Eutrophication of Buttermilk Bay, a Cape Cod Coastal Embayment: Concentrations of Nutrients and Watershed Nutrient Budgets

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ABSTRACT / Nutrient concentrations in Buttermilk Bay, a coastal embayment on the northern end of Buzzards Bay, MA, are higher in the nearshore where salinities are lower. This pattern suggests that freshwater sources may contribute significantly to nutrient inputs into Buttermilk Bay. To evaluate the relative importance of the various sources we estimated inputs of nutrients by each major source into the watershed and into the bay itself. Septic systems contributed about 40% of the nitrogen and phosphorus entering the watershed, with precipitation and fertilizer use adding the remainder. Groundwater transported over 85% of the nitrogen and 75% of the phosphorus entering the bay. Most nutrients entering the watershed failed to reach the bay; uptake by forests, soils, denitrification, and adsorption intercepted two-thirds of the nitrogen and nine-tenths of the phosphorus that entered the watershed. The nutrients that did reach the bay most likely originated from subsoil injections into groundwater by septic tanks, plus some leaching of fertilizers.

Buttermilk Bay water has relatively low nutrient concentrations, probably because of uptake of nutrients by macrophytes and because of relatively rapid tidal flushing. Annual budgets of nutrients entering the watershed showed a low nitrogen-to-phosphorus ratio of 6, but passage of nutrients through the watershed raised N/P to 23, probably because of adsorption of PO_4 during transit. The N/P ratio of water that leaves the watershed and presumably enters the bay is probably high enough to maintain active growth of nitrogen-limited coastal producers. There is a seasonal shift in N/P in the water column of Buttermilk Bay. N/P exceeded the 16:1 Redfield ratio during midwinter; the remainder of the year N/P fell below 16:1. This suggests that annual budgets do not provide sufficiently detailed data with which to interpret nutrient-limitation of producers. Further, some idea of water turnover is also needed to evaluate impact of loading rates. Urbanization of watersheds seems to increase loadings to nearshore environments, and to shift the nutrient loadings delivered to coastal waters to relatively high N-to-P ratios, potentially stimulating growth of nitrogen-limited primary producers.

The gradual urbanization of the coastline of New England and elsewhere inevitably puts intense pressures on the mosaic of landscapes in the coastal zone. One of these pressures is the increased input of nutrients from wastewater, fertilizers, and other sources. Repeated recent reports in the Cape Cod area of increases in algal blooms, fish kills, and reductions of eelgrass beds seem related to eutrophication of coastal waters. Wastewater certainly contributes to the nutrient load carried by groundwater in Cape Cod (Persky 1986) and elsewhere (Yates 1985), and so do other sources, but it is not clear what proportion of nutrients added to coastal watersheds eventually enter bays and lagoons. We therefore need to evaluate the various sources of nutrient loading responsible for coastal eutrophication, as well as the degree of attenuation of nutrients that may take place during passage through watershed soils and sediments. This article assesses water quality, examines sources of nutrients, and evaluates attenuation of nutrient inputs within the watershed of Buttermilk Bay, a coastal bay where significant urban development has taken place.

KEY WORDS: Coastal embayments; Eutrophication; Nitrogen; Phosphorus; Coastal lagoons; Groundwater; Septic tanks; Nutrient loading

Buttermilk Bay is a shallow, semienclosed coastal embayment situated at the northern end of Buzzards Bay, Massachusetts, in the towns of Bourne and Wareham (Figure 1, top). The Buttermilk Bay watershed is 46.2 km^2 in area. The bay has a surface area of 2.14 km^2, a mean depth of 0.9 m MLW, and about 13 km of shoreline. Tidal water floods the bay twice a day, with a tide range of 0.8 to 1.4 m and a mean range of 1 m. All tidal flow is from Buzzards Bay and through Cohasset Narrows (Figure 1, top). A few small streams, of which Red Brook is the largest, supply freshwater to Buttermilk Bay (Figure 1, top). Because Buttermilk Bay is shallow, eelgrass (*Zostera marina* L.) beds and benthic micro- and macroalgae are abun-

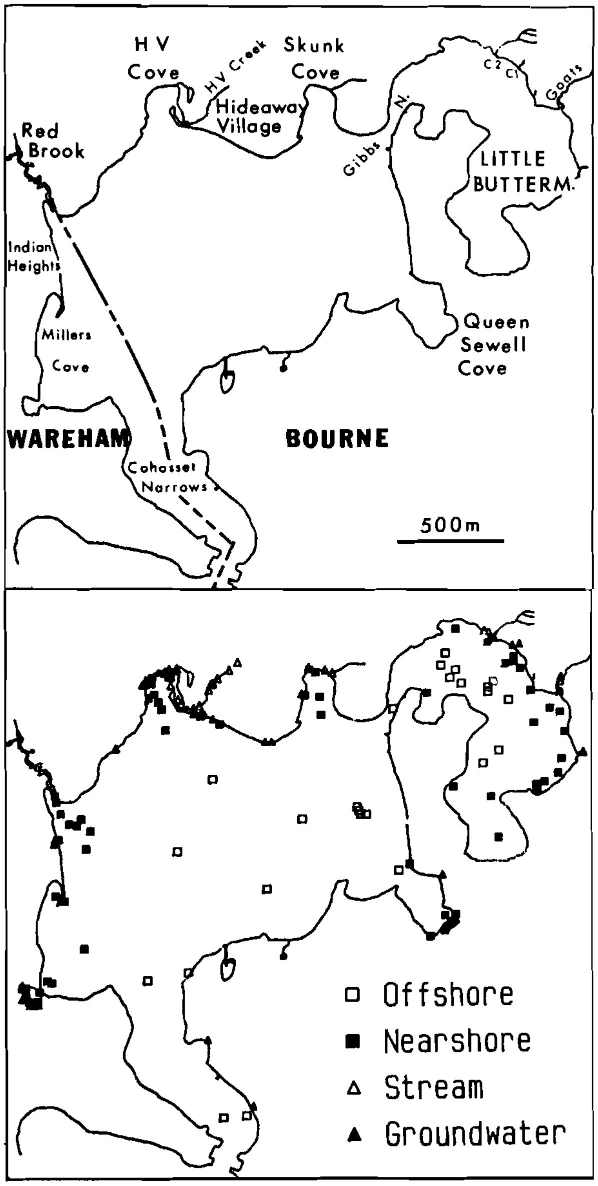

Figure 1. Sites in Buttermilk Bay mentioned in the text (top) and location of sampling stations (bottom).

dant, and together the benthic producers account for 60% of primary production (Costa 1988).

Forests on this watershed have been accreting for most of this century, following secondary succession of abandoned pastures and agricultural parcels. Even though the forests are growing, there is a patchwork of increasing development, particularly along the shore.

Wastewater disposal from the growing number of dwellings in the Buttermilk Bay watershed is carried out by domestic sewage disposal systems constructed near each individual building. Recently built septic systems consist of a holding tank and an attached percolation tank that releases the supernatant fluid into the subsoil, but older systems are typically cesspools, some within the nearshore water table. Dispersal of effluents away from dwellings is facilitated by the very permeable sandy glacial till that underlies the watershed of Buttermilk Bay.

The growing development of the shoreline and watershed of Buttermilk Bay makes it a good system in which to study the impact of wastewater nutrient inputs on water quality, relative to other nutrient sources. In this article we first document nutrient concentrations in the bay, in streams, and in groundwater entering the bay. Second, from measured nutrient concentrations and data on flow of freshwater from different sources, we calculate budgets for waterborne nutrient inputs into the Buttermilk Bay watershed and into the bay itself, so as to evaluate the relative contribution by various sources and the retention of nutrients within the watershed.

