

Nutrient Flux in the Rhode River: Tidal Exchange of Nutrients by Brackish Marshes

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Tidal exchanges of nitrogen, phosphorus, and organic carbon by a high and a low elevation marsh in the Rhode River estuary were measured throughout the year. Both marshes tended to import particulate matter and export dissolved matter, although they differed in the fluxes of certain nutrients. Compared with tidal exchanges, bulk precipitation was a major source of ammonia and nitrate and a minor source of other nutrients. There was a net retention of nutrients by the portion of the Rhode River that included both marshes and a mudflat. However, the marshes accounted for only 10% of the phosphorus retention and 1% of the nitrogen retention while they released organic carbon amounting to 20% of the retention. This suggests that the mudflat acted as a sink for nutrients. The primary role of the marshes seems to be transformation of particulate to dissolved nutrients rather than nutrient retention or release.

Introduction

There have been several studies of the role of tidal marshes in nutrient cycling (reviewed by Nixon, 1980). Early research suggested that salt marshes export large quantities of particulate detritus (Teal, 1962; Odum & de la Cruz, 1967), and dissolved nutrients (Pomeroy *et al.*, 1967) which would enhance the productivity of coastal ecosystems. Paradoxically, it was also suggested that marshes could absorb nutrients from sewage effluent thus protecting coastal waters from eutrophication (Valiela *et al.*, 1976). One way researchers examined these hypotheses was by measuring tidal exchange of nutrients by marshes. Implicit in these studies was the hopeful assumption that marshes behave somewhat alike, yet the results show differences among marshes. For example, Great Sippewissett Marsh, in Massachusetts, exports particulate organic carbon and particulate nitrogen (Valiela *et al.*, 1978), but Flax Pond Marsh, in New York, imports particulate organic carbon (Woodwell *et al.*, 1977) and Carter Creek Marsh in Virginia imports particulate nitrogen (Axelrad *et al.*, 1976). Although these marshes differ in nutrient exchange, the various processes which control exchange may be common among marshes and the net exchanges by a marsh may provide clues as to which processes dominate.

The impact of marshes on nutrient cycling in coastal waters is still in question. Most marshes studied export particulate organic carbon (Nixon, 1980), but the ratios of stable

carbon isotopes in a Georgia estuary suggest that organic matter from marsh plants makes up only a small proportion of that in the estuary (Haines, 1977). However, the isotope data do not preclude the possibility that as much as 40% of the carbon in the estuary comes from marsh plants (Nixon, 1980), or that some of the carbon may come from marsh chemoautotrophs (Howarth & Teal, 1980). Most marshes studied export dissolved nutrients (Nixon, 1980), but dissolved nutrients exported by marshes may be taken up by neighboring mudflat ecosystems (Welsh, 1980), restricting the extent of the marshes' influence.

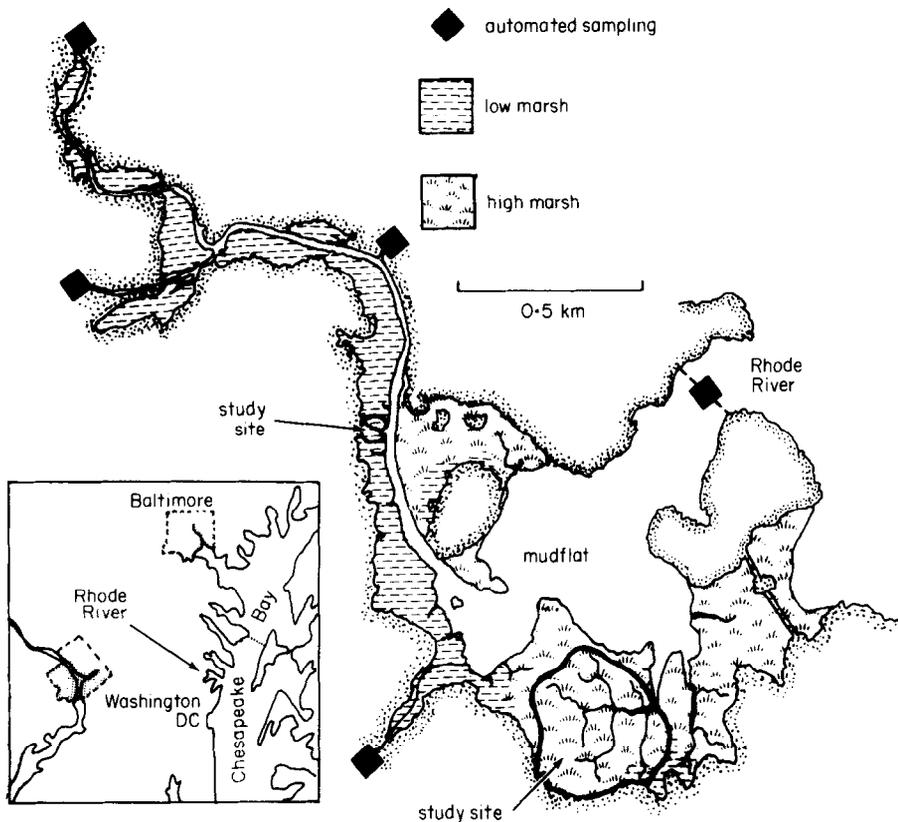


Figure 1. The intertidal zone of the Rhode River including marshes and mudflat. Study sites refer to marsh areas where tidal exchanges were monitored. Inset shows the location of the Rhode River.

In this study we measured tidal exchange of nutrients by two brackish marshes to determine their roles in nutrient cycling. For contrast, we chose two very different marshes: one of low elevation vegetated primarily by *Typha angustifolia*; and one of high elevation vegetated by *Spartina patens*, *Distichlis spicata*, *Iva frutescens*, *S. cynosuroides*, and *Scirpus olneyi*. Both marshes have salinities ranging from 0 to 20 ppt and border the Rhode River (Figure 1), a subestuary of Chesapeake Bay on the east coast of North America ($38^{\circ}51'N$, $76^{\circ}32'W$). We assessed the impact of the marshes on nearby waters by comparing their nutrient exchanges with the nutrient budget for a portion of the Rhode River which includes the marshes and an adjacent mudflat (Figure 1).

