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Annual cycles of nutrients and chlorophyll in Narragansett Bay, Rhode Island

by Michael E. Q. Pilson[1]

ABSTRACT

Nutrient concentrations in Narragansett Bay change in a regular way through the seasons, so that characteristic and well defined cycles are observed, but are different for each nutrient. The cyclic changes are not explainable by processes in the water column alone, nor by advection, even though the replacement time of water in the bay is only 10–40 days. It appears possible to incorporate much of the cycling activity in 13-m^3 microcosms, so these must include the dominating features of the complex biogeochemical processes involved. Observations in the microcosms suggest that the processes maintaining the annual cycles are sufficiently strong that, in the absence of deliberate experimental manipulation, the cycles might continue not significantly altered through at least one year. Therefore, the nutrient cycles in the bay can be driven largely by activities internal to the bay, especially sediment-water exchanges.

1. Introduction

The seasonality of biological activities in temperate marine waters provides a strong stimulus to examine them, and investigations into the forces and conditions controlling the seasonally occurring events have given us much of our understanding of the factors that govern aquatic ecosystems. Even before it was possible to make accurate measurements of nutrients in seawater, Brandt (1901) recognized the close connection between nutrient dynamics and phytoplankton production; interest in the latter stimulated investigation of the nutrients.

The development of suitable quantitative analytical techniques, and their application by British workers such as Atkins (1925, 1930), Cooper (1933, 1938), Harvey (1926) and Armstrong and Harvey (1950), provided our classical evidence of the seasonality of nutrient concentrations in temperate waters such as the English Channel, and showed the importance of the seasonal changes. Riley used the annual variations in nutrient concentrations extensively to provide inputs to his model of plankton dynamics (e.g., Riley, 1947), and many others have dealt with the effects of seasonally changing nutrients on plankton. Some of this history is given in Sverdrup *et al.* (1942) and by Mills (1982), and it seems that such work has focussed mostly on the larger bodies of coastal water.

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Bays and estuaries have not been examined so thoroughly in this respect, perhaps because of their complexity and the strong advective components required of any complete model. Consequently, the transport of substances through, and their recycling within, estuaries are in general poorly understood. Advective processes must largely control the concentrations of any substance in estuaries where the water has a very short residence time, but in the more interesting cases of long residence times the processes of internal cycling may dominate. In temperate estuaries, for example, there are often quite dramatic seasonal changes in the concentrations of the several nutrient elements (D'Elia *et al.,* 1983; Neilson and Cronin, 1981; Nixon and Pilson, 1983; Taft and Taylor, 1976) but quantitative models accounting for these changes appear to be lacking. A recent and unusually satisfying field and modeling study by Kaul and Froelich (1984) dealt with a system with a much more constant temperature regime than is found in most temperate estuaries. If our understanding of the processes affecting even the nutrient concentrations is inadequate, then we may be in a much worse position to make quantitative predictions about the fates of many other substances of interest that pass through these regions on their way to the sea.

Narragansett Bay (Fig. 1) is a relatively saline temperate estuary, and has been extensively studied (see Dunn *et al.;* 1979 for a bibliography of about 1700 entires). Through most of the bay the salinity is usually in the range of 20–32 ‰. There are pronounced seasonal changes in the concentrations of nutrients and chlorophyll (Smayda, 1957; Kremer and Nixon, 1978).

One major difficulty in attempting to model the concentrations of substances in Narragansett Bay is the assumed dominance of large, and difficult to measure, advective fluxes in both directions through the mouth of the Bay to Rhode Island Sound. The southern end of the bay is usually only weakly stratified, but the typical estuarine two-layered flows must still occur and there is a considerable exchange due to the tides. A rough estimate gave the mean residence time of water in the bay as about 30 days (Kremer and Nixon, 1978), while the analysis by Pilson (1985) showed that fresh water input strongly influences the exchange, with normal variations in this input leading to water replacement times ranging from about 10 to about 40 days.

In this paper I report in some detail the seasonality and also the interannual variability in nutrient and chlorophyll concentrations in lower Narragansett Bay, and by elimination attempt to delimit the processes which are largely responsible for the observed cycles.

2. The data base

a. Nutrients. Nutrient samples were obtained from the area of the Graduate School of Oceanography dock. Salinity at the dock normally varies from about 28 to about 31.5 ‰, with occasional excursions to lower values (Hicks, 1963). The latter paper should be consulted for further hydrographic details. The concentrations of ammonia,
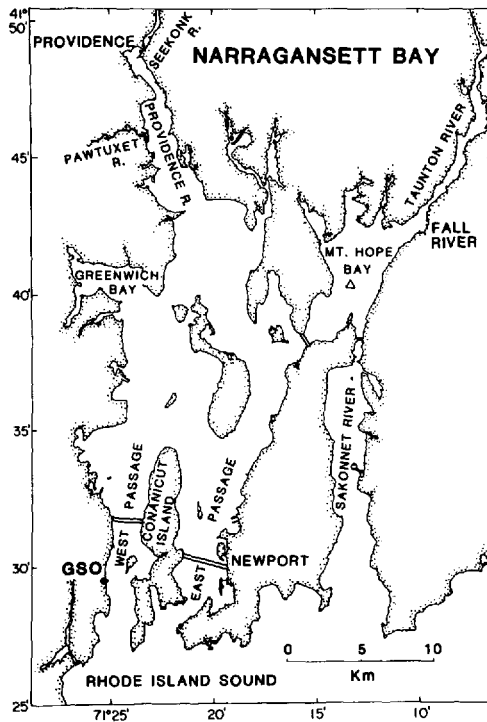
Figure 1. Narragansett Bay, Rhode Island, showing the location of the Graduate School of Oceanography (GSO) Dock, and a sampling station (Δ) in Mt. Hope Bay.

nitrate plus nitrite, silicate, inorganic phosphate and chlorophyll *a* in lower Narragansett Bay at the GSO dock were defined using values obtained at approximately weekly intervals from January 1977 through December 1982. During 1977 and 1978 samples were taken by Niskin bottle from a depth of about 2 m and analyzed as described by Pilson *et al.* (1980). Thereafter, samples were taken from the header tank supplying input water to the MERL microcosms (Pilson *et al.,* 1980). This tank is supplied by diaphragm pumps shown to be nondestructive to plankton. The intake is located under the GSO dock at a depth of 2 to 3 m (depending on tide) below the water surface, the flow is about 170 liters per minute, the residence time of water in the header tank is about 15 minutes, and the tank is well mixed. Therefore, each sample represents approximately 2500 liters of water at the depth of the intake. The tide runs strongly by the dock, sometimes as much as 1 m/s at full flood or ebb, and the sample is drawn from a patch of water ranging from a few meters to nearly one kilometer long. Averaged over several weeks the data should be representative of a region in the lower West Passage of Narragansett Bay, perhaps 10 to 14 km long, centered at the GSO dock. Since the average depth of this segment of the bay is about 9 m (Pilson, 1985),

Table 1. Concentrations of dissolved inorganic phosphate in water taken from a depth of about 3 m at the GSO dock, lower Narragansett Bay, Rhode Island. Each value is the mean of the observations taken each month, with the number of observations in brackets. The overall means for each month and the standard deviations are based on the monthly means. When there were no data for a month, the average concentration for that month from other years was used in calculating the value of the annual mean. Concentrations in μmol/liter.

