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Large-scale coastal wetland restoration on the Laurentian Great Lakes: Determining the potential for water quality improvement

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Abstract

Coastal wetlands around the Laurentian Great Lakes, estimated to cover 1290 km^2 in the USA after extensive losses in the past 200 years, are rarely restored for water quality enhancement of the Great Lakes, despite the need for minimizing phosphorus and other pollutant inputs to the lakes. A simulation model, developed and validated for a series of created experimental marshes in northeastern Illinois, was aggregated and simplified to estimate the nutrient retention capacity of hypothetical large-scale coastal wetland restoration in Michigan and Ohio. Restoration of 31.2 km^2 of wetlands on agricultural land along Saginaw Bay, Michigan, would retain 25 metric tons-P year^{-1} (53% of the phosphorus flow from the upstream watershed). Hydrologic restoration of 17.3 km^2 of mostly diked wetlands in Sandusky Bay, Ohio, would retain 38 metric tons year^{-1} (12% of the phosphorus flow from the upstream watershed). A wetland distribution model developed for the Saginaw Bay site illustrated a technique for identifying sites that have high potential for being transition zones between open water and upland and thus logical locations for wetland restoration. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Coastal wetlands were once found in great abundance along the Laurentian Great Lakes. When compared to the Atlantic, Gulf, and Pacific shoreline lengths of the US, the Great Lakes shoreline is similar in length to the Atlantic plus Gulf shoreline (Fig. 1). Herdendorf (1987) estimated that there were 1209 km^2 of coastal wetlands around the Great Lakes in the US; the number is probably much greater for the Canadian portion of the shoreline: Glooschenko and Grondin (1988) estimated 9000 km^2 of wetlands in southern Ontario alone.

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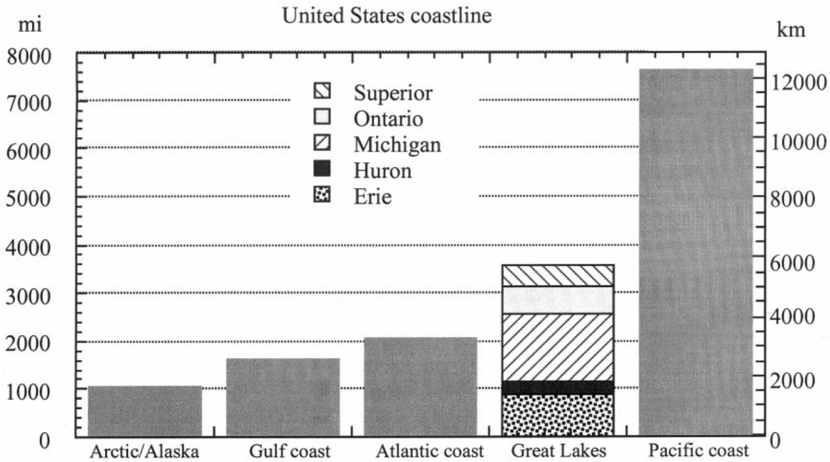


Fig. 1. Shoreline length of the Laurentian Great Lakes in the USA compared to shoreline lengths of the Eastern, Gulf, and Pacific shorelines of the USA.

Only a small percentage of the original extent of wetlands remains around the Great Lakes after over 200 years of intensive development and urbanization. As one example, an estimated 95% of wetlands were lost around the Western Basin of Lake Erie in Ohio and Michigan, including an area known as the Great Black Swamp, a 4000 km^2 swamp/marsh lowland that was essentially the western-most extension of Lake Erie. Unlike tidal wetlands, which are partially protected because the tide returns twice a day with certainty, Great Lakes wetlands were especially vulnerable to filling during low lake level periods, particularly since the water levels of the Great Lakes fluctuate over 1.5 m from a wet year to a dry year. During early European and later American settlement of this coastline, wetland areas were fined and later diked particularly during low water years.

1.1. Water quality as a success criterion for Great Lakes restoration

With so many wetlands lost, it would seem that there are many opportunities for coastal wetland restoration along the Great Lakes. Great Lakes wetlands, unlike coastal wetlands in tidal areas, are influenced by lake levels that can change by 50 cm or more on an annual basis and by over 1.5 m overall. Seiches also cause short-term water level fluctuations and shoreline sediment dynamics, ice action, and watershed pulses can open and close wetlands to the lake seasonally (Mitsch, 1992). Because of all of these variables, most of the wetlands that remain along the shorelines of the Great Lakes are diked to allow human manipulation of water levels.

Wetlands that are restored along the Great Lakes are done so with various goals and with various criteria for measuring success of the restoration (Table 1). Most often, Great Lakes wetlands are restored for the return of vegetation cover and subsequent wildlife enhancement, par-

Table 1
Success criteria used for coastal wetland restoration on the Laurentian Great Lakes

Frequently used
Waterfowl production, esp. ducks
Vegetation cover
Absence of alien species, e.g. *Lythrum salicaria*
Sometimes used
Non-game wildlife enhancement
Exclusion of carp (*Cyptinus carpio*)
Fish spawning and feeding
Furbearer harvesting
Rarely used
Detrital export
Water quality enhancement

