ENVIRONMENTAL CHARACTERISTICS OF RARITAN BAY, A POLLUTED ESTUARY[1]

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ABSTRACT

Temperature, salinity, dissolved O_2, PO_4-P, and NO_3-N in Raritan Bay, N. J. were determined over a 16-month period. Each reflects the circulation pattern in which sea water floods along the northern shore, enters a region of mixing with river discharge in the head of the bay, and then ebbs out along the southern shore.

At the mouth of the bay, salinity was higher on the northern than on the southern side. The mean annual monthly difference at the surface was 1.27‰; departures from the mean were related to river flow.

Surface and bottom dissolved O_2 content were minimal in August and highest during winter. Low concentrations occurred in the Raritan River, especially during the summer preceding operation of a trunk sewer.

The primary source of NO_3-N was outflow from the Raritan River. Prior to operation of a trunk sewer, the river may have discharged significant quantities of PO_4-P into the bay.

Throughout spring and summer, PO_4 concentrations rose and NO_3 decreased. It is postulated that the resultant low N:P ratio was partially due to an efficient nutrient regeneration mechanism that favored the rate of P renewal.

A combination of rich nutrient supplies arising from natural and domestic sources, plus a sluggish circulation, efficient nutrient regeneration mechanism, and scarcity of macroscopic algae combine to form an estuarine environment capable of supporting extremely dense plankton populations.

INTRODUCTION

The Raritan is one of a system of bays and lagoons characterizing the Atlantic Coast of New Jersey. Such waters, affording ready access by ocean-going vessels to industrialized areas, have become an important factor in the economy of the state. Valuable biological populations dwelling within these brackish waters and recreational opportunities provide a variety of occupations. In some areas, including Raritan River and Bay, biological and aesthetic values have suffered greatly from industrialization. Prior to World War I, the bay supported profitable oyster crops and diverse fish stocks. Today, with the surge of urban growth and industrialization, pollution has brought the demise of the oyster industry, greatly reduced abundances of fishes, and all but eliminated recreational aspects. A multimillion dollar trunk sewer, which began operation in the Raritan Valley in January, 1958, gives primary treatment followed by transportation of sludge to offshore disposal areas and discharge of liquid effluents into the head of the bay.

The Raritan system (Fig. 1), approximately 25 miles in length, is oriented in a general east–west direction. It is divisible into three parts progressing seaward: Raritan River, Raritan Bay, and Lower New York Bay. Depths are relatively shallow, increasing gradually from either shore to 22 ft in Raritan Bay and 28 ft in Lower Bay.

Raritan Bay has the triangular shape of a flattened funnel; morphometrically, it typifies an "ideal" estuary. Source waters—fresh from the Raritan River and salt from Lower Bay—enter the basin at opposite ends with a tendency for each to flow to its respective right side. Mixing produces a great counterclockwise gyre of slowly circulating water masses. The net currents of this gyre, illustrated schematically in Figure 2, establish a series of physical-chemical gradients directed along, and at right angles to, the axis of the estuary. This investigation was undertaken to: 1) relate distribution of physical and chemical factors to pattern of circulation, 2) evaluate alterations of estuarine

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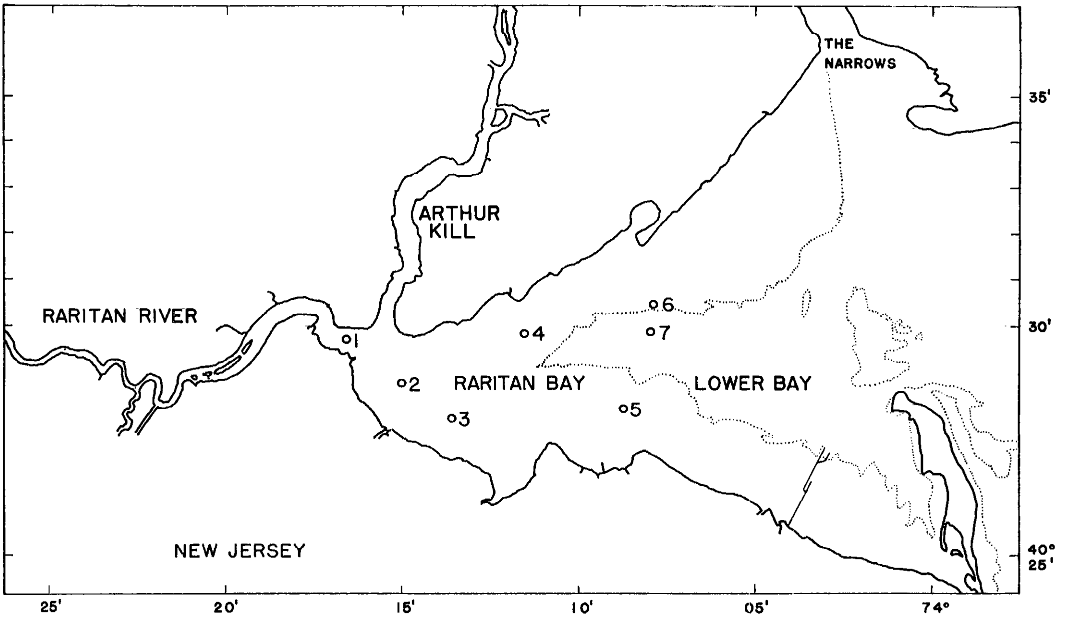

FIG. 1. The Raritan system, showing locations of seven routine collection stations; dotted line indicates 20-ft contour.

nutrient cycles by pollutants, and 3) determine basic conditions of the environment for testing the thesis that estuarine plankton communities create an array of phenomena which reflect physical-chemical gradients. Plankton studies will be presented in subsequent reports.

