FRESHWATER WETLANDS
Ecological Processes and Management Potential

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SEASONAL PATTERNS OF NUTRIENT MOVEMENT IN A FRESHWATER TIDAL MARSH

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Abstract The distribution and movement of dissolved O_2, CO_2, NO_3-N, NH_3-N and PO_4-P in the surface waters of a freshwater tidal marsh were studied. Tidal action, particularly periodic inundation and flushing, resulted in distinctly different patterns of nutrient distribution in the major wetland habitats. Inorganic N and PO_4-P were accumulated in the marsh during summer with emergent vegetation appearing to play an important role in the uptake and retention of nutrients. Although evidence is accumulating that some N and P may be translocated into belowground parts by several perennial macrophytes, most is rapidly leached after death of vascular plants with up to 80% of the total N and even more of the P lost within 1 month. In pond-like areas where filamentous algal blooms develop following the fall dieback of vascular plants, inorganic N and PO_4-P levels remain depressed through the winter and spring. On the basis of presently available evidence, it appears almost all habitats of freshwater tidal marshes may be sinks for inorganic N and PO_4-P during the vascular plant growing season and that certain habitats may continually function as sinks.

Key words *Carbon dioxide, decomposition, dissolved oxygen, emergent aquatic macrophytes, filamentous algae, freshwater tidal marsh, New Jersey, nitrogen, nutrient distribution, phosphorus, tide cycle.*

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INTRODUCTION

Only limited data exist on nutrient movements in freshwater tidal marshes (Stevenson et al., 1977), but it has been suggested that these wetlands may serve as sinks for certain nutrients, at least during part of the year (Good et al. [1975], Grant and Patrick [1970] and Whigham and Simpson [1975, 1976*a*, 1976*b*]). The purpose of this paper is to consider recent studies on nutrient movements in the Hamilton Marsh complex (the northernmost freshwater tidal marsh on the Delaware River) and their relationship to the annual cycle of production and decomposition known to occur in this and other New Jersey freshwater tidal marshes.

The Hamilton Marshes occupy 500 ha of tidal and nontidal land along an old meander adjacent to the Delaware River near Trenton, New Jersey (Fig. 1). Four distinct habitats occur in the marsh: (1) streams and streambanks include Crosswicks Creek, the main stream through the wetland and its tributary channels, (2) pond areas that are continually covered with water although the flow direction reverses with the tide, (3) areas that are pond-like during much of each tide cycle and are drained only at low tide, and (4) high marsh areas (the largest habitat in areal extent) that are covered by shallow water (usually <15 cm) at high tide only (Whigham and Simpson, 1976*a*).

The marsh is dominated by combinations of perennial (*Nuphar advena*, *Peltandra virginica*, *Lythrum salicaria*, *Sagittaria latifolia*, *Typha latifolia*, *Typha angustifolia*, and *Typha glauca*) and annual species (*Bidens laevis*, *Zizania aquatica* var. *aquatica*, *Polygonum arifolium*, *Polygonum sagittatum*, *Ambrosia trifida*, and *Impatiens capensis*) (Whigham and Simpson, 1975). Peak aboveground biomass for 6 vegetation types ranged from 650 to 2,100 g/m^2 and averaged 950 g/m^2 (Whigham and Simpson, 1976*a*). These data, however, underestimate net annual community production because Whigham et al. (1978) have shown that high marsh vegetation produces in excess of 4,000 $g \cdot m^{-2} \cdot yr^{-1}$. After the fall dieback, most of the marsh is devoid of aboveground vascular plants but certain sections, notably the pond-like areas, develop dense mats of filamentous algae. The only major nutrient loading to the marsh comes from the 28.4×10^6 litres of secondarily treated effluent discharged daily by the Hamilton Township Sewage Treatment plant into Crosswicks Creek (Fig. 1).

METHODS

For comparison of the patterns of nutrient distribution in the surface waters of the major wetland habitats throughout the year, water samples were collected for a 1-year period beginning in June 1974 at 4 stream sites (1, 2, 7, 8) on Crosswicks Creek (Fig. 1), 1 pond-like site (4B), 1 pond site (4C), 2 sites (4, 4A) on the tributary linking the pond-like area and Crosswicks Creek, and 2 sites (5, 5A) on a second tributary draining an extensive high marsh area (5A). Sites 4 and 5 were on the tributary streams near their entrances to Crosswicks Creek. Samples were collected at 2-week intervals