Month	1977	1978	1979	1980	1981	1982	Mean	SD
Jan.	0.74(3)	1.52(4)	1.26(5)	0.89(4)	0.78(3)	1.23(3)	1.07	0.31
Feb.	0.42(2)	1.75(3)	0.91(3)	0.73(3)	0.73(4)	1.07(4)	0.94	0.45
Mar.	0.49(4)	0.61(2)	0.55(4)	0.86(4)	0.65(5)	0.46(4)	0.60	0.14
Apr.	0.63(4)	0.48(4)	0.64(4)	0.68(4)	—	0.65(4)	0.62	0.08
May	0.85(3)	0.76(4)	0.77(4)	0.86(4)	—	0.76(4)	0.80	0.05
June	1.35(4)	0.83(3)	0.93(4)	1.10(4)	1.03(5)	0.94(5)	1.03	0.18
July	1.53(2)	1.43(4)	1.21(3)	1.52(4)	1.53(4)	1.31(4)	1.42	0.13
Aug.	1.78(4)	1.81(4)	2.19(8)	2.06(3)	1.79(3)	2.20(4)	1.97	0.20
Sept.	1.48(2)	1.56(4)	2.10(4)	1.79(5)	2.02(4)	1.66(3)	1.77	0.25
Oct.	—	1.62(5)	2.30(4)	1.60(3)	1.75(4)	1.46(5)	1.75	0.33
Nov.	1.57(2)	1.12(3)	1.66(4)	1.62(3)	2.00(5)	1.30(5)	1.55	0.31
Dec.	—	1.33(4)	1.59(4)	1.18(5)	1.48(2)	0.80(4)	1.28	0.31
Annual Means	1.16	1.24	1.34	1.24	1.27	1.15	1.23	0.07

the samples should also be closer to a vertically averaged mean than samples taken nearer the surface or bottom. Turbulence evident at the sampling region must enhance the representative nature of the results.

Data are available for 68 months out of the six year sampling period. While measurements were made four times in most months, the number of measurements per month ranged from one to eight. In order to avoid weighting the results according to the frequency of measurements, the data were accumulated and averaged by month. Table 1 provides an example of the data set at this stage. The monthly means were then used to calculate yearly means and six-year monthly means.

Nutrient concentrations in the MERL control microcosms were also measured weekly, samples being collected during the times of mechanical mixing, and values from the three control tanks averaged for the purpose of these comparisons. The usual mixing regime is: 2 hours on, 4 hours off; the tanks become chemically homogeneous within about 10 min after mixing starts. These tanks are large marine microcosms or mesocosms (Pilson *et al.,* 1980; Grice and Reeve, 1982), and are run outdoors with light and temperature regimes similar to those in lower Narrangansett Bay; they contain a 5-m water column and 35-cm thick layer of sediment with a natural benthos in the bottom; photosynthesis is largely planktonic, as in Narrangansett Bay. The tanks may be run with or without a flow of bay water obtained from the end of the GSO dock. Three MERL tanks were run from January 1977 to August 1977 without the flow of

bay water ("batch mode") and nutrient concentrations in these tanks were also measured and averaged.

b. Water replacement times for Narrangansett Bay. River flow data from USGS (1978–1983) were combined with estimates of the drainage area, sewage input, and rainfall to provide estimates of the monthly mean fresh water input to Narrangansett Bay, calculated as in Pilson (1985). The estimated average water replacement time for each month was calculated from the formulation:

$$T = 41.8 \, e^{-0.00435 \, FW}$$

where T is the water replacement time in days, and FW is the fresh water input in m^3/s.

c. Riverine nutrient fluxes. Starting in November of 1978, and continuing at least through September 1982, the U.S. Geological Survey has reported analyses of water samples taken once monthly from the Blackstone River at Manville, R.I. and the Pawtuxet River at Pawtuxet, R.I., along with the instantaneous flow at the time (USGS 1980–1983). These two locations are only a relatively small distance down stream from the location giving the long-term gauge records (USGS 1978–83) so that the rivers at the sample locations represent about 76% of the total gauged flow toward Narranganset Bay (but only about 35% of the total freshwater input). The monthly concentration data for the rivers were converted to fluxes, summed, and used to compare with bay concentrations, for the months where both sets of data were available.

d. Mt. Hope Bay and Block Island Sound. Samples from Block Island Sound were collected at monthly intervals by Marine Research Inc. at two stations from April 1974 until August 1976 (NEPCO, 1978). Station BIS-A (41 20′50″N; 71 38′52″W) was 9 m deep and Station BIS-B (41 19′38″N; 71 38′11″W) was about 16 m deep. Data from both stations, from surface, mid-depth and bottom for 24 months, and only from mid-depth for five months, were combined and averaged by month.

Samples from Mt. Hope Bay were collected at a station south of Spar Island (Fig. 1) by Raytheon Inc. for three months in 1969, and by Marine Research, Inc. monthly from May 1972 until at least Jan. 1983 (MRI, 1972–1983). Data from two depths were averaged, and the 129 months of available data averaged by month.

3. Results

Plots of the mean concentrations of nutrients and chlorophyll *a* (Figs. 2–7) provide a record of the concentrations of these substances at one location in Narrangansett Bay from 1977 through 1982. The spread of values was calculated using twice the standard
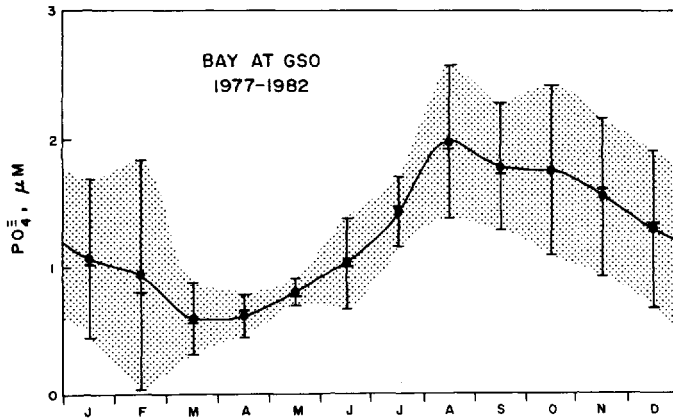
Figure 2. Concentration of inorganic phosphate in water from mid-depth at the GSO dock. Each point is the six-year mean of the monthly means of approximately weekly observations. The ranges given are plus and minus two standard deviations of the monthly means around the overall mean. The shaded area is therefore the field in which it might be expected that approximately 95% of such observations would be found. A small horizontal line indicates the median value.

