHT

J.R. Schubel¹
D.W. Pritchard¹
K.A. Abood²
T.C. Cospers³
M.G. Gross⁴
K. Hunkins⁵
T.C. Malone⁶



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T.C. Cospers³
M.G. Gross⁴
K. Hunkins⁵
T.C. Malone⁶
O.W. Terry¹
P.K. Weyl¹

¹Marine Sciences Research Center, SUNY at Stony Brook, N.Y.

²Lawler, Matusky & Skelly, Pearl River, N.Y.

³Cospers Environmental Services, Inc., Jersey City, N.J.

⁴National Science Foundation, Washington, D.C.

⁵Lamont Doherty Geological Observatory, Columbia University, Palisades, N.Y.

⁶University of Maryland, MD

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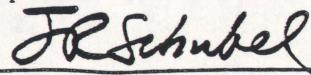

J. R. Schubel

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INTRODUCTION

To what extent are conditions in the New York Bight (NYB) simply the result of conditions and activities in the Estuary? One recent author characterizes their relationship as "...among the classic examples of solving waste disposal problems by transportation. Wastes dumped into the Hudson and Raritan river estuaries flush downstream into the NYB. Dredge spoil contaminated by previously dumped wastes, sewage sludge, chemical wastes and other materials are barged directly to offshore dump sites," (Gunnerson, 1981). In this Report we discuss certain aspects of the connection, the "coupling," between Bight and Estuary and, based on this information, we assess the likely effects on the Bight of several proposed changes in Estuary activities. Management implications are apparent.

We begin by defining and briefly describing what we will mean by the expression "The Estuary." The complex pattern of water exchange between Estuary and Bight, central to our discussion, is next analyzed in considerable detail. Movements of materials are related, as appropriate, to water movements, and so are biological interactions. Next we focus on important human activities in the Estuary which impact, or are generally thought to impact, the Bight. Finally we examine several proposed changes in these activities for their likely effects on conditions in the Bight. Among the changes discussed are improved sewage treatment, modifications of dredging and dredged material disposal strategies, better control of floatable wastes, ship traffic changes, tide gates in the East River, and a research project on coal waste disposal.

Most impacts of the Estuary on the Bight arise from direct transfer of materials; Gunnerson's "disposal by transportation." These materials pass through the Sandy Hook-Rockaway Point Transect (Fig. 1) as dissolved or suspended load in the water or as cargo in vessels. The quantities and qualities of the materials obviously determine their effects upon the Bight and its living marine resources. On the quantities of materials carried by vessels our information is relatively good, at least for the decade of the 70's (not as good for previous years). However, information on the qualities--the physical and chemical properties--of these barged wastes must be described as poor. For substances transported from the Estuary in the water the situation is even worse; we have little information on the characteristics of such materials and even less on their quantities. Despite these major deficiencies, we think the evidence supports several important conclusions.

Not all the present and potential influences of the Estuary on the Bight are direct. For example, some fish populations which spend part of their life cycle in the Bight also spend time in the Estuary. Conditions or activities in the Estuary may affect the abundance of these species or their acceptability as human food. Low levels of dissolved oxygen in the Estuary at critical seasons can influence the migrations of anadromous species. Power plants with once-through cooling systems crop fish eggs, larvae, and juveniles trapped in the cooling water flow. PCB's have been found in the flesh of certain Bight fishes at levels high enough to render them unusable. Presumably such contaminants are taken up during residence in the Estuary, most likely, in the case of PCB's, in the upper Hudson. Most vessel and boat traffic in the Bight either originates or terminates in the Estuary. Port facilities in the Estuary have much to

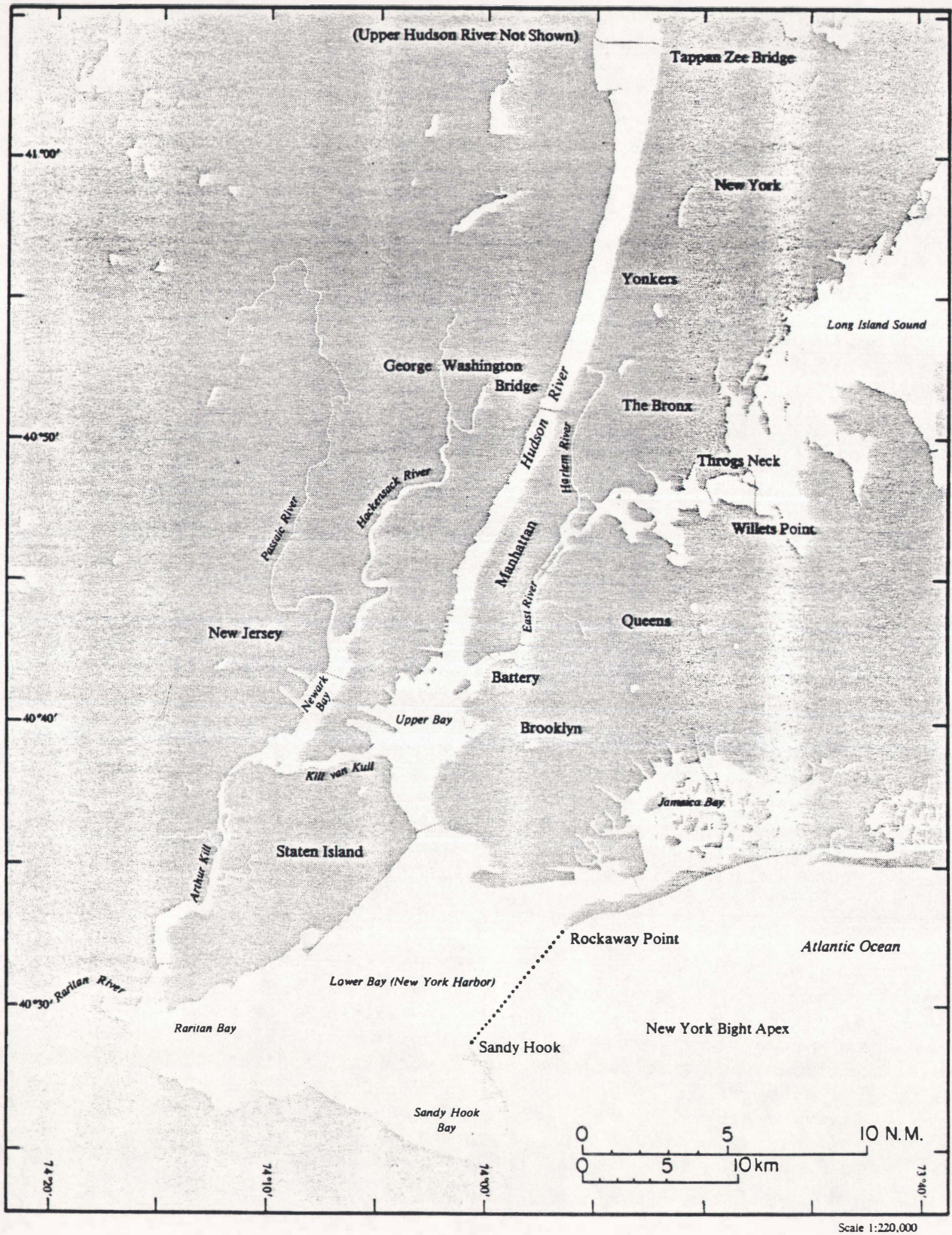


Figure 1. Map of Hudson-Raritan Estuarine System and New York Bight Apex.

do with the nature and volume of that traffic.

Major changes in the Estuary are inevitable with the passage of time. Since there is a strong linkage between Estuary and Bight, influences on the Bight will result. Though it is often quite difficult to predict these influences in detail, even a general knowledge about them should be factored into the planning process at as early a stage as possible.

The Estuary

For our purposes the Estuary is made up of all tidal waterways (waters exhibiting a measurable rise and fall of the water surface of tidal period) inland from the Sandy Hook-Rockaway Point Transect at the seaward end of the Lower Bay of New York Harbor. This definition is consistent with the original derivation of the word estuary from aestus--the tide--though different from the physical oceanographer's definition.* The Estuary as we define it is bounded at its northern end on the Hudson River by the Federal Dam at Troy, at the eastern end of the East River by the Throgs Neck to Willets Point transect, and at its western end by the head of tide in the Raritan River. This Estuary is also referred to as the Hudson River-Raritan River Estuarine System. It includes the Lower Hudson River, Lower Raritan River, Harlem River, East River, Upper Bay of New York Harbor, Newark Bay, Kill Van Kull, Arthur Kill, Raritan Bay, Jamaica Bay and Lower Bay of New York Harbor (Fig. 1).

*"A semi-enclosed coastal body of water freely connected with the ocean within which seawater is measurably diluted by freshwater from runoff" (Pritchard 1967).

All tributary streams of these water bodies, to the head of tide, are also considered to be part of the Estuary.

PHYSICAL COUPLING OF THE ESTUARY AND THE BIGHT

Geography and Hydrography

Freshwater Runoff

The estuary of the Hudson River is considered to extend seaward from the Federal Dam at Troy--the head of tide--to the Battery, a distance of 248 km. This reach, a subunit of what we have chosen to call the Hudson-Raritan Estuary, is in part a tidal river (freshwater) and in part a true estuary by Pritchard's definition. The landward limit of intrusion by measurable quantities of sea salt--the boundary between the tidal river and the estuary proper--varies with river discharge. In times of low river flow, this boundary may occur as far up river as Hyde Park, 132 km above the Battery. During times of high river flow, seawater may extend only as far upstream as about 3 km below the Tappan Zee Bridge, 40 km above the Battery.

A United States Geological Survey stream gauging station is located at Green Island, N.Y., just upstream from the Federal Dam at Troy. This is the most downstream gauging station on the Hudson. The drainage area of the Upper Hudson River Basin above Green Island, including the Mohawk River, is 20,960 km². The long-term (31 year; 1946-1977) average flow at Green Island was 388 m³ s⁻¹. This rate varies considerably from year to year, from season to season, and even over short time intervals within seasons. The maximum daily average discharge rate recorded at

Green Island during this period was $4305 \text{ m}^3 \text{ s}^{-1}$ and the minimum recorded daily average discharge was $25 \text{ m}^3 \text{ s}^{-1}$.

The drainage area of the Lower Hudson River from Troy to the Battery is $13,680 \text{ km}^2$. Some 7200 km^2 or 53 percent of this drainage area is gauged. The total drainage area of the Hudson River estuary above the Battery is thus $34,640 \text{ km}^2$. The estimated long-term average freshwater discharge at the Battery based on the ratio of drainage areas is $640 \text{ m}^3 \text{ s}^{-1}$. This is consistent with Abood's (1978) estimate of $515 \text{ m}^3 \text{ s}^{-1}$ for the long-term average flow at Poughkeepsie, N.Y.

Giese and Barr (1967) summarized the river flow at Poughkeepsie and at the Battery for the water years 1947-65. O'Connor et al. (1977) extended the series through 1974. Figure 2 shows the average of the mean monthly discharges, the maximum of the mean monthly discharges, and the minimum of the mean monthly discharges at the Battery for the water years 1947-1965. More recently, Karim Abood (personal communication) computed the average of the mean monthly discharge at a position about 14 km below Poughkeepsie, for the period 1918-1973, and these data are shown in Fig. 3. These figures exhibit the seasonal flow pattern typical of mid-latitude rivers: high flow in early spring produced by snow melt and rainfall, followed by low to moderate flows throughout the summer and increased runoff in the fall. The range between the minimum and maximum curves in Figure 2 illustrates the large year-to-year variation in flow. The maximum average monthly mean flow at the battery of $1330 \text{ m}^3 \text{ s}^{-1}$ occurs in April.

An additional $7,620 \text{ km}^2$ of drainage area contributes to the reach of the Estuary between the Battery and the Sandy Hook-Rockaway Point Transect. This drainage basin feeds the Passaic and Hackensack Rivers,

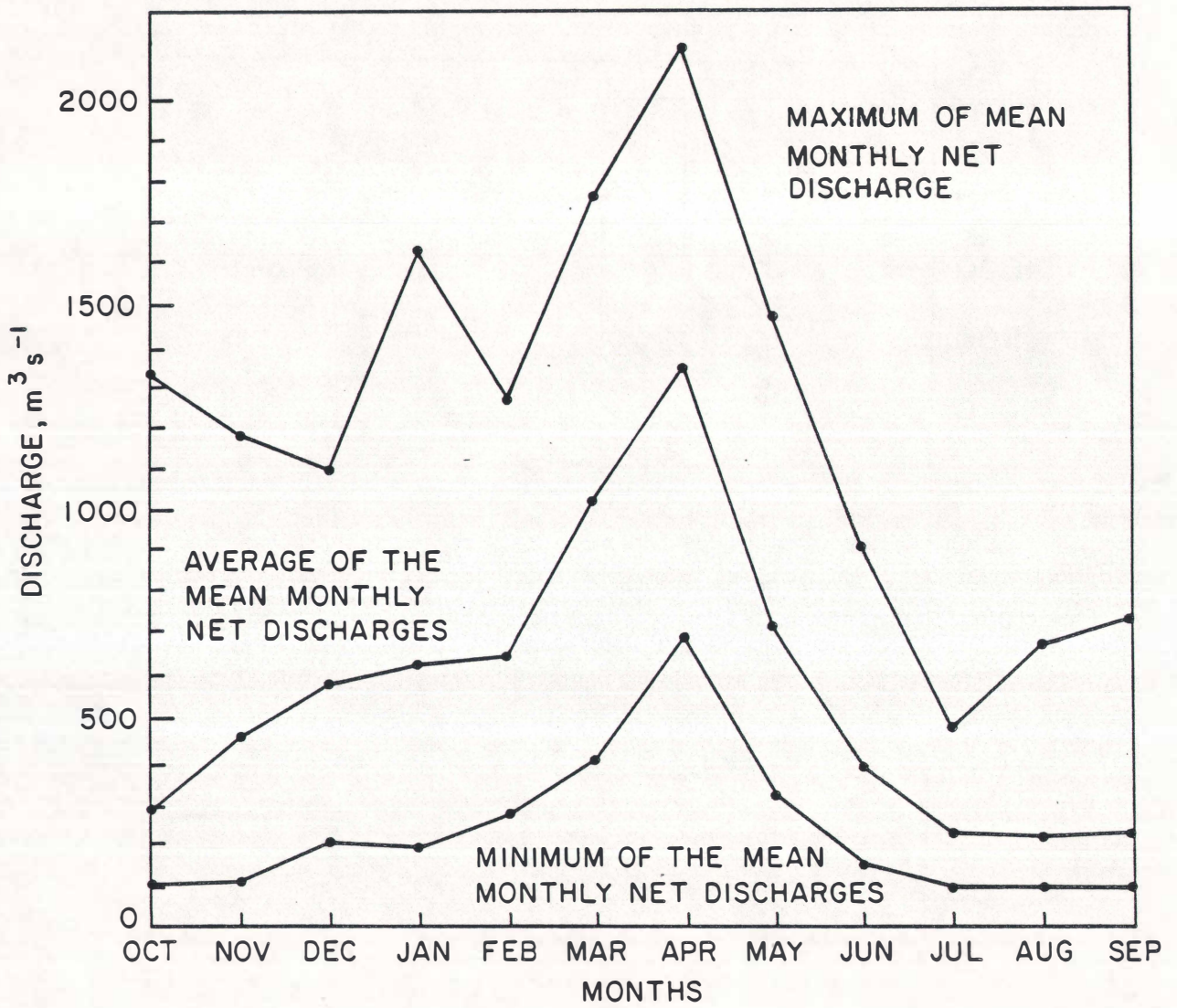


Figure 2. Summary of Mean Monthly Net Discharge Data of the Hudson River at the Battery for Water Years, 1947-1965.