Previous Studies on Circulation of the Raritan

Figure 2 was prepared from the findings of Ketchum (1950), Marmer (1935), Ayers, Ketchum, and Redfield (1949), Rudolfs and Fletcher (1951), and Udell (1951). These intensive, short-term investigations demonstrated that the flushing of Raritan and Lower Bays was dependent primarily on the resultant of localized inequalities in duration and strength of ebb and flood tides. In relation to volume of the embayment, little water escapes with each cycle. Mean tidal range was 5.5 ft, and the surface area of the Raritan system surveyed by Ketchum (1951a) was 1,670 × 10^6 ft^2. Hence, total volume of the tidal prism was 9,200 × 10^6 ft^3, or 300 times more water than was introduced by the river during a tidal cycle in December, 1948. Flushing times calculated by Ketchum (1951b) for Raritan Bay ranged from 32 to 42 tides for maximum and minimum river flows. Sixty tides were required to flush river water through the entire estuary during the December, 1948 survey.

Salinity in Lower Bay was 25–26‰ at the time of Ayers' survey. The component flooding into Raritan Bay approaches its northern shore, continues past station 4 (Fig. 1), and arrives in an area of extensive eddies and

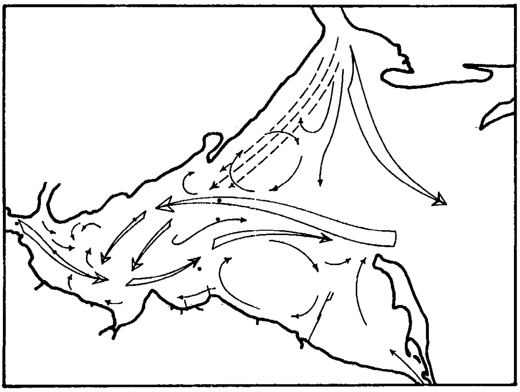

FIG. 2. Schematic representation of net currents in Raritan and Lower Bays.

mixing with fresh water near the confluence of the Raritan River and Arthur Kill. The latter is not a significant source of fresh water but rather a surge basin contributing to mixing processes. A southward thrust of flooding water reaching station 3 nearly bisects the protrusion of Raritan River discharge resulting from the previous ebb tide. According to Ayers, this "appears to exert a *milking action* which accelerates the seaward movement of freshened water along the south shore of Raritan Bay at the same time damming back the water accumulated in the head of the bay."

METHODS

Field Operations

Six principal stations were established in Raritan Bay (Fig. 1). They were visited weekly during the summer of 1957 and biweekly thereafter until September, 1958. A seventh station situated between 5 and 6 was not sampled routinely. An eighth station between 5 and 7 provided additional physical and chemical data. Several collection points in the Raritan River and Lower Bay supplemented the routine program. On principal stations, water temperature was measured with a reversing thermometer, conditions of weather, wind, and waves recorded, and water samples taken with a Foerst bottle for subsequent determinations of salinity, dissolved oxygen, nitrate-nitrogen, and phosphate-phosphorus.

Laboratory Operations

Salinity was measured according to the method of Knudsen modified for use with a 25-ml burette.

Inorganic phosphate-phosphorus was determined by the Deniges-Atkins method as described by Wattenberg (1937). Stock solutions of stannous chloride specified by several authors produced erratic values on standard phosphate solutions. Reproducible results were obtained at high phosphate concentrations with a freshly prepared reagent consisting of 125 mg stannous chloride in 25 ml 1:10 v/v HCL. Optical density was measured in a Lumertron colorimeter with a 660-mμ filter. Apparent phosphate was corrected for salt interference using unpublished standard curves provided by Dr Harold H. Haskin.

Nitrates were determined by the method of Mullin and Riley (1955), giving particular attention to buffer pH. Attempts to derive reliable salt correction factors using bay water depleted of nitrate with *Skeletonema costatum* were unsuccessful, perhaps due to inhibition by variable concentrations of organic matter. A correction factor for each sample was derived by making triplicate determinations. One flask was treated in the routine manner, and 10 μg nitrate-nitrogen were added to sample portions in each of the other flasks. The slope obtained for optical density versus nitrate for these determinations was compared with standards prepared in distilled water, and a correction factor calculated.

Prior to each run of dissolved oxygen samples, N/40 sodium thiosulfate was standardized against potassium biniodate under subdued light.

RESULTS

Regional comparisons are facilitated by considering stations 1, 5, and 6 which form the apices of a triangle encompassing Raritan Bay. Collectively, these stations monitor the entrance and exit of source waters and will be referred to as the "triangle stations." Data are summarized in Table 1 for each season during the course of the investigation using arithmetic means and their 95% confidence intervals.