deviations of the monthly means, so the stippled area represents the field in which approximately 95% of the monthly mean values would be expected to lie. The choice of this statistic to represent the spread of values is arbitrary and imperfect. There are not enough data to define clearly for any month the nature of the statistical distribution (e.g. normal or skewed) of values. In such data it is common to find that occasional
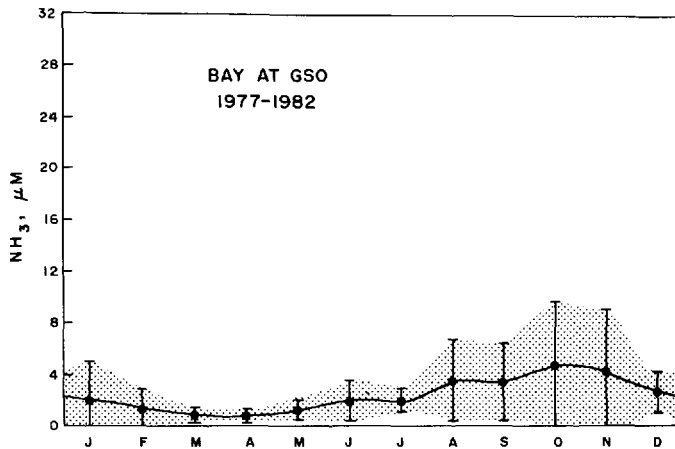
Figure 3. Concentration of ammonia in water from the GSO dock. Rest of legend as for Figure 2.
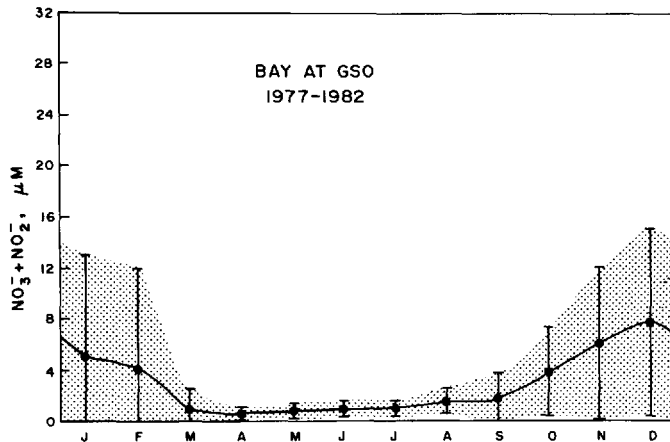
Figure 4. Concentration of nitrate plus nitrite in water from the GSO dock. Rest of legend as for Figure 2.

high values skew the distributions upward. Nevertheless, I thought that, for subsequent analysis, the arithmetic means were the most useful statistic and, for an impression of the variability, the spread of twice the standard deviations would be satisfactory if the reader takes into account that no values can be less than zero. The median values are also inserted on most figures, to provide a rough indication of skewness.

All the nutrient elements show remarkably consistent seasonal patterns. Concentrations are low during March and April, rise through the summer, reach a peak in the
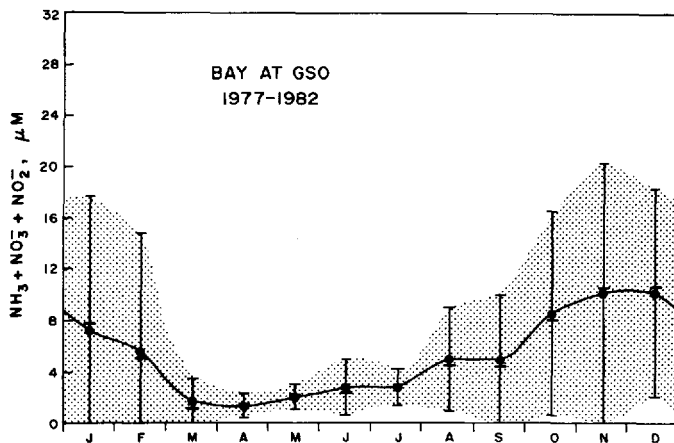
Figure 5. Concentration of total inorganic fixed nitrogen ($NO_2^- + NO_3^- + NH_3$) in water from the GSO dock. Rest of legend as for Figure 2.
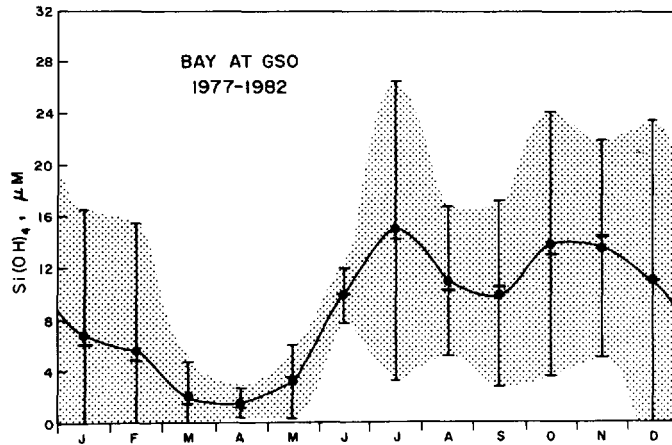
Figure 6. Concentration of dissolved silicate in water from the GSO dock. Rest of legend as for Figure 2.

late summer (phosphorus) or early winter (nitrogen) are high but quite variable in the late winter, and decrease again in the spring. For every element, the concentration is least variable in April or May.

The concentrations of chlorophyll appear more variable than those of the nutrient elements. The means of the monthly relative standard deviations were: chlorophyll *a*, 70%; total inorganic nitrogen, 47%; silicate, 46%; and phosphate, 19%.

The annual changes in nutrient concentrations were different in timing and relative magnitude for the different nutrients. Phosphate showed the simplest and most
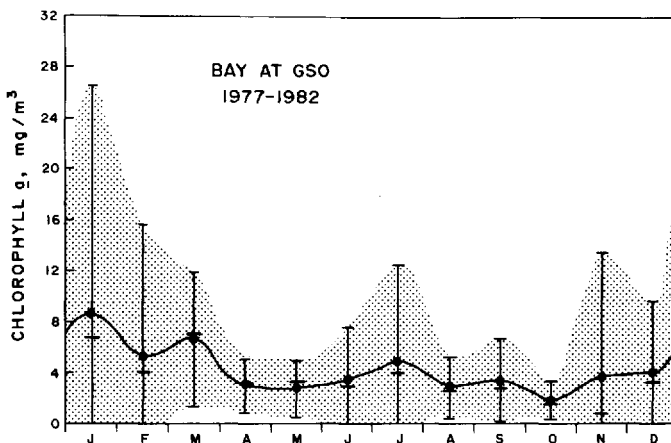

Figure 7. Concentration of particulate chlorophyll *a* in water from the GSO dock. Rest of legend as for Figure 2.
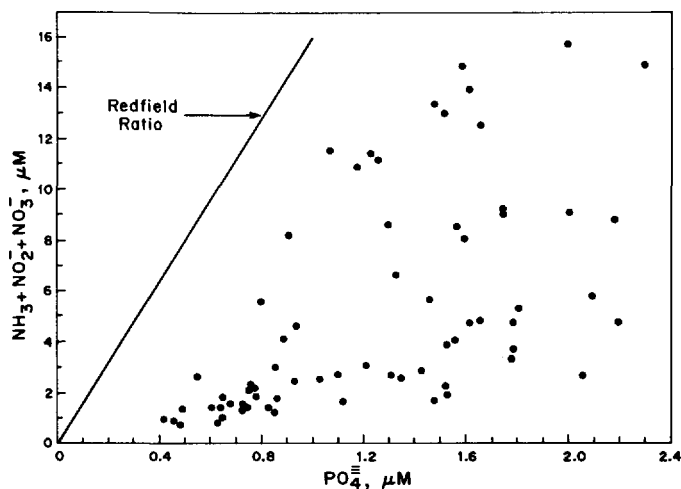
Figure 8. Monthly means of the sum of nitrate, nitrite and ammonia concentrations in water from the GSO dock during six years (1977–1982), vs. the monthly mean concentrations of phosphate. The line represents the usual 16:1 ratio noted for mixed plankton and for nutrients in the deep ocean.

consistent pattern, with a steady rise through the summer, and it never was reduced to really low values, suggesting that it is not usually a limiting nutrient in Narragansett Bay. The inorganic nitrogen species were reduced to low concentrations in the summer, in accord with the common belief that nitrogen is often limiting here (Kremer and Nixon, 1978).

