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The Potential Use of Freshwater Tidal Marshes in the Management of Water Quality in the Delaware River[1]

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Introduction

In 1973 we began a study of the potential use of a natural ecosystem, a freshwater tidal marsh (Hamilton Marshes), in the management of water quality in a portion of the Delaware River. Our initial emphasis was on vegetation composition and primary production.[2] In 1974 we expanded our research to include other functional aspects of the marsh ecosystem, initiating experiments on soil algae distribution and biomass, soil nutrient and organic matter content, plant nutrient content, nutrient movement through the marsh by analysis of surface water, and movement of detritus into and out of the marshes. Preliminary results of this work, parts of which are reported in this paper, clearly demonstrate that the marsh is highly productive and that it is an efficient nutrient processer.

The Delaware River Ecosystem

Degradation of water in the Delaware River estuary system is a problem of local and regional concern. Compared to other east coast estuarine systems, much more biochemical oxygen demand (BOD) is discharged into the Delaware River basin.[3] A recent Delaware River census further demonstrated that areas within the estuarine system are polluted.[4] Organic enrichment, evidence of toxic pollution, and periods of low dissolved oxygen were shown for sections of the estuarine system between Trenton and Salem, N.J. Walton and Patrick suggested that degrada-

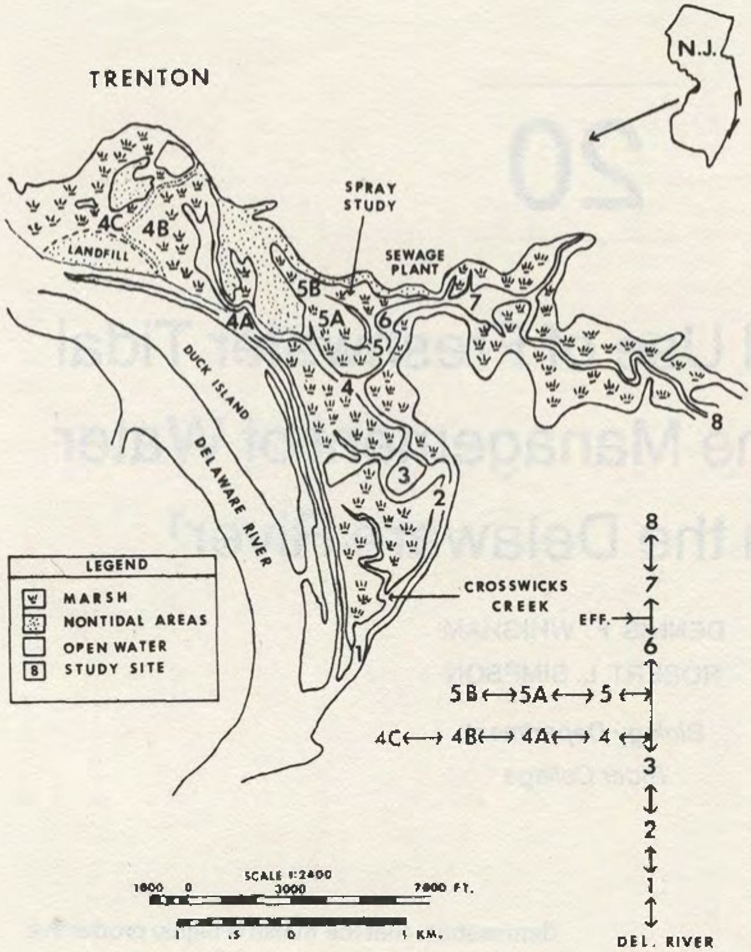

FIG. 20-1. Schematic diagram of the Hamilton Marshes. The pattern of water movement into and out of the marsh is shown at the lower right.

tion was greatest around Philadelphia. Sewage effluent is a major source of pollution in the estuarine system.

Of the approximately 158,000 acres of marshland in the Delaware River estuarine system, 5% are freshwater tidal marshes. These are located along the northern section of the tidal area from south of Philadelphia to Trenton. An analysis of the RANN study shows that the freshwater marshes vary in size from about 20 acres to over 2000 acres and that the average size is approximately 850 acres.[5] Compared to the salt marshes, these freshwater marshes show more evidence of perturbation. There was evidence of organic enrichment in all of the marshes mentioned in the RANN report with most of it coming from sewage treatment plants. In addition approximately 50% of the freshwater marshes are used as sites for landfills or for disposal of industrial wastes. The report suggested that several of the marshes are heavily impacted and in a severely degraded condition.

Of what value are the freshwater tidal marshes and is it important that they be managed? The State of New Jersey has declared that they are valuable natural areas and has included them in the New Jersey Wetlands Act of 1970. The marshes act as impoundments that store excess water during periods of high water flow.

Between Trenton and Bordentown, N.J., more than 30 million gallons per day (mgd) of secondarily treated sewage effluent are discharged either directly or indirectly into the Delaware River.[6] Except for the Ewing-Lawrence and Hamilton Township Sewage Treatment Plants, most of the effluent is discharged directly into the Delaware River. Hamilton Township discharges approximately 7 mgd into Crosswicks Creek, a tributary of the Delaware River. Crosswicks Creek is the largest stream that flows through the Hamilton Marsh ecosystem (Fig. 20-1). To account for a projected increase in utilization of their facility, officials in Hamilton Township are presently contracting for the expansion of their sewage treatment plant to handle 17.5 mgd. They must also decide whether they will continue to discharge their effluent into Crosswicks Creek or pump it directly into the Delaware River. As population increases within the Trenton metropolitan area, other municipalities will also have to expand their capacities and without tertiary treatment or other suitable means of disposal, enrichment of the upper Delaware River estuarine system will surely increase. To prevent further pollution of that system, other disposal alternatives must be examined. This paper will demonstrate the tertiary treatment capabilities of the Hamilton Marshes through analyses of several important marsh functions.