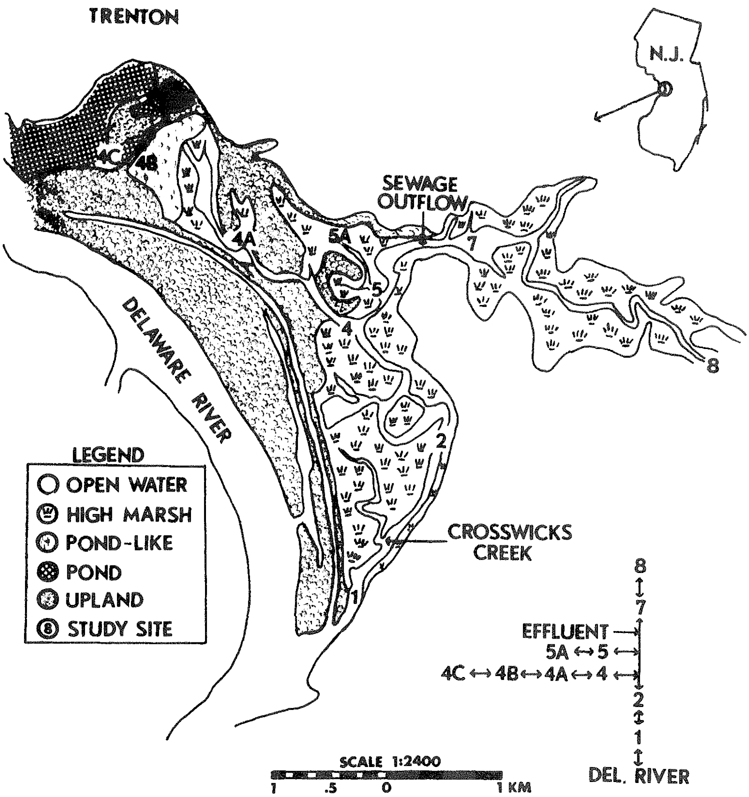

Fig. 1. Map of the Hamilton Marshes showing the major wetland habitats and study sites. Tidal flow within the marsh is indicated by the diagram at the lower right of the map.

during the summer of 1974 and monthly thereafter at morning high slack water (hsw) and afternoon low slack water (lsw).

Based on the results of the 1974–75 study, investigations were conducted at high marsh Site 5A during the summers of 1975 and 1976 to trace the fate of selected nutrients through complete tide cycles. These studies were begun at either hsw or lsw and focused on both the water running off the marsh surface and water remaining on the marsh.

In the laboratory all samples were analyzed for dissolved O_2 (DO) using the azide modification of the Winkler method (American Public Health Association 1971), CO_2 by titration (American Public Health Association 1971), nitrate nitrogen (NO_3-N), nitrite nitrogen (NO_2-N), ammonia (plus amino acid) nitrogen (NH_3-N) and inorganic phosphate (PO_4-P) following Strickland and Parsons (1968) and total phosphate (total P) following Menzel and Corwin (1965). Because the sites were not gauged, all values are expressed in marshwater concentrations rather than total outputs from the wetland.

RESULTS

Dissolved Oxygen and Carbon Dioxide

Patterns of DO and CO_2 are presented in Fig. 2. The Crosswicks Creek sites (1, 2, 7, 8) and those downstream from the high marsh (Site 5) and pond-like areas (Site 4) show typical seasonal DO patterns. The high marsh Site 5A had depressed DO levels in the summer at both hsw and lsw. Morning high slack water values ranged from 5.5 mg/l to <4 mg/l in the early fall with lsw values usually 1–1.5 mg/l lower during this period. When compared to the main channel of Crosswicks Creek, late fall DO at lsw was noticeably depressed coinciding with the period of maximum decomposition of vascular plant material. Pond and pond-like areas (Sites 4B, 4C) were virtually depleted of DO (often <1 mg/l) in the summer and supersaturated to >16 mg/l at afternoon lsw in the winter and spring. The elevated winter values appeared with the development of dense mats of *Rhizoclonium* and other filamentous algae following the death of vascular plants in the fall at these sites. The channel draining the pond-like areas (Site 4A) reflected lsw patterns similar to the pond-like areas but with less intensity as Crosswicks Creek was approached (Site 4). Except for Sites 7 and 8 upstream from the sewage treatment plant outflow, and Sites 4B and 4C during the winter and spring months, all sites had generally lower DO levels at lsw.

High marsh Site 5A had raised CO_2 levels particularly at lsw. Maximum values of 28 mg/l occurred in the fall during the dieback of vegetation. Though less intense, this pattern was reflected downstream at Site 5. Pond and pond-like areas (Sites 4B, 4C) had elevated CO_2 levels during the summer months of DO depletion with pond Site 4C having values >25 mg/l throughout the summer. A noticeable decline in CO_2 to <3 mg/l occurred during the spring DO maximum. Crosswicks Creek (Sites 1, 2, 7, 8) had consistently lower CO_2 levels than the high marsh and pond-like areas with CO_2 levels usually <5 mg/l at hsw, and 10 mg/l at lsw. Afternoon low slack water values were always higher than hsw values except at Sites 7 and 8 upstream from the sewage outflow and Sites 4B and 4C in the pond-like and pond areas.