Ryther and Dunstan (1971) showed that N/P ratio of dissolved inorganic nutrients decreased consistently toward the coast from the open N.W. Atlantic, suggesting that it is N that normally limits the biomass of plankton that can be formed in these coastal regions. A plot of the monthly mean concentrations of nitrogen vs. those for phosphate in lower Narrangansett Bay (Fig. 8) provides support for this suggestion. On part of the graph the points are a nearly featureless scatter, but there are no points at all in the high nitrogen, low phosphate region. Low nitrogen values are found, but no low phosphate. (Since all points are averages of several weekly measurements, some individual nitrogen values were lower than shown—well below 1 μM; but such very low values were never found for phosphate.) Clearly, nitrogen may often be limiting but never phosphate. The observation that a line separating the two fields would have a slope approximating the Redfield slope is suggestive but, beyond that, little additional useful information can be extracted. (In any case, the question of N vs. P limitation depends somewhat on the time and space scales considered [Smith, 1984], and this data set was not designed for examining this question.)

I conclude that processes regulating the concentrations of phosphate and nitrogen must operate sufficiently independently (either pathways or kinetics) that the concen-
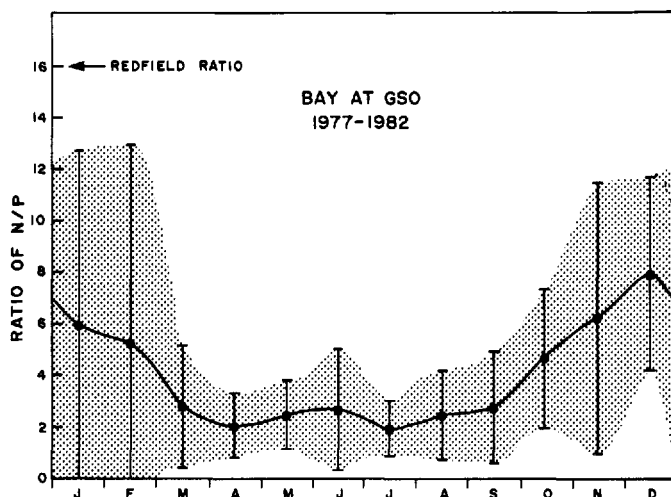
Figure 9. Ratios of the monthly mean concentrations of total dissolved inorganic fixed nitrogen to the dissolved inorganic phosphate in water from the GSO dock. The six-year mean for each month is plotted, and the spread is given by twice the standard deviation of the monthly means.

trations of the two nutrients are not closely coupled. This appears true despite the qualitative similarities in the annual patterns of concentration.

Although the six years of monthly comparisons of nitrogen and phosphate concentrations (Fig. 8) showed little pattern overall, in fact the ratio of N/P was not random but showed a very distinct seasonality (Fig. 9). The ratio never approached the Redfield ratio of 16N:1P, typical of deep water in the open ocean and of average plankton. The generally low values again suggest that phosphorus is not limiting. The failure of the values ever to reach the Redfield ratio suggests that simple decomposition of plankton is seldom or never the dominating process in establishing the observed concentrations.

The disappearance of dissolved nutrients from the water might be expected to correlate with the appearance of nutrients in particulate form. Two tests of this possibility are presented in Figures 10 and 11, which show that the concentrations of particulate chlorophyll *a* and dissolved inorganic N or phosphate exhibit remarkably little relationship. Available data (Fig. 12; Parsons *et al.,* 1977) suggest that the relationship would be expected to show considerable scatter. Nevertheless, if the production of phytoplankton was, by itself, the major determinant of the nutrient concentrations, the pattern should have been detectable. Here, the most that can be said is that the highest chlorophyll concentrations were found only at the lower nutrient concentrations. There is no suggestion of linearity in the relationships.

The total fresh water flow to the bay varies on a daily basis by factors of several hundred, according to the rainfall and season. Even cumulated for a month, the total
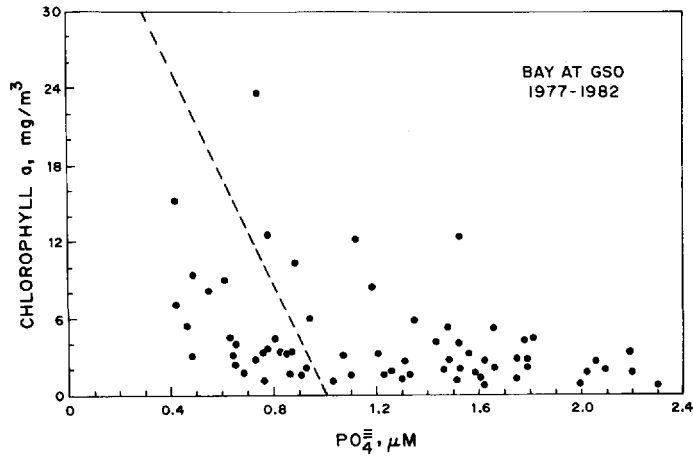
Figure 10. Comparison of the monthly mean concentrations of particulate chlorophyll *a* with the monthly mean concentrations of phosphate in water from the GSO dock, 1977–1982. The dashed line gives the theoretical slope if C/chl *a* = 30, and the Redfield ratio holds (Parsons *et al.*, 1977).

flow varies considerably, and some seasonality is evident in the long time averages (Fig. 13). The hydrologic regime in the bay and the exchange with offshore waters are strongly controlled by the fresh water flow (Pilson, 1985), so it seemed possible that the nutrient concentrations in the bay might be driven or affected by this physical process. This hypothesis is tested by the scatter plot in Figure 14. Evidently the phosphate
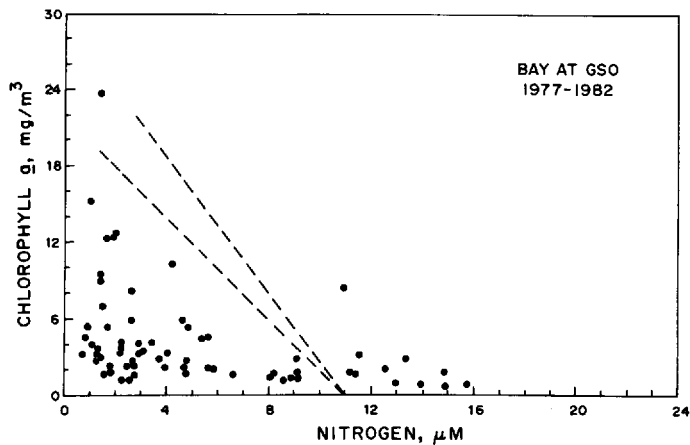

Figure 11. Comparison of the monthly mean concentrations of particulate chlorophyll *a* with the monthly mean concentrations of total dissolved inorganic fixed nitrogen in water from the GSO dock. The upper dashed line means the same as in Figure 10. The lower dashed line is the slope from Figure 12.
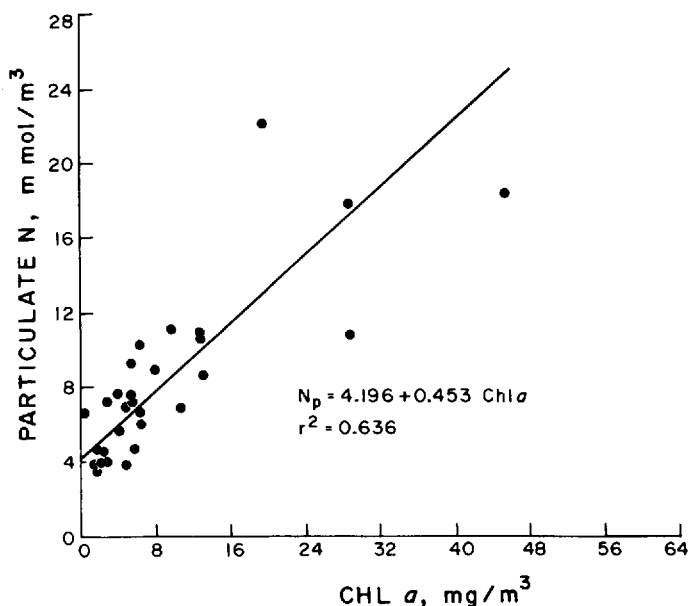
Journal of Marine Research