Methods

We constructed flumes at the mouths of the tidal creeks at the marsh study sites (Figure 1) to facilitate measurements of water flow. We studied 11 tidal cycles throughout the year, roughly one per month with two in July and none in January and February during ice cover. The time period of the study was June 1980–May 1981 with September 1981 and October 1981 sampling to fill a gap in the fall 1980 data. During tidal cycle studies we measured depth and current velocities in the flumes every 5 min, starting at slack low water. Velocities were measured with Marsh–McBirney model 511 electromagnetic current meters. We took water samples every half hour by filling 1-l polyethylene bottles from just below the water's surface. We placed the samples on ice and about every 2 h we composited the samples by volumes proportional to the water flow during the half hour periods they represented. By compositing flood and ebb water separately we could determine the flow weighted concentrations of nutrients entering and leaving the marshes.

Portions of the composites to be analyzed for dissolved nutrients were filtered through Millipore 0.45 μm filters and Schleichter and Schuell glass fibre prefilters. Samples were filtered in the field except in studies conducted from December through May when samples were filtered in the lab since we felt that low water temperatures would minimize change in nutrient concentrations during transport to the lab. Filtered samples were stored on ice or refrigerated until analyzed. Inorganic nutrients were usually analyzed within 24 h of sampling. If longer storage was necessary, 36 N sulfuric acid was added as a preservative (1 ml l⁻¹).

To measure adsorbed nutrients, 50-ml subsamples of the composites were filtered through Nuclepore 0.4 μm filters. The filters were then rinsed with 50 ml of either 1 M KCl or 0.5 N HCl, respectively, to extract ammonium or phosphate adsorbed on particles. The use of 1 M KCl to release readily exchangeable ammonium ions is a common technique in soil analysis (Bremner, 1965). The use of 0.5 N HCl to release phosphate is based upon the principle that in a strong acid phosphate is not ionized and iron phosphate complexes dissolve (Correll & Miklas, 1976). The KCl and HCl extracts were stored on ice or refrigerated until analyzed.

The following techniques were used to determine nutrient concentrations. Total phosphorus was digested to orthophosphate with perchloric acid (King, 1932), and orthophosphate was measured by the stannous chloride technique (American Public Health Association, 1976). The perchloric acid digestion is the most rigorous method in use today and is commonly used to determine the adequacy of other digestion procedures (American Public Health Association, 1976, 474). Nitrate was reduced to nitrite by cadmium amalgam reduction, ammonia was oxidized to nitrite by alkaline hypochlorite, and nitrite was analyzed by reaction with sulfanilamide (American Public Health Association, 1976; U.S. E.P.A., 1974). Total Kjeldahl nitrogen was determined by digestion with sulfuric acid in the presence of Hengar granules and hydrogen peroxide in order to maximize completeness of digestion (Martin, 1972). The resulting ammonia was distilled and analyzed by Nesslerization (American Public Health Association, 1976). Chloride was measured directly with a Dionex model 16 ion chromatograph.

Organic carbon was measured by drying samples at 60 °C, then digesting with potassium dichromate in 67% sulfuric acid at 100 °C for 3 h (Maciolek, 1962) in the presence of HgSO₄ to complex halides (Dobbs & Williams, 1963). After digestion, excess dichromate was measured colorimetrically and chemical oxygen demand (COD) was calculated from the amount of dichromate consumed (Gandy & Ramanathan, 1964). Organic carbon was calculated by dividing COD by 2.86 (Maciolek, 1962).

TABLE 1. Average coefficients of variation (CV) from ten sets of triplicate analyses, for each nutrient

Parameter	Mean CV(%)	Parameter	Mean CV(%)
Total P	5.9	Nitrate	5.0
Orthophosphate	3.6	Ammonia	7.6
Total Kjeldahl N	9.5	Organic carbon	7.6

The precision of our analytical methods was checked by analyzing about 10% of all samples in triplicate. Average coefficients of variation ranged from 3.6% for orthophosphate to 9.5% for Kjeldahl N (Table I).

We measured the concentration of suspended particulate matter of various size fractions. Total particulate matter was measured by filtering with preweighed Millipore 0.45 μm filters and then rinsing, drying and weighing the filters. Because small volume samples may not quantitatively sample large particles which may be few in number but significant in weight, we sampled large particles during tidal cycle studies by pumping water through a series of nested sieves (1 mm, 250 μm , and 45 μm) using a submersible pump. The pump was run at a measured rate of about 6 l min^{-1} for 15 min out of each half hour. Particles were rinsed from the sieves and collected on preweighed filters which then were dried and reweighed. Particles collected on the 45 μm sieve were composited over roughly 2-h periods. Particles on the 1 mm and 250 μm sieve were composited by ebb and flood tides. Very large particles (> 1 cm), mostly plant litter fragments, were sampled by placing wire mesh screens across the flumes during separate half tidal cycles (ebb or flood) other than those sampled for nutrients. Particles caught on the screens were collected, dried and weighed.

