Wetlands Ecology and Management vol. 1 no. 4 pp. 211-222 (1992)
SPB Academic Publishing bv, The Hague

Nutrient and Hydrologic Budgets of a Great Lakes Coastal Freshwater Wetland during a Drought Year*

William J. Mitsch and Brian C. Reeder**
School of Natural Resources and Environmental Biology Program, The Ohio State University, Columbus, OH 43210 U.S.A.

Keywords: freshwater marsh, freshwater wetland, Great Lakes, hydrology, phosphorus, water quality

Abstract

A coastal wetland along Lake Erie (Ohio, U.S.A.) was studied to determine hydrologic and phosphorus budgets and spatial and temporal variation of phosphorus and related chemical parameters. The wetland was influenced by changing Lake Erie water levels, seiches, shifting shoreline sediments, and watershed inflow during a year of severe drought. The water budget for a 7-month period (March - September, 1988) had average inflow of 15 200 $m^3 day^{-1}$ from the watershed and 3.5 $m^3 day^{-1}$ from Lake Erie. The wetland increased in volume by 700 $m^3 day^{-1}$ despite a drought that resulted in 80% more evapotranspiration than rainfall as a barrier beach isolated the wetland from Lake Erie for 77% of the study period. Conductivity decreased by 34% as water flowed through the wetland and turbidity and total suspended solids were variable and statistically similar at inflow and outflow. Average total phosphorus concentrations in the inflow and outflow were also similar (247 and 248 $\mu g\ P\ l^{-1}$ respectively) although total soluble phosphorus and soluble reactive phosphorus decreased significantly (α=0.05) from inflow to outflow (averages 94 to 45 $\mu g\ P\ l^{-1}$ and 7.5 to 4.0 $\mu g\ P\ l^{-1}$ respectively). Nutrient budgets from field data estimate a retention of 36% of the phosphorus, presumably in the sediments (0.8 mg P $m^{-2} day^{-1}$). A general nutrient retention model, an estimated deposition rate from a sediment core and a simulation model predicted higher mass retention of phosphorus but similar percentage retention.

Sommaire

Un marécage qui côtoie le lac Erie (USA) a servi de site expérimental pour en déterminer les budgets d'eau et de phosphore, de même que pour la variation spatiale et temporelle du phosphore et d'autres facteurs chimiques. Le marécage a été influencé par: niveaux d'eau qui changeaient; seiches; sédiments mouvants du littoral; et afflux de la ligne de partage des eaux dans une année de grande sécheresse. Le budget d'eau dans une période de 7 mois (mars-septembre 1988) montre un afflux de 15 200 $m^3 jour^{-1}$ de la ligne de partage, et 3.5 $m^3 jour^{-1}$ du lac Erie. Le volume du marécage a augmenté par 700 $m^3 jour^{-1}$ malgré une sécheresse qui a produit plus d'évapotranspiration (80%) que de pluie pendant qu'une plage-obstacle a isolé le marécage du lac Erie pendant 77% de la période d'observation. La conductivité a diminué par 34% pendant que l'eau coulait, et la turbidité et les TSS ont varié, tout en démontrant des statistiques similaires à l'afflux et au déversement. Les moyennes pour les concentrations du total du phosphore à l'afflux et au déversement ont été similaires (247 and 248 $\mu g\ P\ l^{-1}$), quoique le TSP et le SRP ont diminué (α=0.05) de l'afflux au déversement (donnant des moyennes de 94 à 45 $\mu g\ P\ l^{-1}$ et de 7.5 à 4.0 μg

* From a paper presented at the Third International Wetlands Conference, 19-23 September, 1988, University of Rennes, France
** Present address Department of Biological and Environmental Science, Morehead State University, Morehead, Kentucky, 40351 U.S.A

P l^{-1}). Les budgets de substances nutritives pour les données suggèrent une rétention de 36% du phosphore, évidemment dans les sédiments (0.8 mg P m^{-2} $jour^{-1}$). Un modèle pour la rétention des nutrients, un taux de déposition, estimé par un noyau de sédiments, et une simulation avaient prédit un plus grand taux de rétention de phosphore, mais un pourcentage similaire pour la rétention.

Introduction

Wetlands have always been a part of the shoreline of the Laurentian Great Lakes, expanding and retreating with changing water levels, yet always maintaining themselves as ecotones between the uplands and the lakes. As shorelines were stabilized and the land was drained for agriculture and urban development, these wetlands were destroyed or significantly altered and their buffering capacity was diminished or lost altogether. Herdendorf (1987) estimated that over 4000 km^2 of coastal marshes and swamps in the western Lake Erie basin have been cleared and drained. Most of the remaining 150 km^2 have been artificially diked, blocking access to Lake Erie. It could be surmised that had the surrounding wetlands remained intact, the rate of cultural eutrophication of some of the lakes such as Lake Erie may have been much less severe.

The goal of our research was to use an ecosystem approach to study a western Lake Erie coastal wetland (Ohio, U.S.A.) and determine whether this system was serving as a chemical and hydrologic buffer between the upland and Lake Erie. This study has added interest because there was a major drought throughout the Midwest during this period; few studies have examined the role of wetlands in the landscape during drought conditions. Figure 1 illustrates an overall conceptual phosphorus model used to guide field research in our study wetland. Plant uptake by both plankton and macrophytes, sedimentation, and resuspension were recognized as the most significant intrasystem processes involved in wetland retention and release of phosphorus.

Previous Studies

Few if any comprehensive studies of nutrient cycling and hydrology have been carried out on Great Lakes coastal wetlands, especially on wetland functioning of these ecosystems. This is particularly apparent when compared with the abundant literature available on oceanic coastal salt marshes. Heath (1987) found a significant seasonal reduction in the concentration of total phosphorus from inflow to outflow of our Lake Erie study wetland and noted that during the growing season bioavailable phosphorus decreased as water moved towards the outflow. He suggested that phosphorus uptake was dependent on planktonic activity, not on sediment absorption-desorption kinetics. Based on the nutrient availability, laboratory bioassay results, and the lack of phosphomonoester production, he concluded that plankton were not phosphorus limited. Klarer and Millie (1989) suggested that the wetland's physical structure is conducive to regulating the amount of phosphorus exported to the lake. They found that most of the sediments remained in the marsh and were not exported