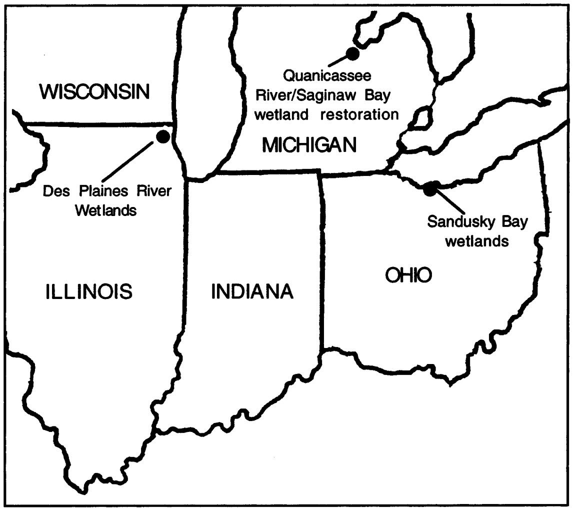


Fig. 2. Locations of wetland sites described in this study. Hypothetical restoration case studies are emphasized for Quanicassee River/Saginaw Bay on Lake Huron and Sandusky Bay on Lake Erie. Models were initially calibrated and validated at the Des Plaines River wetland site in northeastern Illinois.

ticularly for waterfowl (Burton and Prince, 1995a; Warren et al., 1995; Özesmi and Mitsch, 1997). These goals are similar to goals in most coastal wetland restorations (Miller, 1994; Zedler, 1996; Burdick et al., 1997; Weinstein et al., 1997). Some recent Great Lakes wetland restorations have focused on restoring wetlands while restricting carp (*Cyprinus carpio*) and on the use of wetlands for spawning and feeding by lake fish. Rarely have wetland restoration projects been undertaken with a primary goal of enhancing water, quality, despite the importance that has been attributed to water quality in the lakes by conventions such as the Great Lakes Water Quality Agreement between the USA and Canada. In reviewing federal wetlands programs in the US, Whitaker and Terrell (1992) found that despite the fact that many agencies had significant wetland restoration and creation efforts, water quality improvement was neglected in most of these programs. In some cases, areas with high nonpoint source pollution were actually avoided to protect wetland habitat values.

Several studies have suggested the ability of coastal wetlands to reduce nonpoint pollution released from upstream watersheds (Johnston, 1991; Olson, 1992; Mitsch, 1994). Specific to the Great Lakes, Mitsch et al. (1989) calculated that existing wetlands along western Lake Erie have the potential to retain 75–100 metric tons-P year^{-1}, if hydrologically connected to upstream watersheds. A Lake Erie coastal wetland was estimated to retain 17–52% of incoming phosphorus from an upstream watershed. (Mitsch and Reeder, 1991, 1992). As buffer zones between upland and deep water aquatic systems of the Great Lakes, coastal wetlands can have an important role in maintaining the Great Lakes ecosystem's health. With over two-thirds of the Great Lakes' wetlands lost in the last century, the lakes have been more vulnerable to disturbances from nonpoint source pollution from upstream watersheds. Realizing water quality benefits provided by many created and restored wetlands, the US Environmental Protection Agency (USEPA) has mandated that states with Coastal Zone Management programs consider wetland preservation and restoration in their water quality management plans as potential management measures to control nonpoint source pollution.

1.2. Study objectives

While integrating coastal wetland restoration with water quality management plans in the Great Lakes basin has potential to both improve water quality and provide new wetland habitat, the actual reduction of nonpoint source pollution that would result from the restoration of wetlands is unknown. There is a need to develop a rational set of tools for adequate prediction of the success of coastal wetland restoration, particularly in terms of improving water quality. In this study, we take a systems approach combined with a regional analysis to estimate the potential extent and benefits of large-scale wetland restoration at three different case study sites around the Great Lakes: a constructed riparian wetland site in northeastern Illinois where the general model was developed and validated; a wetland area to be restored from farmland on Lake Huron in northeastern Michigan; and a potential hydrologic restoration of wetlands on Lake Erie in northern

Ohio (Fig. 2). This paper predicts the degree to which large-scale wetland restoration along the Great Lakes would reduce nonpoint source pollution to the lakes in these examples and provides a tool for determining possible locations where that restoration could take place.

2. Methods and site descriptions

2.1. General approach

Different complexities and spatial scales of models were chosen to balance the problems, objectives, data sources, and our best knowledge about the systems (Fig. 3). While a detailed ecosystem model provides a tool to identify the key elements in phosphorus cycling in wetlands and to understand the roles of each ecosystem process and compartment in relation to the whole ecosystem, a simple model that ignores complexities can give a view of wetland functions on a larger scale such as a watershed. This hierarchical systems approach was used to predict the water quality role of hypothetical wetland restoration in several locations around the Great Lakes.

2.2. Study sites

2.2.1. Des Plaines River Wetlands, Illinois

Constructed experimental wetlands on the Des Plaines River (Fig. 4) in northeastern Illinois, USA, were used to refine the unit models used to predict phosphorus retention in other created/restored wetlands. Although these wetland basins are not in the Great Lakes watershed (the Des Plaines River drains to the Illinois River, then to the Mississippi), they are only about 15 km from Lake Michigan. The Des Plaines River drains a 545 km^2 watershed composed of 20% urban and 80% agricultural lands. Four hydrologically separate wetland basins, ranging in size from 1.9 to 3.4 ha, were constructed between 1986 and 1988, and began receiving pumped water from the Des Plaines River in 1989 (Fig. 4). Pumping rates were maintained to test different hydrologic flow conditions on wetland functions from 1989 through 1992. This tightly controlled hydrology plus the significant data base developed from the site during its research period allowed the development, calibration, and validation of models to be done in a more precise manner than is usually possible. All four experimental wetlands were dominated by cattails (*Typha latifolia* and *Typha angustifolia*). Research at the Des Plaines River Wetlands Demonstration Project (DPRW) is reported by Sanville and Mitsch (1994), Kadlec and Hey (1994), Cronk and Mitsch (1994), Mitsch and Cronk (1995), and Mitsch et al. (1995). More details of the model validated at this site are given in Wang (1996) and Wang and Mitsch (2000).

