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Nutrient mass balances for the watershed, headwaters intertidal zone, and basin of the Rhode River Estuary[1]

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Abstract

Mass balances were determined for a 13-month period for three parts of the Rhode River ecosystem, a small subestuary of the Chesapeake Bay. Organic matter, nitrogen, and phosphorus budgets were calculated for a 2,300-ha upland watershed dominated by agriculture and secondary successional vegetation, 88 ha of tidal marshes and mudflats, and an estuarine open water basin. Less organic matter moved out to the estuary (27 t of C) than was discharged into the intertidal zone from the watersheds (71 t of C) and deposited in precipitation (3.4 t of C). Of the 2.7 t of P discharged from uplands into the intertidal zone, only 1.9 t moved into the estuary. Generally, high discharges of P from the watersheds were followed in a week or two by high discharges into the estuary from the intertidal zone. Orthophosphate constituted a significantly lower fraction of the P that moved into the estuary (38%) than of the P that was discharged from the watershed (49%). Of the 10 t of N discharged from the watershed into the intertidal zone, only 7.4 t moved into the estuary. These data indicate overall removal and storage of nutrients from land runoff by the intertidal zone. When land runoff was low the intertidal zone scavenged nutrients from tidal waters. Only when runoff was high, due to storms, were some of the stored nutrients flushed from the intertidal zone.

The Rhode River ecosystem is composed of a small subestuary of the Chesapeake Bay in Maryland and its upland watershed (38°51′N, 76°32′W). Between the watershed and the estuarine basin is an 88-ha intertidal zone through which land runoff from 2,300 ha of watershed must pass and mix with shallow tidal waters before entering into the upper part of the Rhode River proper (Fig. 1). The watershed lies in the Atlantic Coastal Plain. The soils are sedimentary and relatively little weathered or leached. Thus, they are high in nitrogen and phosphorus and land runoff is rich in nutrients (Correll 1977). The tides have an average amplitude of about 35 cm but are strongly influenced by weather. The volume of the intertidal zone at mean low water is 1.4×10^5 m^3. Water temperatures range from near 0°C in winter to about 30–35°C in summer. Salinity is affected both by dilution with land runoff from the Rhode River watershed and by the seasonal fluctuation of salinity in Chesapeake Bay proper.

The intertidal zone (enclosed by dotted line in gray area of Fig. 1) is composed of about 32 ha of mudflats and tidal creek channels, 20 ha of high marsh (seldom inundated by the tides), and 36 ha of low marshes (normally underwater). The high marshes are primarily composed of areas dominated by *Spartina patens*/*Distichlis spicata*, *Iva frutescens*, *Spartina cynosuroides*, or *Juncus roemerianus*. The low marshes are almost universally dominated by *Typha angustifolia*. The open-water areas are habitat for such submersed vascular plants as *Myriophyllum spicatum*, *Potamogeton pectinatus*, *Ruppia maritima*, and *Zannichellia palustris* as well as for periphyton.

Among the roles that have been suggested for intertidal marshes in the ecology of estuarine and coastal ecosystems are the export of organic matter as dissolved organic C or detritus and the trapping of N and P from tidal waters (e.g. Simpson and Whigham 1978; Valiela and Teal 1979). My study had as its objective the measurement of dynamics for N, P, and organic matter for this headwaters in-

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tertidal area. Inputs from precipitation and both surface and groundwater runoff were measured continuously, as well as the tidal flux between the intertidal zone and the main estuarine, open water basin, for a 13-month period.