Study Site

The Hamilton Marshes occupy approximately 500 ha of tidal and nontidal land along an old meander adjacent to the Delaware River near Trenton, N.J. (Fig. 20-1). This is the northernmost tidal marsh in the Delaware River basin. Trenton has a typical temperate climate with a cold but not long winter (Fig. 20-2).[7] Precipitation averages 1020 mm annually and it is fairly evenly distributed with a maximum in July and a minimum in October. The average temperature is 12.1°C and the growing season lasts from mid-

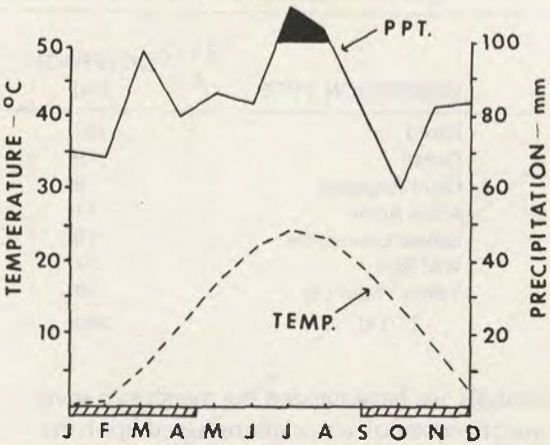

FIG. 20-2. Climatic diagram for Trenton, N.J. The mean annual temperature and precipitation are shown next to the climate station name. Because the precipitation curve is always above the temperature curve, the climate is interpreted as not having a dry season. Along the abscissa are plotted the months of the year (January–December) and a shaded area which shows the number of months during which there is a chance of temperatures that fall below 0°C. Trenton has a Type VI climate according to the system of Walter and Lieth (see note 7). Precipitation above 100 mm per month is plotted on the scale of 1:3 (10°C: 30 mm ppt.).

April until late September. Within the marsh, water supply is always adequate, and temperature, along with photoperiod, seem to be the most important factors controlling biological activities of organisms. The silt and silt-clay soils are highly organic (15–50%).

Vegetation Analysis

The marsh can be divided into 4 habitats: (1) streams and stream banks—including channels that connect streams to high marsh areas, (2) high marsh areas that are covered by shallow water (usually less than 15 cm) at high tide only, (3) areas that are pond-like during much of each tide cycle and are drained only at low tide, and (4) areas that are continuously water covered. Unlike salt marshes, vascular plant diversity is high in freshwater tidal marshes. For purposes of

TABLE 20-1. *Aerial Extent and Total Aboveground Production Estimates for Dominant Vegetation Associations of the Hamilton Marshes.*

VEGETATION TYPE	COVERAGE (ha)	ANNUAL ABOVEGROUND PRODUCTION (t/ha)	TOTAL PRODUCTION (t)
Mixed	137	9.1	1246.7
Cattail	19	13.2	250.8
Giant Ragweed	3	11.6	34.8
Arrow Arum	11	6.5	71.5
Spiked Loosestrife	10	21.0	210.0
Wild Rice	24	9.4	225.6
Yellow Water Lily	58	7.8	452.4
TOTAL	262	X = 9.5	2491.8

analysis, we have divided the marsh into seven major vegetation associations based upon the dominant species (Table 20-1). Vegetation dominated by cattail, *(Typha latifolia, T. angustifolia, T. glauca)*, giant ragweed *(Ambrosia trifida)*, and spiked loosestrife *(Lythrum salicaria)* are common on the high marsh but the mixed vegetation association is most expansive and covers approximately 137 ha. Bur marigold *(Bidens laevis)* is the dominant species in the mixed vegetation type. Other important components are arrow arum *(Peltandra virginica)*, arrowhead *(Saggitaria latifolia)*, halberd-leaved tearthumb *(Polygonum arifolium)*, and arrow-leaved tearthumb *(Polygonum sagittatum)*. Wild rice *(Zizania aquatica)* is also common in this vegetation association.

Primary Production

Measurements of primary production are frequently used as indicators of how ecosystems function. High rates of production are indicative of high rates of nutrient assimilation. Primary production of each vegetation association was examined in 1974. Aboveground biomass was harvested throughout the growing season using

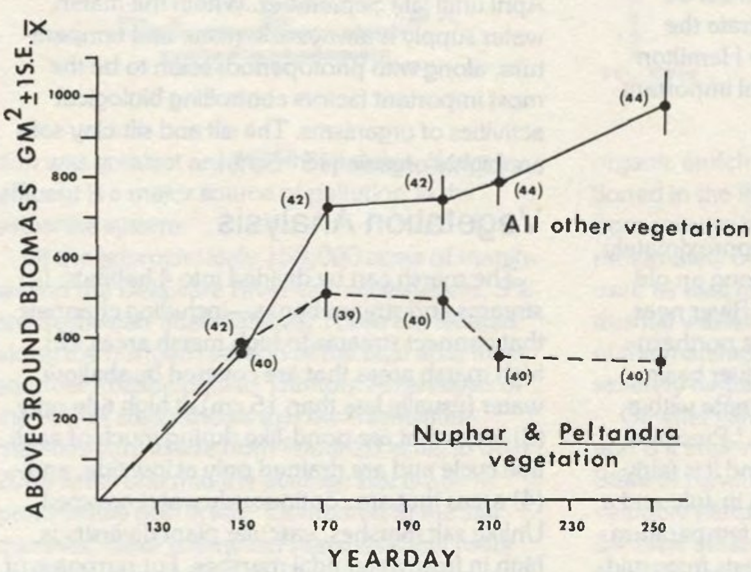

FIG. 20-3. Aboveground primary production for all study sites. As described in the text, data were divided into two categories: (1) vegetation types dominated by *Nuphar advena* and *Peltandra virginica*, (2) all other vegetation types. Numbers in parentheses represent sample size. ($g/m^2 \times 10^{-2}$ = t/ha)