Figure 12. Relationship of particulate N to particulate chlorophyll *a* in water samples taken from Narragansett Bay at Sta. 2 (west of the N. end of Conanicut Island), at various intervals from Dec. 1977 to Sept. 1979. Data from Furnas (1982). The line is the geometric mean approximation to a functional regression (Ricker, 1973).

concentration is independent of the residence time of the water in the bay, or nearly so. The plot is no better if the fresh water input is used directly, instead of the derived replacement time of the bay water. Nor is the relationship improved if the phosphate values are lagged by one month after the fresh water flow values. The distinct tendency of all points to avoid the mean is curious, and no explanation has come forward.
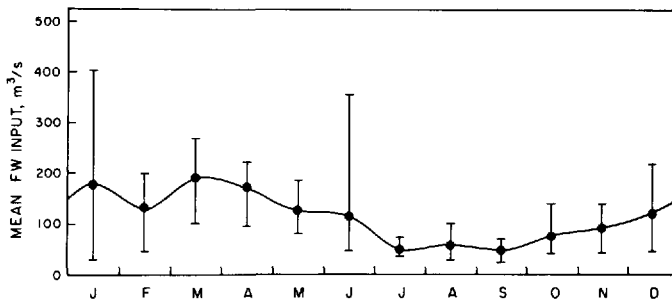

Figure 13. Estimated monthly mean fresh water input to Narragansett Bay, calculated for 1977–1982 (excepting Oct.–Nov. 1982) using gauging station data from USGS (1978–1983) and taking account of the total drainage basin area, sewage and rainfall, as in Pilson (1985).
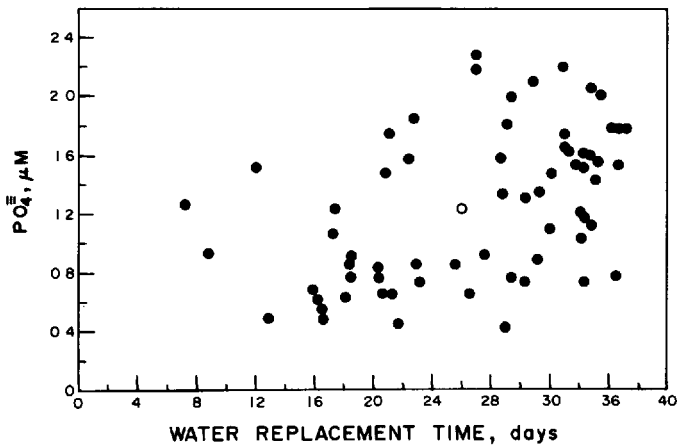
Figure 14. Concentration of inorganic phosphate in water from the GSO dock in lower Narragansett Bay, in relation to the estimated replacement time of the water in the Bay. The open circle is the mean of all points.

The seasonal nature of river flow suggested that the nutrient concentrations in the bay might be driven by the input of nutrients from this source. The USGS data were combined to produce monthly estimates of the measured flux for the years of record (e.g., Fig. 15). These values represent only a portion of the riverine influx, otherwise unmeasured for the years of interest, but presumably the seasonality would be representative. This plot provides very little evidence of seasonality. The largest source of nutrients is probably domestic sewage from communities in the watershed, a source
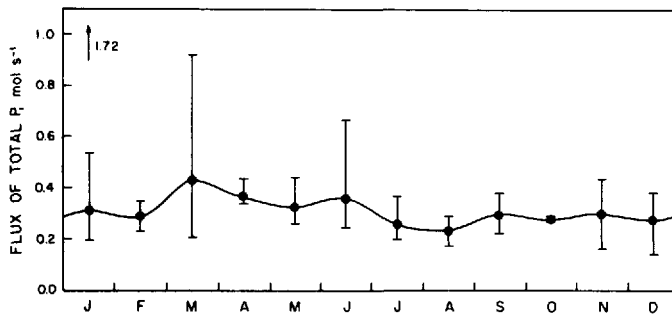

Figure 15. Sums of the flux of total phosphorus toward Narragansett Bay in the Blackstone River sampled monthly at Manville, RI and in the Pawtuxet River at Pawtuxet, RI, from Nov. 1978 through Sept. 1982. Plotted as the means of the monthly totals for each year, with the variability given as the range of values (4 values for each month except 3 values for October). One aberrant value, from Jan. 1979, was excluded from the means. Data from USGS 1980–1983. The drainage area sampled represents about 35% of the total drainage area feeding Narragansett Bay.
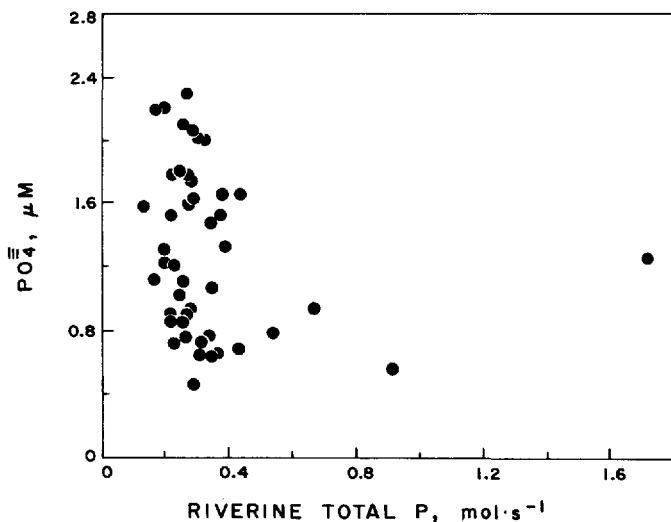
Figure 16. Comparison of the monthly mean concentrations of phosphate in water from the GSO dock with the instantaneously observed flux of riverine total phosphorus, measured at monthly intervals. Riverine phosphorus from USGS (1980–1983).

that is relatively constant, so higher river flows are balanced by lower phosphate concentrations. The flux of total fixed nitrogen, likewise, was not seasonal. The average ratio of total N to total P was 15.9.

A comparison of the riverine flux of total phosphorus with the observed phosphate concentrations at the GSO dock for the months where both records exist (Fig. 16) provides no suggestion that these river inputs control the seasonal changes in the concentration of phosphate in the lower bay. An equal lack of relationship exists between the concentrations of phosphorus in the river and of phosphate in the bay.