Methods

Land drainage into the intertidal zone was measured from five subwatersheds totaling 2,050 ha and comprising about 90% of the watershed (areas 101, 102, 103, 108, 121: Fig. 1). Sharp-crested 120° V-notch weirs were used to measure discharges from four of these subwatersheds whose combined drainage area is 821 ha. The weirs also automatically took volume-integrated samples which were routinely composited over 1-week periods (Correll 1977; Correll and Dixon 1980). Sulfuric acid (25 ml, 15 N) was added to sample containers to act as a preservative. Flow was recorded as digital data on paper tape every 15 min and sample aliquots were taken every 154 m^3. The fifth and largest (1,229 ha) subwatershed (121: Fig. 1) was tidally influenced at the location where discharges were measured. A concrete 4.8-m-wide tidal flume equipped with custom tide gauge, an electromagnetic current meter (Marsh-McBirney, model 711), and an electronic interface which integrated water flux over time were used to sample this discharge (Correll 1977). The current meter sensor was mechanically held in the middle of the water column by a linkage to the tide gauge so that it would best represent water flux (U.S. Dep. Interior 1967). Water samples, whose volume was proportional to water flux, were taken every 30 min and digital flux rate data were recorded on paper tape. These samples were combined to produce volume-integrated, or flow-weighted samples for 1-week periods. Incoming and outgoing tidal waters were combined in separate containers. A calibration factor, determined for the flume by measurement of fluorescein dye dilution over a series of tidal conditions, deviated from the mean <10%. The greatest deviation was at times of very low tidal elevations, when water flux was trivial. At all times of significant water discharge the weirs and the tidal flume had errors <3%. The runoff from the remaining 252 ha of unmonitored watershed basin (gray area 122: Fig. 1) was estimated by simple extrapolation. Since there is an impervious clay layer (the Marlboro Clay) near sea level on the Rhode River watershed and the weir foundations are imbedded in this clay layer (Correll 1977), all groundwater flow from the watersheds into the intertidal part of the system originates from the local watersheds and is measured at the weirs. Inputs from bulk precipitation were measured at the laboratory, which is in a central position at the site (Miklas et al. 1977).

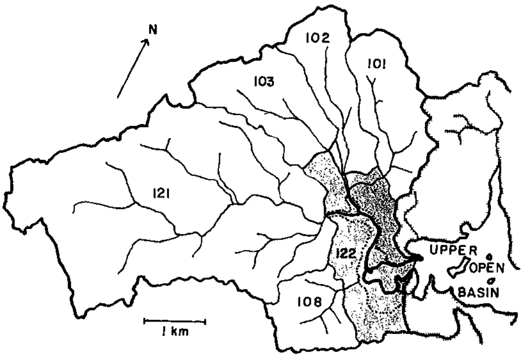

Fig. 1. Map of the upper Rhode River study site. Watersheds from which runoff was measured (101, 102, 103, 108, and 121) shown in white. Unmonitored watershed area and intertidal shown in gray (122). Intertidal zone bounded by dotted line.

Tidal exchange between the intertidal zone and the estuarine basin was measured at the downstream end of the mudflat at a point where it is constricted to a width of 165 m but still has a depth of only about 1 m at MLW. The waters here are well mixed vertically and laterally and only rarely stratify. I failed to detect any differences in particulate total P or suspended sediment concentrations between the surface and bottom of the water column greater than the precision of these methods (C.V. about 3–5%). The cross section of the system at this point was divided into 16 equally spaced (ca. 10 m) stations. Tidal current velocity was

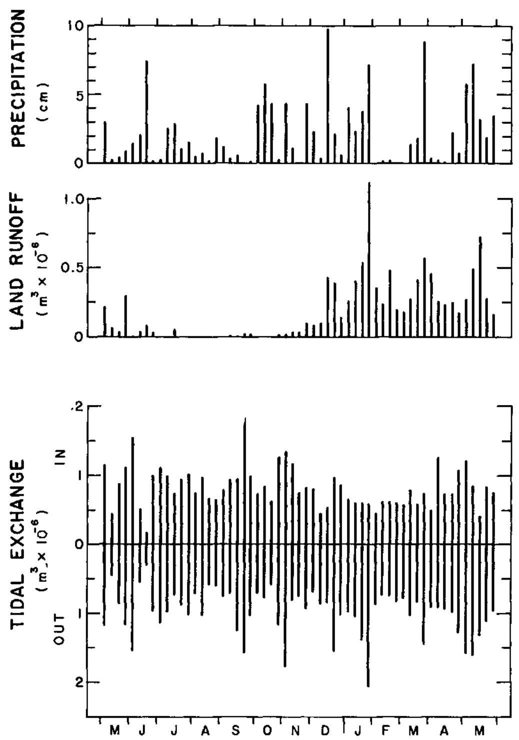

Fig. 2. Weekly totals of precipitation and land runoff which drained directly into intertidal zone and tidal exchange into and out of intertidal zone.