Methods

Water was sampled from offshore and nearshore stations and from streams entering the bay. Offshore stations (Figure 1, bottom) were either located some distance from shore, or in sites with relatively fast water currents. More closely spaced stations nearshore were located along beaches and in shallow coves (Figure 1, bottom). Sampling at 12 permanent stations was repeated at about monthly intervals throughout the year. Groundwater stations and most nearshore stations were sampled less frequently. Most samples were taken during ebbing tides, at least 2 h after high tide and 2 d after any storm. Some samples were taken during or immediately after storms to measure nutrient content in runoff. Samples covered both the range of seasonal changes and meteorological conditions in our area.

Water samples were collected using a 250-ml acid-washed polypropylene bottle, brought to the lab and filtered. Ammonium concentrations were determined within hours after collection using a modified Solorzano method (Parsons and others 1984). Nitrate plus nitrite (hereafter referred to as nitrate, since nitrite was usually one order of magnitude smaller than nitrate and so will be ignored) were measured in a Technicon Autoanalyzer using the cadmium reduction procedure. Phosphate was measured by the molybdate method (Parsons and others 1984). Salinity was measured with a chloridometer or refractometer.

Samples of groundwater about to enter Buttermilk Bay were obtained using a shallow well-point sampler consisting of a 1.5-cm-diameter hollow rod with a hardened steel tip, and screened lateral openings (bored 5–10 cm above the tip). The well point was driven into the sediments at or somewhat above the high tide mark to a depth of about 60 cm, and a sample was obtained using a mechanical vacuum pump.

Sites for collection of groundwater were spaced out along the margin of the bay (Figure 1, bottom). The spacing was irregular, and some areas were more intensively sampled, and we included transects along beaches. Some samples were taken from sites between septic systems and shore. These latter sites were chosen to ensure that our sampling encompassed the entire range of nutrient concentrations in groundwater about to enter the bay. Sample treatment and measurement of NH_4, NO_3, and PO_4 were the same as in the case of bay water samples.

Samples of surface water from the mouth of several streams (Figure 1) were collected using the same methods as those used in sampling the bay. The salinity, NO_3, NH_4, and PO_4 concentrations were measured as above.

Results

Buttermilk Bay

Mixing and Stratification in Buttermilk Bay. Buttermilk Bay is shallow (mean depth is 1 m MLW), and the tidal range is proportionally high (also about 1 m), so that half the volume of the bay leaves twice daily. Because the bay is shallow, wind-driven mixing is significant, and the midbay was rarely stratified. We observed salinity stratification only near the mouths of streams or along beaches with conspicuous groundwater discharges. Stratification seemed so limited that we largely ignored vertical variability and concentrated our sampling on the spatial and seasonal variation over the surface of Buttermilk Bay.

Concentrations of Nutrients and Salinity. The concentrations of NH_4, NO_3, and PO_4 recorded in offshore and nearshore stations for Buttermilk Bay were distributed with a modal low value, but the distributions were asymetrical, with some high values in all cases (Figure 2). The range of concentrations, however, lies well within and to the low end of the range found in other similar environments (Table 1). Nearshore values tended to range higher than offshore values in the bay (Figure 2).

There was no seasonal pattern of salinities in offshore and nearshore stations (data not shown); some stations showed short-lived changes in salinity that probably reflect specific meteorological or tidal events.

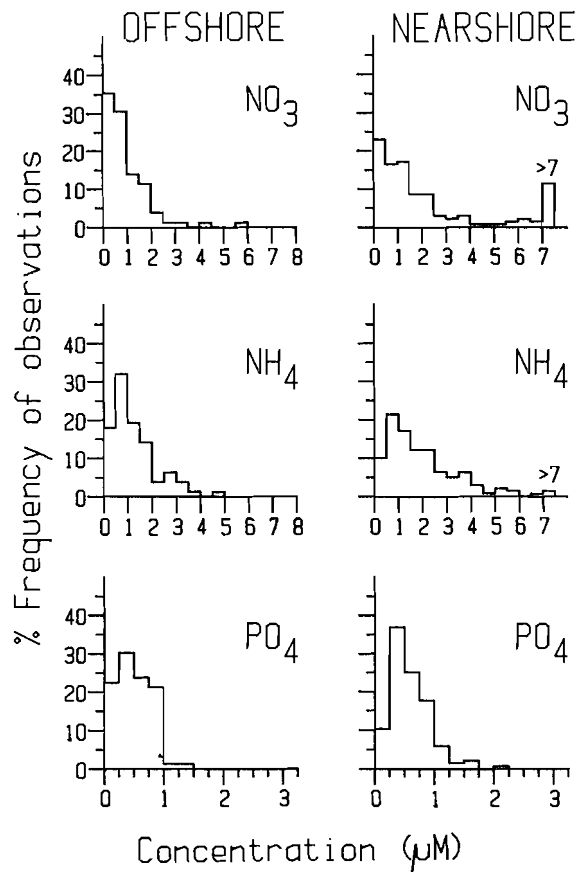

Figure 2. Percent frequency distributions of concentrations of nitrate, ammonium, and phosphate in offshore and nearshore stations of Buttermilk Bay.

To obtain a synoptic picture of the spatial distribution of salinity throughout Buttermilk Bay, we averaged values of salinity measured at different times of the year, to obtain a representative value for each station (Figure 3). For ease of presentation in Figure 3 we also pooled values for stations within 10 m of each

Table 1. Range of nutrient concentrations (uM) reported for a wide variety of coastal and estuarine systems from all over the world in Neilson and Cronin (1981), compared to ranges of nutrient concentrations found in Buttermilk Bay.

	Coastal embayments and estuaries	Buttermilk Bay	
Nitrate	0–200	Offshore	0.1–5.8
		Nearshore	0.2–38
Ammonium	0–600	Offshore	0.0–4.7
		Nearshore	0.2–11.3
Phosphate	0–60	Offshore	0.05–1.4
		Nearshore	0.05–2.2

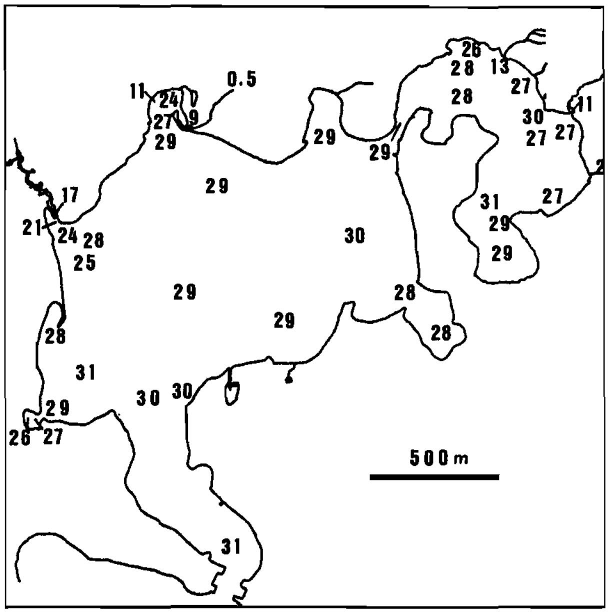

Figure 3. Spatial distribution of salinity (mean annual) over Buttermilk Bay. See text for description.

other. Salinities in the center of Buttermilk Bay (Figure 3) were somewhat fresher than the average salinity of 30.9 ‰ of water at the head of Buzzards Bay (calculated from Anraku 1964 and Rosenfeld and others 1984). Lower salinities were recorded in many nearshore areas of Buttermilk Bay (Figure 3), especially those with visually evident stream and groundwater inputs.