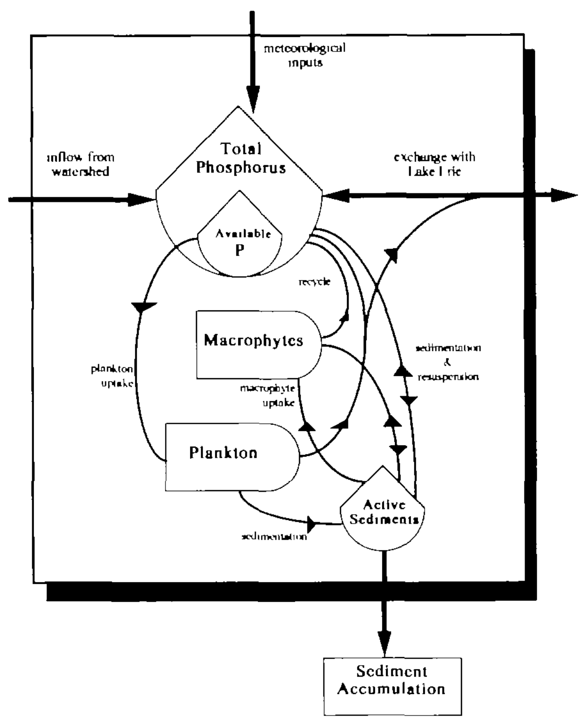


Figure 1. Conceptual model of phosphorus cycling and exchange in Lake Erie coastal wetland.

to the lake even after strong storm events. Up to 80% of the storm water nutrients were retained in the marsh. Both Heath (1987) and Klarer and Millie (1989) lacked critical data on flow rates necessary to calculate mass balances. Recent summaries of many of the aspects of Lake Erie wetlands, including studies of the general area of our study site, are given by Herdendorf (1987) and Mitsch (1989). A comparison of the chemical composition of waters in diked and undiked wetlands along Lake Erie's coastline in Ohio is presented by Robb and Mitsch (in press).

Wetlands of the Great Lakes

Coastal wetlands of the Great Lakes are different from oceanic coastal wetlands. Their hydrology is sometimes described as estuarine (Herdendorf 1987) and yet they are freshwater systems with little or no change in salinity from uplands to the lakes. Characteristics that make them unique ecological systems to study and manage include: 1) water level fluctuations of the Great Lakes, which vary both seasonally and annually; 2) periodic seiches or "wind tides", which may occur many times a season; 3) shifting shoreline sediments, moved during storm events, which can dramatically change the hydrologic, chemical, and biological connections between the wetlands and lake; and 4) varying nutrient loading from the upstream watersheds. These characteristics have one thing in common — they greatly influence the exchange of geological and biological materials in the coastal wetlands from upstream watersheds and the adjacent lake.

Long-term water level fluctuations. Wetlands along the Great Lakes are influenced by water level fluctuations. Over a 125 year record (Fig. 2) there has been a difference of about 1.5 m between low and high water level in Lake Erie, with a record high in 1986. This amplitude and the time between high and low water levels are great enough (period approximately one decade) to affect significantly the structure and function of the coastal wetlands. In presettlement times, high water levels would send the wetlands "inland" while wetlands would extend "lakeward" during low water levels. The wetlands are usually in a state of disequilibrium with the fluctuating water level. A given location will vary from a system dominated by emergent vegetation (during shallow water) to one that is a planktonic or floating-leaved aquatic system (during high water). Fluctuating water levels of the Great Lakes have led to a common practice of marsh management through the construction of artificial dikes. Dikes are constructed around wetlands and pumps are used to maintain suitable water levels in the marshes. Water levels are usually kept low in spring to encourage the growth of various emergent plants and high in the fall to provide habitat for waterfowl.

Seiches. Shorter period water level oscillations due to seiches frequently occur on the Great Lakes. The coastal wetlands along the lakes are subject to water and chemical exchanges from seiches in much the same way that coastal salt marshes are subjected to tides, although these seiches are not as periodic. Sager *et al.* (1985) measured 269 seiche events with a mean amplitude of 19.3 cm and a mean period of 9.9 hours in one year on lower Green Bay on Lake Michigan. Seiches are a common occurrence along Lake Erie, although the contributions of these events to the nutrient budgets and biotic communities of undiked wetlands are not well known. Diked wetlands are generally isolated from seiche exchanges.

Shifting shoreline sediments. For most of the year, the general direction of flow in undiked wetlands is from the wetland to the lake, driven by the difference in elevation between the two bodies of water. Differences in elevation can vary with storm events and short-term lake fluctuations. When the mouth of the stream between the wetland and the lake is closed after a storm, a rather frequent event in our study site, the exchange is stopped or significantly diminished. The wetland then remains closed for several months, after which the combination of high water levels in the wetland and a sudden storm event often opens the wetland again.

Watershed influences. Many coastal wetlands are influenced by runoff from upstream watersheds which are often dominated by agricultural use. While the watersheds are generally small, runoff can be significant in the spring and after storms. The runoff often contains relatively high levels of nutrients from the farmlands (Klarer and Millie 1989). Estimates of