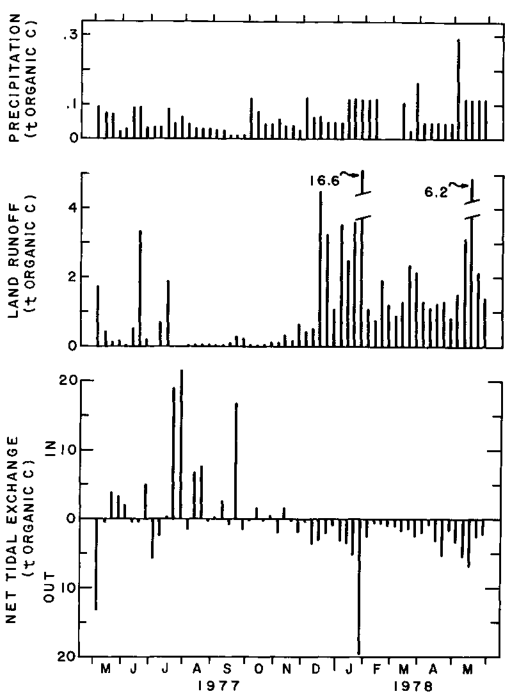

Fig. 3. Weekly organic C mass balance data. Precipitation refers only to bulk precipitation which fell directly onto intertidal zone. Tidal exchange data are net exchanges into and out of intertidal zone.

measured at each station at brief intervals with electromagnetic current meters for several complete tidal cycles. Peak tidal currents are typically 6 cm·s^{-1} with insignificant lateral variability. There is no pronounced channel. A position of mean flux rate for water was determined to be at a reasonably constant location in the cross section. A set of pilings was driven at this location to support an instrument shed equipped with custom tide gauge, current meter, and interfacing analogous to those in the tidally influenced watershed station (121) described above. The principal error encountered in tidal flux measurements by this method is long term drift of current meter and recorder electronic zeros. For each week's data a hydrologic water balance was attained by correcting the instrument zero at this location so that watershed runoff plus flooding tidal flux equaled ebbing tidal flux.

Missing weir sample data were estimated by regression analysis of other weir data taken during the same period. Missing tidal flux station data were estimated by interpolation. Missing data constituted <10% of the total.

Total phosphorus was determined by digestion with perchloric acid (King 1932) followed by reaction with ammonium molybdate and stannous chloride (Am. Public Health Assoc. 1976), orthophospate by the same technique but without digestion. Nitrate plus nitrite was determined by reduction of nitrate to nitrite on an amalgamated cadmium column followed by coupling to sulfanilamide (Am. Public Health Assoc. 1976). Total Kjeldahl nitrogen was determined by Nesslerization (Am. Public Health Assoc. 1976) after digestion of whole water

Table 1. Mass balance summary data.

