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Nutrient Fluxes Within a Small North Temperate Salt Marsh*,**

M. A. Daly and A. C. Mathieson***

Department of Botany and Plant Pathology and the Jackson Estuarine Laboratory, University of New Hampshire; Durham, NH 03824, USA

Abstract

The water exchange between a small (4.1 hectare) salt marsh adjoining the Great Bay Estuary System of New Hampshire, USA was sampled during 16 tidal cycles between July, 1976 and November, 1977. Tidal amplitude, temperature, salinity, nutrient concentrations (ammonia-N, nitrate-N, nitrite-N, orthophosphate-P, total-P, silicates) and suspended particulates were measured. Conspicuous tidal hydrographic patterns were observed. Mean concentrations of nitrate-N and silicates varied with season. The tidal information, combined with volume determinations, was extrapolated to determine the net flux of hydrographic parameters on monthly and yearly bases. Ammonia-N showed a pronounced seasonality of net exchange by regression analyses. Ammonia-N and suspended particulates had a statistically significant import into the marsh. However, the net fluxes of the other materials were not statistically different from O.

Introduction

Salt marshes are productive and important components of the coastal zone of the eastern United States (Chapman, 1974). Consequently, several studies have been initiated to evaluate the flux of nutrients and organic matter between salt marshes and estuaries (Heinle and Flemer, 1976; Settlemyre and Gardner, 1977; Shisler and Jobbins, 1977; Woodwell and Whitney, 1977; Woodwell *et al.*, 1977; Mauriello and Winfield, 1978). The present study was initiated to investigate the seasonal exchange of nutrients and suspended particulates in a Northern New England salt marsh (New Hampshire, USA) and to determine the role of salt marshes within the Great Bay estuary as sources or sinks of these materials.

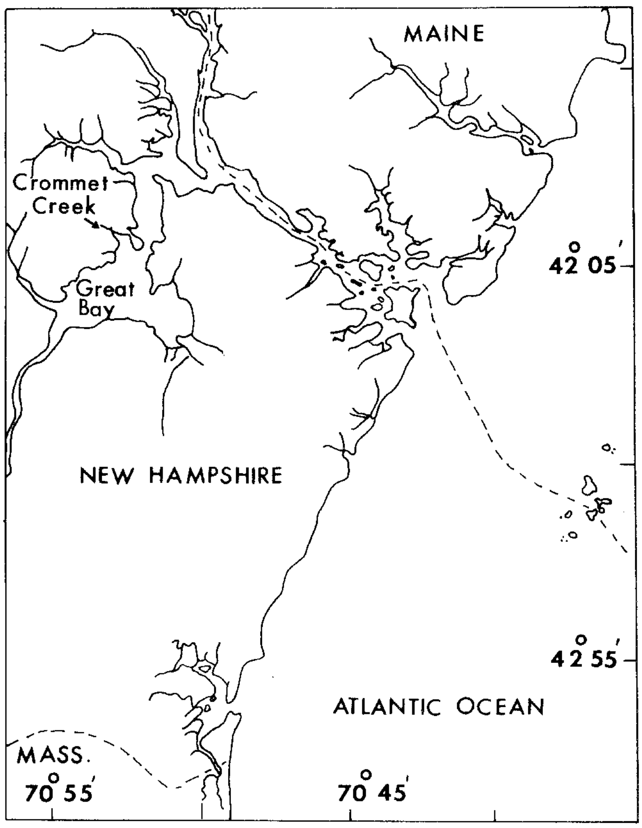

Fig. 1. New Hampshire coastline and location of Crommet Creek

The study site, Crommet Creek, is located in Great Bay, New Hampshire 19.5 km from the open coast (Fig. 1). It is a small salt marsh (4.1 hectares) which is

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Fig. 2. Aerial infrared photograph of Crommet Creek

fed by 3 small freshwater creeks and drains by a single channel into Great Bay (Fig. 2). The vegetation within the marsh is primarily composed of *Spartina alterniflora* and *S. patens* (Davis, 1956).