Inorganic Nitrogen

Nitrate and ammonia (plus amino acid) N patterns are shown in Fig. 3. Nitrate N levels were near the limits of detection during the summer in the pond-like and pond sites (4B, 4C), but rose dramatically in the early winter. Of particular interest is the fact that hsw values at Site 4B were consistently 10–40 μg–atoms N/litre higher than lsw values during the winter and early spring. This pattern was not seen at downstream Sites 4 and 4A. Site 5A had noticeably depressed NO_3-N levels of <40 μg–atoms N/l at lsw during the months of maximum growth of vascular plants. With the fall dieback, hsw and lsw values became about equal at 100 μg–atoms N/l. Mainstream channel

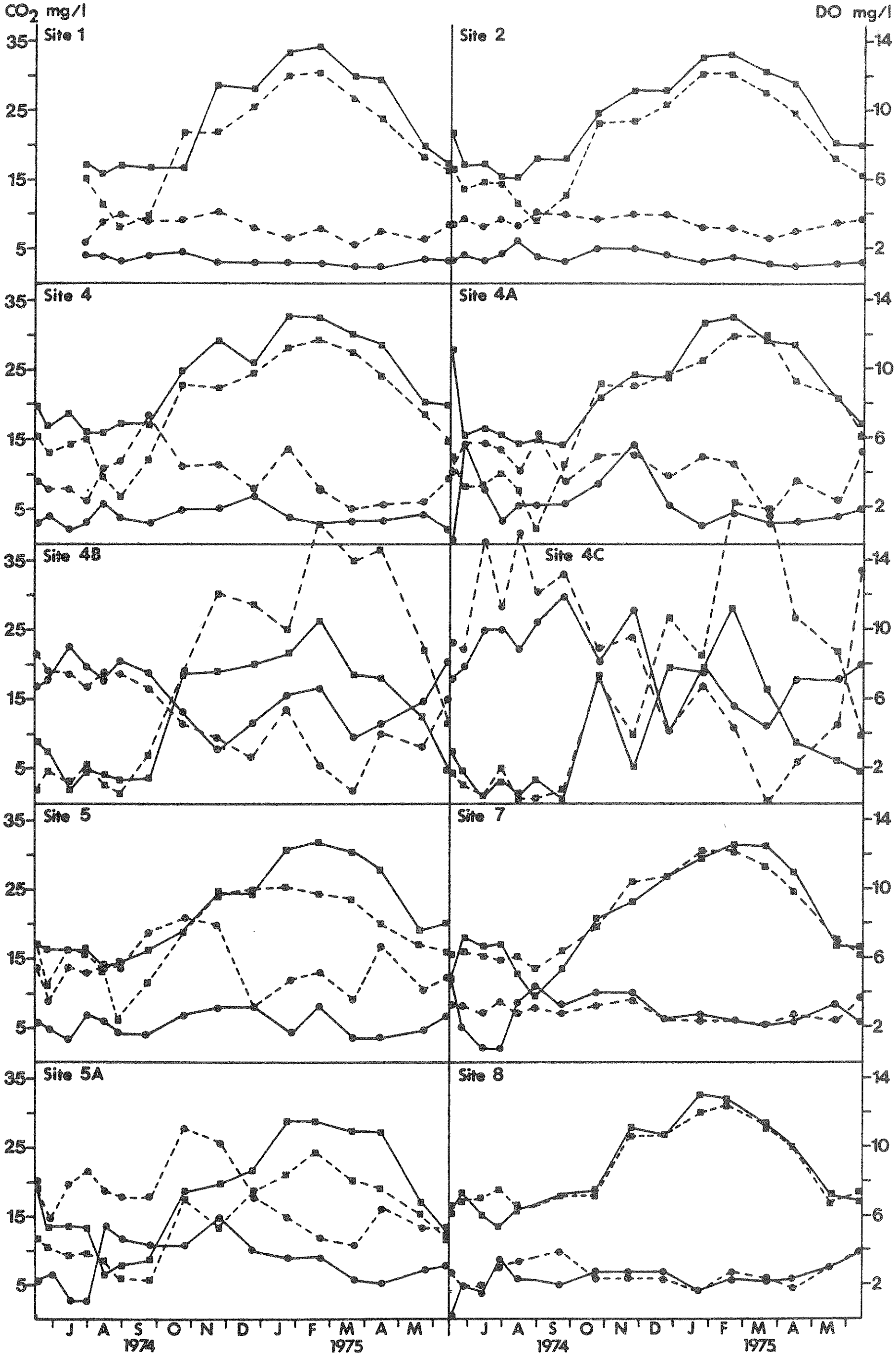

Fig. 2. Changes in DO (squares) and CO_2 (circles) for 10 marsh sites between June 1974 and June 1975. Solid lines represent high slack water and dashed lines low slack water.