	Land runoff	Precip. on intertidal	Tidal exchange*	Residual
		Organic C (t)		
May 77	2.6	0.27	+6.6	−3.8
Jun 77	4.2	0.26	−6.5	11
Jul 77	2.0	0.26	−32	35
Aug 77	0.15	0.13	−13	13
Sep 77	0.61	0.089	−17	18
Oct 77	0.17	0.29	−1.9	2.4
Nov 77	1.2	0.17	+2.5	−2.2
Dec 77	9.8	0.35	+11	−0.67
Jan 78	26	0.38	+31	−4.9
Feb 78	4.9	0.22	+5.1	−0.01
Mar 78	6.8	0.28	+6.9	0.17
Apr 78	5.8	0.22	+13	−7.2
May 78	14	0.46	+21	−6.4
Overall Σ	71	3.4	−27	+55
		Total P (kg)		
May 77	91	2.7	+360	−270
Jun 77	280	4.2	+87	190
Jul 77	130	10	+360	−220
Aug 77	2.8	5.9	−380	390
Sep 77	6.0	1.5	−680	690
Oct 77	5.3	4.5	+16	−6.2
Nov 77	34	2.6	+230	−190
Dec 77	380	5.0	+240	140
Jan 78	600	6.0	+520	92
Feb 78	45	3.6	+64	−15
Mar 78	400	1.1	+320	84
Apr 78	160	5.3	+280	−120
May 78	580	10	+450	140
Overall Σ	2,700	53	+1,900	920
		Total N (kg)		
May 77	290	52	+1,900	−1,500
Jun 77	450	110	−170	720
Jul 77	320	73	−350	750
Aug 77	31	42	−320	400
Sep 77	41	28	−590	660
Oct 77	25	53	−370	440
Nov 77	180	76	+215	44
Dec 77	1,100	43	+1,200	66
Jan 78	3,000	52	+2,400	610
Feb 78	990	31	+770	250
Mar 78	1,400	41	+1,200	280
Apr 78	790	20	+1,200	340
May 78	1,600	120	+1,200	530
Overall Σ	10,000	740	+7,400	3,500
		Nitrate-N (kg)		
May 77	33	17	−52	100
Jun 77	87	43	−20	150
Jul 77	0.54	24	+27	−3.0
Aug 77	0.47	13	+1.8	12
Sep 77	0.28	14	−13	27
Oct 77	3.1	22	−15	40
Nov 77	65	40	−21	130
Dec 77	640	26	+160	500
Jan 78	1,900	30	+1,600	350
Feb 78	680	18	+520	180
Mar 78	810	24	+750	84
Apr 78	340	19	+500	−140
May 78	340	76	−72	490
Overall Σ	4,900	360	3,400	1,900

* Plus sign indicates net exchange from intertidal into estuarine basin.

samples with sulfuric acid and hydrogen peroxide (Martin 1972) and distillation. Organic matter in freshwater samples was determined by wet digestion with sulfuric acid and dichromate to determine the COD (Maciolek 1962). Organic carbon was calculated by dividing by 2.86. Organic carbon content of brackish water samples was determined by drying acidified samples, combustion in an oxygen atmosphere for 15 min at 650°–700°C, purification of the gases to remove halogens, sulfur oxides, and water, and gravimetric determination of CO_2 after binding to ascarite.

Results

Weekly precipitation, water discharge from the combined watershed areas and tidal water exchanges are shown in Fig. 2. Land runoff was very low from July through October, due to relatively low precipitation and high rates of evapotranspiration, but was very high from December until the end of the study.

Weekly inputs to the intertidal zone of organic carbon (Fig. 3) from land runoff and precipitation, which fell directly onto this zone, ranged from <0.1 to 16.7 t. Weekly net tidal exchange ranged from imports into the intertidal zone of over 20 t to exports of almost 20 t of organic carbon to the estuarine basin. Except during a drought (July through November), precipitation represented <12% of land runoff (Table 1); during the drought months, these were very low and tidal exchange was predominantly into the intertidal zone. Fluxes from intertidal zone to es-