Materials and Methods

Sixteen diurnal collections of water samples were taken from a narrow channel connecting Crommet Creek to the Great Bay Estuary (Fig. 2) between July, 1976 and November, 1977. The water was monitored for 12 consecutive hours during each monthly study. No samples were taken in January, 1977 due to impenetrable ice cover. Water elevations were determined by measuring the depth of water at a bench mark in the channel bottom and correcting the values to mean low water (MLW). The elevation of the bench mark above MLW was determined by using the predicted low water and low water correction of 0.0 m for Great Bay sites from the Tide Tables (Anon., 1976), then using surveyor's techniques to measure from a low water point to the bench mark. Records of temperature (accuracy ± 0.5 C°) and salinity (accuracy ± 0.3‰ S) were taken in the field with a Kalhisco *in situ* Electrodeless Salinometer (Model RS5-3). Subsurface water samples were collected with polyethylene bottles, preserved, stored in ice, and then returned to the laboratory for further analysis. Ammonia-N samples were preserved with a 10% phenol-alcohol solution; the other nutrients were preserved with 2% mercuric chloride. Ammonia-N was determined 1 to 4 d after collection, according to the procedures outlined by Solórzano (1969). No significant difference was found among samples processed within 1 d and those processed within 4 d of collection. Orthophosphate-P, nitrate-N, nitrite-N, and reactive silicate were processed on a Technicon Autoanalyser II System (Tarrytown, New York) using their industrial methods (Anon., 1972, 1973 a,b,c), with modification and corrections for salinity (Loder and Glibert, 1976). Unfiltered total phosphorus samples were oxidized (Menzel and Corwin, 1965) and analyzed according to the Technicon orthophosphate system. Total suspended particulates were measured by filtering 250 ml of water through predried and preweighted Whatman No. GF/C glass fiber filters (Stickland and Parsons, 1968).

The volume and depth contours of the creek basin were determined from consecutive infrared aerial photographs taken during a single flood tide (June 16, 1977). Water elevations were measured on the ground while aerial photographs were taken simultaneously. Slides were superimposed on a map of the area, the contours of the water drawn, and the areas for each elevation determined by planimetry. Water volumes were determined by interpolation of areas and Hutchinson's (1957) formula for lake volumes.

A volume-weighted mean method outlined by Heinle and Flemer (1976) was used to determine monthly fluxes of materials between the marsh and estuary. The method corrects for volume exchange bias due to tidal height on the particular sample date. Estimated monthly flood and ebb water flows were multiplied by the volume-weighted mean flood and ebb nutrient concentrations, respectively, to give amounts of each material imported and exported per month. The difference between these 2 values is the net monthly exchange. Monthly ebb and flood water flows were estimated using the following equation:

$$f = \sum_{i=1}^{16} v_i \cdot 1/16 \cdot 56 , \qquad (1)$$

where f = estimated monthly flood or ebb flow; v_i = volume of water ebbed or flooded on the i^{th} sample date; 16 = total number of sample dates; 56 = number of tides per month. The monthly values obtained were 598,640 m^3 flooded and 610,456 m^3 ebbed. Volume-weighted mean concentrations for each sample date were determined by the equation:

$$\overline{x} = \frac{\Sigma x_i}{\Sigma w_i} = \frac{\Sigma (z_i \cdot w_i)}{\Sigma w_i} , \qquad (2)$$

where $\overline{x}$ = volume-weighted mean flood (or ebb) concentration of a material; x_i = amount of material flooded (or ebbed) during the i^{th} sample period; z_i = concentration of material during the i^{th} sample period; w_i = volume of water flooded (or ebbed) during the i^{th} period. Annual exchanges of variables were determined by averaging net fluxes for months with more than 1 sample date, determining a mean net flux per month, and multiplying by 12 to get an annual flux.

Statistical analyses of the results were performed on STATPACK using a DEC-10 computer. The daily net flows and mean values of each parameter were compared by linear regression to maximum tidal height and net water flow. Maximum tidal heights were tested because it has been suggested that the greatest exchange of materials occurs on the highest tides (Valiela *et al.*, 1973; Heinle and Flemer, 1976). Net water flow was checked to see if the net exchange of a parameter was attributable to the water volume exchanged. Polynomial regressions (second to fourth order) of monthly net flow and mean concentration versus month number were processed as a test of seasonality.

