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Continuous Automated Sampling of Tidal Exchanges of Nutrients by Brackish Marshes

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Automated instruments were used to measure tidal exchanges of materials at two brackish marshes of differing elevation. The instruments, located at the mouths of the tidal creeks draining the marshes, measured depth and tidal current velocity, and pumped water samples in volumes proportional to flow. Separate composite samples of flood and ebb water were collected weekly for about two-thirds of the weeks throughout a 2–3-year period and analysed for orthophosphate (PO_4^{3-}), total organic P (TOP), ammonium (NH_4^+), nitrate plus nitrite (NO_3^-), total organic N (TON), total organic C (TOC), and total suspended particles (TSP). Exchanges of these materials differed for the two marshes. At the lower elevation marsh, the largest net flux was an import of TON, but TON was exported by the high marsh. The low marsh also imported TOP, NO_3^-, and TSP, but there were no significant exchanges of these materials at the high marsh. The largest net flux at the high marsh was an export of TOC, but there was no significant net exchange of TOC at the low marsh. Both marshes exported NH_4^+. At the low marsh the tidal exchange of PO_4^{3-} and NH_4^+ differed among years, with PO_4^{3-} exchange differing in direction as well as magnitude. In general, the high marsh was more prone to export materials, especially organic N and C, while the low marsh was more dominated by deposition and tended to import materials. Compared to manual techniques previously used to measure tidal exchanges, automated sampling permits lower-cost observations of many more tidal cycles, including observations during episodic storms or extreme tides. Although strong effects of such episodic events were not detected by the weekly composite sampling used here, the inclusion of such events in the sampling probably increases the accuracy of estimates of average tidal exchanges.

Introduction

How do tidal marshes affect tidal waters? This question has been the subject of much speculation and research beginning with the studies of Teal (1962) and Odum and de la Cruz (1967) which suggested that particulate organic matter exported from tidal marshes may be an important component of coastal and estuarine foodwebs. Later, interest in the role of marshes broadened as research suggested that marshes might also play an important role in removing inorganic nutrients from tidal waters and thereby reduce eutrophication (e.g. Valiela *et al.*, 1976; also see review by Nixon, 1980).

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A direct approach to assessing the effects of a marsh is to measure the flow and take samples of the water that enters and leaves with the tide. Although conceptually simple, this approach is so laborious that it has been applied to relatively few marshes. The results of such studies have differed. For example, some marshes seem to export particulate organic matter (Settlemyre & Gardner, 1975; Axelrad *et al.*, 1976; Heinle & Flemer, 1976; Valiela *et al.*, 1978; Chrzanowski *et al.*, 1982; Borey *et al.*, 1983; Roman & Daiber, 1989), but a few seem to import it (Woodwell *et al.*, 1977; Jordan *et al.*, 1983; Dankers *et al.*, 1984). It is not clear whether these and other differences reflect errors in measurement or real differences among marshes. One problem is that short-lived episodes of rain, wind, or high tidal flows can strongly influence tidal exchanges (Wolaver *et al.*, 1984; Chalmers *et al.*, 1985; Roman & Daiber, 1989), yet such events have been poorly sampled because of the limited number of tidal cycles typically observed in studies of tidal exchanges.

In the present study we employed an automated sampling system for continuous monitoring of tidal exchanges by two contrasting marshes over a 2–3-year period. This technique permits the observation of thousands of tidal cycles, including episodes of unusual tidal exchanges, at a fraction of the effort of manual sampling. In a previous study of the same marshes we manually sampled 11 tidal cycles throughout the year and found that the marshes imported particulate matter and exported dissolved matter, although they differed in the exchange of certain substances (Jordan *et al.*, 1983). The goals of this study were to measure the net balance of fluxes of particulate and dissolved materials, and to investigate the importance of short-term perturbations, and interannual and seasonal differences.

Methods

Study sites

We studied two marshes of differing elevation: a low marsh 25–35 cm above mean low water (MLW) and a high marsh 40–60 cm above MLW. The low marsh is vegetated primarily by *Typha angustifolia* and the high marsh is vegetated by *Spartina patens, Distichlis spicata, Scirpus olneyi*, and several other species. The marshes are located at the head of the Rhode River (38°51′N, 70°36′W, Figure 1), a subestuary on the western shore of Chesapeake Bay. The mean tidal range in the Rhode River is 30 cm, but weather conditions often cause more extreme changes in water level. Salinity varies seasonally from 0 ppt in spring to 18 ppt in fall during years with low runoff.

Automated sampling

Automated instruments housed in small sheds measured tidal flows at the mouths of the creeks draining the marshes and pumped water samples with volumes proportional to the rates of flow. To facilitate measurements of current velocities, a flume was installed in each tidal creek to channel the water flow. These flumes should not be confused with the flumes others have used to measure nutrient exchanges on the marsh surface away from tidal creeks (e.g. Wolaver *et al.*, 1980; Whiting *et al.*, 1989). Our flumes are only 1 m long and simply confine the flow of water in the creek to a defined channel at the measuring station. The flumes have wineglass-shaped cross sections to accommodate the higher flow rates that occur at higher tidal stages as greater areas of marsh become submerged. Current velocities in each flume were measured with a Marsh–McBirney electromagnetic current meter. The current meter probe was suspended in the flume and kept in the middle of the water column at all stages of the tide by a system of pulleys actuated by a float and counter

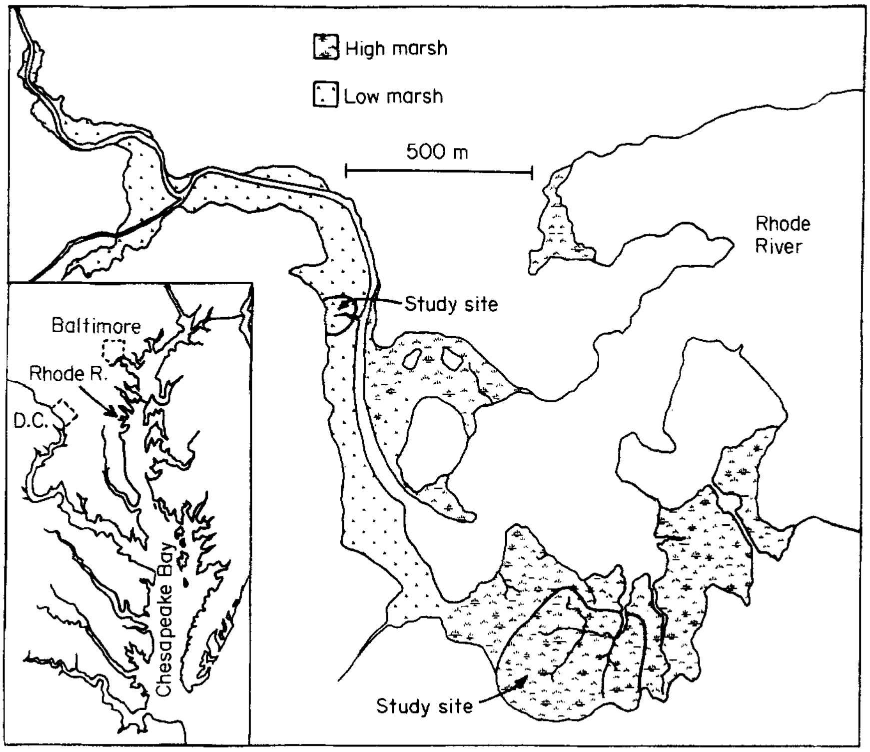

Figure 1. The tidal marshes of the upper Rhode River showing sites where tidal exchanges were monitored. Inset shows location of Rhode River near the cities of Baltimore and Washington D.C.

weight suspended in a stilling well. Water depth was measured with a separate float and counter weight system which turned a potentiometer. The potentiometer and the current meter were linked to a Campbell CR21X data logger. Every 15 min the logger recorded depth and current velocity (positive for ebb, negative for flood), and calculated the flow rate by multiplying the velocity by the cross-sectional area of the submerged portion of the flume as determined from a polynomial equation relating depth to cross-sectional area.

