The Lower Bay Complex

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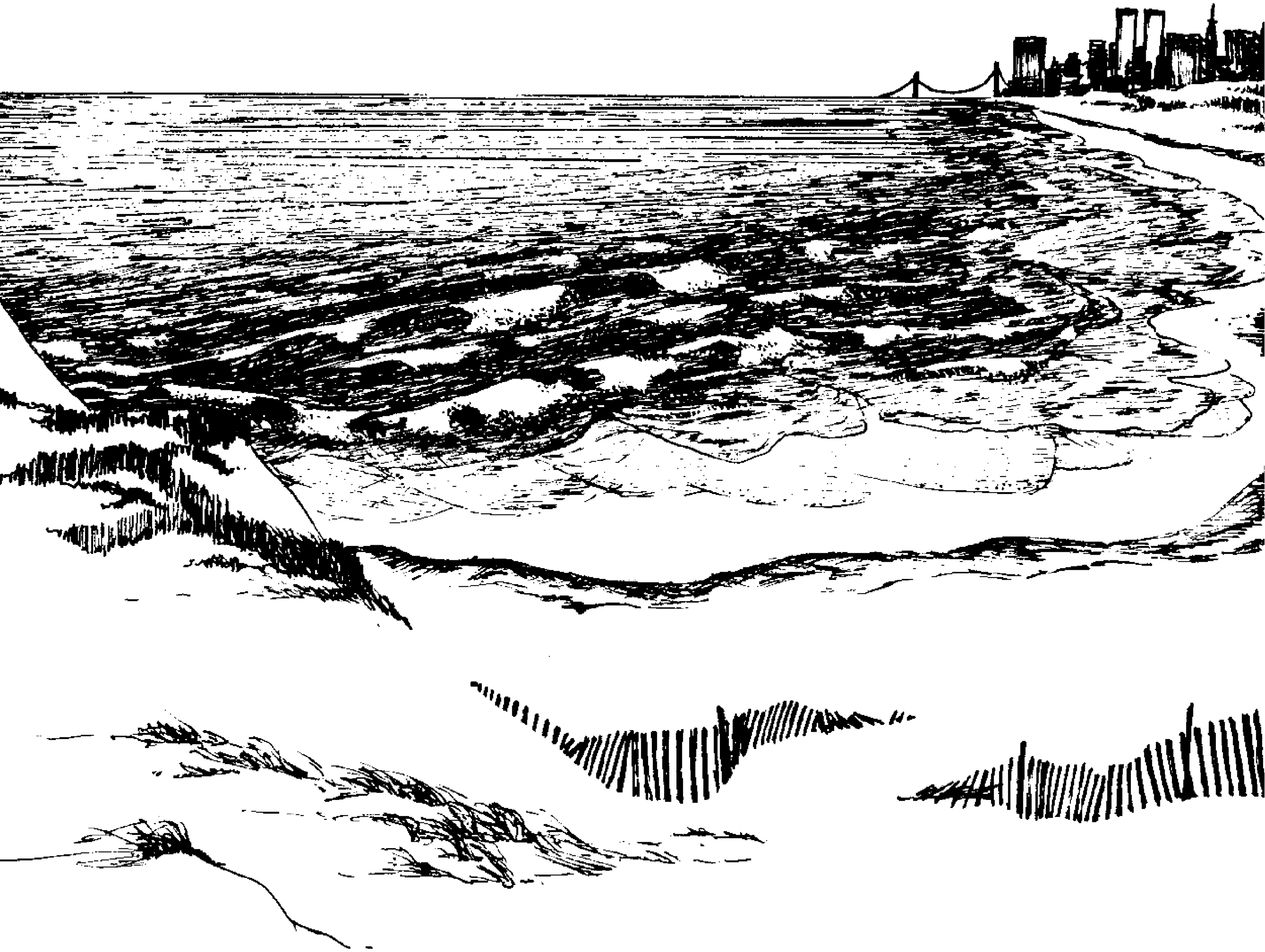
Jeffrey H. Parker



MESA NEW YORK BIGHT ATLAS MONOGRAPH 29

The offshore water in the bend of the Atlantic coastline from Long Island on one side to New Jersey on the other is known as New York Bight. This 15,000 square miles of the Atlantic coastal ocean reaches seaward to the edge of the continental shelf, 80 to 120 miles offshore. It's the front doorstep of New York City, one of the world's most intensively used coastal areas—for recreation, shipping, fishing and shellfishing, and for dumping sewage sludge, construction rubble, and industrial wastes. Its potential is being closely eyed for resources like sand and gravel—and oil and gas.

This is one of a series of technical monographs on the Bight, summarizing what is known and identifying what is unknown. Those making critical management decisions affecting the Bight region are acutely aware that they need more data than are now available on the complex interplay among processes in the Bight, and about the human impact on those processes. The monographs provide a jumping-off place for further research.

The series is a cooperative effort between the National Oceanic and Atmospheric Administration (NOAA) and the New York Sea Grant Institute. NOAA's Marine EcoSystems Analysis (MESA) program is responsible for identifying and measuring the impact of man on the marine environment and its resources. The Sea Grant Institute (of State University of New York and Cornell University, and an affiliate of NOAA's Sea Grant program) conducts a variety of research and educational activities on the sea and Great Lakes. Together, Sea Grant and MESA are preparing an atlas of New York Bight that will supply urgently needed environmental information to policy-makers, industries, educational institutions, and to interested people.

ATLAS MONOGRAPH 29 provides a general description of the physical environment of the Lower Bay complex in the New York Bight area. The complex is a dynamic estuarine system that acts as a catchment for natural and man-induced inputs originating mainly from the Hudson River. The authors—Duedall, O'Connors, Wilson, and Parker—describe tidal phenomenon, estuarine circulation, and the distribution and variation in water properties. Future work in the bay complex should focus on an understanding of the transport and composition of suspended solids. This information, the authors say, is required in order to adequately address the problems of the impact of the New York metropolitan area on the water quality of New York Bight.

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Abstract

The Lower Bay complex is the seaward part of New York Harbor and includes Raritan, Sandy Hook, and Lower bays. It connects with Upper Bay through a narrow constriction between Staten Island and Brooklyn. The bay complex is relatively shallow (5 to 20 m or 16 to 66 ft) but has an irregular topography due mainly to the numerous ship channels in Lower and Raritan bays. The weather in the bay complex is typical of a midlatitude coastal region, with the adjacent Atlantic Ocean acting as a buffer.

A dynamic and complex estuarine system, the bay complex receives a large, seasonally variable inflow of fresh water originating mainly from the Hudson River with lesser amounts from the Raritan and Passaic rivers. Sewage effluent is also a significant source of fresh water. The nontidal inflow of salt water through the Sandy Hook-Rockaway Point transect is confined to Ambrose and Sandy Hook channels and also through the entire water column near Rockaway Point. Because of the variable inflow of fresh water, the distribution of water properties (salinity, nutrients, chlorophyll *a*) also varies seasonally.

Tides and tidal currents in the bay complex are semidiurnal; their patterns are complicated because of the shape of the bay, the variation in freshwater discharge, Coriolis acceleration, and the intricate connection of waterways. Tidal variations in water properties are large and can be perturbed significantly by storms.

Sewage effluent from the New York metropolitan area is the principal source for the high concentrations of nutrients observed in the bay complex. A large fraction of these nutrients are consumed in biological processes occurring within the bay complex. There is a net transport of nutrients and chlorophyll *a* to the apex of New York Bight. The nutrients originating from the bay complex and transported seaward have been implicated as an important factor leading to the decline of oxygen in bottom waters of the Bight during summer periods.

Introduction

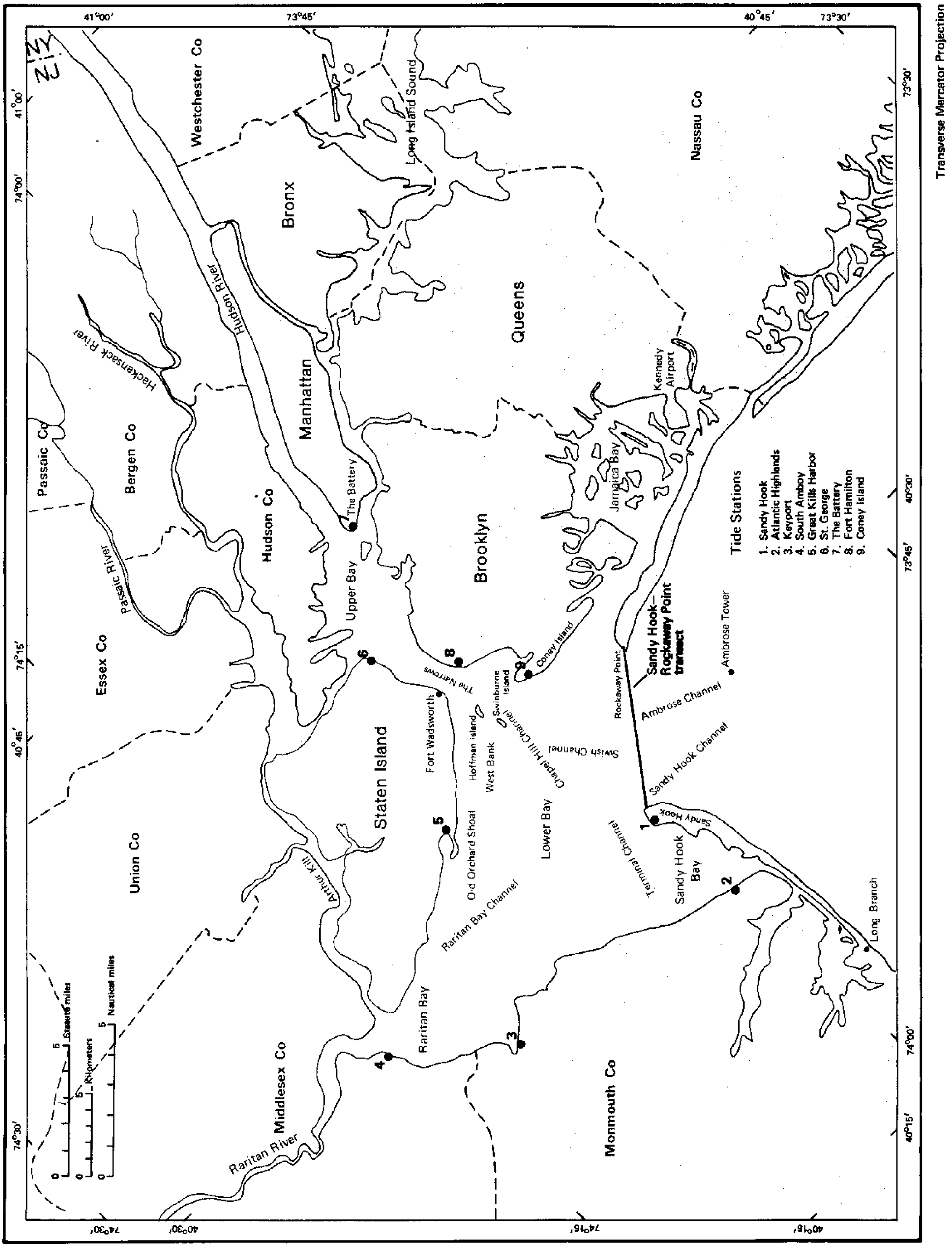
The Lower Bay complex is a triangular coastal plain estuary covering about 290 km^2 (84 nmi^2). It is the seaward part of New York Harbor and forms the estuarine boundary of New York Bight. It includes Raritan, Sandy Hook, and Lower bays, is bordered by Middlesex and Monmouth counties in New Jersey and by the boroughs of Staten Island and Brooklyn in New York City, and is at the mouths of the Hudson and Raritan rivers and Jamaica Bay (Map 1).

Waters of the bay complex exchange and mix with: 1) waters of Upper Bay, mainly through the narrow constriction between Brooklyn and Staten Island, appropriately named The Narrows, and 2) the sea, through the relatively wide ($\sim$10 km or 5.4 nmi) opening between Sandy Hook, NJ, and Rockaway Point, LI, the Sandy Hook-Rockaway Point transect. The Arthur Kill, a tidal canal along the west side of Staten Island, shunts a small amount of Upper Bay waters to Raritan Bay.

The bay complex is not only part of one of the world's busiest seaports (Hammon 1976; Brail and Hughes 1977), it is also used for sand and gravel mining (Schlee and Sanko 1975). Sports and commercial fisheries are major activities in Raritan Bay; thousands of people annually enjoy swimming and recreational boating in Lower and Raritan bays. Millions of gallons per day of sewage flow into the bay complex from shore-based treatment plants (Interstate Sanitation Commission 1974). The impact of these and other activities upon the water properties of the bay complex is dependent upon its physical environment and a variety of transport processes that move and mix water. The purpose of this monograph is to provide a general description of the physical environment of the bay complex. The oceanography of the area will be described with specific emphasis on tidal phenomenon, estuarine circulation, and the distribution and variation in water properties.

Since little quantitative information is available on the impact of the bay complex on the water properties of New York Bight, the flux of chlorophyll *a* and nutrients (ammonium, nitrite, nitrate, phosphate, and silicic acid) to the Bight from the Lower Bay complex will be estimated.

Map 1. General locator—Lower Bay complex



General Features

Climate

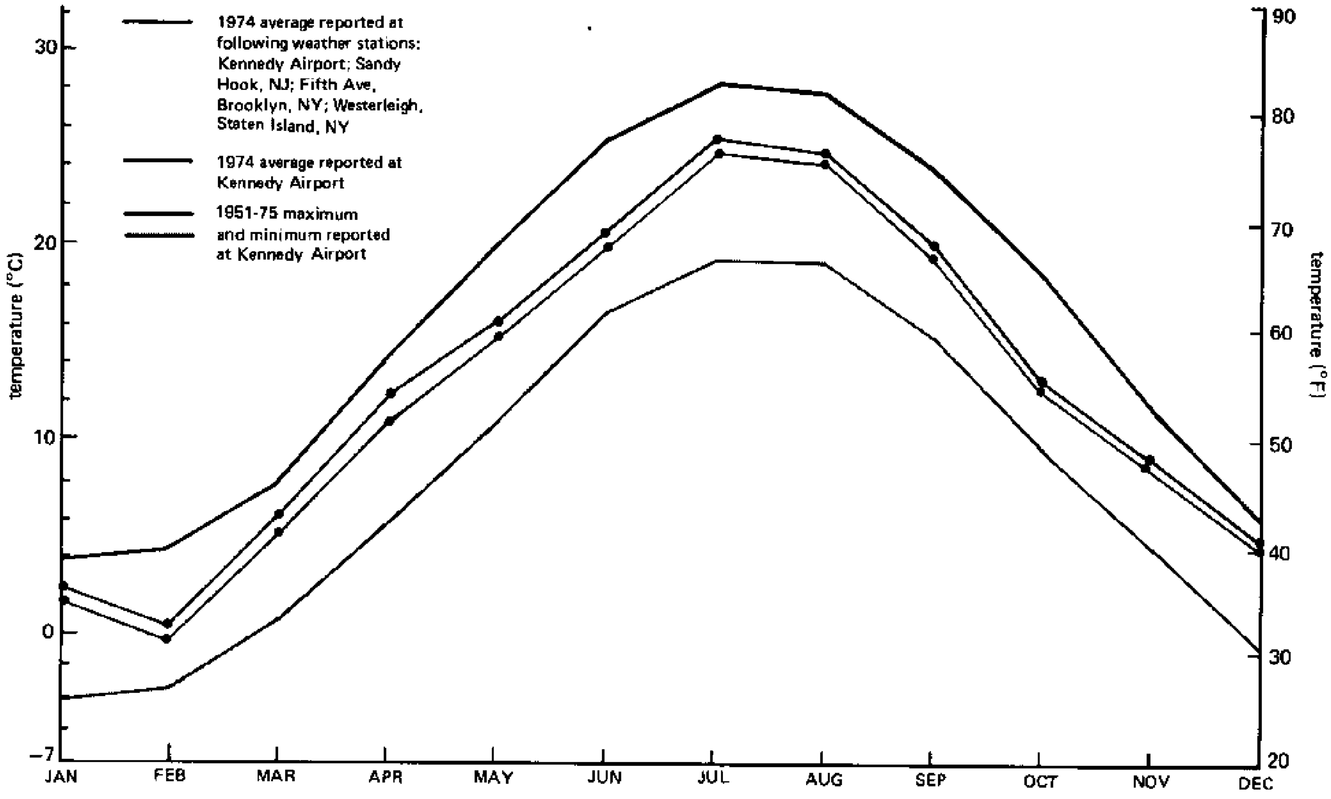
The climate of the Lower Bay complex is that of a temperate, midlatitude coastal region (Lettau, Brower, and Quayle 1976). The bay complex lies in the path of many of the storms and frontal systems that move across the Middle Atlantic states. The adjacent Atlantic Ocean acts as a buffer by preventing extreme summer and winter temperatures.

The following is a brief description of the weather of the bay complex; data were obtained from annual weather summaries (NOAA 1975*a*) that provide a 25-year record for most meteorological parameters. These summaries are available for the John F. Kennedy International Airport weather station. Because of its location, this weather station is a useful anchor station from which to describe the climate of the bay complex. Lettau and associates (1976) summarized the complete marine climatology of New York Bight, including the Lower Bay complex.

Air Temperature. Seasonal variation and range in air temperature are shown in Figure 1. Maximum mean monthly temperatures greater than 26.7°C (80°F) occurred in July and August. During these months the relative humidity often exceeded 60%. Minimum mean monthly temperatures of −6.7° to −1.1°C (20° to 30°F) occurred in January and February. Over the past 25 years, the mean annual temperature has varied between 10° and 12.8°C (50° to 55°F).

According to Lettau and associates (1976), air temperature at the Kennedy Airport, and presumably in the region of the bay complex, has more continental than marine character.

Winds. Examination of wind records from the period 1949 to 1969-70 (Lettau et al 1976) show that in the Lower Bay complex the resultant winds are, on the average, from the northwest from January through March, from the west in April, from the southwest from May through August, from the south in September, and from west-northwest from October through December.



Source: NOAA 1975a

Figure 1. Variation in mean monthly air temperature

Examination of 1973-75 monthly records (NOAA 1975*a*) shows a seasonal wind pattern (Figure 2) similar to the long-term averages. The *resultant wind velocity* (the averaged vector of wind displacement taking direction into account) during 1975 ranged between 1.5 and 14.1 km/hr (0.8 and 7.6 knot). Monthly mean and daily wind speeds without regard to direction can be extremely variable and can have a major effect on the distribution of water properties. Figure 3 gives the daily wind conditions for February and August 1974.

Cloud Coverage. On the average, based on the 25-year record, from November to August there are about seven clear days (Figure 4) per month in the bay complex. In September and October, the number of clear days per month increases to about 10 to 12.

Total Precipitation. Total precipitation is moderate and distributed fairly evenly throughout the year. Figure 5 shows the mean monthly precipitation, including snow, for 1974, an average year in which about 100 cm (39.4 in) of total precipitation were measured. Rainfall from May to October comes mainly from brief but intense thunderstorms, whereas precipitation during other months is likely to be associated with widespread storm areas (NOAA 1975*a*). Figure 5 also shows the 1951-75 record of mean monthly precipitation and the minimum-maximum envelope for this period. In this period, a record low of 0.23 cm (0.09 in) total precipitation fell in October 1963; the record maximum of 44.2 cm (17.4 in) total precipitation fell in August 1955. Figure 6 shows the 25-year record of mean annual precipitation. Over this period, total annual precipitation ranged between a low of about 65 cm (25.6 in) during the drought of the mid-1960s to a high of about 140 cm (55 in) in 1975, a particularly wet year.

The bay complex is characterized by relatively light and variable snowy weather from December to March. Since 1951, mean annual accumulations of snow have ranged from a 1972-73 low of 4.8 cm (1.9 in) to a record high of 144 cm (56.7 in) in 1960-61 (NOAA 1975*a*). The rain equivalent of snow over the Bight coastal region is 100 cm (39.4 in) of snow equals 12.2 cm (4.8 in) of water (Lettau et al 1976). Hail (ice pellets) storms are infrequent (NOAA 1975*a*) and of very short duration and therefore contribute negligibly to the total precipitation.

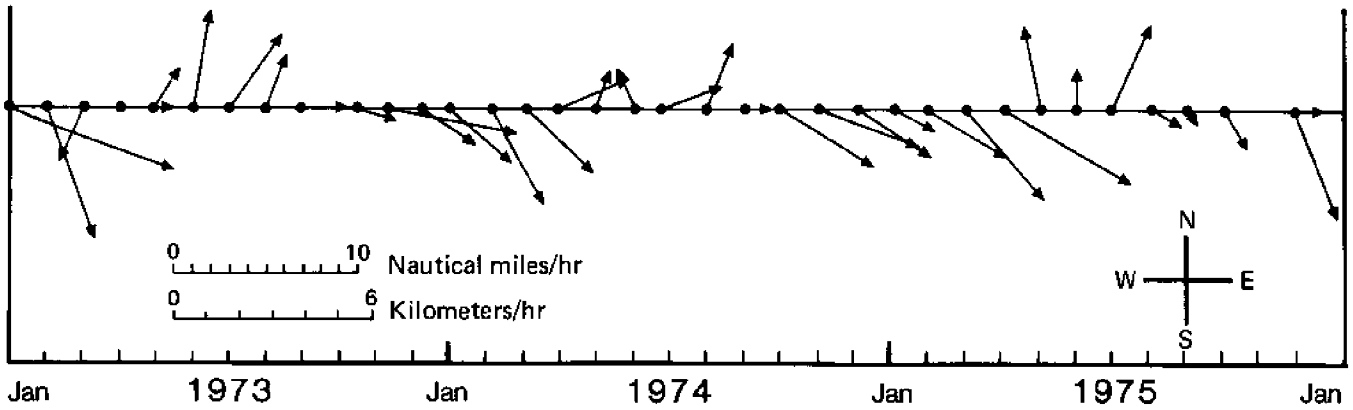
Freshwater Input

The three main drainage basins emptying fresh water into the Lower Bay complex are those of the Hudson, Raritan, and Passaic rivers. Most of the fresh water originates from the Mohawk and Hudson rivers. The Hudson River Basin is the largest single contributor and drains an area of about 35,000 km^2 (13,500 mi^2), nearly all of which is within New York State (Giese and Barr 1967). The Mohawk drains fertile farmland rich in nutrients; the Hudson, above the Troy dam, drains the relatively undisturbed and forested land of the Adirondacks. Several small tributaries flowing down from the Catskill Mountains also drain into the Hudson below the Troy dam.

The Raritan and Passaic basins, drained mainly by the Raritan and Passaic rivers, each having areas of about 1,200 km^2 (463 mi^2), are less important in the total supply of fresh water flowing into the bay complex. The Raritan River, however, has a significant effect on the salinity of upper Raritan Bay because it is the only substantial source of fresh water entering the western end of the bay complex.

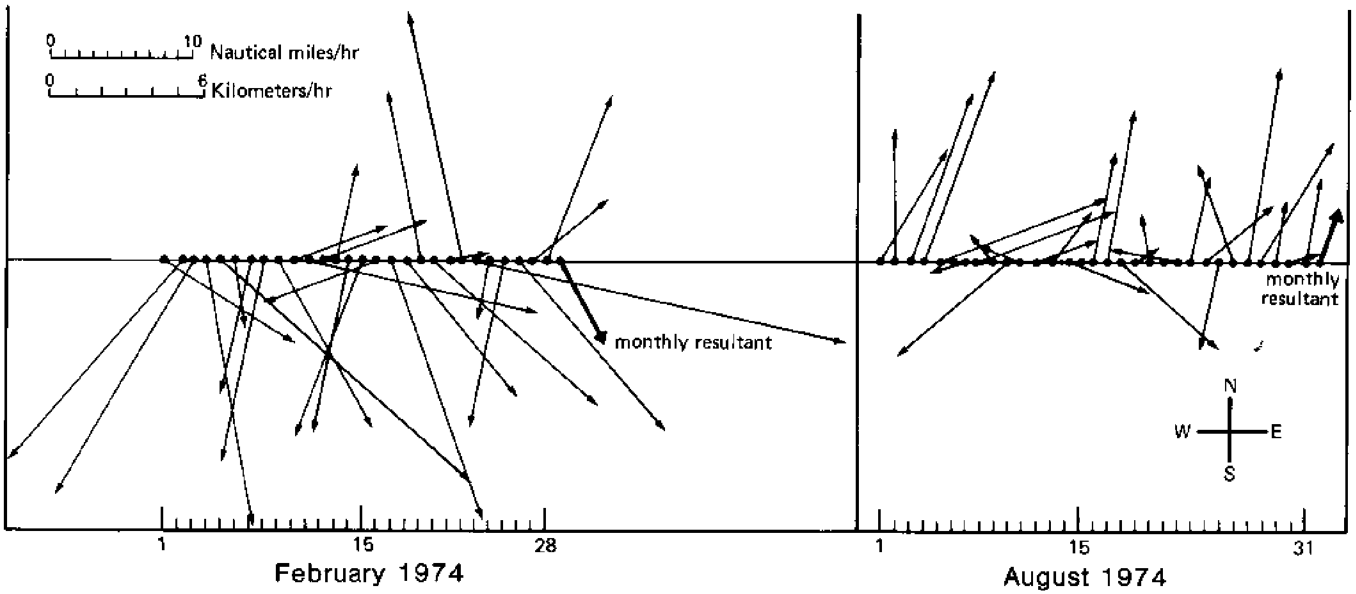
Figure 7 shows the mean monthly discharge of the Hudson, Raritan, and Passaic rivers. Maximum total gauged discharge of about 1,200 to 1,800 m^3/sec (42,400 to 63,600 ft^3/sec) occurs during March, April, and May, and coincides with spring warming. Lowest total flows occur during August when *evapotranspiration* is the greatest. (Evapotranspiration is the combined loss of water during a specified period of time by evaporation from the soil or water surface and by transpiration from plants.) A secondary maximum discharge occurs in December probably in response to decreased evapotranspiration.