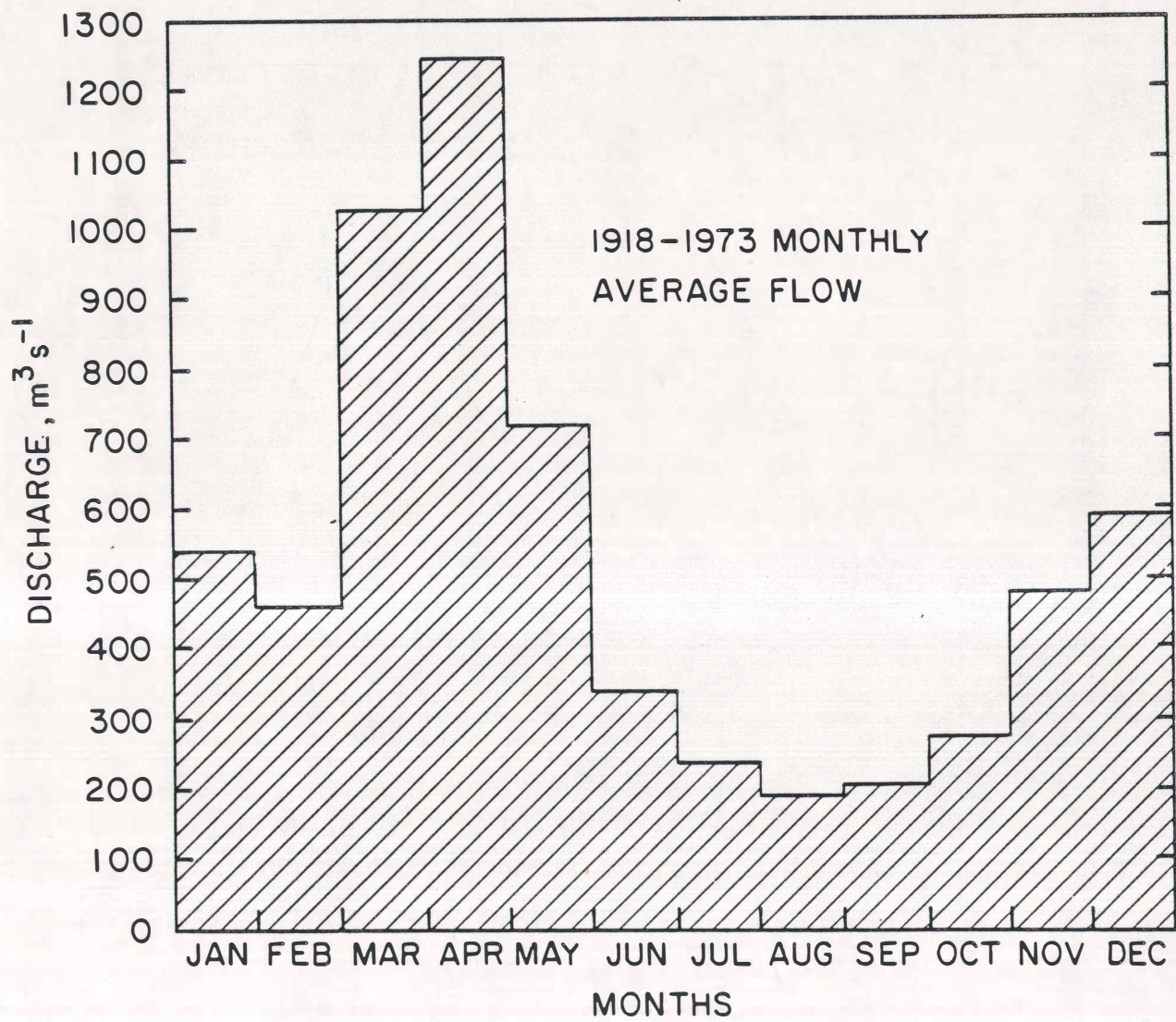


Figure 3. Summary of Mean Monthly Net Discharge Data of the Hudson River Downstream of Poughkeepsie, 1918-1973.

which discharge into Newark Bay, and the Raritan, Rahway, and Elizabeth Rivers which discharge into Raritan Bay. The total drainage area above the Sandy Hook to Rockaway Transect is, then, $42,260 \text{ km}^2$, or just over twice the drainage area above Green Island at the head of the Estuary. The long-term average freshwater flow from all of these sources is about $780 \text{ m}^3 \text{ s}^{-1}$.

Abood (1978) pointed out that the ratio of freshwater flow at a given point in the Estuary to the freshwater discharge gauged at Green Island varies nonlinearly with flow. For our purposes, however, a constant ratio of 2.0 for the ratio of the flow at the Sandy Hook-Rockaway Point Transect to that at Green Island is considered sufficiently precise.

Changes in flow at Green Island are not immediately reflected in corresponding changes at the Battery. According to Abood (1979), the lag time between a change in discharge at Green Island and the resulting change in flow at the Sandy Hook-Rockaway Point Transect is inversely proportional to the 0.4 power of the freshwater discharge. The relationship given by Abood for Indian Point (River Mile 43) can be extrapolated to the Sandy Hook-Rockaway Point Transect, to give

$$T_{SR} = 190/Q_{GI}^{0.4}$$

where T_{SR} is the lag time in days between a flow event at Green Island and its arrival at the Sandy Hook-Rockaway Point Transect, and Q_{GI} is the Green Island freshwater discharge in $\text{m}^3 \text{ s}^{-1}$. For a mean flow at Green Island of $390 \text{ m}^3 \text{ s}^{-1}$ this formula gives a travel time of 17.5 days. For low summer flows of, say, $150 \text{ m}^3 \text{ s}^{-1}$ the travel time would be 26 days, while for a high discharge at Green Island of $1,500 \text{ m}^3 \text{ s}^{-1}$, T_{SR} would be only 10 days.

There are other sources of freshwater runoff to the Bight, as summarized in Table 1. This table was prepared from data given by O'Connor et al. (1977) who divided the freshwater sources in a manner somewhat different from the one we used. O'Connor et al. (1977), for example, include a direct flow of $20 \text{ m}^3 \text{ s}^{-1}$ to the Bight from the New Jersey coast. In addition, the item in Table 1 marked "New York City and Long Island" includes a small direct contribution to the Bight from the South Shore of Long Island. Thus, O'Connor et al. (1977) estimated the long-term average flow through the Sandy Hook-Rockaway Transect to be slightly less than $770 \text{ m}^3 \text{ s}^{-1}$. This is not significantly different from our estimate of $780 \text{ m}^3 \text{ s}^{-1}$.

The Hudson-Raritan estuarine system actually has two connections with the ocean. The primary connection is through the Sandy Hook-Rockaway Point Transect that separates the Lower Bay of New York Harbor from the Bight Apex (Fig. 1). A secondary connection is through the East River to Long Island Sound and ultimately to the sea through Block Island Sound.

East River Contribution

Jay and Bowman (1975) have shown that the long-term average net transport of water through the East River, a tidal strait, is directed from Long Island Sound to the Harbor (Hudson-Raritan Estuary) with a magnitude of $340 \text{ m}^3 \text{ s}^{-1}$. This average flow exits through the Rockaway-Sandy Hook Transect and, therefore, must be added to the average freshwater discharge of $780 \text{ m}^3 \text{ s}^{-1}$ to give a total net discharge of water to the ocean of $1120 \text{ m}^3 \text{ s}^{-1}$. The average salinity of this net flow from Long Island Sound is between 24 o/oo and 25 o/oo.

Table 1. Freshwater Fluxes to the Bight¹

	Average Runoff	Minimum Runoff ($\text{m}^3 \text{s}^{-1}$)	
	<u>($\text{m}^3 \text{s}^{-1}$)</u>	<u>per month</u>	<u>per 7 days</u>
Hudson Basin	575	105	55
N.Y.C. & Long Island	80	10	10
Northern New Jersey ²	115	35	30
New Jersey Coastal ³	<u>20</u>	<u>10</u>	<u>10</u>
Totals	790	160	105

¹After O'Connor et al., (1977) after Hudson Basin Project 1974

²Draining into lower Bay of New York Harbor

³Draining into coastal ocean

The average unidirectional flow results in a flux of water from Long Island Sound to the Hudson-Raritan Estuary. The movement of salt and pollutants, however, is not limited to advection by the average flow. It depends also on the oscillating tidal flow which has an amplitude of $6,300 \text{ m}^3 \text{ s}^{-1}$ (Koppelman et al., 1976, p.181). Averaged over a tidal cycle, the tidal mean flow rate in each direction is $2,000 \text{ m}^3 \text{ s}^{-1}$, or nearly six times the average unidirectional flow. Because salinity in the Sound is greater than salinity in the East River, this tidal exchange increases the flux of salt to New York Harbor over that which would be expected if the only flow were the unidirectional average flow.

The diffusive and advective transports of salt in the East River are in the same direction as the transport of water--toward the Battery. In the case of pollutants, diffusive and advective transports are in opposite directions since the concentrations of most pollutants decrease from the East River to the Sound. The many large sewage plants discharging into the East River cause a peak concentration of sewage effluents within the River. Figure 4 is a plot of phosphate concentration against salinity in the East River measured during a cruise on 9 April 1971 (Koppelman et al., 1976, p.90). The data can be regarded as representing a mixture of three water types: water from the Upper Bay of New York Harbor, water from Long Island Sound, and sewage effluents with a phosphate content of $300 \text{ } \mu\text{g atoms } \ell^{-1}$. The maximum concentration of the sewage component is found at station 12 where it amounts to 1.54 percent by volume. If one assumes that all of the phosphate in Upper Bay water is also derived from sewage, the effective sewage content at station 12 is increased to 2 percent by volume.

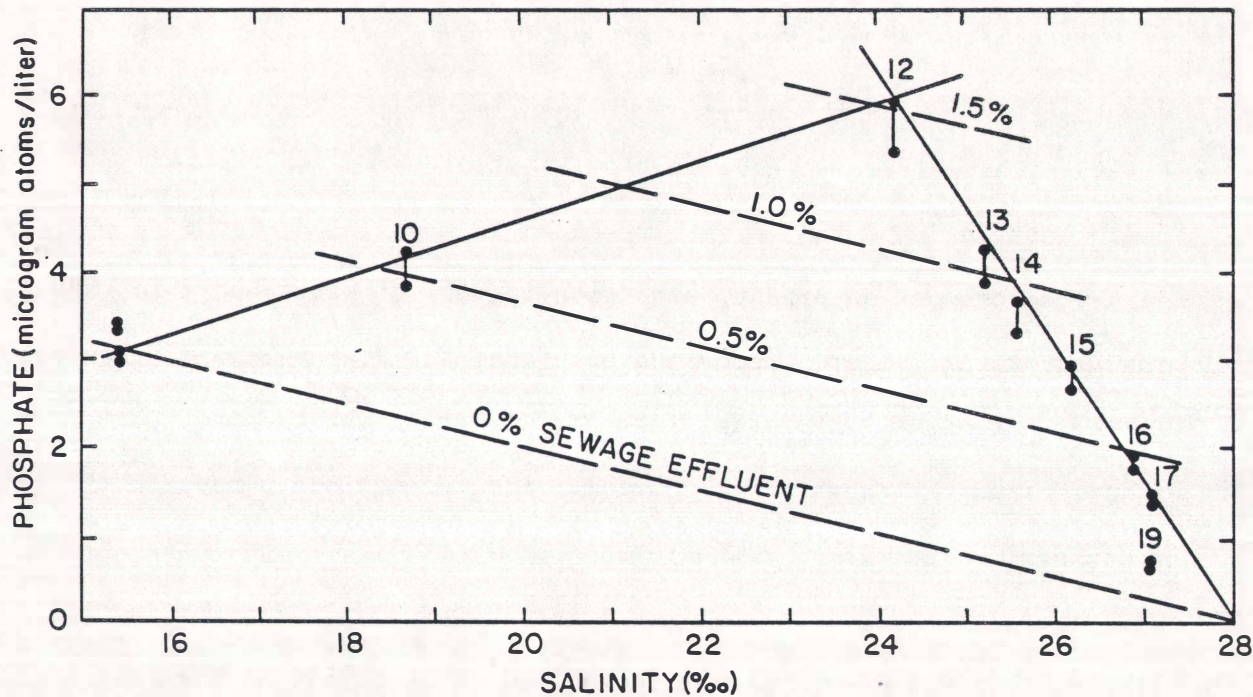


Figure 4. Phosphate-Salinity Relationships in Western Long Island Sound and the East River, 9 April 1971.

The data indicate that in spite of a net transport of water from Long Island Sound to the Hudson-Raritan Estuary, contaminants introduced into the East River are partially discharged into Long Island Sound. The fraction discharged into Long Island Sound will vary depending on the tides and on changes in the water levels produced by meteorological disturbances. The limited observations available do not permit more than a very rough estimate either of the long-term average fractional flux or of its variability. However, since the tidal excursion in the East River is approximately equal to the length of the River, it appears reasonable that one-half of the discharges of pollutants into the East River are added to Long Island Sound.

The somewhat surprising direction of flow of water and salt through the East River, clearly demonstrated by Jay and Bowman (1975), deserves further attention. The tidal range at Willets Point is about 58 percent greater than the range at the Battery, and the various phases of the tide (e.g., high water, low water) occur about 3.3. hours later at Willets Point than at the Battery. Because of this variation in tidal period, a difference in elevation between the two ends of the East River of about ± 1.5 m occurs and produces an hydraulic gradient. This difference in water elevation between the Battery and Willets Point drives the oscillatory hydraulic flow of tidal period in the East River. When the elevation of the water surface at the Battery is greater than that at Willets Point, the flow is directed from the Harbor toward Long Island Sound and a "flood flow" is said to occur in the East River. When the water surface elevation at Willets Point is greater than that at the Battery, the flow is directed from Long Island Sound toward the Harbor and an "ebb flow" is said to occur in the East River. These

designations of ebb and flood flow directions conform to convention for the East River.

The peculiar manner in which the tide wave at the Harbor end of the East River interacts with the tide wave at the Long Island Sound end of the East River results in an average elevation in the East River during the ebb flow about 0.45 m higher than during the flood flow. Consequently the average cross-sectional area during the ebb flow, directed from Long Island Sound towards the Battery, is about 5 percent greater than the average cross-sectional area during the flood flow, which is in the opposite direction. This greater cross-sectional area during ebb flow carries a larger volume of water per unit time than is carried by the smaller cross-sectional area during flood flow, given equal but oppositely directed flow speeds. A net transport results. This tidally-averaged transport, which results from the co-variation of the tidal rise and fall of the water surface and the oscillatory ebb and flood of the hydraulic current is called the Stokes' transport. The Stokes' transport is a well-known property of progressive waves,* but only recently has it been identified as an important component of tidally-averaged transports in estuaries.

*In a progressive wave, there is a maximum flow in the direction of wave travel at the crest of the wave and a maximum flow in the opposite direction in the trough of the wave. In a standing wave, zero flow occurs at the crest and at the trough, with maximum flow in either direction occurring at mean water level. In the case of the tide in an estuary with a single connection with the ocean, a progressive tidal wave would have maximum flood flow at high water and maximum ebb flow at low water. A standing tidal wave would have slack flow at high water and at low water, with maximum flood occurring at mean tide level during the rising phase of the tide and maximum ebb flow occurring at mean tide level during the falling phase of the tide. In relating this description to the East River, one must be careful to note the particular convection chosen for designating the ebb and flood directions since it has two connections with the ocean.

For equal and oppositely directed hydraulic gradients in the East River, there will be less frictional resistance during the ebb flow because of the greater cross-sectional area than during flood flow, and hence the average velocity during ebb flow will be greater than during flood flow. This factor will augment the Stokes' transport to contribute to a greater flux of water during the ebb flow period than during the flood flow period.