Calculation of nutrient fluxes from the marshes was complicated by the irregularity of tides in the Rhode River. Mean tidal amplitude is about 40 cm but the water level often fluctuates more due to meteorological influences. As a result the height of high tide is unpredictable and tides are often asymmetrical. Since asymmetry of tidal volumes would have undue influence on calculations of nutrient flux, we assumed that flood and ebb volumes are equal on the average and calculated fluxes from monthly average tidal volumes. This assumption seems reasonable because monthly changes in mean water level, averaging about 6 cm, are much smaller than tidal changes in water level which occur about 60 times per month (Cory & Dresler, 1980). Monthly average tidal volumes were calculated from the water flows measured during tidal cycles and from three years of tide gauge data for the Rhode River (R. Cory, SERC, Edgewater, MD, unpublished data). To do this, we first grouped the measurements of current velocities and depths during tidal cycles into depth ranges of 0–5 cm, 5–10 cm, 10–15 cm, etc. From these measurements we calculated the average volumes of water that flowed in or out of the marsh as the depth changed over the 5-cm intervals. From these volumes we could calculate the flow during given tides using the depths at low and high tides. A computer program calculated the tidal volume corresponding to each tide gauge record of sequential low and high tide depths. Finally, the calculated tidal volumes were averaged by month.

The areas of the marshes drained by the tidal creeks monitored were determined from the volumes of water filling 5 cm depth increments after the surfaces of the marshes were

completely submerged. The areas were 2.5 ha for the high marsh and 0.23 ha for the low marsh.

Nutrient concentrations were weighted by the water flows measured during sampling. This was accomplished in part by compositing samples. However, when composite samples represented portions of the flood or ebb, flow-weighted concentrations for the entire flood or ebb were calculated by multiplying the concentration in each sample by the flow which occurred during sampling, summing the products, and dividing by the total flood or ebb flow.

Nutrient fluxes were calculated by multiplying flow-weighted nutrient concentrations for the flood and ebb tides of each study by the average tidal volume for the month of the study. Flow-weighted concentrations for months when data were missing were calculated by averaging the concentrations for the months immediately following and preceding.

Most of the tidal cycles we studied were during the day, roughly 0600 to 1800 h, but one tidal cycle in July and one in August ran from 0000 to 1200 h. We did not see any obvious diurnal differences in concentrations of fluxes of nutrients, and therefore, we have ignored possible diurnal effects in this study.

Inputs of nutrients by bulk precipitation (rainfall and dryfall) were measured in a continuation of the study reported by Miklas *et al.* (1977) and Correll & Ford (1982). Briefly, bulk precipitation was collected in a 28 cm diameter polyethylene funnel attached to a polyethylene bottle and rainfall volume was measured with rain gauges.

Measurements of nutrient flux through the entire intertidal zone, including both marshes and mudflat, were made using automated sampling stations (Figure 1) as described by Correll (1981). Inputs to the intertidal zone from 2300 ha of upland watersheds were measured at V-notch weirs where volume-integrated samples were taken automatically. Tidal exchanges of nutrients between the intertidal zone and the Rhode River were monitored at a station which measured water flow with an electromagnetic current meter (Marsh-McBirney, model 511) interfaced to a tide gauge and took separate volume-integrated samples of flood and ebb tides. Samples taken at automated stations were preserved with about 2 ml l⁻¹ of 36 N sulfuric acid.

To determine the amounts of phosphorus and organic matter in sediments, marsh and mudflat sediments were sampled to a depth of 20 cm with coring tubes. The samples were analyzed for total phosphorus by digestion with perchloric acid followed by reaction with ammonium molybdate, and reduction and extraction with isobutanol (Correll & Miklas, 1976). Organic matter in high marsh sediment was measured as weight loss after ashing at 550 °C.

Results

The tidal volumes of the marshes, that is, volumes flooding onto and ebbing from the marshes, vary greatly among tides and the monthly average volumes vary slightly among years (Figure 2). However, on the average, tidal volumes are highest in September and lowest in January and February. The tides we studied varied in volume randomly throughout the seasons and often flood and ebb volumes were unequal (Figure 2). There was no significant systematic difference between observed flood and ebb tidal volumes (paired *t* test, $P = 0.21$, low marsh; $P = 0.33$, high marsh) or chloride concentrations (Table 2, $P = 0.11$, low marsh; $P = 0.24$, high marsh). This suggests that there was little or no efflux of fresh ground water from the marshes. This may have been due to a drought

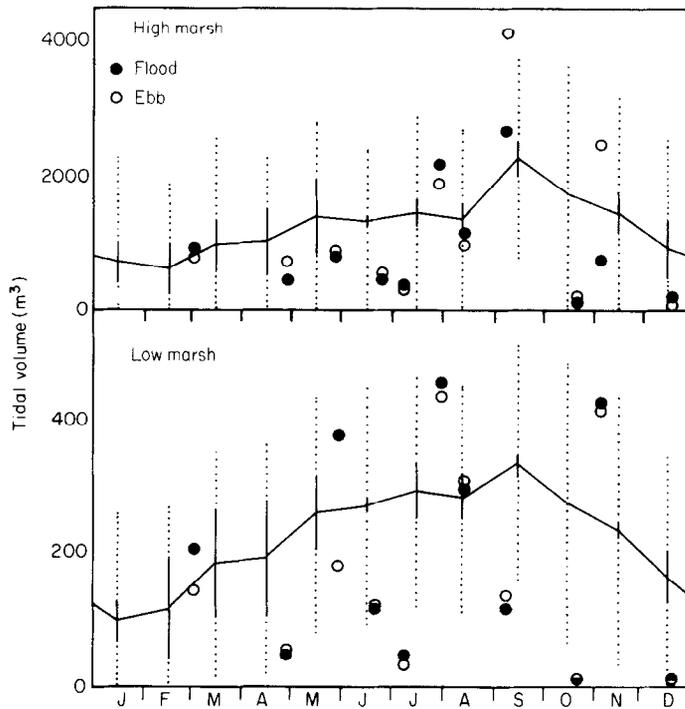


Figure 2. Tidal volumes of the high and low marsh throughout the year. Data points represent tidal cycles that were studied. The lines are drawn through monthly averages (see text). Solid and dotted vertical lines are \pm the standard deviation of yearly means and individual tides, respectively. Data for October are from only one year.

which persisted throughout the study. The apparent lack of ground water efflux suggests that flood and ebb tidal volumes were equal on the average, an assumption we made in calculating nutrient fluxes.