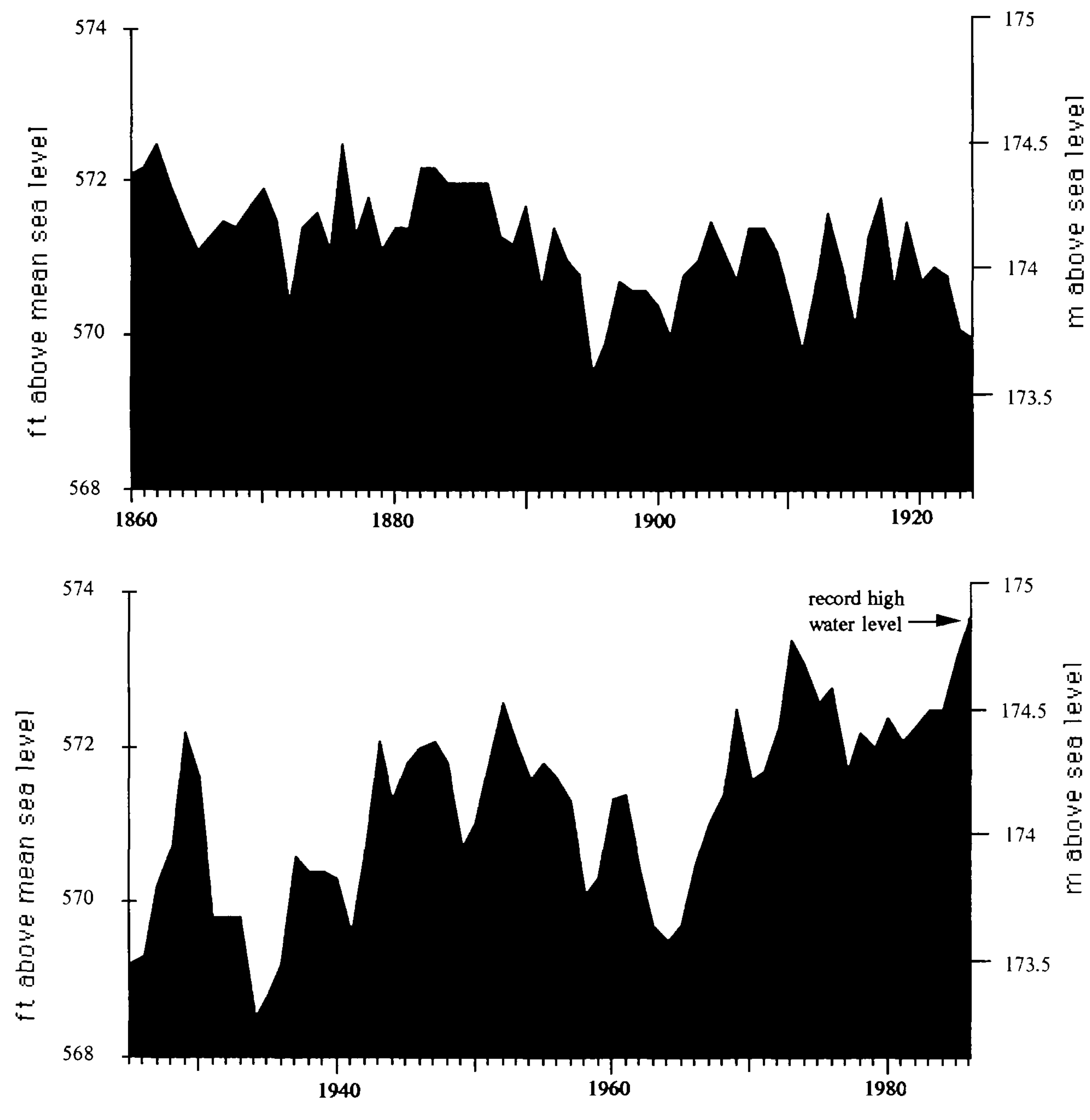


Figure 2. Average annual water level of Lake Erie from 1860 to 1986. Data are from station at Cleveland, Ohio.

nutrient loading from several watersheds in northwestern Ohio into Lake Erie basin are 0.5 to 2.5 kg P ha^{-1} yr^{-1} (Johnson *et al.* 1978, Novotny 1986). A study group of Great Lake's pollution called PLUARG (Pollution from Land Use Activities Reference Group) presents a range of 0.1 to 9.1 kg P ha^{-1} yr^{-1} for similar watersheds draining into Lake Erie (IJC 1980).

Methods

Study Area

Old Woman Creek State Nature Preserve and National Estuarine Research Reserve are part of a coastal wetland located adjacent to Lake Erie in Erie County, Ohio (Fig. 3). The wetland itself is 30 ha and extends about 1 km south of the Lake Erie shoreline (see Mitsch 1988, 1989; Mitsch *et al.* 1989; Klarer and Millie 1989 for site details). It is approximately 0.34 km wide at its widest point. Wetland depths may reach up to 3.6 m in the inlet stream channel but are usually less than 0.5 m. Klarer and Millie (1989) estimated that the retention time of the wetland varies between 24 hours (at peak flow) and 114 hours (at average flow). The wetland has an outlet to Lake Erie that is often open but which can be closed for extended periods by shifting sands forming a barrier beach. Rare but dramatic seiches on Lake Erie can reverse the flow, causing lake water to spill into the wetland. Kreiger (1985) and Klarer (1988) found lake plankton in Old Woman Creek wetland during high lake levels and, conversely, after prolonged heavy storm events, wetland plankton were exported to the lake. Aquatic habitats within the wetland include open water plankton systems and extensive embayment marshes with American lotus *(Nelumbo lutea)*. There are also areas with white water lilies *(Nymphaea tuberosa)*, spatterdock *(Nuphar advena)*, arrow arum *(Peltandra virginica)*, and cattails *(Typha angustifolia)*, and wooded wetlands in certain shallow areas. The major land use within the watershed (68.6 km^2) is agricultural. Sedimentation in the wetland was estimated to have been 0.76 mm yr^{-1} prior to agricultural development in the early 1800s and more than 10 times that (10 mm yr^{-1}) at present (Buchanan 1982). Due to its status as a National Estuarine Sanctuary, the marsh remains relatively undisturbed and is frequently used for nature education, recreation, and scientific study. Sanctuary facilities include a visitors' center and an aquatic ecology research laboratory.

Hydrology

Daily rainfall was recorded at Old Woman Creek using a National Oceanographic and Atmospheric Administration certified gauge. Daily inflows (near Station 10 on Fig. 3) and wetland levels (near the center of the marsh) were recorded by the United States Geologic Survey. Evapotranspiration (ET) was estimated from evaporation pan data measured at Old Woman Creek. On days when the pan was not functioning properly, values from pan evaporation data at Tiffin, Ohio, were used. Ken Krieger (pers. comm.) averaged the data to obtain monthly estimates. Daily evapotranspiration was determined by weighting the monthly averages by daily temperatures and multiplying the value by 0.7 to correct for the effects of the pan (Linsley and Franzini 1979). The condition of the barrier beach was recorded daily by Old Woman Creek staff. The volume of water in the marsh was determined by integrating the values obtained from a bathymetric survey conducted on 11 October 1988. Groundwater inflow was assumed to be insignificant.

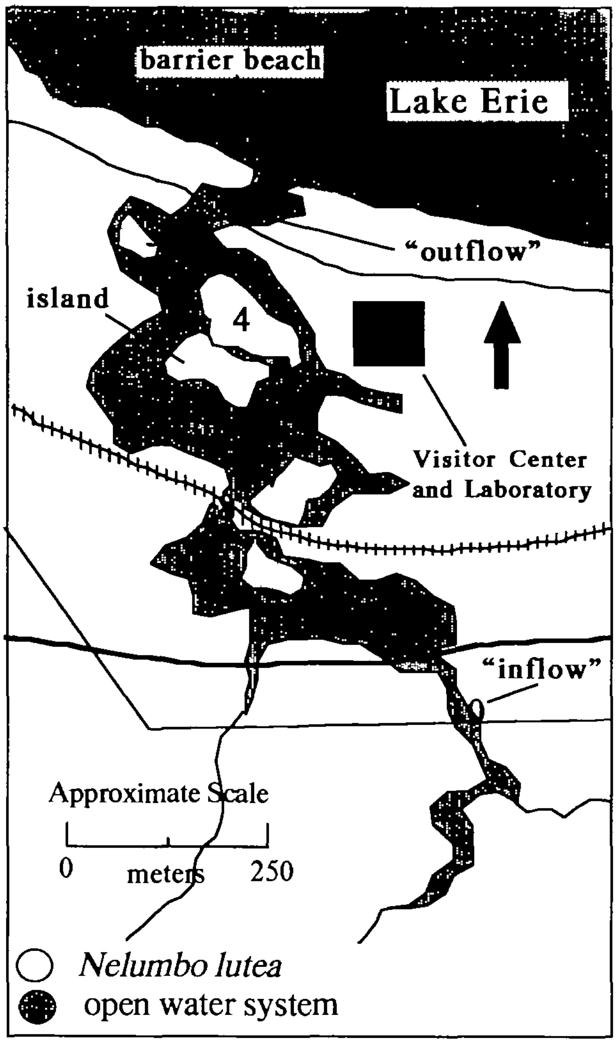


Figure 3. Old Woman Creek Wetland study site adjacent to Lake Erie in northern Ohio, U.S.A., with sampling stations (1-10) and macrophyte extent shown. Lines across wetlands are roads and a railroad.