Temperature and Salinity

Regional temperatures reflected circulation patterns with greatest clarity during spring, when a pronounced lag in the rate of vernal warming developed on the northern side of the bay. From mid-April through June, station 6 was 1.7 to 3.5°C cooler than 5 at the surface. These variations are attributed to flood tides carrying cool high salinity water through the northern portion of the bay. This water warmed less rapidly in the depths of Lower Bay than Raritan River discharge which flows along the axis of the odd-numbered stations extending down the southern shore.

Size of the confidence intervals for sur-

TABLE 1. *95% confidence intervals for true mean temperature (°C), salinity (‰), dissolved oxygen (ppm), inorganic phosphate-phosphorus (μg-at/L), and inorganic nitrate-nitrogen (μg-at/L) at stations 1, 5, and 6. Summer, 1957–summer, 1958*

TEMPERATURE

	Surface stations			Bottom stations		
	1	5	6	1	5	6
Summer	24.3 ± 0.9	23.0 ± 1.0	23.2 ± 0.9	23.7 ± 0.7	22.1 ± 0.7	21.7 ± 0.8
Fall	11.7 ± 4.5	9.7 ± 4.3	11.1 ± 4.2	11.9 ± 4.0	10.0 ± 4.1	12.1 ± 5.2
Winter	3.4 ± 2.9	2.9 ± 1.6	2.4 ± 1.8	3.0 ± 2.0	3.4 ± 1.8	2.3 ± 1.5
Spring	14.1 ± 6.0	13.6 ± 5.5	12.0 ± 4.5	13.4 ± 5.3	12.4 ± 5.1	11.6 ± 4.9
Summer	24.0 ± 2.8	23.2 ± 3.0	22.8 ± 2.9	23.6 ± 1.2	22.3 ± 2.6	21.6 ± 2.5

SALINITY

	Surface stations			Bottom stations		
	1	5	6	1	5	6
Summer	24.02 ± 1.14	26.37 ± 0.46	26.91 ± 0.60	24.26 ± 1.12	26.59 ± 0.54	27.10 ± 0.41
Fall	21.77 ± 2.24	26.12 ± 1.20	27.14 ± 0.71	22.71 ± 2.45	26.35 ± 1.22	27.28 ± 0.82
Winter	12.88 ± 6.86	19.55 ± 1.38	23.27 ± 2.17	18.93 ± 4.42	21.46 ± 3.14	22.75 ± 3.26
Spring	11.82 ± 6.91	17.98 ± 4.47	19.13 ± 6.41	16.50 ± 4.07	19.80 ± 4.36	20.69 ± 4.56
Summer	25.09 ± 2.22	26.23 ± 1.42	26.74 ± 0.82	24.95 ± 1.32	26.59 ± 1.72	27.39 ± 0.80

DISSOLVED OXYGEN

	Surface stations			Bottom stations		
	1	5	6	1	5	6
Summer	4.17 ± 0.89	8.76 ± 1.44	7.84 ± 1.85	3.73 ± 0.81	7.13 ± 1.22	6.24 ± 0.80
Fall	4.32 ± 1.33	8.68 ± 2.38	8.03 ± 1.17	4.57 ± 2.02	8.41 ± 1.78	7.87 ± 1.17
Winter	9.12 ± 1.14	9.94 ± 0.32	9.89 ± 0.67	9.03 ± 1.15	9.74 ± 0.51	9.60 ± 0.44
Spring	6.18 ± 2.08	7.64 ± 1.57	8.31 ± 3.01	5.56 ± 2.56	7.30 ± 2.85	7.93 ± 3.14
Summer	4.80 ± 0.45	6.86 ± 2.98	8.07 ± 3.85	3.77 ± 1.44	5.65 ± 1.60	5.83 ± 1.65

INORGANIC PO_4-P

	Surface stations			Bottom stations		
	1	5	6	1	5	6
Summer	2.76 ± 0.76	2.20 ± 0.78	4.29 ± 2.00	3.82 ± 1.30	2.93 ± 0.85	4.16 ± 1.52
Fall	3.67 ± 1.85	3.55 ± 0.33	4.33 ± 0.79	4.37 ± 0.45[a]	3.65 ± 0.26[a]	4.34 ± 0.55[a]
Winter	2.05 ± 1.15	2.69 ± 1.73	1.99 ± 0.45	—	—	—
Spring	1.79 ± 1.01	1.78 ± 0.76	3.25 ± 2.59	—	—	—
Summer	3.05 ± 1.38	2.58 ± 2.14	3.38 ± 1.70	—	3.53 ± 1.81[a]	4.81 ± 0.46[a]

INORGANIC NO_3-N

	Surface stations[b]		
	1	5	6
Winter, Spring	95.9 ± 41.7	34.7 ± 13.6	26.3 ± 11.6
Summer	27.9 ± 16.0	13.6 ± 9.4	6.7 ± 9.7

[a] mean ± standard deviation, N = 2.
[b] 1958 only.

face salinity in Table 1 indicates spatial differences in mixing of ebb and flood tidal currents and seasonal variation in river flow rates (Table 2). These intervals are maximal at station 1, denoting mixing of fresh and salt waters in the head of the bay, and minimal during the summer (1957 in particular) when river flows were low and relatively constant.