The west passage of Narrangansett Bay is a region of active tidal motion, with considerable mixing. It is reasonable to ask whether the seasonal cycles of nutrient concentrations are driven largely by processes elsewhere, the observed concentrations being merely the result of advection and mixing. I could find no data from offshore contemporaneous with the 1977–1982 GSO data. A 29-month study during 1974–1976 in connection with an environmental impact assessment of a proposed power plant, however, has provided a record of nutrient concentrations at two stations in Block Island Sound about 13 km west of the mouth of the bay (Figs. 17–19). These data are sufficient to provide an indication of the concentrations and seasonal changes typical of the region. Concentrations were generally less than those in lower Narrangansett Bay, and the seasonality was less pronounced. Therefore, the observed seasonal changes in the lower bay cannot be driven by changes in the offshore water, although there are short times during the year when it appears that there may well be a small net import of nutrient elements into the bay from offshore.
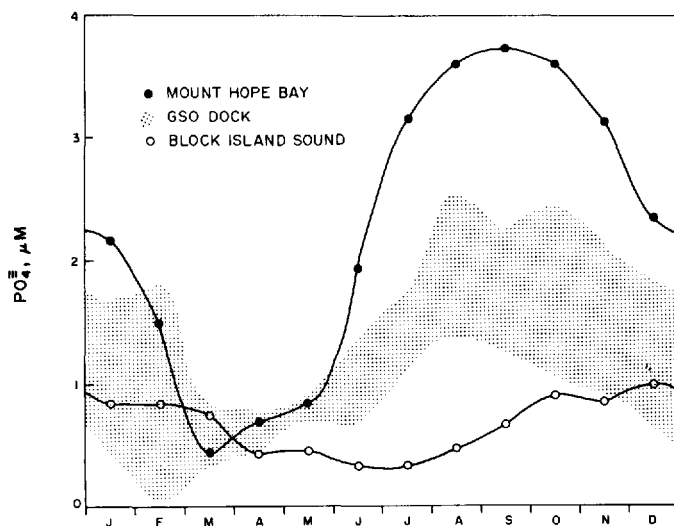
Figure 17. Comparison of phosphate concentrations measured at the GSO dock from Jan., 1977 through Dec., 1982 (stippled area, as in Fig 2), with concentrations measured in near-by regions. Monthly means of data from Block Island Sound collected April, 1974 through Aug., 1976 (NEPCO, 1978). Monthly means of data from Mt. Hope Bay collected for three months in 1969 and from May, 1972 through Jan., 1983 (MRI, 1972–1983).

Mt. Hope Bay receives one third of the fresh water input to Narragansett Bay, and considerable industrial and domestic waste, so it is a source of nutrients for the rest of the bay. A station in Mt. Hope Bay (Fig. 1) has been occupied at monthly intervals from 1972, with some observations in 1969, and a total of 129 months of data were used to construct Figures 17–19. For most of the year, concentrations of nutrients are
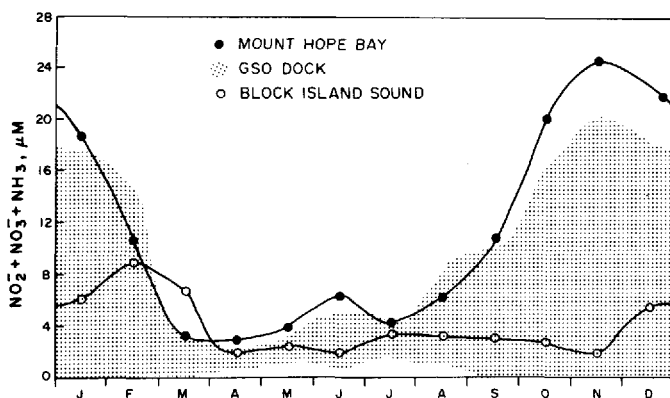

Figure 18. Concentrations of total dissolved inorganic fixed nitrogen in water from Block Island Sound about 13 km west of Narragansett Bay and from Mt. Hope Bay, in comparison with the concentrations observed at the GSO dock. Rest of legend as for Figure 17.
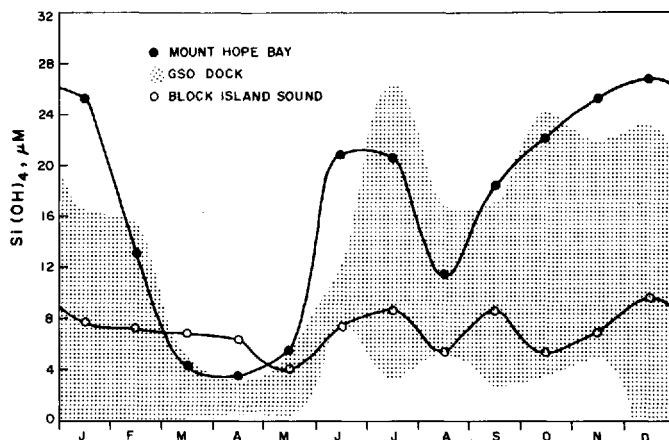
Figure 19. Concentrations of silicate in water from Block Island Sound about 13 km west of Narragansett Bay and from Mt. Hope Bay, in comparison with the concentrations observed at the GSO dock. Rest of legend as for Figure 17.

considerably higher in Mt. Hope Bay than in lower Narragansett Bay, and the seasonal changes are rather more dramatic; these observerations are similar to those by Kremer and Nixon (1978) of the seasonal cycle during 1972–1973 in upper Narragansett Bay and the Providence River; indeed their data show that all parts of the bay they examined exhibited qualitatively similar patterns. Figures 17–19 reveal several notable features of the regime of nutrient dynamics in the bay system. During the spring, phosphate concentrations in Mt. Hope Bay appear to be driven as low or lower than those in lower Narragansett Bay or even in Block Island Sound. The apparently anomalous drop in silicate concentration during August is found in all data sets, independently collected, and was also observed at other locations in the Bay by Kremer and Nixon in 1972–1973.

One could conclude (from Fig. 17–19) that the nutrient concentrations observed at the GSO dock are largely the result of simple mixing between offshore water with its small seasonal variations and upper bay water with its large seasonal variations. This explanation would only displace the question, however, for we would then ask about the causes of the seasonal changes observed in the upper bay regions.

Experimental evidence for the nature of those processes which dominate the seasonal changes of nutrient concentrations is provided by the MERL tank ecosystems. Nutrient concentrations in the MERL tanks displayed the same seasonal trends as those in the bay, regardless of whether bay water was flowing through or not (Figs. 20–22). This finding suggests that it is not necessary to invoke advective or other exchange processes to explain the seasonal changes in average concentrations of nutrients. Internal processes alone appear to be sufficient to drive the seasonal changes seen in the lower bay.
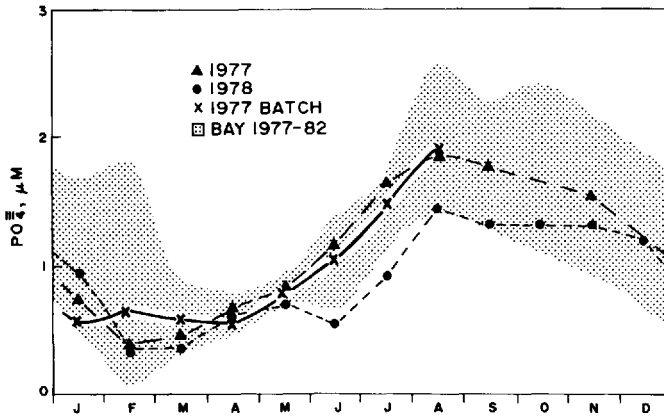
Figure 20. The stippled field, as in Figure 2, represents the area on the graph in which would be found approximately 95% of the monthly mean concentrations of phosphate in the water column of the lower west passage of Narragansett Bay, based on data from 1977–1982. The dashed lines represent the monthly mean concentrations of phosphate in MERL control tanks that received input water sufficient to replace the water volume each 27 days, during 1977 and 1978. The solid line represents the monthly mean concentrations of phosphate in three MERL tanks that received no input water, during 1977.