Outflow (or inflow from Lake Erie) was determined using the following equation:

$$So = Si + P - ET - \Delta V / \Delta t$$

where,

So = surface outflow (+) or Lake Erie inflow (-)
Si = surface inflow
P = direct precipitation
ET = evapotranspiration
$\Delta V / \Delta t$ = daily increase in water level

Water chemistry

Water samples were taken at ten sites which included an upstream site that received little lake influence and a lakeshore water site (Fig. 3). Samples were taken monthly or biweekly in acid washed bottles. Within two hours of collection, 100 ml of each sample was filtered through a 0.45 μm membrane filter (soaked overnight in distilled water to remove any traces of contamination; APHA 1985). The filtered water was immediately placed in a freezer until analyzed. Samples were analyzed for all chemical species within 72 hours of collection.

Total suspended solids (TSS) were measured according to standard methods (APHA 1985). A 100 ml sample from each site and sample date was vacuum filtered through a dry, pre-weighed, 0.45 μm glass fiber filter. The filter and filtrant were dried for at least 24 hr at 104° C and then weighed. Turbidity of a 25 ml sample was measured with a Hach colorimeter (Hach Chemical Corporation 1984).

Bioavailability of phosphorus was determined by measurements of three phosphorus fractions following the guidelines of Logan *et al.* (1979) for Great Lakes tributaries. Soluble reactive phosphorus (SRP) was determined as molybdate reactive phosphorus (APHA 1985) which passed through a 0.45 μm membrane filter. Total phosphorus in unfiltered (TP) and filtered (TSP) water was determined as othophosphate released after digestion with ammonium persulfate (APHA 1985). Fifty ml of acidified sample was treated with 1 ml sulfuric acid solution and 0.4 g ammonium persulfate. This was autoclaved for 30 minutes at 98-137 kPa, cooled, neutralized to a faint pink phenolphthalein with 5 N sodium hydroxide then analyzed for orthophosphorus. Particulate phosphorus was considered the difference between TP and TSP.

The persulfate digestion method was checked against the more rigorous perchloric acid digestion (Sommers and Nelson 1972) for ten water samples from Old Woman Creek and nine samples from other western Lake Erie wetlands (samples courtesy of D. Robb, School of Natural Resources, The Ohio State University). Even with such a diverse array of samples, there was still less than 2% difference between the two methods.

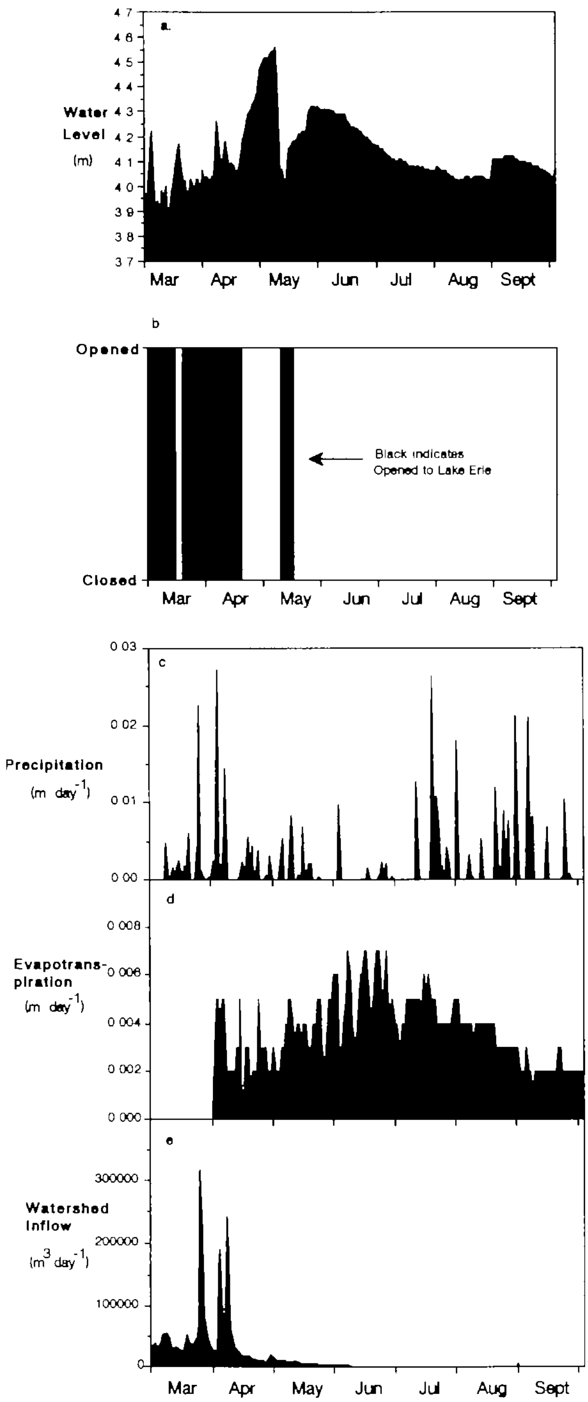
Nutrient budget

A nutrient budget was calculated using data on hydrology and water chemistry. Inflows and outflows of phosphorus were estimated from phosphorus concentrations measured at the inflow (Station 10) and outflow (Station 2) and from Lake Erie (Station 1). When the barrier beach was closed, we assumed that no phosphorus was being exchanged with the lake. Phosphorus cycling by plankton was calculated from metabolism measurements (Reeder and Mitsch 1989a) and from an assumed ratio of 0.001 g P $kcal^{-1}$ for plankton (Jørgensen and Johnsen 1981). To estimate macrophyte uptake, randomly selected *Nelumbo* plant samples were analyzed for phosphorus content by the Ohio Agricultural Research and Development Center (OARDC) laboratory in Wooster by dry ashing the sample, bringing it into solution, then recording emissions on a Inductively Coupled Plasma Spectrometer.