Differences between mean monthly salinities at stations 5 and 6 provide a series of indices which are related to variations in the dynamics of flushing. A positive value in Figure 3 expresses the extent to which station 6 was more saline than 5 in parts per thousand. Control lines establishing confidence limits for the difference between annual means at the two stations were calculated by pairing monthly data according to the method given by Dixon and Massey (1957, p. 128). Positive values less than 1.27‰, the mean annual difference, occurred from June through December, 1957, and then increased abruptly, attaining a peak in February. This relationship indicates the extent of bilateral separation of ebb and

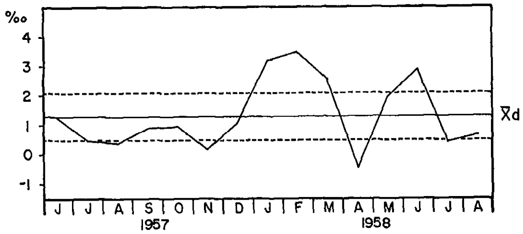

FIG. 3. Differences between monthly mean salinities at stations 5 and 6. The relationship is positive when station 6 is more saline than 5. Annual mean difference and 95% confidence interval for difference between paired means are indicated.

flood water masses. Extremely low river flow during the summer was apparently well mixed with bay water before ebbing much beyond the mouth of the river. In this locality, surface and bottom salinities generally differed by less than 1‰ from June through November, 1957. Pronounced bilateral salinity differences from January to March were associated with river discharge increasing 6 to 50 times over summer and autumn rates. The precipitous decline from a bilateral difference exceeding the upper control limit in March to a reversal of the usual relationship in April may have been due to Hudson River flow, augmented by spring thaws in its upper drainage basin. This helped to produce a dilute source sea water for Raritan Bay. By the distribution of coliform bacteria, Udell (1951) demonstrated a tongue of water extending from The Narrows toward station 6 during summer. The full force of fresh water from the Hudson River system may have arrived here in April and expanded the usually limited flow into the bay.

Dissolved Oxygen

Dissolved oxygen concentrations rose from minima in August, 1957 (less than 2.5 ppm at station 1) to values near saturation for the bay in general during the following winter and spring. Throughout the first half of the field program, the Raritan River was extremely polluted; in August no oxygen could be detected in surface and bottom samples taken 3.8 and 7.4 miles upstream from the river's mouth. This condition was reflected by relatively low oxygen concentrations in the head of the bay and progressive increases in oxygen content along the southern shore as river water became further diluted with bay water (Table 3). A trunk sewer serving the Raritan Valley began operation in January, 1958. Immediately thereafter, oxygenation improved rapidly at station 1 and in the river. Higher surface than bottom values in Table 1 are doubtless associated with phytoplankton photosynthesis in surface strata overriding oxygen consuming processes of organic decomposition and respiration by benthic animals (Patten 1961).

TABLE 2. *Mean daily discharge rate of Raritan River in ft^3/sec, 1957–1958*

Month	1957	1958
January	925	2,739
February	1,754	1,854
March	1,578	3,716
April	3,022	3,246
May	648	2,359
June	280	557
July	131	709
August	95	360
September	122	346
October	148	—
November	283	—
December	2,393	—

Inorganic Nitrate-Nitrogen

In the mouth of the Raritan River, concentrations exceeding 100 μg-at/L occurred during the spring of 1958 and were higher for the most part than at bay stations during the remainder of the investigation. Several samples taken within the river gave still higher readings and ranged from 106 to 194 μg-at/L indicating that the river is an important source for plant nutrient and must play a sig-

TABLE 3. *Mean concentration of oxygen (ppm) at surface stations along the New Jersey shore. Alternate months, August, 1957 to July, 1958*

Month	Station			
	1	2	3	5
August	3.71	4.38	5.71	9.90
October	4.59	6.10	7.33	9.00
January and February	8.66	8.55	9.34	10.06
March	9.43	9.26	9.17	9.86
May	5.90	5.08	5.20	7.03
July	4.90	6.79	5.39	6.69

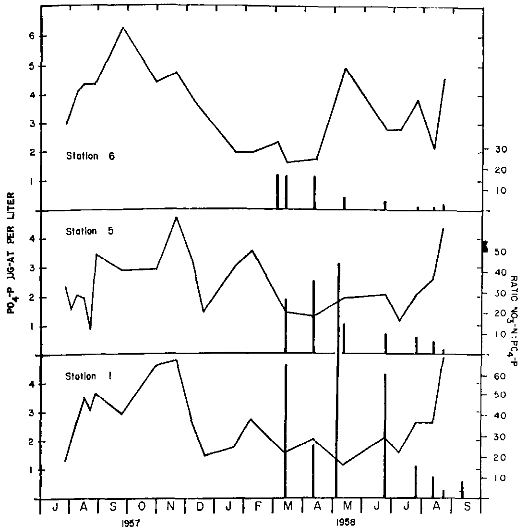

FIG. 4. Surface inorganic phosphate-phosphorus and nitrate to phosphate ratio (bar graphs) at stations 1, 5, and 6.

nificant role in the primary productivity of Raritan Bay.