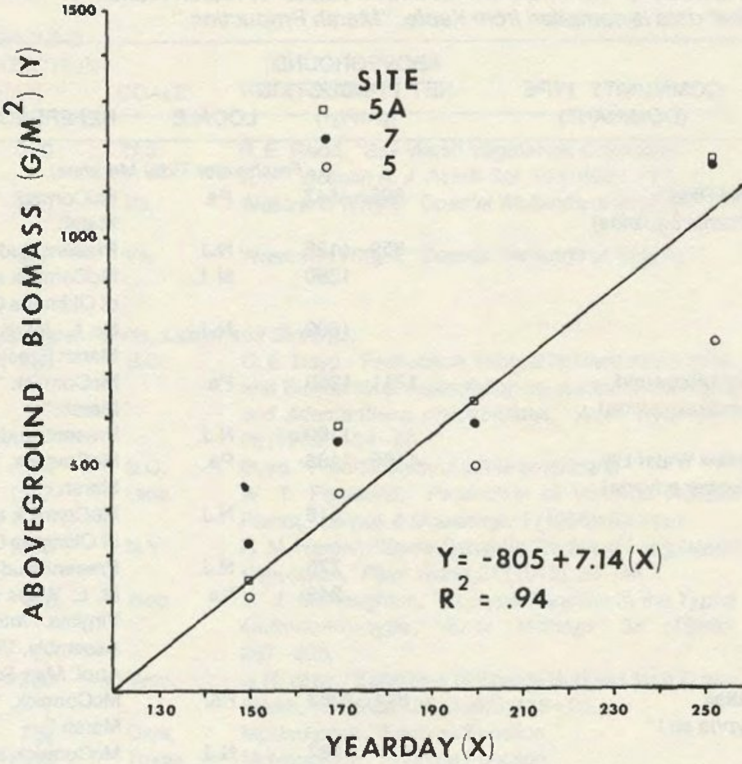

FIG. 20-4. Aboveground primary production of mixed vegetation, primarily bur marigold *(Bidens laevis)*. ($g/m^2 \times 10^{-2}$ = t/ha)

0.25 m^2 quadrats. On each sampling date, three quadrats were harvested from each study site. Fig. 20-3 is a composite of our productivity data for the entire marsh. The data have been separated into two categories: (1) sites dominated by arrow arum *(Peltandra virginica)* and/or yellow water lily *(Nuphar advena)*, and (2) all other sites. This separation was necessary because of bimodal patterns of production for both arrow arum and yellow water lily. Both species assumed aspect dominance throughout the marsh during the early part of the growing season. As other species became dominant, both species began a widespread dieback as seen in Fig. 20-3. We estimate overall aboveground net primary production at 9.5 t/ha/yr (Table 20-1). Production values for the dominant community types varied from 6.5 t/ha/yr for arrow arum dominated communities to 21.0 t/ha/yr areas dominated by spiked loosestrife. Cattail and giant ragweed dominated stands were also highly productive. The mixed vegetation type was most expansive and averaged 9.1 t/ha/yr. Fig. 20-4 shows seasonal changes at one of the high marsh sites dominated by bur marigold. There was a linear increase in aboveground biomass throughout the growing season and we estimated that a total of 1246.7 tons of biomass were produced during the growing season. That value was approximately 50% of our estimated total aboveground net primary production for the entire marsh. We have completed preliminary analysis of the vegetation for total nitrogen content using a modified Kjeldahl technique.[8] Average nitrogen content for the species in the mixed vegetation type is 2.49%. The value falls well within reported data for plants from other marsh ecosystems.[9] We estimate total nitrogen uptake within that vegetation type at 32 tons.

TABLE 20-2. *Summary of Production Values for Marsh Plants. Most data is compiled from Keefe, "Marsh Production."*

COMMUNITY TYPE (DOMINANT)	ABOVEGROUND NET PRODUCTION ($g/m^2/yr$)	LOCALE	REFERENCE
	(I - *Freshwater Tidal Marshes)*		
Wild Rice (*Zizania aquatica)*	605–1547	Pa.	McCormick, "The Natural Features of Tinicum Marsh."
	659–1125	N.J.	Present study
	1390	N.J.	McCormick and Ashbaugh, "Vegetation of a Section of Oldmans Creek Marsh."
	1699	N.J.	R. A. Jervis, "Primary Production in a Freshwater Marsh Ecosystem," thesis, Rutgers University, 1964.
Giant Ragweed (*Ambrosia trifida)*	1211–1250	Pa.	McCormick, "The Natural Features of Tinicum Marsh."
	1160	N.J.	Present study
Yellow Water Lily (*Nuphar advena)*	1166–1188	Pa.	McCormick, "The Natural Features of Tinicum Marsh."
	516	N.J.	McCormick and Ashbaugh, "Vegetation of a Section of Oldmans Creek Marsh."
	775	N.J.	Present study
	245	Va.	M. L. Wass and T. D. Wright, "Coastal Wetlands of Virginia," Interim report to the Governor and General Assembly, Virginia Inst. of Marine Sci., Spec. Rept. in *Appl. Mar. Sci. and Ocean Eng.* 10 (1969).
Cattail (*Typha* sp.)	874–2063	Pa.	McCormick, "The Natural Features of Tinicum Marsh."
	987	N.J.	McCormick and Ashbaugh, "Vegetation of a Section of Oldmans Creek Marsh."
	1119–1528	N.J.	Present study
	930	Va.	Wass and Wright, "*Coastal Wetlands of Virginia.*"
	1905	N.J.	Jervis, "Primary Production in a Marsh Ecosystem."
Mixed (*Bidens laevis)*	516– 897	Pa.	McCormick, "The Natural Features of Tinicum Marsh."
	756–1162	N.J.	Present study
Primrose Willow (*Jussiaea repens)*	403– 583	Pa.	McCormick, "The Natural Features of Tinicum Marsh."
Arrowhead (*Saggitaria* sp.)	628	Pa.	McCormick, "The Natural Features of Tinicum Marsh."
Arrow arum (*Peltandra virginica)*	269	Pa.	McCormick, "The Natural Features of Tinicum Marsh."
	500– 800	N.J.	Present study
Sweet Flag (*Acorus calamus)*	712– 940	N.J.	Present study
Loosestrife (*Lythrum salicaria)*	1749	Pa.	McCormick, "The Natural Features of Tinicum Marsh."
	2104	N.J.	Present study
Waterhemp (*Acnida cannabina)*	762	Pa.	McCormick, "The Natural Vegetation of Tinicum Marsh."
	(II - *Salt Marshes between New York and Va.*)		
Saltwater Cordgrass (*Spartina alterniflora)*	1332	Va.	Wass and Wright, "*Coastal Wetlands of Virginia.*"
	445	Del.	M. H. Morgan, "Annual Angiosperm Production on a Salt Marsh," thesis, Univ. Delaware, 1961

TABLE 20-2. (cont.)