Flow-weighted flood and ebb concentrations varied greatly among tidal cycles (Table 2), but they tended to vary in parallel, that is, ebb tide concentrations reflected corresponding flood tide concentrations. Analysis of variance of concentration data from all dates revealed that the effect of factors related to date was greater than the effect of tide (flood *vs.* ebb) for each nutrient measured. In general, the concentrations of inorganic and organic forms of phosphorus were about equal but the concentrations of organic forms of nitrogen exceeded the concentrations of inorganic forms. Phosphorus, nitrogen and organic carbon were divided about equally into dissolved and particulate fractions. Particles larger than 45 μm represented a relatively minor component of the total particulate matter.

Since differences between flood and ebb concentrations of nutrients may be related to the amount of water exchanged by the marsh, we tested for correlations between the observed tidal volume and the difference between flood and ebb concentrations. The only significant correlation was for total particulate matter in the low marsh (Figure 3). Total particle concentrations in flood water exceeded those in ebb water to an extent which increased as tidal volume increased.

Both dissolved and particulate (adsorbed) phosphate concentrations varied seasonally attaining peaks in summer (Figure 4). A summer maximum in phosphate concentration

TABLE 2. Average flow weighted concentrations \pm standard deviation, with number of samples in parentheses

	High marsh		Low marsh	
	Flood	Ebb	Flood	Ebb
<i>Phosphorus ($\mu\text{g l}^{-1}$)</i>				
Dissolved PO_4	86 \pm 77 (11)	82 \pm 59 (10)	59 \pm 37 (11)	98 \pm 59 (11)
Dissolved organic	33 \pm 29 (11)	30 \pm 29 (11)	29 \pm 21 (11)	31 \pm 18 (11)
Particulate PO_4	54 \pm 39 (10)	39 \pm 20 (10)	83 \pm 64 (11)	69 \pm 34 (11)
Particulate organic	51 \pm 29 (10)	50 \pm 36 (10)	66 \pm 46 (11)	52 \pm 31 (11)
<i>Nitrogen ($\mu\text{g l}^{-1}$)</i>				
Dissolved NH_4	90 \pm 76 (10)	79 \pm 55 (10)	49 \pm 35 (10)	69 \pm 48 (10)
$\text{NO}_3 + \text{NO}_2$	21 \pm 58 (11)	22 \pm 58 (11)	23 \pm 65 (11)	19 \pm 46 (11)
Dissolved organic	378 \pm 122 (10)	505 \pm 105 (10)	373 \pm 83 (10)	401 \pm 131 (10)
Particulate NH_4	22 \pm 16 (10)	28 \pm 28 (10)	18 \pm 24 (11)	15 \pm 13 (11)
Particulate organic	383 \pm 268 (10)	332 \pm 294 (10)	579 \pm 284 (11)	530 \pm 394 (11)
<i>Organic carbon (mg l^{-1})</i>				
Dissolved	5.9 \pm 2.8 (10)	7.0 \pm 2.8 (10)	5.2 \pm 2.1 (9)	5.6 \pm 2.4 (9)
Particulate	5.2 \pm 5.2 (10)	5.6 \pm 7.3 (10)	3.5 \pm 2.1 (9)	3.1 \pm 2.1 (9)
<i>Chloride (g l^{-1})</i>				
	5.9 \pm 1.8 (6)	5.8 \pm 1.8 (6)	5.0 \pm 2.3 (4)	4.7 \pm 2.4 (4)
<i>Particulate matter (mg l^{-1})</i>				
Total	16 \pm 7 (8)	10 \pm 5 (8)	26 \pm 13 (11)	16 \pm 9 (11)
45–250 μm	1.4 \pm 1.0 (7)	1.1 \pm 0.4 (7)	1.1 \pm 0.8 (7)	1.2 \pm 1.1 (7)
250–1000 μm	0.44 \pm 0.75 (7)	0.14 \pm 0.17 (7)	0.14 \pm 0.11 (7)	0.12 \pm 0.16 (7)
$\geq 1000 \mu\text{m}$	0.67 \pm 1.7 (7)	0.06 \pm 0.07 (7)	0.05 \pm 0.06 (7)	0.08 \pm 0.11 (7)
$\geq 1 \text{ cm}$	0.16 \pm 0.28 (4)	0.29 \pm 0.52 (4)	0.48 \pm 0.60 (9)	0.14 \pm 0.14 (5)

is typical of inshore waters and may be due to increased rates of phosphate regeneration from the sediments (Nixon *et al.*, 1980). The differences between flood and ebb phosphate concentrations also varied seasonally. In the low marsh, ebb concentrations of dissolved phosphate were in greatest excess over flood concentrations in summer (Figure 4). This suggests that regeneration of dissolved phosphate from the low marsh peaks in summer. In the high marsh the seasonal trend in the difference of ebb and flood concentrations of dissolved phosphate was unclear. Two of the tidal cycles in summer stand out as different from the rest showing high dissolved phosphate concentrations and an excess of phosphate in flood waters above that in ebb waters (Figure 4). Perhaps the high marsh imports dissolved phosphate when concentrations are high and exports it when concentrations are low thereby buffering phosphate concentrations in tidal waters. In both marshes, flood concentrations of particulate phosphate were higher than ebb concentrations in the summer, indicating import of particulate phosphate (Figure 4).

Nitrate and nitrite were the only other nutrients besides phosphate to vary seasonally. Their combined concentration was less than $10 \mu\text{g N l}^{-1}$ most of the year but rose to about $200 \mu\text{g N l}^{-1}$ in March in both marshes.