Figure 21. The stippled field, as in Figure 5, represents the area on the graph within which would be found approximately 95% of the monthly mean concentrations of dissolved inorganic nitrogen in the lower west passage of Narragansett Bay. The lines are coded as in Figure 20.
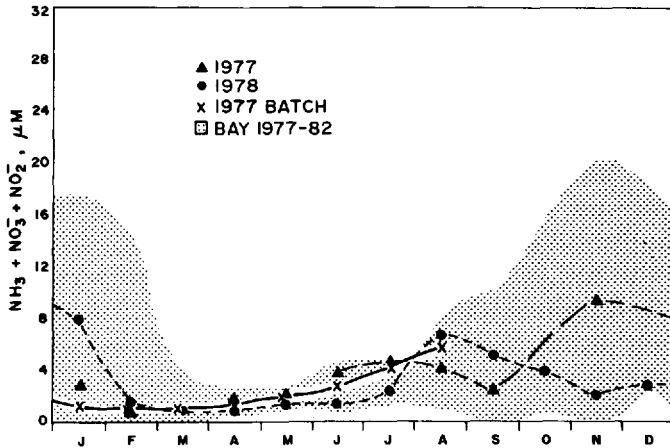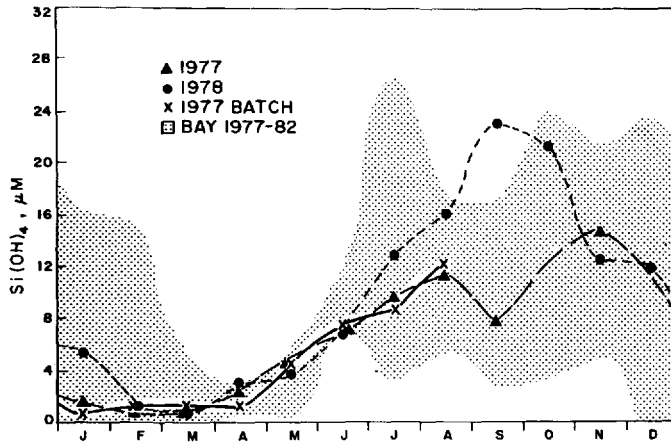
Figure 22. The stippled field, as in Figure 6, represents the area on the graph within which would be found approximately 95% of the monthly mean concentrations of silicate in the lower west passage of Narragansett Bay. The lines are coded as in Figure 20.

4. Discussion

The regularity of the annually recurring changes in concentrations of nutrients is impressive and remarkable. The narrow range of phosphorus concentrations, especially in April and May, must require a surprisingly uniform balance of rates. The low variance at the GSO dock in the late spring, however, could be simply a consequence of the situation that the biological and other processes drive the concentrations to be quite uniform throughout the region examined, from Mt. Hope Bay to Block Island Sound, so that there is less "noise" caused by normal variations in the rates of advective and mixing process between regions of typically high and typically low concentrations.

In fresh water systems the analytically determined concentration of inorganic phosphate sometimes includes only a small component that is really ionic and accessible to phytoplankton. The remaining fraction is in some (presumably organic) combined form that is nevertheless accessible to the usual molybdate reagent (Rigler, 1968; Tarapchak and Rubitschun, 1981). Studies have not yet been done to establish whether such a circumstance pertains in Narragansett Bay. If it does, then perhaps the concentrations of phosphate seen at the minimum in the spring include a component that is not accessible to the phytoplankton.

The primary production in the bay is nearly entirely planktonic, because marshes, sea grasses, and subtidal or intertidal algae occupy a negligible portion of the total area. The production of phytoplankton certainly consumes nutrients in proportion to the fixation of carbon (although for several reasons the exact proportion may of course vary from time to time). Nevertheless, it appears that plankton processes, in the water column alone, cannot account for the seasonal changes in the concentrations of nutrients. River input and advective exchange with the offshore water likewise appear
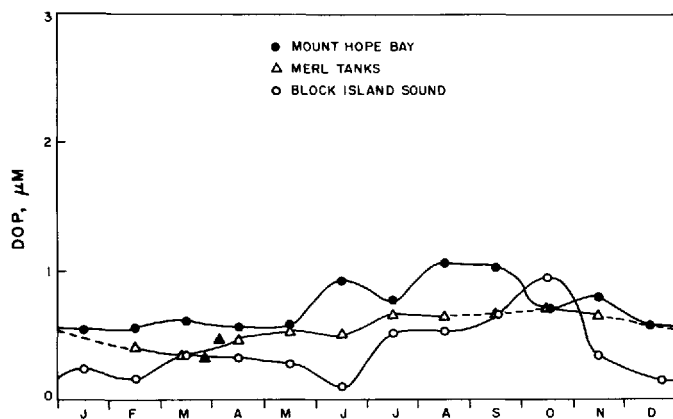
Figure 23. Concentrations of dissolved organic phosphorus in and near Narragansett Bay.
Monthly mean values accumulated in the same way as inorganic phosphate (Figs. 2, 17). Data
from Mt. Hope Bay summarize 30 months of measurements during 1969–1975 at the station
south of Spar Island. Data from R.I. Sound summarize 12 months of measurements during
1974–1975, each point being the mean of surface, mid-depth, and bottom values at each of
two stations. Data from MERL tanks summarize 17 months of single measurements in each of
three control tanks, from 1978 to 1981, collected from an incubation chamber at the start of
the incubation (J. Kelly, personal communication; Kelly, 1983). Closed triangles from Darzi
et al. (1973) and Evans *et al.* (1972), respectively, for March and April, are each means of two
stations occupied once in each year, several km N and S of the GSO dock. The time-weighted
annual mean values are: Mt. Hope Bay, 0.73; MERL tanks, 0.55; R.I. Sound, 0.39.

not to be the primary cause of the seasonal changes. Property/salinity plots, often so
useful in evaluating estuarine processes (e.g. Boyle *et al.,* 1974; Kaul and Froelich,
1984), are not helpful here. The length of time between samplings, the fact that most
samples come from only two stations, the usually restricted range of salinity variation
at any one station, and the evidence for strong internal processing on a seasonal time
scale, all reduce their usefulness. In fact, such plots turn out to be largely featureless, so
none are presented.

Armstrong and Harvey (1950) interpreted the inverse correlation of dissolved
organic phosphorus (DOP) with dissolved inorganic phosphate (DIP) in the water
column of the English Channel near Plymouth as being a reflection of a relatively
constant total phosphorus in the system. They ascribed the seasonal change in DIP as
being largely due to conversion to DOP in the early summer, and conversion back to
DIP in the fall and winter, with only a small portion of the change due to changes in the
standing stocks of phytoplankton, zooplankton and detritus. That scenario does not
work here. We have many fewer measurements of DOP than of DIP, but those
available (Fig. 23) provide no evidence of an inverse relationship between DOP and
DIP, for either Mt. Hope Bay or Block Island Sound (compare Figs. 23 and 17).
Insofar as data from the MERL tanks may be taken as surrogates for data from the
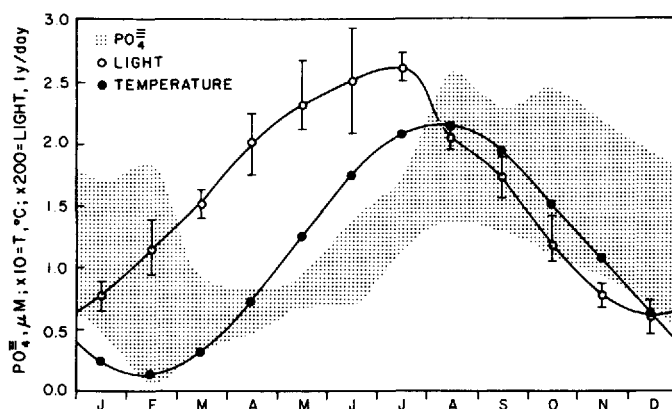
Figure 24. Comparison of monthly mean concentrations of phosphate at the GSO dock, light energy in Langleys (g-cal cm^{-2}) per day, and temperature (°C) in lower Narragansett Bay; Jan. 1977–Dec. 1982. Phosphate concentrations from Figure 2; light energy received at Newport, R.I., from Eppley Laboratories, the bars represent twice the std. dev. of the monthly means; temperature data provided by Perry Jeffries (personal communication) are the monthly means of weekly measurements taken at two stations approximately equidistant, 5 km north and south of the GSO dock.