The spatial distribution of nitrate and ammonium (data not shown) seemed related to freshwater inputs. Both NO_3 and NH_4 were high in areas where there were stream inputs, such as near Red Brook, Hideaway Village Creek, Goats Creek, and two culverts in Little Buttermilk. NO_3 and NH_4 were also high in Skunk Cove and Millers Cove, where most freshwater entered as groundwater.

The relation of nutrient concentration to salinity has often been explored in estuarine research by use of concentration vs salinity graphs. In Buttermilk Bay the freshwater "end member" (left margins of Figure 4) is apparently made up of multiple local sources bearing very different nutrient loads. There is a trend, nonetheless, of lower concentrations of nutrients as salinity increased (Figure 4). This trend roughly parallels the curves that indicate the dilution of nutrients by simple mixing of waters of different salinity (Figure 4). The trends of Figure 4 suggest that freshwater inputs from the watershed are major sources of nutrients to Buttermilk Bay, and that some processes—perhaps tidal flushing and denitrification, or nutrient uptake by phytoplankton and benthic macro- and microphytes—may lower concentrations offshore.

Seasonal Variation. Seasonal variation in nutrient concentrations was clearer in offshore stations than in nearshore stations. Nitrate in the offshore water column increased fourfold up to 5 μM during late fall and winter, decreased rapidly after the spring bloom, and was depleted by midsummer (Figure 5, top left). Ammonium concentrations (Figure 5, middle left) peaked in winter, had a low in spring to early summer, and peaked again in late summer. During winter, NO_3 concentrations were about twice as large as those of NH_4; in late summer there was as much NH_4 as NO_3 (Figure 5, top and middle left). In nearshore stations, NH_4 and NO_3 were higher and more variable during the year (Figure 5, top and middle right). Phosphate decreased during fall–winter in both nearshore and offshore stations (Figure 5, bottom left and right) and showed a slight peak in midsummer.

There were also distinct seasonal changes in the ratio of N (NH_4 + NO_2 + NO_3) to P (PO_4). The N-to-P ratio in water (Figure 6) was low during the warm months and increased above the Redfield ratio (N/P = 16) during fall and winter. Since a 16:1 ratio of N to P is used by algae to build cells (Redfield and others 1963), the seasonal pattern of N/P in offshore water in Buttermilk Bay (Figure 6, bottom) suggests that growth of phytoplankton might be nitrogen-limited most of the year. The seasonal pattern of the ratio of N to P in nearshore stations resembled that of offshore stations, but was more variable, and more often exceeded the 16:1 Redfield ratio (Figure 6, top). Phytoplankton and benthic algae would be less likely to be nitrogen-limited in nearshore than in offshore stations (Figure 6, bottom).

It is not clear what the residence time of water and algal cells might be in the nearshore, nor how much horizontal exchange of nutrient- and algal-rich water there is from the nearshore to the offshore. Lower nutrient concentrations in the midbay and the large tidal exchange suggest that there must be a significant export of nutrients and phytoplankton out of Buttermilk Bay or appreciable and rapid uptake by benthic algae, and that nutrients in the nearshore must be replenished at a rather significant rate.

Streams Entering Buttermilk Bay

Ranges of Concentrations. The frequency distribution of stream nutrients varies widely and has modes toward the low end of the range (Figure 7). The nutrient concentration of streams (Figure 7, left), however, reaches greater values than those of nearshore and offshore stations (Figure 2).

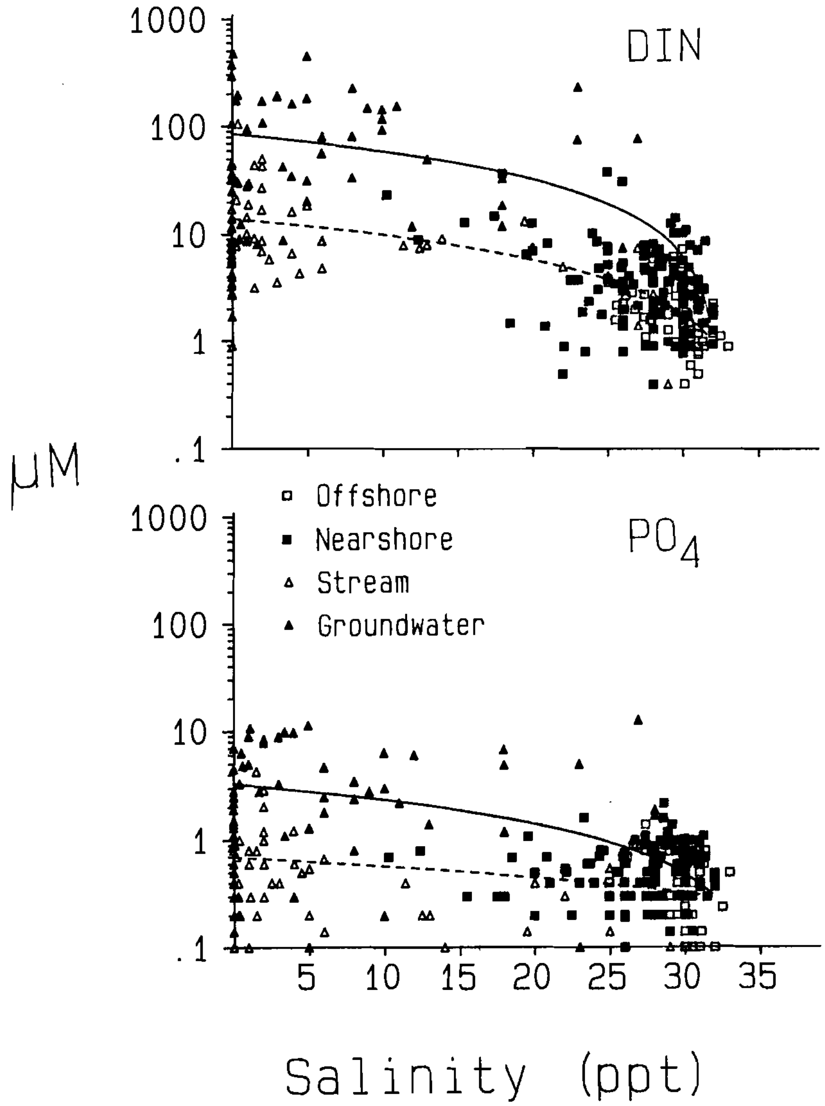

Figure 4. Salinity vs concentration of DIN (top) and PO_4 (bottom) for all stations. Solid lines are calculated simple mixing curves for groundwater; dashed lines are simple mixing curves for streamwater.

Seasonal Distribution. There were no marked seasonal patterns in the concentration of nitrate in any of the sampled streams (data not shown), but there were differences among different streams. For example, Red Brook and Goat Creek, both of which drain wetlands and account for most flow into the bay, discharge most of their N as NO_3. In contrast, Hideaway Village Creek, which drains a housing development and a cranberry bog, released much higher concentrations of N, primarily NH_4.

Groundwater

Ranges of Concentration. Groundwater nitrate concentrations were the most variable of all water types sampled, ranging from 0.2 to over 450 μM (Figure 7, top right, and compare to Figure 2, top). This range is very similar to results of Persky (1986), who carried out an extensive survey of Cape Cod groundwater and found that groundwater from watersheds with the lowest dwelling density had the lowest NO_3 contents, about 21 μM. Higher values were measured at higher dwelling densities. The higher values in our case (Figure 7, top right) may also be caused by increased human inputs. We need to note that nitrate concentrations in "clean groundwater" (21 μM) are higher than concentrations of nitrate found in the bay or in streams (compare with Figures 2, top, and 7, top left).

Ammonium concentrations in groundwater also varied widely (0.2 to 450 μM, Figure 7, middle right). Concentrations of NH_4 in groundwater ranged somewhat higher than streamwater (Figure 7, middle).