2.2.2. Saginaw Bay, Michigan

The Michigan Department of Natural Resources (MDNR) has been investigating for several years the restoration of wetlands at the mouth of the Quanicassee River where it enters Saginaw Bay on Lake Huron, Michigan (Fig. 5; Paulson, 1993; Burton and Prince, 1995b). The river drains into Saginaw Bay through what was former wetland but is now mostly drained hydric soils that support agricultural-crops such as potatoes, sugar beets, beans, and corn (Burton and Prince, 1995b). The average flow of the Quanicassee River is 11 m^3 s^{-1} with an annual phosphorus loading of 48 metric tons year^{-1}; the river contributes about 3% of the total 1544 metric tons of phosphorus loading from the whole 2100 km^2 Saginaw Bay watershed. In the study area, there are presently 131 ha of wetlands along the Quanicassee River, and 564 ha of wetlands along the coastline. The hypothetical restoration area that served as the basis for the simulations comprises a much larger area (3120 ha), roughly 15% of the total Quanicassee River watershed (Fig. 5).

2.2.3. Sandusky Bay, Ohio

Sandusky Bay, located on the southwest shore of Lake Erie, Ohio, is approximately 25 km long and 5–7 km wide (Fig. 6). The Sandusky River is the major tributary that enters the Sandusky Bay with a mean annual river flow of 25.1 m^3 s^{-1}. Where the Sandusky River and the much smaller Muddy Creek enter the bay at the far western end there is a concentration of marshes (Fig. 6). Most

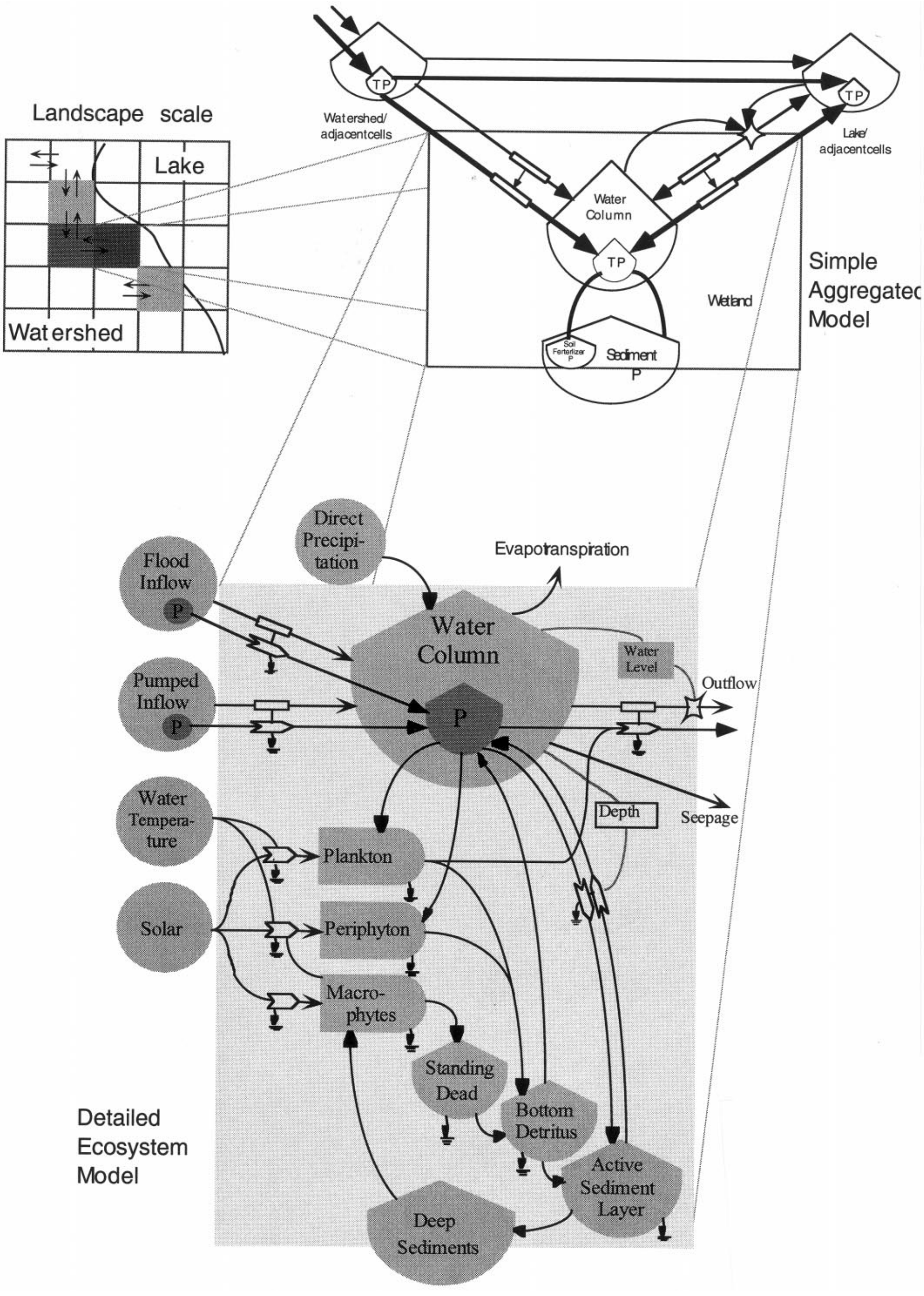


Fig. 3. Hierarchy of wetland simulation models for phosphorus retention at different ecosystem details and spatial scales. Upper left is full spatial scale, upper right is simplified model approach, and bottom is detailed ecosystem model approach.

of the marshes in this delta area to Sandusky Bay have been diked since the late 19th century in the support of hunting and trapping activities. The simulations investigated the potential water quality role of these wetlands were it possible to restore riverine hydrology to these diked wetlands.