The principal minimum mean discharge of the Raritan River occurs about one month after the minimum discharge of the Hudson and Passaic rivers (Figure 7). The difference in the discharge of the Raritan River may be explained by geography and differences in the relative amounts of snow received by the drainage basins (J. Murphy, US Geological Survey, personal communication). In the Raritan Basin, which is more southern and closer to the coast, snowfall is relatively light when compared to the Passaic and Hudson basins. The first discharge peak of the Raritan River occurs January-February and is probably due to melting snow. Accumulations of snow in colder Passaic and Hudson basins are greater, and it is not until the general spring warming that this



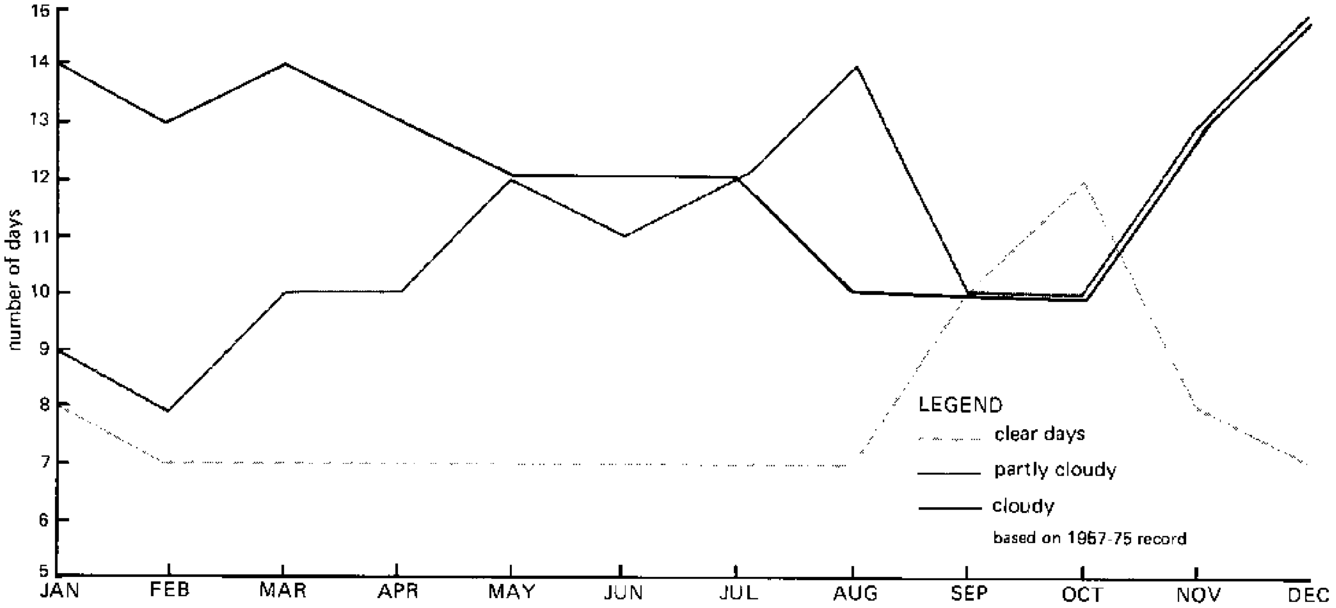
Source: NOAA 1975a

Figure 2. Monthly wind speed and direction at Kennedy Airport



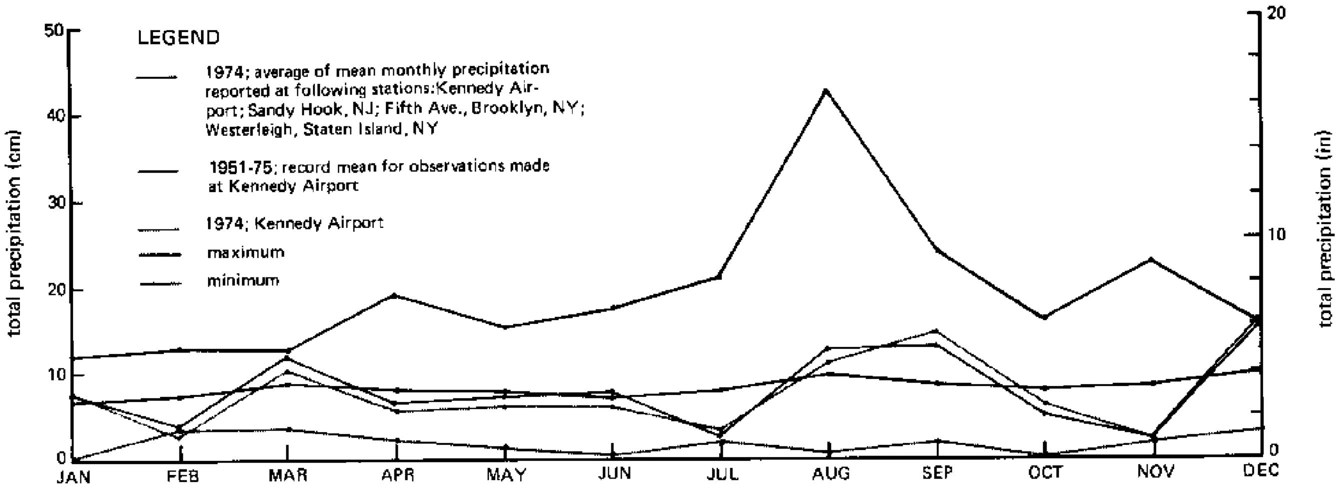
Source: NOAA 1975a

Figure 3. Daily wind speed and direction at Kennedy Airport



Source: NOAA 1975a

Figure 4. Number of clear, partly cloudy, and cloudy days per month at Kennedy Airport



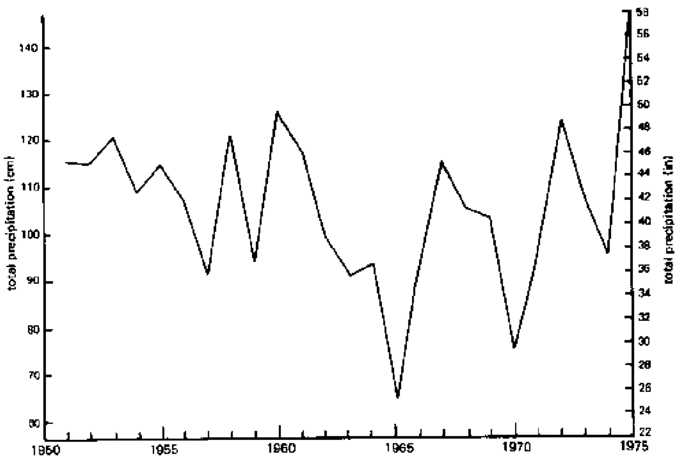
Source: NOAA 1975a

Figure 5. Variation in mean monthly total precipitation (rain and snow) at Kennedy Airport

precipitation is melted, leading to the observed peak mean discharges for the Hudson and Passaic rivers in March and April. A second and third peak in the Raritan River discharge, occurring in the April-May to June-July period and followed by the annual minimum discharge, are caused by late spring rains and thunderstorms.

The seasonal impact of river flow on the salinity of the Bight apex can be demonstrated by comparing discharge with surface salinity. Figure 8 shows a six-year record of two month running means of surface salinity observed at Ambrose Tower, and total freshwater discharge from rivers. Peak river flows during spring warming correspond to rapidly decreasing salinities. Minimum salinity occurs about one month after the peak discharge. This lag could be interpreted as a crude estimate of the time required for Hudson River waters at the main gauging station at Green Island (near Albany) to move to Ambrose Tower in the apex—a distance of about 240 km (130 nmi). Tides affect the flow of the Hudson all the way to Green Island. Weyl (1976) found that the peak discharge of fresh water entering Long Island Sound also leads the salinity minimum by about one month; here the principal source of fresh water is the Connecticut River, tidal all the way to Hartford.

Large fluctuations also exist in the annual mean flows of the Hudson, Raritan, and Passaic rivers. Figure 9 shows the presence of the drought that began in 1961 and ended in 1970. In 1965 there was a dramatic decrease in discharge of the Hudson and Passaic rivers. Low freshwater discharge decreases flushing of the bay complex.

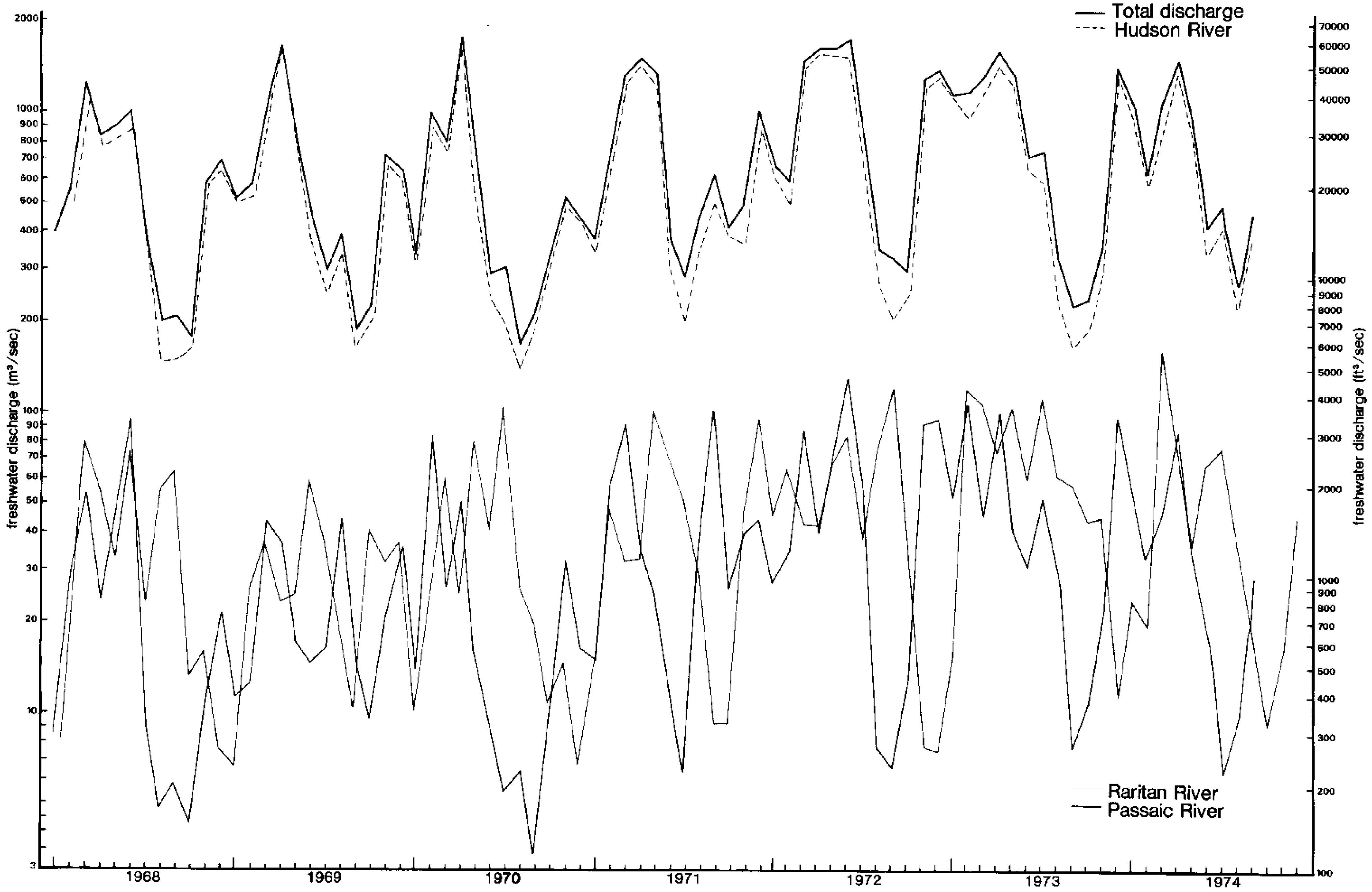


Source: NOAA 1975a

Figure 6. Variation in mean annual precipitation (rain and snow) at Kennedy Airport

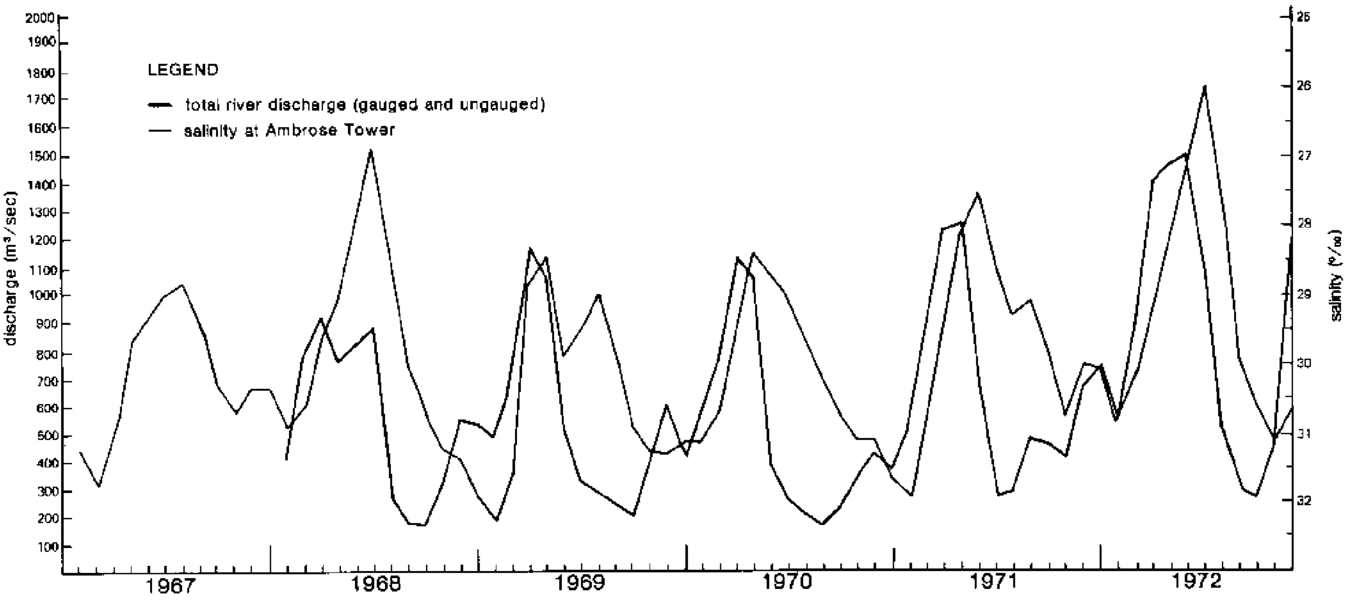
In addition to riverine inputs, the bay complex receives fresh water from rain and snow (Figures 5 and 6). During the winter, total precipitation exceeds evaporation; in the summer, evaporation is greater than precipitation. Because of the many sources of heat in the bay complex, it is difficult to make an accurate estimate of the heat budget in order to calculate the evaporative loss of water in the bay complex. However, assuming that annual evaporation is about one-half the annual input of total precipitation for the bay complex, the net (annualized) freshwater input from precipitation amounts to about 4.3 m^3/sec (152 ft^3/sec).

The bay complex also receives a considerable volume of fresh water from sewage effluent and city street runoff (Figure 9). Data from sewage treatment records indicate that about 60 m^3/sec (2,120 ft^3/sec) of treated and untreated effluent are discharged into



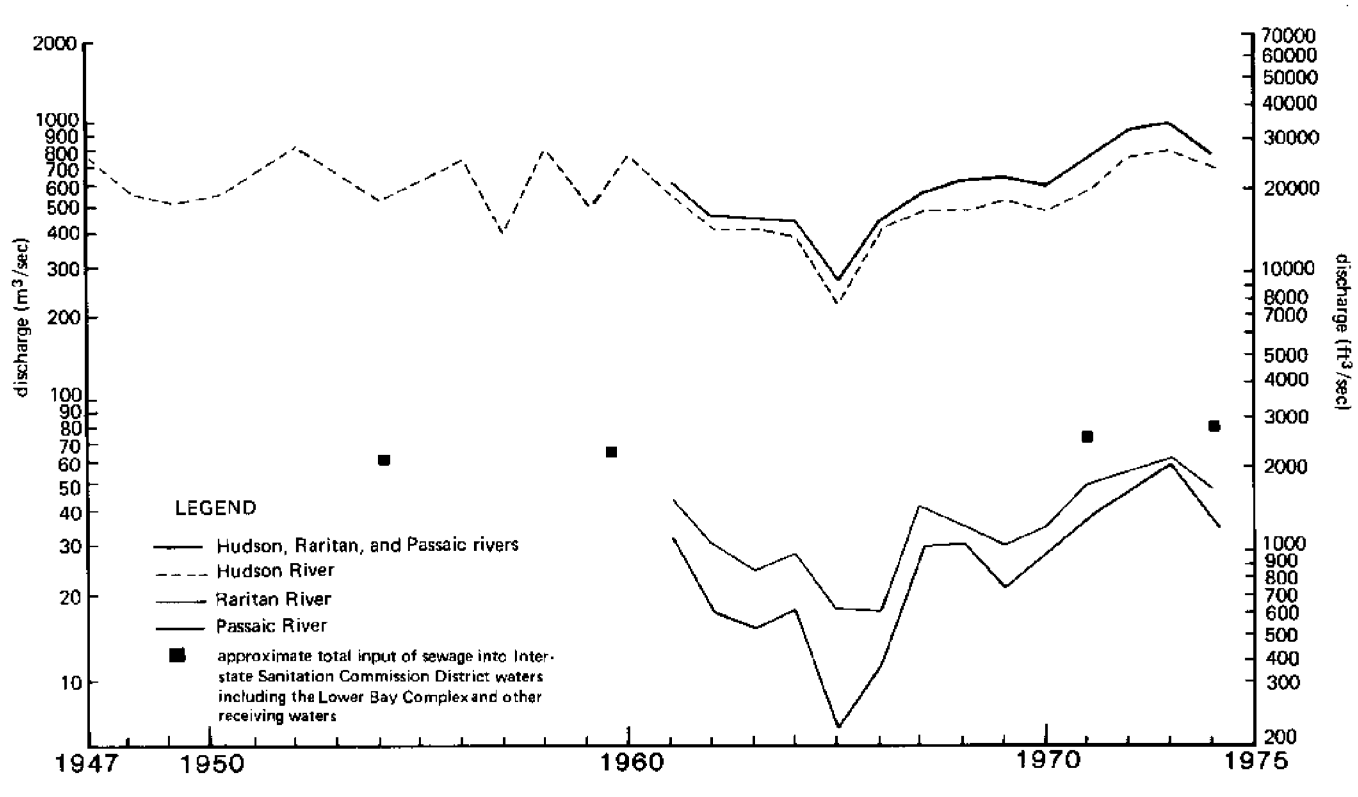
Sources: US Geological Survey 1969, 1970, 1971, 1972, 1973, 1974, 1975a, undated

Figure 7. Monthly discharge of Hudson, Raritan, and Passaic rivers



Sources: US Geological Survey 1968, 1969, 1970, 1971, 1972, 1973, undated; Chase 1969, 1971a,b,c, 1972; Kangas 1973, 1974

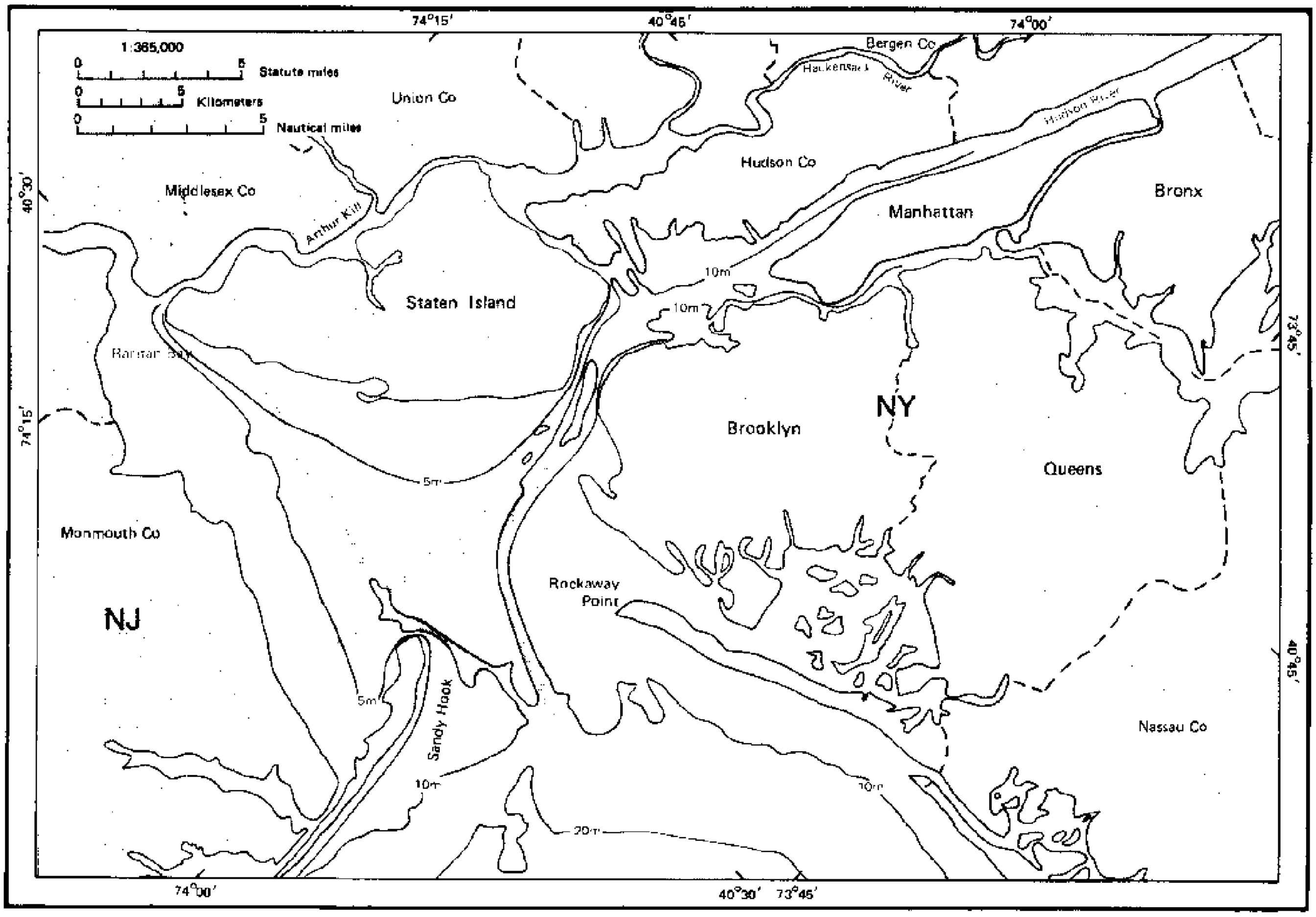
Figure 8. Surface salinity at Ambrose Tower (see Map 1) and river discharge



Sources: US Geological Survey 1962, 1963, 1964, 1965, 1967, 1968, 1969, 1970, 1971, 1972, 1973, 1974, 1975a,c, undated; Interstate Sanitation Commission 1974; Thomas Glenn, Interstate Sanitation Commission, personal communication

Figure 9. Annual mean discharge of Hudson, Raritan, and Passaic rivers into Lower Bay complex