After each flow measurement, the logger switched on a pump to draw a volume of sample proportional to the flow rate. The sample was drawn through plastic tubing with an inlet suspended in the tidal creek near the current meter probe. The tubing was rinsed with tidal water for several seconds at the beginning of each sampling cycle. After the rinse, the outlet of the tubing was moved by a solenoid to a position over a funnel. The sample was then pumped into the funnel for a time proportional to the tidal flow rate. There were separate funnels for samples of ebbing or flooding water. The logger controlled solenoids to position the outlet of the sampling tube over the appropriate funnel depending on the sign of the current velocity. Two hoses exited from the bottom of each funnel to conduct separate portions of the sample to a 20-l jug with sulphuric acid (25 ml, 15 N) added as a preservative and to a jug without preservative. Thus, separate preserved and unpreserved samples of ebbing and flooding water were mixed in proportion to the tidal flow rate. These composite samples were collected weekly for analysis.

We also monitored discharges from the Rhode River watershed with a network of automated samplers (Figure 1) that measure water flow and take samples in volumes proportional to the flow (Correll, 1977, 1981; Jordan *et al.*, 1986*a*). Rain- or snowfall was measured and sampled after each precipitation event at a weather station on the Rhode River watershed (Correll & Ford, 1982).

Chemical analyses

We used the following techniques for analysis of N, P and organic C species in the acid-preserved samples. Total P was digested to orthophosphate with perchloric acid (King, 1932). Orthophosphate (PO_4^{3-}) was analysed by reaction with stannous chloride and ammonium molybdate (APHA, 1976). Total organic P (TOP) was calculated by difference. Total Kjeldhal N was digested with sulphuric acid, Hengar granules, and hydrogen peroxide (Martin, 1972). The resultant ammonia was distilled and analysed by Nesslerization (APHA, 1976). Ammonium (NH_4^+) was oxidized to nitrite by alkaline hypochlorite (Strickland & Parsons, 1972), nitrate was reduced to nitrite by cadmium amalgam, and nitrite was analysed by reaction with sulphanilamide (APHA, 1976). We will present data on the sum of nitrate and nitrite concentrations (NO_3^-). Total organic N (TON) was calculated by difference. Total organic carbon (TOC) was analysed by drying samples at 60 °C, followed by reaction with potassium dichromate in 67% sulphuric acid at 100 °C for 3 h (Maciolek, 1962) with $HgSO_4$ added to complex halides (Dobbs & Williams, 1963). Organic carbon was calculated from the amount of unreacted dichromate measured colorimetrically (Maciolek, 1962; Gaudy & Ramanathan, 1964). Since we used sulphuric acid as a preservative we could not distinguish between particulate and dissolved forms of N, P, and C.

We measured conductivity and the concentration of particulate matter in the unpreserved samples. Conductivity was measured with a Yellow Springs Instruments, Model 32, conductivity meter. Particulate matter was analysed by filtering a measured volume of sample through a preweighed 0·45-µm membrane filter, rinsing with distilled water to remove salts, and then reweighing the filter after drying it in a vacuum desiccator.

Results

Water flow

An example of depth and flow data recorded by instruments at the low marsh illustrates the irregularity of the tides at our marshes (Figure 2). Seiches with periods shorter than a tidal cycle are often superimposed on tidal depth changes (e.g. 24 May, Figure 2). Longer-period depth changes also occur, such as the period of low water from 25 to 26 May (Figure 2) induced by north-westerly winds. Many tides do not flood the marsh. When flooding does not occur, tidal flow rates are low. Generally, the ebb tide is longer than the flood tide and includes a period of slow drainage.

We deduced the elevation of the marsh surface and the area of marsh drained by the tidal creek from the amount of flow per change in water depth. Flow (m^3) divided by change in depth (m), gives an estimate of the area (m^2) covered by the water that flowed in or out of the marsh. We calculated flow per change in depth for 15-min intervals when depth changed 1–2 cm. Data from intervals when depth changed <1 or >2 cm gave highly variable estimates of flow per change in depth. To average flow per change in depth we grouped data according to ebb or flood flow, and by 5-cm depth increments based on the average depth during each 15-min interval.

As the surface of the marsh floods, the flow per change in depth increases rapidly as depth increases (Figure 3). From this we can infer that the low marsh floods at depths of

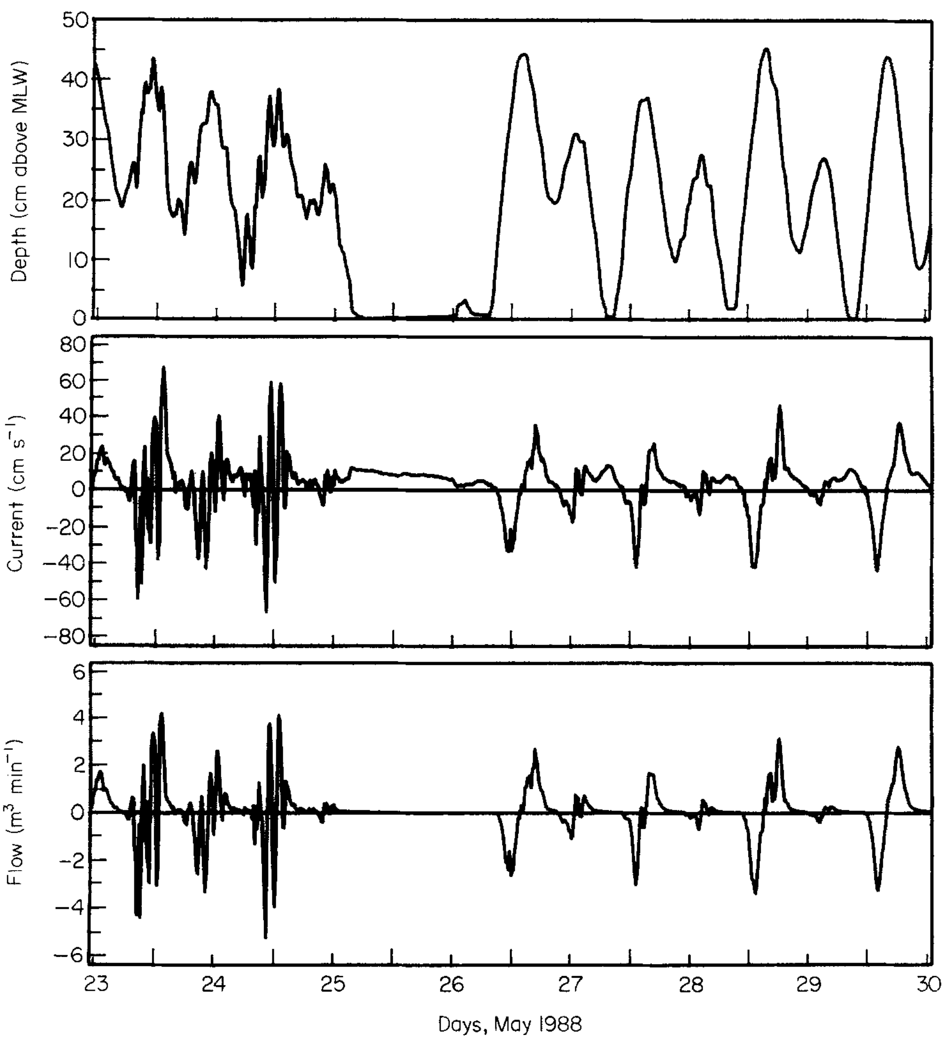

Figure 2. An example of 1 week of depth, current velocity and flow data from the automated sampler at the low marsh.