COMMUNITY TYPE (DOMINANT)	ABOVEGROUND NET PRODUCTION (g/m²/yr)	LOCALE	REFERENCE
	300	N.J.	R. E. Good, "Salt Marsh Vegetation, Cape May, N. J.," *Bulletin N. J. Acad. Sci.* 10 (1965): 1-11.
Salt-meadow Grass (*Spartina patens*)	805	Va.	Wass and Wright, "*Coastal Wetlands of Virginia.*"
Spike Grass (*Fimbristylis* sp.)	360	Va.	Wass and Wright, "*Coastal Wetlands of Virginia.*"
(III - *Freshwater Ponds, Lakes, and Streams*)			
Bulrush (*Scirpus americanus*)	150	S.C.	C. E. Boyd, "Production, Mineral Nutrient Absorption, and Biochemical Assimilation by *Justicia americana and Alternanthera philoxeroides*, *Arch. Hydrobiol.* 66 (1969): 139–60
Cattail (*Typha latifolia*)	684	S.C.	Boyd. "Production by *Justicia americana*."
	1527	Okla.	W. T. Penfound, "Production of Vascular Aquatic Plants," *Limnol. & Oceanogr.* 1 (1956): 92–101.
	1358	N.Y.	R. M. Harper, "Some Dynamic Studies of Long Island Vegetation," *Plant World* 21 (1918): 33–46.
Typha glauca	416	Neb.	S. J. McNaughton, "Ecotype Function in the *Typha* Community-type," *Ecol. Monogr.* 36 (1966): 297–325.
	1360	Minn.	J. R. Bray, "Estimates of Energy Budgets for a *Typha* Marsh," Science 136 (1962): 119–20.
Typha sp.	730	Okla.	McNaughton, "Ecotype Function."
	1336	Texas	McNaughton, "Ecotype Function."
Sedges (*Carex* sp.)	1340	N.J.	Jervis, "Primary Production in a Marsh Ecosystem."
Rice Cutgrass (*Leersia oryzoides*)	1545	Va.	Wass and Wright, "*Coastal Wetlands of Virginia.*"
Water Hyacinth	1276	La.	Penfound. "Production of Vascular Aquatic Plants".
(*Eichhornia crassipes*)	1478	La.	W. T. Penfound and T. T. Earle, "The Biology of the Water Hyacinths," *Ecol. Monogr.* 18 (1948): 447–72.
Water-willow (*Justicia americana*)	640	Ala.	Boyd, "Production by *Justicia americana.*"
Alligator-weed (*Alternanthera philoxeroides*)	841	Ala.	Boyd, "Production by *Justicia americana.*"

Table 20-2 compares data for salt marshes, freshwater tidal marshes, and other freshwater marshlands. With the exception of the freshwater tidal marsh data, most of the data has been taken from C. W. Keefe's summary of marsh production.[10] It is apparent that there is much variability in the data and that it is difficult to determine which habitat supports the highest overall primary production. In two closely related studies, biomass accumulation was observed in two freshwater tidal marshes along the Delaware River.[11] For similar vegetation types, production values are comparable. It is obvious that freshwater tidal marshes are highly productive and that they are as productive as estuarine salt marshes. Production values for salt marshes between Virginia and New York ranged from 300–1331 $g/m^2/yr$. The reported range of aboveground production for nontidal marshes is approximately 150–2000 $g/m^2/yr$.

Soil Algae

Studies are currently assessing the role edaphic algae play in the Hamilton Marshes. Working with the top two centimeters of marsh soil, we have estimated soil algal standing crop using chlorophyll extraction techniques outlined by H. L. Golterman and modified for our system.[12] Fig. 20-5 summarizes our findings for chlorophyll *a* and its degradation production phaeophytin. Mean chlorophyll *a* levels in the top two centimeters of soil show definite seasonal patterns and range from a high of 6.29 μg/top 2 cm^3 in early summer to a low of 1.96 μg/top 2 cm^3 in mid fall. These values are considerably lower than those reported for estuarine mudflats.[13] Mean phaeophytin values always exceed chlorophyll *a* reaching a maximum of 16.29 μg/top 2 cm^3 in early fall.

Soil algal standing crop appears to be influenced by the dominant vascular plant communities in the marsh. Areas dominated by yellow water lily consistently have chlorophyll *a* levels greater than mean values while high marsh areas dominated by mixed vegetation (bur marigold and others) have chlorophyll *a* values below the mean. This relationship appears to be a function of differences in soils in the marsh. Silty sand soils of low organic content (about 15%) found in the yellow water lily areas provide the best substrate for algal growth, and silty clay soils of high organic content (25–50%) found in the mixed vegetation and cattail communities provide the poorest substrate. Shading by the higher plants also influences algal standing crops with the highest values occurring in the spring and early summer while the vascular plants are still relatively small. As the higher plants grow, chlorophyll *a* values decline and phaeophytin levels rise correspondingly.

Peak algal biomass for the marsh, estimated from chlorophyll *a* values using Wetzel's factor of 60 for conversion of chlorophyll *a* to organic matter in nonnutrient limiting environments, was 37.7 kg/ha, which was two to three orders of magnitude less than the peak biomass of the vascular plants.[14] Nevertheless the edaphic algae cannot be overlooked, since they are the only functioning producers in the marsh for almost eight months of the year. Furthermore, it has been found that soil algae may contribute up to 25% of the total annual production in Delaware River salt marshes with a substantial part of this production coming during the winter and spring when the vascular plants are dormant.[15]

Water Quality

Surface water quality is being examined at eleven sites (Fig. 20-1) located on Crosswicks Creek and the major side channels in the marsh with emphasis on chemical species known to reflect metabolic processes in aquatic environments. Water is collected at morning high slack water (hsw) and afternoon low slack water (lsw) biweekly in the summer and at monthly intervals otherwise. All samples are analyzed for dissolved oxygen (azide modification[16]), carbon dioxide,[17] nitrogen (reactive nitrate, reactive nitrite, and ammonia plus amino acids[18]), and reactive phosphate.[19] Based on water quality differences, the marsh may be conveniently subdivided into three regions, the main channel of Cosswicks Creek, side channels draining the high marsh, and pond-like areas. Selected sites from each of these subdivisions will be discussed separately.