Results

Hydrology

The components for the water budget for 1 March through 30 September 1988 for Old Woman Creek are summarized in Figure 4. The water level of the wetland reached a high of 4.56 m above datum (460 feet; approximately 1 m deep) on 8 May before a storm of only 1.37 cm led to a breakthrough of the barrier beach and a water level drop to 4.01 m in two days (Fig. 4a). The barrier beach was open for most of March, half of April, and for a short period during May (Fig. 4b). After those openings, the beach closed



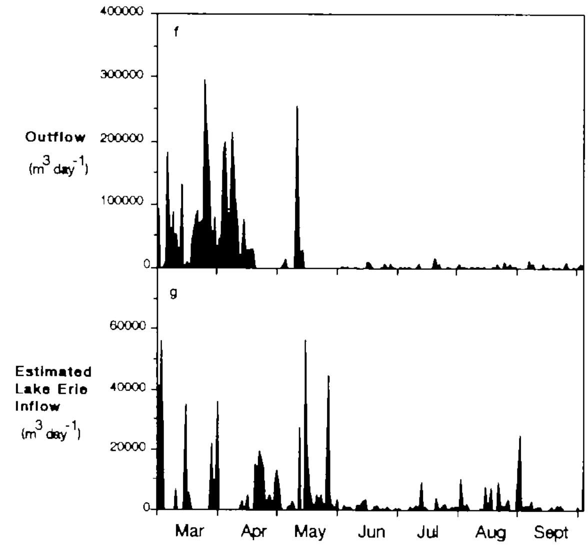


Figure 4. Hydrologic budget of Old Woman Creek for 1 March - 30 September 1988, showing a) water level in m above Great Lakes datum, b) state of barrier beach at outlet of wetland to lake Erie (black indicates wetland open to Lake Erie), c) precipitation, d) evapotranspiration, e) surface inflow, f) outflow to Lake Erie, and g) estimated inflow from Lake Erie.

for the remainder of the measurement period. The wetland was open to Lake Erie for 50 days, or 23% of the study period. It is normal for the wetland to be opened to Lake Erie during the spring and then closed during the summer. The barrier beach caused the water level to rise to 4.32 m before beginning a consistent drop during the summer until a 2.6 cm rain storm in late August.

The precipitation pattern (Fig. 4c) shows a significant drought period from mid-April through the middle of July. This drought was predominant throughout the Midwest, caused in part by a relatively high rate of evapotranspiration (Fig. 4d). Most of the surface inflow, which peaked at 300 000 m^3 day^{-1} in late March, was completed by the end of April and did not resume at any significant volume through the rest of the study period (Fig. 4e).

Outflow from the wetland to Lake Erie is limited primarily to the periods when the barrier beach was open (Fig. 4f). The water budget calculations predict very little flow when the beach is closed. These small fluxes could be groundwater outflow and/or water budget error. Our calculations also show several peaks of flow into the wetland, either from Lake Erie or as an error estimate in the hydrologic budget through the rest of the study period (Fig. 4g). As with the outflows, inflows are predicted primarily when the barrier beach is opened. In May, the water level in the wetland increased 8 cm with no rainfall event and no increase in inflow due to the stream. We estimated that 44 000 m^3 day^{-1} entered the wetland from Lake Erie during that day. The wetland again had a slight increase at the end of August (9 cm) that suggested 24 000 m^3 day^{-1} from sources other than those measured.

An estimate of the daily water budget for the study period demonstrated that surface inflow from the watershed averaged 15 200 m^3 day^{-1} while Lake Erie provided 3500 m^3 day^{-1} (Fig. 5). The flow from Lake Erie represents 18% of the water flow into the wetland. As expected, evapotranspiration was higher than precipitation (by 80%) because of the summer drought. The water volume in the wetland actually increased slightly during the study period by 700 m^3 day^{-1}, even with the drought conditions, because of the contribution by the lake to the wetland.

Water chemistry

Conductivity was generally highest in the inflow stream (Station 10) and decreased by an average of 34% as the water flowed through the wetland (Table 1). The decrease between the inflow (Station 10) and the outflow (Station 2) for conductivity was significant (α=0.05). Changes in turbidity and total suspended solids from inflow (Station 10) to outflow (Station 2) were not significant (α=0.05) although there was little streamflow through the wetland after May. Comparison of Station 8 (flow under bridge in upstream reach of wetland) with Station 2 (flow under bridge at outflow) may be more appropriate because both sites are deeper and flowing (Fig. 3). In that comparison, turbidity decreased from 139 to 88 FTU and total suspended solids decreased from 108 to 75 mg l^{-1} (Table 1).

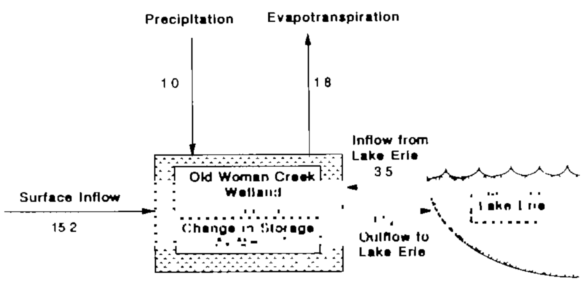


Figure 5. Estimated water budget for 1 March - 30 September 1988 for Old Woman Creek wetland. Units are m^3 day^{-1} x 1,000.

Phosphorus concentrations decreased as water flowed through the wetland, although the patterns were not consistent (Table 1 and Fig. 6). Retention of total phosphorus was more variable in the marsh and concentrations were often higher at the outflow. During periods of high inflow concentrations, total phosphorus outflow remained relatively low. Nevertheless, total phosphorus at the inflow (Station 10) and the outflow (Station 2) were not significantly different (α=0.05). Total soluble phosphorus (TSP) averaged a decrease of about 50 μg P l^{-1} from inflow to outflow, but the decrease was not consistent. Soluble reactive phosphorus (SRP) concentrations were extremely low (averaging 4 to 5 μg P l^{-1} in the wetland) throughout the study period but were significantly lower than the average concentration of SRP in the inflow concentrations at Station 10 (α=0.05). Concentrations of total phosphorus in Lake Erie shoreline waters (ave. = 160 μg P l^{-1}) remained about half the concentrations in the wetland (ave. = 323 μg P l^{-1}).

Few strong correlations are found between most of the chemical variables except for turbidity and total suspended solids (r=0.94). Total phosphorus showed little correlation with turbidity (r=0.36) and suspended solids (r=0.28) and there is little correlation between total suspended solids and particulate phosphorus (r=0.24). Normally one would expect to find a relationship between particulate phosphorus and the amount of suspended sediments in the wetland. Due to significant resuspension in shallow waters, probably from biotic causes (e.g. carp), no such relationship was found.