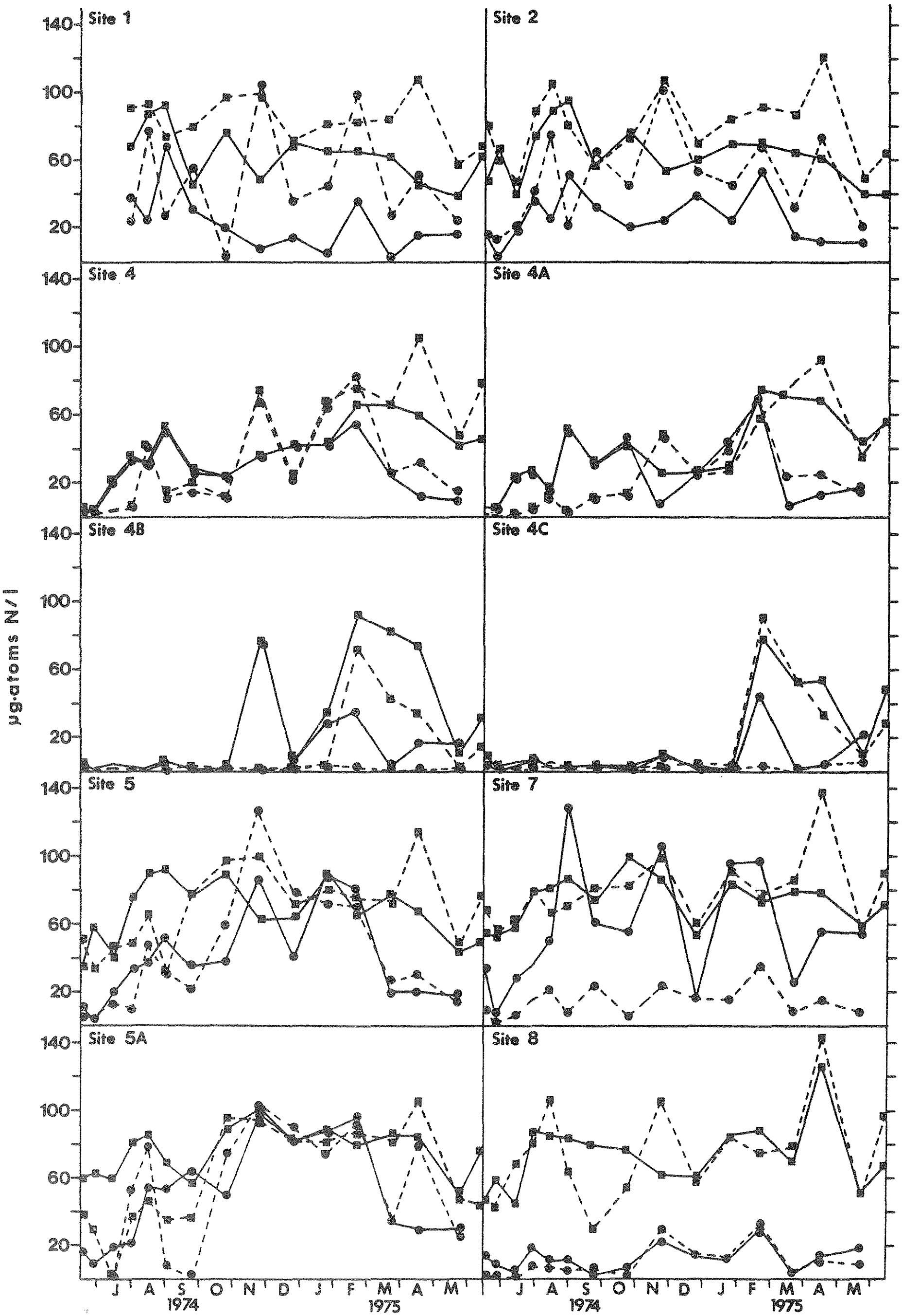

Fig. 3. Changes in NO_3-N (squares) and NH_3-N (circles) for 10 marsh sites between June 1974 and June 1975. Solid lines represent high slack water and dashed lines low slack water.

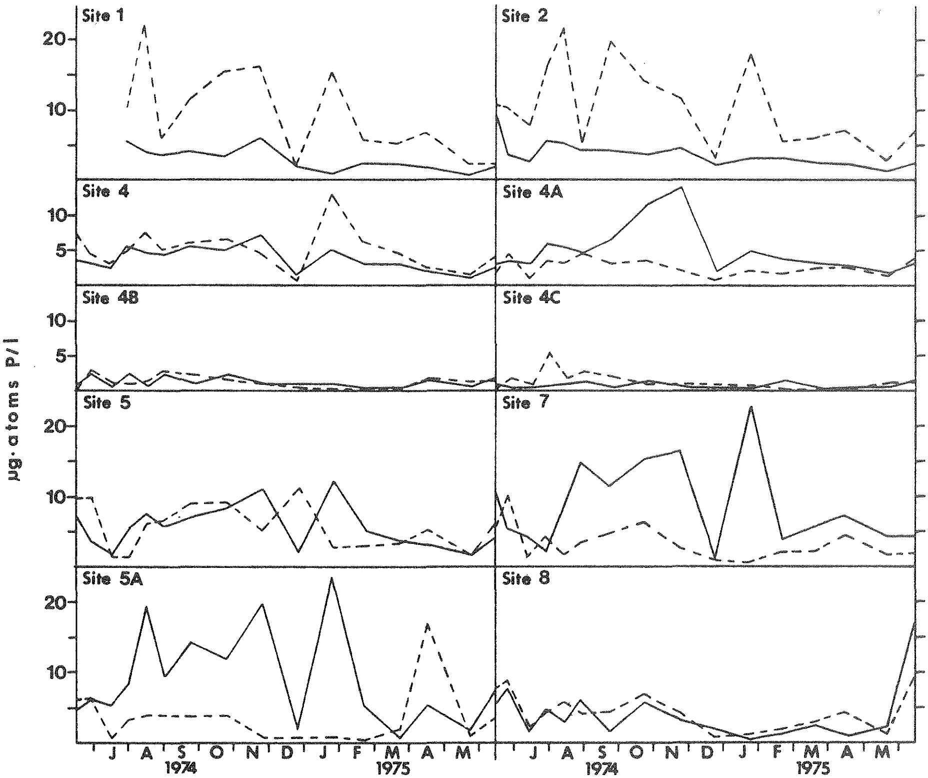

Fig. 4. Changes in PO_4-P for the 10 marsh sites between June 1974 and June 1975. Solid lines represent high slack water and dashed lines low slack water.

sites (1, 2, 7, 8) showed no particular patterns except that lsw NO_3-N values were generally 10–40 μg–atoms N/l higher than hsw levels downstream from the sewage outflow.