The major unnatural perturbation of the surface waters in the Hamilton Marshes is the Hamilton Sewage Treatment Plant, which releases 7 million gallons of secondarily treated effluent into Crosswicks Creek daily. This impact is noticed in the main channel of Crosswicks Creek at hsw at Site 7 above the effluent release point and at Sites 1, 2, and 6 downstream from the release point at lsw. Water quality at Site 2

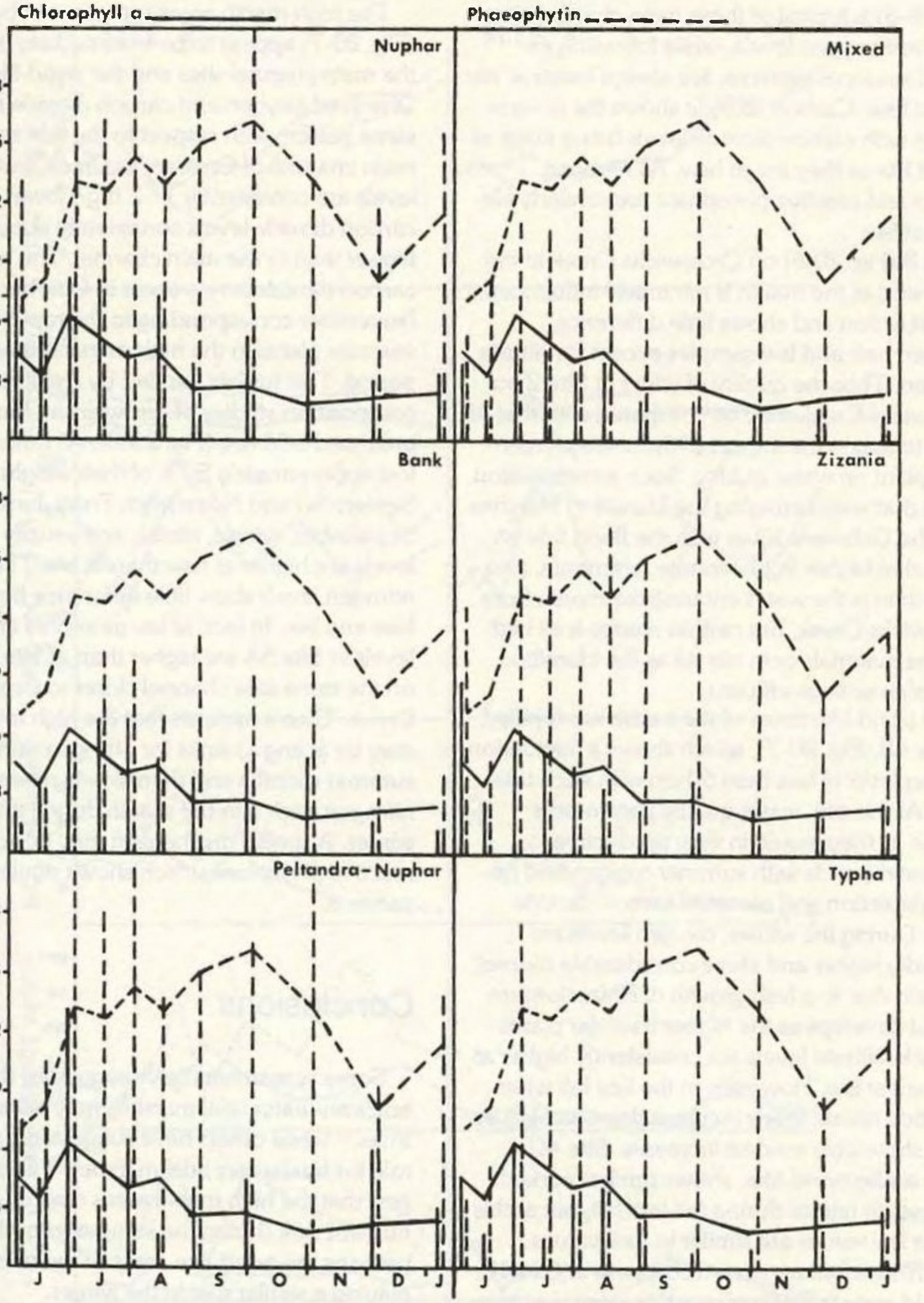

FIG. 20-5. Changes in chlorophyll a and phaeophytin concentrations in the top two centimeters of the marsh soil from June 1974 through January 1975. Vertical lines represent values for each dominant vegetation type sampled. Horizontal lines give mean chlorophyll *a* and phaeophytin values for the entire marsh. In each case, solid lines represent chlorophyll a and dashed lines represent phaeophytin.

(Fig. 20-6) is typical of these main channel sites. Dissolved oxygen levels, while following expected seasonal patterns, are always lower at lsw than at hsw. Carbon dioxide shows the reverse pattern with carbon dioxide levels being twice as high at lsw as they are at hsw. All nitrogen species and reactive phosphate are similarly elevated at lsw.

Site 8 (Fig. 20-6) on Crosswicks Creek at the upper end of the marsh is minimally influenced by tidal action and shows little difference between hsw and lsw samples except for nitrate nitrogen. Thus the quality of water at Site 2 on Crosswicks Creek may be compared with that of Site 8 to assess the impact of the sewage treatment plant on water quality. Such a comparison shows that water entering the Hamilton Marshes from the Delaware River with the flood tide is somewhat higher in phosphate, ammonia, and nitrite than is the water entering the marsh from Crosswicks Creek, but neither source is as high in these materials or in nitrate as the Hamilton Township sewage effluent.

The pond-like areas of the marsh are typified by Site 4B (Fig. 20-7), which shows a fluctuation in water level of less than 50 cm with each tide cycle. At this site, water quality parameters behave as they would in very productive freshwater ponds with summer oxygen and nutrient depletion and elevated carbon dioxide levels. During the winter, oxygen levels are markedly higher and show considerable diurnal variation due to a lush growth of *Rhizoclonium* sp. that develops as the higher vascular plants die back. Nitrate levels are consistently higher at hsw than at lsw. However, in the late fall when flood tide nitrate levels increase dramatically, lsw levels show only modest increases. Site 4C, which is also pond-like, shows similar marked increases in nitrate during the late fall, but at this site the lsw values are similar to hsw values. Since *Rhizoclonium* does not appear at Site 4C, it would appear that perhaps this algae is acting as a sink for nitrate during the winter months. Unlike nitrate, phosphate levels never exceed 5 μg/l and show no tidal influence at Site 4B.