Discussion

Nutrient budget

Two mass balances of phosphorus in Old Woman Creek are shown in Fig. 7. Figure 7a illustrates an estimate of the inflow and retention of nutrients determined from representative loading rates for similar Lake Erie watersheds (0.5 - 1.0 kg ha^{-1} yr^{-1} from Johnson *et al.* 1978, IJC 1980, and Novotny 1986) and from phosphorus removal efficiency plots based on a number of wetlands by Richardson and Nichols

Table 1. Chemical concentrations for samples in Old Woman Creek Wetland, inflow stream, and Lake Erie shoreline for period of 1 April - 6 November 1988. Numbers indicate averages ± standard deviation (number of samples).

Station	pH	conductivity (μmhos/cm)	turbidity (FTU)	total suspended solids (mg l⁻¹)	total P (μg P l⁻¹)	total soluble P (μg P l⁻¹)	soluble reactive P (μg P l⁻¹)
Lake Erie Shoreline							
1	8.0±0.7 (8)	286± 28 (12)	34± 25 (13)	35± 38 (11)	160±128 (13)	30±24 (13)	3.9±1.5 (9)
Old Woman Creek Wetland							
2	7.6±0.6 (8)	457± 88 (12)	88± 32 (13)	75± 21 (11)	248±147 (13)	45±23 (13)	4.0±3 2 (9)
3	8 2±0.5 (8)	501± 96 (11)	114± 50 (13)	112± 52 (11)	267±252 (13)	46±25 (13)	3.9±1.2 (9)
4	7.9±0.5 (8)	508± 90 (12)	163±138 (13)	182±186 (11)	378±296 (13)	47±31 (13)	4.8±2.2 (9)
5	7.8±0.6 (8)	528±125 (12)	167± 83 (13)	193±108 (11)	309±216 (13)	50±21 (13)	4.2±1.2 (9)
6	8.1±0.6 (8)	534±107 (12)	161± 80 (13)	142± 56 (11)	323±225 (13)	65±25 (13)	4 3±1.2 (9)
7	8.0±0.5 (8)	520± 63 (12)	182±106 (13)	182±133 (11)	353±329 (13)	56±24 (13)	4.5±1.6 (9)
8	7.8±0.5 (8)	534± 82 (12)	139± 44 (13)	108± 41 (11)	430±350 (13)	66±38 (13)	3.9±1.4 (9)
9	7.7±0.7 (7)	563± 42 (12)	143± 72 (13)	141± 51 (11)	278±174 (13)	66±37 (13)	4.7±2.1 (9)
Inflow Stream to Wetland							
10	8.0±0.4 (8)	698±102 (12)	75± 52 (13)	59± 50 (11)	247±238 (13)	94±63 (13)	7.5±2.7 (9)

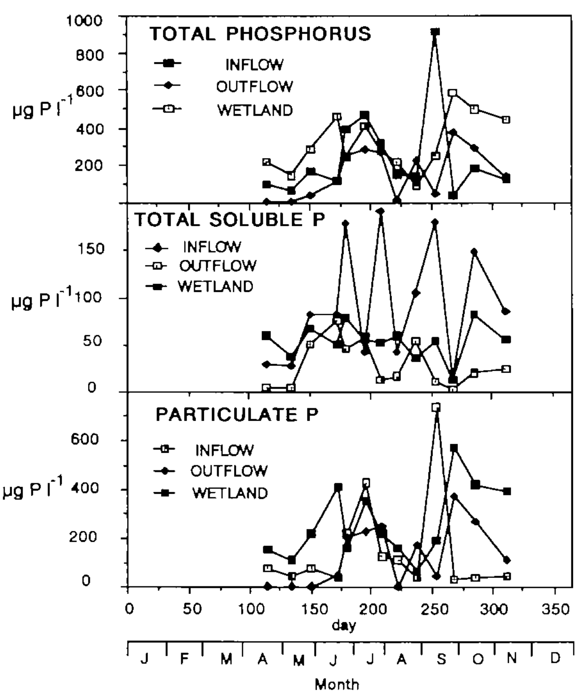


Figure 6. Concentrations of total phosphorus, total soluble phosphorus, and particulate phosphorus in inflow (Station 10), outflow (Station 2) and wetland (average of Stations 3 through 7 and 9) over 1988 growing season.

(1985). An input of phosphorus to the wetland of 6.1 to 12.2 g P m^{-2} yr^{-1} (17 - 33 mg P m^{-2} day^{-1}) and a retention, ultimately in the sediments, of 2.9 to 4.6 g P m^{-2} yr^{-1} (8 - 13 mg P m^{-2} day^{-1}) are estimated by this method. This suggests a range of 39 to 47% retention. These numbers can serve as a "norm" by which we can compare our field results.

A phosphorus budget for the period 1 March 1 through 30 November 1988 (Fig. 7b) based on the hydrology budget and phosphorus measurements described above, presents a different picture than the model in Figure 7a. Because this phosphorus budget is calculated for a drought year, phosphorus loading from the watershed is considerably less than that estimated from other watersheds for normal years. The phosphorus loading is estimated to be about 10% of that seen in an average year from comparable watersheds in the Lake Erie basin. Outflow of phosphorus, which is calculated to occur only when the barrier beach is open, is estimated to be 64% of the inflow. Thus we estimate that there was a retention of approximately 36% of the phosphorus in the wetland during the study period. The Richardson and Nichols model would have predicted a much higher retention of phosphorus (80 to 100%) at this low loading rate.