Phosphate concentrations in groundwater ranged to 12.8 μM PO_4 (Figure 7, bottom right). Concentrations of phosphate in the groundwater were consider-

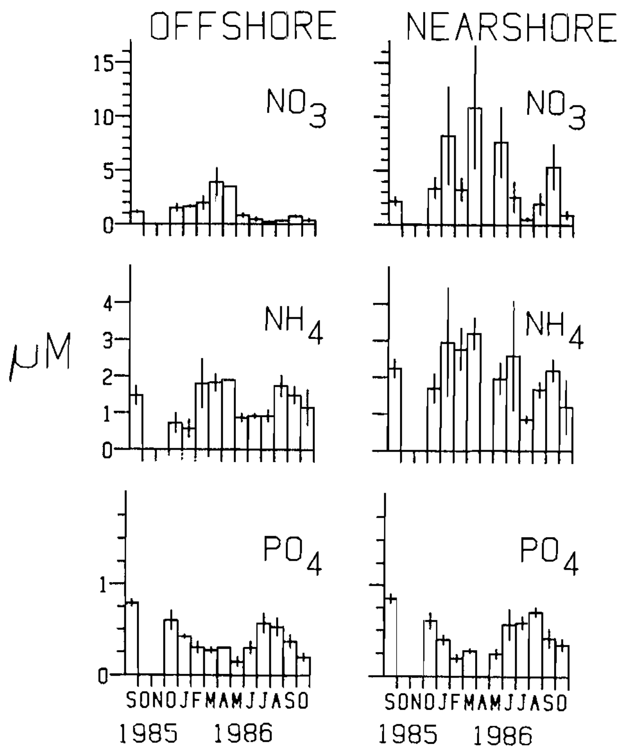

Figure 5. Seasonal variation in concentrations of nitrate, ammonium, and phosphate in offshore and nearshore stations in Buttermilk Bay (x ± s.e. for each month).

ably higher than those found in the bay (Figure 2, bottom) or in streams (Figure 7, bottom left).

Spatial Distribution. The nutrient content of groundwater varied over the shoreline of the bay but there was no clear geographical pattern (Table 2). Some of the groundwater samples must have contained some seawater (Figure 4, left margin). Since concentrations of nutrients in seawater from Buttermilk Bay were considerably lower than those in fresh groundwater, as mentioned above, mixing with bay water should amount to a dilution of groundwater. Therefore, our measurements of nutrient concentration in groundwater samples underestimate to an extent true groundwater concentrations. The mixing with seawater was not, however, the only factor accounting for nutrient concentrations, since our plot of nutrient content in groundwater samples vs salinity showed large scatter (Figure 4). In addition, NO_3, NH_4, and PO_4 concentrations did not correlate with each other in groundwater samples (data not shown), suggesting the presence of other effects in addition to simple mixing and dilution of two end members.

Natural and anthropogenic heterogeneities probably cause groundwater to be a rather locally variable nutrient source. Proximity to septic tanks may be another major source of the variability in groundwater nutrient concentrations. Transects along beaches in

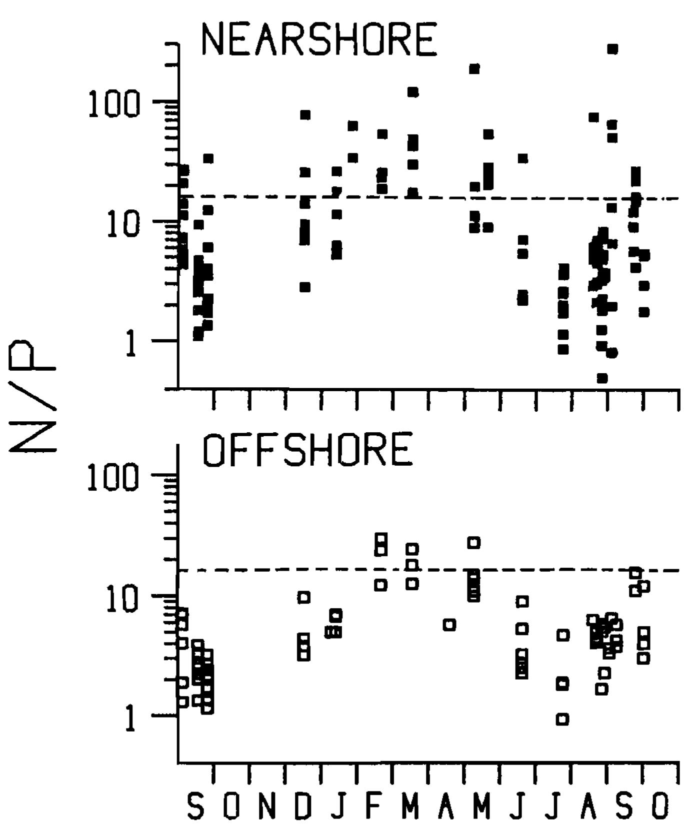

Figure 6. Seasonal variation in ratio of N to P in nearshore (top) and offshore (bottom) stations. Dashed line is Redfield ratio of 16:1.

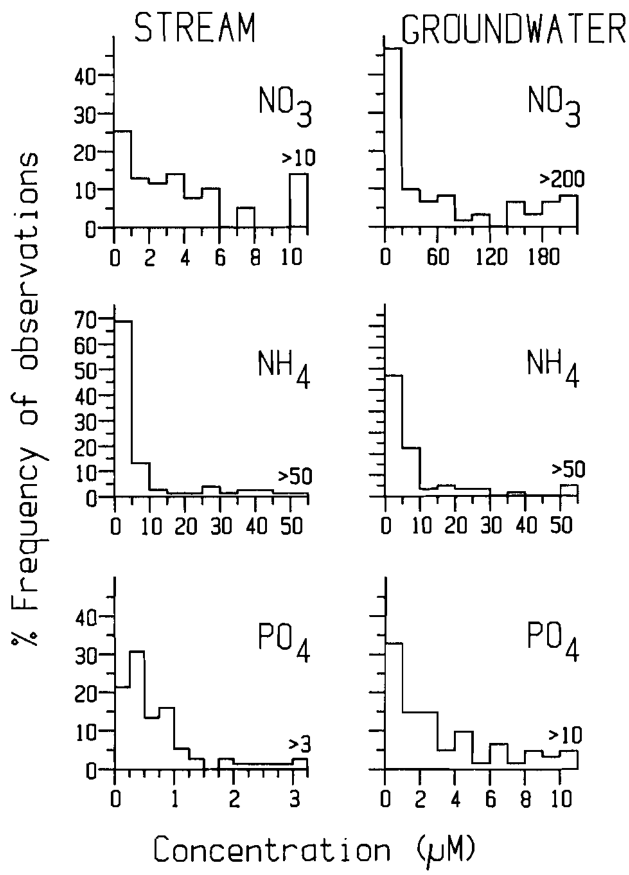

Figure 7. Percent frequency distribution of concentrations of nitrate, ammonium, and phosphate in streams and groundwater samples near Buttermilk Bay.

Buttermilk Bay showed that there were distinct plumes from septic tanks up to at least 50 m from shore (ms. in preparation). Some of the high ammonium concentration we found may have been caused by septic tank plumes.

Table 2. Mean concentrations ($x \pm se$) of nutrients in groundwater from various areas of Buttermilk Bay. Individual groundwater stations shown in Figure 1 were pooled into one of these eight areas.