The pattern was a gradient of consecutively lower concentrations extending down the river and along the southern shore. In mid-summer, when river flow and the amount of nitrate discharged into the bay were minimal, station differences were less; however, they maintained the same general relationship. The trunk sewer is evidently not the most important source of nitrate since relatively low values, often intermediate between those at stations 1 and 3, were obtained at 2, located 400 yards southeast of the sewer outfall. According to Dr Myron Rand, Chief Chemist of the Middlesex County Sewage Authority, domestic sewage contains about 1 ppm of nitrate-nitrogen. This is the same order of magnitude as Raritan River water. Even though the volume of effluent from the sewer is considerable, distribution of phosphate, discussed below, in the vicinity of the outfall indicates rapid dilution of discharged waste materials. In most instances, nitrate was minimal at station 6 indicating lesser contributions from the sea than from the river.

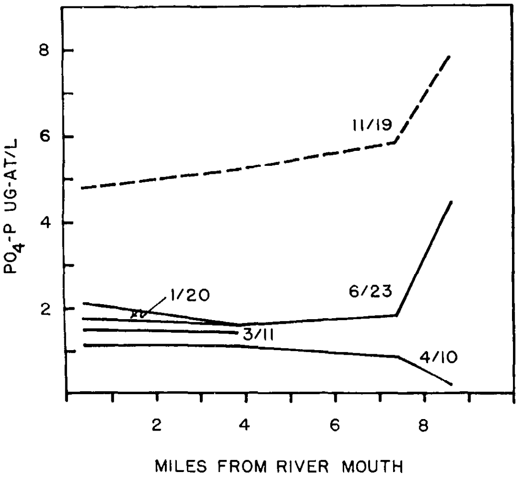

FIG. 5. Spatial distribution of surface phosphate-phosphorus in the Raritan River before (broken line) and after (solid lines) operation of the trunk sewer.

Inorganic Phosphate-Phosphorus

A general non-parametric distribution for phosphate which reflects the course of tidal currents can be described for Raritan Bay. The following pattern, showing rank order of surface phosphate concentration at the various stations, was obtained for the period of sampling with the sign test. Values were maximal at station 6 in most instances and smallest at station 5, directly across the bay.

$$6 > 4 > (1 = 2 = 3) > 5$$

Noting relationships at the "triangle stations" (1, 5, and 6) and in the Raritan River (Figs. 4 and 5), it is apparent that there are two major phosphate sources. The first and perhaps more important is Lower Bay water flooding into Raritan Bay along the northern shore. On all but 4 cruises, concentrations were higher in this area than directly across the bay at station 5. Influx of phosphate, perhaps by an incursion of Hudson River drainage, is suggested by dilution of the tongue upon progressing into the bay.

Contributions of phosphate originating from discharged sewage and land runoff are not distinct in the head of the bay since values varied randomly in this intensive mixing zone. Previous to operation of the trunk sewer, phosphate content increased progressively going upriver and exceeded 7.7 μg-at/L upon reaching fresh water 8.6 miles from the mouth (Fig. 5). Waste materials then discharged into the river may have been responsible for the upstream gradient. Following initiation of trunk sewer operation in January, 1958, concentrations in the river were lower, for the most part, than in the bay. Rapid mixing of sewer effluent and bay water was demonstrated by phosphate concentrations in the immediate vicinity of the outfall. Surface samples taken on an ebb tide 100 yards to the east and west of the outfall showed a threefold difference in concentration: 2.90 μg-at/L on the river side and 9.35 μg-at/L immediately downstream from the discharge point, but 400 yards southeast at station 2, the content was 2.83 μg-at/L.

DISCUSSION

Spatial distribution of the physical and chemical properties reported here exhibit gradients directed along and at right angles to the axis of the estuary. Degree of development depends upon season and specific property considered. Variations in regional temperature and salinity relationships are due to amount of fresh water inflow, different heat budgets in source areas of fresh and salt waters, and changes in the salinity of source sea water. During wet seasons, partially mixed river discharge flows over more saline bottom water with increased rapidity and is deflected toward the southern shore as the flushing mechanism adjusts to an increased fresh-water load. Gravitational forces tend to spread the less dense mixture across the surface of the bay (Ayers, *et al.* 1949), but when runoff is high, a larger proportion of river water probably ebbs along the southern shore than in dry periods. Biological populations dwelling in the head of the bay or any material introduced into this area will be transported out of the estuary faster than expected by the proportionate increase in river discharge over periods of low flow rates.