Ammonia N levels were extremely low ranging from 5 μg–atoms N/l to undetectable in the pond-like and pond areas (Sites 4B and 4C) during the summer. For the remainder of the year, values stayed <5 μg–atoms N/l at lsw, but typically ranged from 20–80 μg–atoms N/l at hsw. Much of the hsw NH_3-N present at downstream Sites 4 and 4A never reached these areas during the summer months. High marsh (Site 5A) levels were variable during the summer but on several occasions during this period, levels approaching zero were recorded at lsw. At other times during the year, levels were approximately the same at both hsw and lsw with maximum values of 100 μg–atoms N/l occurring during the winter. Ammonia N values at Site 8 at the head of the marshes on Crosswicks Creek were always low, generally being <20 μg–atoms N/l with little difference between hsw and lsw. The main stream channel Sites 1 and 2 normally had elevated values at lsw

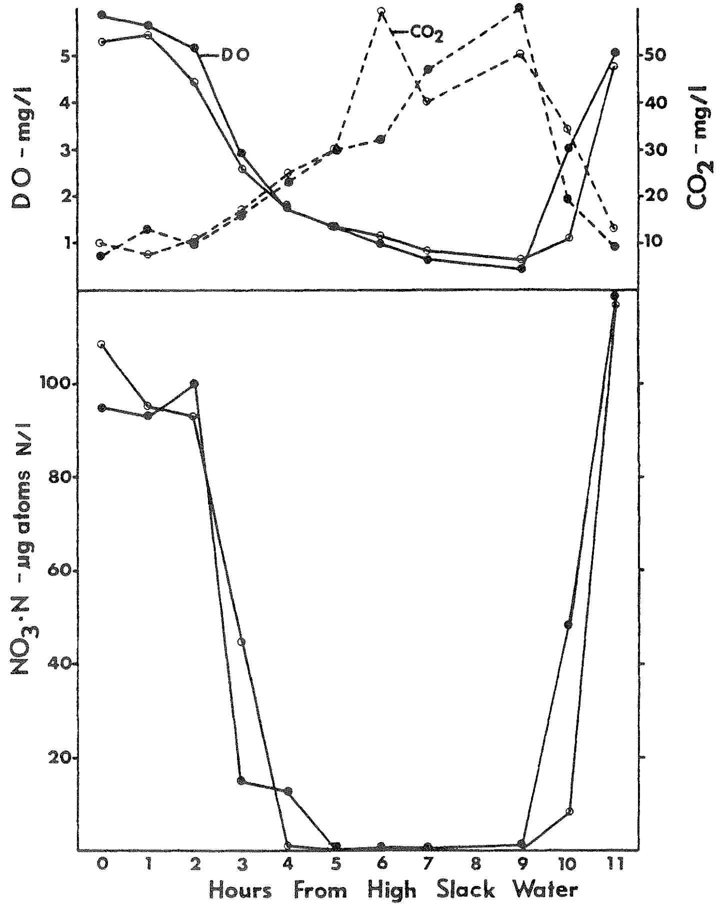

Fig. 5. Changes in DO, CO_2 and NO_3-N during 1 complete tide cycle (beginning with high slack water) at 2 locations on the high marsh surface near Site 5A on 13 June 1975.

while Site 7 upstream from the sewage outflow always had elevated NH_3-H levels at hsw.

Nitrite N during the summer months ranged from 4–8 μg–atoms N/l at high marsh Sites 5 and 5A and stream channel sites (1, 2, 7, 8). Pond-like areas had much lower values with hsw NO_2-N levels <2 μg–atoms N/l and lsw levels <0.5 μg–atoms N/l. Generally, values <2 μg–atoms N/l NO_2-N were found during the winter and spring at all sites, with <0.5 μg–atoms N/l present in the pond-like and pond Sites 4B and 4C.