Station	Concentrations (μM) NH$_4$	NO$_3$	PO$_4$	No. Obs.
Queen Sewell Cove	10.9 ± 1.1	81.6 ± 3.6	4.8 ± 0.2	21
Little Buttermilk (northeastern shore)	1.2 ± 0.8	3.5 ± 1.2	0.8 ± 0.4	2
Cohasset Narrows (eastern shore)	4.8 ± 0.3	23.5 ± 21.3	1.6 ± 0.2	2
Millers Cove	12.4 ± 1.3	145.6 ± 16.8	4.8 ± 0.4	10
Indian Heights Beach (near Red Brook)	3.2 ± 0.1	0.2 ± 0.0	1.8 ± 0.5	2
Hideaway Village Cove	9.8 ± 1.0	28.9 ± 3.7	1.6 ± 0.2	16
Hideaway Village	77.2 ± 33.4	75.9 ± 17.6	1.8 ± 0.4	6
Skunk Cove	5.3 ± 3.0	65.6 ± 32.1	3.7 ± 1.2	3

Water and Nutrient Budgets for Buttermilk Bay and Its Watershed

Calculation Methods and Results

To evaluate the relative importance of the various fresh waterborne sources of nutrients *into the watershed* of Buttermilk Bay, we first calculated the inputs of nitrogen and phosphorus that entered the watershed via precipitation, septic systems, and domestic and agricultural use of fertilizers. Next we calculated annual nutrient inputs *to Buttermilk Bay itself* via groundwater, streams, runoff, and direct fall of precipitation. We used these two budgets to evaluate the relative importance of different sources of nutrients to watershed and bay, and to examine retention or attenuation of nutrients during passage through the watershed.

The nutrient inputs brought onto the watershed by precipitation were calculated from rain gauge data for 1985–86 taken at a station 2 km away from Buttermilk Bay (Heufelder 1987) and local nutrient concentrations in rainwater (Valiela and others 1978). The average annual amount of precipitation during those 2 yr (1.13 m yr^{-1}) was multiplied by the area of the watershed (46.2 km^2) to obtain the total volume of precipitation on the watershed (52.2×10^6 m^3). This number was multiplied by the average concentration of NO_3, NH_4, and PO_4 in local precipitation (Table 3) to obtain inputs of 1.2×10^6 mol DIN yr^{-1} and 1.5×10^5 mol PO_4 yr^{-1}.

The contribution of nutrients to the watershed by septic tank effluent was calculated by first estimating the number of dwellings (2000 units) within the watershed (delimited by Moog 1987) by examining aerial photographs of the watershed taken in 1981. We used estimates of 3.8 kg N produced per person per year

Table 3. Mean concentrations of nutrients in source waters for Buttermilk Bay used in nutrient budget calculations. N/P expressed by atoms.

Source	Mean concentration (μM) NH$_4$	NO$_3$	DIN	PO$_4$	N/P
Streams[a]	8.6	5.5	14.0	0.7	20
Groundwater[b]	16.2	70	86	3.3	26
Surface runoff[c]	6	21	27	1.2	23
Precipitation[d]	8.7	13.7	22.4	2.9	7.9

[a] Mean annual concentrations from Red Brook.

[b] Data shown in Figure 8.

[c] Data from samples taken in 5 sites around Buttermilk Bay, 18 Aug 86 (average: 6.0 ± 1.1 μM NH_4, 20.6 ± 13.4 μM NO_3, 1.2 ± 0.5 μM PO_4).

[d] Data from Valiela and others (1978), weighted mean concentration of precipitation during a year and a half of collections.

and occupancy of 2.7 people per dwelling to obtain a loading of 1.5×10^6 mol DIN yr^{-1} from septic systems to the watershed. For phosphorus, we used a value of 1.4 kg P $person^{-1}$ $year^{-1}$, and obtained a loading of 2.5×10^5 mol P yr^{-1}. The various estimates used in these calculations were from studies and reviews of data reported in Koppelman (1978), EPA (1980), Giblin and others (1983), and Gaines and others (1983).

Nutrient inputs into the watershed by domestic use of fertilizer, principally for lawns, were calculated assuming that 4.05 kg N was applied per house per year (sources for these data were the same as for septic tank contributions). Lawn fertilizers in our region are principally 26:4:6, so that about 0.63 kg P per house per year were applied. The calculated results were that 5.79×10^5 mol N yr^{-1} and 4.1×10^4 mol P yr^{-1} were delivered by domestic use of fertilizer.

Agricultural (predominantly cranberry cultivation) use of fertilizer also conveyed N and P into the Buttermilk Bay watershed. We estimated this source by first digitizing areas of cranberry bogs (143.7 ha) in air photographs of the watershed. Use of N fertilizer by cranberry growers in the area is estimated at 22.5 kg ha^{-1} yr^{-1} (Deubert 1974), so that 2.3×10^5 mol N yr^{-1} were introduced into the watershed as agricultural fertilizer. Assuming that 5:10:10 fertilizer was used, 45 kg ha^{-1} yr^{-1} of P were applied, and the delivery to the watershed was 2.1×10^5 mol P yr^{-1}.

The above calculations refer to nutrient inputs *into the watershed* of Buttermilk Bay; some portion of these traverse the watershed and presumably enter *Buttermilk Bay itself* through streams, groundwater flow, and by surface runoff. In addition, direct precipitation onto the bay and waterfowl also convey nutrients into the bay. Our next step was to estimate the relative contribution of each of these inputs into Buttermilk Bay itself.

Our estimate of nutrients entering Buttermilk Bay via streams was obtained by multiplying streamflow by the average nutrient content of streamwater. Moog (1987) obtained records of flow through Red Brook using a stream stage recorder and calculated annual flow. The other streams contributed 15% of the total flow, as demonstrated by measurements of their flow compared to that of Red Brook (Moog 1987). Total stream flow into the bay was calculated by extrapolation from the Red Brook annual rate. This calculation yielded a stream flow of 8×10^6 m^3 yr^{-1}. Multiplication of average concentrations of NO_3, NH_4, and PO_4 in Red Brook water (Table 3) by streamflow gave estimates of 1.12×10^5 mol DIN yr^{-1} and 5.6×10^3 mol P yr^{-1} delivered to the bay by streams.

The rates of groundwater flow into Buttermilk Bay were calculated from estimated rates of freshwater flow. Moog (1987) estimated the entry of total freshwater discharge into Buttermilk Bay in four different ways. The estimates ranged threefold. The methods of estimating freshwater discharge included calculations (a) using piezometer and hydraulic conductivity data in stream tubes drawn from a water table map, which yielded 9.8×10^6 m^3 yr^{-1}; (b) using data from stage records and discharge data from Red Brook, which gave 11.4×10^6 m^3 yr^{-1}; (c) using regional hydrological equations for mean annual discharge based on US Geological Service gauging station records, which gave an estimate of 28.5×10^6 m^3 yr^{-1}; and (d) using a water budget based on estimates of annual precipitation and evapotranspiration, which gave the largest estimate, 28.7×10^6 m^3 yr^{-1}.

Each method used to calculate flow of freshwater into the bay has good features and drawbacks. Since we could not objectively decide which method was likely to be most accurate, we averaged Moog's (1987) four estimates to obtain 19.6×10^6 m^3 yr^{-1}, the mean total freshwater flow. We then subtracted streamflow from the total to evaluate groundwater flow directly into Buttermilk Bay, 11.6×10^6 m^3 yr^{-1}. This flow rate was then multiplied by the average nutrient concentrations in groundwater (Table 3), to give 5.8×10^5 mol DIN yr^{-1} and 3.2×10^3 mol P yr^{-1}.