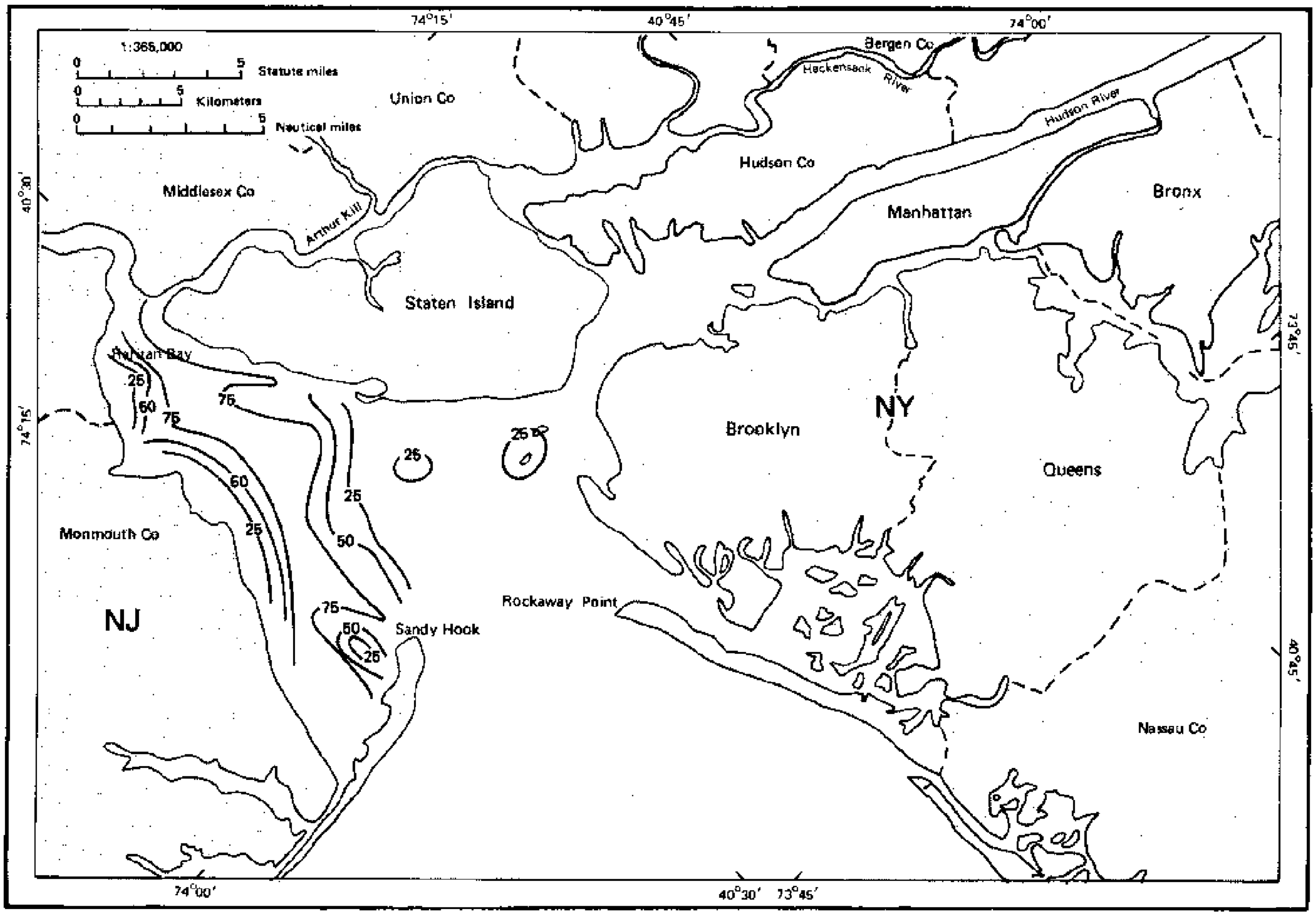
Map 2. Bottom features of Lower Bay complex



Source: Fray 1969

Transverse Mercator Projection

Map 3. Percent silt in Raritan Bay



Source: Fray 1969

Transverse Mercator Projection

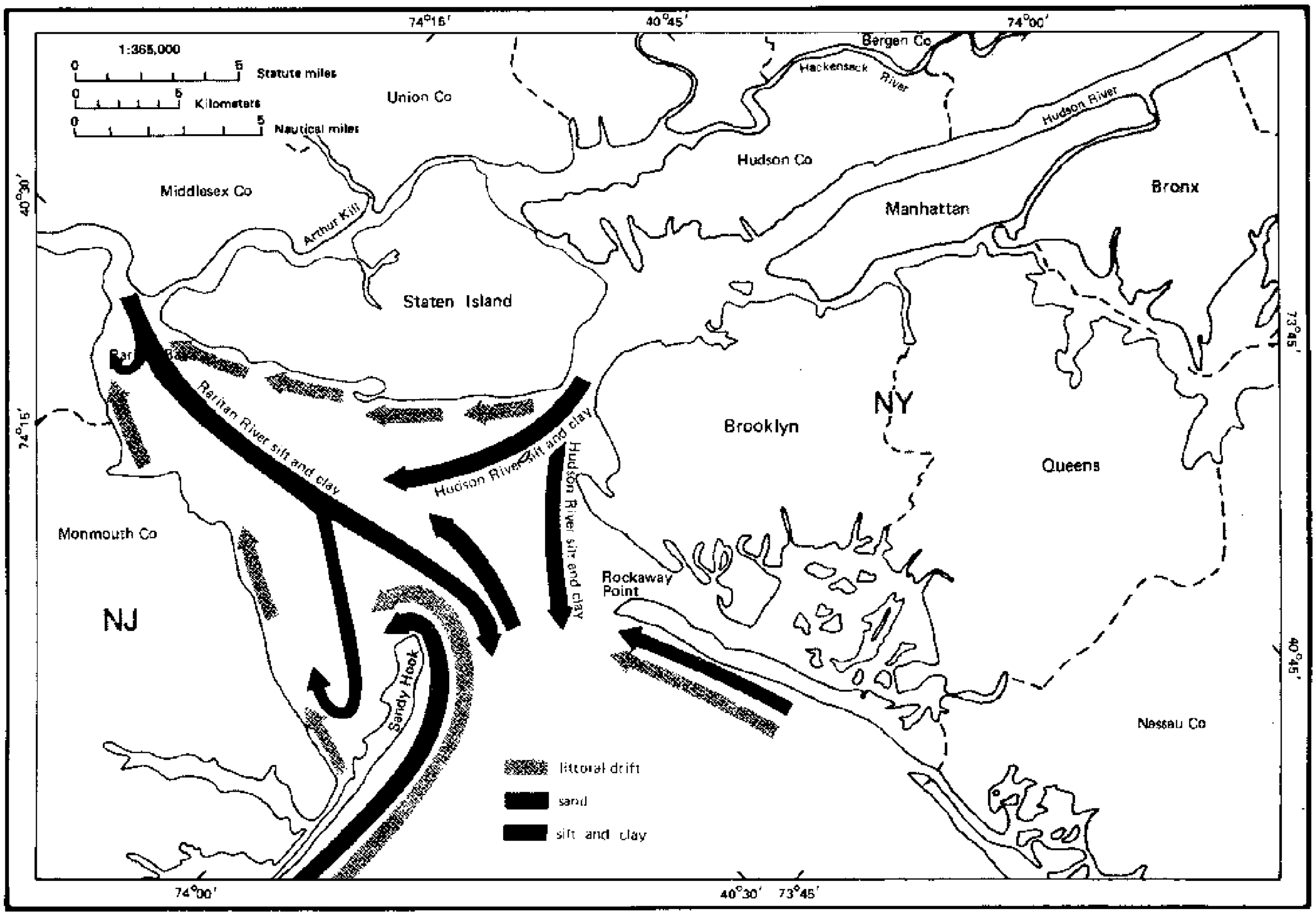
the local waters surrounding the New York metropolitan area (Interstate Sanitation Commission 1974; T. Glenn, Interstate Sanitation Commission, personal communication). Thus, sewage effluent is a major source of fresh water during periods of reduced riverine input.

The impact of runoff from city streets during and immediately after a heavy rainfall is difficult to assess because of the combined sewer overflow system used in the New York metropolitan area. In this overflow system, untreated sewage, other wastes, and street runoff are combined in the same sewer line. During heavy rainfall, the volume of these combined wastes exceeds the hydraulic capacity of the treatment plants. Under this condition, the combined load is intercepted at regulator stations throughout the metropolitan area, then diverted directly to local receiving waters.

To assess the adverse impact of this combined sewer overflow system, the Interstate Sanitation Commission (ISC) (1972) conducted two 24-hour dry and wet weather sampling surveys of the interceptor regulators at the Newtown Creek (Brooklyn and Queens) and the Bayonne, NJ, sewage treatment drainage basins. In the ISC survey, heavy rainfall flows to the treatment plant or to receiving waters were estimated at three-hour intervals. Samples of sewer waters at the regulators were also taken at three-hour intervals and analyzed for various dissolved and particulate contaminants.

ISC results showed that within a short period of time heavy rainfall can produce at least an order of magnitude increase in the flow rate of wastes entering receiving waters and a 20-fold increase in the concentration of suspended solids. At one regulator, the quantity of total suspended solids discharged over a nine-hour period was 16% of the total suspended solids discharged for the entire month. Concentrations of other contaminants, such as oil and greases, were also measured by ISC and found to be greater in wet weather grab samples. The results demonstrated that the frequency, intensity, and duration of episodic rain storms have significant effects on the concentrations of pollutants entering the receiving waters.

Map 4. Idealized sediment transport in Lower Bay complex



Source: Fray 1969

Transverse Mercator Projection

Bottom Topography

The Lower Bay complex is relatively shallow (5 to 20 m or 16 to 66 ft) but has an irregular submarine topography composed of numerous shoals, banks, and ship channels (Maps 1 and 2). These features were best described by Fray (1969). For instance, West Bank, extending south from Fort Wadsworth, has water depths over it from 0.3 to 5 m (1 to 16 ft). From just south of Fort Wadsworth, a dredged channel 1.5 to 3.3 m (5 to 11 ft) deep extends south to Swinburne and Hoffman islands, artificial islands built on West Bank (Map 1).

Sandy Hook Bay is more than 9 m (30 ft) deep off the northern tip of Sandy Hook but shoals gradually south to a depth of about 2 m (6 ft), 0.3 to 1.3 km (0.17 to 0.72 nmi) offshore. Raritan Bay is less than 5.5 m (18 ft) deep except for a small area at the eastern end of the bay and the dredged channels. Hammon (1976) provides a detailed description of New York Harbor's dredged channel system.

Sediment

The physical character and regional distribution and composition of the surface sediments (top few centimeters) of the bay complex were also reported by Fray (1969). Bottom sediments in Raritan Bay are primarily silts (Map 3). In Lower Bay the bottom sediments are mainly sands and gravels. The organic carbon content of the sediment is between 0.1% and 6.2%; higher percentages are found near the head of Raritan Bay and lower percentages in Lower Bay.

The origin of the bottom surficial sediments has not been clearly identified, and no one has yet attempted to work out the suspended sediment budget of New York Harbor (D. Swift, personal communication). It is likely that Sandy Hook, Raritan and Hudson rivers, the Arthur Kill, and the Bight apex represent possible significant sources of sediment for the bay complex (Map 4).

According to Fray (1969), the rate of sedimentation in Raritan Bay has been particularly small for the past 100 years. The only major accumulation takes place in dredged channels. Thus, there is little sand to supply undernourished Raritan Bay beaches.

Tidal Characteristics

The distribution of water properties in the Lower Bay complex is complicated because of seasonal variation in river discharge and because of the intricate connection of bays, rivers, and tidal passages. Rapid river flows tend to keep to the right, due to the earth's rotation and resulting *Coriolis acceleration* —the apparent force from the earth's rotation, turning moving bodies right in the Northern Hemisphere. Water periodically moves up and down with the tides. Tidal currents move water back and forth, and the turbulence associated with this movement causes mixing. Estuarine circulation, the accelerated inflow of salt water along the lower layer of an estuary as a result of the seaward movement of fresh water, superimposes a nontidal circulation on these various tidal movements. Transient winds increase the variability in direction and intensity of water movement and increase water column mixing.

The tides (Figure 10) in the bay complex are *semidiurnal*, that is, the tide rises and falls twice daily, and the tidal currents (Figure 11) reverse direction four times daily. Figure 10 compares tides observed 1-9 February 1974 at Sandy Hook and The Battery. The record shows that the tide varies from day-to-day but the *diurnal* (daily) inequality—the difference between successive highs or lows at a tide station—is relatively small. Minimum diurnal inequality is a characteristic of most east coast tides. The results (Figure 10) also show that the range in the tide at Sandy Hook is nearly the same as that observed at The Battery. The time of high or low tide at Sandy Hook occurs slightly before high or low tide at The Battery.

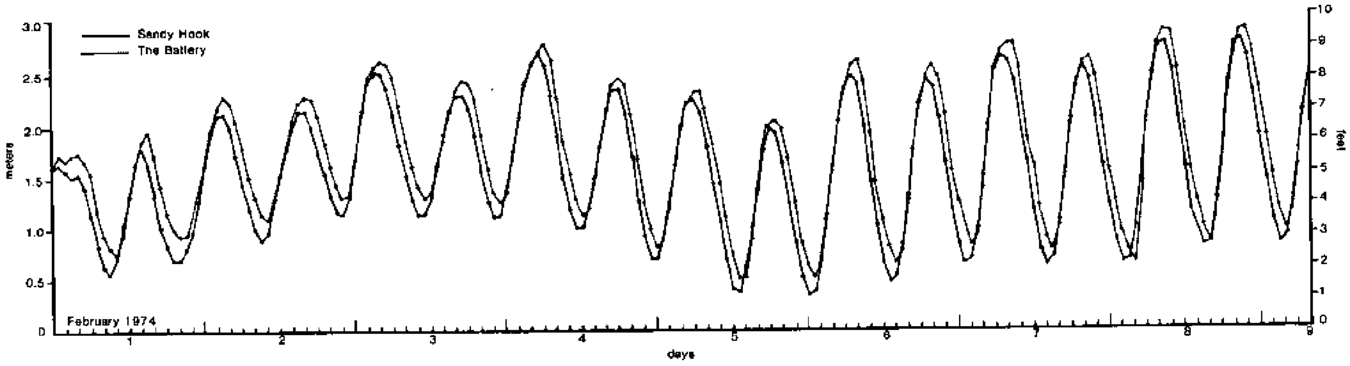
Figure 11 shows observed and mean tidal currents near Sandy Hook for the period 21-25 May 1958, the last time the currents in Lower Bay were measured in any systematic way. Twice daily the speed of the current goes to zero, a condition of slack water. The observed record shows considerable short-term irregularities due to nontidal effects such as winds. In the smooth curve (Figure 11), the mean strength of the current at peak ebb is greater than that observed at peak flood. This is due to the riverine inflow which in effect tries to push back the flooding seawater.

Under normal conditions the mean range, *spring range* (tide having the greatest rise and fall), and *neap range* (tide having the least rise and fall) can be accurately predicted from previous years of daily tide observations. The National Oceanic and Atmospheric Administration (NOAA) maintains tide stations at The Battery, Coney Island, Sandy Hook, and Ambrose Tower (Swanson 1976). Table 1 gives the tidal ranges for specific locations in the Lower Bay complex (NOAA 1975*b*); the mean tidal range is 1.4 to 1.5 m (4.6 to 4.9 ft) and the spring range is 1.7 to 1.8 m (5.6 to 5.9 ft).

Table 1 also indicates that high or low water occurs everywhere in the bay complex within about 20 minutes. However, tidal currents advance at different rates in different regions of the bay complex; times of high and low water do not follow times of slack water. In Map 5, the rapid rate of advance of the slack water on the north and south ends of the Sandy Hook-Rockaway Point transect demonstrates the strong influence of the Hudson River, which retards the advancing tidal current in Lower Bay. A comparison of Map 5 with the tidal range data in Table 1 shows that while only three to five minutes are required for high or low tide to pass from the Sandy Hook-Rockaway Point transect to The Narrows, slack water arrives at The Narrows about 1 hour 40 minutes after it passes through the Sandy Hook-Rockaway Point transect. Concurrently, slack water entering shallow Raritan Bay moves very rapidly across Lower Bay. However, the rate of advance of slack water into Sandy Hook Bay is greatly reduced.

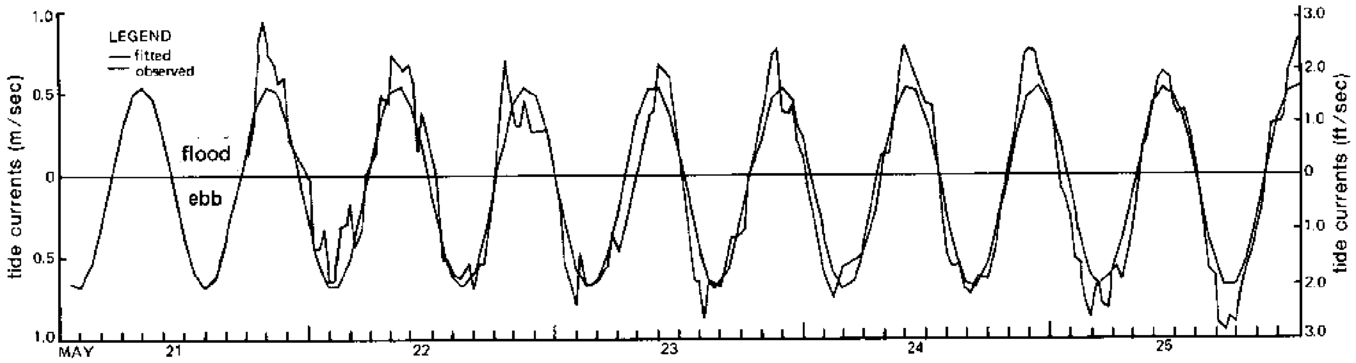
The complicated relationships between tides and tidal currents are due largely to the effects of river discharge, bottom topography, and the landshapes bordering the bay complex (Marmer 1935).

Since tidal currents, present in the entire water column, are primarily responsible for the circulation and flushing of the bay complex, the direction and velocity of tidally moved water during a tidal cycle



Source: National Ocean Survey, unpublished tide height records

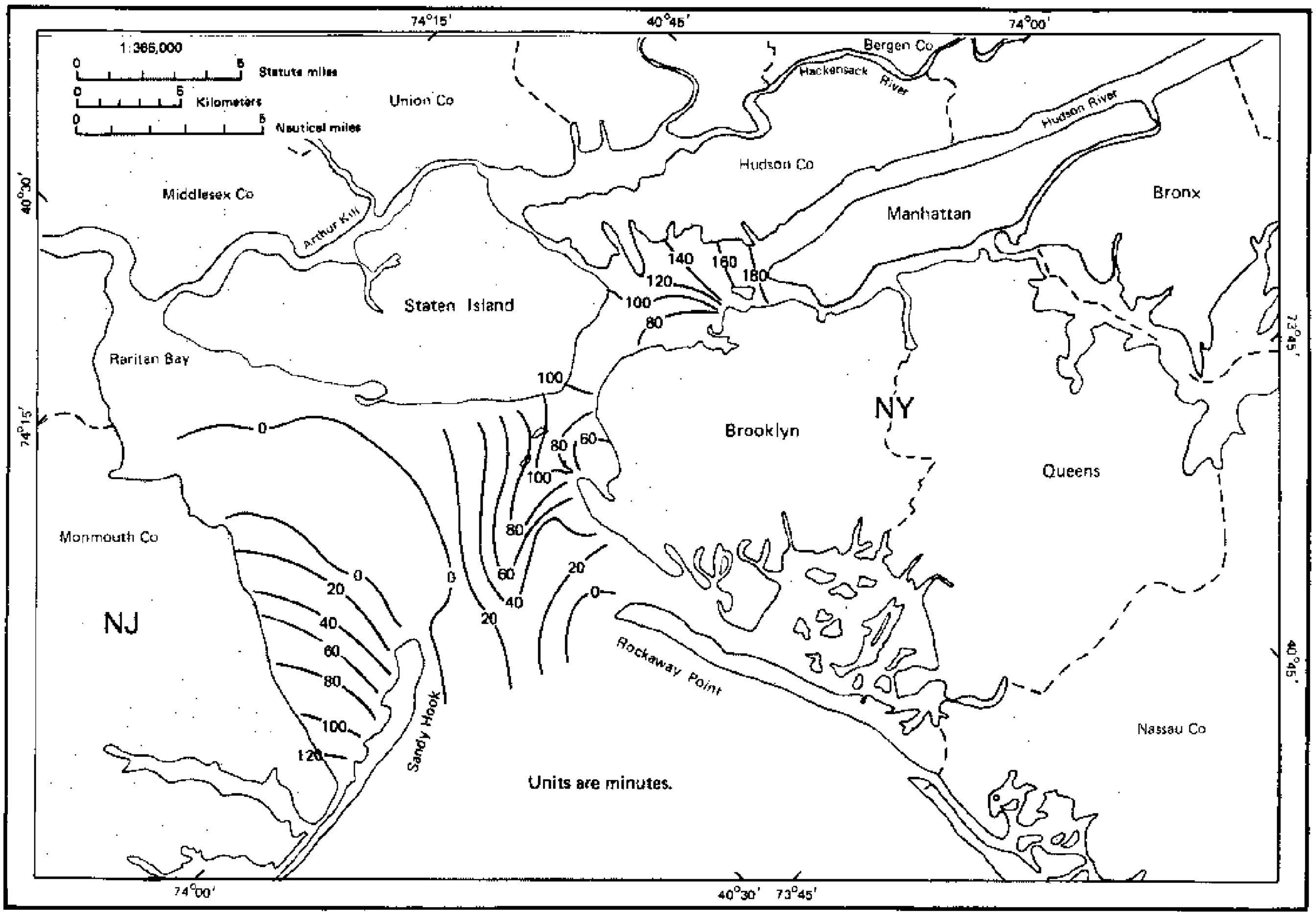
Figure 10. Observed tidal height 1-9 February 1974 at Sandy Hook and The Battery tide stations



Source: National Ocean Survey, unpublished current meter records

Figure 11. Observed and averaged tidal currents May 1958 along Sandy Hook-Rockaway Point transect

Map 5. Rate of advance of slack water



Units are minutes.

Source: NOAA 1975c

Transverse Mercator Projection

Table 1. Mean values of range and times of high and low water in 1976

Station[a]	Lat	Long	Mean Range		Spring Range		Greenwich[b] High Water Interval		Greenwich[b] Low Water Interval		Relative Time[c] of High or Low Water	
			m	ft	m	ft	hr	min	hr	min	Low Water min	High Water min
1 *Sandy Hook*	40°28'	74°01'	1.40	4.6	1.71	5.6	12	42	6	42	0	0
2 Atlantic Highlands	40°25'	74°02'	1.43	4.7	1.74	5.7	12	42	6	42	−1	0
3 Keyport	40°26'	74°12'	1.52	5.0	1.83	6.0	12	54	7	00	8	19
4 South Amboy	40°29'	74°17'	1.52	5.0	1.83	6.0	12	48	7	00	5	15
5 Great Kills Harbor	40°33'	74°08'	1.43	4.7	1.74	5.7	12	54	7	00	7	19
6 St. George	40°39'	74°04'	1.37	4.5	1.65	5.4	13	00	7	00	23	22
7 *The Battery*	40°42'	74°01'	1.37	4.5	1.65	5.4	13	24	7	18	44	40
8 Fort Hamilton	40°37'	74°02'	1.43	4.7	1.74	5.7	12	48	6	48	3	5
9 *Coney Island*	40°34'	73°59'	1.43	4.7	1.74	5.7	12	42	6	24	−3	−19

Italicized stations are only stations for which tide data are taken; others are locations for which predictions are made in tide tables based on past data.

[a] Refer to Map 1 for station locations

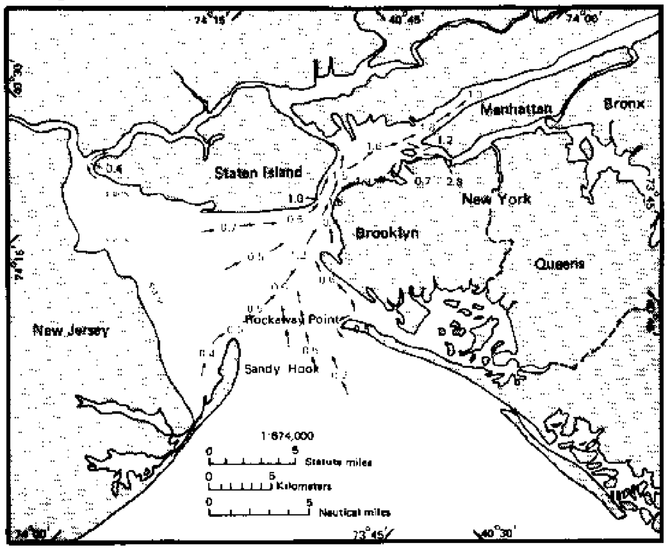
[b] Greenwich interval is the time of high or low water after the moon crosses the Greenwich meridian (Swanson 1976).

[c] Relative times of high or low water are referenced to the Sandy Hook tide station.