Results

Tidal Patterns

The physical and chemical characteristics of the water at Crommet Creek are affected by the tidal stage, time of day, and season. Even so, several hydrographic patterns were observed during the tidal cycles (Figs. 3 and 4). For consistency all of the tidal plots are initiated at low water. Most variables showed a distinct seasonal pattern. In general, the concentration differentials between ebb and flood tides were not indicative of the direction of net flux. This occurred when extremely high concentrations measured during 4 h of low water still resulted in net influx. In such cases, the volume of ebbing water was too low to compensate for large volumes of flooding water with somewhat lower concentrations. Both the seasonality and ebb/flood differentials at Crommet Creek contrast with the study of Heinle and Flemer (1976) in Maryland, which showed a correlation between net flux and tidal patterns but no seasonality of tidal patterns.

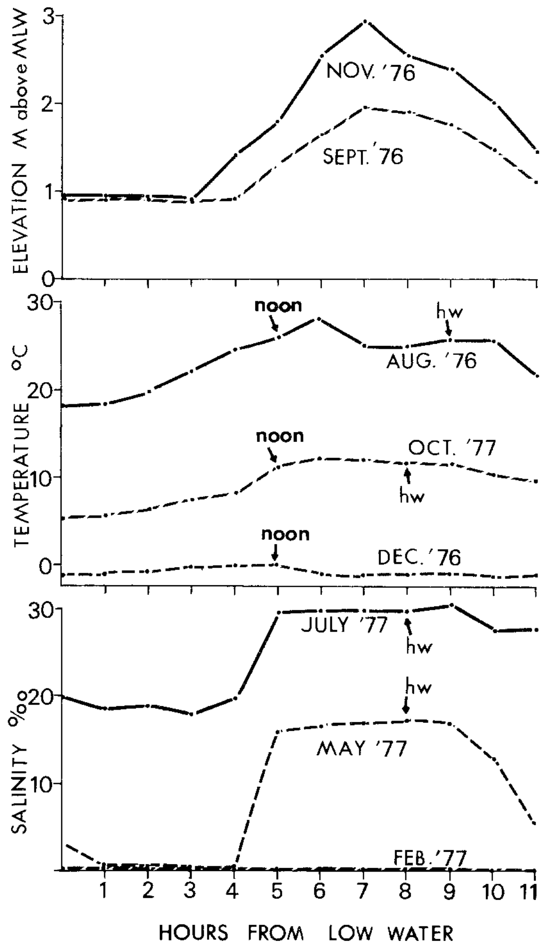

Fig. 3. Tidal patterns of elevation, temperature, and salinity

The maximum tidal height ranged from +1.96 to +2.95 m. The +0.87 m elevation of channel bottom at the study site resulted in approximately 4 h of "low water" or drainage per tidal cycle (Fig. 3). The temperatures ranged from −1.4 ° to 28.2 °C, being primarily dependent upon season (Fig. 3). However, daily temperature patterns were influenced by interactions between time of day and tidal stage. As would be expected, the water was more affected by air temperatures and insolation during low than high water. The annual variation of salinities was 0 to 30.7‰ S (Fig. 3). During spring runoff (February, 1977) the salinities were 0‰ S throughout the tidal cycle. By April a pattern was established, with decreasing values during low water, an increase through flood tide, and a maximum at high water. The extent of the low water dip was dependent upon season, being near 0‰ S in the spring and fall but 15‰ S or greater in July and August (Fig. 3). The salinity during the high water maximum was higher in the summer than the spring or fall.