To obtain the nutrient loading from precipitation directly on the bay, mean local precipitation during 1985 and 1986 (1.13 m yr^{-1}) was multiplied by the area of Buttermilk Bay (2.1×10^6 m^2). This volume of precipitation (2.3×10^6 m^3 yr^{-1}) was multiplied by the average nutrient content of local precipitation (Table 3), and yielded 5.4×10^4 mol N yr^{-1} and 6.9×10^3 mol P yr^{-1} as the input via direct precipitation into the bay. The relatively high nutrient concentrations in precipitation exceed nutrient content of receiving water (compare Figures 2 and 5 with values in Table 3). Such inputs have been thought to be able to enhance marine primary production (Paerl 1985).

Surface runoff in the Cape Cod area is usually low because of the highly permeable sands that underlie the area. To estimate runoff we therefore concentrated on impervious surfaces. Heufelder (1987) estimated the area near the bay that was covered by pavement or hard impervious surfaces, and calculated the volume of water that drained into gutters and entered the bay through drainpipes (8×10^4 m^3 yr^{-1}). Multiplication by the nutrient concentrations for surface runoff from such impervious surfaces (Table 3) gave 2.16×10^4 mol N yr^{-1} and 9.6×10^1 mol P yr^{-1} as the average annual nutrient inputs by surface runoff.

Waterfowl in the bay and their production of feces were measured by Heufelder (1987) from direct census of birds over an entire year (the average was 100 birds day^{-1}) and literature values of defecation weights (20 g feces at 5% N). To maximize the estimate of waterfowl nutrient inputs, we assumed that waterfowl fed outside the bay but defecated within the bay. The N contributed by waterfowl, 2.6×10^3 mol N yr^{-1}, was small compared to other inputs.

Water Quality and Nutrient Budgets

Inputs into the Watershed

The watershed of Buttermilk Bay is exposed to considerable nutrient loading via different sources. Septic systems introduced the largest amounts of N (43%), while precipitation accounted for 34% of the entering N (Table 4). Use of fertilizer accounts for 24% (Table 4). Septic inputs were also a major mechanism of phosphorus entry, contributing about 38% of the phosphorus, while precipitation added 23% and fertilizer use added about 39% (Table 4).

The specific contribution of specific nutrient source in any one particular coastal watershed depends on the idiosyncrasies of the specific geographical setting and its degree of development. If a watershed is relatively undeveloped, precipitation will be the major nutrient source. If a watershed is urbanized, wastewater becomes more important. This effect of the land use mosaic is doubtless the reason why different coastal water bodies' contributions of nitrogen from sewage may vary from 0 to 100% of total inputs (Nixon 1983), and why contribution of wastewater phosphorus could be 5–84% of total P loading to water bodies (Jaworski 1981). In the case of the Buttermilk Bay watershed, even though large portions of the watershed remain undeveloped, septic systems and domestic fertilizer have already become major sources of nutrients (Table 4).

Inputs into Buttermilk Bay

The highest nutrient concentrations in Buttermilk Bay occur in the nearshore and seem associated with freshwater inputs (Figure 4). Indeed, groundwater transported over 85% of the DIN entering Buttermilk Bay, and streams carried an additional 10% of the DIN input (Table 5). Because of the very porous soil, Cape Cod streams are virtually completely fed by groundwater seeping through springs. If we add the inputs by groundwater and streams, we see that almost 95% of the DIN entering Buttermilk Bay has passed through groundwater. Precipitation added a small amount (<5%) of N to the bay, and surface runoff and defecation by the abundant waterfowl in the bay were negligible (Table 5).

Groundwater carried more than 75% and streams 11% of the phosphorus that entered Buttermilk Bay. Direct precipitation contributed a smaller but significant amount of P into Buttermilk Bay (13.5%, Table 5).

Table 4. Inputs of nitrogen and phosphorus into the watershed of Buttermilk Bay. N/P expressed by atoms.

	Nitrogen inputs		Phosphorus inputs		
	mol × 10^3 yr^{-1}	% of total	mol × 10^3 yr^{-1}	% of total	N/P
Precipitation onto watershed	1169	33.9	149	23.1	7.7
Septic systems	1466	42.6	247	38.3	5.9
Domestic use of fertilizers	579	16.8	41	6.3	14.2
Agricultural use of fertilizers	231	6.7	209	32.3	1.1
Totals	3445		645		5.3

Table 5. Measured annual nitrogen and phosphorus inputs into Buttermilk Bay. Values are the product of the average concentration of N and P (Table 1), and annual flows of water from each source, calculated as described in text.

	N inputs		P inputs		
Sources	mol × 10^3 yr^{-1}	% of total	mol × 10^3 yr^{-1}	% of total	N/P
Streams	112	9.6	5.6	11.0	20.0
Groundwater	1000	85.4	38.3	75.3	26.1
Surface runoff	2.2	0.2	0.1	0.2	22.5
Precipitation	54.4	4.6	6.9	13.5	7.9
Waterfowl	2.6	0.2	—		—
Total	1171		50.9		23.0

Interception and Through-put of Nutrients in the Watershed

Very large proportions of the nutrients (an average of 68% of the N and 93% of the P) that entered the watershed were intercepted within the watershed and failed to reach the bay (Table 6). Some assessment of the variation to be expected to be associated with these mean estimates of interception by the watershed can be obtained by calculating the retention of nutrients using the available upper and lower estimates of groundwater flow (Moog 1987). These calculations give ranges of 45–92% of the N and 89–98% of the P that could be retained within the watershed (Table 6). It seems safe to say that half to virtually all the N and nine-tenths to all the P are intercepted in the watershed.

A variety of mechanisms are probably responsible for the interception of nitrogen in watersheds, including plant uptake, fixation and adsorption of ammonium, and denitrification of nitrate. Although we did not carry out measurements of these processes, we can calculate rough estimates of their likely magnitude. The woodlands on most of Cape Cod have been recovering from deforestation for most of this century. Forest growth thus results in increases in nitrogen storage as tree biomass. The pine–oak forests (at least 2/3 of the area of the 46.2 km^2 of the Buttermilk Bay watershed) of our area may accrete 5–10 kg N ha^{-1} yr^{-1} (J. Melillo, personal communication), so that the annual increase in N storage could reach 1.1 to 2.2 $\times$ 10^6 mol N yr^{-1}. This range of uptake is equivalent to 56–110% of the N input by surface inputs (precipitation and fertilizer) to the watershed (Table 4).

Loss of nitrogen from soils may be an additional mechanism that prevents nitrogen from being transported to coastal waters. We do not have local data, but denitrification rates have been measured in a variety of terrestrial soils, so we can roughly estimate the range of likely rates of denitrification.

Table 6. Inputs and outputs of nitrogen and phosphorus into and out of the watershed of Buttermilk Bay.

	N (mol $\times$ 10^3 yr^{-1})	P (mol $\times$ 10^3 yr^{-1})	N/P
Inputs into watershed[a]	3445	645	5.3
Outputs from watershed into Buttermilk Bay[b]	1112 (267–1896)	43.9 (11.5–73.9)	25
% Intercepted in watershed	68 (45–92)	93 (89–98)	

[a] This is the total of inputs from precipitation, septic systems, and fertilizer use from Table 4.
[b] This is the sum of inputs to Buttermilk Bay via groundwater and streams from Table 5. Numbers in parentheses are the absolute range of loading based on the lowest and highest estimates of groundwater flow from Moog (1987).

In a variety of unfertilized terrestrial soils denitrification rates have ranged from 0.024 to 19 kg N ha^{-1} yr^{-1}, while fertilized soils may lose up to 50 kg N ha^{-1} yr^{-1} (Frissel 1977). Recent values obtained using carefully researched methods yielded 0.3 to 1 kg N ha^{-1} yr^{-1} for an aggrading New Hampshire forest (R. Bowden, personal communication), and 8.8 and 36 kg N ha^{-1} yr^{-1} in unfertilized and fertilized fields in Georgia (Groffman and others 1986). The rates of denitrification in the watershed of Buttermilk Bay are likely to be intermediate in the terrestrial range, since there is some use of fertilizer in the Buttermilk Bay watershed, and since there are significant amounts of N in precipitation (Valiela and others 1978). The denitrification rates in the watershed thus seem likely to fall between 1 and 5 kg N ha^{-1} yr^{-1}. This range of denitrification rates suggests that between 17% and 83% of the nitrogen inputs added at the *surface* of the Buttermilk Bay watershed may be lost by this process.