The high marsh areas represented by Site 5A (Fig. 20-7) appear to be intermediate between the main channel sites and the pond-like sites. Dissolved oxygen and carbon dioxide show the same pattern with respect to the tide as in the main channel of Crosswicks Creek, but oxygen levels are consistently 1–2 mg/l lower and carbon dioxide levels consistently about 10 mg/l higher than in the main channel. The highest carbon dioxide levels occur in October and November corresponding to the rapid dieback of vascular plants in the high marsh during this period. This further verified by results of litter decomposition studies of arrow arum, bur marigold, and wild rice (Fig. 20-8). All three species lost approximately 50% of their weight between September and November. From June through September, nitrate, nitrite, and usually ammonia levels are higher at hsw than at lsw. The fall nitrogen levels show little difference between hsw and lsw. In fact, at lsw ammonia and nitrate levels at Site 5A are higher than at Site 5 located on the same side channel closer to Crosswicks Creek. Thus it appears that the high marsh areas may be acting as sinks for nitrogen during the summer months and then slowly releasing this nitrogen back into the marsh during the fall and winter. A similar mechanism may be acting for reactive phosphate which shows similar seasonal patterns.

Conclusions

Some researchers have suggested that brackish-water tidal marshes may act as nutrient sinks,[20] while others have suggested a similar role for freshwater tidal marshes.[21] Our data suggest that the high marsh areas may be acting as a nutrient sink during the summer months and that perhaps the pond-like areas of the marsh may be playing a similar role in the winter.

Salt marsh plots fertilized with sewage sludge have been shown to retain substantial amounts of the applied nutrients and thus may be poten-

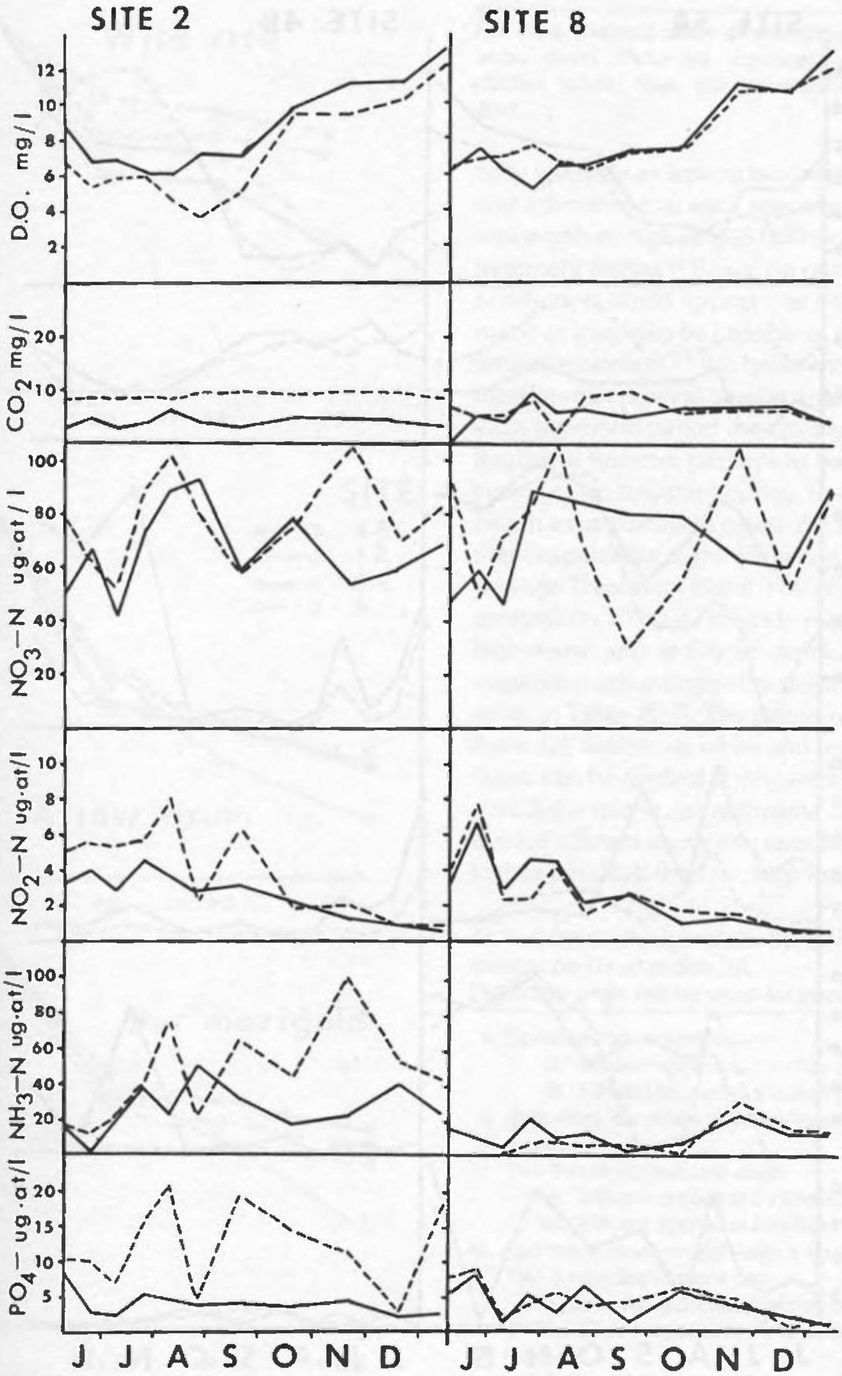

FIG. 20-6. Changes in water quality parameters at Sites 2 and 8 on Crosswicks Creek between June 1974 and January 1975. Solid lines represent high slack water (hsw) and dashed lines low slack water (lsw).