Inorganic Phosphate

Inorganic phosphate changes during the study are presented in Fig. 4. Inorganic phosphate levels were always low usually being <5 μg–atoms P/l

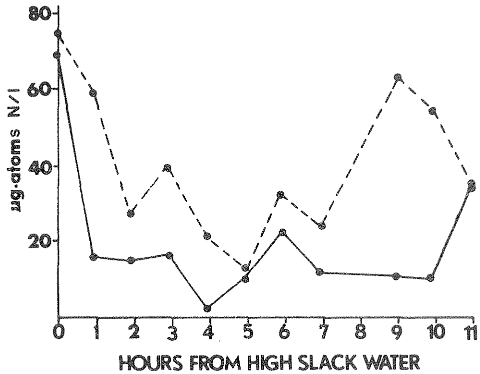

Fig. 6. Changes in NO_3-N leaving the high marsh surface (solid line) and in the adjacent stream channel (dashed line) during 1 complete tide cycle (beginning with high slack water) near Site 5A on 12 August 1976.

in pond-like and pond areas (Sites 4B and 4C). In these areas little difference was found between hsw and lsw. Inorganic phosphate was consistently higher at Site 4A, particularly at hsw, than at pond-like Site 4B. Except for April 1975, the high marsh Site 5A had substantially higher PO_4-P levels at hsw than at lsw. Indeed, levels were considerably higher than those at Site 5 which was a short distance downstream within the same channel. This extra PO_4-P loading most likely came from seepage from a nearby sludge lagoon. Substantially less PO_4-P was found at lsw at Site 5A. Except for Site 8 which is minimally influenced by the tide, all sites on Crosswicks Creek show elevated PO_4-P levels often exceeding 15 μg–atoms P/l that correspond to the direction of tidal movement.

Tide Cycle Studies

Figure 5 shows changes in DO, CO_2 and NO_3-N on the high marsh surface at 2 study areas near Site 5A through a complete tide cycle beginning at hsw. Dissolved O_2 levels were >5 mg/l until the tide ebbed when they dropped rapidly to <1 mg/l where they remained until the next flood tide covered the marsh surface. Then DO levels again rose to >5 mg/l. Carbon dioxide levels showed the reverse pattern, but rose more gradually from ≈ 10 mg/l to >50 mg/l during the 9 hours that the high marsh was not inundated, and then dropped rapidly to initial levels as the marsh flooded again. Nitrate N dropped dramatically from nearly 100 μg–atoms N/l while the marsh was flooded to undetectable levels during the hours when the marsh drained, and then rose quickly to nearly 120 μg–atoms N/l with the next high tide.

Studies of runoff from the high marsh surface into the tributary channel (Fig. 6) show similar NO_3-N patterns. Here it appears, however, that NO_3-N concentrations may decline somewhat more slowly. Nitrate N levels in the adjacent stream channel were almost always higher than levels leaving the

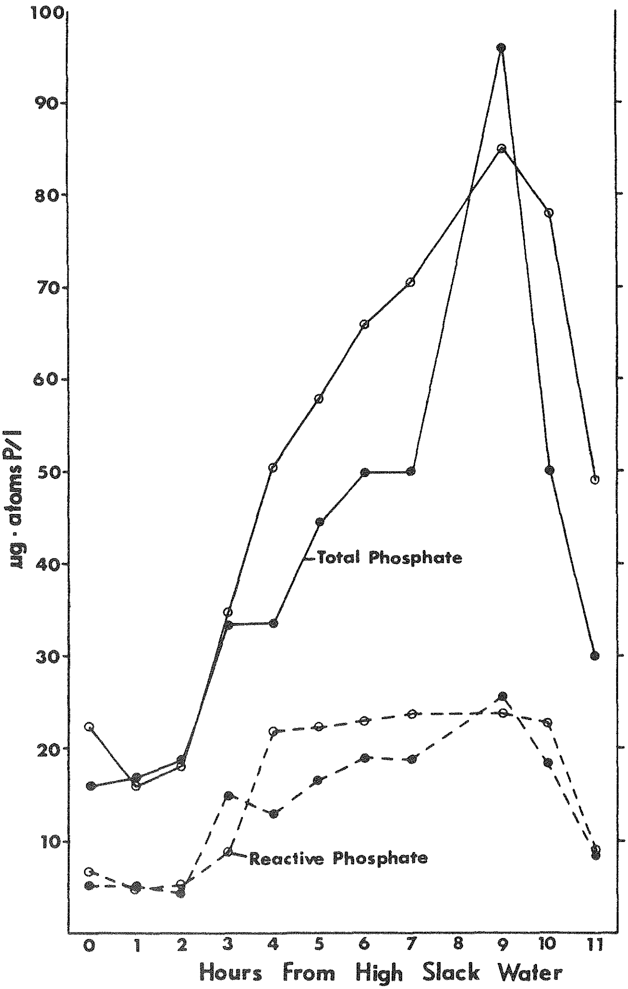

Fig. 7. Changes in PO_4-P and total-P during 1 complete tide cycle (beginning with high slack water) at 2 locations on the high marsh surface near Site 5A on 13 June 1975.

marsh surface. Ammonia N concentrations in this runoff water were always at or near the limits of detection.

Figure 7 shows PO_4-P and total-P levels on the high marsh surface for the same 2 high marsh study areas. Inorganic phosphate levels were at 5–7 μg–atoms, P/l while the marsh surface was flooded and then slowly rose to 20 μg–atoms P/l before falling rapidly back to 8 μg–atoms P/l as the next flood tide covered the high marsh surface. Total phosphate followed the same general pattern, but the magnitude of the increase was much larger going from a value of $\approx$20 μg–atoms P/l at hsw to nearly 100 μg–atoms P/l immediately before the marsh reflooded.