25–35 cm above MLW and the high marsh floods at depths of 40–60 cm above MLW (Figure 3). Our depth data indicate that the low marsh is fully submerged about 30% of the time and the high marsh is fully submerged about 2% of the time. After the marsh is completely flooded water can enter or leave the marsh by flowing over the marsh surface without flowing through the tidal creek. Therefore, as depth increases above the surface of the marsh, the flow through the creek per change in depth decreases as more water bypasses the creek (Figure 3).

From the curves of depth *vs.* flow per change in depth (Figure 3), we estimate that the low marsh creek drains an area of about 0·18 ha, and the high marsh creek drains an area of about 3 ha. The shapes of these curves differ for ebbing and flooding water (Figure 3). Generally, when depth is below the surface of the marsh, ebb flows are greater than flood flows, but when the marsh is inundated, flood flows are greater than ebb flows.

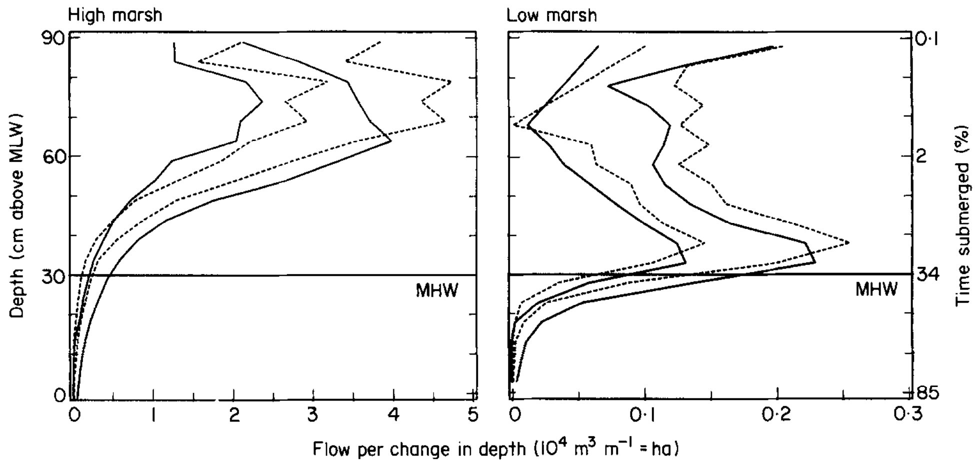

Figure 3. Water depth (cm) above mean low water (MLW) *vs*. the flow per change in depth ($10^4\,m^3\,m^{-1}$ = ha), calculated as described in text. Lines mark the 25th and 75th percentiles of the flow data grouped by ebb and flood flow, and by depth in 5-cm intervals. ----, Flood tides; ———, ebb tides. The percentage of the time that different elevations are submerged are also indicated on the vertical axis. Mean high water (MHW) is 30 cm above MLW.

The tidal volume (the average of ebbing and flooding volumes) varied weekly reflecting erratic fluctuations and a winter minimum in the height of high tide (Figure 4). At the high marsh there were also interannual differences in the seasonality of tidal volume with a maximum in late spring in 1988 and a maximum in late summer–early fall in 1989.

At the high marsh the conductivity of ebb water was significantly lower than that of flood water ($P < 0{\cdot}05$, sign rank test) suggesting a net discharge of freshwater. We calculated the apparent discharge of freshwater from the change in conductivity and the tidal volume. This discharge was correlated with the rate of discharge from the upland watershed and was equivalent to the discharge from 20 ha of watershed (Figure 5). Apparently, the high marsh receives inflow from about 20 ha of adjacent watershed, either as overland flow or groundwater flow. We used the regression equation relating freshwater discharge from the high marsh to discharge from the upland watershed to estimate freshwater discharge when conductivity data were not available. Weekly discharge of freshwater from the high marsh was less than 5% of the tidal volume during 70% of the weeks studied, but ranged from 20 to 45% of the tidal volume during 9% of the weeks studied.

At the low marsh, ebb and flood water did not differ significantly in conductivity suggesting that freshwater discharge was negligible relative to the tidal volume. Two factors may account for this. First, the lower elevation of the low marsh results in a higher tidal volume per unit area than at the high marsh. Second, the area of adjacent upland which drains directly into the low marsh may be small.

At both marshes, the measured ebb flow per week usually exceeded the measured flood flow by more than the freshwater discharge. Perhaps a greater proportion of flood than ebb flow escapes our measurement by bypassing the creek when the marsh is submerged as noted by Miller and Gardner (1981).

Nutrient and particle concentrations

Nutrient concentrations were similar in water flooding the high and low marshes but there were some differences. For example, the concentrations of PO_4^{3-} and NO_3^- were usually

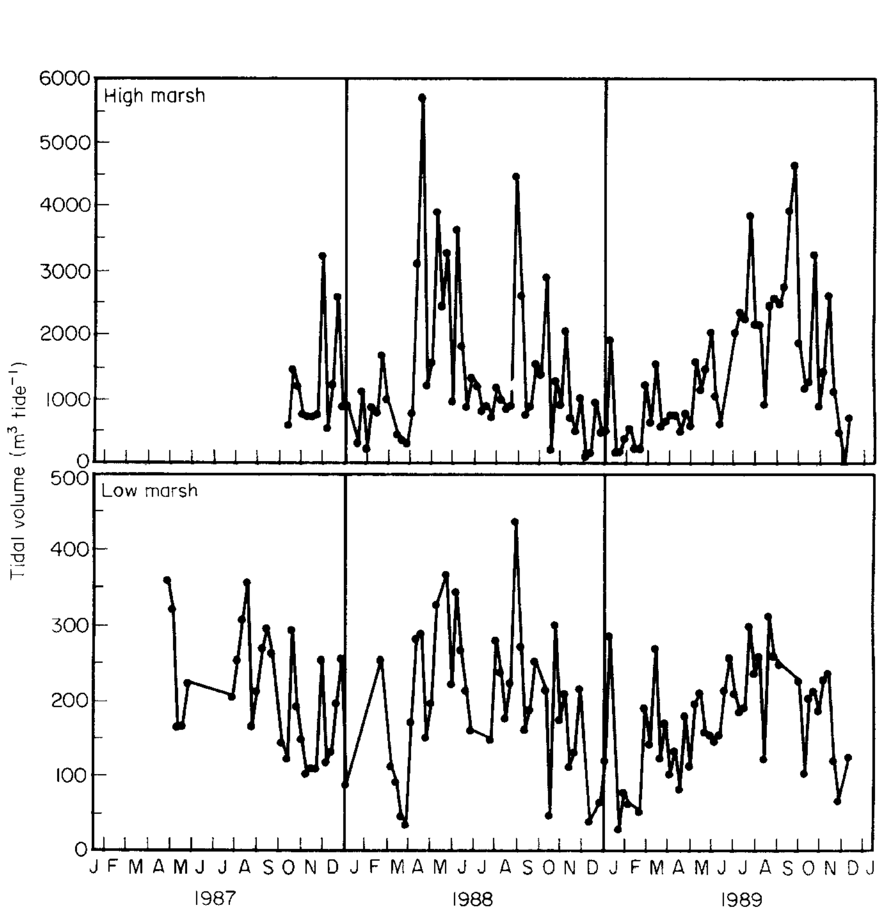

Figure 4. Tidal volume (average of flood and ebb volumes) at the low and high marshes through time.