On a yearly basis, both marshes tended to import particulate matter and export dissolved matter but fluxes of certain nutrients differed between the marshes (Figure 5). For example, on an areal basis much more phosphorus was exchanged by the low marsh than

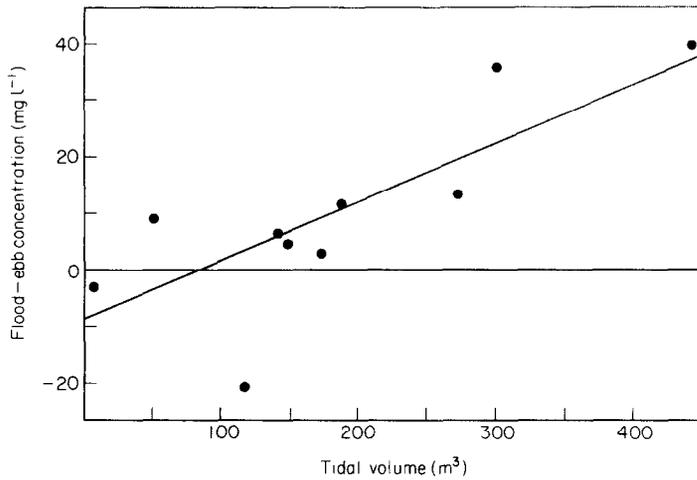


Figure 3. The difference between flow weighted flood and ebb concentrations of total particulate matter versus observed tidal volume in the low marsh. Line fit by linear regression; $r=0.78$, $P<0.01$.

by the high marsh and much more dissolved organic nitrogen (DON) was exported from the high marsh than from the low marsh. Also, dissolved ammonia was exported by the low marsh while it was imported slightly by the high marsh. Unlike the low marsh, the high marsh exported particulate organic carbon (POC). In both marshes, particles larger than $45\ \mu\text{m}$ made up a small proportion of the total particle flux (Figure 5).

It is difficult to judge whether our measurements of yearly fluxes are statistically significant. Fluxes may change in magnitude and direction seasonally, so several years of

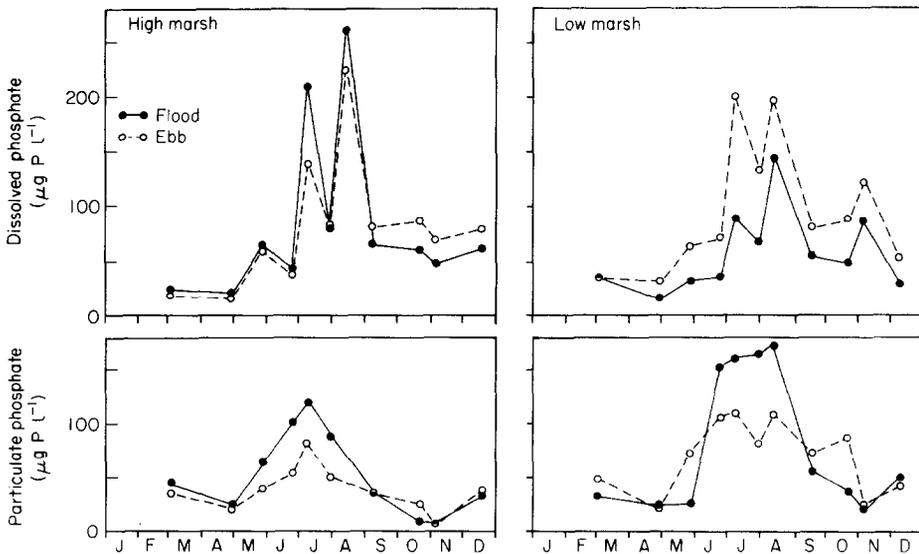


Figure 4. Flow weighted ebb and flood concentrations of dissolved and particulate phosphate versus date.