Thus, the combined loss of nitrogen from storage in tree biomass in the accreting forest and from denitrification losses suggest that only a small proportion, if any, of N added to the watershed surface may actually reach the subsoil or the groundwater table.

M. Jordan (personal communication) of the Marine Biological Laboratory has used tension lysimeters inserted into Cape Cod forest soils and found little evidence of nutrient transport away from surface soils. These direct measurements in nearby sites with soils very similar to those in the Buttermilk Bay watershed corroborate the conclusion based on our rough estimates of nitrogen accretion and denitrification.

Similarly, phosphorus added to the surface of the watershed may be sequestered in plant biomass, but the well-known adsorptive and precipitation reactions of P with soils are probably the major factor accounting for P attenuation within the watershed. This is shown clearly in groundwater samples where DIN concentrations may exceed several hundred μM, but nearly all samples contained less than 5 μM phosphate (Figure 7).

While nitrogen arriving at the surface of a watershed may be therefore largely intercepted near the surface, the N inputs by septic tanks injected below the subsoil seem less likely to be intercepted. Denitrification in porous sand, or in groundwater, may not be appreciable because there is insufficient dissolved organic carbon to support microbial activity, and because groundwater in our area is aerobic. We therefore hypothesize that a large portion of the nitrogen injected into sediments below the subsoil travels freely with the groundwater and reaches coastal waters.

To check whether the amount of nitrogen injected below the subsoil is similar to the amount of N entering coastal waters, we can compare the relative size of subsurface inputs from septic tanks into the watershed relative to groundwater transport of nutrients into Buttermilk Bay (Table 7). Such subsurface nitrogen inputs are similar to inputs of nutrients transported into the bay. There is an apparent 24% "retention" in passage, but in view of the variation that is possible because of the large range of the estimates of groundwater transport (Table 6), it is unlikely that our measured retention of N is quantitatively significant. The retention of P, however, may be large enough to be meaningful. We have to some undetermined extent underestimated insertion of nutrients to the subsoil in Table 7, since we did not include leaching of domestic fertilizers. Inclusion of this added source would have somewhat increased the calculated retention within the watershed. In any case, the general conclusion is that most of the N and less of the P injected below the subsoil travel through the watershed to receiving waters.

There are few other examples of calculation of nutrient interception by a watershed and throughput to receiving waters. Jordan and others (1986) show such calculations for a watershed emptying into the Rhode River Estuary in Maryland. In their rural and wooded watershed 1% of the nitrogen and 7% of the phosphorus reached the estuary. Monbet and others (1981) calculated that 26–92% of the N and 3–21% of the P inputs into five small urbanized watersheds draining into the Bay of Brest reached the bay. The results show that although attenuation of nutrients during passage through specific watersheds is variable, it appears quantitatively significant in most watersheds, as it is in Buttermilk Bay.

Development and urbanization of a watershed with concomitant increase in wastewater release, use of fertilizers, and decrease of forests seem most likely to increase the through-put of nutrients to receiving waters. Persky (1986), for instance, found a significant positive relation between nitrate concentration in groundwater of Cape Cod, MA, and the density of housing units on the wastershed surface. Nutrient loading of groundwater from septic tanks bypasses the mechanisms of nutrient removal near the soil surface. The more development—with its corresponding increase in septic systems and use of fertilizer and less plant biomass—the higher the loading of nitrogen of the groundwater and nutrient loading in the receiving water body.

Table 7. Estimates of subsurface nitrogen and phosphorus inputs into the watershed of Buttermilk Bay compared to estimates of groundwater borne nutrients transported into the Bay.

	N (mol × 10^3 yr^{-1})	P (mol × 10^3 yr^{-1})	N/P
Septic tank inputs into watershed[a]	1466	247	5.9
Outputs from watershed into Buttermilk Bay[b]	1112	43.9	25
% Intercepted in watershed	24	82	

[a] From Table 4.

[b] This is the sum of groundwater and streamflow into Buttermilk Bay from Table 5.

Nutrient Loading and Eutrophication of Buttermilk Bay

Nutrient concentrations in Buttermilk Bay, despite watershed loadings, are not very high compared to the ranges of concentrations measured in a variety of other estuaries, some highly enriched (Table 1). Nonetheless, there is appreciable eutrophication in Buttermilk Bay, since concentrations of NH_4, NO_3, and PO_4 in Buzzards Bay, the body of water into which Buttermilk Bay empties, are generally below 1 μM, whereas some areas of Buttermilk Bay may have much higher concentrations (Table 3 and Figures 2 and 5).

There is one other consideration that makes direct comparisons of concentration data as in Table 1 difficult. Some of the coastal embayments and estuaries included in Table 1 are large, relatively deep water bodies, with phytoplankton dominating primary production. Buttermilk Bay is a shallow coastal lagoon, with a shallow enough bottom so that macrophytes are held within the photic zone and so can grow profusely. The production of macrophytes in Buttermilk Bay (Costa 1988) and other shallow coastal lagoons (Nixon 1986) exceeds production by phytoplankton. In such coastal systems, nutrient loadings may be incorporated to a significant degree into macrophyte biomass, so that concentrations in the water remain deceptively low. The incorporation of large amounts of nutrients into macrophyte biomass poises shallow lagoons in an unstable state. Any meteorological or hydrogeographical event that may harm the macroalgae may have deleterious consequences for the entire ecosystem, because death of macrophytes may result in release of nutrients (Sassi and others 1988) and increased oxygen demand in the water column.

Nutrient loading of coastal water bodies has been much discussed, but guidelines to be used in assessing the impacts of different degrees of loading are not well established (Nixon and others 1986). Nixon (1983), Nixon and Pilson (1983), Lee and Olsen (1985), and Gaines (1985) calculated nitrogen loading of several coastal ecosystems on a per-m^2 and per-m^3 basis. We converted our calculated nitrogen inputs to Buttermilk Bay (Table 5) into the appropriate units, and found that Buttermilk Bay lies in an intermediate range of loadings on a per-m² basis compared to other published studies, but in a high range of loading on a per-m³ basis because of its shallow depth (Table 8).

In bays with equal nutrient loading, inputs would have less impact where water turnover is faster. Hence, another and perhaps more appropriate way to compare loading rates would be to include some notion of water turnover rate. This is not a simple objective because assessment of turnover is difficult.

We roughly calculated a turnover time for Buttermilk Bay in two ways. We calculated turnover by the tidal prism method [T, in no. of tidal cycles = (volume of low tide + tidal volume)/tidal volume; Dyer 1973]. This technique yielded a turnover time of 1 day^{-1}, but the method can give an order of magnitude lower estimate of flushing time than methods based on calculations of flushing time (Dyer 1973, Pilson 1985) because it ignores returning ebb water during the following flood. Incomplete water replacement occurs in Buttermilk Bay because we have data collected at the mouth of the bay during tidal cycles that shows bay water salinity may drop as much as 2 ‰ during ebbing, but much of this water returns during the following flood tide.

In our second method, we calculated flushing time from the mean annual salinities of offshore Buttermilk Bay stations (29.6%) and upper Buzzards Bay stations (30.9%, as above). We treated Buttermilk Bay as a single water mass and divided the volume of freshwater in the bay by freshwater inflow rate (see Dyer 1973). This gave us a flushing time of 5 d.