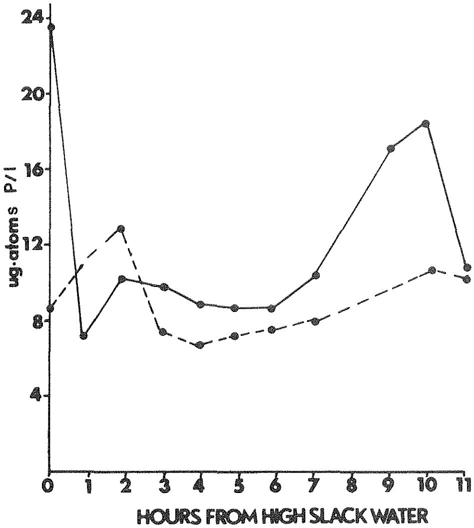

Fig. 8. Changes in PO_4-P leaving the high marsh surface (solid line) and in the adjacent stream channel (dashed line) during 1 complete tide cycle (beginning with high slack water) near Site 5A on 12 August 1976.

Surface waters leaving the high marsh show a somewhat different pattern for PO_4-P (Fig. 8). There was an initial rapid decline in PO_4-P just before water left the marsh surface, then a gradual increase in PO_4-P leaving the marsh through the remainder of the tide cycle. Unlike NO_3-N, PO_4-P concentrations in the adjacent stream channel were generally lower than those of water draining from the high marsh.

The patterns of change in all nutrients were basically the same regardless of when sampling was initiated in the tide cycle.

DISCUSSION

Different patterns of nutrient distribution were found in the major habitats of the marsh. Pond and pond-like sites (4B, 4C) were depleted of PO_4-P and NH_3-N throughout the year, NO_3-N from late spring to midwinter (especially at lsw) and DO in the summer and fall. Carbon dioxide values were elevated during the period of DO depletion with the pond site (4C), the site least affected by tidal action, exceeding 30 mg/l in the summer months. In winter and spring, CO_2 was virtually absent, particularly at afternoon lsw in close correspondence with the growth of dense *Rhizoclonium*-dominated mats of filamentous algae following the dieback of the emergent vegetation.

The major nutrient source for the pond and pond-like sites (4B and 4C) was flood tide Delaware River water that entered the area through tributary Sites 4 and 4A. High slack water inorganic N and PO_4-P concentrations at the tributary sites were always higher than those found at the pond and pond-like sites indicating that both inorganic N and PO_4-P were trapped in the pond-like area upstream from Site 4A. Low slack water inorganic N and PO_4-P concentrations were well below hsw levels at Sites 4 and 4A suggesting that trapped nutrients did not leave the pond-like area with the ebb tide.

Although there were differences in magnitude, marsh water nutrients as high marsh Site 5 were very similar to those in the pond and pond-like sites but only during the emergent macrophyte growing season. There were similar patterns of lsw DO depression, elevated CO_2, depletion of NO_3-N and usually NH_3-N, and depressed PO_4-P levels. Carbon dioxide levels were very elevated in October which corresponded with the period of most rapid decomposition of emergent plants. Similarities between high marsh and pond and pond-like sites disappeared following death and dieback of the emergent vegetation as little difference between hsw and lsw nutrient levels were seen at the high marsh sites during the winter and spring.

In contrast to high marsh, pond and pond-like areas, stream channel sites on Crosswicks Creek (Sites 1, 2, 7 and 8) did not show seasonal depletion of nutrients. Discharge from the Hamilton Township sewage treatment plant greatly influenced inorganic N and PO_4-P concentrations in the main stream channel. Sites 1 and 2 downstream from the discharge point had consistently lower DO and higher CO_2, inorganic N and PO_4-P levels at lsw and Site 7 upstream from the effluent discharge point displayed the reverse pattern. Site 8 at the head of the wetland was not perceptibly influenced by either Delaware River water or effluent. This site consistently displayed little difference in hsw and lsw DO and CO_2 levels, always had low NH_3-N and PO_4-P values, but did have variable NO_3-N levels in part due to runoff from the surrounding watershed following storm events.

These patterns of nutrient distribution were clearly influenced by the action of the tides within the wetland. The main stream channel which experiences a tidal fluctuation of $\approx$2 m (and strong tidal currents) was completely flushed with each tide cycle. The high marsh was likewise flushed with each tide cycle, but the water gently spreads to a depth of 10–15 cm over the wetland surface before receding. In contrast the pond and pond-like areas with a tidal amplitude of 30 cm or less were at best only partially flushed.

The impact of the completeness of flushing and rate of water movement was seen in the distribution of DO in the wetland with the well flushed stream channel sites being near saturation and the poorly flushed pond and pond-like sites constantly approaching complete depletion of DO especially during the summer and fall. The importance of this tidal action was also felt on the high marsh where the periodic inundation insured a renewed supply of DO that tide cycle studies show was virtually depleted within 2–4 h after the tide ebbs.