Orthophosphate-P concentrations varied from 0.50 to 4.71 µg-at/l. During June to August of 1976 and

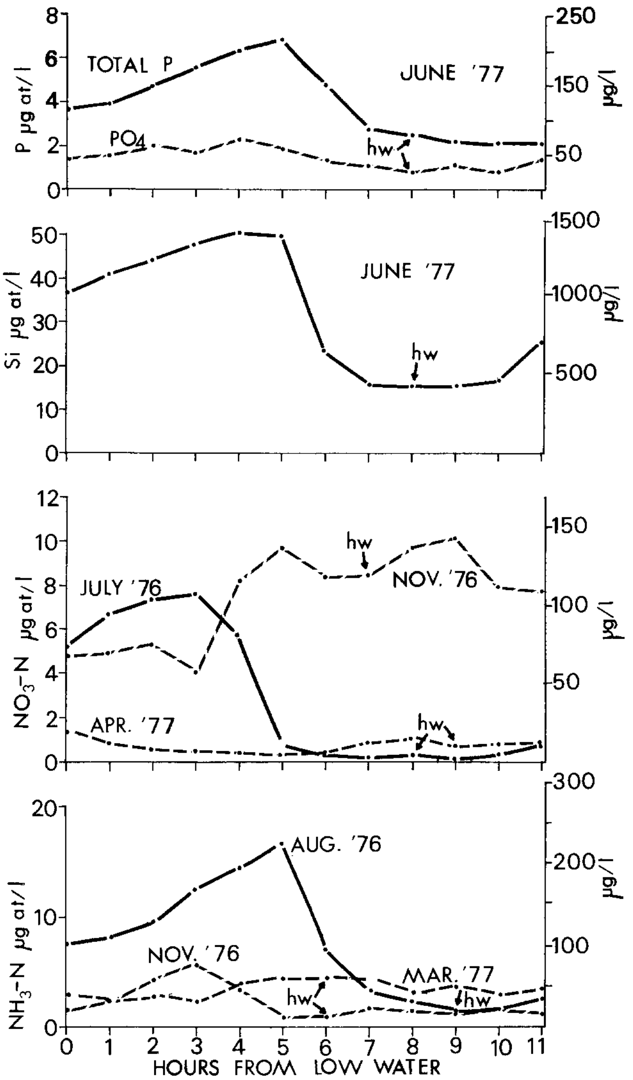

Fig. 4. Tidal patterns of orthophosphate-P, total phosphorus, silicates, nitrate-N, and ammonia-N

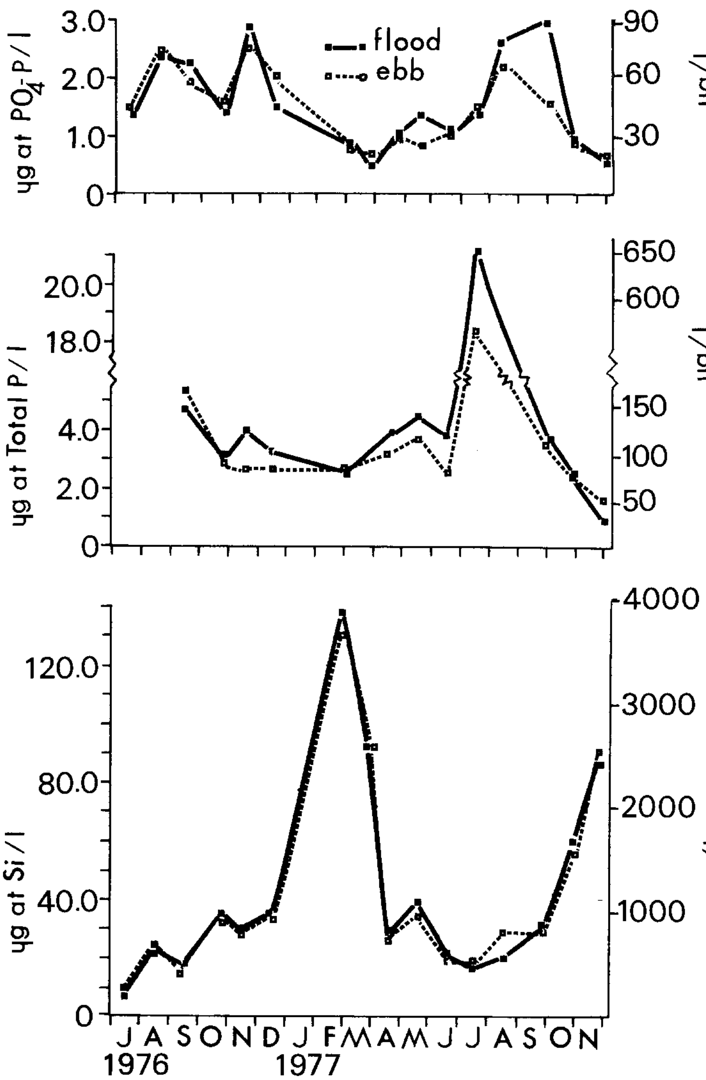

Fig. 5. Mean flood and ebb concentrations of orthophosphate-P, total phosphorus and silicates