higher at the low marsh than at the high marsh, while the concentration of NH_4^+ was usually higher at the high marsh (Figure 6). PO_4^{3-} and, to a lesser extent, NH_4^+ peaked in concentration in the summer. NO_3^- concentrations peaked in spring in 1988, but in spring and summer in 1989. Suspended particles, and organic P and C did not show clear seasonal or spatial trends, but organic N showed vague summer and fall peaks.

The concentrations of several constituents appeared systematically different in ebbing water than in flooding water (Figure 7). However, the statistical analysis of these differences is complicated by the problem of defining a replicate measurement. It could be argued that the only true replicate measurement would arise from study of a replicate marsh site. For example, we would need to sample three different low marsh creeks to obtain three replicate measurements for low marsh in general. Alternatively, we can ask whether the differences between ebb and flood concentrations are statistically significant at our particular study sites. One approach is to treat each weekly measurement as a replicate. However, the weekly measurements may not be independent since, for example, a phenomenon that influences the measurement in 1 week may persist for subsequent weeks. If weekly measurements are not independent, then treating them as replicates could artificially inflate the power of the statistics.

To assess the independence of measurements from consecutive weeks, we analysed the correlation between the difference of flood and ebb concentration in each week with that of

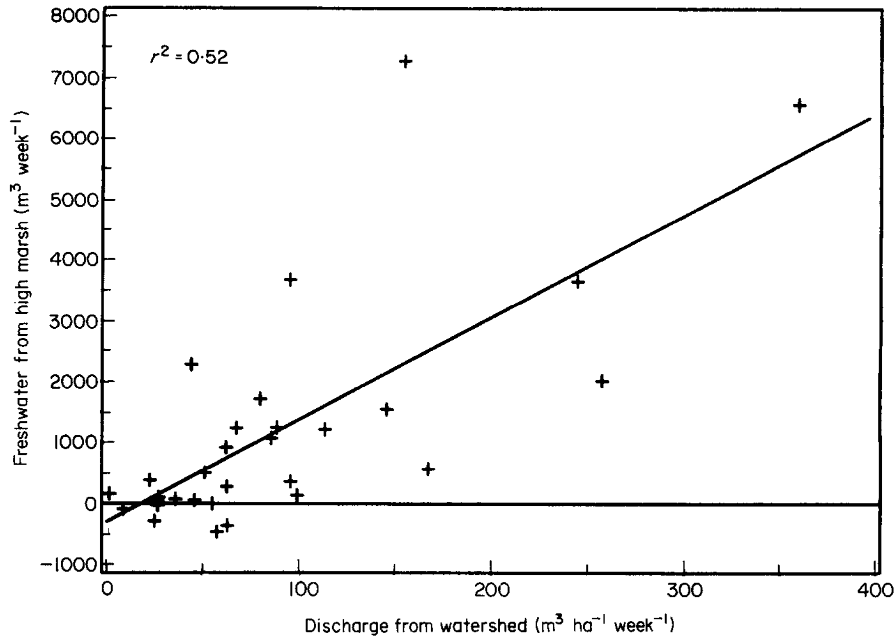

Figure 5. Freshwater discharge at the high marsh, calculated from conductivity data and the tidal volume, *vs.* the rate of water discharge per area from upland watersheds of the Rhode River. Line fitted by linear regression.

the previous week. In other words, we tested for autocorrelation at a lag of 1 week. For most of the constituents we measured, the weekly differences between ebb and flood concentrations do not show significant ($P<0.05$) autocorrelation at a lag of 1 week, suggesting that they are independent. However, at the low marsh there is significant autocorrelation for PO_4^{3-} ($r^2=0.14$), NH_4^+ ($r^2=0.14$), and NO_3^- ($r^2=0.12$). Therefore, for these nutrients, statistical analyses that treat individual weeks as replicates may have artificially exaggerated power, but may be useful nevertheless as preliminary analyses.

We used a non-parametric sign ranks test (SAS, 1985) to assess whether the differences between the ebb and flood concentrations were significantly different from zero. At both the low and high marshes the concentrations of NH_4^+ were significantly higher ($P<0.05$) in ebb than in flood water indicating a net export of NH_4^+ (Figure 7). Similarly, the high marsh showed significant export of organic N and C. In contrast, the low marsh showed significant import of organic N and P, NO_3^-, and total suspended particles (TSP).

We used analysis of covariance (ANCOVA) to investigate the influence of year, season, and other variables on the differences between flood and ebb concentrations. Tidal volume, rainfall and watershed discharge were treated as covariates in separate analyses with year and season as fixed classification factors. Seasons were: spring, March–May; summer, June–August; and fall, September–November. Winter data from both marshes and 1987 data from the high marsh were omitted from the ANCOVAs since few weeks were successfully sampled then.

In almost all cases the covariates had no significant effects independent of the effects of year or season. The only exception was tidal volume which affected TON ($P<0.05$) at the low marsh and NH_4^+ ($P<0.0001$) at the high marsh. These effects, however, explained little of the total variance (Figure 8). At the low marsh, ebbing water usually had lower