Still another factor contributes to the predominance of ebb flow over flood flow in the East River. Under average conditions, the water surface elevations at Willets Point are higher than those at the Battery during more than half the tidal cycle. Thus, even were the tidal-median water surface level to be the same at both ends of the East River, the average cross-sectional area and the current speed both would be greater during ebb flow than during flood flow and the duration of ebb flow would be greater than the duration of flood flow. These factors all contribute to a net flux of water from Long Island Sound into the East River and subsequently into the Upper Bay of New York Harbor at the Battery.

The tidally-averaged water surface elevation at any given location varies from tidal cycle to tidal cycle, from day to day, from week to week, from month to month, and over longer averaging periods. The tidally-averaged elevations at the Battery or at Willets Point may change because of variations in wind stress and atmospheric pressure distribution over the Estuary from that over Long Island Sound. Variations in the mean density of the water column, which also can cause changes in the tidally-averaged water surface elevation, can result from fluctuations in temperature or salinity. These factors do not act in

exact concert at the Battery and at Willets Point, and hence a tidally-averaged difference in water surface elevations at the two ends of the East River can occur. This mean slope or hydraulic head produces a net non-tidal flow in the East River, which may be in either direction depending on the direction of the tidally-averaged slope. An analysis of the long-term tidal records at the Battery and at Willets Point, adjusted for the relative levels of the tide gauges using the First-Order Level Net of the U.S. Coast and Geodetic Survey, shows that a tidally-averaged water surface slope directed downwards from Willets Point towards the Battery occurs more frequently than does a slope in the opposite direction (Jay and Bowman, 1975).

For the 40-year period, 1932 to 1971, the average difference in the non-tidal elevations at the two ends of the East River was 4.0 cm, with the water surface at Willets Point standing higher than that at the Battery. The 40-year average of elevation differences for individual months varied from 3.1 cm for June and September to 5.0 cm for February, with all the single month average elevations for Willets Point higher than those for the Battery. The monthly average non-tidal water surface elevation at Willets Point was higher than that at the Battery for 448 of the 480 individual months of the 40-year period. The yearly mean elevation difference ranged from zero (1964) to 5.7 cm (1971), with the yearly mean elevation at Willets Point higher than at the Battery for all years except 1964.

This is a rather surprising result. The tidal mean elevation at any point should depend, at least in part, upon the mean density of the water column. Less dense water stands higher than more dense water. The water off the Battery usually has lower salinity, and consequently

lower density, than the water off Willets Point. On the basis of density alone, the water surface elevation should be higher at the Battery than it is at Willets Point. That the observed non-tidal slope is in the opposite direction suggests that meteorologically-induced elevation differences dominate density-induced differences.

The result of all of these processes is a net non-tidal flux of water into the Hudson-Raritan Estuary from Long Island Sound through the East River most of the time. The long-term average net non-tidal flow through the East River is estimated to be $340 \text{ m}^3 \text{ s}^{-1}$ toward the Battery. There is a seasonal variation which results in a long-term average net flow of $270 \text{ m}^3 \text{ s}^{-1}$ for September and of $410 \text{ m}^3 \text{ s}^{-1}$ for March. This seasonal variation is again surprising since the maximum flow toward the Battery occurs in March when the high freshwater flow in the Hudson should result in a maximum salinity difference between the Battery and Willets Point and therefore a maximum density-induced hydraulic head from the Battery toward Willets Point.

For short averaging periods the net non-tidal flow through the East River may be in either direction, and can be quite large. For averaging periods of two to four tidal cycles, the flow may be as much as $2000 \text{ m}^3 \text{ s}^{-1}$ toward the Battery or as much as $1000 \text{ m}^3 \text{ s}^{-1}$ toward Willets Point.

Net non-tidal flow also produces a net flux of salt from Long Island Sound into the Upper Bay of New York Harbor. The average salinity at Willets Point is about 25 o/oo, resulting in a long-term average advective flux of salt towards the Battery of about $8.5 \text{ tonnes s}^{-1}$, or $0.7 \times 10^6 \text{ tonnes d}^{-1}$.

In the eastern portion of the East River an estuarine circulation

pattern exists. There is a net flow directed toward Long Island Sound in the upper half of the water column and a corresponding net flow in the opposite direction in the deeper layers. This net flow pattern is superimposed on the sectional mean non-tidal flow which, as we have seen, is directed predominantly toward the Battery. As shown by Jay and Bowman (1975), the estuarine flow directed toward Long Island Sound in the upper layers is in balance with the return flow in the lower layers and there is no net flow of water from estuarine circulation through the Throgs Neck-Willets Point Transect. However, although the volume flows of water are in balance, the salinity is slightly higher in the deeper layers than it is in the upper layers so that the estuarine flux of salt into the East River from Long Island Sound in the lower layers is greater than the flux of salt from the East River into Long Island Sound in the upper layers. Thus estuarine circulation also contributes to a net flux of salt through the East River toward the Battery; small in comparison with the non-tidal advective flux of salt. Although there is a net long-term flux of water and salt towards the Battery, the estuarine circulation in the East River can induce a net flux of freshwater from the East River into Long Island Sound. It all depends upon the magnitude of the flux of water induced by the estuarine circulation relative to the sectional mean non-tidal flow. Since the salinity decreases from Willets Point to the Battery, there is an additional diffusive flow of salt from Long Island Sound through the East River into Upper New York Bay.

As pointed out previously, more than $35 \text{ m}^3 \text{ s}^{-1}$ of sewage effluent are discharged into the East River. A portion (on the order of 50 percent) of this waste is transported into Western Long Island Sound

as a result of the estuarine circulation with its surface layer flow toward the Sound. There is also a diffusive flux of pollutant from the region of higher concentration in the East River toward the region of lower concentration in the Sound. The other 50 percent of this waste is transported with the sectionally-averaged net non-tidal flow. Therefore some of the pollutants introduced into the East River are transported into Western Long Island Sound, and the rest are transported into the Upper Bay of New York Harbor. Any consideration of the fluxes of water, salt, and of dissolved and suspended pollutants from the Hudson-Raritan Estuary into the Bight must take into account the fluxes of these materials from the East River into Long Island Sound.

Flux of Water Through the Sandy Hook-Rockaway Point Transect

Abood (1978) demonstrated that in the portion of the Estuary between the Battery and the upper limit of sea salt intrusion--the physical oceanographer's estuary--there is a classic net non-tidal estuarine circulation pattern with a tidally-averaged flow directed seaward in the upper layer and up the Estuary in the lower layer. This two-layered estuarine circulation pattern also appears to exist in the lower Estuary seaward of the Battery, as shown by current meter observations obtained at the Narrows and at the Sandy Hook-Rockaway Point Transect.

The U.S. Coast and Geodetic Survey made time series measurements of current speed and direction at a number of stations within the Estuary in 1952, 1958, and 1959. Current meters were moored on the

Sandy Hook-Rockaway Point Transect during 2-7 June 1952, 21-25 May 1958, and 12-16 August 1959. In 1952, 16 current meters were deployed among seven stations located in the Transect. In 1958 and 1959, eleven current meters were distributed among four stations. The data from these last two years suffer from the lack of current observations below a depth of about 8 m in Ambrose Channel.

The flux of water through the Sandy Hook-Rockaway Point Transect can be estimated from these current meter data. Doyle and Wilson (1978) using values of the tidally-averaged velocity component normal to the Transect as determined for each current meter location of the three survey periods as reported by Kao (1975) found that there was a tidally-averaged seaward flow in the upper 8 m of the southern three-fourths of the width of the Transect during all three measurement periods. In the deeper layers below about 8 m and over the full depth of the water column in the one-fourth of the cross-section nearest Rockaway Point, the tidally-averaged flow was into the Estuary (Fig. 5).

A comparison of the times of the phases of the tide with the times of the phases of the tidal current, e.g., the times of high water and low water compared with the times of maximum flood and ebb current, show that the tide wave at the Sandy Hook-Rockaway Point Transect is intermediate between a progressive wave and a standing wave.* As a consequence of this intermediate character of the tide, the average water surface elevation during the period of flood current is slightly higher than that during the period of ebb current. Thus, even if the

*See footnote on page 15.

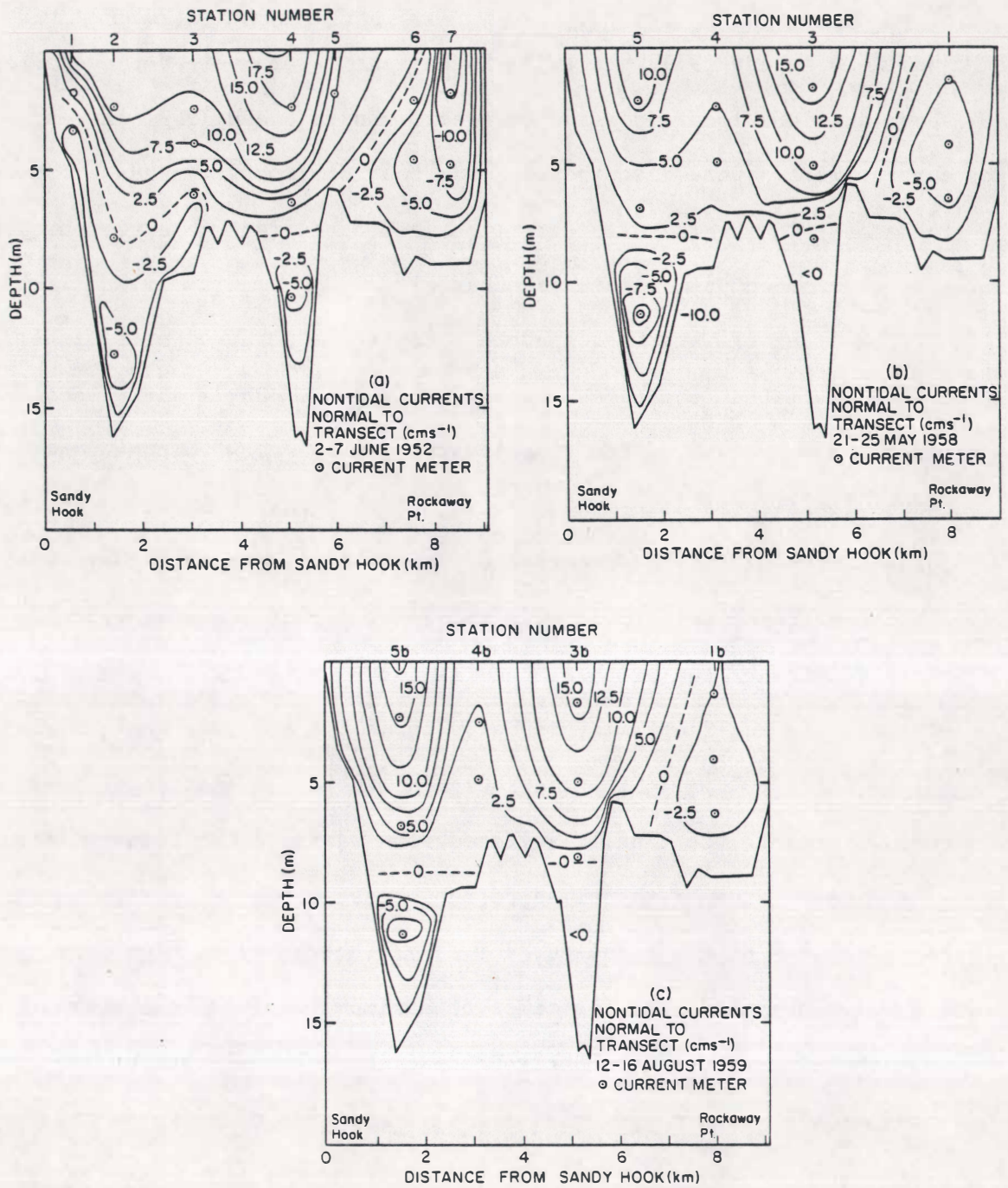


Figure 5. Non-tidal Currents normal to the Sandy Hook to Rockaway Point Transect Computed for (a) 2-7 June 1952, (b) 21-25 May 1958, and (c) 12-16 August 1959.

speed and duration of the flood and the ebb currents were equal, there would be a net inflow of water from the Bight into the Estuary, as a result of this co-oscillation of the tidal elevation and the tidal current. This part of the total tidally-averaged transport, sometimes called the Stokes' transport, produces an effect similar to that found in tidally-averaged transport from Long Island Sound into the East River.

Using the distribution of the tidally-averaged current speed normal to the Sandy Hook-Rockaway Point Transect as given by Doyle and Wilson (1978) for 2-7 June 1952, 21-25 May 1958, and 12-16 August 1959, the net flux of water seaward, Q_{out} , and the net flux of water into the Estuary, Q_{in} , were computed by numerical integration. Data from the Tide Tables and Tidal Current Tables were then used to obtain estimates of the Stokes' transport into the Estuary, Q_{Stokes} , through the transect. The net non-tidal flux of water through the Transect, Q_T , is

$$Q_T = Q_{out} - Q_{in} - Q_{Stokes}$$

Transports for the three measurement periods are given in Table 2.

If over the four to five days of each measurement there was little change in the total volume of water within the Estuary, i.e., if one assumes that the mean tide level did not change appreciably, then the total non-tidal flux of water out of the Estuary, Q_T , must equal the total inflow of freshwater to the Estuary, Q_R , plus the non-tidal flux of water from Long Island Sound into the East River, Q_{ER} .

$$Q_T = Q_R + Q_{ER}$$

Table 3 gives estimates of Q_R and Q_{ER} .

Table 2

Values of the net nontidal fluxes in $\text{m}^3 \text{s}^{-1}$ of water through the Sandy Hook-Rockaway Point Transect calculated from current meter observations.

<u>Period</u>	<u>Flux Terms ($\text{m}^3 \text{s}^{-1}$)</u>			
	Q_{out}	Q_{in}	Q_{Stokes}	Q_{T}
2-7 June 1952	3487	1437	640	1410
21-25 May 1958	3265	1221	640	1410
12-16 August 1959	3674	1008	640	2026

The computed values of the total net non-tidal flux of water out of the Estuary through the Sandy Hook-Rockaway Point Transect (Q_T in Table 2) differ from the values of Q_T estimated from the sum of the freshwater inflow plus the non-tidal inflow from Long Island Sound to the East River (Table 3) by $-861 \text{ m}^3 \text{ s}^{-1}$ for 1952, by $-276 \text{ m}^3 \text{ s}^{-1}$ for 1958, and by $+1285 \text{ m}^3 \text{ s}^{-1}$ for 1959. These differences are of about the same size as the river inflow of freshwater. They illustrate the difficulty of obtaining a balance between values of inflow and outflow of an estuary computed from current meter observations and estimates obtained in other ways, at least over short time periods.

It should be noted, however, that the weighted average value of Q_T for the three periods, using the number of days in each period as the weighting factor, is $1598 \text{ m}^3 \text{ s}^{-1}$ for the values in Table 2 and $1618 \text{ m}^3 \text{ s}^{-1}$ for the values in Table 3, a difference of only slightly more than 1 percent of the mean value.

The cross-sectional area of the Sandy Hook-Rockaway Point Transect is $84,975 \text{ m}^2$. The estimates of the non-tidal inflow and outflow through this section are based on current measurements made at only eleven or sixteen points, depending on which period is considered. Each meter location must, therefore, be assumed to be representative of $5,310 \text{ m}^2$ or $7,725 \text{ m}^2$ of cross-sectional area. Taking into account the spatial and temporal variability of the current meter records it is doubtful that the estimates of Q_{out} and Q_{in} given in Table 2 are accurate within 20%. The Stokes Transport depends only on the amplitudes of the tides and tidal currents and on their differences. This information comes from a long series of observations and the uncertainties in the Stokes Transport term probably do not exceed $\pm 10\%$ of the values of Q_{Stokes}

given in Table 2.

The estimates of the freshwater inflow to the Estuary above the Sandy Hook-Rockaway Point Transect (Table 3) were found by multiplying the measured discharge of the Hudson River at Green Island by a factor related to the relative sizes of the drainage areas above these two locations. The period over which the average was taken depended upon an empirically determined time lag. Both the multiplicative factor and the time lag are probably dependent upon the river flow and, hence, on the season of the year. These uncertainties make even the freshwater inflow to the estuary, Q_R , questionable to within $\pm 10\%$.