1977 orthophosphate-P values were higher during low than high water (Fig. 4). The orthophosphate-P values during the rest of the year were low and fairly constant during both ebb and flood tides. The total phosphorous values were higher than orthophosphate-P, being 1.58 to 31.65 μg-at/l. No distinct tidal pattern was apparent, except in June and July of 1977 and the fall of 1976, when it was similar to orthophosphate-P (Fig. 4).

The silicate concentrations varied from 9.52 to 139.8 μg-at/l. Basically, the seasonal and diurnal patterns of silica concentration were the inverse of salinity. During spring runoff, silicate concentrations were 134.0 to 139.8 μg-at/l. As spring progressed the silicate values remained constant over a tidal cycle but the absolute values became lower. By June a pattern was established, with higher values at low rather than high water (Fig. 4).

Nitrate-N had the most complex tidal patterns with seasonal values ranging from 0.10 to 26.11 μg-at/l (Fig. 4). From spring runoff to June, nitrate-N was generally low. During July and August nitrate-N showed the same patterns as silicates. In contrast, during fall the nitrate-N concentrations decreased during the 4 h low water period and then increased until high water. Nitrite-N showed a seasonal pattern similar to nitrate-N but ranged from 0.07 to 1.44 μg-at/l. During July and August the nitrite-N concentrations were higher during low than high water; in contrast, during the early fall the situation was the reverse. Throughout the remainder of the year the diurnal nitrite-N values were consistently low (<1 μg at /l).

Ammonia-N ranged from 0.37 to 19.85 μg-at/l. During spring runoff the diel ammonia-N concentrations were low (2.43 to 4.60 μg-at/l) and fairly constant (Fig. 4). By June a pattern was established with increasing ammonia concentrations during the low water period, a decrease thereafter, and a minimum at high water (Fig. 4). The greatest diurnal range was found during the summer.