2.3. Simulation modeling

2.3.1. Detailed model

Based on the available data, knowledge of the ecosystem, and the objectives of this study, a detailed conceptual model (Fig. 3, bottom) was first developed for the Des Plaines River Wetlands (DPRW) in northeastern Illinois. Extensive field data existed for the wetlands at this site; data for the model were obtained primarily from the DPRW research database (Mitsch et al., 1993) that contains data collected by several researchers at that wetland site. Four linked submodels — a hydrology, primary productivity, sediment, and phosphorus — were developed and described by a set of nonlinear, ordinary differential equations. The model was integrated by using the software STELLA™ II, a high-level visually oriented pro-

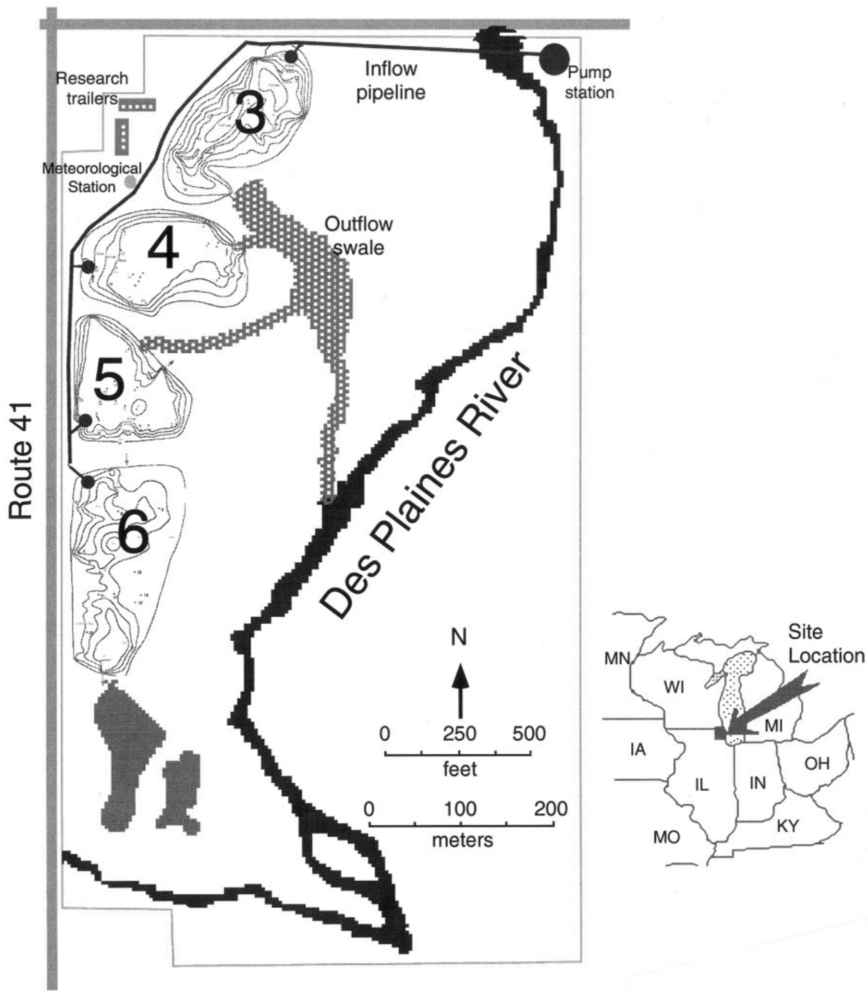


Fig. 4. Des Plaines River Wetland Demonstration Project, showing the four experimental wetland basins where a detailed model similar to the one in Fig. 3 (bottom) was calibrated and validated for phosphorus dynamics (Wang, 1996).