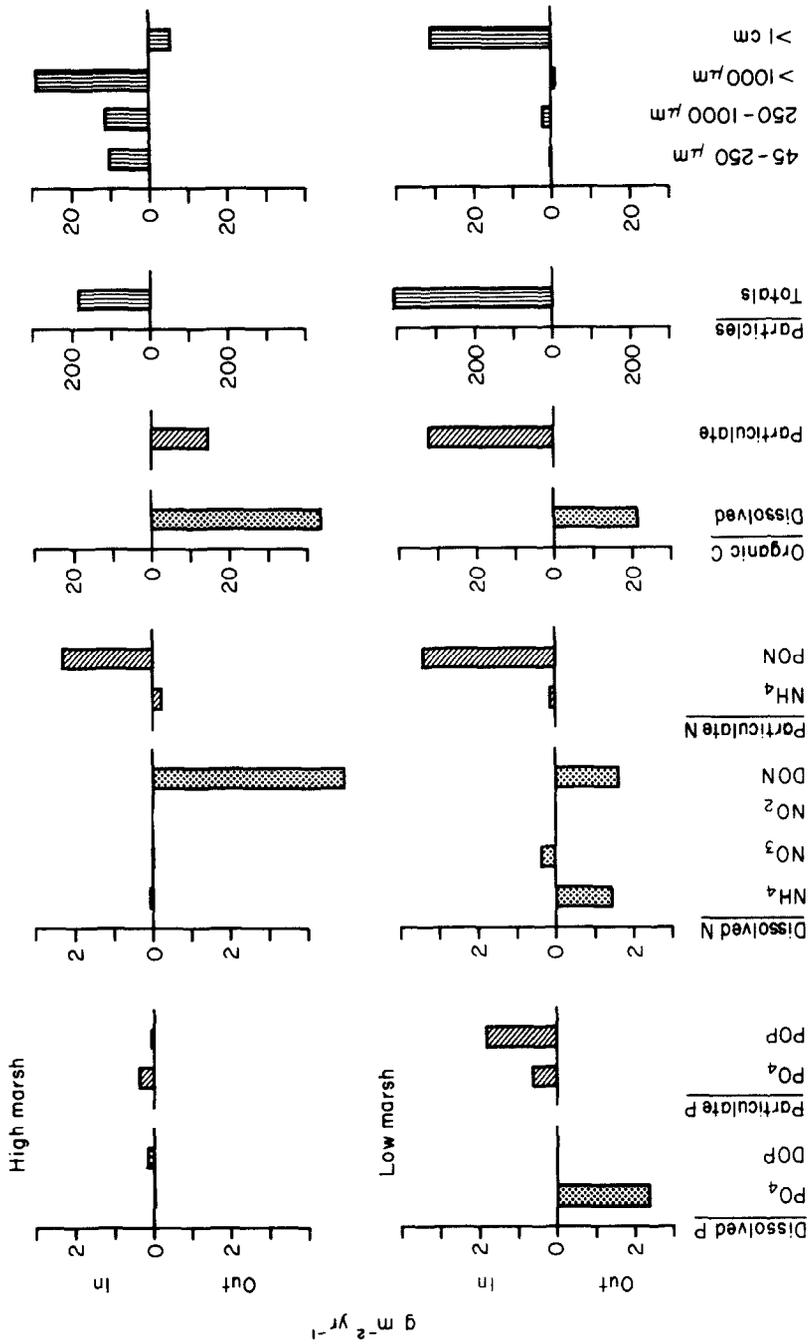


Figure 5. Yearly net tidal exchanges.

data would be needed to distinguish complex seasonal trends. However, if a flux is consistent throughout the year, the monthly measurements can be treated as replicates and the flux measurement can be tested statistically. This was done using a paired *t* test to compare flood and ebb flow weighted concentrations paired by date. Nutrients whose flood and ebb concentrations were significantly different included dissolved ammonia ($P < 0.05$) and dissolved phosphate ($P < 0.01$) in the low marsh, and dissolved organic nitrogen ($P < 0.01$) and total particulate matter ($P < 0.01$) in the high marsh. This means that the fluxes of these nutrients were consistent in direction throughout the year and large enough to be distinguished from random error.

TABLE 3. Yearly nutrient fluxes (kg C, N, or P) into the intertidal zone during the time period of the marsh studies. Fluxes of particulate and dissolved nutrients are summed. Positive tidal exchanges are net inputs, and negative exchanges net outputs

	Land runoff	Precipitations on intertidal	Tidal exchange	Retention
<i>Phosphorus</i>				
Total phosphorus	542	40.0	+ 586	+ 1170
Phosphate	219	9.22	- 70	+ 158
Organic phosphorus	323	30.8	+ 656	+ 1010
<i>Nitrogen</i>				
Total nitrogen	3180	908	+ 7860	+11 900
Ammonia	235	208	- 225	+ 218
Nitrate plus nitrite	461	334	+ 16.7	+ 812
Organic nitrogen	2490	365	+ 8070	+10 900
<i>Carbon</i>				
Total organic carbon	26 700	2820	+ 28 900	+ 58 500

TABLE 4. Bulk precipitation input and net tidal exchange by the marshes, $\text{gm}^{-2} \text{yr}^{-1}$. Particulate and dissolved fractions are summed. Positive tidal exchange is net input, and negative exchange net output

	Bulk precipitation	Tidal exchange	
		High marsh	Low marsh
<i>Phosphorus</i>			
Total phosphorus	+0.051	+0.57	-0.54
Phosphate	+0.012	+0.35	-1.7
Organic phosphorus	+0.040	+0.22	+1.2
<i>Nitrogen</i>			
Total nitrogen	+1.2	-2.9	+0.91
Ammonia	+0.27	-0.15	-1.3
Nitrate plus nitrite	+0.43	-0.070	+0.35
Organic nitrogen	+0.47	-2.6	+1.8
<i>Carbon</i>			
Total organic carbon	+3.7	-58	+11

Comparing the tidal exchanges of nutrients by the marshes with nutrient fluxes through the entire intertidal zone (Figure 1) provides a means of evaluating the marshes' impact on their surroundings. Fluxes of particulate and dissolved nutrients through the intertidal were not measured separately, so the fluxes we will discuss represent the sums of particulate and dissolved fractions. Fluxes through the intertidal vary throughout the year but most nutrients do not show clear systematic seasonal trends. We will confine our presentation to a summary of yearly fluxes during the time period of the marsh studies. Data on fluxes during earlier time periods are discussed in detail by Correll (1981) and Correll & Ford (1982).

During the marsh studies, bulk precipitation onto the intertidal zone represented a minor input of nutrients except for ammonia and nitrate (Table 3). Runoff from the uplands was the largest source of nitrate influx to the intertidal while tidal exchange with the Rhode River provided the largest influx of organic nitrogen and organic phosphorus. Runoff and tidal exchange were about equal sources of organic carbon influx. Tidal exchange resulted in outputs of phosphate and ammonia countering inputs from runoff. By adding the fluxes in and out of the intertidal zone (Table 3) we can calculate the amount of nutrients retained, that is, the amount which either accumulated within the system or was converted to another form and released. Retained nitrogen and organic carbon includes the amounts

TABLE 5. Net retention of nutrients (kg C, N or P yr⁻¹) in sections of the intertidal zone, prorated by total areas: high marsh, 29 ha; low marsh, 17 ha; mudflat 32 ha. Data represent sums of retentions of particulate and dissolved nutrients (intertidal = high marsh + low marsh + mudflat).

	Intertidal	High marsh	Low marsh	Mudflat
<i>Phosphorus</i>				
Total phosphorus	+ 1170	+ 180	- 84	+ 1070
Phosphate	+ 158	+ 104	- 291	+ 345
Organic phosphorus	+ 1010	+ 75.4	+ 287	+ 728
<i>Nitrogen</i>				
Total nitrogen	+11 900	- 490	+ 352	+12 000
Ammonia	+ 218	+ 35.4	- 172	+ 355
Nitrate plus nitrite	+ 812	+ 104	+ 131	+ 577
Organic nitrogen	+ 10 900	- 629	+ 391	+11 100
<i>Carbon</i>				
Total organic carbon	+ 58 500	15 600	+ 2470	+ 71 600

which were converted to gaseous forms. In general, the intertidal zone acted as a sink for nutrients, retaining most of the ammonia and phosphate inputs and all of the other nutrient inputs (Table 3).