The estimates of the inflow to the Estuary from Long Island Sound through the East River (Table 3) were based on the monthly average values listed by Jay and Bowman (1975). It is known that for intervals of time of say, 4 to 6 days, the non-tidal flux of water through the East River can be as much as $1000 \text{ m}^3 \text{ s}^{-1}$ into the Estuary or as much as $500 \text{ m}^3 \text{ s}^{-1}$ into Long Island Sound. The range of uncertainty in Q_{ER} as given in Table 3 is at least $\pm 500 \text{ m}^3 \text{ s}^{-1}$; about $\pm 100\%$ of the listed values.

Taking into account the various uncertainties in the individual transport terms, it is not surprising that there are large differences between estimates of the net non-tidal seaward flux of water through the Sandy Hook-Rockaway Point Transect and the sum of the freshwater inflow plus the inflow through the East River from Long Island Sound for periods as short as 4 to 6 days.

Table 3

Estimates of the total inflow of freshwater, Q_R , the inflow through the East River, Q_{ER} , and outflow of water from the Estuary, Q_T , in $m^3 s^{-1}$ during each of three observational periods.

<u>Period</u>	<u>Flux Terms ($m^3 s^{-1}$)</u>		
	<u>Q_R</u>	<u>Q_{ER}</u>	<u>Q_T</u>
2-7 June 1952	1866	405	2271
21-25 May 1958	1424	256	1680
12-16 August 1959	256	485	741

II. WATER-BORNE TRANSPORT

Fluxes of Salt and Dissolved Material

Since we have had such difficulty finding a precise estimate of the mass balance of water flow into and out of the Estuary, it is evident that there will be even larger uncertainties in our estimates of the more elusive net fluxes of dissolved or suspended materials.

An attempt was made to estimate the flux of salt into and out of the estuary for the period 21-25 May 1958. This interval shows the best agreement between the estimates of the inflow and the net outflow of water. Our salt balance calculations indicate that for this period there was a net discharge of salt from the Estuary to the Bight through the Sandy Hook-Rockaway Point Transect of about 2.3 million tonnes per day. About 25% of this salt flux can be attributed to the non-tidal inflow of salt water from Long Island Sound through the East River. There is also a diffusive flux of salt into the Estuary from the Bight through the Sandy Hook-Rockaway Point Transect. The magnitude of this flux cannot be estimated from existing data.

Despite these uncertainties, we offer zero order estimates of the fluxes of dissolved salt and of other dissolved materials from the Estuary to the Bight. These computations are based on our best estimates of the long term fluxes of water: (a) $3080 \text{ m}^3 \text{ s}^{-1}$ for the non-tidal seaward transport of water through the upper, southern portion of the Sandy Hook-Rockaway Point Transect and (b) $2030 \text{ m}^3 \text{ s}^{-1}$ for the transport of water into the Estuary through the deeper parts and northern portion

of the Transect. These flux estimates include the Stokes Transport.

The long-term average salinity in that part of the Transect with non-tidal flow directed out of the Estuary is estimated to be 25.90 o/oo and the average salinity in the part of the Transect having a non-tidal flow into the Estuary is estimated to be 28.70 o/oo. The resulting non-tidal flux of salt out of the Estuary through the upper portion of the Transect is $79.8 \text{ tonnes s}^{-1}$, while the non-tidal flux of salt into the Estuary through the lower and northern portions of the Transect is $58.3 \text{ tonnes s}^{-1}$. The difference gives an apparent net non-tidal flux of salt through the entire Transect of $21.5 \text{ tonnes s}^{-1}$ seaward. The long-term average flux of salt from Long Island Sound into the Estuary through the East River accounts for about $8.6 \text{ tonnes s}^{-1}$ of this excess seaward flux, leaving $12.9 \text{ tonnes s}^{-1}$ to be balanced by a diffusive flux of salt into the Estuary.

Fluxes of Suspended Solids and Particle-Associated Contaminants to New York Bight

The previous sections describing fluxes of water and salt between the Hudson Raritan Estuary and the Bight provide a necessary background for dealing with flows of materials of greater present concern--suspended particles and associated contaminants. Unfortunately there are few data on the distribution of suspended solids in the lower Estuary near the Sandy Hook-Rockaway Point Transect. Duedall, et al. (1977) reported values of the surface concentration of total suspended solids at a series of stations along a longitudinal section on the axis of the Estuary from the Battery to Sandy Hook-Rockaway Point Transect.

They found the mean concentration of total suspended solids in January 1974 to be $15 \text{ mg } \ell^{-1}$ with a standard deviation of sample values of $3.8 \text{ mg } \ell^{-1}$. In March the corresponding values were $13 \text{ mg } \ell^{-1}$ and $5.7 \text{ mg } \ell^{-1}$. In April 1974 the concentration of total suspended solids decreased from about $45 \text{ mg } \ell^{-1}$ at the Battery to $12 \text{ mg } \ell^{-1}$ at the Sandy Hook-Rockaway Point Transect. In June 1974 they found suspended solids concentrations greater than $30 \text{ mg } \ell^{-1}$ in the lower salinity waters near the Battery and about $12 \text{ mg } \ell^{-1}$ in the higher salinity waters near the Sandy Hook-Rockaway Transect.

Drake (1974) reported measurements of the distribution of total suspended solids in the Bight Apex during September–November 1973. Unfortunately, only one of his 25 stations was on the Sandy Hook-Rockaway Transect; the remainder were farther seaward. The near-surface concentrations at his Transect station ranged from 2 to $5 \text{ mg } \ell^{-1}$ and averaged about $3 \text{ mg } \ell^{-1}$. The concentrations at 10 m ranged from 4 to $12 \text{ mg } \ell^{-1}$, and averaged $7 \text{ mg } \ell^{-1}$.

If we assume that the long-term average concentration of suspended solids in the waters having a non-tidal flow directed out of the estuary is $10 \text{ mg } \ell^{-1}$, the non-tidal flux of sediment directed out of the Estuary with these waters is $2660 \text{ tonnes } \text{d}^{-1}$. If the average suspended solids concentration in the waters having a non-tidal flow directed into the Estuary is taken to be $15 \text{ mg } \ell^{-1}$, the non-tidal flux of sediment directed into the Estuary with these waters is $2630 \text{ tonnes } \text{d}^{-1}$. The difference, $30 \text{ tonnes } \text{d}^{-1} = 1.1 \times 10^4 \text{ tonnes } \text{y}^{-1}$, is small compared with the $5.5 \times 10^6 \text{ tonnes } \text{y}^{-1}$ of sediment barged to sea and dumped into the Bight. No reasonable modification of the estimates of net flows or of the average suspended solids concentrations is likely to change the

conclusion that the transport of suspended solids from the Estuary to the Bight through the Sandy Hook-Rockaway Point Transect by water motions is small compared to the transport of such materials by barging.

If correct this is a very important conclusion. In its support let us consider some extreme but conceivable (though perhaps unlikely) variations to the assumptions used above. First note that available published data do not show any measured concentration of suspended sediment in the surface waters at the Sandy Hook-Rockaway Point Transect exceeding about $12 \text{ mg } \ell^{-1}$, even in the spring period of high river flow. The few measurements that have been made of the vertical variation in concentration generally show an increase in concentration with depth. Even so, assume that the annual mean sediment concentration in the waters exiting the Estuary through the Transect is $12 \text{ mg } \ell^{-1}$, and that the concentration in the flow into the Estuary from the Bight is $10 \text{ mg } \ell^{-1}$. This reversal of the normally observed variation with depth favors a maximum export of sediment. Using the earlier stated best estimates for the long-term average transport of water out of the Estuary through the upper, southern portions of the Transect of $3080 \text{ m}^3 \text{ s}^{-1}$, and for the transport of water into the Estuary through the deeper parts and through the northern portion of $2030 \text{ m}^3 \text{ s}^{-1}$, the average flux of sediment in the outflowing waters would be $3193 \text{ tonnes d}^{-1}$, and in the inflowing waters, $1754 \text{ tonnes d}^{-1}$. The difference, $1439 \text{ tonnes d}^{-1}$, or $5.25 \times 10^5 \text{ tonnes y}^{-1}$, is less than 10% of the estimated $5.5 \times 10^6 \text{ tonnes y}^{-1}$ of sediment barged to sea and dumped into the Bight.

Over an annual period, the difference between the net non-tidal inflow and the net non-tidal outflow cannot be significantly different

from the $1050 \text{ m}^3 \text{ s}^{-1}$ originally assumed. However, actual values of the average inflow and outflow might differ widely from the values assumed above. Consider two extremes. First, assume that the net non-tidal inflow is zero, giving then a net non-tidal outflow of $1050 \text{ m}^3 \text{ s}^{-1}$. With a surface layer sediment concentration of $12 \text{ mg } \ell^{-1}$ (the concentration elsewhere is not important since the sediment flux into the estuary through the Transect would be zero for any concentration), the net non-tidal flux out of the estuary would be $1089 \text{ tonnes d}^{-1}$ or $4.0 \times 10^5 \text{ tonnes y}^{-1}$. This value is about 7.3% of the amount of sediment barged to the Bight per year. At the other extreme, assume that the non-tidal inflow is twice the value taken as the best estimate, or $4060 \text{ m}^3 \text{ s}^{-1}$. The annual average non-tidal outflow would then be $5110 \text{ m}^3 \text{ s}^{-1}$. The resulting net loss of sediment to the Bight, assuming a sediment concentration in the outflowing waters of $12 \text{ mg } \ell^{-1}$, and in the inflowing waters of $10 \text{ mg } \ell^{-1}$, would be $6.5 \times 10^5 \text{ tonnes y}^{-1}$, or 12% of the barged transport.

Finally, it is possible that the major transport of sediment seaward takes place during the spring period of high fresh water inflow, when the net flow conditions at the Transect might be considerably different from the annual average. As noted previously, April has the highest long-term monthly average river flow, which at the Battery is $1330 \text{ m}^3 \text{ s}^{-1}$. This is equivalent to a net fresh water discharge at the Sandy Hook-Rockaway Point Transect of $1620 \text{ m}^3 \text{ s}^{-1}$. Adding the high spring value of inflow through the East River of $410 \text{ m}^3 \text{ s}^{-1}$ gives as a first estimate for the difference between the non-tidal outflow and the non-tidal inflow through the Transect of $2030 \text{ m}^3 \text{ s}^{-1}$. If the average non-tidal outflow and the non-tidal inflow through the deeper parts and

the northern portion of the Transect for April were taken to be the same as the best estimate annual average of $2030 \text{ m}^3 \text{ s}^{-1}$, then the April average non-tidal outflow through the upper layers of the Transect would be $4060 \text{ m}^3 \text{ s}^{-1}$. The suspended sediment concentration of the Transect in Spring might be somewhat higher than the small existing set of observations indicate. For this computation, assume a value of $20 \text{ mg } \ell^{-1}$, and take the extreme view that the concentration in the deeper layers is half this value, or $10 \text{ mg } \ell^{-1}$. The resulting net loss of suspended sediment to the Bight would be $5262 \text{ tonnes } \text{d}^{-1}$. This high value is applicable, however, to just the month of April, and the net flux for this 30 day period is 1.6×10^5 tonnes, again a small fraction of the tonnage of sediments barged to the Bight.

Mueller et al. (1976) estimated that the total additions of solids to the Bight amounted to about 2.4×10^4 tonnes d^{-1} . They attributed 68% of this total, 1.632×10^4 tonnes d^{-1} , to direct additions by barging and 31%, 7.44×10^3 tonnes d^{-1} , to discharge through the Sandy Hook-Rockaway Transect. The remaining 1% was attributed to direct runoff from New Jersey and Long Island. The New York 208 study (1979) reported average suspended solids discharges through the Transect to the Bight of $900 \text{ tonnes } \text{d}^{-1}$. Both of these estimates appear to be too high, although $900 \text{ tonnes } \text{d}^{-1}$ is not unreasonable considering the uncertainty in our knowledge of suspended solids concentrations.

An average flux of $900 \text{ tonnes } \text{d}^{-1}$, which equals 3.285×10^5 tonnes y^{-1} , thus appears to be an upper limit for the probable seaward transport of suspended sediment through the Sandy Hook-Rockaway Point Transect. This transport is only about 6% of the mass of material transported to the Bight each year by barging.

The above conclusion that the transport of suspended solids to the Bight through the Transect is small compared to the transport of these materials by barging can be expected to hold for most particle-associated contaminants such as PCBs and metals. However, these constituents are preferentially adsorbed to finer particles and the solids carried out of the estuary in suspension are somewhat finer than those deposited within the Estuary and later barged to sea. Nearly all of the particulate matter transferred from the Estuary to the Bight by water motion is fine-grained silt and clay. Even so, since the quantity of material barged is on the order of 15 times greater than that discharged through the Transect from the Estuary to the Bight, the conclusion that the transport of particle-associated contaminants by water transport is small compared to the transport of these materials by barging remains most probably correct.

Effects of Dredging and Dredged Material Disposal

The Port of New York has long been the nation's leading port in ship arrivals and cargo tonnage (Hammon, 1976). To meet the changing needs of transportation and shipping, the waterways and wetlands of the Port region have been extensively altered. In addition to frequent port construction projects, annual dredging is required to maintain channel depths and other port facilities. Gross (1976) has reviewed these changes, the volumes of material removed from the Harbor, and the disposition of the materials.

As mentioned elsewhere, material dredged from the Hudson-Raritan estuarine system and barged to the Bight is the Bight's largest single

source of sediment (Gross, 1972, 1976; Freeland et al., 1976). Once deposited in the Bight, the dredged materials appear to remain at or near the point of discharge where they fill valleys and create small hills on the continental shelf (Williams, 1975).

About half the annual maintenance dredging in New York Harbor produces relatively coarse-grained, clean sand from the entrance channels, Table 4. This material derives primarily from beach sands carried along the coast and deposited in the entrance channels (Kastens et al., 1978). Most of it is sold for fill.

Nearly 20% of the dredged material is removed from channels in the Lower Hudson River. Much of this material is presumed to be recently deposited Hudson River sediment (Table 4). Materials removed from Upper Bay have no obvious riverine source. A large part may be particulate matter from municipal wastewaters and urban storm water discharges.

The troublesome constituents in dredged materials--industrial metals, petroleum hydrocarbons, and synthetic organic compounds--are likely to come from wastewater discharges and to be associated with particles in those discharges. Thus these constituents will be most concentrated in materials removed during maintenance dredging of areas which, like the Upper Bay, receive large volumes of municipal and industrial wastewaters.

There is little data available on the physical and chemical composition of suspended sediments in the Hudson Estuary (Biscayne and Olsen, 1978) or of the sediment deposits in New York Harbor or New York Bight (Gross, 1976). The data that are available indicate that dredged materials are the largest single source of copper, cadmium, lead, and chromium for the Bight. Zinc comes primarily from runoff and atmospheric discharges (Mueller and Anderson 1978).

Table 4 Volume and estimated mass of wastes and sediments dredged from New York Harbor each year, 1930-1970. (Data from New York District, U.S. Army Corps of Engineers; after Gross, 1976).