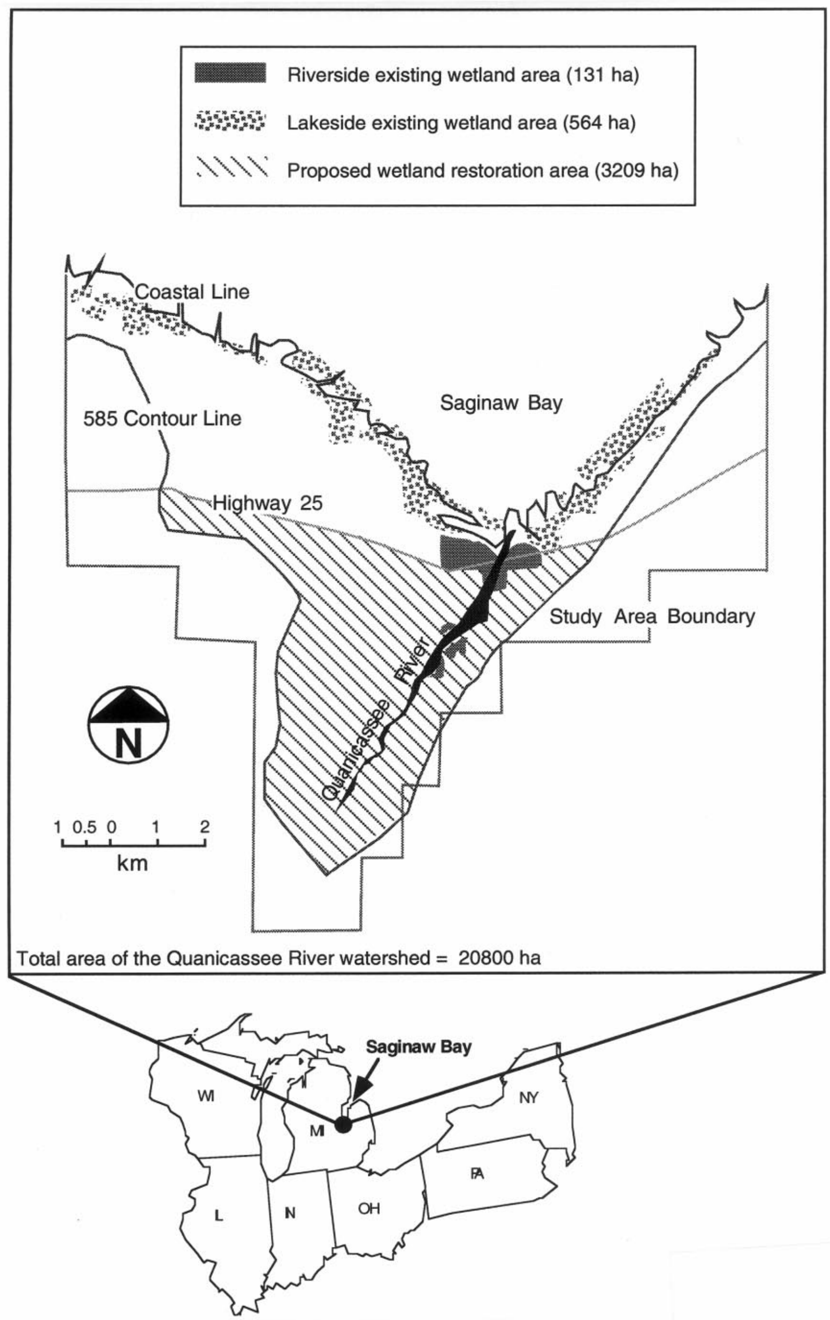


Fig. 5. Quanicassee River study area on Saginaw Bay, Lake Huron, northeastern Michigan, USA (from Wang and Mitsch, 1998).

gramming and simulation language (Richmond and Peterson, 1992). Fourth-order Runge–Kutta integration methods was used with a time step of 0.1 week. Calibration was accomplished by adjusting selected parameters in the model to obtain a best fit between the model calculations and field data (Oct. 1989–Sept. 1990). A step-wise method (Mitsch and Reeder, 1991) was used in this process by first calibrating the hydrology submodel, then the primary productivity submodel and sediment submodel, and finally the phosphorus submodel. At each step, values of parameters determined during the previous step were not varied from previous calibrated values. With this technique, several unknown coefficients in the model could be determined. Independent data sets with different hydrological conditions, from Oct. 1990 to Sept. 1991, and from Oct. 1991 to Sept. 1992, were used to validate the model. The model described above was based on earlier versions of nutrient retention models by Mitsch and Reeder (1991) and Christensen et al. (1994). Details of model validation can be found in Wang (1996) and Wang and Mitsch (2000).

2.3.2. Simplified model

A simplified version of the above model (Fig. 3, upper right) was used to estimate the phosphorus retention that would occur with extensive wetland restoration on Saginaw Bay and Sandusky Bay. The model used a Vollenweider-type approach to treat the wetland as a 'black-box' and was validated for several wetlands and years at the DPRW (Mitsch et al., 1995). The model has the following form:

$$dTP/dt = P_{in} - P_{out} - TP \cdot k + TP_s \cdot k_s \quad (1)$$

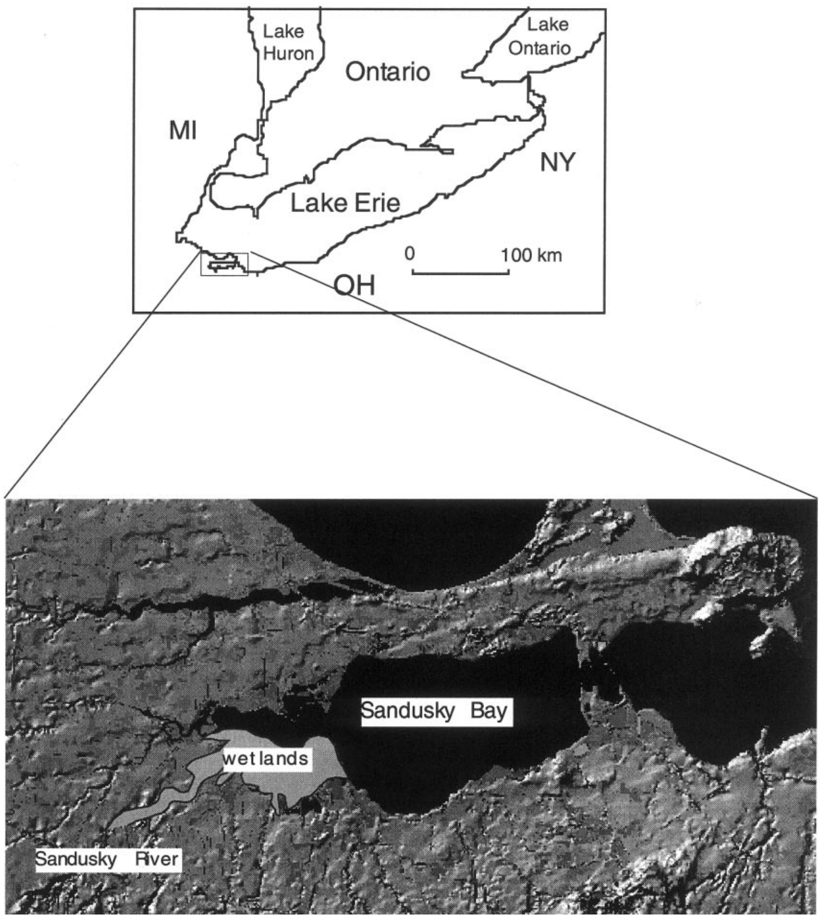


Fig. 6. Sandusky Bay study area on Lake Erie, northern Ohio, USA, showing area of major wetlands used in simulations.

where, TP, phosphorus in wetland (g); P_{in}, inflow of phosphorus (g day^{-1}); P_{out}, outflow of phosphorus (g day^{-1}); k, phosphorus retention coefficient (day^{-1}); TP_s, excess phosphorus in soil (g); k_s, phosphorus leaching coefficient (day^{-1}).