Gradients exhibited by non-conservative properties—dissolved oxygen and nutrients—also reflect circulation processes. Regional variations in concentration are determined not only by physical mixing processes but, in addition, are coordinated with seasonal rates of biological activity. The ebb circulation directed along the southern shore is enriched with nitrate emanating from the Raritan River. Nitrate concentrations at station 5, in the path of the ebb flow at the mouth of Raritan Bay, averaged 1.5 times higher than 2.8 miles directly north across the bay at station 6, located on the axis of the flood current. Phosphate is supplied to Raritan Bay at its landward and seaward extremes in the fresh and salt waters entering the bay. Consequently, regional differences are less marked than those for nitrate. When phosphate concentrations at 6 stations are arranged in a decreasing rank order, the relationship (station $6 > 4 > (1 = 2 = 3) > 5$) indicates that phosphate is maintained in Raritan Bay in the following manner: 1) Waters high in phosphate enter the bay with the net landward tidal flow along the northern shore. 2) Absorption by phytoplankton reduces the concentration progressing into the head of the bay, where contributions from the river and trunk sewer are then received. 3) Utilization continues in the net ebb current directed along the southern shore with the result that water leaving the bay is relatively low in phosphate. This phosphate conservative intake-discharge mechanism is probably associated with extremely high chlorophyll levels during summer (Patten 1959) and bears a resemblance to the process described by Hulbert (1956b) for Falmouth Great Pond.

A pronounced spring maximum similar to that obtained for nitrate did not occur. Since we must assume that land runoff during wet spring months contains quantities of phosphate in addition to nitrate, there may be a selective mechanism of phosphate removal especially operative at this time. Turbidity is very high during spring; indeed, visible evidence of the ebb current along the southern shore was shown on 1 March by a distinct band of muddy water leading from the river across station 5. In the river itself, suspended material became so dense that a coarse plankton net was completely clogged and the attached bucket filled with tracheophyte detritus. Phosphate adsorbs onto colloidal micelles and other suspended material, and with settling, the nutrient is probably removed from biological circulation in Raritan waters until summer when detritus feeders become active. Carritt and Goodgal (1954) suggested that dissolved substances are removed in the turbid headwaters of an estuary and then released following transport into the area where fresh and salt waters mix. Jitts (1959) showed that estuarine silts can trap 80 to 90% of the high concentration of phosphate present during periods of high fresh water runoff and later release it when conditions are more stable, thereby contributing to the high level of productivity characteristically maintained in an estuary.

Part of the explanation for the less distinct seasonal cycle of phosphate in comparison with nitrate is due to buffering action by the above mechanism and the fact that sewage entering the bay in a number of scattered places has a low N:P ratio. Twelve primary treatment plants are situated on the shores of the Raritan estuary. Their effluents may tend to cancel temporal and regional differences in phosphate concentrations without markedly altering the distribution of nitrate.

Ratio of Nitrate-Nitrogen to Phosphate-Phosphorus

Diminishing concentrations of nitrate from winter through summer agree with the seasonal cycle in the sea. However, phosphate increased during this period, and, consequently, the ion ratio of nitrate to phosphate shown in Figure 4 decreased. Redfield (1934) demonstrated a constant ratio of the two ions that holds for all oceans and is maintained within certain limits regardless of absolute concentrations. Departures have been discussed by Ketchum, Vaccaro, and Corwin (1958), but the tremendous range observed here, from 111.4:1 to 1.3:1, indicates that nutrient utilization, regeneration, and transport are quantitatively not the same in the estuary and offshore. Reduction of river flow carrying concentrations of nitrate and the aforementioned benthic release mechanism for phosphate must be partially responsible for the summer decrease in the ratio. In addition, bacterial action on discharged sewage may be more active during summer than winter, producing an absolute increase of phosphate and a drop in the ratio during the warm seasons.

It is postulated that a primary cause of the decreasing ratio in Raritan Bay is a seasonal change in the relative rates of nitrate and phosphate regeneration. At the primary producer level, algal phosphatases dephosphorylate organic phosphorus in phytoplankton tissue yielding orthophosphate when the plants die (Matsue 1949). Enzymes acting in a similar nature on proteins to release nitrate are not known. Consequently, rapid decomposition of organic phosphorus could be partially responsible for reducing the NO_3:PO_4 ratio. During the seaward progression of a dead estuarine planktont, regeneration returns relatively more inorganic phosphorus than nitrogen to estuarine circulation. Upon reaching the ocean, the remains of the organism are higher in nitrogen than phosphorus in comparison with its composition at the time of death within the estuary.

Animal feeding and digestion may well be involved in producing high summer phosphate concentrations. This is an extension of Newcombe's (1940) hypothesis attributing short-term changes in phosphate content of Chesapeake Bay waters to the metabolic activities of plankton. Copepods, compared with phytoplankton, are relatively rich in nitrogen (Sverdrup, Johnson, and Fleming 1942, p. 234). The residual excess of plant-phosphorus taken in as food and passed out in the feces in the form of partially digested and less complex molecules further diminishes the NO_3:PO_4 ratio. According to Harvey (1955), phosphorus in copepod fecal pellets dissolves in salt water and does not remain in voided plant particles. Dephosphorylation by plant enzymes doubtless takes place in the digestive tract of a copepod, a process which could also occur in bottom animals. Metabolic orthophosphate is excreted regardless of food intake and phosphorus passes so rapidly through a copepod that Conover, Marshall, and Orr (1959) found it necessary to correct for this factor when measuring the feeding rate of *Calanus finmarchicus* with P^{32}-tagged diatoms.