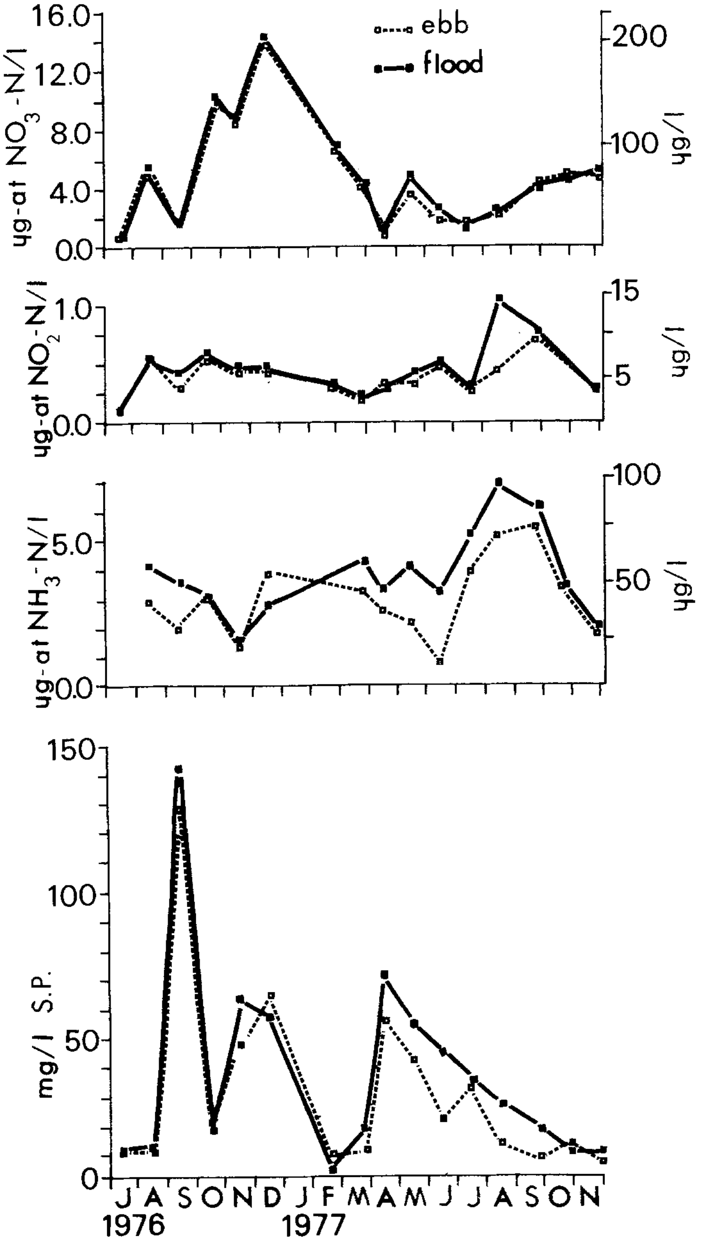

Fig. 6. Mean flood and ebb concentrations of nitrate-N, nitrite-N, ammonia-N and suspended particulates

Suspended particulates ranged from 0.52 to 133.55 mg l^{-1}. During 6 months the values were higher at high than at low water. No distinct seasonality or pattern was evident.

Seasonal Mean Concentrations

Ebb and flood volume-weighted mean concentrations are presented in Figs. 5 and 6. The monthly volume weighted means (ebb and flood combined) of the variables were compared to maximum measured tidal height and net water flow. Maximum tidal height had no apparent effect on the mean concentrations of hydrographic variables and only silicate concentrations were correlated with net water flow. The high silicate values measured on months of net water export suggest that land runoff was involved in mean silicate concentrations. A linear regression of mean silica concentrations and salinity was significant to 0.01 and revealed a –0.82 correlation coefficient. The mean concentrations of nitrate-N and silicates varied with season. The monthly mean values of nitrate-N and silicates were highest during winter (Figs. 5 and 6). The above described relationships were supported by polynomial regressions of nitrate-N and silicates versus month which were significant at the 0.01 level for second degree polynomials. The mean concentration values of the other parameters showed no seasonality using polynomial regressions.

Net Flux

The mean high water volume of the marsh was 10962 ± 1250 m^3 (1 standard error) while mean low water volume was 206 ± 77 m^3 (1 se). The volume of water exchanged on an ebb or flood tide was lowest (6015 m^3) on a September, 1976 ebb tide and highest (25272 m^3) on a November, 1976 flood tide. The net exchange of water [(volume flooded-volume ebbed)/volume flooded x 100] ranged from + 1.24 to – 7.03%. The average net exchange was –2.19 ± 0.68% (1 se). Greatest net losses of water occurred during high runoff times, i.e., the spring melt of February 1977 and during a particularly wet fall in November 1977.

The net exchanges of nutrients and suspended particulates each month are summarized in Table 1. The net fluxes of the parameters did not correlate with maximum tidal heights or net water flows, when compared by regression analyses. Ammonia-N was the only nutrient to show a significant seasonal trend, being exported in winter and imported the remainder of the year, with a maximum in spring. Ammonia-N yielded a significant ($P < 0.01$) second degree polynomial regression when compared seasonally. None of the polynomial regressions for the other materials were significant.

The annual net exchanges of nutrients and suspended particulates are listed in Table 2. All of the parameters, except silicates, were imported into the marsh. Ammonia-N and suspended particulates showed statistically significant importation at the 95% confidence level. However, none of the other net annual fluxes were statistically different from 0 at the 95% level.