The value for the phosphorus sedimentation rate k is 0.93 day^{-1}, estimated from the validated DPRW model described above. The last term in Eq. (1) ($TP_s \cdot k_s$), leaching from the soil, was not necessary in the Sandusky Bay application of this model. A phosphorus sediment storage (TP_s) added to the Saginaw Bay model allowed excessive phosphorus in the soil from years of intensive agriculture to be released to the overlying waters of the restored wetlands. This pathway was not necessary for the Sandusky Bay simulation that involved hydrologic restoration of existing wetlands rather than agricultural land.

All simulations were performed with STELLA™ II and EXTEND™ 3.1 (Diamond and Hoffman, 1995). Euler's method was used as the integration technique with a time step of 0.5 day. Total simulation time each year was 9 months, starting from day 61 and ending with day 335 of each year.

2.3.3. Model assumptions, limitations, and uncertainty analysis

The simple model used for the Sandusky and Saginaw Bay sites, by definition, involves lumping of several parameters into one or two coefficients (k and k_s). The assumption is that wetlands behave as whole systems in fundamentally the same way, given the same hydrology, basin configurations, soil initial conditions, and climate. The limitations of this model is that it is restricted to those conditions and is probably needs calibration outside of the Great Lakes region.

To account for parameter and data uncertainty, 'Monte Carlo' simulations were used in the model to provide a better understanding of the model estimates. Input variables and parameters were sampled randomly from predefined probability distributions. At the beginning of each Monte Carlo iteration, all sensitized variables and parameters were selected randomly and then remained the same during each simulation until next iteration occurred. Thus, various possible scenarios (different combinations of uncertain parameters) could be accounted for in the final results. All parameters were picked up without correlation except for flow and phosphorus concentrations since they usually are positively correlated in a watershed.

2.4. Wetland distribution model

Most of the spatial data for the Sandusky Bay spatial model were obtained from the Center for Mapping at The Ohio State University Individual coverages, including 11 hyposographic and 12 hydrographic: data layers, are in US Geological Survey Digital Line Graph (DLG) data format with 1:24 000 scale and UTM projection. Any unavailable quadrangle was directly digitized from USOS, 7.5 min quadrangle maps at the Center for Mapping and Department of Geography of The Ohio State University Several NOAA and ACOE navigation maps were also digitized to provide nearshore bathymetric data. Field water quality, hydrology, and lake water level data were obtained from USGS Detroit District and USGS's water resources data for Ohio (Shindel et al., 1995).

Spatial data coverages from various sources were converted into ARC/INFO format. Individual hydrographic and hypsographic coverages (73-min) were edited, edgematched, and finally merged into one large coverage for the study region. All data layers were projected to the Universal Transverse Mercator System (UTM). Spot elevation, contour coverage, bathymetric coverage, and natural depressions were derived from the hyposography. Hydrography was used to extract coverages of coastal shoreline and strewn network.

All coverages were then fed into an ARC/INFO program, TOPGRID, to generate a digital elevation model (DEM). The DEM was then verified with original USCS, quadrangle maps, aerial photo, and ground truth. The model then simulated five different wetland categories determined by long-term lake level data. Water depths used for boundaries between categories are based on general knowledge of optimum water levels for marsh plants as described by Fassett (1957),

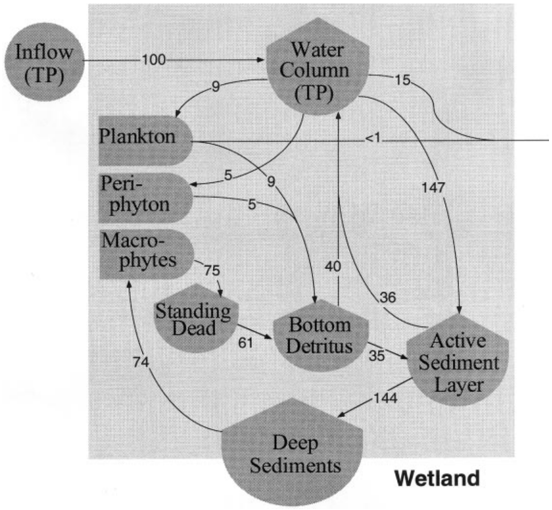


Fig. 7. Phosphorus flow intensities for the Des Plaines River Wetlands standardized for a phosphorus inflow of 100. Flows are averages of model runs for all four wetlands from October 1989 to September 1991.

Mitsch and Gosselink (1993), and Thunhorst (1993) in the following categories: (a) open water — has a water depth at least more than 70 cm for more than 4 months or 3 consecutive months in a year; (b) deep marsh — has a water depth between 20 and 70 cm for at least 3 months in that year and is not defined as open water; (c) shallow marsh — has a water depth between 0 and 20 cm for at least 3 months in that year and is not defined as open water nor deep marsh; (d) not flooded — has a water depth < 0 cm for the whole growing season; and (e) intermittently flooded — is not included in any of above categories. The model was written in C programing language and monthly Lake Erie water levels from 1900 to 1990 were used for model simulations.