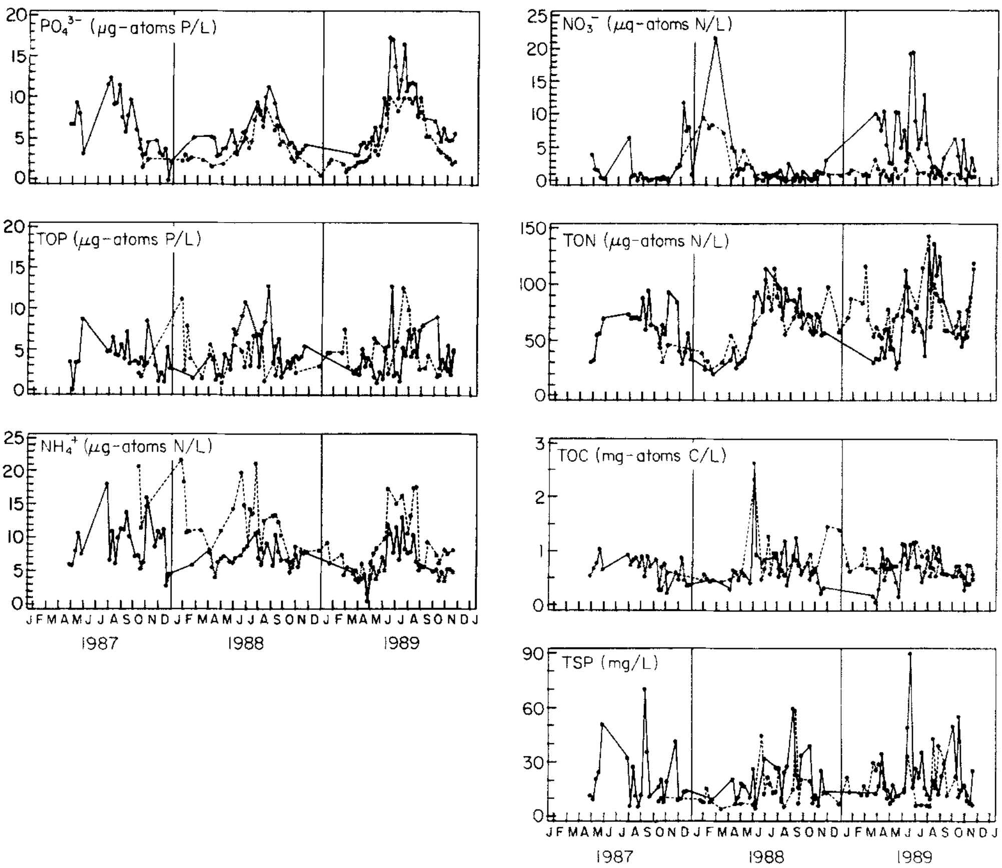

Figure 6. Concentrations of materials in weekly composite samples of flooding waters at the high (– – – –) and low (————) marshes through time.

concentrations of TON than flooding water and this concentration difference increased with increasing tidal volume (Figure 8). At the high marsh, ebbing water usually had higher concentrations of NH_4^+ than flooding water but this concentration difference decreased with increasing tidal volume, and, at very high tidal volumes, ebb water actually had lower NH_4^+ concentrations than flood water (Figure 8).

When covariates were not significant, we omitted them from the analysis and tested for year and season effects with two-way ANOVA. At the low marsh, the difference between flood and ebb concentrations differed significantly ($P<0{\cdot}01$) among years for PO_4^{3-} and NH_4^+, and almost significantly for NO_3^- ($P=0{\cdot}06$). Interannual differences were especially pronounced for PO_4^{3-} which appeared to be exported in 1987 and 1988, but imported in 1989 (Figure 7). Similarly, NH_4^+ export decreased and NO_3^- import increased throughout the 3 years. In general, there were no clear seasonal patterns in the differences between flood and ebb concentrations. However, at the low marsh, the difference between ebb and flood concentrations of NO_3^- differed significantly ($P<0{\cdot}05$) among seasons, and was highest in spring (Figure 7).

The effects of year on differences between flood and ebb concentrations of PO_4^{3-} and NH_4^+ at the low marsh could be related to interannual differences in watershed discharge or rainfall. Rainfall and watershed discharge were highest in 1989 when rainfall totalled

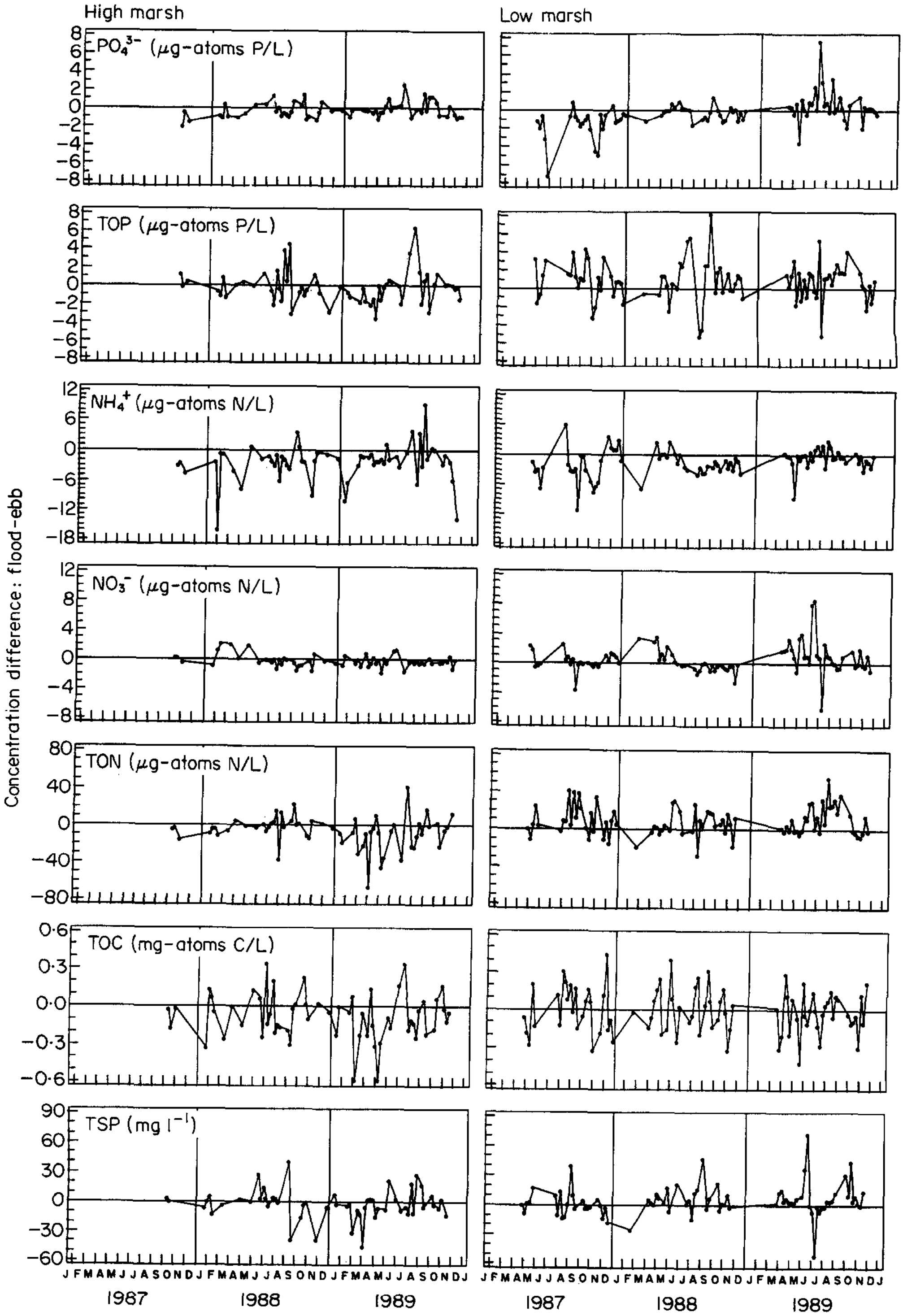

Figure 7. Difference of flood–ebb concentrations of materials at high and low marshes through time. Positive difference implies import to marsh, negative implies export.