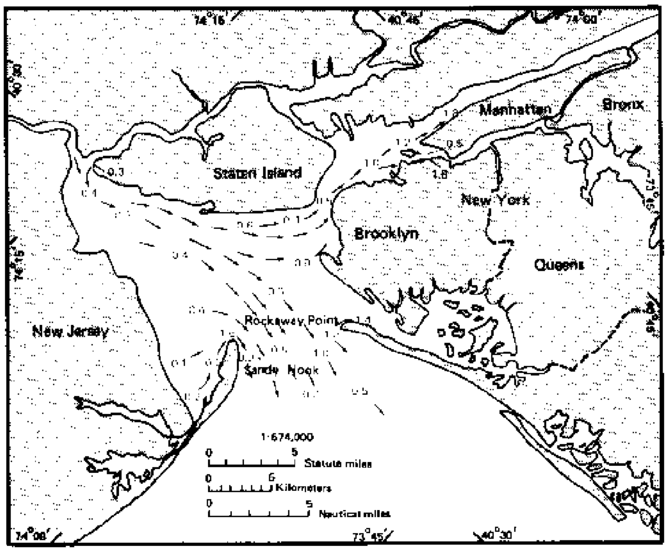
Source: Swanson 1976

Map 6. Tidal currents (knots)

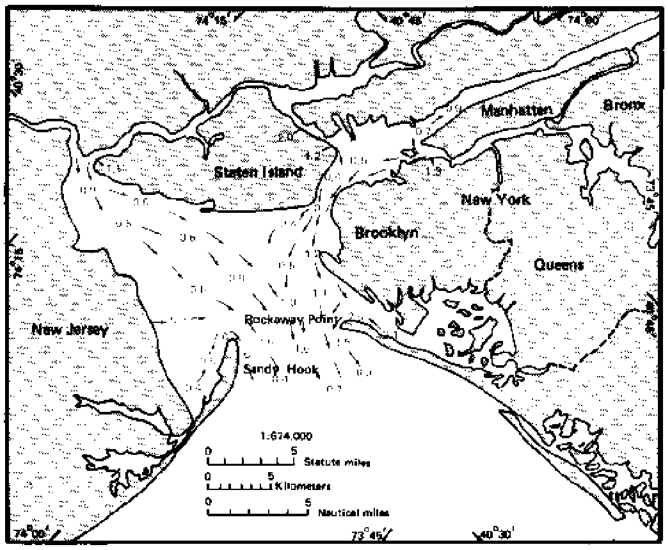
A. High Water



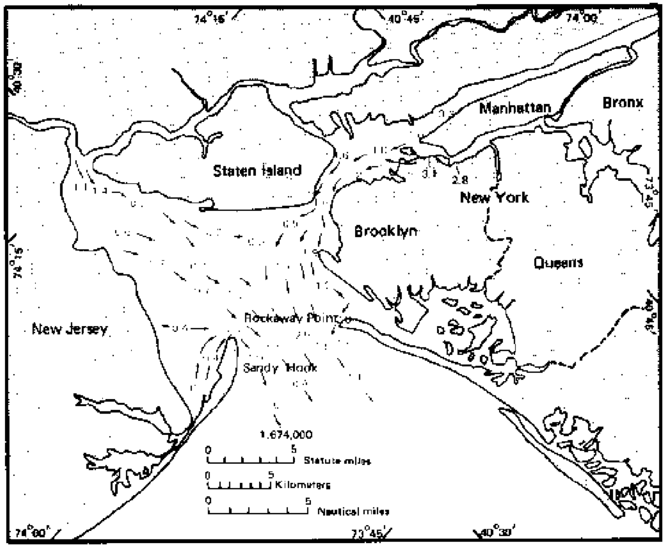
B. One Hour after High Water



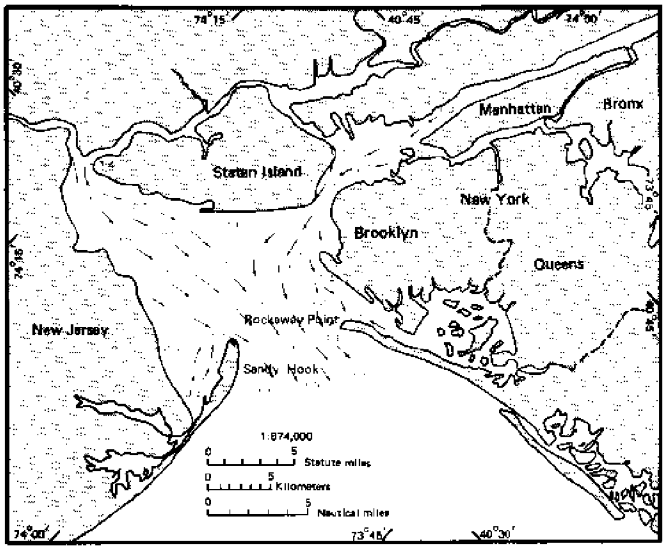
C. Two Hours after High Water



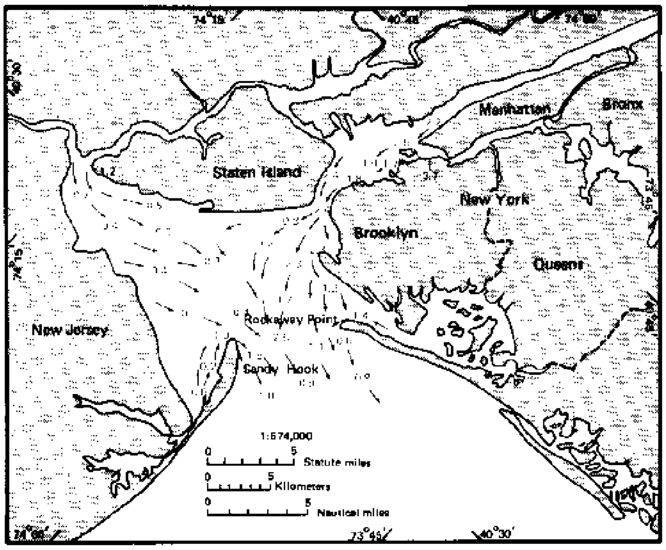
D. Three Hours after High Water



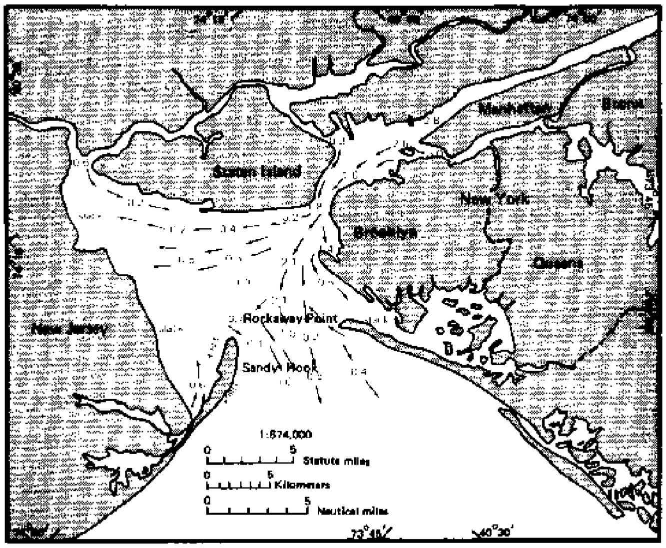
E. Four Hours after High Water



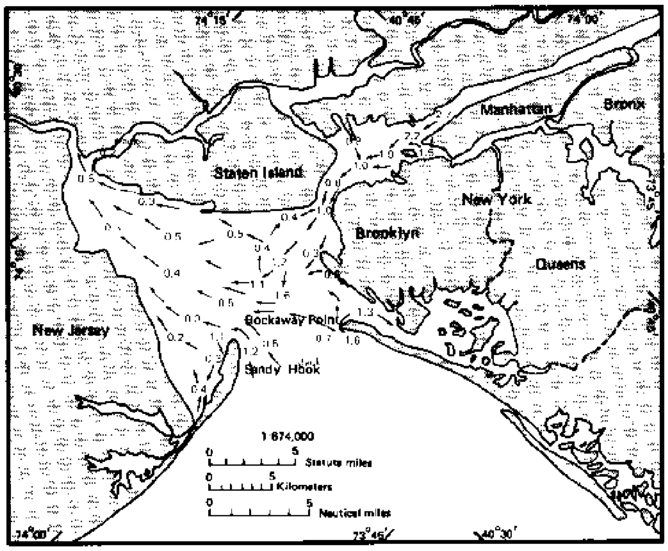
F. Five Hours after High Water



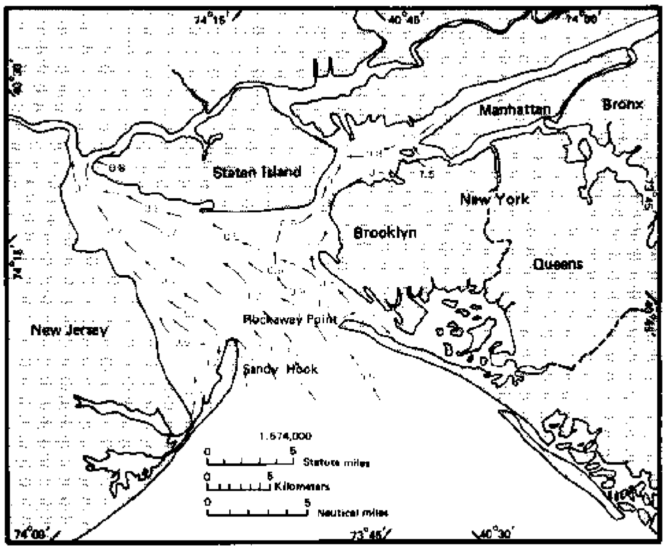
G. Low Water



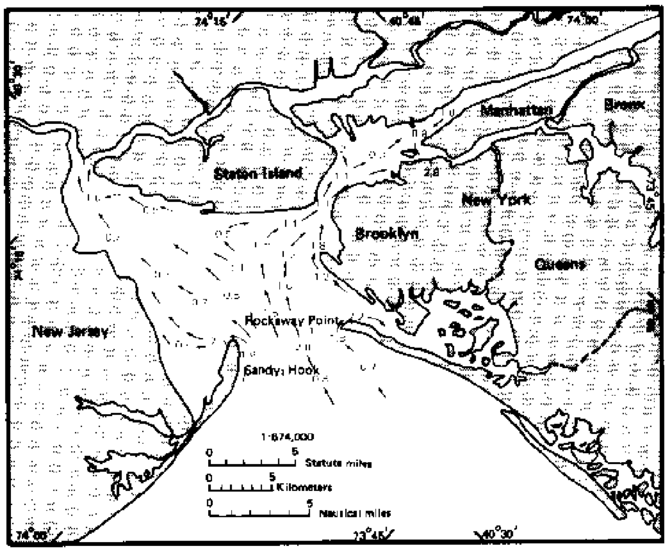
H. One Hour after Low Water



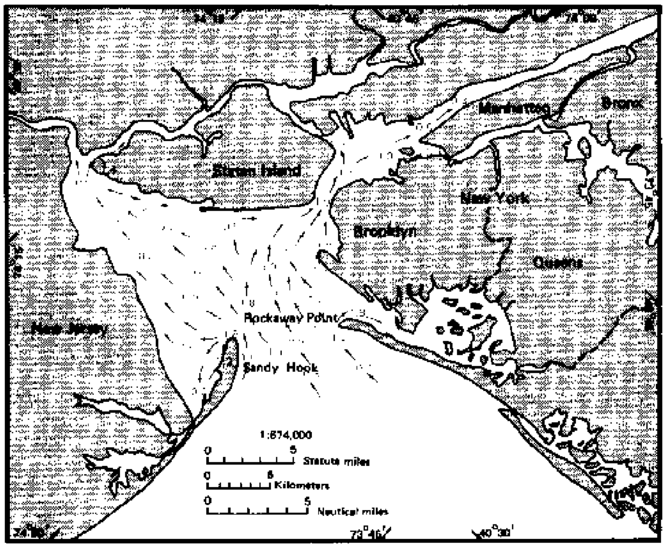
I. Two Hours after Low Water



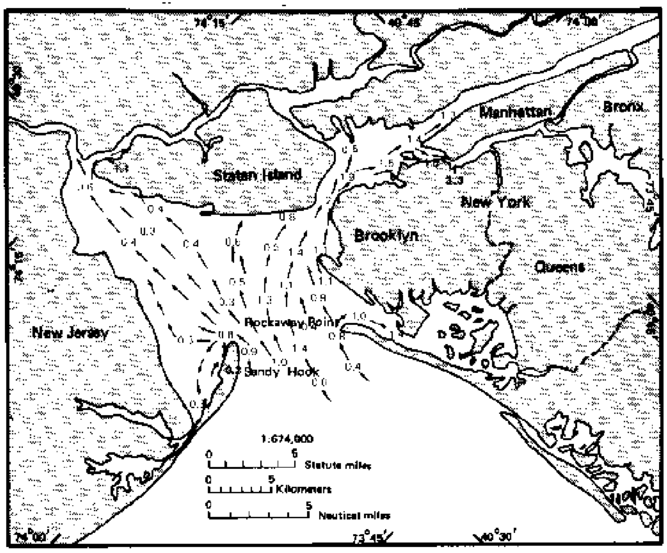
J. Three Hours after Low Water



K. Four Hours after Low Water



L. Five Hours after Low Water



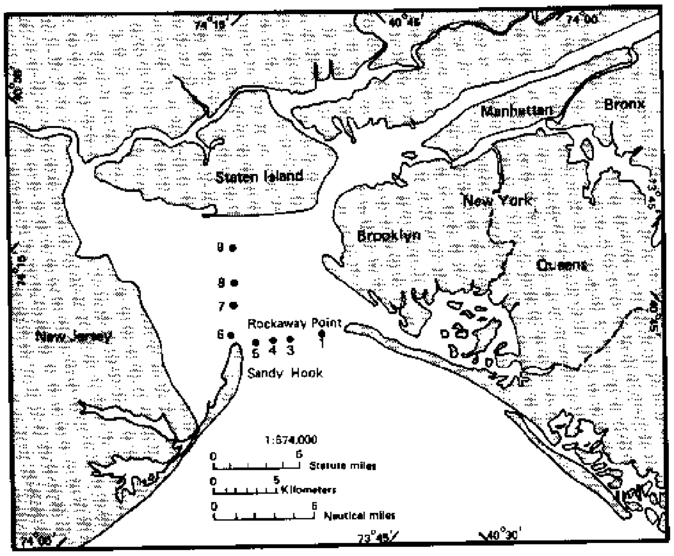
Transverse Mercator Projection

Source: Coast and Geodetic Survey 1956

Table 2. Tidal velocities, durations, and excursions in Lower Bay

Station	Depth (m)	Ebb Current Velocity m/sec	Ebb Current Duration (hr)	Ebb Current Excursion (km)	Flood Current Velocity m/sec	Flood Current Duration (hr)	Flood Current Excursion (km)
1	1.4	0.606	5.9	8.2	0.732	6.5	10.9
	4.1	0.568	5.9	7.7	0.652	6.5	9.7
	6.4	0.433	5.8	5.7	0.549	6.6	8.3
3	1.7	0.897	6.7	13.8	0.671	5.7	8.8
	5.0	0.830	6.7	12.7	0.652	5.7	8.5
	8.2	0.811	6.4	11.9	0.491	6.0	6.8
4	2.4	0.617	6.1	8.6	0.635	6.3	9.2
	4.9	0.583	6.4	8.6	0.529	6.0	7.3
5	2.3	0.635	6.8	10.7	0.540	5.6	6.9
	6.8	0.630	6.5	9.4	0.574	5.9	7.8
	11.4	0.289	5.0	3.3	0.559	7.4	9.4
6	1.5	0.701	7.0	11.2	0.457	5.4	5.7
	4.2	0.599	5.8	8.0	0.709	6.6	10.7
	6.7	0.527	5.2	6.3	0.753	7.2	12.4
7	2.2	0.195	5.1	2.3	0.339	7.3	5.7
	4.5	0.103	5.0	1.2	0.253	7.4	4.3
8	1.7	0.129	5.1	1.5	0.265	7.3	4.4
	3.4	0.031	2.7	0.2	0.225	9.7	5.0
9	1.5	0.081	—	—	0.263	12.4	7.5
	3.0	0.107	—	—	0.221	12.4	6.3

Locator



Source: National Ocean Survey, unpublished current meter records can be traced hourly. Map 6 shows tidal current directions and velocities taken from tidal current charts for New York Harbor (Coast and Geodetic Survey 1956). The tidal current velocities are for the time of spring tides, thus the currents are stronger than average.

When high water reaches The Battery (Map 6A) the northward flowing tidal currents are at their maximum velocities (2.8 to 3.5 km/hr or 1.5 to 1.9 knot) within The Narrows and the Hudson, where the movement of the tidal stream is constricted. Slack water is observed at this time within Raritan and Jamaica bays. One hour following high water (Map 6B), the tidal currents flow seaward out of Raritan Bay except for a shoreward flow through The Narrows and up the Hudson. Two hours after high water, all the tidal currents flow seaward (Map 6C). Maximum current velocities of 3.2 to 4.4 km/hr (1.7 to 2.4 knot) occur in the Hudson and The Narrows five hours following high water (Map 6F). When low water reaches The Battery (Map 6G), a tidal current pattern similar to that observed at high water (Map 6A) occurs, except that the flow is into Raritan Bay or seaward. One hour following low water at The Battery (Map 6H) the tidal currents have turned in the Sandy Hook-Rockaway Point transect and flow shoreward and into Raritan Bay. Currents emanating from The Narrows continue to flow seaward. Two to five hours following low water all the tidal currents flow shoreward into Raritan Bay and up the Hudson (Maps 6I–L).

For many parts of the bay complex, ebb currents for surface waters are greater and have a longer duration than flood currents. (Compare the velocities in Map 6E with those in Map 6H.) Conversely, in deep waters ebb currents are weaker and of shorter duration than flood currents. These inequalities between ebb and flood currents are due to freshwater inflow (river discharge) and aid in flushing the bay complex. The distance a parcel of water travels during flood or ebb, *tidal excursion*, can be approximated. Table 2 shows calculated tidal excursions for selected stations in Lower Bay.

Tides and tidal currents are related parts of the same phenomenon—the movement of the oceans caused by the attraction of the moon and sun. Swanson (1976) described the propagation and range of tides in New York Bight, including the bay complex. Marmer (1935), in his classic study of the tides and currents of New York Harbor, gave a comprehensive account of all aspects of tidal phenomena in the harbor. Storm surges can also greatly influence the normal character of tides and tidal currents, as discussed by Pore and Barrientos (1976).

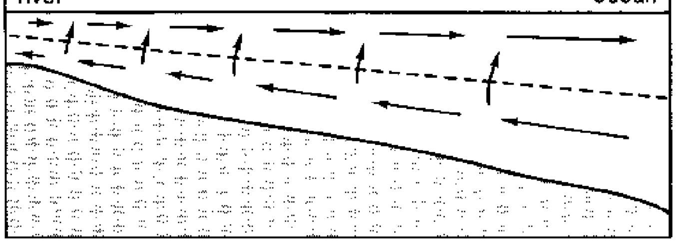
Nontidal Circulation Patterns

Nontidal currents in the Lower Bay complex are maintained primarily by the freshwater inflow of the Hudson and Raritan rivers (Figure 7). Because the bay complex is broad and shallow, surface wind stress and spatial structure of the tidal currents can also affect nontidal current patterns. These patterns are spatially complex and can change considerably with time due to variations in wind and freshwater inflow. Present knowledge of nontidal circulation patterns within the bay complex is based on current observations from a number of old National Ocean Survey studies described by Abood (1972). A more detailed picture of this circulation must await a comprehensive modern survey.

The bay complex exhibits many features characteristic of an estuary; there is both tidal action and a dilution of seawater by river discharge. In a typical estuary, horizontal density gradients—caused by salinity gradients—are established by the freshwater input at the head of the estuary (Pritchard 1952, 1954, 1956). Gravitational forces associated with these gradients maintain a net circulation in which the upper, less saline layer moves seaward and the lower, more saline layer moves up the estuary (Figure 12). As the bottom saline water flows upstream it mixes vertically and becomes entrained in the overlying waters to be carried seaward. Individual volume transports of waters in the upper and lower layers can, therefore, be much greater than the river flow.

In the lower Hudson estuary, a two-layer flow is well developed (Abood 1972; Overland 1973). The vertical section of nontidal currents at The Narrows in Figure 13 illustrates the seaward flow in the surface layers and upriver flow at depth. Because of Coriolis acceleration the boundary between the two layers of net flow has a lateral slope, deeper on the right side of the estuary (looking downstream) than on the left. Figure 13 also illustrates the nontidal flow structure within the Sandy Hook-Rockaway Point transect where inflow occurs at depth within the Sandy Hook and Ambrose channels and at all depths on the Rockaway Point side of the transect. According to Doyle and Wilson (in press) this structure is well described by: 1) a lateral momentum balance between Coriolis acceleration due to the nontidal flow; 2) centripetal accelerations associated with tidal currents within the transect; and 3) the lateral pressure gradient due to the increase in density toward the Rockaway Point side of the transect. Because of bottom topography and channel configurations (Map 2), inflow of seawater through Ambrose Channel proceeds upstream through The Narrows, and much of the inflow through Sandy Hook Channel proceeds into Raritan Bay (Map 7). Inflowing waters at the right side of the transect flow northwestward and mix laterally with seaward flow from The Narrows.

Raritan Bay contributes another estuarine system. Freshwater discharge from the Raritan River produces east-west salinity gradients that drive an estuarine circulation consisting of a modest flow of saline waters westward at depth. These waters enter Lower Bay through Sandy Hook Channel and remain confined to the channel as they flow westward. Some saline waters may also enter Raritan Bay through Chapel Hill and Swash channels (Map 2 and Figure 14A). In addition to these deep flows, there is a seaward drift of fresh water confined to the south side of Raritan Bay; it is separated horizontally from the westward flow of slightly more saline waters. This structure is characteristic of many wide estuaries and is a result of Coriolis acceleration. Circulation in Raritan Bay is described in more detail by Ayers, Ketchum, and Redfield (1949).



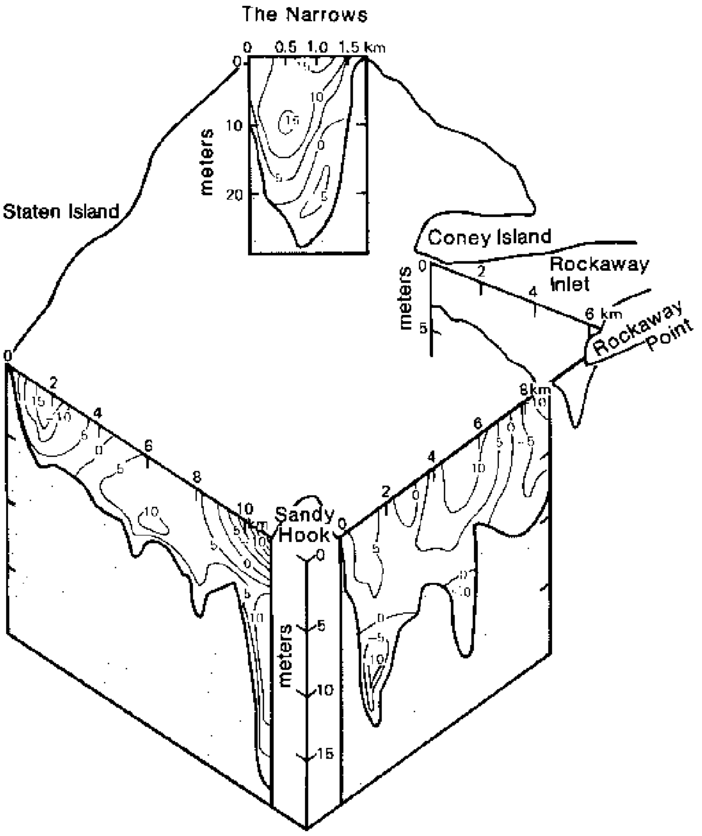
Source: Bowden 1975

Figure 12. Estuarine circulation

The intensity of the estuarine circulation within the bay complex depends on the magnitude of horizontal salinity gradients and, therefore, on the magnitude of freshwater inflow. Nontidal circulation is most intense during high flow periods in late winter and spring and least intense during low flow periods in late summer. Winds primarily from the northwest in winter and from the southwest in summer can also affect nontidal circulation patterns.

Maps 7A and B present an idealized picture of nontidal circulation in Lower Bay based on current observations from numerous surveys described by Abood (1972). Map 7A shows that south of Old Orchard Shoal (Map 1), outflow from The Narrows is deflected to the right by Coriolis acceleration into the north central part of Raritan Bay. Some of this water penetrates into Raritan Bay where it mixes and becomes part of the westward drift. There is also some evidence that Old Orchard Shoal (Map 1) produces a blocking effect and causes flow to the northeast along Staten Island. Map 7B shows that deep estuarine flow is primarily confined to deep channels (Map 2).

Nontidal current (cm/sec)



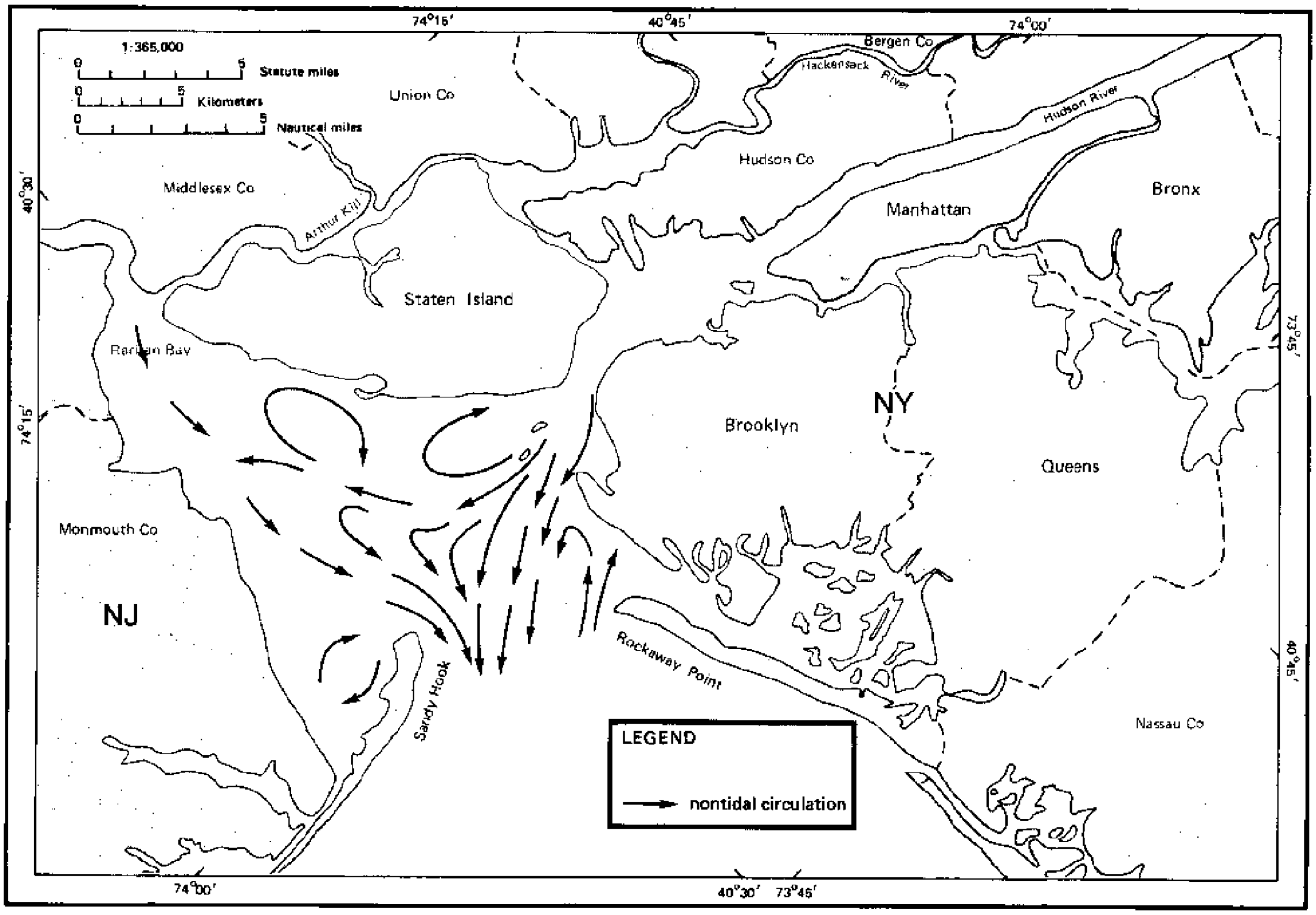
Note: (—) currents are moving into the section. Current meter data are unavailable for Rockaway Point - Coney Island transect.