3. Results and discussion

3.1. Constructed riverine wetlands

The detailed ecosystem model with hydrology, primary productivity, sediment, and phosphorus submodels (Fig. 3, bottom) simulated phosphorus cycling reasonably well with one set of parameters for a total of 10 wetland-years for the four created riparian wetlands at the Des Plaines River site in Illinois. The model was used to explore the role of different functions or structures of the wetland ecosystem on phosphorus retention, to integrate collected data, to better understanding the dynamics of created wetlands, and to predict the sediment and phosphorus retention under different hydrologic conditions.

Annual phosphorus budgets from model simulations showed that these four wetlands retained an average of 85% phosphorus between Oct. 1989 and Sept. 1991 (Fig. 7) at annual retention rates ranging from 0.25 to 2.58 g-P m^{-2} $year^{-1}$. Overall, the retention rate was 1.44 g-P m^{-2} $year^{-1}$ (Table 2). The dominant phosphorus retention pathway was physical sedimentation. Biological assimilation of phosphorus from the water column by plankton and periphyton represented an average of only 14% of the phosphorus contained in the inflow. Phosphorus taken up by macrophytes from deep sediments is in the relative amount of 74% of total phosphorus in the inflow; however, most phosphorus cycled through macrophytes is later reincorporated into the sediments.

While the complex and detailed wetland model of the DPRW was successfully used to explore the role of different functions or structures of the wetland ecosystem in relation to phosphorus dynamics, this model required a large amount of data only available at extensively studied sites such as the Des Plaines River. Based on the detailed ecosystem model, a refined simple Vollenweider-type model (Fig. 3, upper right) which treats a wetland as a 'black-box' was used in the two subsequent study described below that looked at the potential for restoring wetlands along the Great Lakes coastline. This model was also validated with extensive Des Plaines River data (Mitsch et al., 1995).

3.2. Restored coastal wetlands in agricultural land

The simple model was applied with accompanying uncertainty analysis to potential wetland restoration in a small (208 km^2) agricultural watershed in northeastern Michigan.

Table 2
Model predictions of phosphorus retention in constructed and restored wetlands at three different watersheds around the Great Lakes

	Des Plaines River Watershed[a]	Quanicassee River Watershed	Sandusky River Watershed
Watershed			
Drainage basin area, km^2	378	208	3240
Mean annual flow, $m^3\ s^{-1}$	3.2	11	28.8
Mean phosphorus concentration, $\mu g\ l^{-1}$	155	138	338
Total phosphorus loading, t $year^{-1}$	15.7	48	307
Phosphorus yield, g-P m^{-2} $year^{-1}$	0.042	0.231	0.095
Wetland			
Area of wetlands, km^2	0.1	31.2	17.3
Percent of watershed, %	0.03	15	0.53
Percent of upstream flow passing through wetland, %	0.8	92	50
Average hydraulic loading rate, m $year^{-1}$	12.8	9.3	8.2
Phosphorus loading, g-P m^{-2} $year^{-1}$	1.69	1.04	2.7
Phosphorus retained, g-P m^{-2} $year^{-1}$	1.44	0.81	2.2
t $year^{-1}$	0.15	25.3	38
Total watershed phosphorus reduction, %	1	53	12
Phosphorus-equivalent watershed: wetland ratio[b]	35	4	23

[a] Technically out of Great Lakes drainage basin but created wetlands were used to calibrate and validate model.
[b] Phosphorus-equivalent watershed-wetland ratio (m^2 watershed/m^2 wetland) = (phosphorus retained in wetland, g-P m^{-2} $year^{-1}$)/(phosphorus yield in watershed, g-P m^{-2} $year^{-1}$.

The estimates found that there is the potential for 31.2 km^2 of wetland restoration in the area being investigated by the Michigan Department of Natural Resources (MDNR) south of the Michigan Highway 25 and within the 585 feet contour line (Fig. 5). The model results illustrated the relative importance of inflows, wetland water depth, antecedent soil conditions, and amount of restoration (details in Wang and Mitsch, 1998). According to the simple model, wetland restoration to maximize phosphorus reduction should consider designing restored wetlands to receive as much upstream river or runoff water as possible. The model estimates that the restoration of 15% of the Quanicassee River basin to wetlands (3120 ha) would result in a reduction of more than half (53%) of the phosphorus that enters Saginaw Bay from that basin (Table 2), assuming that a proper hydrologic connection between the wetlands and the river could be established. The model also illustrated that initial phosphorus storage in the soils prior to wetland restoration was a relatively small effect ($<15\%$) in long-term phosphorus retention by the wetlands (Fig. 8).

Nevertheless, phosphorus loading from the Quanicassee River watershed represents only about 3% of the total phosphorus load to Saginaw Bay from all sources. To make a significant impact on the control of phosphorus entering

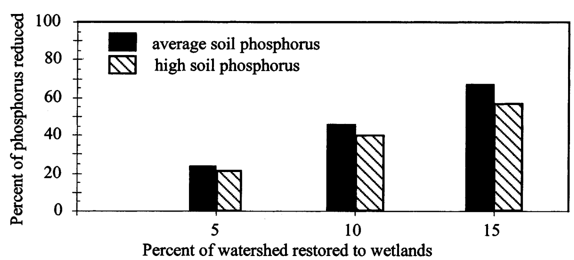


Fig. 8. Percentage of total phosphorus reduction versus percentage of watershed restored to wetlands, in the Quanicassee River watershed, Michigan. Assumes 30-cm average depth of wetlands and 9.3 m $year^{-1}$ inflow. Two conditions are for average (10.1 g m^{-2} or 90 lb $acre^{-1}$) and high (24.9 g m^{-2} or 222 lb $acre^{-1}$) initial soil phosphorus levels.