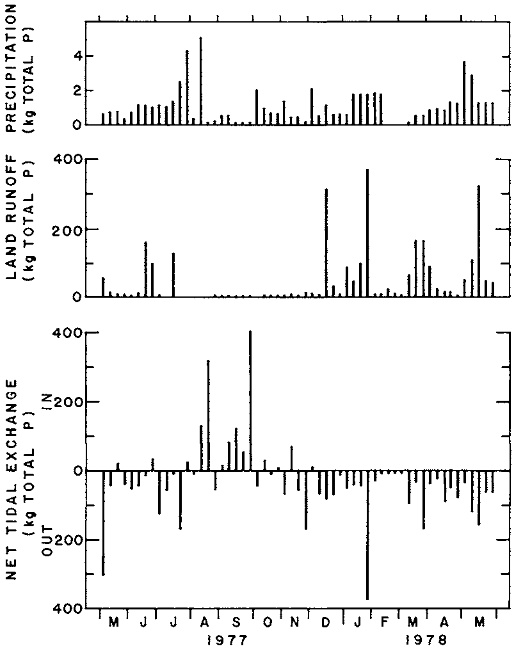

Fig. 4. As Fig. 3, but for total P.

tuarine basin were high in winter and spring 1978, when high volumes of land runoff resulted from heavy rainfall. The overall incoming totals for the 13 months were 71 t of organic carbon from land runoff and 3.4 t from bulk precipitation, and a net export to the estuarine basin of 27 t of organic carbon, leaving a residual in the intertidal zone of 55 t of C. Thus, the intertidal zone was not functioning as a source of organic carbon to the estuarine basin but only as a conveyor of a portion of the organic matter it received from the watershed and atmosphere.

Mass balance data for total phosphorus, analogous to those for organic carbon, are given in Fig. 4 and Table 1. P introduced by bulk precipitation directly into the intertidal zone ranged from 1.1 to 10 kg per month, by land runoff from 2.8 to 600 kg per month. Bulk precipitation always provided <8% of the combined inputs except in drought months when land runoff was very low. Movement between the intertidal zone and the estuarine basin by tidal exchange and flushing was into the basin except in August and September, when large amounts (380 and 680 kg) moved from the basin into the intertidal zone. Overall, 53 kg of P were deposited in the intertidal zone as bulk precipitation and 2,700 as land runoff, while 1,900 were exported to the estuarine basin, leaving a residue of 920 in the intertidal zone. During the 4 months of drought there was a net movement of 690 kg of P from the basin to the intertidal zone. Orthophosphate (both dissolved and particulate) constituted much less of the phosphorus exported from the intertidal zone to the basin (avg = 38%) than of that imported as land runoff (avg = 49%); this situation was even more pronounced in spring (March, April, and May) when orthophosphate constituted only 16% of the phosphorus exported to the basin but 45% of the land runoff. In winter (December, January, and February), however, orthophosphate constituted 53% of land runoff phosphorus and 67% of that exported to the basin.

When weekly mass balance data are plotted it becomes apparent that the intertidal zone is not simply responding immediately to short term surges in income from the watershed by analogous surges in export (Fig. 4). Two storms a month apart in June and July produced runoff peaks. Intertidal zone output peaks followed after lags of 2 and 1 week; then, in a few weeks, a large peak of phosphorus flux from the basin back into the intertidal zone was observed. In December a large input from a storm coincided with a low amplitude, broad tidal exchange peak in export, but no clearcut input/output response was observed. In the summer storms, flushing rates were low (Fig. 2), while in December they were high. Additions to and export from the intertidal zone thus seemed to be only loosely or indirectly coupled.

Weekly mass balance data for total N and for nitrate are given in Figs. 5 and 6 and summarized in Table 1. Although additions of total N to the intertidal zone via direct precipitation were always small (ranging from 2 to 60 kg N $\cdot$ week^{-1}: Fig. 5) they were a larger proportion of the total income than was the case for or-