Source: Parker 1976

Figure 13. Nontidal current

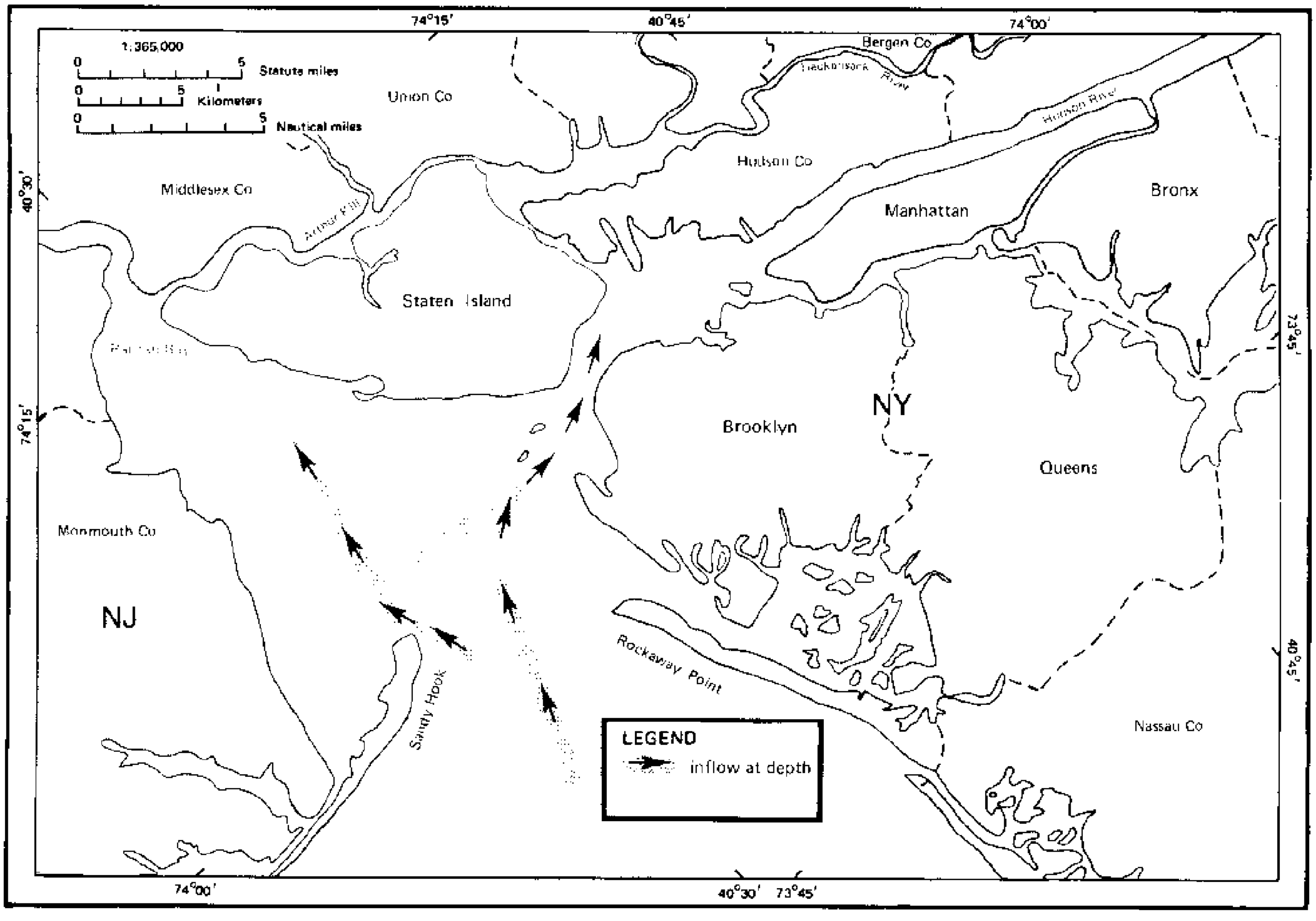
Map 7. Nontidal surface circulation patterns and associated inflow at depth

A



Transverse Mercator Projection

B



Transverse Mercator Projection

Distribution of Water Properties

Tidally Averaged Water Properties

Knowledge of the distribution of dissolved and particulate constituents for a body of water can be used by oceanographers to infer patterns of flow and to identify the source and fate of water masses. However, in an estuarine environment like the Lower Bay complex, the values of such observed water characteristics may vary greatly in a day because of the semidiurnal tide. Between October 1973 and June 1974, the Marine Sciences Research Center (MSRC) at Stony Brook conducted several oceanographic cruises in the bay complex in order to determine tidal variability in water properties (Duedall and O'Connors 1976).

Figure 14 shows the summer tidally averaged distribution of salinity, nutrients (ammonium, nitrite, nitrate, phosphate, silicic acid), and chlorophyll *a* along the hypothetical boundaries of Lower Bay. The tidal averaging procedure is described by Parker (1976). The distribution of these components is in large measure determined by the nontidal estuarine circulation previously discussed. The Bightward flow of Hudson-Raritan waters in the surface layer near Sandy Hook, accompanied by the harborward flow of Bight waters at depth near Sandy Hook and throughout the water column near Rockaway Point, produced the observed salinity gradient across the Sandy Hook-Rockaway Point transect (Figure 14A). Salinities less than 24°/oo, associated with the Bightward flow, extend at the surface from Sandy Hook to near the middle of the Sandy Hook-Rockaway Point transect. Salinities greater than 27°/oo were observed to be associated with the flow at depth near Sandy Hook and from surface to bottom over the northward third of the channel (Figure 13). The maximum tidally averaged salinities were observed at depths greater than 5 m (16 ft) in Ambrose Channel and near Rockaway Point and were associated with a harborward flow (Figure 13).

The movement of salt into Raritan Bay was confined to depths greater than about 4 m (13 ft) in Sandy Hook Channel. Similarly, higher salinity waters were observed to be confined to the south side of Rockaway Inlet. The distribution of tidally averaged salinity in The Narrows showed the expected increase in salinity with depth.

Except for nitrate concentrations, primarily associated with riverine input (Duedall et al 1977), the distribution of the tidally averaged nutrient concentrations (Figures 14B-F) were observed to be associated with the lower salinity waters, resulting from the introduction of these nutrients with sewage effluent (Table 3). Similarly, the distribution of tidally averaged chlorophyll *a* concentrations (Figure 14G) corresponded to that of lower salinity waters. However, the most likely source of chlorophyll *a* concentrations in the Sandy Hook-Rockaway Point transect was the very high chlorophyll *a* concentrations observed in Raritan Bay near Sandy Hook (Parker et al 1976). Tidally averaged concentrations of chlorophyll *a* in The Narrows and in Rockaway Inlet were much lower than those observed in Raritan Bay or the Sandy Hook-Rockaway Point transect (Figure 14G).

The nontidal current velocities shown in Figure 13 coupled with the tidally averaged nutrient and chlorophyll *a* concentrations shown in Figures 14B-G imply a large flux of nutrients and chlorophyll *a* through the Sandy Hook-Rockaway Point transect into the Bight apex.

Seasonal Variation in Tidally Averaged Properties

Figure 15 consists of vertical sections in the Sandy Hook-Rockaway Point transect showing the principal seasonal features in the tidally averaged distribution of salinity, temperature, sigma-t (σ_t or |density-1| x 1000), ammonium, nitrite, nitrate, phosphate, silicic acid, chlorophyll *a*, and suspended solids, respec-

Table 3. Annual mean concentrations and annual mean input rates of sewage effluent contained nutrients discharged into New York Harbor

Sewage Component	Annual Mean Concentrations (μM)[a]	Annual Mean Input Rates (mole/sec)
Organic nitrogen	646	63.0
Ammonium plus ammonia	726	71.0
Nitrite	7.7	0.8
Nitrate	27	2.6
Phosphate	62	6.1
Silicic acid	115	7.2

[a] 1 μM equal 10^{-6} mole/l

Source: O'Connors and Duedall 1975

tively. (Map 8 shows the station location [A-H] along the transect.)

The distribution of salinity shows the presence of high salinity Bight waters near Rockaway Point and low salinity estuarine waters near Sandy Hook (Figure 15A). This condition was present during each sampling period in the transect and is in response to the nontidal circulation process under the influence of the earth's rotation. As would be expected, salinities are more variable near Sandy Hook due to the seasonal variation of freshwater inflow entering the bay complex (Figure 8).

The distribution of temperature during November shows that the more saline bottom waters were warmer (12.6° to 13°C or 54.7 to 55.4°F) than the less saline surface waters whose tidally averaged temperatures were between 11.6°C (52.9°F) and 12.2°C (54°F) (Figure 15B). In January, a similar temperature inversion was present, but the entire water column cooled to 3.6° to 5°C (38.5° to 41°F). In March, the water column had warmed slightly but was nearly isothermal from top to bottom, with tidally averaged temperatures ranging between 5.4°C (41.7°F) and 5.7°C (42.3°F). In April, tidally averaged surface temperatures increased to 9°C (48.2°F) and bottom temperatures in the water column had increased substantially; in June, tidally averaged surface tempertures were at 17°C (62.6°F) and bottom values at 15.8°C (60.4°F).

The densest waters were the bottom waters near Rockaway Point (Figure 15C). Here the tidally averaged σ_t values were between 22.0 and 24.5 for all cruises. The least dense waters were found at the surface between Sandy Hook and Ambrose Channel where salinities are lowest. The density between Sandy Hook and Ambrose Channel is affected by seasonal variation in freshwater flow.

Nutrient and chlorophyll *a* concentrations (Figures 15D-I) were higher and more variable between Sandy Hook and Ambrose Channel due to the combined effects of seasonal variation in biological utilization and physical processes, such as variations in freshwater flow from the Hudson, and the advection of Raritan Bay waters into the transect.

Suspended solids concentrations also showed some variability in the transect (Figure 15J). Highest concentrations are usually found between Sandy Hook and Ambrose Channel, but are not necessarily associated with peak freshwater discharge.

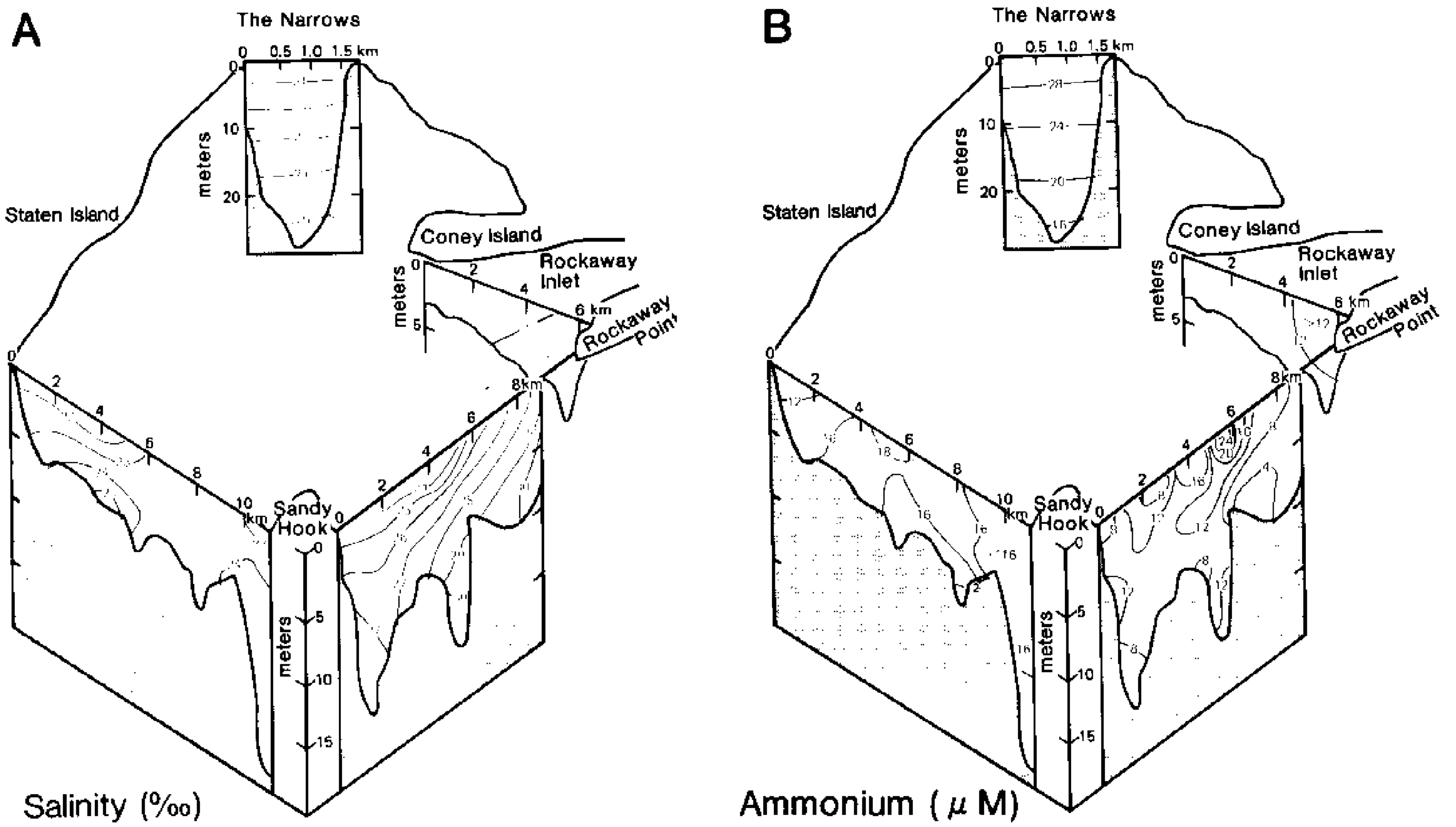
Water Properties in Slack Water

Samples in slack water after ebb or flood as the slack water and the sampling platform (the research vessel) progress in phase with the tide can determine approximate maximum and minimum values of water properties. This was done (Duedall and O'Connors 1976) 29 April 1974 for two consecutive slack periods and 6 June 1974 for slack after flood for a number of different water properties between the transect and The Battery (stations 66-77 on Map 8). Here the objective was to establish the source of the nutrients observed in the Sandy Hook-Rockaway Point transect by discounting variations that would otherwise be introduced by sampling different locations at different phases of the tidal cycle. The values of the water properties for this sampling scheme are presented in Figure 16.

The high concentrations of ammonium in Upper Bay at slack after ebb demonstrate the strong effect of the large sewage treatment plants nearby. Some spatial variability in the ammonium concentrations and salinity can probably be attributed to patches of fresh sewage effluent, which were only partially mixed with the saltier receiving waters.

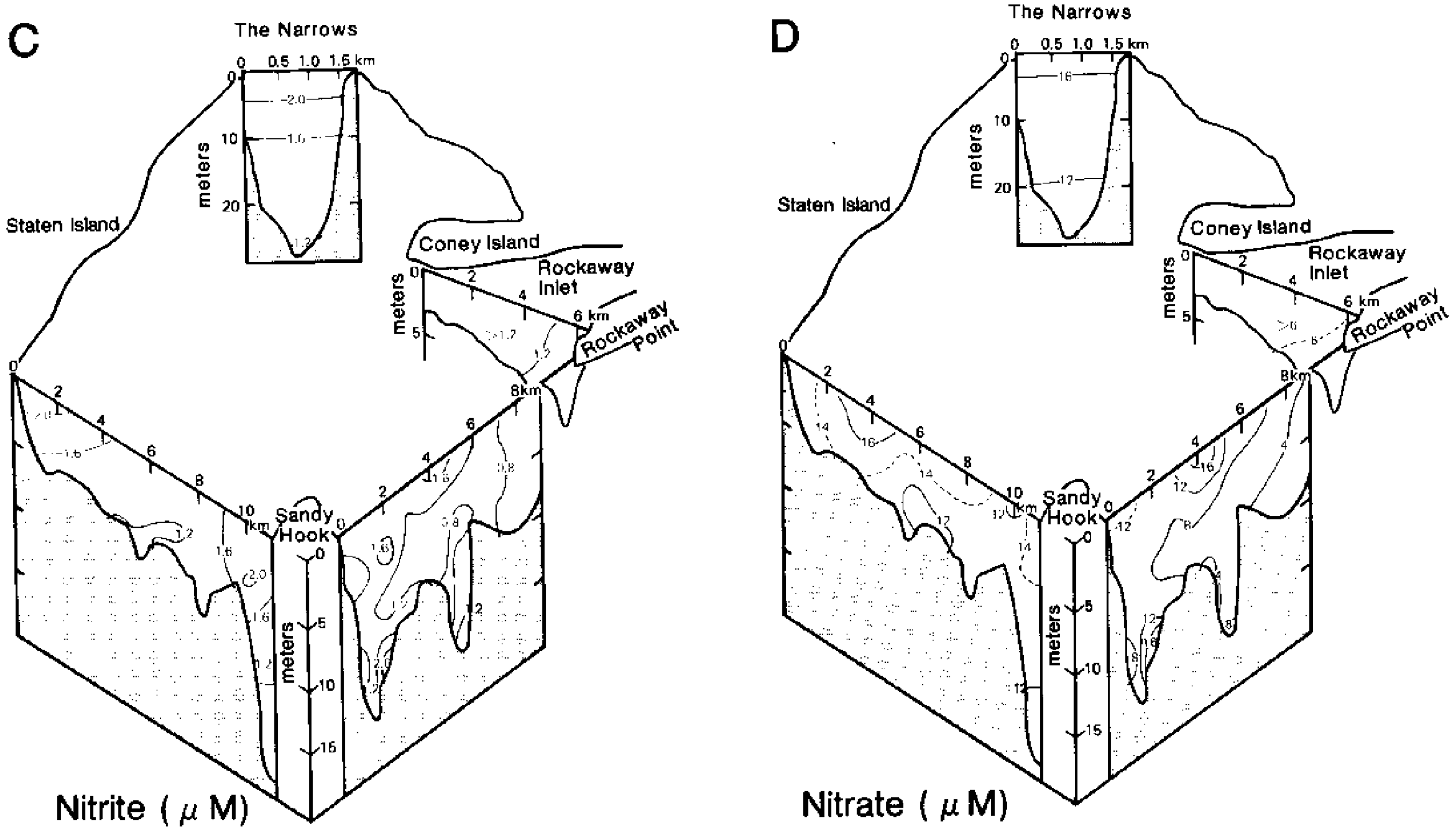
On 29 April, the chlorophyll *a* concentrations in turbid Upper Bay waters during ebb tide were less than those observed at the Sandy Hook-Rockaway Point transect. In Lower Bay, concentrations of chlorophyll *a* steadily increased toward the transect as concentrations of suspended matter decreased. Because of increased transparency in Lower Bay, phytoplankton may have been able to take greater advantage of available nutrients. This is evident from results obtained during the 6 June sampling. Here suspended solids and ammonium concentrations were very high but chlorophyll *a* abundances were reduced considerably from the 29 April values measured.

Trends in Figure 16 can be explained in large part by advection due to river flow and tidal forces. The distance a parcel of water is transported along the cruise track is fixed by the tidal excursion (Table 2). During ebb tide, the turbid and nutrient-enriched Upper Bay waters are transported downstream to Lower Bay where they mix and become diluted with the less turbid and less nutrient-enriched Lower Bay waters. On flood tide, currents are reversed and this Lower Bay water mixture is advected upstream.



Salinity (‰)

Ammonium (μM)



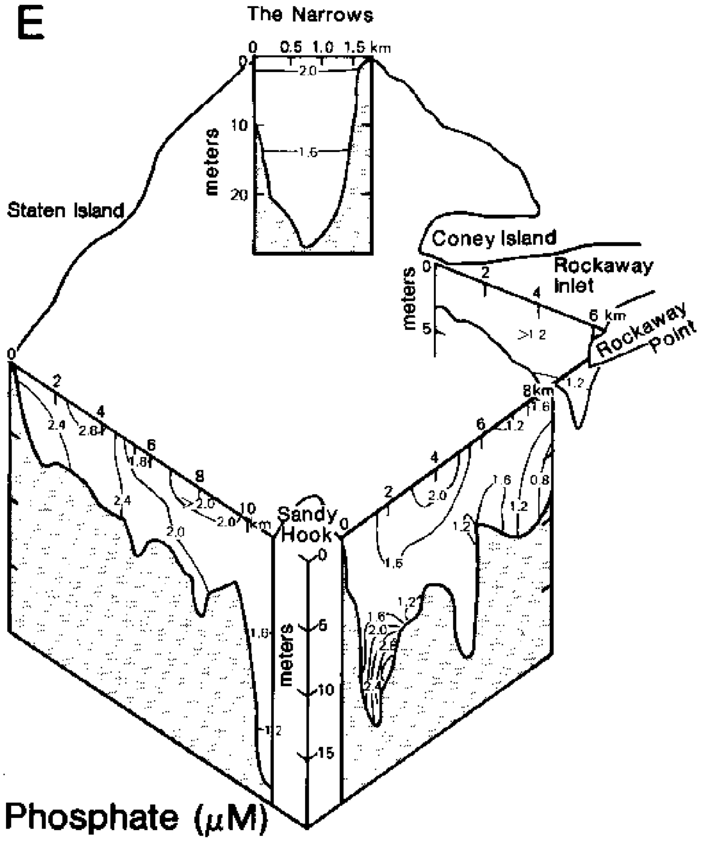
Nitrite (μM)

Nitrate (μM)

Note: μ M = 10^{-6} mole/l

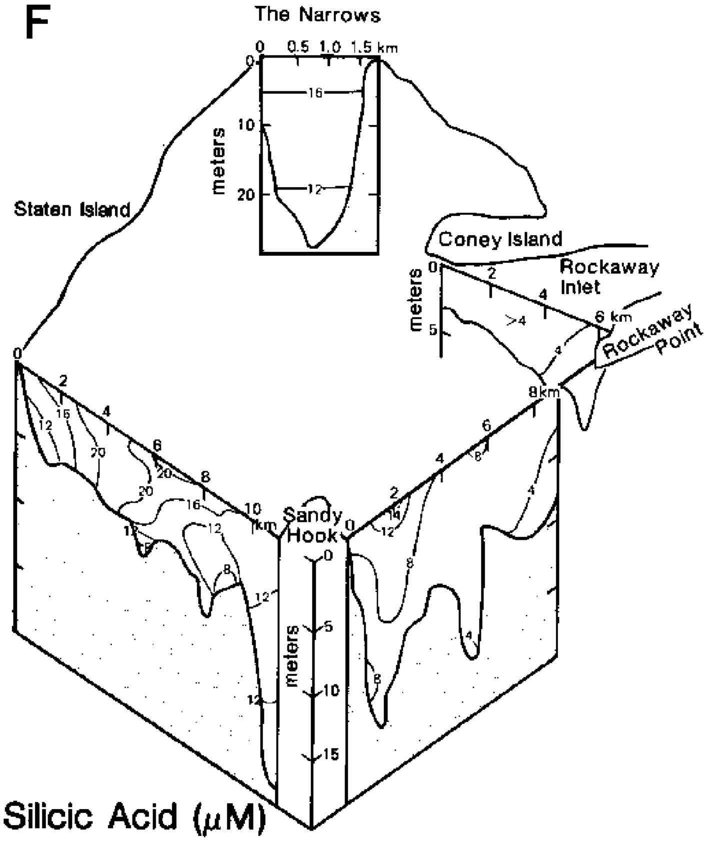
Figure 14. Tidally averaged properties

E



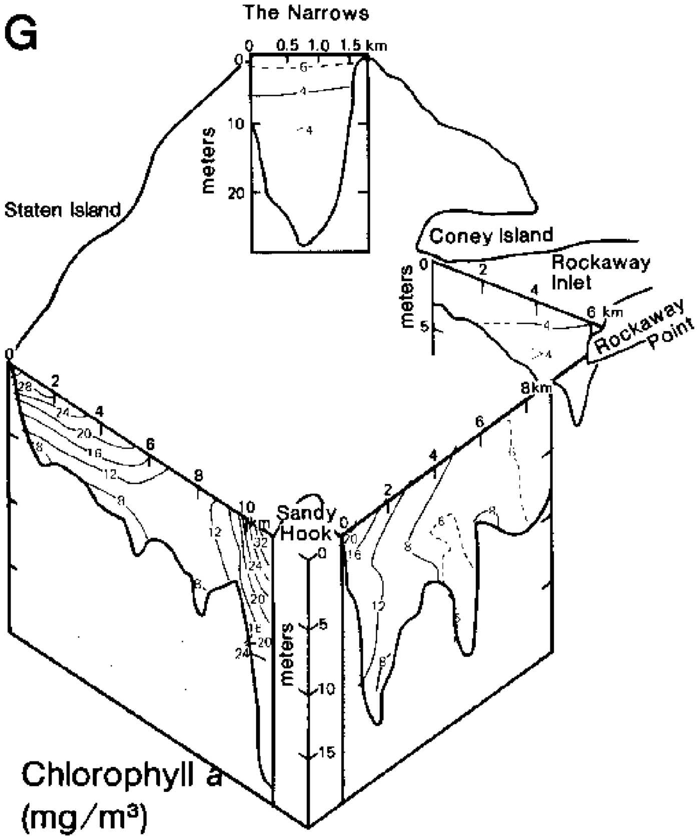
Phosphate (μM)