Areas Dredged	<u>Volume</u>	<u>Estimated Mass</u>	
	$10^3 \text{ m}^3 \text{ y}^{-1}$	10^3 tonnes	% Total
Harbor entrance channels	611	1040	48.6
Ambrose Channel (1)	424	720	33.7
Bayside-Gedney (1)	187	320	14.9
Lower Bay	798	400	18.7
NY-NJ Channels, including Kills (2)	440	220	10.3
Main Ship Channel (2)	68	30	1.6
Raritan River (2)	289	140	6.8
Newark Bay (2)	206	100	4.8
Upper Bay	419	210	6.8
Buttermilk Channel (2)	122	60	2.9
Bay Ridge-Red Hook Channels (2)	224	110	5.2
East River (2)	7	3	0.1
Anchorage (2)	60	33	1.5
Lower Hudson River	818	410	18.6
Weehawken-Edgewater Channel (2) (3)	660	330	14.4
Hudson River Channel (2)	158	80	3.7
TOTALS	2852	2200	99.9

(1) Solid content $1.7 \text{ tonnes m}^{-3}$ (dry weight basis)

(2) Solid content $0.5 \text{ tonnes m}^{-3}$ (dry weight basis)

(3) Data for 1946-1970

Synthetic organic compounds, for example PCBs, in the Hudson River and Estuary are primarily associated with fine-grained sediment. Such material is dredged from the navigation channels and barged to disposal sites in New York Bight (Bopp, et al. 1970). PCBs are also transported in the water column in solution or adsorbed to fine-grained suspended particulate matter. Barging is by far the largest source of PCBs to the Bight, followed next by the discharge of PCBs on fine-grained particulate matter through the Sandy Hook-Rockaway Transect, and last by the additions of soluble PCBs through the Transect. The relative strengths of these sources of PCBs to the Bight are probably in the ratio of 100:10:1.

Floatables

A variety of floatables are commonly present in the New York Bight, including tar and grease balls, sewage-related items (e.g., condoms and tampon applicators), trash (e.g., paper, plastic wrappers, straws and cups), and charred wood (MESA, 1977). These come from both chronic and episodic sources. Chronic sources include: discharge from the Estuary through the Sandy Hook-Rockaway Point Transect, discharges from vessels passing through the Bight, and sewage sludge dumped in the Bight. Episodic sources include oil spills and various other accidental releases such as that associated with the Bay Park sewage storage tank explosion in 1976. Also included among the sources are storm drains, sewage treatment plant outfalls, industrial outfalls, pier fires, losses from barges, and illegal dumping.

The estuarine discharge through the Sandy Hook-Rockaway Point

Transect is the largest source of floatables for the Bight (MESA, 1977). It has been estimated that waste water and combined sewer outfall discharges are the largest contributors of floatables to the Estuary (MESA, 1977). Past investigations have indicated that sewage sludge dumping in the Bight has been only a minor contributor to the accumulation of noxious floatables found on many beaches in the area. There is a relatively large inventory of floatables in the Bight at all times, which can be substantially increased in the short term by large rainfall events. Such events increase the input of floatables from storm drains and sewage treatment plants to the Estuary and the rate of transfer of these floatables to the Bight by estuarine discharge through the Sandy Hook-Rockaway Point Transect as well.

Whenever there is a persistent, strong south-to-south-westerly wind these floatables, always present in the Bight, are concentrated and stranded along the beaches of the South Shore of Long Island. These are some of the conditions thought to account for well-publicized strandings of floatables in June 1976. Surface winds over the Bight are usually south to southwesterly during late spring and summer. During June 1976 they were unusually persistent from the south-southwest. These conditions can be expected to recur periodically.

The probability of recurrence of June 1976 meteorological conditions was estimated by comparing historical atmospheric pressure patterns and the frequency of departures from the norm (MESA, 1977). This analysis suggests that departures from the norm similar to that observed for the 15 day period in June 1976 are not unusual and "...can be expected to recur, perhaps on average as often as once a year, during the late spring and summer months" (MESA, 1977). They are less likely in other

months, and especially in winter, with the seasonal predominance of westerly to northwesterly winds. The probability of a repeat occurrence of the whole complex of factors apparently involved in the 1976 episode-- high rainfall, high river flow, winds, etc., is difficult to estimate.

In any case, as pointed out previously, ocean dumping of sewage sludge is only a minor source of floatables to the Bight. The only way to reduce significantly the abundance of floatables in the Bight is to control their abundance in the Estuary.

NUTRIENTS AND BIOLOGICAL COUPLING

Enrichment of the Bight by the Estuary

Nutrient enrichment of the Bight by the discharges from the Estuary can be estimated from the phosphate concentration in surface waters of the Bight in winter when the water column is well mixed and primary productivity is at a minimum. Usable data for the period 3-9 December 1975 are available from NOAA, R/V KELEZ cruise XWCC-7. The surface phosphate data are plotted and from the distribution one estimates the excess phosphate contributed by the Estuary. Data far from the Apex are used to estimate the phosphate distribution in the absence of input from the Estuary. The cumulative areas over which the phosphate concentration is increased by Y or more microgram atoms per liter due to the input from the Estuary is shown in Fig. 6. This estimate is conservative.

Phosphate addition in the absence of primary production is in excess of 1 microgram atom ℓ^{-1} over an area of about 150 km² and in excess of

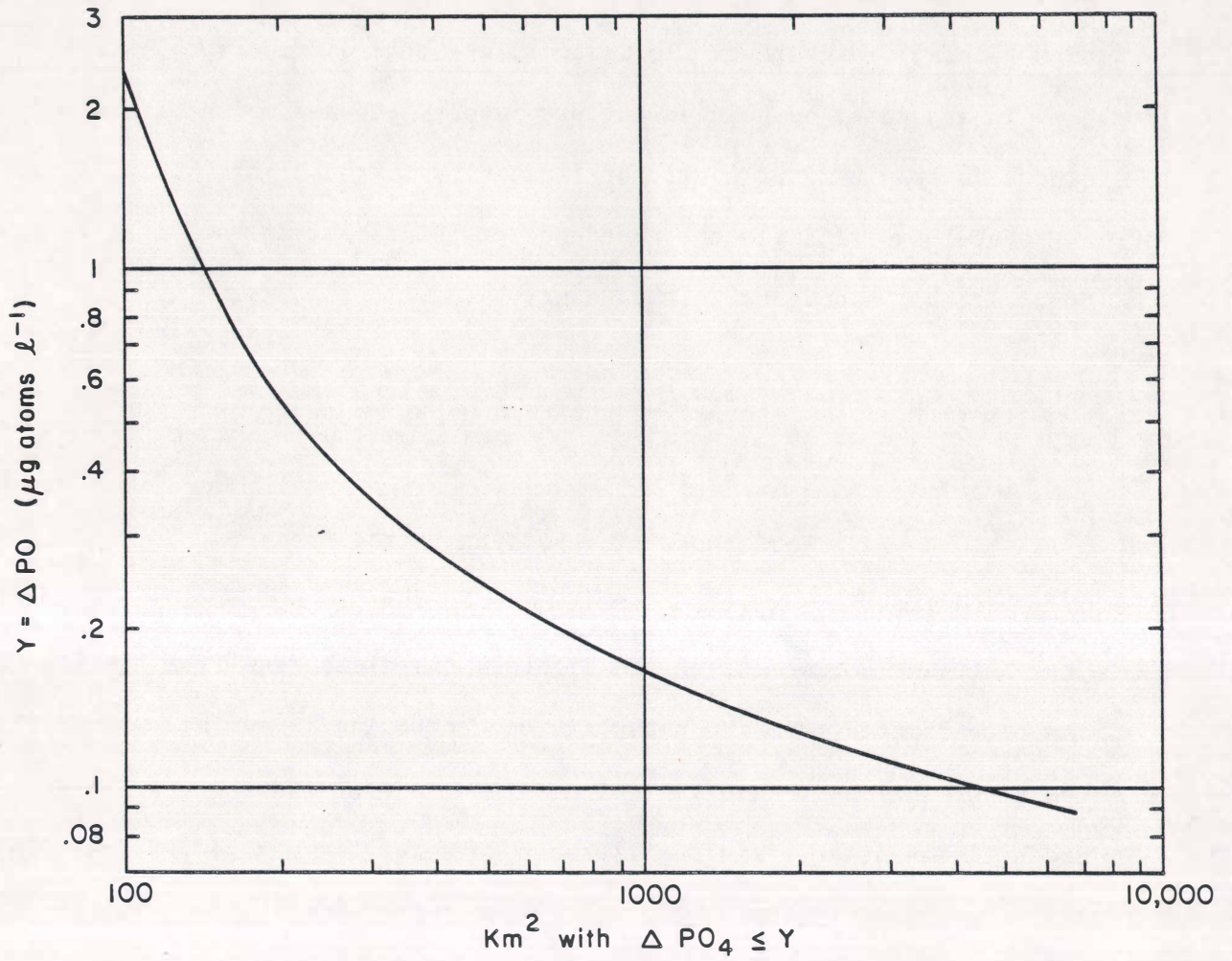


Figure 6. Area having excess phosphate concentration attributable to discharge from the Hudson-Raritan Estuary.

0.1 microgram atom ℓ^{-1} over an area of approximately 4,000 km^2 .

Nutrients and Phytoplankton

The Hudson-Raritan Estuary, below the limit of sea salt intrusion, receives about $8.6 \times 10^6 \text{ m}^3 \text{ d}^{-1}$ of sewage waste water; more than 95% of this is discharged into the Upper Bay of New York Harbor. This waste water contains about $1.6 \times 10^5 \text{ kg N d}^{-1}$ and $1.3 \times 10^4 \text{ kg P d}^{-1}$, which produce high concentrations of dissolved inorganic nitrogen and phosphorous in the lower estuary and Bight Apex throughout the year, (Table 6 Howells et al., 1970; Garside et al., 1976; Simpson et al., 1977).

In spite of these high rates of nutrient supply, phytoplankton biomass and primary productivity in the salt intruded reach of the Estuary are relatively low. The chlorophyll a content of the euphotic zone is generally less than 30 mg m^{-2} and productivity has never been reported to exceed $2.5 \text{ g C m}^{-2} \text{ d}^{-1}$ (Malone, 1977c; unpubl. data). Productivity is typically less than $0.5 \text{ g C m}^{-2} \text{ d}^{-1}$ over most of the lower Estuary except during summer when rates above $1.0 \text{ g C m}^{-2} \text{ d}^{-1}$ are frequently observed. This input of carbon accounts for 5 to 50% of particulate organic carbon inputs to the lower Estuary with an annual mean of about 15% (Malone, background paper). Such low productivity is a consequence of (1) relatively high flushing rates that prevent large accumulations of biomass and (2) high concentrations of suspended sediments that limit the euphotic zone to depths of 1 to 5 m (Malone, 1977a).

Estimates of nutrient fluxes from the Estuary to the Bight have been made by several investigators using a variety of techniques (O'Connors

and Duedall, 1975; O'Connors et al., 1977; Garside et al., 1976; Simpson et al., 1977). The uncertainties of flux calculations based on direct water transport measurements have already been discussed. Estimates of the flux of dissolved inorganic nitrogen (DIN) through the Sandy Hook-Rockaway Transect based on current meter measurements and measured concentrations of nutrients range from $0.8 \times 10^5 \text{ kg N d}^{-1}$ (O'Connors and Duedall, 1975) to $2.1 \times 10^5 \text{ kg N d}^{-1}$ (O'Connors et al., 1977). Garside et al. (1976) estimated DIN fluxes to the Bight as the difference between sewage inputs and phytoplankton uptake within the Estuary and obtained rates of $1.2 \times 10^5 \text{ kg N d}^{-1}$ (summer) and $1.6 \times 10^5 \text{ kg N d}^{-1}$ (remainder of year). Simpson et al. (1977) used a one-box model for phosphate in the Upper Bay to estimate the phosphate fluxes into and out of the Upper Bay. They found a phosphate flux of $1.8 \times 10^4 \text{ kg P d}^{-1}$ from the Upper Bay through the Verrazano Narrows. The mean molar N:P ratio in the Upper Bay is 21 (Malone, 1976) giving an equivalent DIN flux of $1.6 \times 10^5 \text{ kg N d}^{-1}$. Given the uncertainties associated with these calculations, a reasonable first approximation of DIN export to the Bight is $1.5 \times 10^5 \text{ kg N d}^{-1}$. Thus, nutrient uptake by phytoplankton has little effect on the concentration of nutrient in the Estuary and most anthropogenic nutrient inputs to it are exported directly to adjacent coastal waters. This export is relatively constant since variations in flow are compensated for by variations in nutrient concentration, i.e., sewage inputs are relatively constant.

Most of the inorganic nutrient flux to the New York Bight is assimilated by phytoplankton within the 1250 km^2 of the Apex (Malone, background paper). In contrast to the situation in the Estuary, phytoplankton productivity accounts for 70-80% of the input of

particulate organic matter to the Apex (Table 5; Segar and Berberian, 1976; Garside and Malone, 1978). Geographically, productivity in the Apex tends to be highest within 20 km of the mouth of the Estuary and decreases with distance offshore, as nutrient and chlorophyll a concentrations decrease and salinity increases (Malone, 1976).

Seasonal variations in primary productivity in the Bight are characterized by two bloom periods: (1) February-April when phytoplankton biomass is highest and chain-forming diatoms usually dominate and (2) June-August when phytoplankton productivity is highest and small, solitary algae dominate (Malone, 1976, 1977b). As in the Estuary, phytoplankton growth appears to be light- and temperature-dependent under most conditions. Since these factors vary seasonally but exhibit little geographic variations within the Bight, spatial variations in productivity are mainly a function of phytoplankton biomass in the surface layer as determined by mixing, sinking, and grazing rates. During winter and early spring mixing and sinking control the distribution of biomass in the Bight. As the surface layer warms and the water column becomes thermally stratified, most primary productivity occurs in the upper layer above the base of the thermocline where an increasing fraction is grazed by zooplankton and recycled in the upper layer (Malone, 1976; Chervin, 1978; Malone and Chervin, 1979). Copepods alone assimilate an average of 30% of all phytoplankton productivity within the Bight during the summer. Organic detritus forms a large portion, 30 to 80%, of the particulate matter assimilated by copepods, and zooplankton fecal pellets may be the major mechanism for transporting organic matter to the bottom.

Table 5. Total potential oxygen demand from major sources in the N.Y. Bight Apex.

Source	Oxygen Demand kg O ₂ d ⁻¹
Sewage sludge dumping*	1.1 x 10 ⁶
Dredge spoil dumping*	2.1 x 10 ⁶
Primary production**	
Average	5.7 x 10 ⁶
Summer	1.7 x 10 ⁷
River input**°	5 x 10 ⁶

*From COD data (Mueller et al. 1975).

**From organic carbon and Redfield ratio of carbon to oxygen (Redfield et al. 1963). Assumes complete oxidation.

°Considerable uncertainty exists.

In summary, it is clear that most of the nutrients discharged into the Estuary are transferred directly to the Bight through the Sandy Hook-Rockaway Transect. Because most estuarine runoff moves south along the coast of New Jersey, phytoplankton biomass is usually higher off New Jersey than off Long Island. The amount of biomass that accumulates in the water column depends upon time of year and on grazing pressure by pelagic metazoans, primarily copepods. During the winter and early spring, most of the organic matter is packaged as chain forming diatoms and sinks to the bottom. During the late spring and summer most of the organic matter produced by phytoplankton is packaged as small, unicellular algae which are grazed before they can sink or mix into the lower layer. Reduction in nutrient inputs to the Estuary by upgrading sewage treatment plants would probably not substantially change levels of primary productivity in the lower Estuary. Phytoplankton productivity would decrease in the Apex, which could have a negative impact on local fisheries.

Dissolved Oxygen

The influence of the Estuary has been blamed for various undesirable or harmful conditions in the Bight, sometimes on rather limited evidence. Probably the most serious of these conditions, in terms of actual economic cost, has been the sporadic occurrence of low dissolved oxygen levels in waters of the Bight adjacent to the New Jersey shore (Swanson and Sindermann 1979). The most recent such episode, in the summer and early fall of 1976, caused a massive die-off of benthic fauna extending some 90 km southward from the Bight Apex and up to 60 km

seaward from the coast. Total monetary losses to the fishing industry were estimated in the hundreds of millions of dollars (Figley et al. 1979). To what extent--if at all--was estuarine influence responsible?