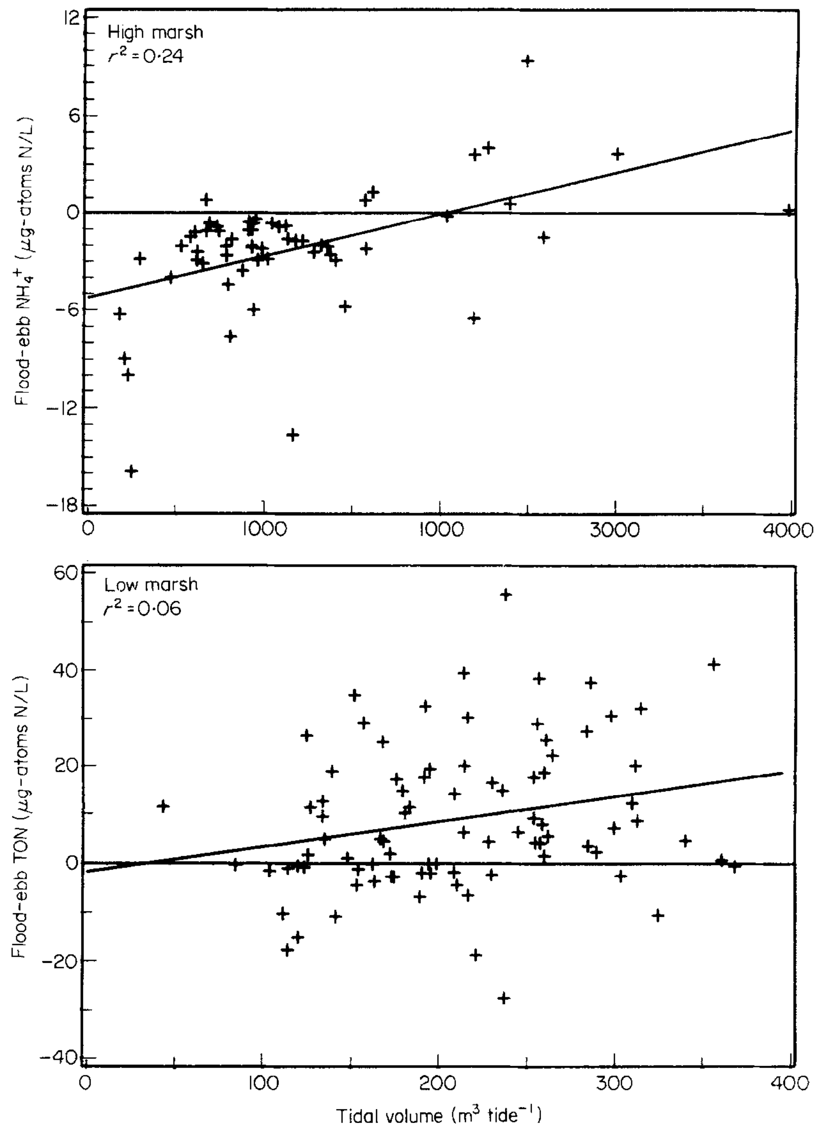

Figure 8. Difference of flood–ebb concentrations of NH_4^+ at the high marsh and TON at the low marsh *vs*. tidal volume. Lines fitted by linear regression. Slopes were significant ($P < 0{\cdot}0001$, NH_4^+; $P < 0{\cdot}05$, TON).

151 cm, compared to 100 cm in 1987 and 92 cm in 1988. Similarly, the seasonal effects on tidal differences in NO_3^- concentrations at the low marsh may be linked to seasonal changes in watershed discharge. NO_3^- concentrations in flooding waters and the excess of NO_3^- in flood compared to ebb waters were highest in spring when watershed discharge was also highest.

Net annual tidal exchanges

We calculated the average yearly tidal exchanges from the tidal volumes, the flood and ebb concentrations, and (for the high marsh) the rates of freshwater discharge. Rates of tidal

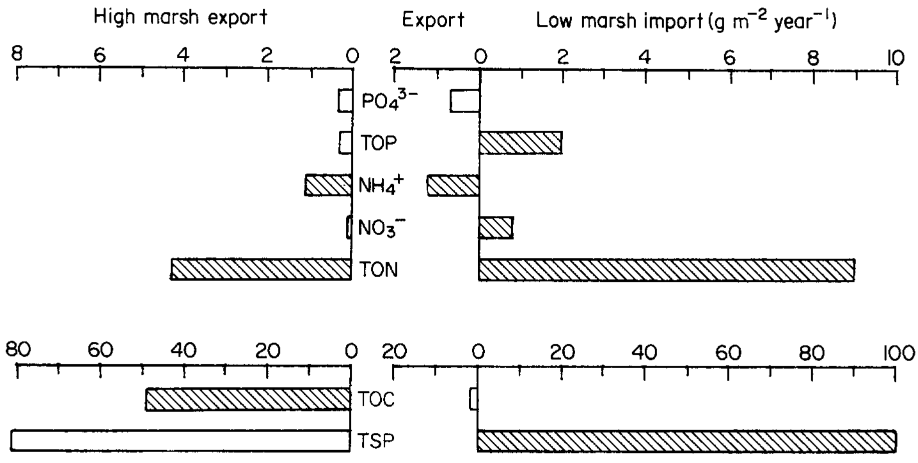

Figure 9. Annual net exchanges at high and low marshes. Bars are shaded if the differences between flood and ebb concentrations were significant ($P<0{\cdot}05$, sign rank test).

exchange were expressed per area using area estimates based on flow data (Figure 3). We assumed that actual water flows must balance although measured ebb water flow usually exceeded the measured flood water flow by more than the freshwater discharge. Therefore, we used the average of the measured ebb and flood flows (the tidal volume) in our tidal exchange calculations. We adjusted the tidal flows for freshwater discharge at the high marsh assuming that the ebb volume was equal to the flood volume plus the freshwater discharge. Thus, flood volume was calculated as the tidal volume minus half the freshwater discharge and ebb volume as the tidal volume plus half the freshwater discharge.

There were several weeks when our automated samplers failed. The most common problem was ice blocking the sampling tube during winter. This prevented sampling of water but not measurement of flow. Another problem with water sampling was pumping too much sample and overflowing the sample jugs. Occasionally, malfunctions of the current meter ruined both the flow data and water sample. Altogether, 86 out of 135 weeks at the low marsh and 60 out of 113 at the high marsh were successfully sampled. Good flow data were obtained for 109 weeks at both marshes. When data were missing, we estimated tidal exchange by substituting seasonal means of ebb and flood concentrations of materials, and flow rates, as needed, for the missing data. The seasons were defined as: winter, December–February; spring, March–May; summer, June–August; and fall, September–November.

Finally, we calculated average annual exchange rates from the weekly data. First, tidal exchange rates for each (approximately) weekly sampling period were converted to rates per day based on the number (and fraction) of days in the period. Then these daily rates were averaged and the average multiplied by 365·25 to calculate the yearly tidal exchange.