Cooper's (1935) investigation showed that phosphate liberated by decomposing zooplankton attained concentrations greater than the sum of phosphate initially present in the water plus added plankton-phosphorus. The excess was produced from dissolved organic phosphorus initially present in the water. We might expect, therefore, that the digestive, excretory, and death processes of spring and summer plankton populations tend to promote initial regeneration rates of phosphate with respect to nitrate.

Generally higher bottom than surface phosphate concentrations (Table 1) may indicate the significance of benthic populations in control of the NO_3:PO_4 ratio. In addition to the metabolic activity of benthic populations, stratification is probably due to a combination of differential rates of phosphate removal from surface and bottom waters and regeneration of plankton-phosphorus in the lower part of the water column. Data are not available to evaluate these rates, but their relative significance may be inferred. Absorption by phytoplankton in surface waters and regeneration in lower levels could produce phosphate stratification in the absence of turbulence, but bottom concentrations as much as 1.95 μg-at/L greater than at the surface persisted during summer periods of tidal overmixing, and similar differences occurred during late fall when chlorophyll was present in occasional trace quantities. This indicates that factors such as the metabolic activity of benthic organisms may have contributed to the observed vertical distribution of phosphate. Regeneration of phosphate in shallow mud bottom was suggested by Cooper (1951), and Stephenson (1949) observed phosphate emanating from the bottom of a polluted estuary. Harvey (1955) mentioned that autolysis of bacteria in sediments releases considerable amounts of phosphate to interstitial water, and Riley (1941a, b), suggesting that a low N:P ratio is characteristic of shallow regions, drew attention to decomposition of organic sediments at high summer temperatures.

Comparison with Other Areas

Low estuarine N:P ratios have been observed by a number of authors. High dissolved phosphorus levels in Florida estuaries reported by Odum, *et al.* (1955) and others were ascribed to terrigenous and sewage contributions. Sources of similar nature pertain to Raritan Bay, but it seems unlikely that they alone could account for the tremendous seasonal range of the ratio.

Maximum surface nitrate concentrations recorded in Raritan Bay, excluding station 1, were 3 to 7 times higher than those obtained in Long Island Sound (Riley and Conover 1956), Georges Bank (Riley 1941b), and Friday Harbor (Phifer and Thompson 1937). The lowest value recorded in Raritan Bay, 2.8 μg-at/L at station 6, was still higher than the mean summer level in Long Island Sound; phosphate showed a lesser difference, averaging about 1.5 to 2 times higher in Raritan Bay.

Nash (1947) drew attention to the concentrations of nutrients in Chesapeake Bay, but his Figure 44 for the lower portion of one of its tributaries, the Patuxent River, shows that nitrate is maintained at approximately 1 μg-at/L, except during the spring when values are several times higher. According to Newcombe, Horne, and Shepherd (1939), phosphate ranges between 0.6 and 1.6 μg-at/L. In Narragansett Bay, concentrations are less than 1 μg-at/L during winter and spring and generally range between 1.5 and 4 μg-at/L in the summer (Pratt personal communication). Comparison of these values with Table 1 demonstrates the extreme richness of plant nutrients in Raritan Bay. In spite of fertilization by pollutants, vertical eddy conductivity in the shallow and weakly stratified bay waters is apparently sufficient to insure oxygenation at all levels.

An almost complete absence of benthic algae beneath the intertidal zone in Raritan Bay may be indirectly associated with higher summer phosphate and nitrate levels than were found in the lagoons investigated by Hulbert (1956a, b), J. Conover (1958), and R. Conover (1961). A large portion of the bottom in each of these embayments is covered with a dense algal mat in which *Ulva* and *Cladophora* abound. Odum, Kuenzler, and Xavier (1958) showed a high rate of P^{32} uptake by these forms which, according to J. Conover (1958), have their major growth period from spring through early autumn.

Rich nutrient supplies arising from natural and domestic sources coupled with a sluggish circulation and efficient nutrient regeneration produce an environment capable of supporting dense biotic communities. Subsequent papers discuss the zooplankton.

REFERENCES

Ayers, J. C., B. H. Ketchum, and A. C. Redfield. 1949. Hydrographic consideration relative to the location of sewer outfalls in Raritan Bay. Woods Hole Oceanogr. Inst., Ref. No. 29–13. (Unpublished ms.)

Carritt, D. E., and S. Goodgal. 1954. Sorption reactions and some ecological implications. Deep Sea Res., **1**: 224–243.

Conover, J. T. 1958. Seasonal growth of benthic marine plants as related to environmental factors in an estuary. Publ. Inst. Mar. Sci. Univ. Texas, **5**: 97–147.

Conover, R. J. 1961. A study of Charlestown and Green Hill ponds, Rhode Island. Ecology, **42**: 119–140.

———, S. M. Marshall, and A. P. Orr. 1959. Feeding and excretion of *Calanus finmarchicus* with reference to the possible role of zooplankton in the mineralization of organic matter. Woods Hole Oceanogr. Inst., Ref. No. 59–32, 12 pp. (Unpublished ms.)

Cooper, L. H. N. 1935. The rate of liberation of phosphate in sea water by the breakdown of plankton organisms. J. Mar. Biol. Assoc., **20**: 197–200.