There appear to be two ways in which Estuary-originating wastes might depress dissolved oxygen levels in continental shelf waters. One is by the direct contribution of organic matter which undergoes bacterial decomposition, consuming oxygen in the process. The other is by supplying nutrients which stimulate primary production in Bight waters. The resulting biomass also consumes oxygen upon decomposition. Both these influences obviously exist, but how significant are they compared to the various natural environmental factors which are also involved in the creation of low dissolved oxygen (DO) conditions?

Since low DO episodes do not occur every summer the natural environmental factors must have an important role. Several such factors have been implicated. For example, a study by Armstrong (1979) proposed a hydrographic explanation for the location of the 1976 low-DO episode, off New Jersey but not south of Long Island. The shallower than normal lens of cold winter water remaining below the pycnocline when seasonal stratification developed contained a smaller than normal initial stock of oxygen. For a stratification characterized by a sigma-T difference of 3 units he finds monthly rates of oxygen depletion of $1.06 \text{ ml } \ell^{-1}$ off New Jersey and $0.85 \text{ ml } \ell^{-1}$ off Long Island, due to the fact that the average depth of the cold water lens off New Jersey is only about 9 m while that off Long Island is about 13 m. The same rate of oxygen demand input per unit area would lead to a faster rate of oxygen depletion off New Jersey and the depth contrast is sufficient to account for the difference in rates.

O'Connor, et al. (1977) compared dissolved oxygen levels in the New York Bight Apex for August 1949 with those reported for August 1969, and for August 1974 on two spatial scales: (1) small scale defined as the vicinity of the sludge and dredge material disposal area, and (2) large scale defined as Apex-wide, excluding the disposal area. They found that on an Apex-wide scale the levels of dissolved oxygen increased in near-surface waters, upper 5 m, and decreased in near-bottom waters, lowest 5 m, between 1949 and the latter two dates. In terms of percent saturation values the Apex-wide changes were + 10% for near-surface waters and - 20% for near-bottom waters. Their analysis revealed that the mean percent saturations for 1949 for both near-surface and near-bottom waters were significantly different at the 95% confidence level from the mean percent saturation values for 1969 and for 1974. The only comparison that was not statistically significant was that for near-bottom waters in 1969 and 1974. Their conclusion was that oxygen levels have changed on an Apex-wide scale over the past 30 years. They found special significance in the change "...at the bottom, where a noted downward trend in dissolved oxygen may be due to the increased waste disposal in the Apex with the possible accumulation of sludge or the distribution of oxygen-demanding sediments at the bottom." The authors pointed out that they could not account for the increase in near-surface values with the available biological data.

In view of the large year-to-year variations characteristic of the distribution of dissolved oxygen in the Bight Apex, statistically significant differences in mean August DO values for three years over a 30 year period do not establish "trends" in the levels of DO as claimed by O'Connor, et al. (1977). Three data points which show a trend are

insufficient evidence for any real change.

Similarly, O'Connor, et al.'s (1977) interpretation of dissolved oxygen data in the sludge and dredge material disposal areas was that the data "showed a distinct downward trend in near-bottom waters"; percent saturation values decreased from about 67% in 1949 to 30% in 1974. Again, while the data may show a "trend" this does no more than suggest environmental change in view of the large year-to-year variations.

Segar and Berberian (1976) evaluated the oxygen depletion of New York Bight water below the thermocline and concluded that the major part of the demand results from sinking organic matter produced locally by photosynthetic production. For the summer period they estimated that this material would account for more than 95% of the oxygen depletion and concluded that cessation of dumping of sewage sludge and dredged material would have little effect on the oxygen deficiency. They also concluded that the problem of low oxygen in the Bight was primarily a result of the response to nutrient-loading of the Bight by discharge from the Estuary. Conditions in the low-DO area during 1976 were atypical in several respects (Swanson and Sindermann 1979). Spring stratification of the water column became established earlier than usual, augmented by an early and unusually large spring freshet from the Estuary (Armstrong 1979). A lower than normal incidence of storms during the spring and summer left the stratification relatively undisturbed. An increased frequency of southerly winds also slowed circulation, minimizing the usual influx of oxygenated bottom water to the region (Falkowski et al. 1980, Starr and Stemle 1979).

Clearly the natural rate of supply of DO below the pycnocline was

subnormal in 1976; what about consumption rates? Here differences of interpretation of the limited data become substantial. Central to the discussion is the role of a single pelagic dinoflagellate species, Ceratium tripos. For reasons unknown an enormous bloom of C. Tripos developed over much of the Bight during the late spring of 1976 and a considerable biomass of this diatom was advected by currents to the anoxia region. Although normally present there during the summer the 1976 population was far larger than usual. Most of the cells were found near the pycnocline where little photosynthesis was possible. Respiration and ultimate decomposition of these cells is assumed to have significantly increased DO consumption below the pycnocline (Falkowski et al. 1980). There is no evidence that the C. tripos bloom had any connection with estuarine influences.

Certainly the oxygen-consuming wastes from the Estuary, water-borne and vessel-carried, also entered the picture (Falkowski et al. 1980, Han et al. 1979, Segar and Berberian 1976, Swanson et al. 1979, Thomas et al. 1976). An oxygen budget has been published by Falkowski et al. (1980) (Table 6) which shows a substantial depletion of DO arising from the various waste loads. The relative importance of the several components in such a budget is, of course, debatable (Malone et al. 1979).

O'Connor (1979) notes that "...realistic ranges are great for oxidation rates of POC [particulate organic carbon] and DOC [dissolved organic carbon] in bottom waters." and comments on the lack of quantitative data on, particularly, the DOC fraction, its sources and oxidation rates. He concludes that "The extent of human contribution to this coastal eutrophication and seasonal oxygen depletion remains

TABLE 6. A Summer Oxygen Budget ($\text{m}^3 \text{O}_2 \text{ m}^{-2} \text{ d}^{-1}$)
for the New York Bight Apex During 1976.

(After Falkowski et al., 1980).

Above the pycnocline:

Computed respiration:		Observed respiration:	
Phytoplankton	460	Water column	
Metazoan	550		
Sludge	1000		
Dissolved organic carbon	<u>2000</u>		
	4010		<u>4050</u>
Gross photosynthetic input:	4640		
Time scale for anoxia:			
	~ infinity		

Below the pycnocline:

Computed respiration:		Observed respiration:	
Fecal pellets	300	Benthic	360
		Water Column	1350
		<u>C. tripos</u>	<u>5400</u>
			7110
Vertical diffusive input:		Horizontal advective input:	
with K_z of $1.0 \text{ cm}^2 \text{ s}^{-1}$	7000	with K_z of $0.01 \text{ cm}^2 \text{ s}^{-1}$	
with K_z of $0.1 \text{ cm}^2 \text{ s}^{-1}$	700		700
Time scale for anoxia:		Time scale for anoxia:	
at K_z of $1.0 \text{ cm}^2 \text{ s}^{-1}$	~ 600 days		
at K_z of $0.1 \text{ cm}^2 \text{ s}^{-1}$	~ 30 days		~ 30 days

arguable." Undoubtedly there is a substantial contribution but its overall importance for the production of low-DO conditions is far from clear.

IMPACTS OF PROPOSED CHANGES IN THE ESTUARY

Improved Waste Treatment

In 1975 the consulting firm of Lawler, Matusky and Skelly used a mathematical model to relate present and projected waste loads to the distribution of dissolved oxygen (DO) in the lower Hudson River and in Upper and Lower New York Bays, from Mile Point-30* (Kilometer Point--48) to Mile Point 154 (Kilometer Point--248). The model includes the effects of waste loads, biological oxygen demand (BOD) generated within the water column, exchange with the atmosphere, and benthic oxygen demand. BOD is a measure of the amount of oxygen consumed in the biological processes that break down organic matter and is hence a measure of the organic pollutant load. It does not take into account the interactions among nutrients, phytoplankton, zooplankton, and dissolved oxygen. A parametric analysis using field data collected in 1966 and 1967 by the New York State Department of Environmental Conservation indicates that phytoplankton have a minimum effect on DO in the River because of high turbidity which limits photosynthetic activity. Calibration and verification of the model utilized DO and BOD data

*Mile Points are distances upriver (positive numbers) and down (negative numbers) from the Battery (Fig. 1).

collected by New York State Department of Environmental Conservation in 1967. These are the best river-wide DO and BOD data for the Hudson at the present time. Figure 7 shows excellent agreement between the measured levels of DO in the Hudson River in 1967 and the pattern predicted by the mathematical model.

To estimate the potential impact of different treatment levels on dissolved oxygen, four different projected loads were simulated using normal summertime riverflow, about $150 \text{ m}^3 \text{ s}^{-1}$ at Green Island, in the Hudson River, Table 7.

The DO profiles associated with these four cases are shown in Fig. 8. Cases (0) and (1) are oxygen levels calculated for actual waste loads in 1973 and 1977 respectively. In general, the overall water quality of the Hudson River as measured by the distribution of DO reflects the stress of large populations in New York City and Albany. It is good in the Mid-Hudson region where DO values are near saturation and the water meets drinking water standards and is used for that purpose. DO concentrations in the Albany area under 1977 actual load conditions are slightly improved over 1973 levels. The improvement can be attributed, primarily, to the two major treatment plants that went on-line in the Albany area in 1974. The middle portion of the estuary in both 1977 and 1973 was characterized by a relatively high DO level. In the lower reaches of the estuary and Upper New York Harbor, the 1977 calculated DO profile is somewhat lower than that for 1973 because it was assumed that several of the discharges, particularly those from the North River treatment plant, had interceptors operational by 1977 but had no treatment facilities to handle the increased loads. In the Bight Apex Area, the 1973 and 1977 profiles approach each other with

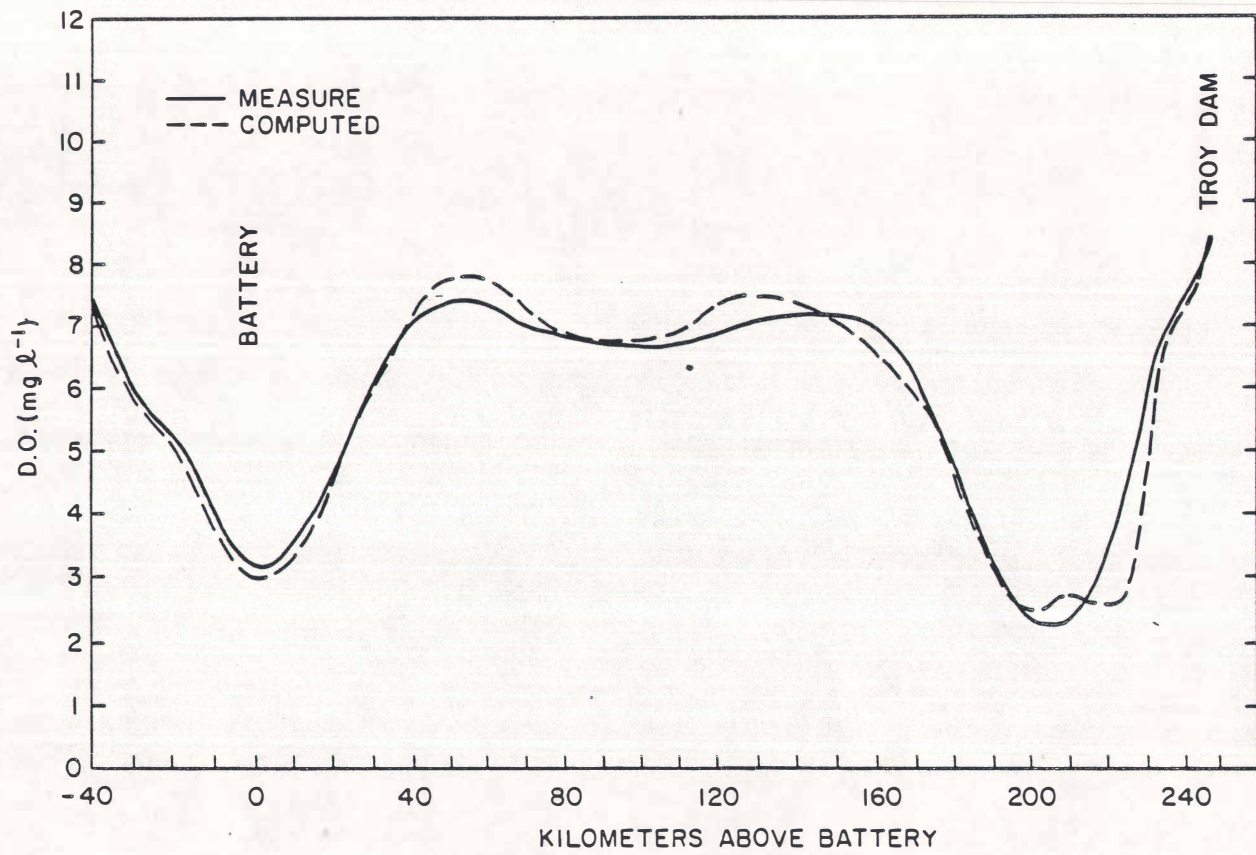


Figure 7. Measured and Computed Values of Dissolved Oxygen along the Axis of the Hudson River and Estuary.

TABLE 7. BOD levels from different degrees of treatment (LMS model)

<u>Case No.</u>	<u>Condition</u>	<u>Municipal Loads tonnes d⁻¹</u>	<u>Industrial Loads tonnes d⁻¹</u>
0	Actual BOD (1973)	843	33
1*	Best Practical Technology BOD (1977)	211	6
2	Best Available Technology BOD (1983)	209	4
3**	Elimination of Discharge (1985)	0	0

*The 1977 profile shown in Figure 7 represents actual loads rather than the 1977 Best Practical Technology loads tabulated here.

**Assumes no oxygen demand from point sources and that the only depression of DO below saturation is from the so-called "background" BOD which arises from non-point sources and from natural oxygen demand.

AVERAGE SUMMER CONDITIONS —
CASE

- ① 1973 ACTUAL CONDITIONS
- ② 1977 ACTUAL CONDITIONS
- ③ 1983 (BAT - BEST AVAILABLE TECHNOLOGY) or 1977 (BPT - BEST PRACTICAL TECHNOLOGY) THEORETICAL CONDITIONS
- ④ 1985 (EOD - ELIMINATION of DISCHARGE) CONDITIONS

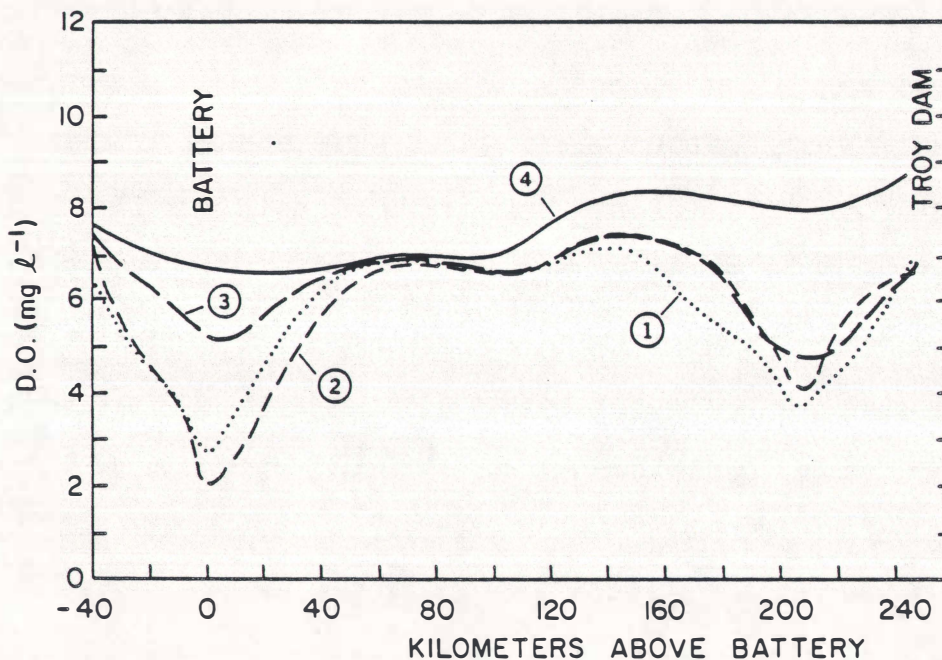


Figure 8. Predicted Dissolved Oxygen Profiles in the Hudson River for Different Conditions: Present, Best Practical Technology (BPT), Best Available Technology (BAT), and Elimination of Discharge (EOD), Summer.