F



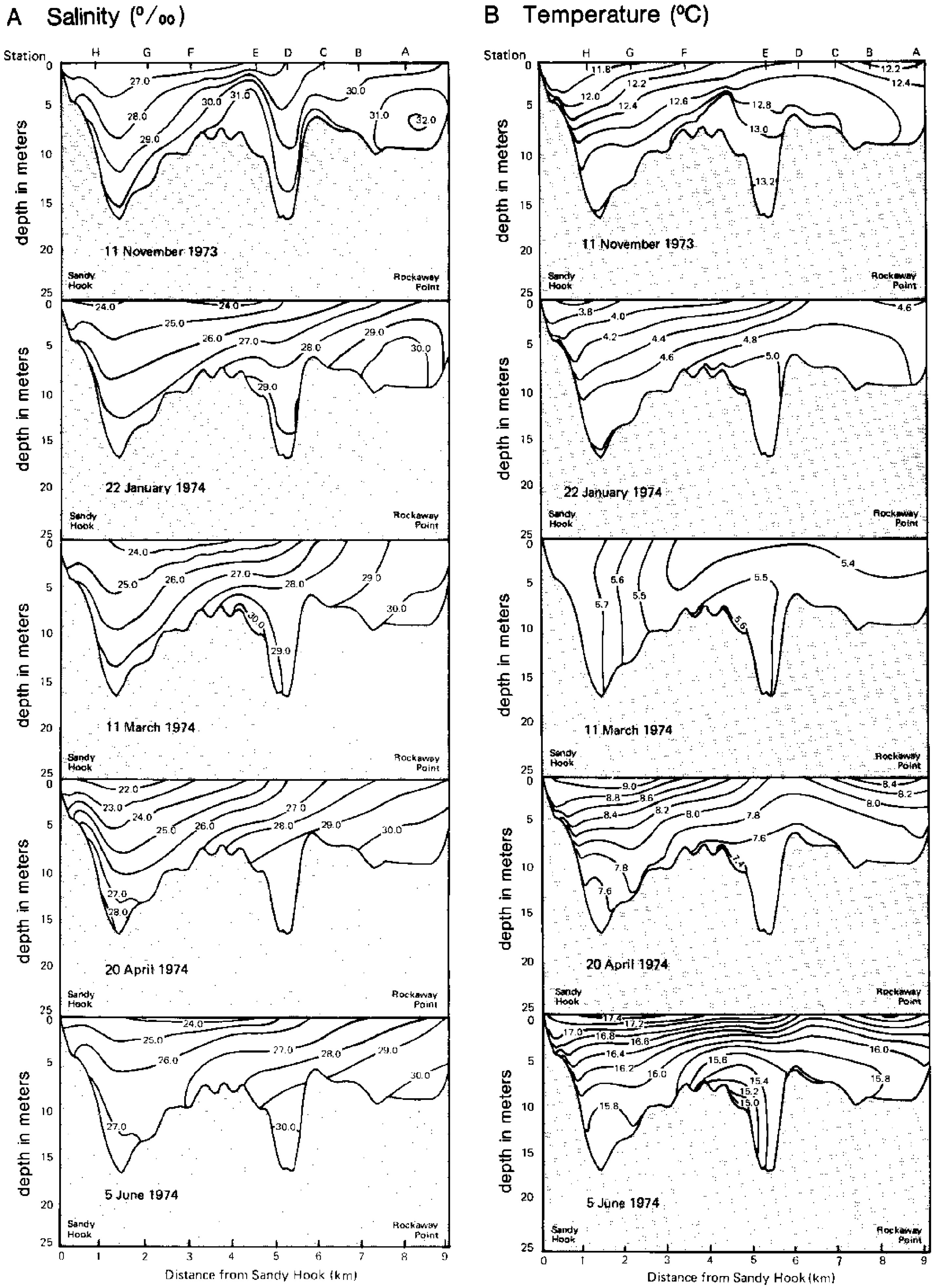
Silicic Acid (μM)

G



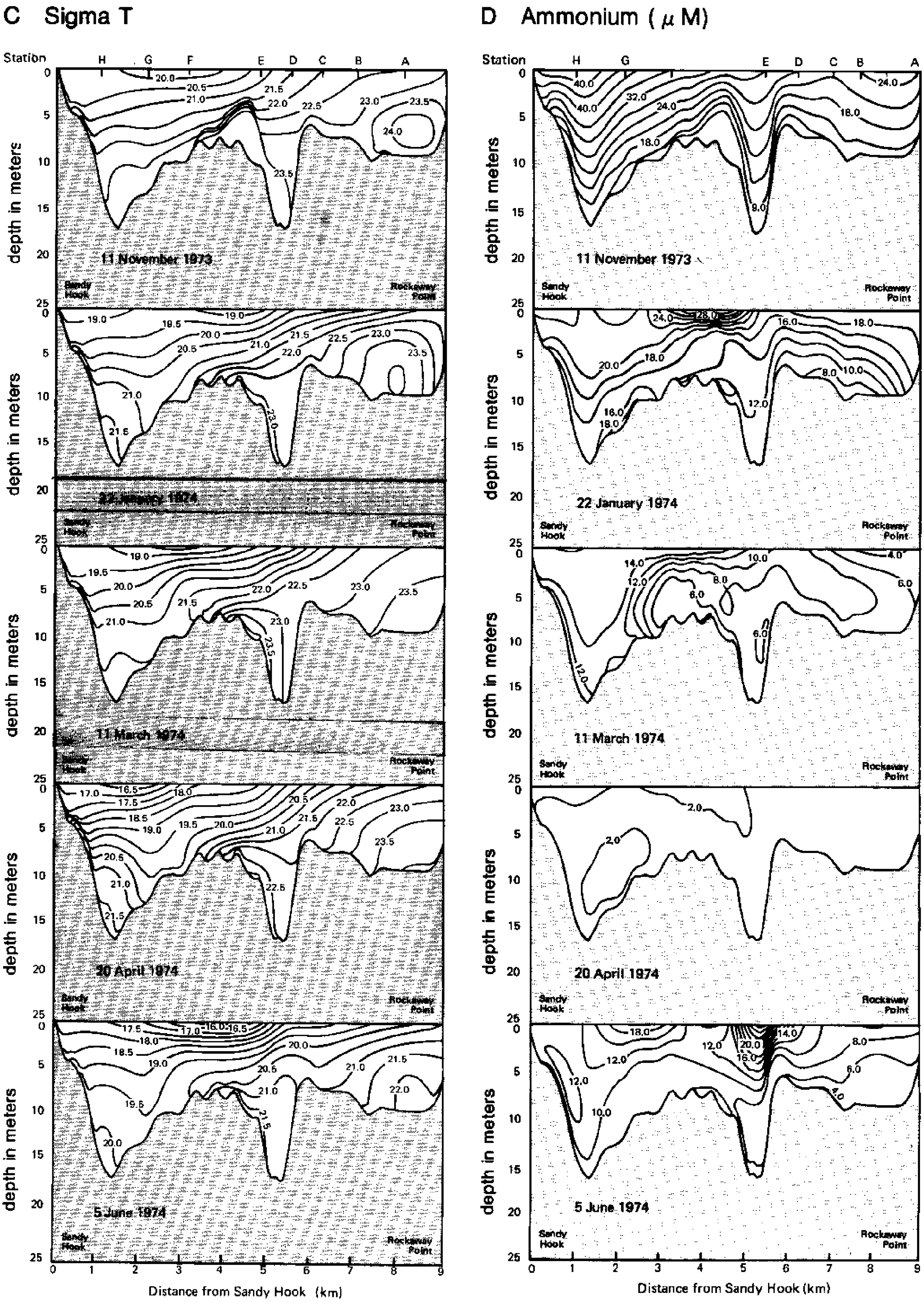
Chlorophyll a (mg/m³)

Source: Parker 1976

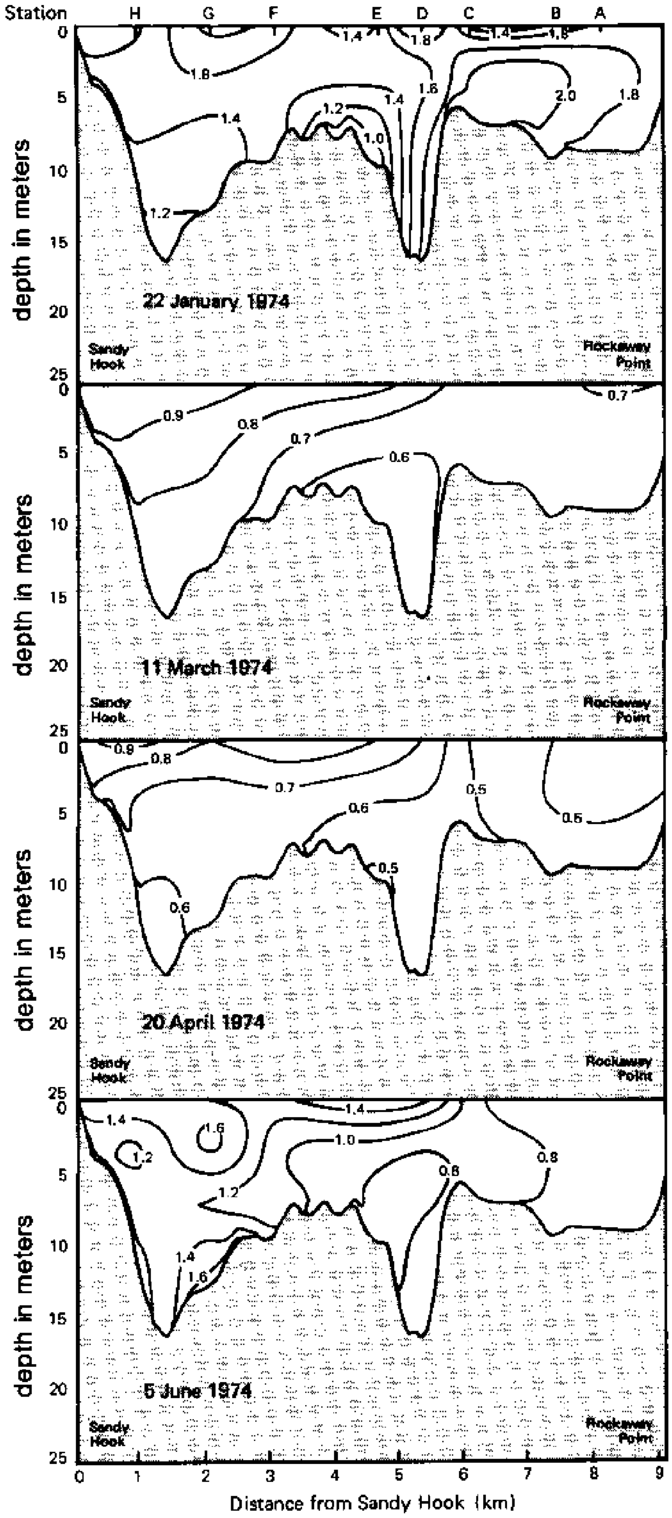

A Salinity (‰)

B Temperature (°C)

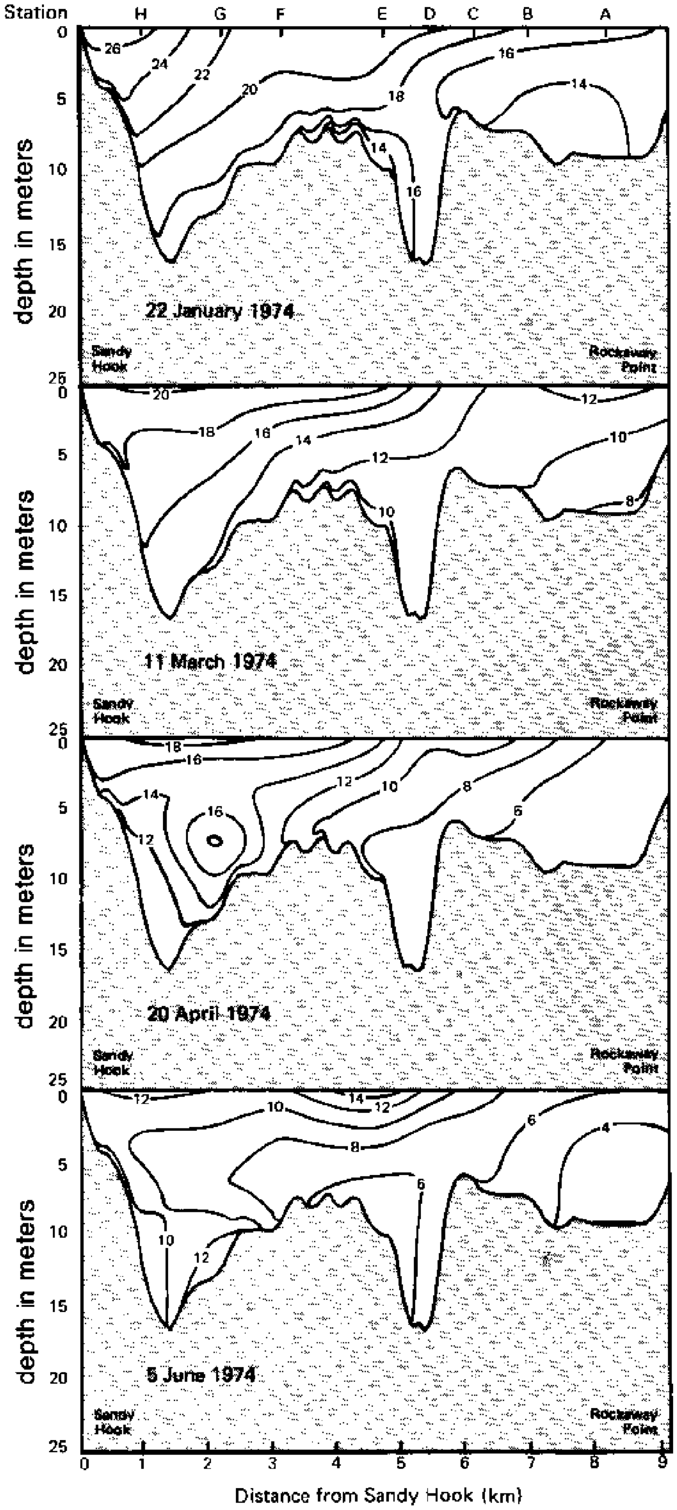
Figure 15. Seasonal variation in tidally averaged properties


C Sigma T
D Ammonium (μ M)
Station
H G F E D C B A
depth in meters
0 5 10 15 20 25
11 November 1973
22 January 1974
11 March 1974
20 April 1974
5 June 1974
Sandy Hook
Rockaway Point
Distance from Sandy Hook (km)
0 1 2 3 4 5 6 7 8 9
20.0 20.5 21.0 21.5 22.0 22.5 23.0 23.5 24.0
19.0 18.5 20.0 21.5 22.5 23.0 20.5 21.0 22.0 23.5 21.5 23.0
19.0 19.5 20.0 20.5 21.5 22.0 22.5 23.0 23.5 21.0 23.0 23.5
17.0 16.5 17.5 18.0 18.5 19.0 19.5 20.0 20.5 21.0 21.5 22.0 22.5 23.0 23.5
17.5 17.0 16.0 16.5 18.0 18.5 19.0 20.0 20.5 21.0 21.5 22.0 19.5 21.0 21.5 20.0
40.0 32.0 24.0 18.0 8.0 24.0 18.0
24.0 28.0 16.0 18.0 20.0 18.0 8.0 10.0 16.0 18.0 12.0
14.0 10.0 4.0 12.0 8.0 6.0 6.0 6.0 12.0
2.0 2.0
18.0 14.0 12.0 20.0 16.0 8.0 12.0 6.0 12.0 4.0 10.0

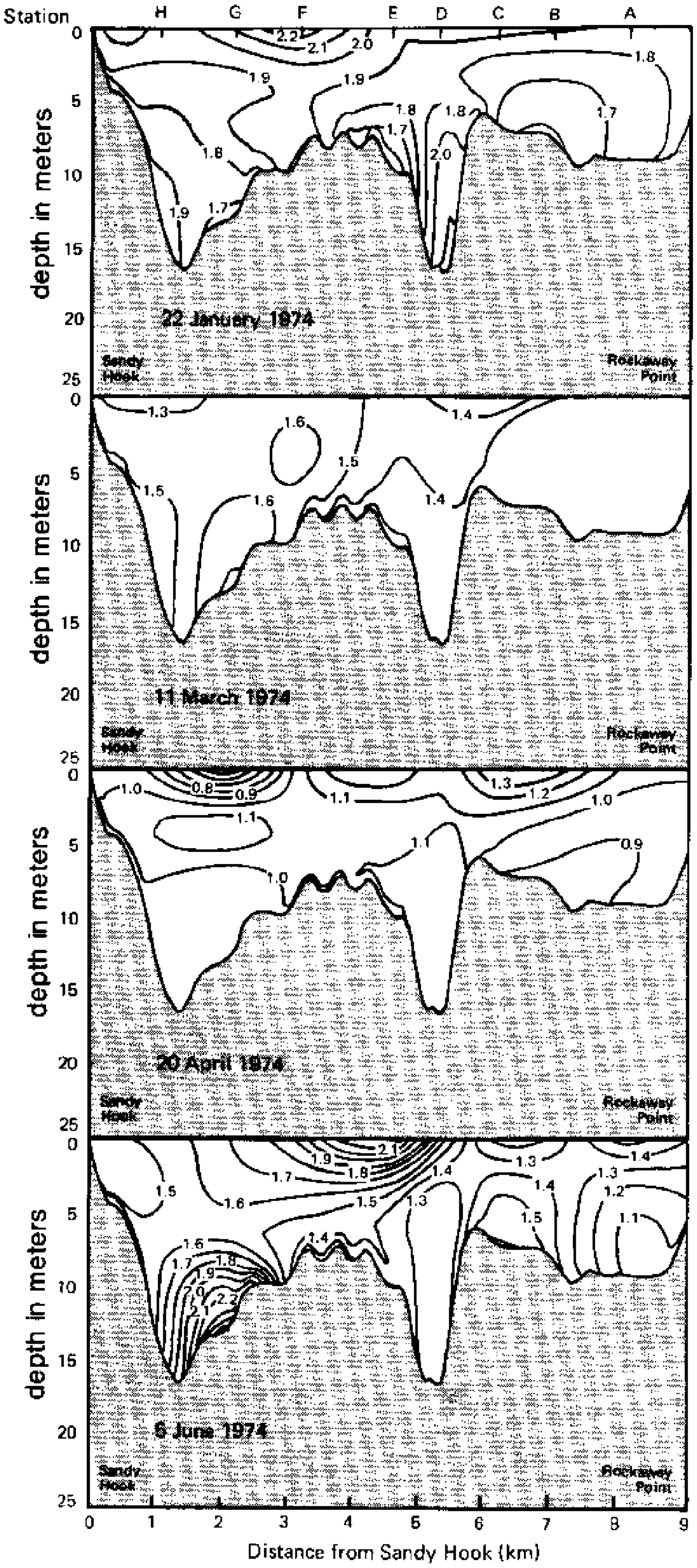
E Nitrite (μ M)



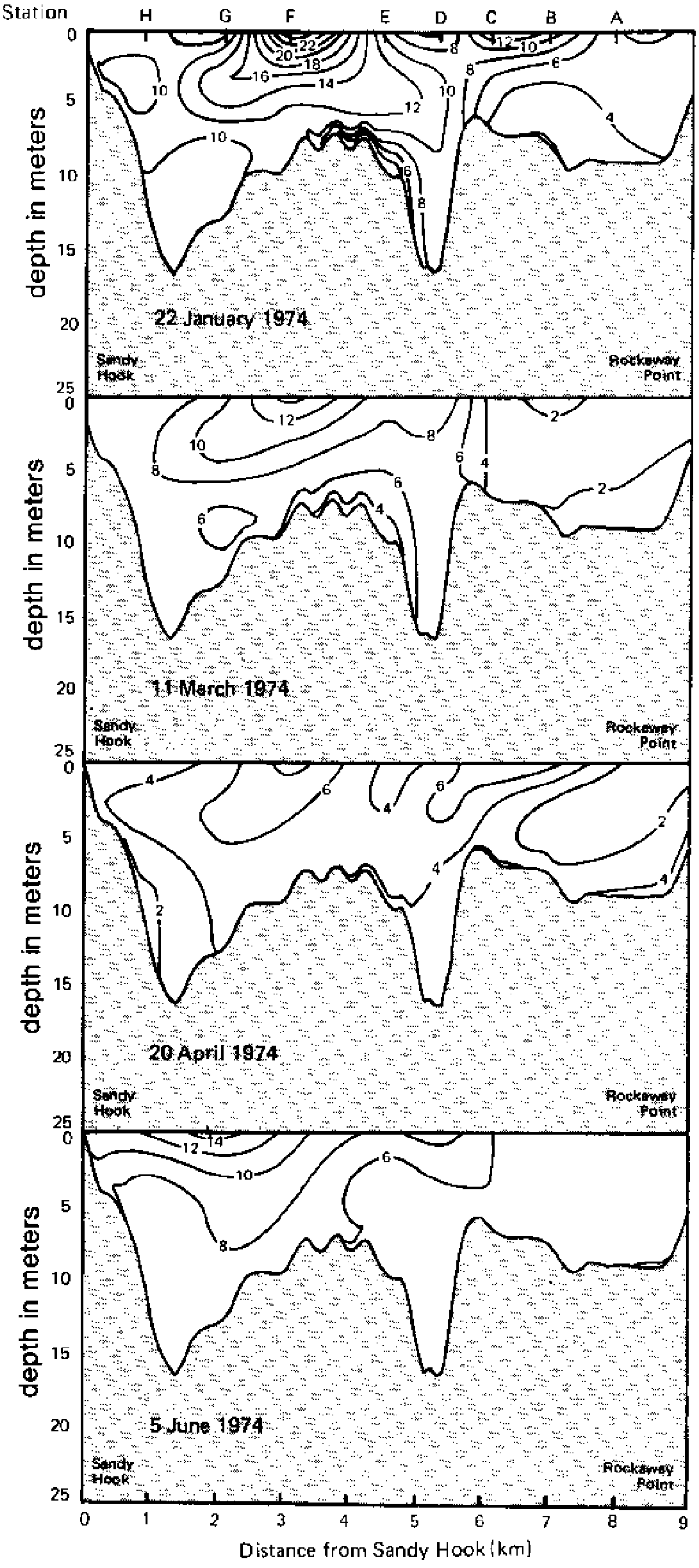
F Nitrate (μ M)



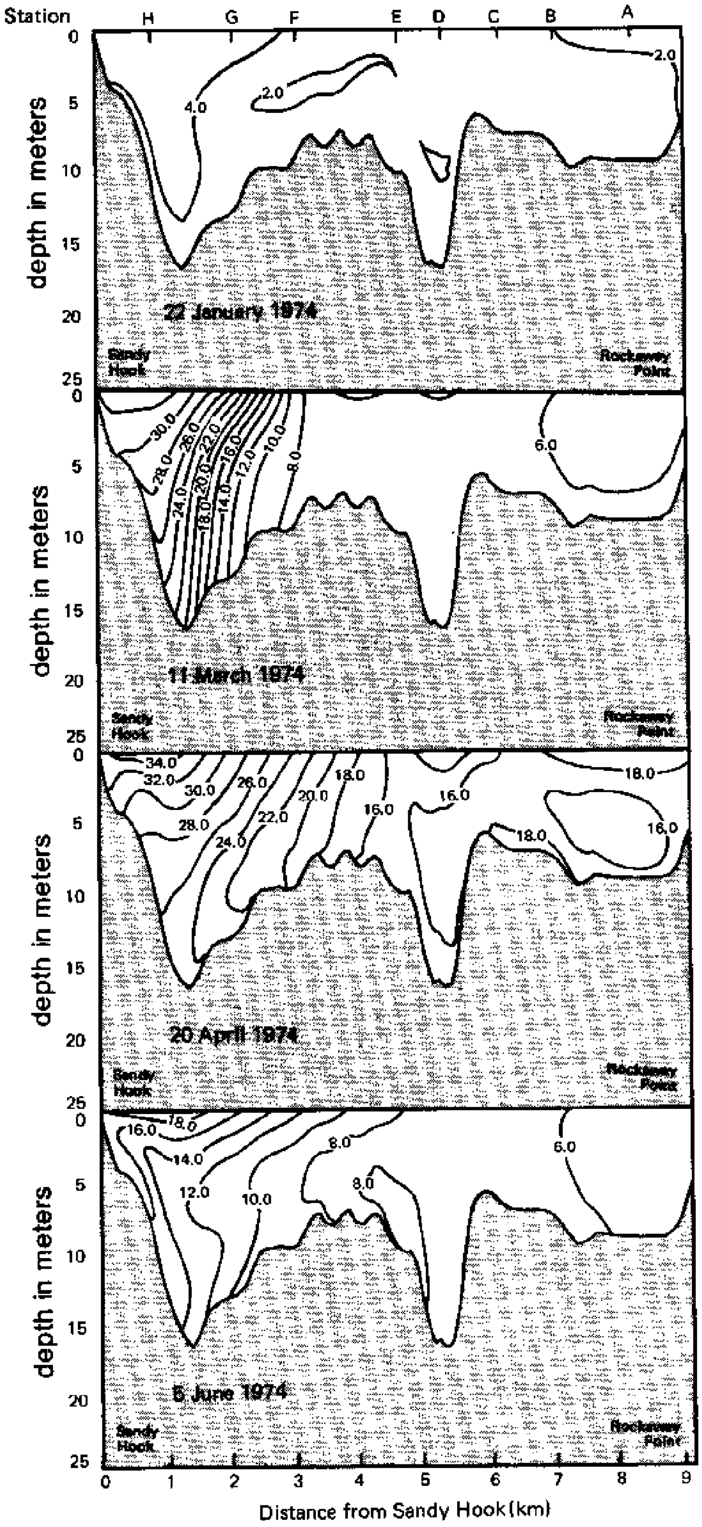
G Phosphate (μM)