Compared with tidal exchanges by the marshes, bulk precipitation was a major source of ammonia and nitrate and a minor source of other nutrients (Table 4). In the high marsh, precipitation inputs more than offset net tidal exports of total ammonia (dissolved plus particulate bound) and nitrate plus nitrite. In the low marsh, precipitation inputs were about equal to net tidal imports of total nitrogen and the nitrate plus nitrite. One reason that precipitation inputs assume such importance is that tidal exchange by the marshes

exported dissolved nutrients and imported particulate nutrients. Thus, the sum of particulate and dissolved fluxes is relatively small.

Adding precipitation inputs to net tidal exchange yielded an estimate of net retention (or release) of nutrients by the marshes. Net retention data were then prorated by the areas of high marsh and low marsh within the intertidal zone and compared to retention by the entire intertidal zone (Table 5). Retention by the mudflat (including tidal creeks) was estimated by subtracting retention by the marshes from retention by the entire intertidal zone.

Retentions by the marshes were generally very small compared with retention by the entire intertidal zone (Table 5). This suggests that the mudflat acts as a sink for nutrients and that the behavior of the intertidal zone is largely a reflection of the behavior of the mudflat. The low marsh retained a relatively large amount of organic phosphorus but it released total phosphate and total ammonia. These releases offset the retention of the mudflats somewhat. In most cases the high marsh and low marsh behaved oppositely in retaining nutrients so they tended to cancel each other's effects (Table 5).

Since phosphorus is not converted to gaseous forms, retention of phosphorus is due solely to accumulation of phosphorus in the sediment. Therefore, we can estimate accretion of the marshes and mudflat from our measurements of phosphorus retention (Table 5) and from the density and phosphorus content of the sediment (Table 6). By this calculation the high marsh and mudflat are accreting about 3 mm per year. This rate is similar to the rate of rise of sea level, 4.2 mm per year [measured at Annapolis from 1929–1972 (Hicks & Crosby, 1973)]. Likewise, Redfield (1972) found that a marsh and its tidal creeks accreted in pace with sea level rise. In contrast, the low marsh had an apparent accretion rate of -0.7 mm per year. However, it seems unlikely that the low marsh is really losing sediment since it imported particulate matter (Figure 5). The negative accretion rate may instead reflect a decrease in the phosphorus concentration of the sediment equivalent to a 3% decrease per year in the top 20 cm of sediment. Alternatively, the apparent negative accretion could reflect random error in the data. Our calculation of accretion is only a rough estimate primarily because of the uncertainty involved in measuring retention. However, the agreement between estimated accretion of the mudflat and sea level rise suggests that our estimation of phosphorus retention in the mudflat is not unreasonable although it was found by difference (Table 5). The mudflat can retain more phosphorus than the marshes without substantially greater accretion in terms of depth because of the relatively high density of mudflat sediments (Table 6).

TABLE 6. Calculation of accretion based on phosphorus retention. Retentions are from Table 5. Phosphorus concentration and density measurements are given \pm standard deviation with numbers of replicates in parentheses

	High marsh	Low marsh	Mudflat
Retention g P m ⁻² yr ⁻¹	+0.62	-0.49	+3.3
mg P (g dry sediment) ⁻¹	1.6 \pm 6.2 (33)	2.2 \pm 0.5 (33)	1.6 \pm 0.4 (30)
Accretion (g dry sed.) m ⁻² yr ⁻¹	+390	-220	+2700
Density g dry sed. cm ⁻³	0.15 \pm 0.02 (10)	0.30 \pm 0.05 (52)	0.63 \pm 0.15 (7)
Depth of accretion mm yr ⁻¹	+2.6	-0.74	+3.3

TABLE 7. Tidal exchange of nutrients, g C, N or P m⁻² yr⁻¹. Export is negative; import is positive. Numbers in parentheses and centred between two columns represent the sum of the two corresponding nutrients

	Organic carbon			Phosphorus				Nitrogen				
	particulate		dissolved	particulate		dissolved	particulate		dissolved			
				POP	PO ₄	DOP	PO ₄	PON	NH ₄	DON	NH ₄	NO ₂
High marsh (this study)	-14	-43	+0.029	+0.38	+0.19	-0.031	+2.3	-0.24	-4.9	+0.092	+0.002	-0.073
Low marsh (this study)	+32	-21	+1.2	+0.64	+0.005	-2.4	+3.4	+0.14	-1.6	-1.4	-0.007	+0.34
Carter Creek, VA (Axelrad <i>et al.</i> , 1976)	-120	-25	(+0.84)	-0.17	-0.60	(+4.7)	-9.3	+0.29	+0.024	+0.31		
Ware Creek, VA (Axelrad <i>et al.</i> , 1976)	-35	-80	(+1.1)	-0.22	-0.049	(-0.027)	-2.3	-2.9	-0.13	+2.3		
Crommet Creek, NH (Daly & Mathieson, 1971)				+0.56					+2.1	+0.037	+0.28	
Gott's Marsh, MD (Heinle & Flemer, 1976)	-7.3		(-0.14)	(-0.19)			(-0.25)	-2.1	-0.39	0	-0.93	
Dill Creek, SC (Settlemyre & Gardner, 1975)	-300			-6.4								
Great Sippewisset, MA (Valiela & Teal, 1979, Valiela <i>et al.</i> , 1978)	-34			-0.28			(-3.0)	-4.4	-1.9	-0.025	-1.7	
Flax Pond, NY (Woodwell <i>et al.</i> , 1977; 1979; Woodwell & Whitney, 1977)	+61	-8.4					-1.4	-2.1	+0.1	+1.1		