Discussion

Tidal Patterns

All of the dissolved nutrients studied at Crommet Creek exhibited tidal patterns that varied seasonally, contrasting with the non-seasonal patterns recorded in Maryland (Heinle and Flemer, 1976). During the summer, the

Table 1. Net exchange of nutrients and suspended particulates (SP) in kg month^{-1}. Positive values are import, negative values are export from the marsh

Date		NO_3–N	NO_2–N	NH_3–N	PO_4–P	Total P	SP	Si
1976	July	– 0.90	+ 0.20	–	– 2.11	–	+ 733	– 13.46
	Aug.	– 4.76	– 0.10	+ 8.71	– 1.49	–	+ 938	– 65.53
	Sept.	+ 3.11	+ 0.53	+ 12.54	+ 6.75	–14.53	+ 6883	+ 53.85
	Oct.	– 0.97	+ 0.14	+ 0.73	– 3.56	+ 0.77	–1132	+ 17.72
	Nov.	– 2.94	+ 0.31	+ 2.28	+ 13.35	+ 16.76	+ 8961	+ 6.80
	Dec.	– 1.79	+ 0.01	–10.69	–10.25	+ 8.58	–5855	– 9.78
1977	Feb.	– 0.50	+ 0.08	–	+ 0.15	– 3.81	+ 1547	– 7.64
	Mar.	+ 3.24	+ 0.10	+ 6.37	– 1.36	–	+ 4281	– 47.98
	Apr.	– 0.92	– 0.13	+ 5.07	+ 1.46	+ 10.10	+ 7985	+ 15.06
	May	+ 11.12	+ 0.34	+ 14.89	+ 8.52	+ 12.73	+ 6558	+ 61.24
	June	+ 5.67	+ 0.43	+ 20.04	+ 1.24	+ 26.33	+13064	+ 43.65
	July	– 2.80	– 0.03	+ 10.79	– 2.04	+ 45.13	+ 1301	– 22.70
	Aug.	+ 0.39	– 0.24	+ 13.60	+ 5.33	–	+ 8292	–137.11
	Sept.	– 1.54	+ 0.36	+ 6.72	+ 25.31	+ 8.58	+ 6155	+ 24.35
	Oct.	– 3.21	– 0.03	+ 1.62	+ 0.15	– 1.77	–1585	+ 43.17
	Nov.	+ 1.16	+ 0.00	+ 1.88	+ 0.53	– 8.98	+ 1918	– 76.69

Table 2. Net Annual exchange of nutrients and suspended particulars (SP) in kg yr^{-1} for the whole marsh and in g m^{-2} yr^{-1}

Material	Flux for marsh kg yr^{-1}	1 SE	Flux (g) m^{-2} yr^{-1}	1 SE
NO_3–N	11.55	15.11	0.28	0.37
NO_2–N	1.53	0.74	0.04	0.02
NH_3–N	84.61	32.17	2.06	0.78
PO_4–P	22.77	24.50	0.56	0.60
Total P	132.63	63.36	3.23	1.54
SP	47,796	18,240	1,166	445
SI	– 33.0	171.54	0.81	4.19

concentrations of orthophosphate-P, nitrite-N, nitrate-N, ammonia-N and silicates during low water were higher than at high water (Fig. 4). Nitrate-N and nitrite-N had the reverse pattern in winter. Orthophosphate-P was constant from fall to spring. Ammonia-N and silicate maintained the summer diurnal pattern described above, except during spring runoff. The seasonal data for ammonia-N and silicates as well as the summer orthophosphate-P values from Crommet Creek concur with Gardner's (1975) South Carolina study, which found that marsh runoff during low water was enriched in dissolved silica, phosphate, and probably ammonia. The nutrient enrichment during low water may be due to two factors: 1) diffusion; 2) temperature differentials between high and low tides in the summer and the resultant effects on benthic metabolism (Hartwig, 1974; Gardner, 1975; Hale, 1975; Nixon *et al.*, 1976b). In general, the above workers have found that the release of ammonia-N was enhanced with increasing temperatures and that the uptake/release of inorganic phosphorus was dependent upon temperature. The summer tidal patterns that result are a reflection of the aforementioned factors during low water and of ambient concentrations in the adjacent Great Bay Estuary (Norall and Mathieson, 1976) during high water.

The nitrate-N seasonal tidal patterns observed at Crommet Creek were also evident in Delaware (Aurand and Daiber, 1973). The seasonal values of high water nitrite-N and nitrate-N at Crommet Creek corresponded to those in the Great Bay Estuary (Norall and Mathieson, 1976). However, low water values during different seasons were not attributable to different temperatures and the consequent effects on benthic metabolism (Nixon *et al.*, 1976b).