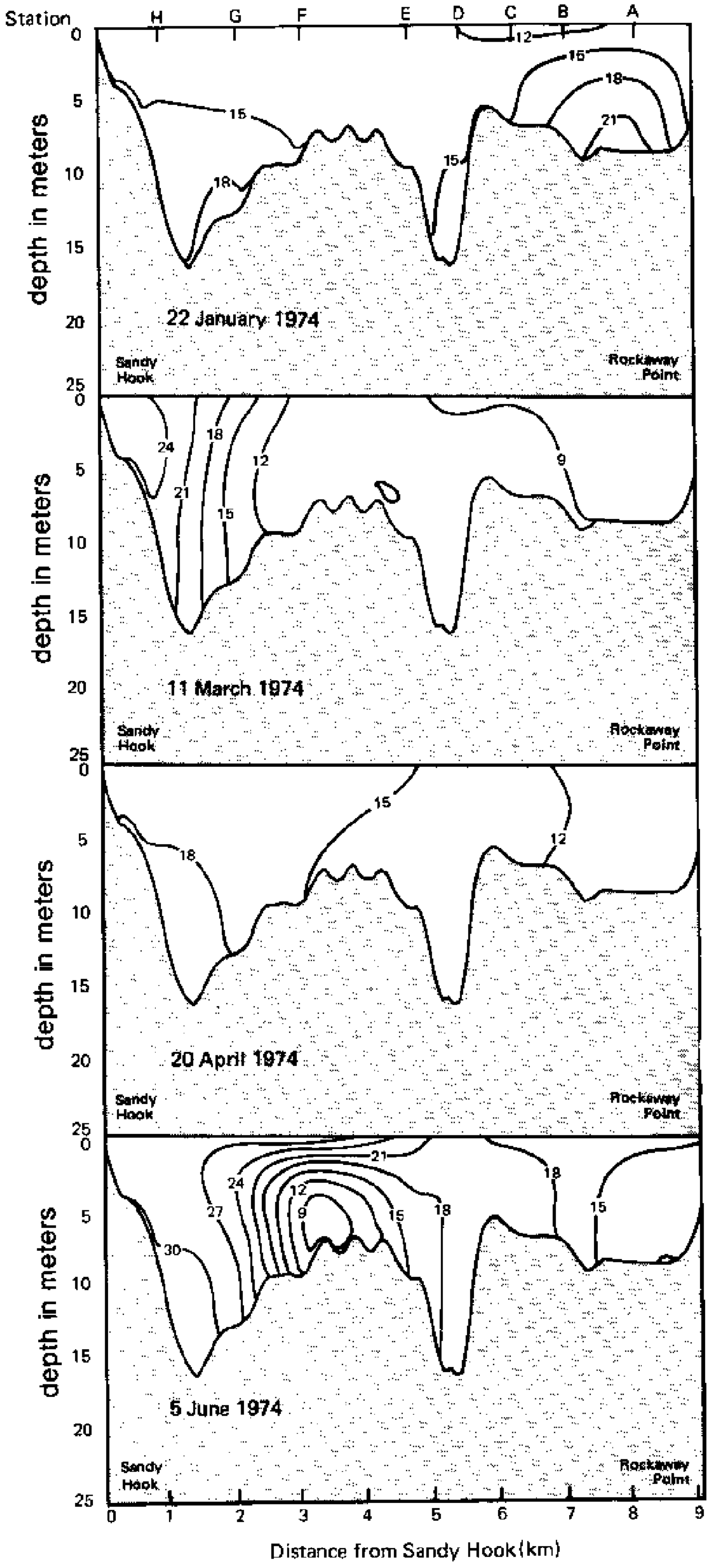
H Silicic Acid (μM)



I Chlorophyll *a* (mg/m³)



J Suspended Solids (mg/l)



Note: See Map 8 for station locations

Source: Duedall and O'Connors 1976

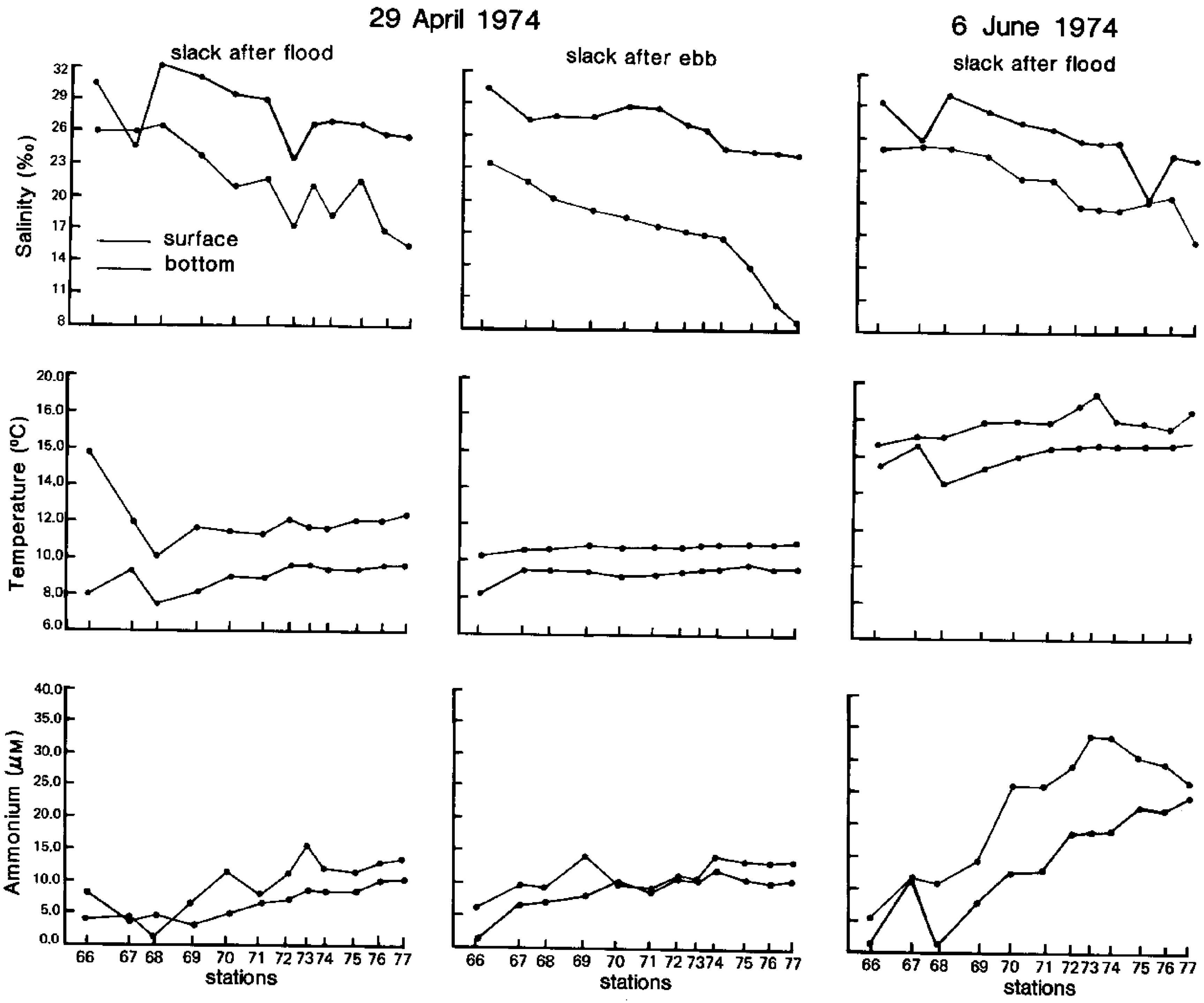
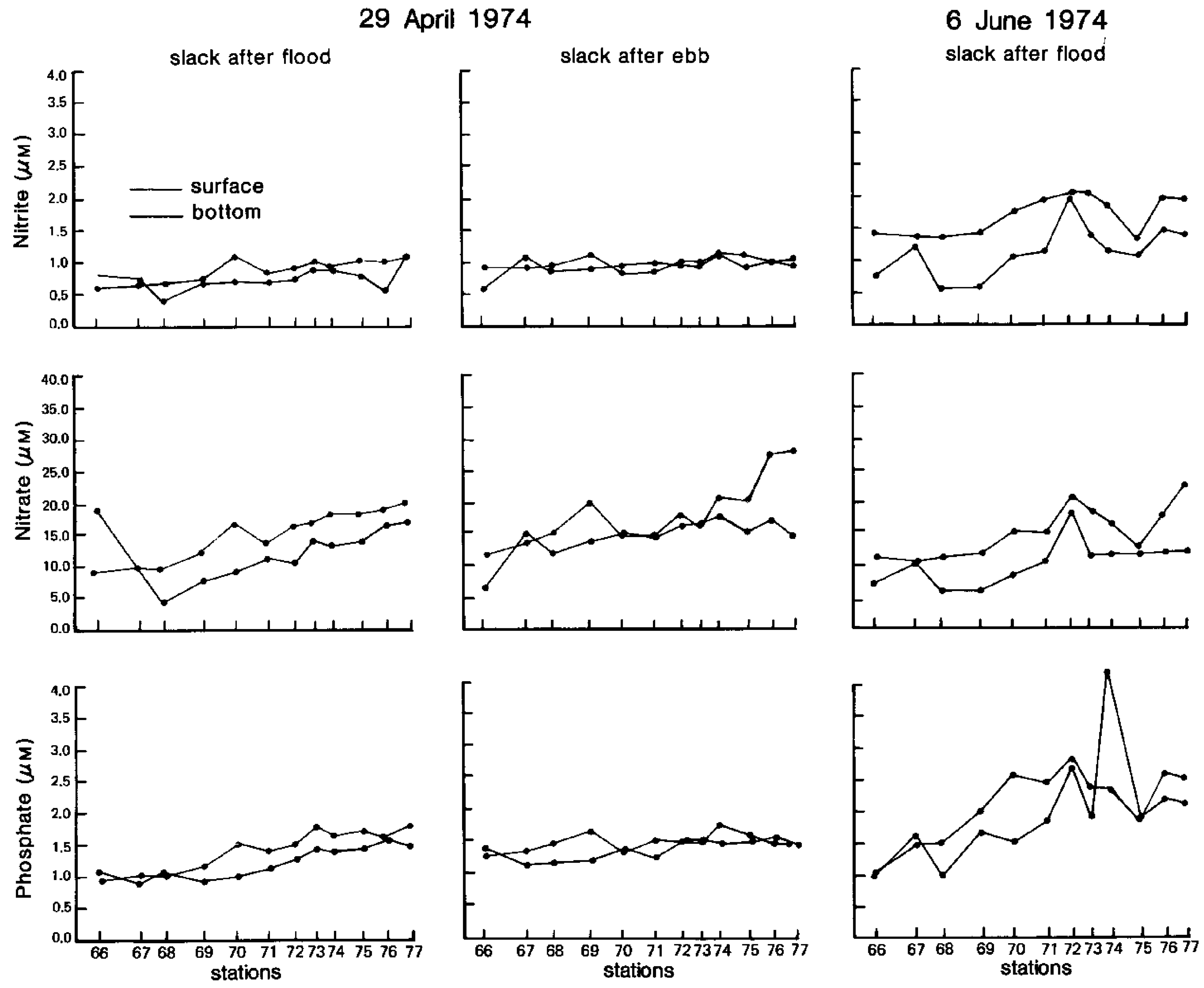
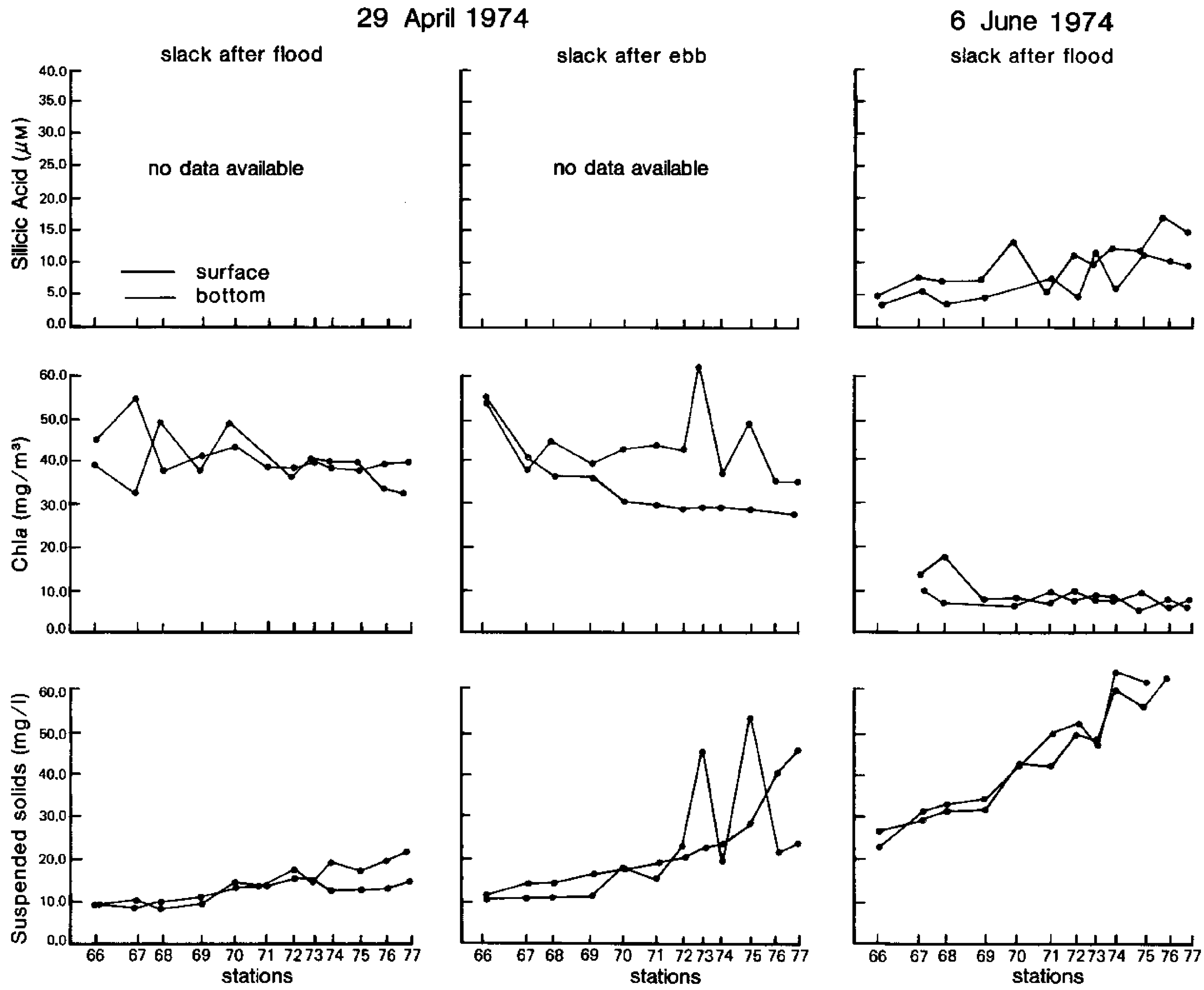


Figure 16. Water properties in slack water

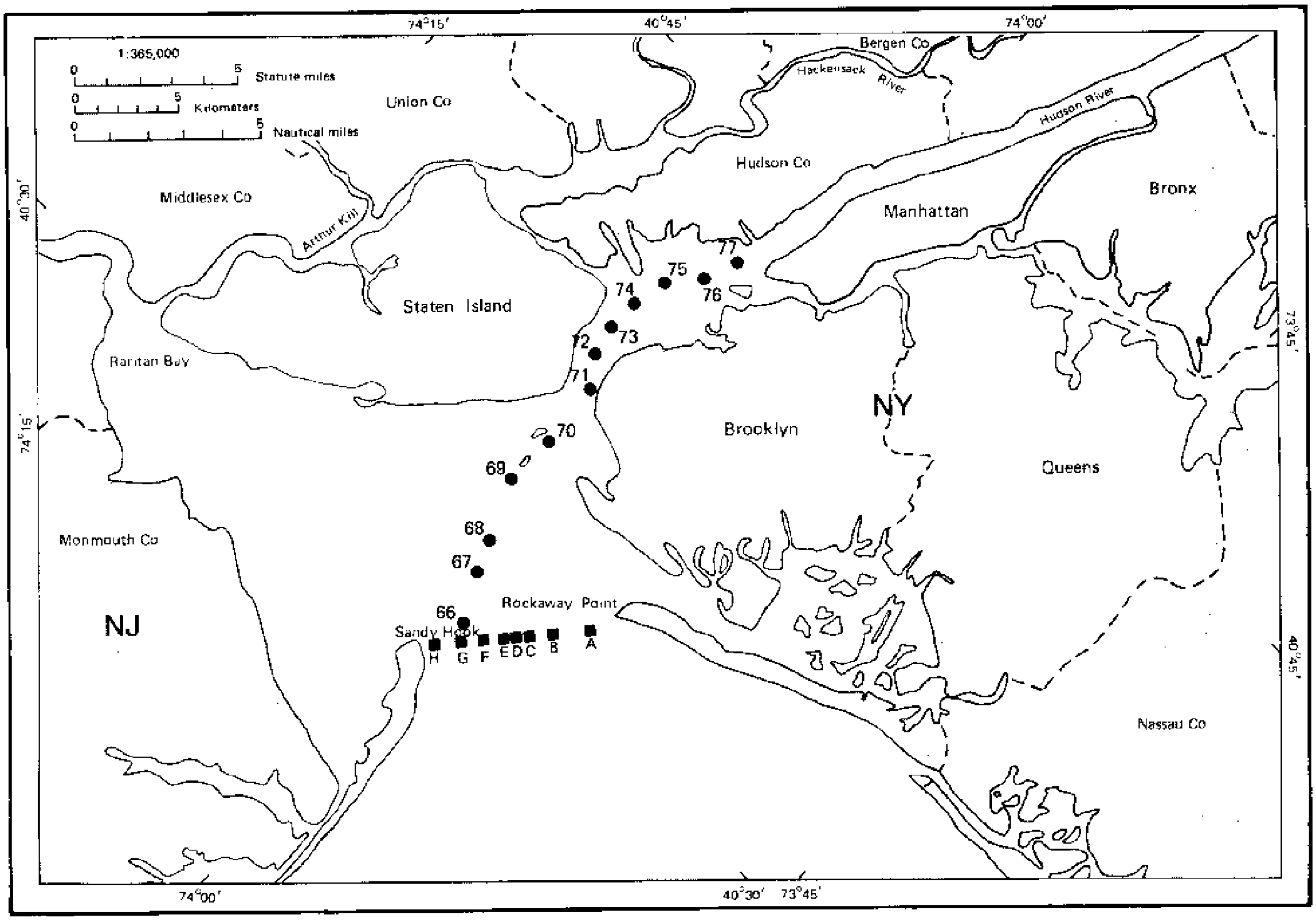

29 April 1974
6 June 1974
slack after flood
slack after ebb
slack after flood
surface
bottom
Nitrite (µM)
Nitrate (µM)
Phosphate (µM)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
66
67
68
69
70
71
72
73
74
75
76
77
stations



Note: See Map 8 for station locations

Source: Duedall and O'Connors 1976

Map 8. Water column stations in Lower Bay complex (Figures 15 and 16)



Transverse Mercator Projection

Source: Duedall and O'Connors 1976

Effects of Storms

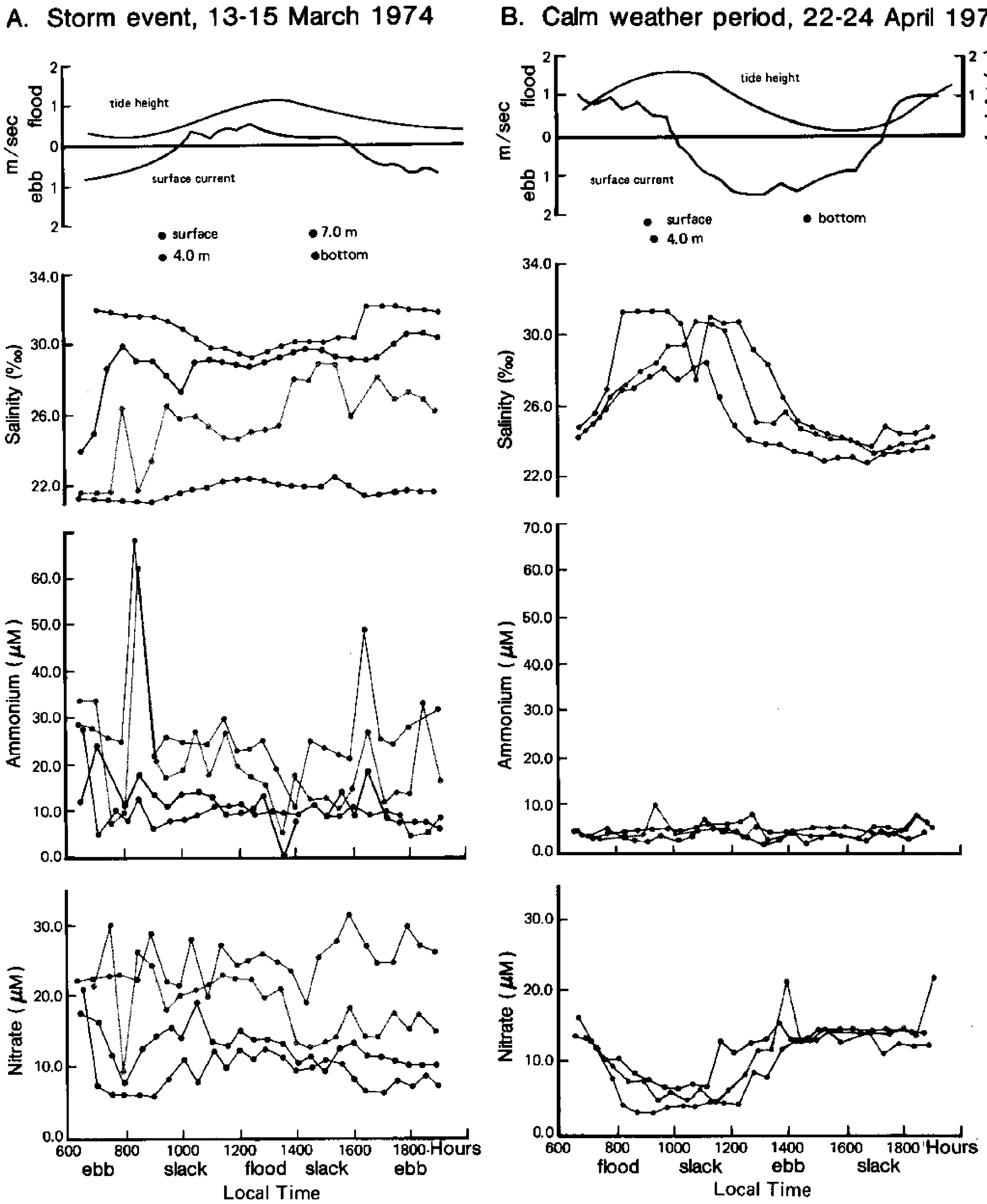
The instantaneous value for a given water property can be significantly different from its tidally averaged value, depending upon weather and tide conditions. Figure 17A presents the few available water column data for the Lower Bay complex that show water column perturbations brought about by irregularities in weather.

Samples were taken 15 March 1974 for 12 hours every half hour at a single station in the Sandy Hook-Rockaway Point transect while a strong storm (Figure 18A) passed through the area (Duedall and O'Connors 1976). All observed water properties showed erratic variability, which could only be attributed to the recent storm. For instance, prior to and during the sampling period winds had been strong and from the northwest (Figure 18A). Correlation of salinities with ammonium and nitrate concentrations (Figure 17A) showed the presence of patches of low salinity, nutrient-rich water, which presumably were wind-advected parcels of water from Upper Bay where several large sewage treatment plants exist.

The 12-hour sampling scheme was repeated 24 April 1974, but in considerably calmer weather. The record (Figures 17 and 18) shows the presence of south-southwest winds two to three days prior to the study; these gradually changed direction before sampling. The tidal variability in water properties during this sampling was smooth and periodic when compared to the 15 March results.