lower West passage of Narragansett Bay (Fig. 20) the tank data provide no evidence for an inverse relationship there either (compare Figs. 23, 17, and 20). In fact, direct correlations of DOP with DIP, in each of the three regions, suggest essentially no relationship in Block Island Sound and weak positive correlations both in Mt. Hope Bay and in the MERL tanks. Therefore, the observed annual changes in DIP cannot be ascribed to changes in the form of phosphorus while in dissolved state. This argument is not in contradiction with the observation of Taft and Taylor that evidence for increased alkaline phosphatase activity in phytoplankton during low-phosphate times of the year suggested increased planktonic utilization of phosphate mono-esters. Whether this occurs in Narragansett Bay or not, the evidence here is that increased molybdate reactive phosphate does not come from dissolved organic phosphorus.

It must be true that changes in temperature and the input of light energy (Fig. 24) largely control the seasonal changes observed, but the mechanisms will surely turn out to be exceedingly complex, with many time lags involved (Zeitschel, 1980). The occurrence of plankton blooms is affected by light, temperature, nutrient concentrations and the stability and critical depth of the water column. The delivery of fixed carbon to the sediments must also be affected by its concentration, temperature, water column stability, zooplankton concentrations, turbulence, and other factors. Blooms can occur at any time but they commonly occur in late winter and early spring (Fig. 7; Smayda, 1957). If this new organic matter is delivered to the sediments, it will not be remineralized as quickly in the cold months as it would be later, during the summer

(Nixon, 1981), and will be stored temporarily in the sediments. This may explain the consistent drop in nutrient concentrations seen every spring.

The sediments and associated benthic organisms comprise a large, complex and dynamically important reservoir of nutrients. For example, the total phosphorus content of dried sediment from the top 10 cm in the broad, flat region north of Conanicut Island is about 19 μmol/g (Beach, 1981). The average depth of water in Narragansett Bay is 8.3 m and, if the rapidly bioturbated top 10 cm of the sediment is considered to be an active part of the ecosystem, only about 0.5 to 1.0% of the phosphorus in the system is in the water column; the rest is in the sediments. Very small changes in the chemical and biological behavior of the sediment can therefore have large effects on the concentrations in the water column above. The phosphorus must be held in the sediment in many ways—as part of the biomass of benthic organisms, adsorbed to mineral particles such as clays or especially to iron oxides and manganese oxides, possibly in crystalline mineral phases, and in non-living but organic chemical combination. Much the same can be said for each of the other nutrients, each with its own chemical and biological individuality.

These sediments are affected by biological activities such as the construction of worm and clam holes introducing oxygenated water into anoxic regions, the transport of anoxic sediments to the surface, the burial of oxygenated sediments and detrital organic matter in anoxic regions, and the respiration of the organic matter by various biota (Aller, 1982). All these processes, as well as the numerous physical-chemical interactions between the water and oxygenated and reduced sediments, and both advective and diffusive processes in the sediments, are affected by temperature and must respond in complex ways to changes in the productivity of the overlying water. Nixon *et al.* (1976, 1980) and Kemp and Boynton (1981) showed that fluxes of fixed nitrogen and phosphate from the benthos are strongly influenced by temperature. The various storages and lags in consumption or release of organic matter and nutrients, as temperature and seasonal inputs change, must be different for each substance, but seem consistent from year to year for each one.

There has been some debate in the literature on the question of whether sediments "buffer" the concentration of phosphate in the overlying water. The data presented by Pomeroy *et al.* (1965) certainly supported earlier suggestions that sediments act as a phosphate buffer, as did the data and analysis by Boynton *et al.* (1980), while Nixon *et al.* (1980) argued that the evidence for continued phosphate fluxes out of the sediments, even when overlying concentrations were considerably elevated, weighed against the concept of the sediment as a buffer. My own view is that the sediments must act as buffers in the physical chemical sense (otherwise the laws of physics would be violated), but the extent to which this is apparent or effective in real systems must vary with the circumstances. Transport of phosphate to and into the sediments may occur largely via particles. The large reservoirs of phosphate in the sediments of Narragansett Bay may act rather as a "fly wheel," with the many complex exchange

processes interacting with and influenced by the water column as well, so that the observed annual cycle is generally maintained.

It seems that hundreds of chemical and biological processes in the water column and in the sediments must conspire and combine to poise the nutrient concentrations as they are at any time and as they change through the year. From the evidence at hand I conclude that in a relatively shallow system such as Narragansett Bay the sediment-water interactions are sufficiently strong as to exert a dominating influence on the chemistry of the water column above. This is true even though the water resides in the bay only 10–40 days.

The importance of the benthos in the recycling of nutrients in shallow water systems was recognized long ago, as was the importance of chemical exchanges (Cooper, 1951; Rochford, 1951; Smayda, 1957; Nixon *et al.,* 1976; Boynton *et al.,* 1980; Nixon, 1981; and D'Elia *et al.,* 1983), and Nixon *et al.* (1980) showed that the summer rise in phosphate concentration in Narragansett Bay could be quite well accounted for by the flux from the sediments. Dame *et al.* (1980) showed that benthic filter feeders could have a large impact on the plankton and nutrients in an estuary in North Carolina. Cloern (1982) suggested that the benthos in south San Francisco Bay, a shallow system where the benthos often has access to most of the water column, could control the biomass of phytoplankton there; the general importance of this situation was considered by Officer *et al.* (1982). While it seems probable that the low nutrient concentrations in the spring are accounted for by delivery of the winter-spring plankton bloom (Smayda, 1957) to the benthos, it is not clear how this delivery is accomplished. The season is a time of minimal activity by benthic animals, on account of the temperature.

Nevertheless, the apparently dominating influence of benthic chemical and biological exchange processes in controlling the nutrient concentrations so closely over such a long period of time in even such a comparatively large system as Narragansett Bay has not hitherto been widely appreciated. This dominating importance of sediment-water interactions is also supported by the surprising similarity of the annual cycles in the MERL tanks to those in the lower bay. The benthic exchange processes are also driven, with some time delay, by the biotic processes in the water column. While it seems that the seasonal changes are driven by many complex and interacting processes, the observation that a large proportion of the activity of these processes can be contained in a 13-m^3 microcosm suggests that the important features of the system can be subjected to direct experimental examination, even while acting in concert.

The gradient in the mean concentration and in the magnitude of the annual change in concentration of each nutrient, from Upper Narragansett Bay (Kremer and Nixon, 1978) or Mt. Hope Bay (Figs. 17–19) to Lower Narragansett Bay, along with the similarity of MERL mesocosm behavior to that of the lower bay, suggests that each part of the bay has adapted itself over the years to the mean gradient of nutrients from the sources of nutrient (in the rivers and sewage discharges) to the offshore waters, so

that the observed annual changes are maintained in each region. Whether this is so, and how it comes about, will be interesting subjects for further investigation.

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