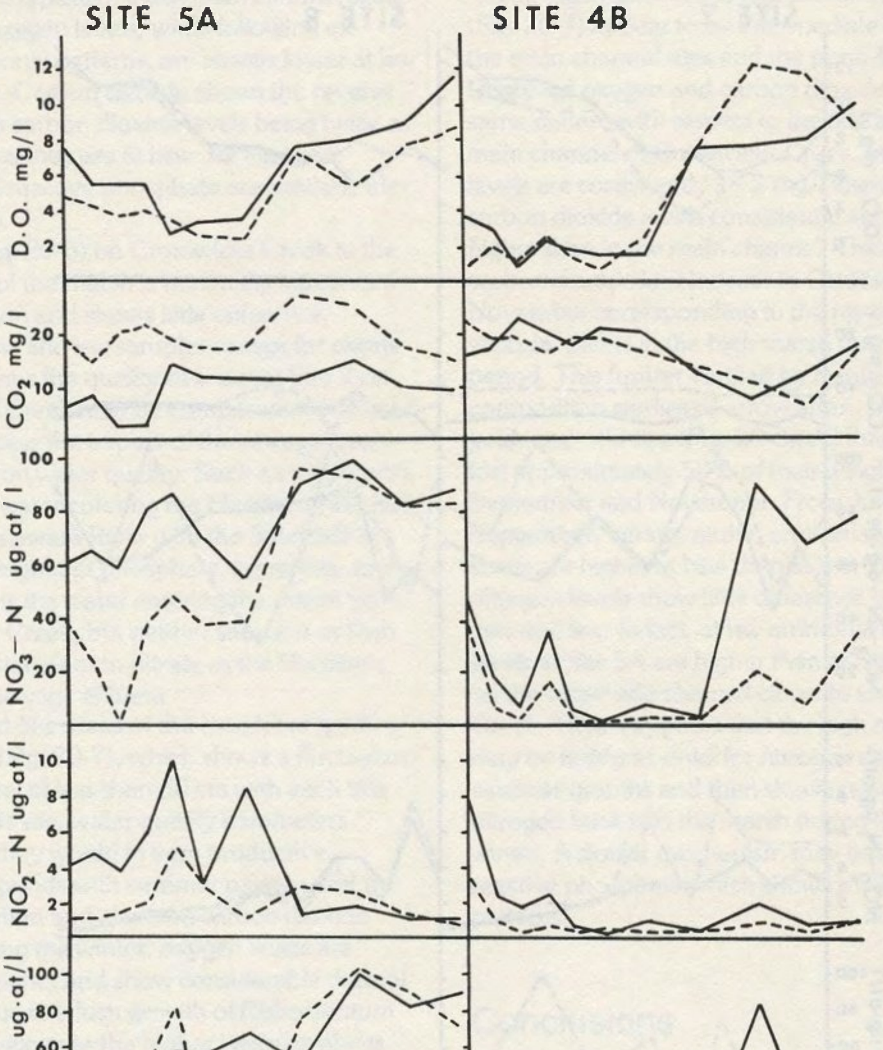

FIG. 20-7. Changes in selected water quality parameters at Sites 4B (pond-like area) and 5A (high marsh area) between June 1974 and January 1975. Solid lines represent high slack water (hsw) and dashed lines low slack water (lsw).

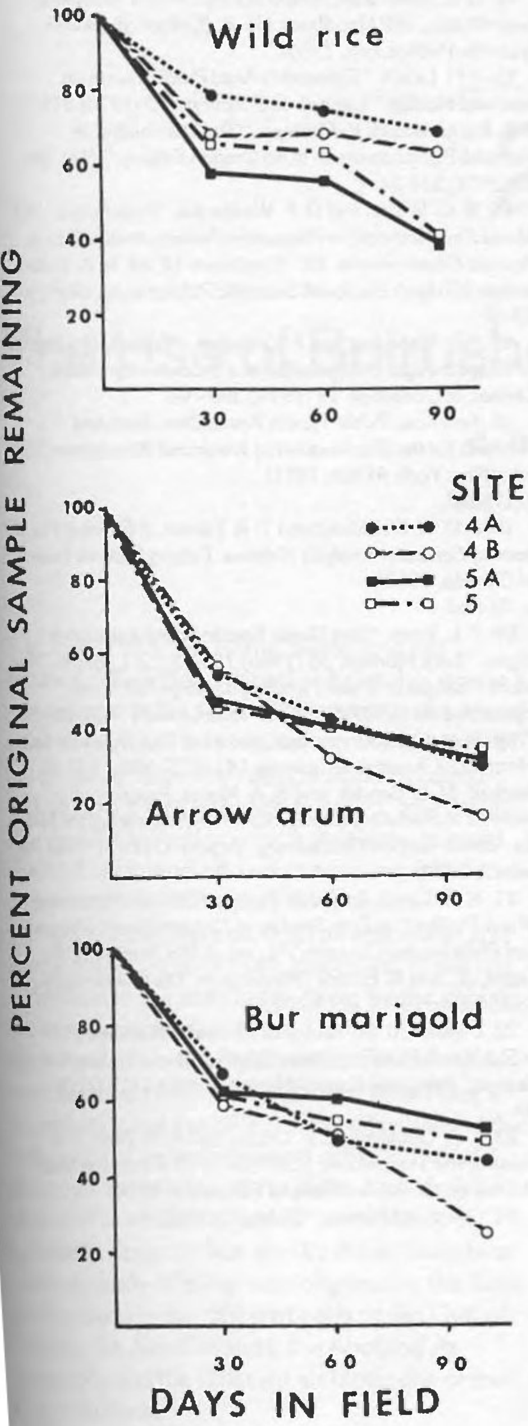

FIG. 20-8. Decomposition of wild rice *(Zizania aquatica)*, arrow arum *(Peltandra virginica)*, and bur marigold *(Bidens laevis)* litter. Site locations are shown on Fig. 20-1.

tially valuable as tertiary treatment systems.[22] It was estimated that each acre of salt marsh was worth as high as $83,000 as a tertiary treatment facility.[23] Based on our data, and that of others, it would appear that freshwater tidal marshes may also be capable of performing tertiary treatment.[24] We believe that, these tidal marshes can process greater amounts of effluent each treatment period than many biological treatment systems, perhaps as much as 2–5 inches of wastewater per day. In April 1975 we began experiments to assess the tertiary treatment capabilities of the Hamilton Township Sewage Treatment Plant. The effluent was sprayed on 10 by 20 m study plots located in a high marsh area at Site 5A dominated by mixed vegetation according to the treatment regime given in Table 20-3. The results of this experiment will determine when and how much effluent can be applied during each treatment period. If the marsh can assimilate secondarily treated effluent at our low treatment level (2 inches per day), then the high marsh areas

TABLE 20-3. *Design of the Spray Irrigation Experiment to be Used at Site 5A. Duplicate plots will be used for each experiment.*

I. Sprinklers on continuously:
   - IA. Effluent applied at 2 inches per day.
   - IB. Effluent applied at 5 inches per day.