Discussion

Tidal exchange of nutrients differs among marshes previously studied but most of the fluxes we observed are within the range of those observed by others (Table 7). In general, dissolved nutrients other than nitrate and nitrite are exported by marshes. Some of these nutrients may be released from pore waters by either diffusion or seepage. Gardner (1975) suggested that dissolved phosphate was released from pore waters of a South Carolina salt marsh mainly by diffusion. Tidal export of dissolved phosphate by our marshes reflects their pore water chemistry. The low marsh which exports the most dissolved phosphate per m² also has the highest concentrations of dissolved phosphate in its pore waters but we are not certain if the exported phosphate comes from pore waters by either seepage or diffusion (Jordan & Correll, in prep.). Export of dissolved nutrients may be balanced by tidal imports of particulate matter, precipitation, gaseous exchange (e.g. nitrogen, or carbon dioxide), or inflow of fresh ground water. The inflow of ground water seems to determine whether nitrate and nitrite are imported or exported. Marshes without much groundwater input may import nitrate and nitrite due to denitrification occurring in the anaerobic marsh soil (Nixon, 1980). This may explain our observation of nitrate import by the low marsh. Conversely, substantial ground water input of nitrate may result in tidal export of nitrate and nitrite as in Great Sippewissett Marsh (Valiela *et al.*, 1978) and Gott's Marsh (Heinle & Flemer, 1976).

Depending on a number of factors, particulate matter may be either exported or imported by tidal marshes (Table 7). Marshes accrete sediments, keeping pace with the rise in sea level (Redfield, 1972), but they also produce particulate matter in the form of plant litter some of which may be exported. Net exchange of particulate matter may be influenced by how long or how often the marsh surface is submerged. While submerged, the marsh surface can act as a sediment trap because the vegetation slows water currents and provides surfaces for impaction of suspended particles. Also, when water spreads over the marsh surface its velocity drops because it is no longer canalized by creek banks. Longer submergence may lead to more trapping of sediment. This may explain why the low marsh imports more particulate matter per m² than the high marsh (Figure 5) and why this import increases with increasing tidal volume (Figure 3).

Particle exchange may also be influenced by the shape of the intertidal drainage basin (Odum, 1980). For example, Flax Pond Marsh has a more restricted opening than Great Sippewissett Marsh and this may be the reason that Flax Pond Marsh imports particulate organic carbon while Great Sippewissett Marsh exports particulate organic carbon (Valiela *et al.*, 1978). The marshes we studied have similar drainage systems with very little standing water at low tide. In some marshes filter feeding bivalves may play an important role in trapping sediment (Jordan & Valiela, 1982), but bivalves are not abundant in the marshes we studied. Factors that we have not addressed that may influence particle exchange include erosion by storms, rafting of detritus in winter ice, and bedload transport.

Some marshes export particulate organic carbon but import particulate phosphorus and nitrogen [Table 7: Ware Creek and Carter Creek, Axelrad *et al.*, (1976), high marsh, this study]. In this case the C:P and C:N ratios of particles leaving the marsh are higher than those of particles entering the marsh, a possible consequence of the relatively high C:N and C:P ratios of marsh plant litter. In the marshes we studied a significant proportion of the particulate nitrogen and phosphorus concentration and flux consists of adsorbed ammonia and adsorbed phosphate (Tables 2 and 7, Figure 5) but previous studies have not measured these fractions (Table 7).

Since carbon can be exchanged in gas phase, net retention (Table 5) represents both accretion and loss of gaseous forms, primarily CO_2 . Drake & Read (1981) measured a net uptake of $310 \text{ g m}^{-2} \text{ yr}^{-1} \text{ CO}_2\text{-C}$ in a section of the Rhode River high marsh. We estimated accretion of high marsh sediment from their measurement of CO_2 exchange and our measurement of retention of organic carbon (Table 5). We measured about 75% organic matter in high marsh sediment. Assuming that organic matter is about 50% carbon, we estimate accretion to be about 4 mm per year, roughly agreeing with sea level rise, 4.2 mm per year (Hicks & Crosby, 1973), and accretion based on phosphorus exchange, 3 mm per year (Table 5). Drake & Read (1981) found that respiration in the high marsh represented 60% of production. Comparing our results with theirs suggests that 7% of the organic carbon produced in the high marsh is exported and 33% accumulates in the marsh.

We do not have measurements of gaseous exchanges of nitrogen but the observed net release of nitrogen by the high marsh (Table 3) suggests that nitrogen fixation exceeds denitrification there. In contrast, Kaplan *et al.* (1979) found that denitrification exceeded nitrogen fixation in a New England salt marsh. However, denitrification in the marsh they studied may be unusually high due to high input of nitrate in fresh ground water. Nixon (1980) suggests that in most marshes nitrogen fixation exceeds denitrification.

Since marshes differ in their tidal exchange of nutrients, their relative impact on neighboring ecosystems also differs. Tidal exchanges of nitrogen by our marshes were about the same as precipitation inputs (Table 2). In contrast, Valiela & Teal (1979) found that precipitation inputs of nitrogenous nutrients were small compared to net tidal exchanges by a New England salt marsh. However, they found relatively high net tidal exports (Table 7) possibly because that marsh received large amounts of ground water. Our marshes have a minimal effect on the total mass balance of nutrients in comparison to the mudflat (Table 5). The mudflat retains by far the most nutrients. The relatively large releases of ammonia and phosphate by the low marsh are equaled by the estimated retention in the mudflat. Similarly, Welsh (1980) found that a New England salt marsh released ammonia and phosphate which was taken up by adjacent mudflats. Net retentions of nutrients by the marshes we studied were relatively small (Table 5) because import of particulate nutrients roughly balanced export of dissolved nutrients (Figure 5). Thus, the marshes act as transformers of particulate to dissolved nutrients rather than as sources or sinks for nutrients.

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