———. 1938. Redefinition of the anomaly of the nitrate-phosphate ratio. J. Mar. Biol. Assoc., **23**: 179.

———. 1951. Chemical properties of the sea water in the neighborhood of the Labadie Bank. J. Mar. Biol. Assoc., **30**: 21–26.

Dixon, W. J., and F. J. Massey. 1957. Introduction to Statistical Analysis. McGraw-Hill Book Co., New York, 488 pp.

Harvey, H. W. 1955. The Chemistry and Fertility of Sea Waters. Cambridge Univ. Press, 224 pp.

Hulbert, E. M. 1956a. The phytoplankton of Great Pond, Massachusetts. Biol. Bull., **110** (2): 157–168.

———. 1956b. Distribution of phosphorus in Great Pond, Massachusetts. J. Mar. Res., **15**: 181–192.

Jitts, H. R. 1959. The adsorption of phosphate by estuarine bottom deposits. Australian J. Mar. Freshw. Res., **10**: 7–21.

Ketchum, B. H. 1950. Hydrographic factors involved in the dispersion of pollutants introduced into tidal waters. J. Boston Soc. Civil Eng., **37**: 296–314.

———. 1951a. The exchanges of fresh and salt water in a tidal estuary. J. Mar. Res., **10**: 18–38.

———. 1951b. The flushing of tidal estuaries. Sewage and Industr. Wastes, **23**: 198–208.

———, R. F. Vaccaro, and N. Corwin. 1958. The annual cycle of phosphorus in New England coastal waters. J. Mar. Res., **17**: 282–301.

Marmer, H. A. 1935. Tides and Currents in New York Harbor. Spec. Publ. No. 111, U. S. Dept. of Commerce, Coast and Geodetic Survey, 198 pp.

Matsue, Y. 1949. Phosphate storing by a marine diatom. J. Fish. Inst. Japan, **2**: 29. (In Japanese—referred to by Harvey, 1955).

Mullin, J. B., and J. P. Riley. 1955. The spectrophotometric determination of nitrate in natural water with particular reference to sea water. Analytica Chimica Acta, **12**: 464–480.

Nash, C. B. 1947. Environmental characteristics of a river estuary. J. Mar. Res., **6**: 147–174.

Newcombe, C. L. 1940. Studies on the phosphorus content of the estuarine waters of Chesapeake Bay. Proc. Amer. Phil. Soc., **83**: 621–630.

———, W. A. Horne, and B. B. Shepherd. 1939. Studies on the physics and chemistry of estuarine waters in Chesapeake Bay. J. Mar. Res., **2**: 87–116.

Odum, E. P., E. J. Kuenzler, and M. Xavier. 1958. Uptake of P^{32} and primary productivity in marine benthic algae. Limnol. Oceanogr., **3**: 340–348.

Odum, H. T., J. B. Lackey, J. Hynes, and N. Marshall. 1955. Some red tide characteristics during 1952–54. Bull. Mar. Sci. Gulf and Caribbean, **5**: 247–258.

Patten, B. P. 1959. The diversity of species in net phytoplankton of the Raritan estuary. Ph.D. dissertation, Rutgers University Library.

———. 1961. Negentropy flow in communities of plankton. Limnol. Oceanogr., **6**: 26–30.

Phifer, L. D., and T. G. Thompson. 1937. Seasonal variations in the surface waters of San Juan Channel during the five-year period, January 1931 to December 30, 1935. J. Mar. Res., **1**: 34–53.

Redfield, A. C. 1934. On the proportions of organic derivatives in sea water and their relation to the composition of plankton. *In*: James Johnstone Memorial Volume, pp. 176–192, Liverpool Univ. Press, 348 pp.

Riley, G. A. 1941a. Plankton studies III. Long Island Sound. Bull. Bingham Oceanogr. Coll., **7**(3): 1–93.

———. 1941b. Plankton studies IV. Georges Bank. Bull. Bingham Oceanogr. Coll., **7**(4): 1–73.

———, AND S. M. CONOVER. 1956. Oceanography of Long Island Sound, 1952–1954 III. Chemical oceanography. Bull. Bingham Oceanogr. Coll., **15**: 47–61.

RUDOLFS, W., AND A. H. FLETCHER. 1951. Report of status of the Raritan River and Bay and effects of discharging into the bay mixed effluents. Mimeo rept., Dept. of Sanitation and Div. of Environmental Sanitation, New Jersey State Dept. of Health.

STEPHENSON, W. 1949. Certain effects of agitation upon the release of phosphate from mud. J. Mar. Biol. Assoc. U. K., **28**: 371–380.

SVERDRUP, H. U., M. W. JOHNSON, AND R. H. FLEMING. 1942. The Oceans, Their Physics, Chemistry, and General Biology. Prentice-Hall, New York, 1087 pp.

UDELL, H. 1951. Bacterial pollution of Raritan and Lower Bays and its relation to shellfish. Typewritten rept., Fed. Security Agency, Publ. Health Serv.

WATTENBERG, H. 1937. Methoden zur Bestimmung von Phosphat, Silikat, Nitrit, Natrat und Ammoniak im Seewasser. Rapp. Proc. Verb. Cons. Int. Explor. Mer, **103**: 4–26.