II. Sprinklers on when tidal water is not on the high marsh. Two 9-hour applications daily:
   - IIA. Effluent applied at 2 inches per day.
   - IIB. Effluent applied at 5 inches per day.

III. Sprinklers on when tidal water is on the high marsh. Two 3-hour applications daily:
   - IIIA. Effluent applied at 2 inches per day.
   - IIIB. Effluent applied at 5 inches per day.

IV. Controls:
   - IVA. Sprinklers on continuously. Tap water applied at a rate of 5 inches per day.
   - IVB. No application of tap water or effluent.

dominated by mixed vegetation should be able to process over 18 million gallons of effluent per day, about two and a half times the current daily flow from the Hamilton plant into Crosswicks Creek.

Notes

1. Financial support for our work has been provided by the Hamilton Township Environmental Commission, the National Geographic Society, Sigma Xi, and a Rider College Grant-in-Aid. We thank Jerry Herrera, Dick Klockner, Haig Kasabach, Earl Wood, and other Hamilton Township officials and personnel for assisting us in countless ways during this study. Thanks also go to our wives and our students.

2. D. Whigham, "Preliminary Ecological Studies of the Hamilton Marshes" (mimeographed progress report, 1974).

3. D. C. Sweet, *The Economic and Social Importance of Estuaries* (Washington, D.C.: Environmental Protection Agency, Water Quality Office, 1971).

4. T. E. Walton III and R. Patrick, "Delaware River Estuarine marsh survey," in *Delaware Estuary System: Environmental Impacts and Socio-economic Effects,* a report prepared for the National Science Foundation (RANN), (Philadelphia: Academy of Natural Sciences, 1973).

5. *Ibid.*

6. *Ibid.*

7. H. Walter and H. Lieth, *Klimadiagram—Weltatlas,* VEB (Jena: Gustav Fischer Verlag, 1967).

8. American Society of Agronomy, Inc. *Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties.* (Madison, Wisc: American Society of Agronomy, 1965).

9. C. W. Keefe, "Marsh Production: A Summary of the Literature," *Contributions to Marine Science* 16 (1972):163-81.

10. *Ibid.*

11. J. McCormick, "The Natural Features of Tinicum Marsh, with Particular Emphasis on the Vegetation," In *Two Studies of Tinicum Marsh, Delaware and Philadelphia Counties, Pa.,* ed. J. McCormick, R. R. Grant, Jr., and R. Patrick (Washington: The Conservation Foundation, 1970); J. McCormick and T. Ashbaugh, "Vegetation of a Section of Oldmans Creek Tidal Marsh and Related Areas in Salem and Gloucester Counties, New Jersey," *Bulletin of New Jersey Academic Sciences* 17 (1972):31-37.

12. H. L. Golterman, *Methods for Chemical Analysis of Fresh Waters,* IBP Handbook No. 8, (Oxford: Blackwell Scientific Publications, 1969).

13. J. H. Leach, "Epibenthic Algal Production in an Intertidal Mudflat," *Limnol. & Oceanogr.* 15 (1970):514-21; R. Z. Riznyk and H. K. Phinney, "The Distribution of Intertidal Phytopsammon in an Oregon Estuary," *Mar. Biol.* 13 (1972):318-24.

14. R. G. Wetzel and D. F. Westlanke, "Periphyton," in *A Manual on Methods for Measuring Primary Productivity in Aquatic Environments.* IBP Handbook 12, ed. R. A. Vollenweider (Oxford: Blackwell Scientific Publications, 1969), pp. 33-40.

15. J. L. Gallagher and F. C. Daiber, "Primary Production of Edaphic Algal Communities in a Delaware Salt Marsh," *Limnol. & Oceanogr.* 19 (1974):390–95.

16. American Public Health Association, *Standard Methods for the Examination of Water and Wastewater,* 13th ed., (New York: APHA, 1971).

17. *Ibid.*

18. J. D. H. Strickland and T. R. Parson, *A Practical Handbook of Seawater Analysis* (Ottawa: Fishing Reserve Board of Canada, 1968).

19. *Ibid.*

20. J. L. Blum, "Salt Marsh Spartinas and Associated Algae," *Ecol. Monogr.* 38 (1968):199-221; J. L. Blum, "Nutrient Changes in Water Flooding the High Salt Marsh," *Hydrobiol.* 34 (1969):95-99; D. Aurand and F. C. Daiber, "Nitrate and Nitrite in Surface Waters of Two Delaware Salt Marshes," *Chesapeake Science* 14 (1973):105-11; D. M. Axelrad, M. E. Bender, and K. A. Moore, *Function of Marshes in Reducing Eutrophication of Estuaries of the Middle Atlantic Region* (Blacksburg, Virginia: Office of Water Research, 1974).

21. R. R. Grant, Jr. and R. Patrick, "Tinicum Marsh as a Water Purifier," in *Two Studies of Tinicum Marsh, Delaware and Philadelphia Counties, Pa.,* ed. J. McCormick, R. R. Grant, Jr., and R. Patrick (Washington: The Conservation Foundation, 1970), pp. 105-23.

22. I. Valiela, J. M. Teal, and W. Sass, "Nutrient Retention in Salt Marsh Plots Experimentally Fertilized with Sewage Sludge," *Estuarine Coastal Marine Science* 1 (1973):261-69.

23. J. G. Gosselink, E. P. Odum, and R. M. Pope, *The Value of the Tidal Marsh,* LSU-SG-74-03 (Louisiana State University: Center for Wetland Resources, 1974).

24. Grant and Patrick, "Tinicum Marsh."