Yearly tidal exchanges were quite different for the two marshes (Figure 9). The largest net flux at the low marsh was a net import of TON, but TON was exported by the high marsh. The low marsh also imported TOP, NO_3^- and suspended particles, while at the high marsh there was no significant exchange of these materials based on a sign rank test of the difference of ebb and flood concentrations. The largest net flux at the high marsh was an export of TOC, but there was no significant exchange of TOC at the low marsh. The

TABLE 1. Comparison of old (Jordan *et al.*, 1983) with new measurements of annual net tidal exchanges (g m^{-2} $year^{-1}$). Positive numbers indicate import to the marsh, negative numbers indicate export. Old measurements were adjusted to reflect the new estimates of the areas of the marshes drained by the monitored tidal creeks (high marsh area previously estimated as 2·5 ha, now 3·0 ha; low marsh previously 0·23 ha, now 0·18 ha)

	High marsh		Low marsh	
	Old	New	Old	New
PO_4^{3-}	+0·29	−0·33	−2·2	−0·68
TOP	+0·18	−0·26	+1·5	+2·0[a]
NH_4^+	−0·13	−1·1[a]	−1·6	−1·2[a]
NO_3	−0·061	−0·10	+0·43	+0·84[a]
TON	−2·2	−4·3[a]	+2·3	+9·0[a]
TOC	−48·0	−49·0[a]	+14·0	−1·8
TSP	+160·0	−81·0	+520·0	+100·0[a]

[a]Flood and ebb concentrations are significantly different according to new measurements ($P < 0.05$, sign rank test).

one similarity of the marshes was their export of NH_4^+. However, at the low marsh the difference between flood and ebb concentrations of NH_4^+ as well as PO_4^{3-} was subject to interannual variation (Figure 7). Therefore, the direction and magnitude of flux of these nutrients may also differ among years. For example, tidal differences in PO_4^{3-} concentration suggest import in 1987 and export in 1989.

Discussion

Previously, we measured tidal exchanges at the high and low marshes by manually measuring flow and sampling water during 11 tidal cycles throughout the year. We concluded that both marshes acted as nutrient transformers, importing particulate matter and exporting dissolved matter (Jordan *et al.*, 1983). However, with so few tidal cycles studied, it was difficult to assess the statistical significance of the exchanges. In the present study we sampled *c.* 2300 tidal cycles at the low marsh and *c.* 1600 at the high marsh, but, since we used sulphuric acid as a preservative, we could not distinguish between particulate and dissolved fractions of N, P, and C species. Net transport of particulate and dissolved fractions combined is more difficult to measure than transports of the separate fractions, because particulate matter is transported in the opposite direction from dissolved matter. Nevertheless, our results clearly suggest net transport of some materials (Figures 7 and 9).

In each case when the concentrations in ebb and flood waters differ significantly the apparent direction of net exchange based on our present data agrees with that based on our previous non-automated study (Table 1). However, the estimated magnitude of transport differs greatly in some cases, especially for NH_4^+ at the high marsh and TON at the low marsh (Table 1). When concentrations in ebb and flood waters do not differ significantly, the two studies often disagree on the direction of transport. The present study is probably more accurate since it sampled over 100 times more tidal cycles than the study of Jordan *et al.* (1983). There is also the possibility that some differences between the two studies

TABLE 2. Inputs from atmospheric precipitation to the marsh surface and inputs from an adjacent watershed to the high marsh (mg m^{-2} $year^{-1}$). Precipitation inputs are a long-term average from Peterjohn and Correll (1984). Watershed inputs are estimated from the freshwater discharge by the high marsh and from unpublished average concentrations of nutrients in discharge from a nearby forested watershed

	Precipitation	Watershed
PO_4^{3-}	13	100
TOP	30	110
NH_4^+	280	110
NO_3^-	480	87
TON	660	720
TOC	3600	16 000

represent real interannual differences in transport as observed in the present study for inorganic nutrients in the low marsh.

Besides exchanging materials with tidal waters the marshes receive inputs from atmospheric precipitation and from adjacent watersheds. Tidal exports of materials could be partly attributed to these inputs. Precipitation on the marsh surface is an important source of N and C but not P (Table 2). Precipitation of NH_4^+ on the low marsh could account for about 20% of the net tidal export. Precipitation of NH_4^+, TON and TOC on the high marsh could account for 7–25% of the net tidal exports. The precipitation of NO_3^- far exceeds the tidal export at the high marsh indicating that the high marsh is actually a sink for NO_3^-. In addition, the high marsh receives inputs from an adjacent, mostly forested, watershed. This is an especially important source of TOC (Table 2). In total, precipitation and watershed inputs to the high marsh could account for about 30–50% of the tidal exports of nutrients other than NO_3^-. The inputs of NO_3^- to the high marsh were over five times its tidal export.

The tidal marshes of the Rhode River, like most others, accrete sediment and, therefore, must accrete P. The low marsh accretes 730 g sediment m^{-2} $year^{-1}$ (Jordan *et al.*, 1986*b*) which contains 2·2 mg g^{-1} P (Jordan *et al.*, 1983). Thus, we expect an accretion of 1·6 g P m^{-2} $year^{-1}$ which is close to the measured tidal import of 1·3 g m^{-2} $year^{-1}$. In contrast, we measured net tidal export of P from the high marsh, although the difference between flood and ebb concentrations was not significant ($P > 0{\cdot}05$, sign rank test). However, about 40% of the export could be attributed to inputs from precipitation and the adjacent upland watershed. Also, the rate of accretion of P by the high marsh, estimated as for the low marsh, is 0·9 g m^{-2} $year^{-1}$, which would be harder to detect in the tidal exchange data than the more rapid accretion at the low marsh.

Many studies have concluded that tidal exchanges by marshes, especially exports of organic C, can be strongly influenced by rain, strong winds, or unusual tides. For example, Wolaver *et al.* (1984) suggest that wind events resuspend sediments, rain scours the marsh surface, and high tidal velocities scour creek bottoms. Chalmers *et al.* (1985) attribute much of the POC export to rain erosion of particles from the marsh surface. Roman and Daiber (1989) observed enhanced POC and DOC exports during a tropical storm and a rain shower. The advantage of automated sampling is the observation of rare, potentially important events in the tidal exchanges of materials. This increases the accuracy of estimates of annual exchanges and affords the chance to investigate the effects of rainfall, tidal volume and watershed discharge. Surprisingly, we found these variables had little or no effect on the tidal differences in concentrations independent of the effects of year and season. Perhaps the effects of such short time-scale phenomena would be more evident at the time-scale of individual tidal cycles rather than weeks.

The effect of tidal volume on the tidal difference in TON concentrations at the low marsh (Figure 8) may reflect increased trapping of particulate matter on the marsh surface with increased time of submergence (Jordan & Valiela, 1983; Jordan *et al.*, 1986*b*). In our previous study of the low marsh, we found that as tidal volume, and, consequently, submergence time increased there was a greater excess of suspended particles in flood water compared to ebb water (Jordan *et al.*, 1983). However, this effect on suspended particles was not observed with our automated sampling.

As with TON at the low marsh, the effect of tidal volume on the tidal difference in NH_4^+ concentrations at the high marsh (Figure 8) may reflect trapping of particles on the marsh surface. However, it could also reflect uptake of dissolved NH_4^+. Studies employing flumes have found uptake of dissolved NH_4^+ by the vegetated marsh surface despite its release by the combined marsh and tidal creek system (e.g. Wolaver *et al.*, 1980, 1983). Thus, release of dissolved NH_4^+ by drainage at creek banks (Jordan & Correll, 1985) and by diffusion from creek bottoms may predominate unless the marsh surface is submerged for unusually long periods when tidal volume is high.