DO values close to saturation values at Mile Point-30 (Kilometer Point--48.)

Case (2) is the distribution of DO predicted for the levels of BOD that would result from the discharge into the Hudson River under Best Available Technology projected for 1983 (BAT). These BOD levels are not significantly different from the case (1) 1977 Best Practical Technology (BPT) values. The major difference between BAT-1983 and BPT-1977 is an increased treatment level of the part of the load from industrial discharges. Achieving the BPT mandated for 1977 or the BAT in 1983 would eliminate over 80% of the waste load and would result in markedly improved dissolved oxygen (DO) concentrations. Improvement in the lower segment of the Hudson River and in the Upper and Lower Bays, with values well above the 5 ppm DO criterion is particularly marked.

(Case (3) considers elimination of the pollutant mass or elimination of discharge (EOD) without elimination of the water discharge. With no oxygen demand from point sources, the only depression of DO below saturation arises from non-point sources; natural oxygen demand of the river and small residual concentrations from point sources. Under EOD conditions the increase over 1983 in DO levels in the upstream reaches of the Hudson River is more significant than in the lower reaches and in the Harbor and Bight.

The 1983 BAT, which is applicable only to point sources, should produce DO levels that meet current DO standards under normal steady-state conditions. Non-point sources alone cannot bring DO levels below standard, primarily because of the high flows associated with these sources (mostly combined system overflows) and also because of the extremely small effects on water quality from "background" sources.

Table 8. BOD Loads, Summer 1977

Total Basin Input of BOD = 909 tons d^{-1}

Total flux at 3 miles above Battery = 188 tons d^{-1}

Total flux at Sandy Hook = 69 tons d^{-1}

In summary, the model indicates that the various treatment levels would increase DO levels in the Hudson River and the New York Bays to above the present criterion of 5 ppm, but would not significantly influence DO levels in the Bight Apex. The 1977 BOD loads under summer conditions at various points within the system, Table 8, support this conclusion. In other words, only about 8% of the total input of BOD to the Hudson-Raritan Estuary passes through the Sandy Hook-Rockaway Point Transect to the Bight.

It is important to remember that the model from which these conclusions are drawn does not consider secondary BOD generated by the conversion of nutrients to organic matter by photosynthesis. It should be pointed out also that the 1977 BPT goal was not met in that year, and indeed has not been met at the time of this revision (1982).

Sand and Gravel Mining

Several proposed modifications of present dredging policies in the Estuary and Bight Apex area could have significant effects on water quality in the Bight. For a number of years the Lower Bay of New York Harbor has been a major source of sand and gravel for construction aggregate and for

fill. It has provided much of the aggregate and fill required for construction in metropolitan New York and New Jersey, and is, undoubtedly, one of the nation's largest "open-pit" sand mines. Since 1967, the rate of removal has averaged about $4.2 \times 10^6 \text{ m}^3 \text{ y}^{-1}$.

In 1974 the New York Department of Environmental Conservation restricted sand dredging to the east bank of Ambrose Channel and to the Chapel Hill North Channel. These restrictions are still in effect today. While material from these areas is too fine-grained for aggregate, it is an important source of fill for metropolitan New York.

Imposition of restrictions on the location of mining areas was predicated upon several assumptions: (1) that dredging in other parts of the Lower Bay of New York Harbor might have a greater impact on water quality and also adversely affect productive shellfish and finfish areas west of Ambrose Channel, (2) that dredging in other areas might accelerate shore erosion on Staten Island, (3) that the sand deposits of the Ambrose Channel and the area to the east are replenished by littoral drift along the south shore of Long Island, and are thus a renewable resource that can be "cropped" without being depleted, and (4) since material is continually being supplied to the designated area the mining provides a necessary and useful service, maintenance dredging of the shipping channel.

In 1975, the Marine Sciences Research Center of the State University of New York began a comprehensive study of these assumptions.

Wong and Wilson (1979) used a finite element, vertically-integrated tidal model developed at the Massachusetts Institute of Technology (Wang and O'Connor, 1975) to investigate changes in tidal currents and water surface elevations that would result from modifications of bathymetry by

a variety of hypothetical sand mining strategies near Sandy Hook, Staten Island, and Rockaway Point. In the use of this model the subject area is divided into small, triangular shaped sub-units called elements. The model computes water surface elevations and current velocities as a function of time at the corners of the elements. In general, the effects of mining are to decelerate the flow within the pit and accelerate the flow around its perimeter. The magnitude of these changes increases as the size of the hole increases. There is also a deflection of flow toward the hole on its upstream side. The magnitudes of some of the current vectors before and after mining a small and a large hole near Sandy Hook are summarized in Table 9. The element locations are shown in Fig. 9. The corresponding flow fields before and after mining are shown graphically in Fig. 10.

Wong and Wilson's calculations also indicate that significant changes in water surface elevation could occur along Staten Island for certain changes in bathymetry produced by sand mining, particularly for areas near the mouth of the Lower Bay. Figure 11 shows tidal elevation as a function of time at node 10 near Staten Island for small and large holes near Sandy Hook. Approximately the first 7×10^3 sec are the spin-up of the model and should be disregarded. The figure indicates that mining sand near Sandy Hook could produce a significant increase in tidal range off Staten Island, an area already experiencing severe shore erosion.

Wong and Wilson find that mining operations near the Transect can increase the tidal prism in the Lower Bay and the average tidal flow through the Transect by as much as 20 percent. Modifications near the Transect can also alter the fraction of water recirculated during the

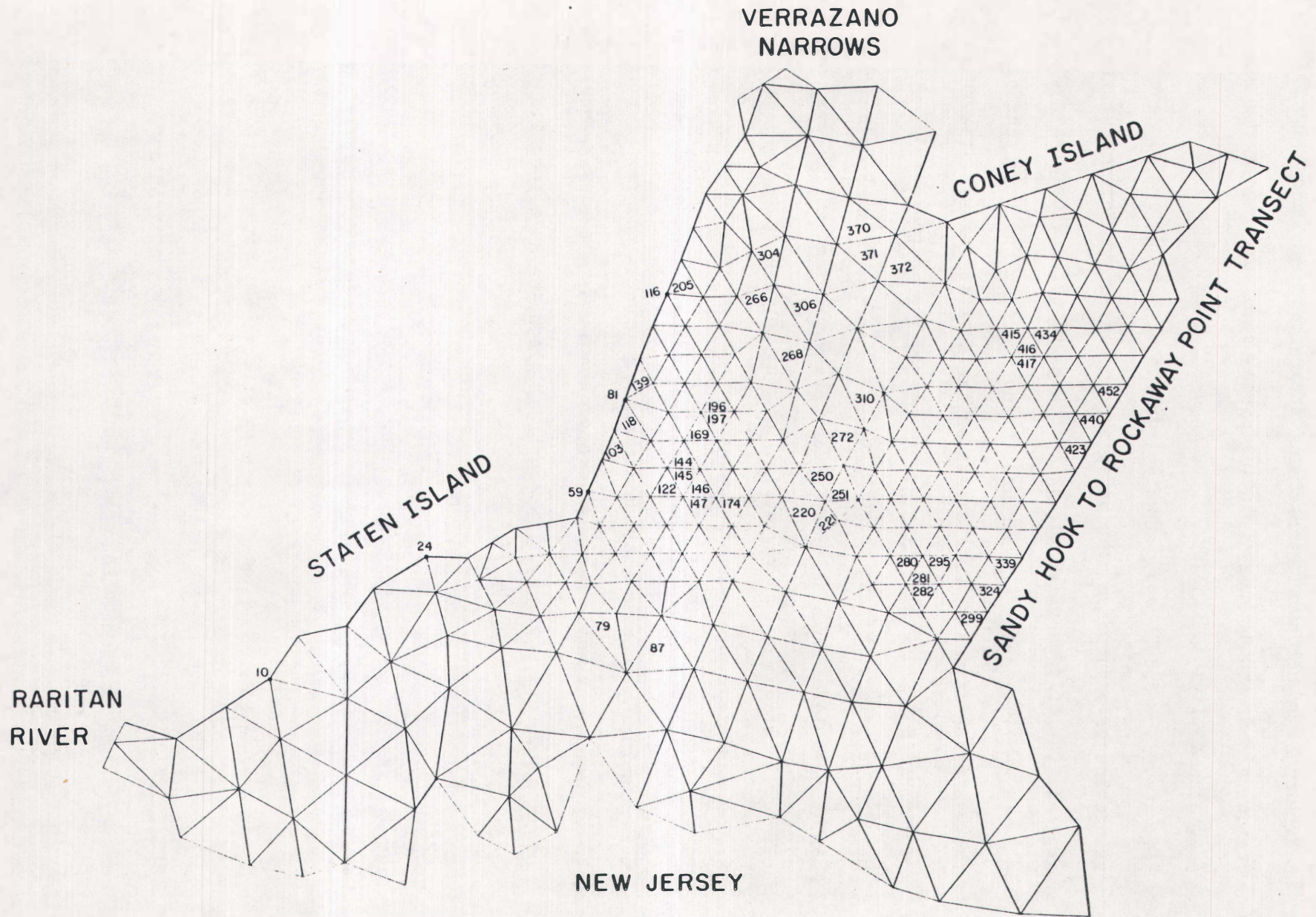


Figure 9. Finite Element Grid for Lower Bay of New York Harbor Showing Numbers of Selected Nodes.

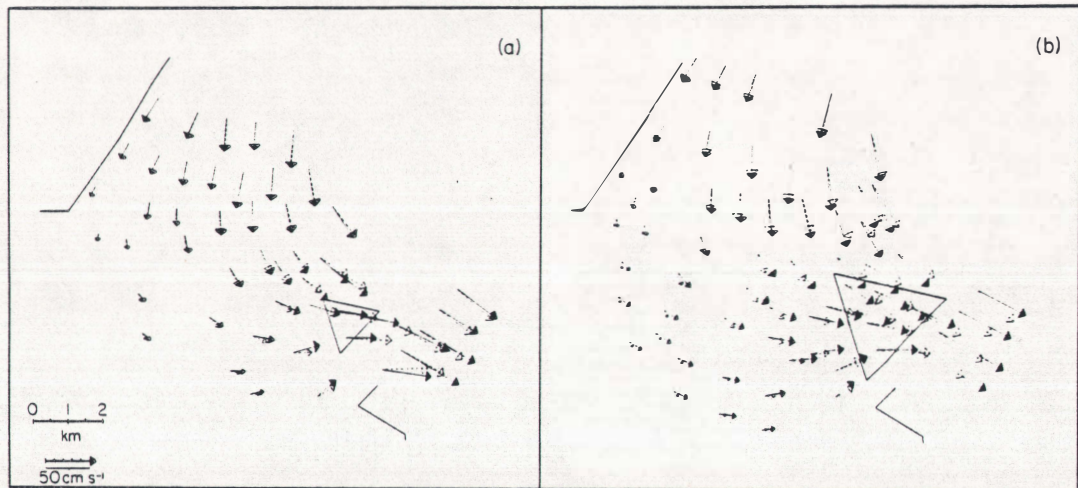


Figure 10. Comparison of Tidal Current Vectors Near Maximum Ebb at Sandy Hook Computed for Existing Bathymetry (dashed arrows) and for Altered Bathymetry (solid arrows) for (a) Small Region Mined Near Sandy Hook, (b) Large Region Mined Near Sandy Hook.

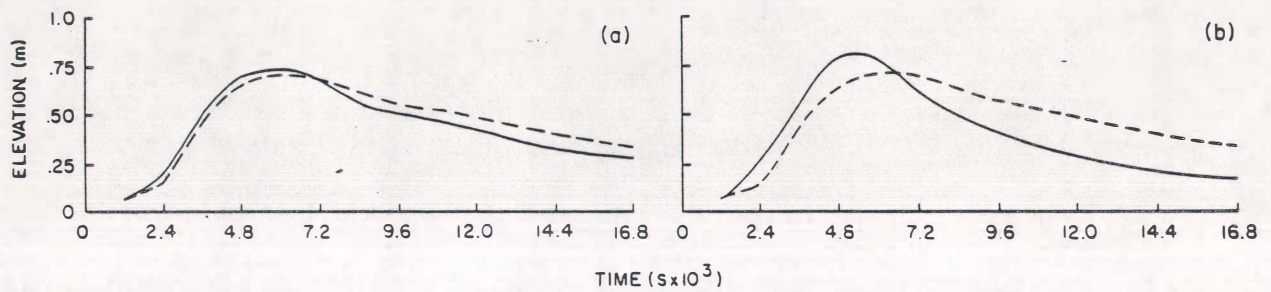


Figure 11. Comparison of Tidal Elevation along Staten Island at Node 10 (Fig. 9) Computed for Existing Bathymetry (dashed lines) and for Altered Bathymetry (solid lines) for (a) Small Region Mined Near Sandy Hook (Fig. 10) and (b) Large Region Mined Near Sandy Hook (Fig. 10).

TABLE 9. Effects of sand mining on tidal
current magnitudes near Sandy Hook

Tidal Current Magnitudes (cm s^{-1})*

<u>Element No</u>	<u>Before Mining</u>	<u>Large Hole</u>	<u>Small Hole</u>
280	42.0	36.2	30.2
281	48.2	41.6	33.6
282	48.0	39.2	30.2
295	58.8	45.8	35.6
299	47.6	53.4	51.6
324	52.4	80.8	71.8
339	54.2	78.4	68.2
220	21.6	30.4	25.8
250	28.2	38.2	30.8
272	32.8	39.6	34.2
310	43.6	47.6	44.2

*at $t = 8000$ seconds

flood. Doyle and Wilson (1978) showed that the asymmetry of the tidal flow through the Transect, discussed on pages earlier, is primarily due to a balance between the centrifugal and Coriolis forces modified slightly by bottom friction. The asymmetry results in a net inflow of water into the Estuary near Rockaway and a net outflow near Sandy Hook.

While there is no compelling evidence that previous sand and gravel mining operations in the Lower Bay of New York Harbor have had any significant deleterious effects on water quality, the biota of the Estuary, or that of the Bight (Kastens et al., 1978; Wong and Wilson, 1979; Schwartz and Brinkhuis, 1979; Jones et al., 1979), there are now data which suggest that sand mining could be used to improve water quality in the Estuary and the Bight. One possibility that should be thoroughly assessed is to combine sand and gravel mining with disposal of contaminated dredged materials in the resulting borrow pits. The final step would be to cap the contaminated material with clean fill of a texture similar to that found in surrounding areas. A successful exploitation of this possibility requires deposition of the contaminated material precisely in the hole--not on contiguous areas--keeping it there until the hole is nearly filled and then being able to cap it effectively. Such a sequence of operations is technically feasible (Johansen, et al., 1976). Capping, the last step in the sequence, appears to offer the most difficulty. Precise deposition also presents problems since most contaminated materials are fine-grained with high water content and poor engineering properties. Still, the potential benefits are so great that the feasibility of combining dredging with disposal should be fully evaluated.

The projected demand for sand in the metropolitan New York area

over the three years, 1979-1981, had been estimated at $20 \times 10^6 \text{ m}^3$ (James Marotta, personal communication, 1978). The amount of material dredged from New York Harbor each year for maintenance and new work averages about $8 \times 10^6 \text{ m}^3$ of which approximately 10 - 20% or 0.8×10^6 to $1.6 \times 10^6 \text{ m}^3$ would probably be considered contaminated, i.e., would probably not pass the bioassay tests required for its disposal in the ocean (Dennis Suszkowski, personal communication). For the past 20 years the rate of removal of sand from the Lower Bay for fill and aggregate has averaged about 1.5×10^6 to $2.3 \times 10^6 \text{ m}^3$ per year (Kastens, et al., 1978). The volumes of contaminated dredged spoil and sand removed each year are therefore comparable.