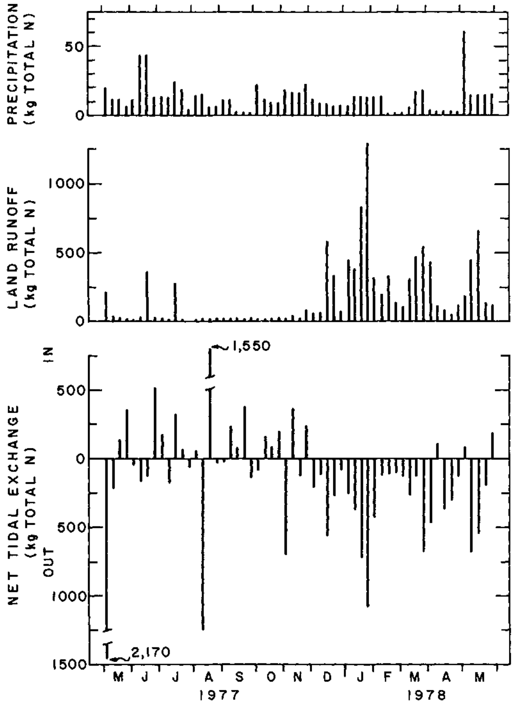

Fig. 5. As Fig. 3, but for total N.

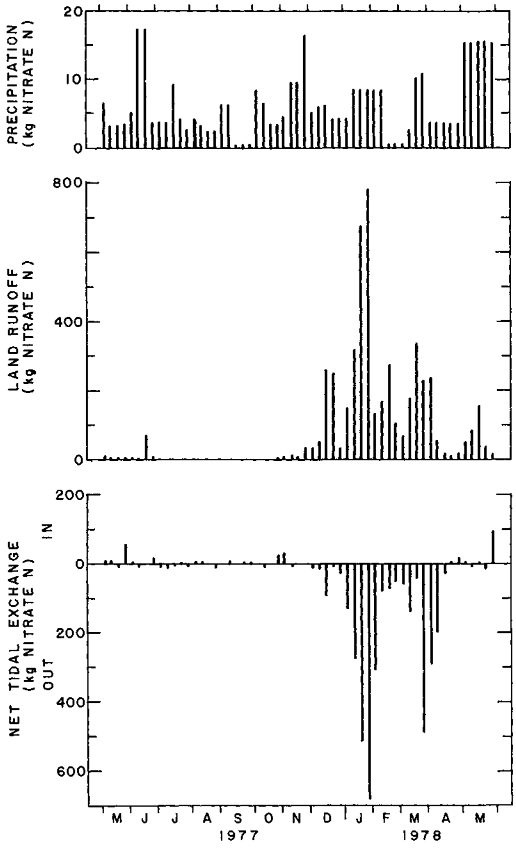

Fig. 6. As Fig. 3, but for nitrate-N.

ganic carbon or phosphorus. For the 13-month period, precipitation accounted for only 7.4% of the incoming total nitrogen, but during 4 months of drought (July–October) it accounted for 47%. On the average, 49% of the nitrogen in precipitation was in the form of nitrate, at times even higher (e.g. April—95%). Overall, 10 t of total N arrived via land runoff with the highest amounts in winter and spring 1978. Of this land runoff 4.9 t were nitrate. Exports from the intertidal zone to the estuarine basin were 7.4 t of total N and 3.4 t of nitrate-N, leaving a residue of 3.5 t of total N and 1.9 t of nitrate-N in the intertidal zone. During the months of June through October, there was a net import of 1.80 t of total N from the basin to the intertidal zone, while only 0.019 t of nitrate-N moved from the basin into the intertidal zone.

Discussion

In comparing the results of this study with those from other studies, several important considerations should be kept in mind. The intertidal zone in this study is an estuarine-headwaters habitat and thus different, at least in degree, from a coastal salt marsh in that it receives a large volume of land drainage, as well as having tidal exchanges with the estuary. This land drainage has many effects. It causes flushing of buffer zone waters, particularly after storms. It brings in large amounts of mineral nutrients and causes rapid oscillations in salinity. All marshes receive direct precipitation, of course, but the fact that all or almost all marshes also receive at least some land runoff (surface and groundwater) is not as obvious. Many investigators have ignored these additions or discounted them without adequate documentation. An unmeasured nutrient income from these sources might easily reverse the nutrient mass balance conclusion of many studies or at least seriously modify them (Valiela et al. 1978).