Raritan and Sandy Hook Bays

To illustrate the spatial distribution of water properties in Raritan and Sandy Hook bays, surface and bottom contours (Map 9) were constructed for salinity and concentrations of ammonium and chlorophyll *a* from data gathered during an MSRC cruise in Raritan Bay 3 June 1975 (Parker et al 1976). The condition of the tide during this particular survey was approximately slack after flood. At other phases of the tide, values of water properties will be different. For instance, Map 10, showing salinity contours reported by Ayers and associates (1949), contrasts the surface salinities at high and low water.



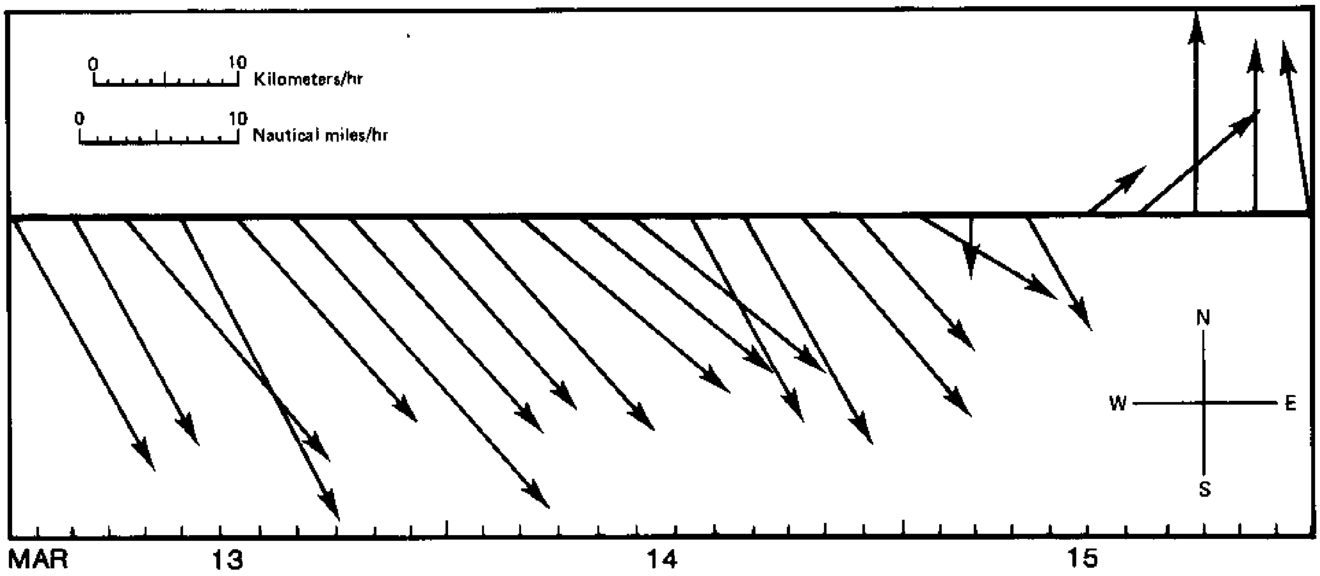
A. Storm event, 13-15 March 1974

B. Calm weather period, 22-24 April 1974

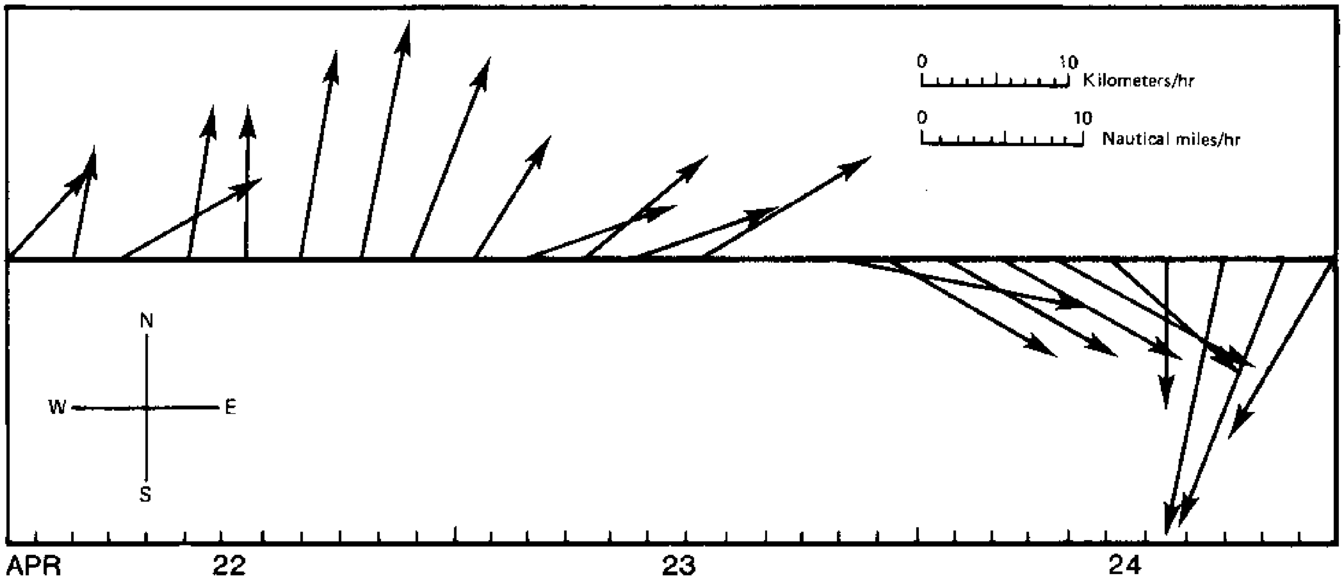
Source: Duedall and O'Connors 1976

Figure 17. Water column properties during a storm event (A) and during a calm weather period (B)

A. Storm event, 13-15 March 1974



B. Calm weather period, 22-24 April 1974



Source: NOAA 1975a

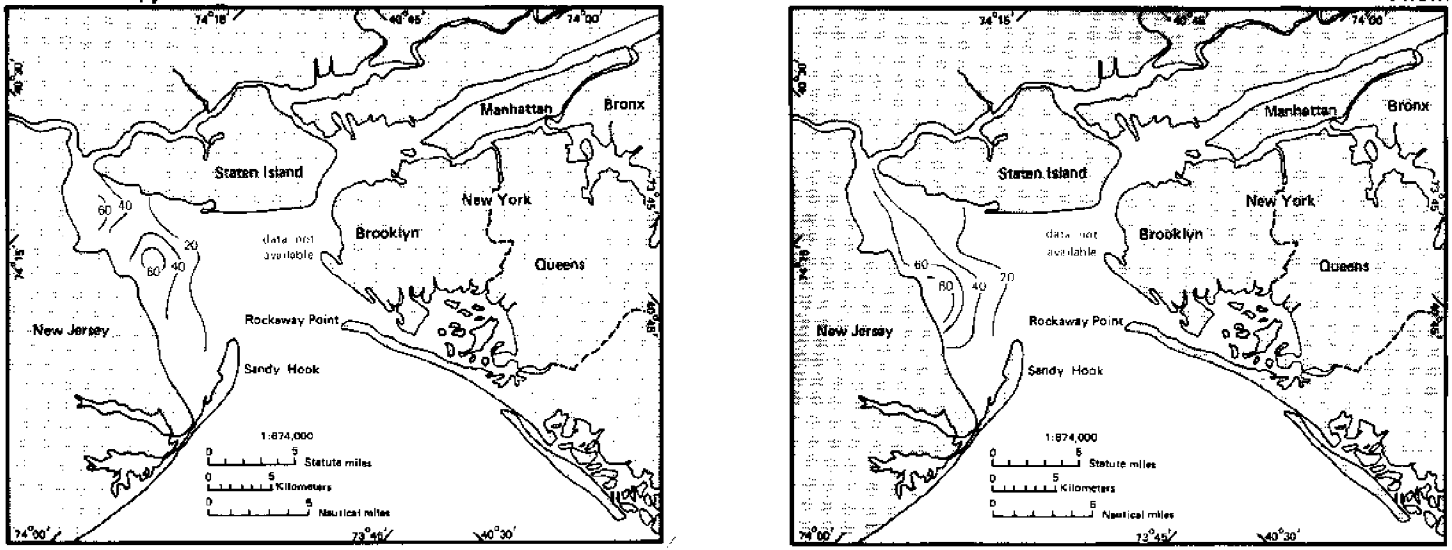
Figure 18. Wind vectors during a storm event (A) and during a calm weather period (B)

The distribution of salinity illustrates that Raritan River waters move southward into the bay complex. The higher bottom salinities on the north side of the bay demonstrate the presence of incoming Lower Bay waters (Map 9). These features are consistent with the nontidal flows and circulation patterns shown in Figure 13 and Map 7. The nontidal drift (Map 7) southwestward near the middle of Raritan Bay and eastward on the south side suggests the presence of a counterclockwise gyre (Ayers et al 1949; Jeffries 1962). The resulting sluggish circulation may provide adequate time for a buildup of chlorophyll *a* although it would seem easily perturbed by the presence of the periodic tidal currents, the variability in freshwater discharge, and storm weather. However, according to Ayers and associates (1949), this circulation is fairly stable and is only disrupted by severe storms; earlier conditions are normally established within about two days.

Using the modified tidal prism model developed by Ketchum (1951), Parker and associates (1976) calculated the flushing or residence time of Raritan Bay from the *exchange ratio* (the proportion of water removed on the ebb tide) for segments of Raritan

Map 9. Distribution of water properties of Sandy Hook and Raritan bays

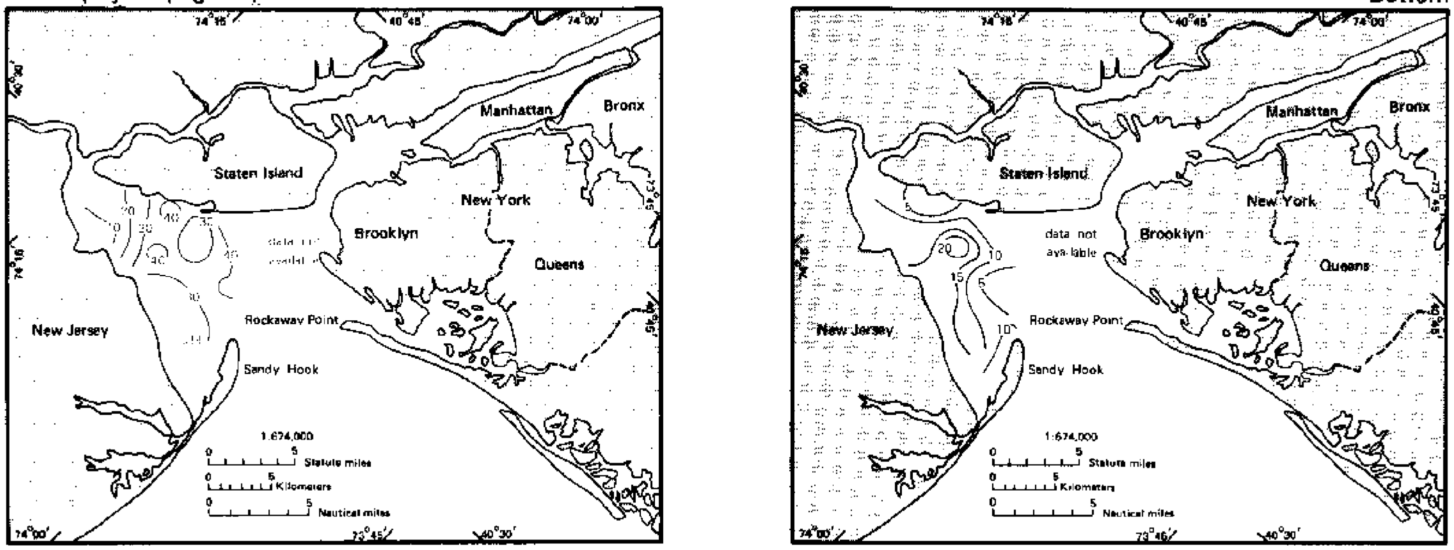
Ammonium (μM)



Surface

Bottom

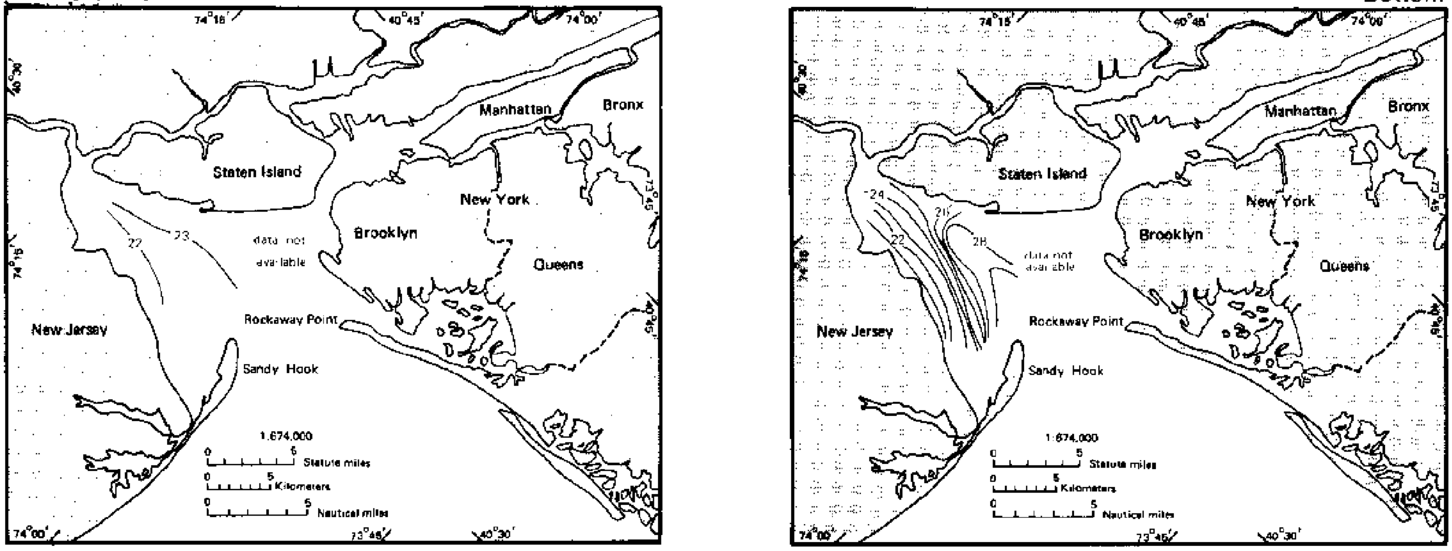
Chlorophyll *a* (mg/m³)



Surface

Bottom

Salinity (°/₀₀)



Surface

Bottom

Source: Parker et al 1976

Transverse Mercator Projection

Bay. The areas in Raritan Bay having the longest flushing times correspond well to those regions where ammonium and chlorophyll *a* concentrations are greatest.

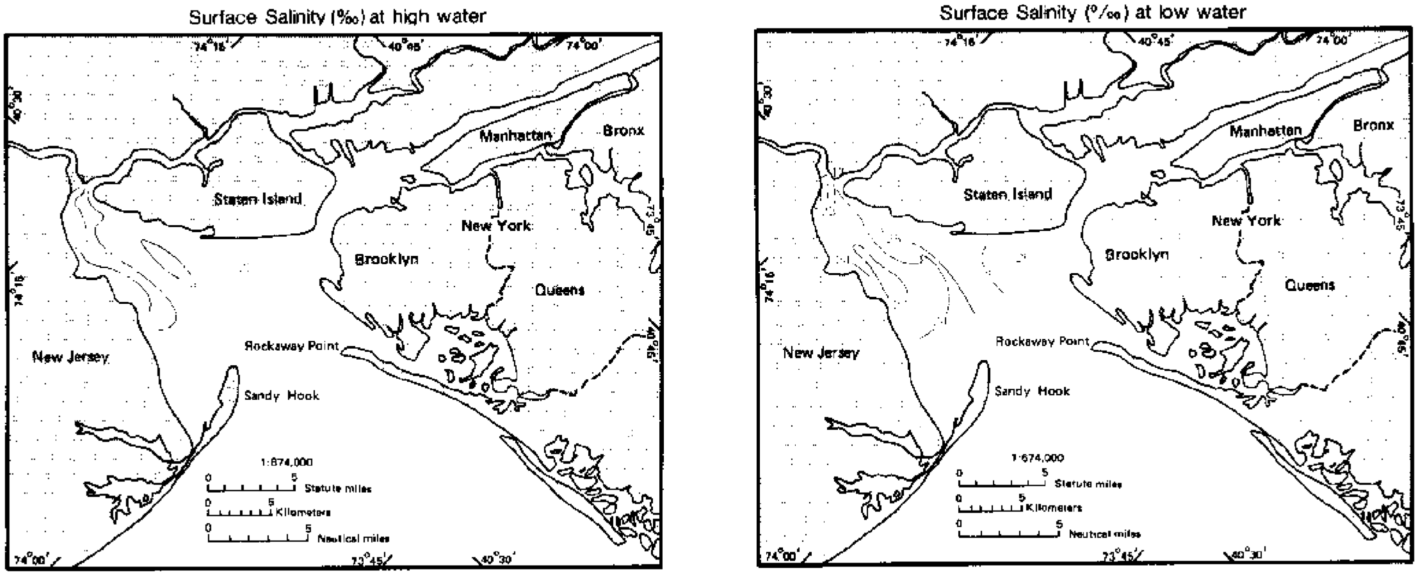
Jeffries (1962) described the nitrate and phosphate chemistry in Raritan Bay where he found an apparent rapid regeneration of phosphate relative to nitrate. This rapid renewal of phosphate coupled with the relative sluggish circulation was suggested as an important factor leading to the observed dense populations of phytoplankton. Parker and associates (1976) calculated that in Raritan Bay, ammonium and other nutrients advected from nontidal currents originating from Lower Bay are biologically consumed. They also calculated that Raritan Bay exports chlorophyll *a*. Recently, Thomas, O'Reilly, and Evans (personal communication) reported record high values of 700 to 1,050 g carbon/m^2/yr of primary productivity for Raritan Bay. This evidence points to Raritan Bay as capable of absorbing by biological processes a significant fraction of the nutrients discharged from sewage sources.

Nutrients and Chlorophyll *a* Input to the Bight

To demonstrate the impact of the Lower Bay complex on New York Bight, the advective fluxes (Table 4) and the nutrient loads in sewage effluent and in the Hudson, Raritan, and Passaic rivers were used by Duedall and associates (1977) to prepare a simple approximation of a 24-hour nutrient budget for the Sandy Hook-Rockaway Point transect. The following were assumed in preparation of the budget: 1) nutrients released from sediments upstream of the transect are included in the rivers' nutrient load; 2) nutrient loadings equivalent to 70% of the sewage discharged from the four largest sewage treatment plants on the East River are transported to Long Island Sound; and 3) diffusive nutrient fluxes, not possible to calculate from the data, can be neglected. The last assumption may not be valid for ammonium or other nutrient species since there can be a strong ammonium gradient between nutrient-rich Lower Bay and the Bight apex (Figure 16). The net Bightward inputs (Table 4, column d) calculated in this study thus reflect the minimum amount of nutrient species transported to the apex.

The relatively large and negative differences (Table 4, column e) between the river plus sewage input (column a) and the net Bightward flux (column d) through the transect for ammonium, silicic acid, and phosphate suggest that these nutrient species were being utilized above the transect by phytoplankton. This conclusion is supported by the large chlorophyll *a* flux out of the harbor, the recent calculations by Parker and associates (1976) for Raritan Bay and the primary production rates reported by Garside, Roels, and Sharfstein (1976) for the harbor and by Thomas, O'Reilly, and Evans (personal communication) for Raritan Bay. The small but positive differences for nitrate and nitrite suggest that these nutrient species may be produced by bacterial oxidation of ammonium or organic nitrogen in the waters of the bay complex.

Map 10. Historical record of salinity in Raritan Bay


Surface Salinity (‰) at high water

Surface Salinity (‰) at low water

Source: Ayers et al 1949

Transverse Mercator Projection

The phosphate flux is particularly interesting because the combined input of phosphate from sewage and river (Table 4, column a) appears nearly in balance with the Bightward flux (column b) to the apex. Thus the harborward flux of phosphate (column c) from bottom Bight waters may alone be sufficient to maintain the observed standing stocks of phytoplankton in the bay complex. The near balance in phosphate may also be due, in part, to the rapid regeneration of phosphate in Raritan Bay (Jeffries 1962).

Based on data for assimilation of total inorganic nitrogen and for the *per capita* production of sewage in the metropolitan area, Garside and associates (1976) reported 8.6 x 10^6 moles/day of ΣN enter the apex from the harbor during summer. Their value agrees very well with the ΣN = 5.6 x 10^6 moles/day reported by Duedall and associates (1977), considering the difference in approach taken by the two.

The deleterious impact of the dissolved inorganic nitrogen loading on water quality in the Bight apex has been discussed by Segar and Berberian (1976). They examined the April, June, August, and September-October 1974 distributions of dissolved oxygen concentrations in the apex. According to Segar and Berberian, the estuarine input of dissolved nitrogen can lead to the production of excessive quantities of phytoplankton (see also Hardy 1975) which, when transported to below the thermocline, are decomposed rapidly leading to the observed low dissolved oxygen concentrations in bottom waters. Segar and Berberian reported dissolved oxygen concentrations of less than 30% of saturation in the bottom waters during the summer when the thermocline was most stable.

In the summer of 1976, there was a major fish kill in New Jersey waters. Dissolved oxygen concentrations of 0-2 mg/l (0 to 22% of saturation at salinity 34‰, 10°C) were observed for bottom waters in an area between Long Branch and Barnegat Inlet, NJ, in a band 5.6 to 37 km (3 to 20 nmi) offshore (National Science Foundation 1976). The large flux of nutrients from the bay complex has been implicated (Segar and Berberian 1976) as a possible factor in the aggravation of the natural conditions occurring in the Bight. For the most part, these nutrients are confined within the plume of the waters leaving the bay complex through the Sandy Hook-Rockaway Point transect.

Table 4. 24-hour nutrient budget for Sandy Hook-Rockaway Point transect

			(x 10^6 moles)		
Nutrient	(a) Discharge Above Transect from Sewage and River Sources[a]	(b) Bightward Through the Transect	(c) Harborward Through the Transect	(d) Net Bightward Flux [(b)−(c)]	(e) Non-conservative Loss [(d)−(a)]
Ammonium plus ammonia	5.4	4.4	1.2	3.2	−2.2
Nitrite	0.074	0.4	0.14	0.26	+0.19
Nitrate	1.9	3.2	0.95	2.2	+0.3
Phosphate	0.51	0.54	0.22	0.32	−0.19
Silicic acid	5.4	2.7	0.86	1.8	−3.6

[a] Calculated from Table 3. The average May, June, and July concentrations from 1974 water year data at Chelsea station on Hudson River (US Geological Survey 1975*d*); values include loadings for Raritan and Passaic rivers (US Geological Survey 1975*b*,*c*)

Source: Duedall et al 1977

Conclusions

The Lower Bay complex is a dynamic estuarine system that acts as a catchment for natural and man-induced inputs originating from the Hudson, Raritan, and Passaic rivers and from street-runoff and sewage and industrial wastes discharged from outfalls. A variety of physical processes, such as tides and tidal currents, freshwater discharge, and storms, produce a highly variable pattern in the distribution of water properties in the bay complex.

We are only now beginning to understand how the bay complex works. We know, for instance, that a sizeable fraction of the nutrient loading is consumed in Raritan Bay by the phytoplankton community. There exists a seasonally variable input of phytoplankton to the Bight apex which may be an important supply of particulate food for zooplankton herbivores during different times of the year.

Future work in the bay complex should focus on an understanding of the transport and composition of suspended solids. We know very little about the elemental composition of suspended solids and virtually nothing about their role as scavengers for contaminants. This information is required in order to adequately address the problem of the impact of the New York metropolitan area on the water quality of New York Bight.

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19 **Recreation** E. Glenn Carls, University of Waterloo, Ontario

20 **Port Facilities and Commerce** Alfred Hammon, The Port Authority of New York and New Jersey

21 **Sand and Gravel** John S. Schlee, US Geological Survey, with a section by Peter T. Sanko, NY Sea Grant Advisory Service

22 **Jurisdictional Zones and Governmental Responsibilities** Paul Marr, SUNY at Albany

23 **Demographic Patterns** Charles Koebel and Donald Krueckeberg, Rutgers University

24 **Transportation** Richard K. Brail and James W. Hughes, Rutgers University

25 **Electricity Generation and Oil Refining** H.G. Mike Jones, Harold Bronheim, and Philip F. Palmedo, Brookhaven National Laboratory

26 **Waste Disposal** M. Grant Gross, Chesapeake Bay Institute, Johns Hopkins University

27 **Water Quality** Donald J. O'Connor, Robert V. Thomann, and Henry J. Salas, Hydroscience, Inc.

28 **Air Quality** Volker A. Mohnen, Atmospheric Sciences Research Center, SUNY

29 **The Lower Bay Complex** Iver Duedall, Harold O'Connors, Robert Wilson, and Jeffrey H. Parker, Marine Sciences Research Center, SUNY

30 **Industrial Wastes** James A. Mueller and Andrew R. Anderson, Manhattan College

31 **Marine and Coastal Birds** Marshall A. Howe, Roger B. Clapp, and John S. Weske, US Fish and Wildlife Service

32 **Environmental Health** Joseph M. O'Connor, Chun Chi Lee, and Merril Eisenbud, Institute of Environmental Medicine, NYU Medical Center

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