Periodic inundation with water from the Delaware River likewise insured a relatively constant supply of N and P to the high marsh and pond-like

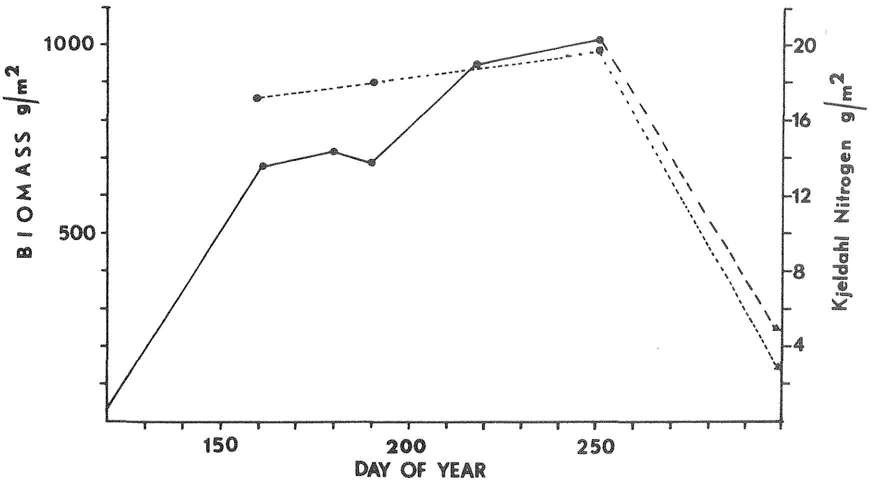

Fig. 9. Aboveground primary production (solid line) and Kjeldahl-N incorporated in that biomass (dashed line) for 1 high marsh study area near Site 5A during 1975. The values for year day 298 (triangles) represent litter mass and Kjeldahl-N in that litter ≈30 days after the end of the 1976 growing season in the same study area.

areas. The high marsh, where flood tide water gently flowed over the surface, apparently acted as a sink for inorganic N during the summer months and the pond-like and pond areas which are only partially flushed appeared to accumulate inorganic N throughout the year. Similar patterns of inorganic N uptake have been reported for the Tinicum Marsh on the Delaware River south of Philadelphia (Grant and Patrick, 1970). Likewise, brackish water marshes of Chesapeake Bay (Stevenson et al., 1977) and Hog Island and adjacent marshes on the Mullica River, New Jersey (Durand and Nadeau, 1972) seem to assimilate inorganic N during the late spring and summer growing period.

Nitrogen was rapidly incorporated by the emergent macrophytes early in the growing season as shown in Fig. 9. After this initial incorporation, N standing crop in the plants remained relatively constant. However, if leaf turnover which has been shown by Whigham et al. (1977) to be substantial is considered, the vegetation likely continues to need a N source to produce new tissue until growth ceases in late summer. It was precisely during this summer period of biomass accumulation that NO_3-N levels appeared lowest in the surface waters of the marsh. Likewise summer tide cycle studies showed NO_3-N was rapidly depleted on the high marsh surface once the flood tide waters recede. It appears, therefore, that at least part of this NO_3-N may have been assimilated by the plants. The fact that marsh vegetation exposed to sewage effluent high in inorganic N had substantially more tissue N than vegetation not exposed to sewage (Whigham and Simpson, 1976*b*) supports this conclusion.

Following death and dieback of the vascular plants at the first frost, there was a rapid loss of weight and even more dramatic loss of N from the standing dead plants. Within a month after death, 80% of the N incorporated in the litter standing on the marsh was lost. Similar losses of N have been found using litterbags placed on the marsh surface although there was only ≈ a 50% loss of N in the 1st month probably because of microbial colonization of the litter on the wetland surface (R. L. Simpson and D. F. Whigham, *personal observation*). Some N however, may be withdrawn from above-ground parts of marsh perennials including *Peltandra*, *Typha* and perhaps *Nuphar* (Good and Good, 1975; R. Walker and R. E. Good, *personal observation*) prior to the end of the growing season.

With death and dieback of vegetation in the fall, hsw and lsw inorganic N levels became roughly equal in the high marsh suggesting no net exchange of inorganic N between the marsh and Delaware River during the fall and winter. In contrast Stevenson et al. (1977) found a net export of inorganic N from a Chesapeake Bay low salinity marsh during the fall. This difference may be due to the fact that the Chesapeake Bay marshes are in agricultural areas whereas the Hamilton Marshes are more isolated from such activities. Although the fate of organic N is unknown for the Hamilton Marshes, studies of the Hog Island Marsh (R. E. Good, *personal communication*) and Chesapeake Bay low salinity marshes (Stevenson et al., 1977) suggest that freshwater and brackish tidal marshes may export organic nitrogen to the estuary.

In the Hamilton Marshes it appears that there was a net import of PO_4-P into pond-like areas. Differences in hsw and lsw surface water concentrations suggest that the high marsh also took up PO_4-P. However, unlike with inorganic N, substantial PO_4-P may be returned to the surface waters after the flood tide waters recede from the high marsh. Phosphorus appeared to be lost quickly when the high marsh vegetation decomposes in the fall with up to 95% of the P incorporated in living tissue lost within the 1st month after frost (R. L. Simpson and D. F. Whigham, *personal observation*). The net annual flux of P is unknown for the Hamilton Marshes, but Stevenson et al. (1977) have found that Chesapeake Bay low salinity marshes export P on an annual basis.

ACKNOWLEDGMENTS

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