Also the intertidal zone in this study is a complex of high marshes, low marshes, and adjacent mudflats and tidal channels, all of which communicate and interact with each other (e.g. Walsh 1980). This is far different from a single small tidal creek and the adjacent marsh which floods and drains through it. So far we can form conclusions about mass balances for this complex buffer zone, but not for its component subsystems. Although the buffer zone is apparently not a long term source of organic matter to the estuarine basin, it would be unreasonable to say anything about whether the marshes are sources of organic matter to the adjacent intertidal shallows.

In their studies of Hamilton Marsh, Simpson and Whigham (1978) found evidence of nitrate and dissolved orthophosphate assimilation during the growing season. In the Rhode River system the assimilation of total orthophosphate by the intertidal zone was essentially zero in winter, but became much higher than the assimilation of total P in spring, which seems in agreement with their conclusions. However, nitrate seemed to follow an opposite course: in spring and summer the residual value (assimilation) for nitrate was less than for total N, while in winter it was higher (Table 1). Of course, significant amounts of nitrate were assimilated on an annual basis.

Stevenson et al. (1976) concluded that Horn Point Marsh exported inorganic nitrogen and phosphorus in winter and imported them in spring. By comparison, outputs of orthophosphate and of nitrate from the Rhode River intertidal zone were high in winter and reduced in spring, but seemed to be responding primarily to the magnitude of land runoff on a seasonal basis.

Heinle and Flemer (1976) found a consistent tidal export of total P and N from Gott's Marsh, but very little export of organic matter. Results from my study generally agree with these findings, except during an unusual drought when land runoff was very low. Land runoff was not considered in the Gott's Marsh study.

Axelrad et al. (1976) reported that two marshes on the York River exported significant amounts of organic matter and small amounts of nitrogen, but imported small amounts of phosphorus. Land runoff was not measured. In my study 26.8 t of organic C were exported from the intertidal zone to the estuarine basin (Fig. 2), but the income of organic matter from precipitation and land runoff was of greater magnitude, so that the intertidal zone functioned as a sink for organic matter. If only tidal exchanges had been measured, it would have appeared that the intertidal zone was a source of organic matter. Similar conclusions would apply to N and P data.

The results of my study during summer drought months may be compared with other results for salt marshes. The Rhode River intertidal zone imported dissolved and fine suspended particulate organic matter during the drought, as did Flax Pond Marsh (Woodwell et al. 1977). Comparisons with the results of Valiela et al. (1978) and Woodwell and Whitney (1977) are difficult, since the parameters measured were significantly different. I can make no conclusions about particulate vs. dissolved nutrients, since samples were composited in acid preservative.

Caution should be used with regard to the generality of results from this study, even for the Rhode River system. The results for the single month of overlapping data (May) were considerably different for the 2 years. One may expect a high variance in system responses from year to year, depending on meteorological variations. Thus, for example, the data from summer 1977 are no doubt unusual, because of a fairly severe drought. Many of the results of this study would seem to have seasonal connotations; however, phenomena such as drought can occur in any season in this region. Many more data over a longer period would be needed to reach valid conclusions about seasonality or of the impact of unusual weather conditions.

The effects of variations in tidal amplitudes, water level at slack water, weather conditions, and other short term variables should be a cause for concern when we attempt to analyze the meaning of studies of tidal exchanges from a somewhat random sampling of a sixtieth of the tidal cycles over a 1- or 2-year period. Since my study involved continuous sampling of tidal exchanges, these data do provide an accurate summary of nutrient fluxes during this 13-month period.

The extreme importance should also be stressed of including in a mass balance study measurements of precipitation and both surface and groundwater land runoff (e.g. Valiela et al. 1978; this study). If these measurements are not included, conclusions about the role of intertidal mudflats and marshes in the nutrient dynamics of estuarine and coastal ecosystems could be very misleading.

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