Sedimentation is the most important process of

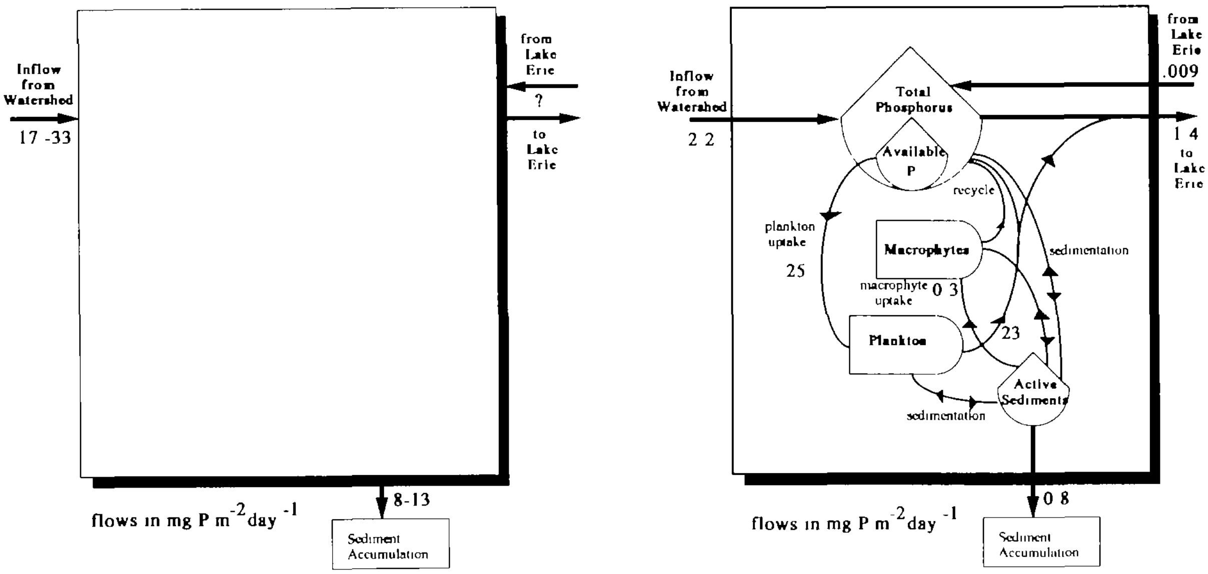


Figure 7. Phosphorus mass balance for study wetland a) as estimated from loading rates and Richardson and Nichols (1985) model, and b) as estimated for the period 1 March - 30 November 1988 from data in this study.

phosphorus retention in the wetland. We have found it almost impossible to overcome field measurement problems to measure sedimentation directly with sediment sampling devices. Our estimate of a net phosphorus retention by the sediments (0.8 mg P m^{-2} day^{-1}) is based on measurements of surface water concentrations and the water budget. An average phosphorus deposition rate of 22 mg P m^{-2} day^{-1} over several years was estimated from one deep sediment core taken from the wetland in early 1988 (Reeder 1989). This sediment core deposition rate is considerably more than that estimated from the Richardson and Nichols model or the field estimate reported here, suggesting that there may be more phosphorus coming into Old Woman Creek wetland on the average than estimated by either nutrient budget in Figure 7. A fourth method that recently attempted to estimate the sedimentation by use of an ecosystem model resulted in a net sedimentation rate of 2.9 mg P m^{-2} day^{-1} for these conditions (Mitsch and Reeder, in press).

Role of Primary Producers

Significant quantities of phosphorus are transformed by plankton and a smaller amount transformed by the wetland's macrophytes. The uptake of 25 mg P m^{-2} day^{-1} of phosphorus by plankton shown in Figure 7b is estimated from annual productivity measurements (Reeder and Mitsch 1989a) and exceeds the phosphorus contributed by streamflow by an order of magnitude. Because the requirement of phosphorus by the ecosystem is not met by the supply coming from the uplands during this study year, the deficit had to be made up through intrasystem recycling and resuspension of phosphorus from the sediments. We have previously suggested (Mitsch *et al.* 1989) that phosphorus in Old Woman Creek wetland is transformed from bioavailable to nonbioavailable forms by primary producers. Plankton seemed to be the most significant transformer, since soluble reactive phosphorus levels decreased the most when planktonic populations were most productive. Now we believe that there is a rapid recycling of phosphorus and resuspension of nutrients from the sediments so that an adequate amount is always available to support the productivity.

Although Old Woman Creek wetland is not dominated by macrophytes, the floating-leaved vegetation *(Nelumbo lutea)* also contributes to phosphorus transformation, with its source primarily the phosphorus-rich sediments. We estimated uptake of 0.3 mg P m^{-2} day^{-1} by macrophytes from plant harvests and phosphorus analyses (Reeder and Mitsch 1989b). The floating-leaved plants may be pumping the nutrients from the sediments to the water column (when the leaves die and decay), thus serving as a phosphorus source to the wetland (Prentiki *et al.* 1978; Kopatek 1978).

Sink or Transformer

We cannot conclude that Old Woman Creek wetland is a permanent sink of phosphorus based on a seven month analysis, particularly since measurements were taken during a drought year. Some phosphorus inflow was lost before it reached the outlet to Lake Erie but most of it was in soluble form. There was no significant difference from inflow to outflow in total phosphorus concentrations through the study period. Since the wetland was closed to the lake throughout the growing season, bioavailable phosphorus was probably transformed or buried before the barrier beach opened again the following winter. Nevertheless, the amount of phosphorus transported from inflow to outflow was estimated to decrease by 36% in our nutrient budget. This is possible, even without a significant decrease in total phosphorus concentrations between inflow and outflow, because decreases did occur in the spring when the barrier beach was open and the bulk of the surface transport through the wetland occurred. Wetlands such as Old Woman Creek have a major role in the nutrient dynamics of Lake Erie and its watershed, but just as likely as nutrient transformers as nutrient sinks.

Actual and Potential Role of Wetlands in Western Lake Erie

Preliminary calculations suggested that the existing wetlands along western Lake Erie could be retaining approximately 75 to 100 metric tons yr^{-1} if they are hydrologically connected to upstream watersheds (Mitsch *et al.* 1989). Non-point phosphorus loading to western Lake Erie was estimated to be about 2100 metric tons yr^{-1} for 1978-80 (Yaksich *et al.* 1982). This suggests that the remaining wetlands along the western basin could be retaining about 3.5 to 5% of the non-point source loading to the Lake if they were hydrologically connected to their watersheds. This is not the case, as 85% of the wetlands on Ohio's shoreline of western Lake Erie are contained in dikes (Robb and Mitsch in press) and are thus essentially isolated from their watersheds and Lake Erie. If we determine that these coastal wetlands are nutrient sinks, it may be possible to redesign the diked wetlands and construct new wetlands along the Great Lakes to take advantage of that function. For example, a program to develop 1000 km^2 of open wetlands along the western Lake Erie shoreline (one fourth of the extent of presettlement wetlands) could conceivably lead to a 24 to 33% reduction in non-point loading of phosphorus to the western basin. Economic valuation of coastal wetlands will also be more feasible as a result of these kinds of studies. Studies of this type will provide criteria for ecological engineers to design wetlands along the Great Lakes for their assimilative capacity in the landscape and cause for conservationists to rightly call for their protection.

Acknowledgments

We appreciate the assistance of Dave Klarer of Old Woman Creek National Estuarine Sanctuary and State Nature Preserve. Support was provided in part by the Division of Natural Areas of the Ohio Department of Natural Resources, by the Ohio Sea Grant Program and by the School of Natural Resources and the Environmental Biology Program at The Ohio State University.

References

American Public Health Association. 1985. Standard Methods for the Examination of Water and Wastewater. 16th edition. APHA, Washington, DC, U.S.A., 1134 pp.

Buchanan, D. 1982. Transport and deposition of sediment in Old Woman Creek Estuary of Lake Erie. Master's Thesis, The Ohio State University, Columbus, OH, U.S.A. 198 pp.

Hach Chemical Company. 1984. Procedures manual. Hach Chemical Co., Loveland, CO, U.S.A.