A number of authors (Aurand and Daiber, 1973; Gardner, 1975; and Heinle and Flemer, 1976) have interpreted diel concentration differences as indicative of the direction of net flow. In this study high and low water readings were better representative of extreme concentrations. The volumes of nutrient enriched runoff were small in comparison to volumes exchanged at higher tide levels and were thus rendered insignificant in the net nutrient exchange. The differential between mean ebb and mean flood concentrations closely paralleled the flux of materials.

Seasonal Mean Concentrations

The mean concentrations of silicates and nitrate-N at Crommet Creek are similar to the seasonal patterns in Great Bay (Norall and Mathieson, 1976). High concentrations occurred during winter and lower concentrations during summer. Studies in the Tijuana Estuary (Mauriello and Winfield, 1978) also showed similar seasonal nitrate-N concentrations as at Crommet Creek. The correlation of silicate concentration with net water flow and salinity and the diurnal patterns observed point to freshwater input as controlling silicate levels. The highest silicate values were obtained during spring runoff and lowest values were obtained during the low runoff period of summer.

Net Flux

The direction of net exchanges of materials between salt marshes and adjacent estuaries are still in question. A comparison of Crommet Creek data and data collected by other authors reveals many differences. On a yearly basis, an insignificant importation of orthophosphate-P and total phosphorus were found with no seasonal pattern of import or export. Heinle and Flemer (1976) found a small net export of phosphorus fractions and no seasonal patterns in Maryland. Reimold and Daiber (1970) also state that salt marshes are a source of phosphorus in Delaware Bay. In contrast, Woodwell and Whitney (1977) showed no net flux of phosphorus on Long Island Sound, but a definite seasonal exchange for several phosphorus fractions.

In general, Axelrad (1974) and Heinle and Flemer (1976) found a net export of nitrogen with inorganic fractions occasionally being imported. The ammonia-N uptake during May to July in the Heinle and Flemer study was similar to the present one. Trattner and Mattson (1976) found a net import of nitrogen in a New Jersey salt marsh. In contrast, Woodwell *et al.*, (1975) showed that ammonia-N was exported during the summer, possibly due to a mussel bed at the mouth of the drainage area (Nixon *et al.*, 1976a). In the Tijuana Estuary, Mauriello and Winfield (1978) demonstrated that the bodies of water involved in the exchange are important factors in the direction of net flux. In their study ammonia-N was imported to the marsh from tidal channels, whereas it was exported from the estuary to the Pacific and from an area with irregular fresh water input to the estuary.

In South Carolina, Settlemyre and Gardner (1977) found a net annual export of total suspended sediments with export in the summer and import in winter under normal tidal conditions. At Crommet Creek, the annual import was significant, with particulates only being exported during 3 of the 16 months, October, 1976 and 1977 and December 1976. One reason for this discrepancy may be that Crommet Creek does not empty directly into a bay but first passes though about 1 km of salt marsh. Therefore, on flood tides detritus from this section of marsh is carried back into Crommet Creek.

The exchange of nutrients via macrodetritus is difficult to quantify. Estimates of such exchange are variable, ranging from approximately 100% of production on ice scoured marshes to 1% on stable, poorly flooded marshes (Heinle and Flemer, 1976). Teal (1962) estimates that 45% of the marsh production is exported. In contrast, Woodwell *et al.* (1977) found no discernible net transport over a tidal cycle and concluded that any net flow was inward and small. The macrodetrital flux from Crommet Creek is currently being quantified.

Conclusion

The Crommet creek salt marsh appears to be a sink for ammonia-N and suspended particulates. If an exchange of any other parameters occurs, it is a small export of silicates and small imports of the other nutrients. A seasonality of net flux was only demonstrated for ammonia-N. Silicate variations were closely tied to the net water exchange (i.e., runoff). Both nitrate-N and silicates showed seasonality in mean concentrations. All variables except suspended particulates had seasonal tidal patterns that reflected runoff, temperature differentials, benthic metabolism, and diffusion.

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