The residence time of water in Buttermilk Bay probably lies between the 1 and 5-d periods calculated. We used the longer residence time (5 d) to be conservative, and calculated loading (per volume) for Buttermilk (Table 8). This calculation changes considerably the loading rank of the different coastal ecosystems of Table 8 (column 4). For several bays in which residence times were not available, residence was calculated as 5× the tidal prism method as a rough approximation. Because the tidal prism of Buttermilk Bay is large compared to its volume, the turnover-weighted loading suggests that the bay is one of the least loaded systems. Buttermilk Bay may therefore be less threatened than most bays, but not because of low nutrient loading rates; rather, the hydrographic characteristics of the bay reduce moderate loading rates to fairly low levels. We have to hasten to add that these water turnover comparisons based on tidal volumes are coarse and that more precise measurements of

Table 8. Nutrient loading (per m³, per m², and turnover-weighted) for Buttermilk Bay and other estuaries and embayments. Data taken from Nixon and Pilson (1983), Lee and Olsen (1985), Gaines (1985) and Nixon (1983).

	Loading		Turnover times (d)	Turnover-weighted loading (m mol N $m^{-3}r^{-1}$)
	m mol N $m^{-3}yr^{-1}$	m mol N $m^{-2}yr^{-1}$		
Long Island Sound	30	400	166	13.6
Kaneohe Bay	40	230	2	0.2
Lagoon Pond	57	261	24.5[a]	3.8
Chesapeake Bay	80	510	56	12.3
Narraganset Bay	100	950	26	7.1
Town Cove	100	315	26	7.1
Patuxent Estuary	110	600	51	15.4
Delaware Bay	140	1300	97	37.2
Potomac Estuary	140	810	45	17.3
Apalachicola Bay	213	560	6	3.5
Point Judith Pond	240	430	12.5[a]	8.2
Pamlico Estuary	250	860	26	17.8
Ninigret Pond	280	340	24.5[a]	18.8
Barataria Bay	290	570	—	—
North San Francisco Bay	290	2010	107	85.0
South San Francisco Bay	310	1600	320	271.8
Raritan Bay	330	1460	—	—
Buttermilk Bay	390	543	5	5.6
Mobile Bay	400	1280	12	13.2
Green Pond	500	1121	20[a]	27.4
Green Hill Pond	780	620	56.5[a]	>120.7
Potter Pond	1050	710	25[a]	>71.9
New York Bay	4550	31930	3	37.4

[a] Calculated by the tidal prism method × 5 as a best estimate; other values as reported in literature by various methods. See text for explanation of calculation of loadings and turnover times.

water turnover measurements should be obtained, but this procedure shows promise in assessing relative impact of loading in small coastal embayments. We need to reiterate, however, that there will also be seasonal changes that might be of importance, and that slow long-term changes over periods of years are also likely.

N/P Entering the Watershed and Buttermilk Bay

Coastal phytoplankton are thought to be nitrogen-limited (Ryther and Dunstan 1971, and references reviewed in Valiela 1984). In addition to absolute concentration of the limiting nutrient, the ratio of N to P affects algal and plant growth rates. N/P ratios exceeding 16:1 would promote growth of coastal producers (Jaworski 1981).

The array of sources that input nitrogen and phosphorus into the watershed and into Buttermilk Bay did not convey the same proportions of the two nutrients. For inputs into the watershed, the overall N/P was 5.7 (Table 4), whereas the N/P presumably entering the bay was 23 (Table 5). The N/P ratio borne by freshwater entering Buttermilk Bay—and the much larger absolute concentrations of N and P compared to bay water (see Figure 2 and Figure 7)—seem high enough to prompt increased algal and plant growth in the bay.

The N/P of subsurface injections of nutrients was about 6, whereas the N/P in groundwater entering the bay was 25 (Table 7). This difference is probably due to strong adsorption of phosphate by soils and sediments along the travel path of groundwater. We measured DIN concentrations as high as several hundred μM. PO_4 concentrations never exceeded 12 μM, and the modal concentration in groundwater was less than 1 μM (Figure 7). We frequently observed in some samples of groundwater N/P above 100 and as high as 1500. Some of the high N/P values in Figure 6 are probably due to local injection of groundwater bearing high N/P. Such high ratios are likely to promote producer growth in coastal waters.

As mentioned earlier, there was a very clear-cut seasonal variation in N/P in the water (Figure 6). Seasonal differences in inputs of N and P (D'Elia and others 1986, Webb and Eldridge 1987) and seasonal differences in nutrient dynamics within coastal ecosystems (Pennock and Sharp 1987) have been reported to occur elsewhere. We have found an unexplained seasonality in groundwater nutrient content in groundwater flowing into a Cape Cod coastal ecosystem (Valiela and others 1978). From our earlier data we calculate that N/P delivered by groundwater was 50:1 during winter, and only 10:1 during summer. These values lie well in the range of values of N/P found during winter and summer in the water of Buttermilk Bay (Figure 6, top). We might therefore expect that the seasonal differences in N and P inputs lead to nitrogen limitation in the warm months and phosphorus limitation during cold months. This is also what we might surmise from the N/P ratios of Buttermilk Bay (Figure 6). We are unsure how the seasonal pattern is produced in Buttermilk Bay; it might indeed be that the seasonal change in nutrient inputs of groundwater in the Cape Cod nearshore produces the seasonal shift in the bay, or processes within Buttermilk Bay may be responsible. This topic needs further study.

The importance of water turnover, and the seasonality of supply and concentrations of nutrients in the water suggest that neither annual mass budgets nor studies of concentrations at any one time are sufficient to interpret the role of nutrient limitation or the impact of eutrophication. In addition, there are year-to-year changes, not highlighted in this article, that also need consideration. Long-term seasonal studies, including estimates of water turnover, seem necessary to understand the origin and impact of eutrophication.

Changes in N to P ratios within a watershed have been seen elsewhere and may be a common but variable phenomenon that depends on the land use and natural mosaic. Development, agriculture, and wetlands in a watershed may all raise N/P of outputs to coastal waters. N/P entering fairly developed or urbanized watersheds that drain into the Bay of Brest range from 5.3 to 11.7 and average 7.2; the N/P ratios leaving the watersheds and entering the Bay of Brest are much higher, ranging from 22.1 to 241, and average 131 (Monbet and others 1981). These trends qualitatively agree with those we saw in Buttermilk Bay (Table 6). These data suggest that landscape development may emphasize the shift to high N/P entering receiving waters. Nutrient inputs in croplands usually have low N/P, but discharge of water from these units of landscape bear higher N to P ratios (Jordan and others 1986). If groundwater passes through a salt marsh on its way to the receiving coastal water body, its N/P changes from 12.9 to 23.7 (Valiela and others 1978).

Buttermilk Bay is urbanized nearshore, but away from shore it is largely wooded, with some agriculture and suburban development. When we consider all sources, only a small fraction of nutrients added to the watershed enter the bay. Would our results have been different if the wooded area was smaller than the urbanized area, if salt marshes were of considerable importance, or if all homes were located much farther away from the bay shore? Does degree of development over the entire watershed matter, or is it only the septic tanks and lawns near the shore that are significant? Our observations and some preliminary data (ms. in preparation) suggest that nutrient inputs nearshore, especially from septic systems, affect the concentrations and signature of nutrients in groundwater and streams, and thus the net inputs of nutrients into Buttermilk Bay.

The spatial arrangement of nutrient sources, and the mosaic of land use may be key features essential to both understanding the basic dynamics of nutrients near coastal water bodies and developing management schemes. Studies of these features are a needed next step in the study of couplings between watersheds and coastal waters.

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