Heath, R.T. 1987. Phosphorus dynamics in the Old Woman Creek National Estuarine Sanctuary - a preliminary investigation National Oceanic and Atmospheric Administration (NOAA) Technical Memorandum, NOS MEMD 11, Washington, DC, U.S.A., 105 pp.

Herdendorf, C.E. 1987. Coastal wetlands along western Lake Erie: a community profile. U.S. Fish and Wildlife Service Biological Report 85(7.9), Fish & Wildlife Service, U.S. Department of Interior, Washington, DC, U.S.A., 172 pp.

International Joint Commission. 1980. Pollution in the Great Lakes basin from land use activities. IJC Report to the Governments of the United States and Canada. International Joint Commission, Windsor, Ontario, Canada, 141 pp.

Johnson, M.G. and several authors. 1978. Management information base and overview modelling. PLUARG Technical Report No. 002 to the International Joint Commission, Windsor, Ontario, Canada, 90 pp.

Jørgensen, S.E. and Johnsen, I. 1981. Principles of Environmental Science and Technology. Elsevier, Amsterdam, The Netherlands, 516 pages.

Klarer, D.M. 1988. The role of a freshwater estuary in mitigating stormwater inflow. Old Woman Creek Technical Report Number 5. Ohio Department of Natural Resources Division of Natural Areas and Preserves, Columbus, Ohio, U.S.A., 65 pp.

Klarer, D.M. and Millie, D.F. 1989. Amelioration of storm-water quality by a freshwater estuary. Archiv Hydrobiol. 116:375-389.

Klopatek, J.M. 1978. Nutrient dynamics of freshwater riverine marshes and the role of emergent macrophytes. pp. 195-216. *In:* Freshwater Wetlands: Ecological Processes and Management Potential. Edited by R.E. Good, D.F. Whigham, and R.L. Simpson. Academic Press, New York, New York, U.S.A.

Kreiger, K.A. 1985. A comparative study of crustacean zooplankton community structure and dynamics in a Lake Erie Marsh and the adjacent wave zone. Report to U.S. Dept. of Commerce, NOAA, Sanctuary Programs Div., Washington, DC, U.S.A., 49 pp.

Linsley, R.K. and Franzini, J.B. 1979. Water Resource Engineering, 3rd ed. McGraw-Hill Book Co., New York, New York, 716 pp.

Logan, T.J., Verhoff, F.H. and DePinto, J.V. 1979. Biological availability of total phosphorus. Technical Report Series, Lake Erie Wastewater Management Study, U.S. Army Corps of Engineers, Buffalo, New York, U.S.A., 42 pp.

Mitsch, W.J. 1988. Ecological engineering and ecotechnology with wetlands: applications of systems approaches. pp. 565-580. *In:* Advances in Environmental Modelling. Edited by A. Marani. Elsevier, Amsterdam, The Netherlands.

Mitsch, W.J., ed. 1989. Wetlands of Ohio's Coastal Lake Erie - A Hierarchy of Systems. Ohio Sea Grant College Program, The Ohio State University, Columbus, Ohio, U.S.A. 186 pp.

Mitsch, W.J., Reeder, B.C. and Klarer, D.M. 1989. The role of wetlands for the control of nutrients with a case study of western Lake Erie. pp. 129-159. *In:* Ecological Engineering: An Introduction to Ecotechnology. Edited by W.J. Mitsch and S.E. Jorgensen. J. Wiley & Sons, New York, New York, U.S.A.

Mitsch, W.J. and Reeder, B.C. in press. Modelling nutrient retention of a freshwater coastal wetland: estimating the roles of primary productivity, sedimentation, resuspension, and hydrology. Ecological Modelling.

Novotny, V. 1986. A review of hydrologic and water quality models used for simulation of agricultural pollution. pp. 9-35. *In:* Agricultural Nonpoint Source Pollution: Model Selection and Application. Edited by A. Giorgini, A. and F. Zingales. Elsevier, Amsterdam.

Prentiki, R.T., Gustafson, T.D. and Adams, M.S. 1978. Nutrient movements in lakeshore marshes. pp. 169-194. *In:* Freshwater Wetlands: Ecological Processes and Management Potential. Edited by R.E. Good, E.F. Whigham, and R.L. Simpson. Academic Press, New York, New York, U.S.A.

Reeder, B.C. 1989. Quaternary history of Old Woman Creek wetland. pp 97-109. *In:* Wetlands of Ohio's Coastal Lake Erie - A Hierarchy of Systems. Edited by W.J. Mitsch. Ohio Sea Grant College Program, The Ohio State University, Columbus, Ohio, U.S.A.

Reeder, B.C. and Mitsch, W.J. 1989a. Seasonal patterns of planktonic and macrophyte productivity of a freshwater coastal wetland. pp. 49-68. *In:* Wetlands of Ohio's Coastal Lake Erie - A Hierarchy of Systems. Edited by W.J. Mitsch. Ohio Sea Grant College Program, The Ohio State University, Columbus, Ohio, U.S.A.

Reeder, B.C. and Mitsch, W.J. 1989b. Bioavailable phosphorus and a phosphorus budget of a freshwater coastal wetland. pp. 81-95. *In:* Wetlands of Ohio's Coastal Lake Erie - A Hierarchy of Systems. Edited by W.J. Mitsch. Ohio Sea Grant College Program, The Ohio State University, Columbus, Ohio, U.S.A.

Richardson, C.J. and Nichols, D.S. 1985. Ecological analysis of wastewater management criteria in wetland ecosystems. pp. 351-391. *In:* Ecological Considerations in Wetlands Treatment of Municipal Wastewaters. Edited by P.J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado. Van Nostrand Reinhold Co., New York, New York, U.S.A.

Robb, D.M. and Mitsch, W.J. in press. Selected chemical parameters of diked and undiked Lake Erie marshes. *In:* Proceedings of a Conference, Wetlands of the Great Lakes. Edited by J. Kusler. Association of State Wetland Managers, Berne, New York, U.S.A.

Sager, P.E., Richman, S., Harris, H.J. and Fewless, G. 1985. Preliminary observations on the seiche-induced flux of carbon, nitrogen and phosphorus in a Great Lakes coastal marsh. pp. 59-68. *In:* Coastal Wetlands. Edited by H.H. Prince and F.M. D'Itri. Lewis Publishers, Chelsea, Michigan, U.S.A.

Sommers, L.E. and Nelson, D.W. 1972. Determination of total phosphorus in soils: a rapid perchloric acid digestion procedure. Soil Sci. Soc. Am. Proc. 31:752-756.

Yaksich, S.M., Melfi, D.A., Baker, D.B. and Kramer, J.W. 1982. Lake Erie nutrient loads, 1970-1980. Lake Erie Wastewater Management Study, U.S. Army Corps of Engineers, Buffalo, New York, U.S.A. 194 pp.