Borrow pits could be created wherever sand and gravel suitable for aggregate or fill are found. It may be objected that back-filling a hole with contaminated material is an irreversible decision in that it permanently commits that part of the bottom of the Lower Bay to disposal. This is not, however, inherently bad as an alternative to present policy. We are now assigning some parts of the Bight as receiving areas for wastes, without the protection that capping would provide. Better that such decisions be made consciously with foresight and knowledge of probable impacts. It should also be noted that the deeper the holes are dredged, the smaller the areas required for a given amount of contaminated material. This reduction in surface area could itself have positive effects.

Selective mining might also be used to improve the flushing of the Harbor. If the presently asymmetric inflow described earlier could be enhanced by suitable modification of the bottom topography, the fraction of Estuary outflow water recirculated to the Estuary could be reduced.

Such a change would lead to a decrease in the Pollution Susceptibility of the Transect, that is to a more rapid dilution of water-borne contaminants.

The Steady State Pollution Susceptibility (PSS), as defined by Weyl (1976) is, in essence, the inverse of the volume of water per unit time available for the dilution of a fixed quantity of contaminant. For an estuary with a fresh water river inflow of $R \text{ km}^3 \text{ d}^{-1}$

$$\text{PSS} = 1/[\text{T}(1 - f) + R]$$

where T is the average of the absolute value of the tidal flow through the transect at the mouth of the estuary in $\text{km}^3 \text{ d}^{-1}$ and f is the fraction of the ebb flow that re-enters the estuary on the next flood. In the case of the Hudson-Raritan Estuarine System, a term representing the inflow through the East River from Long Island Sound, Q_E , must be included in the above equation.

$$\text{PSS} = 1/[\text{T}(1 - f) + R + Q_E]$$

Characteristic values of T, R, and Q_E for the Hudson-Raritan Estuarine System at the Sandy Hook-Rockaway Point Transect are $1.5 \text{ km}^3 \text{ d}^{-1}$, $0.0605 \text{ km}^3 \text{ d}^{-1}$, and $0.0305 \text{ km}^3 \text{ d}^{-1}$ so that

$$\text{PSS} = 1/[1.5(1 - f) + 0.091]$$

Using values for the rate of discharge of nitrogen in waste waters and for the concentration of total nitrogen at the Transect during January, 1974,

when primary production was low (Duedall et al. 1977), it is possible to estimate PSS using the relationship $\bar{c}_p = q_p \times \text{PSS}$, where \bar{c}_p is a weighted mean concentration of a pollutant and q_p is its mean rate of introduction into the estuary. Then f can be computed by inverting the above equation:

$$\text{PSS} = 3.2 \quad f = 0.85$$

and under the stated conditions, then, 85% of the ebb flow reenters the Estuary at the following flood tide. If selective sand mining reduced this fraction of recirculated water from 85 to 70 percent, it would reduce the Pollution Susceptibility from

$$\begin{aligned} \text{PSS} &= 1/(\text{T} \times 0.15 + \text{R} + \text{Q}_E) \\ &= 1/0.316 = 3.2 \end{aligned}$$

to

$$\begin{aligned} \text{PSS} &= 1/(\text{T} \times 0.30 + \text{R} + \text{Q}_E) \\ &= 1/0.54 = 1.85 \end{aligned}$$

For typical values of R and Q_E a reduction of about 42% in the Pollution Susceptibility for the lower reaches of the estuary could thus be anticipated. Extensive model studies would, however, be necessary to more thoroughly explore the potential for improving the flushing of the lower estuary through selective sand mining.

Port Facilities Changes

During the 1960's and 1970's the port facilities of the Port of New York and New Jersey were substantially modified to meet the changing needs of world maritime trade. New terminal facilities were constructed for containerized freight, including roll-on, roll-off terminals (Port Authority, 1978). Anchorages in the Harbor were expanded and deepened (Hammon, 1976).

There is however, little evidence that improvement of port facilities has caused any major change in ship traffic. It might be argued that failure to deepen navigation channels, now with depths of 10.7 m and 13.7 m, to accommodate deep-draft super tankers, whose drafts range from 19.8 m to 30.5 m, together with the lack of deep-draft terminal facilities offshore, has kept super tankers out of New York Bight (Hammon, 1976).

Decreased Channel Dredging

The 78 Federally authorized waterways in greater New York Harbor are maintained by the U.S. Army Corps of Engineers (Hammon, 1976). A large fraction of the materials dredged from these channels has traditionally been barged to sea for disposal in the New York Bight (Gross, 1976). Some of the projects require frequent dredging to maintain project depth and some of the areas accumulate materials containing troublesome pollutants such as metals, PCBs, and oils and greases. Sediments removed from these locations are a major source of particle-associated contaminants to the New York Bight.

In view of the threat of PCBs and other contaminants to organisms in the Bight, and because of the possibility that more stringent ocean disposal criteria will soon prohibit dumping some of these materials in the Bight, it would be worthwhile to determine if some of these routinely dredged channels could be allowed to simply fill in and remain undredged. For example, what effect would reduced channel depths in the Edgewater-Weehawken Channels of the lower Hudson River have on traffic in and through the Port of New York? If this channel were allowed to accumulate sediments up to the depth of the surrounding river bottom, we would have eliminated the need for dredging about $3 \times 10^6 \text{ m}^3$ of material. This is equivalent to 4-5 years of maintenance dredging of this channel, at the actual dredging rates in use between 1930 and 1970 (Gross, 1976).

Relatively unpolluted materials removed during the construction of new facilities, for example widening and deepening channels and anchorages, might be used to cover up existing troublesome deposits in areas no longer required for navigation.

Recreational Boating

Boating facilities are few in some areas of the New York Metropolitan region (Carls, 1978). These shortages may have inhibited local growth in recreational boating.

Other factors which could limit future recreational boating include increased costs of fuel and boat services as well as tightened controls on the disposal of bilge and sewage wastes from boats.

Larger populations in the New York Metropolitan Region (Koebil and

Krueckeberg, 1975) combined with increased affluence of the region's population suggest that an increased demand on the region's water-related recreational facilities is likely to develop.

High-Flow Skimming of Fresh Water

The U.S. Army Corps of Engineers' Hudson River Flood Skimming project calls for withdrawal, near Kingston, New York (mile point 95) of water at rates up to $42 \text{ m}^3 \text{ s}^{-1}$ during the high flow periods of April and May. The water withdrawn would be used to augment municipal system supplies. During those years when the April and May river flow is low, and during all low-flow months, withdrawal would be kept below $4 \text{ m}^3 \text{ s}^{-1}$ or even stopped. Such skimming of freshwater would affect the position of the boundary between freshwater and saltwater, and might also affect certain fish populations.

If the skimming of freshwater occurred at the maximum rate suggested above, we estimate that the salt front would be displaced northward (up-river) about 1.8 - 3.7 km, depending upon river flow. The overall net effect on the Estuary would probably be somewhat less than the displacement of the front might suggest, since more than 70 percent of the water withdrawn would be returned to the system in the vicinity of New York City. The average displacement of the front is expected to be 0.9 - 1.8 km. With the salt front at, or below, the Tappan Zee Bridge, as it normally would be during the withdrawal months of April and May, no adverse effects are anticipated on anadromous fish populations in the region of the front or on resident biological assemblages because of this displacement. If there were a measurable

biological perturbation, it would likely arise from removal and 100% mortality of fish eggs and larvae in the skimmed water and mortalities of adult and juvenile fish impinged on the intake screens.

Among the more important anadromous species, tomcod adults could be affected since they move as far north as Albany after spawning in the winter months. Larvae, however, are more abundant in the salt wedge area, even though they have been reported as far north as Roseton at mile point 66 (LMS, 1977).

Striped bass spawning generally occurs from late April to mid-June. In 1973 eggs were collected over broad segments of the River from mile point 22 to mile point 133. Major concentrations were found between mile point 41 and mile point 90 (Texas Instruments, 1973). Since young striped bass tend to move downstream, the effect on them of the withdrawal of large amounts of water at mile point 95 would probably be minor in most years.

The largest-scale migration which occurs within the Estuary is that of the anadromous genus Alosa, which includes American shad (Alosa sapidissima), alewife (Alosa pseudoharengus), and blueback herring (Alosa aestivalis). Their migrations and subsequent spawning activities cover the entire Estuary from Manhattan to Albany. The blueback (summer) herring are late arrivals, reaching peak abundance during May and June, and therefore would be affected the least. Alewives spawn during late April and May, so their larvae would be subject to removal in the Kingston area by the skimming. Since spawning occurs above and below Kingston, however, the impact would probably not be major.

Peak abundance of spawning shad occurs during April. The greatest spawning activity occurs between Kingston at mile point 95 and Albany at

mile point 142. Talbot (1954) stated that the major spawning area for shad in the Hudson River was between Port Ewen at mile point 90 and Cocksackie at mile point 124. This area is considered so important as a spawning ground for the commercially-valuable shad that the Commercial Inland Fisheries Law prohibits shad fishing from March 15 - June 15 each year "beginning at the red buoy north of Kingston Point" northward, an area known as "The Flats" (LMS, 1975).

The quantity of water withdrawn and, more particularly, the timing of that withdrawal are two considerations which could adversely affect successful recruitment to American shad populations.

Tide Gates Across Upper East River

Most potential future modifications of the Estuary, including those discussed here, would cause relatively minor changes in the pollution susceptibility of the Bight at the Sandy Hook-Rockaway Transect. One exception is the proposal of Bowman (1976) to reduce pollution of the western end of Long Island Sound by placing tide gates across the upper East River. These gates would be used to allow flow from the Sound to New York Harbor, but to block the reverse flow. Tide gates operated in this way would affect flow through the Transect in two ways:

- 1) They would increase the rate of discharge of pollutants to the Hudson-Raritan Estuary by the flux that now enters Long Island Sound through the East River. The total discharge of municipal wastewater into the East River is currently about 39 percent of the total wastewater load to the Hudson-Raritan Estuary below the George Washington Bridge (Mueller et al., 1976). Assuming

that one half of this waste load is at present transferred to the Sound and the other half to the Hudson-Raritan Estuary, the total flux to the Hudson-Raritan Estuary would be increased by about 20 percent with tide gates.

- 2) The net flow from Long Island Sound to the Transect would be increased from its present estimated value of $0.03 \text{ km}^3 \text{ d}^{-1}$ to about $0.22 \text{ km}^3 \text{ d}^{-1}$. This would reduce the pollution susceptibility at the Transect, under average runoff conditions, from 3.2 to $2.0 \text{ d}^{-1} \text{ km}^3$. As a result, the average concentration of a conservative pollutant would be changed by a factor of $2.0/3.2 = 0.63$, a reduction of 27 percent.

Installation of the tide gates would reduce the concentration of pollutants in the Estuary. It would also decrease the concentration of pollutants in the Bight close to the Transect. The total flux of pollutants in the Bight Apex, however, would be increased, because of the diversion of these pollutants from Long Island Sound (with corresponding benefit to Sound water quality). Of course, other possible effects of tide gates across the East River, including effects on the ecosystem and on water uses, would have to be thoroughly evaluated before Bowman's proposal could be seriously considered.

Coal Wastes

Significant changes to the Bight might ultimately result from the conversion of oil-fired steam electric generating stations along the Estuary to coal. Scrubbers would then be required to maintain air quality and the resulting scrubber wastes and fly ash would pose a major waste

disposal problem. One option currently under investigation at the State University of New York's Marine Sciences Research Center is to convert these wastes into solid blocks, approximately a cubic meter in volume, and to use the blocks for building artificial fishing reefs off the south shore of Long Island.

The operation of a single 1000 MW power plant for one year requires 2.0×10^6 tonnes of coal from which come about 0.3×10^6 tonnes of fly ash and 0.6×10^6 tonnes of scrubber sludge (with a water content of approximately 50 percent). This amount of waste would yield 0.6×10^6 tonnes of blocks, or approximately 3.4×10^5 blocks, with a volume of one cubic meter each. Since the total fossil fuel electrical generating capacity on the estuary is about 13,000 megawatts, the potential yield is about 4.4×10^6 blocks y^{-1} .

A reef about 10 meters high and 1 km wide with a 30 percent inter-block porosity would use 7×10^6 blocks km^{-1} of length. Thus, if all power stations went to this disposal option their annual production of blocks would produce a 0.6 km length of reef each year and the reef could extend the entire length of Long Island (ca 190 km) in about 317 years.

SUMMARY

We can now briefly summarize what is known about the influence of the Estuary on the Bight and how some proposed changes in Estuary activities might affect their interaction. We find that the flux of suspended sediment across the Transect is, by any reasonable estimate, small compared to the tonnage of dredged sediment dumped in the Bight

from vessels. Since most of the contaminants we are concerned about are sediment-associated, we have to conclude that dredged material is the principal transport mechanism of concern. In the case of PCB's, the ratio of introduction by barging, to water transport on suspended particles, to transport in solution, is estimated at 100:10:1.

Dissolved contaminants, notably the plant nutrients nitrogen and phosphorus from sewage, move across the Transect in the water column. Relatively little of this vast nutrient supply is consumed by phytoplankton in the Estuary. The rest supports productivity in the Bight, mainly in the Apex where phytoplankton account for 70-80% of the annual input of particulate organic matter. The extent to which nutrient input from the Estuary (including DOM), and the resulting phytoplankton contribution of POM, influence summer development of low DO conditions in the Bight is still unresolved. Some authorities conclude, however, that the upgrading of New York City sewage treatment, even to the point of eliminating nutrient discharge from this major source, would have little effect on the incidence of low-DO conditions in the Bight.

Floating wastes, such as those responsible for the 1976 fouling of Long Island beaches, come mainly from the Estuary. A recurrence of this unfortunate experience depends primarily on the repeat of a particular combination of meteorological conditions, a combination, however, which is not wildly improbable. The only sure way to prevent future floatable episodes is to initiate widespread changes in waste-handling and disposal practices in the Estuary and its drainage basins.

Dredging activities in the Estuary and inner Bight have, as noted, a significant influence on Bight conditions. Proposed changes in the manner in which those activities are conducted could modify their influence in

important respects. Some fraction of the present burden of contaminated dredged material could probably be eliminated, at acceptable cost, by simply ceasing to maintain little-used channels. Merely changing the location of sand and gravel mining operations in the Transect area could increase average tidal flow by perhaps 20%, with proportionate reduction of Pollution Susceptibility values. If the contaminated material from Estuary dredging could be dumped in the borrow pits left by sand mining, and then capped with clean material, a major present source of contamination to the Bight would be essentially eliminated.

A proposed seasonal diversion of fresh water from the mid-Hudson ("skimming") would probably have only minor influence on Bight water quality but could affect fish populations. In contrast, a system of tide gates across the upper East River could be expected to significantly improve water quality, not only in the Sound but in the inner Bight as well. Any influence on the remainder of the Bight should be inconsequential.

The anticipated future conversion of Estuary electric generating plants from oil to coal will create a major waste disposal problem. Large quantities of fly ash and scrubber sludge will have to be disposed of at minimum cost and environmental damage. One novel solution now under study at the Marine Sciences Research Center is to use this material to construct artificial fishing reefs in the ocean south of Long Island. The ash and sludge would be compacted into solid concrete-like blocks that could be dumped at sea to form the reef. Long-term effects of this procedure are still under study but do not now appear objectionable. This may even constitute the ideal situation in which a potential pollution problem in the Estuary can be made to have a

positive impact on the Bight. In most other cases some alleviation of negative impacts by informed management is the best that can be expected.

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