Interannual differences in NH_4^+ and PO_4^{3-} exchanges at the low marsh (Figure 7) may reflect shifts in the balance of uptake of particulate matter and release of dissolved matter. Such shifts could be induced by changes in the input of particulate matter from the watershed. Much of the deposition of particulate matter in the upper Rhode River estuary follows episodic high discharges of particulate matter from the watershed during storm runoff (Jordan *et al.*, 1986*b*). Thus, we would expect particulate inputs to predominate in years of high rainfall such as 1989, and release of dissolved nutrients to predominate in years of low rainfall such as 1987 and 1988. We would also expect this effect to be most pronounced for PO_4^{3-} since it is discharged from the watershed mostly in particulate form and converted to dissolved forms in the marshes and tidal creeks (Jordan *et al.*, 1991). Another potential source of interannual variation is variation in inputs due to precipitation and, for the high marsh, runoff from the adjacent watershed. However, we did not see interannual variation in tidal exchanges at the high marsh, and the variations at the low marsh were toward greater import during the year with higher rainfall.

Our study and others demonstrate that tidal exchanges differ among marshes (Table 3). Exchange of organic C has received much attention because of the hypothesis that marshes supply organic carbon to coastal foodwebs. Indeed, most of the marshes studied export TOC (Table 3). The highest estimated rate of export is 503 g m^{-2} $year^{-1}$ from the North Inlet saltmarsh (Chrzanowski *et al.*, 1982, 1983). This export rate seems surprisingly high since it equals the annual above-ground net primary production of the marsh macrophytes (Chrzanowski *et al.*, 1983). However, most of this export is attributable to DOC export which may have been overestimated due to the infrequency of sampling and the high variance among sampling periods (Chrzanowski *et al.*, 1983). Net imports of TOC have been found at two saltmarshes both of which import POC and export DOC (Woodwell *et al.*, 1977; Dankers *et al.*, 1984) as found previously at our low marsh (Jordan *et al.*, 1983). Apparently, the tidal exchange of TOC by these systems is dominated by trapping of suspended particles. Both the low and high marshes seem to export TOC, but only at the high marsh were ebb and flood concentrations of TOC significantly different. At the low marsh, the apparent TOC export only equalled about 0·6% of the C in the peak above-

TABLE 3. Annual net tidal exchanges (g m^{-2} year^{-1}) at different marshes. Dots indicate no data

	TOC	NO_3^-	TN	TP
High marsh, this study[a]	−50·	−0·10	−5·6	−0·59
Low marsh, this study[a]	−1·8	+0·83	+8·5	+1·3
Carter Cr, Axelrad *et al.* (1976)[a]	−145·	+0·33	−4·0	+0·07
Ware Cr, Axelrad *et al.* (1976)[a]	−115·	+2·2	−3·1	+0·83
Woodwell *et al.* (1977, 1979)	+53·	+1·2	·	·
Chrzanowski *et al.* (1982, 1983), Whiting *et al.* (1987)	−503·	−0·60	·	·
Dankers *et al.* (1984)	+125·	+4·0	·	·
Borey *et al.* (1983)	−25·	·	·	·
Roman and Daiber (1989)	−159·	·	·	·
Heinle and Flemer (1976)[a]	·	−0·93	−3·7	−0·33
Valiela and Teal (1979)	·	−1·7	−11·	·
Daly and Mathieson (1981)	·	+0·32	·	·

[a]Chesapeake Bay marshes.

ground biomass (biomass data from Whigham *et al.*, 1989, assume 45% C). At the high marsh, the tidal export of TOC equalled about 15% of the C in peak above-ground biomass (biomass data from W. Arp, pers. comm.) but about 40% of the export could be attributed to inputs from precipitation and the adjacent watershed (Table 2). This suggests that export of TOC originating from the high marsh itself only amounts to about 9% of the C in peak above-ground biomass.

Tidal marshes also differ in their NO_3^- exchanges (Table 3). The highest tidal export is 1·7 g m^{-2} year^{-1} from Great Sippewissett saltmarsh (Valiela & Teal, 1979). However, that marsh actually consumes NO_3^- and the net export is due to inputs from ground water from its upland watershed (Valiela *et al.*, 1978). Similarly, our high marsh consumes NO_3^- as well as exporting it. Marshes may consume NO_3^- due to denitrification, which is favoured in their waterlogged, predominantly anaerobic soils (Kaplan *et al.*, 1979), but production of NO_3^- by nitrification may also occur (Bowden, 1986). NO_3^- concentrations in interstitial water at our low marsh exceed those in tidal water in fall (Jordan *et al.*, 1989) suggesting nitrification and the possibility of export of NO_3^-. In fact, ebb concentrations of NO_3^- appear to exceed flood concentrations in the fall, although the reverse is true on average (Figure 7).

Our high marsh and most other marshes studied export total N (Table 3). This may reflect N fixation or the existence of other inputs of N such as from ground water (Valiela *et al.*, 1978), or precipitation (Valiela & Teal, 1979; Jordan *et al.*, 1983). Since marshes accrete sediment they must import total P (Nixon, 1980). However, in two Chesapeake Bay marshes, our high marsh and Gott's marsh (Heinle & Flemer, 1976), exports of total P have been observed (Table 3), but this may simply be due to the imprecision of the measurements or to unaccounted inputs.

In addition to the tidal exchanges we and others have measured (Table 3), there are fluxes that have been mostly ignored. These include transport in floating detritus, surface films, bedload (particles moving along the bottom), and mobile organisms. Transport in floating detritus is probably minor in our marshes, as at the North Inlet saltmarsh (Dame, 1982), since, at our marshes, tidal amplitude is relatively low and extensive wrack deposits are not present. We have no information about the importance of surface films or bedload, but we have evidence that transport in mobile organisms may be important at the low marsh. There the killifish *Fundulus heteroclitus* feeding on the marsh and defaecating in the creeks may move as much TOC out of the marsh as the net tidal export, although its effects on N and P transports are probably minor (A. Hines, pers. comm.).

Further comparative studies are needed to elucidate the many factors that could influence tidal exchange of nutrients by marshes. Our study compared two neighbouring marshes which are flooded by similar water but which differ in elevation and vegetation. Both marshes act primarily as nutrient transformers, converting particulate nutrients to dissolved forms (Jordan *et al.*, 1983), but they differ in the balance between particulate and dissolved exchanges. This may reflect differences in sediment accretion. There are two main sources of the accreted sediment: deposition of suspended particles from the water column and *in situ* production of organic matter. As marshes increase in elevation, they are submerged for less time and thus accrete less by deposition and more by *in situ* production. We have noted this difference in accretion in the low and high marshes of the Rhode River (Jordan *et al.*, 1986*b*). It follows that higher elevation marshes, which are producing a greater excess of organic matter, should be more prone to export materials, especially organic matter, while lower elevation marshes, which are more depositional environments, should be more prone to import materials. The findings of this study (e.g. Figure 9) are consistent with this hypothesis. Of course, other factors may also be important. For example, the concentration of suspended matter in the tidal waters, which was similar for the two marshes we studied (Figure 6), probably influences the amount of deposition. Also, marshes receiving direct watershed inputs should be more prone to export materials in tidal waters.

Progress in understanding the influence of tidal marshes on coastal waters has been impeded by the laboriousness of measuring tidal exchanges from marshes. Until this study, estimates of annual exchanges have been based on small subsamples of tidal cycles throughout the year, despite findings that annual exchanges may be influenced by episodic storm events. The use of automated sampling greatly reduces the labour of sampling and permits observation of rare, potentially important, events.

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