Saginaw Bay and thereby control the symptoms of eutrophication there, a concerted effort of wetland restoration on a similar scale would have to take place throughout all of the river basins that drain into the Saginaw Bay. The means by which water would be routed through these restored wetlands and drainage systems altered to allow for the proper hydrology would require further investigation.

3.3. Hydrologically restored wetlands

To estimate the potential contribution of coastal wetland restoration to water quality improvement, a total of 17.3 km^2 of coastal wetlands in the Sandusky River delta were identified from a spatial data base to have the potential to receive water from the river (Fig. 6). The simple phosphorus model similar to the one used for the Saginaw Bay site was run with mean river flow (1924–1994) to estimate the potential role of these coastal wetlands for phosphorus retention. The 1730 ha coastal wetlands at the mouth of Sandusky River have the potential to reduce 12% (38 metric tons $year^{-1}$) of the total phosphorus that enters Sandusky Bay from the upstream watershed (Table 2). This situation, of course, would require that the wetlands in the western reach of the Bay that are currently diked (most of the 1730 ha) and thus isolated from the river would be restored hydrologically to allow the river water to flow through them.

3.4. Comparison of sites

These three watersheds ranged from 200 to 3200 km^2 with mean annual flow rates ranging from 3 to 29 $m^3\ s^{-1}$ (Table 2). Average simulated hydraulic loading rates to the wetlands were between 8 and 13 m $year^{-1}$. The Quanicassee River watershed yields 0.231 g-P m^{-2} $year^{-1}$ of phosphorus, the highest among the three watersheds. One unit area of wetlands there is able to remove phosphorus yielded from 4 unit areas of watershed. In other words, restoration of only 1% the watershed into wetlands would result in the removal of 4% of the total watershed phosphorus loading. For low-phosphorus yield watersheds such as the Sandusky River (0.095 g-P m – 2 $year^{-1}$) and the Des Plaines River (0.042 g-P m^{-2} $year^{-1}$), restoration of 1% of the wetlands could remove 23 and 35% of total watershed phosphorus loading, respectively. Large-scale wetland restoration appears to be a viable management practice for controlling phosphorus and other nonpoint source pollution from entering the Great Lakes, although its effectiveness is clearly site specific.

3.5. Finding potential wetlands along the Great Lakes

The above dynamic model applications assume that a suitable area for wetland restoration has been found. A GIS-based modeling approach was applied for identifying areas where wetland restoration would be most suitable in the Sandusky Bay area. Finding such sites is complicated along the Great Lakes because lake water levels change from year to year. For example, Lake Erie has shown a range of 1.8 m in its average monthly water level over the past 100 years, from the highest water level in July 1986 (175.0 m amsl (above mean sea level)) to the lowest water level in March 1934 (173.2 m amsl) (Fig. 9). Coastal wetlands along the Great Lakes were basically moving bands of vegetation and habitat, depending on the lake level in that particular year (Mitsch, 1992).

A DEM with a 1:24 000 scale and 39 m resolution was created for the study area around Sandusky Bay to illustrate the area where wetlands could or do occur, i.e. where inundation occurred over the past 95 years within the 1.8 m of water level fluctuation of Lake Erie. The total land area in Fig. 10a is about 940 km^2 with elevations ranging from 168.2 to 197.8 m with a mean of 175.8 m. About 10% of this area around Sandusky Bay study area is potentially affected by the range of historic monthly average lake levels of 173.2–175 m amsl (Fig. 10a).

Simulations were developed with the wetland distribution model for the 95-year record of water level changes, assuming that dikes were not present, to illustrate the distribution of wetland types that are potential for this arm (Fig. 10b).

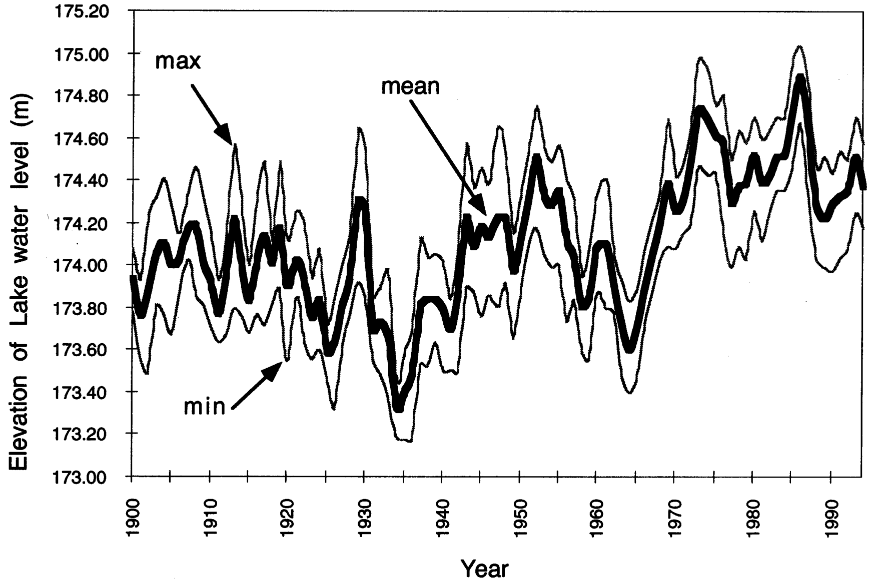


Fig. 9. Water levels of Lake Erie in elevations above sea level from 1900 to 1994. These data were used to simulate the rise and fall of lake levels and subsequent frequency distribution of wetland types in digital elevation model used on Sandusky Bay.

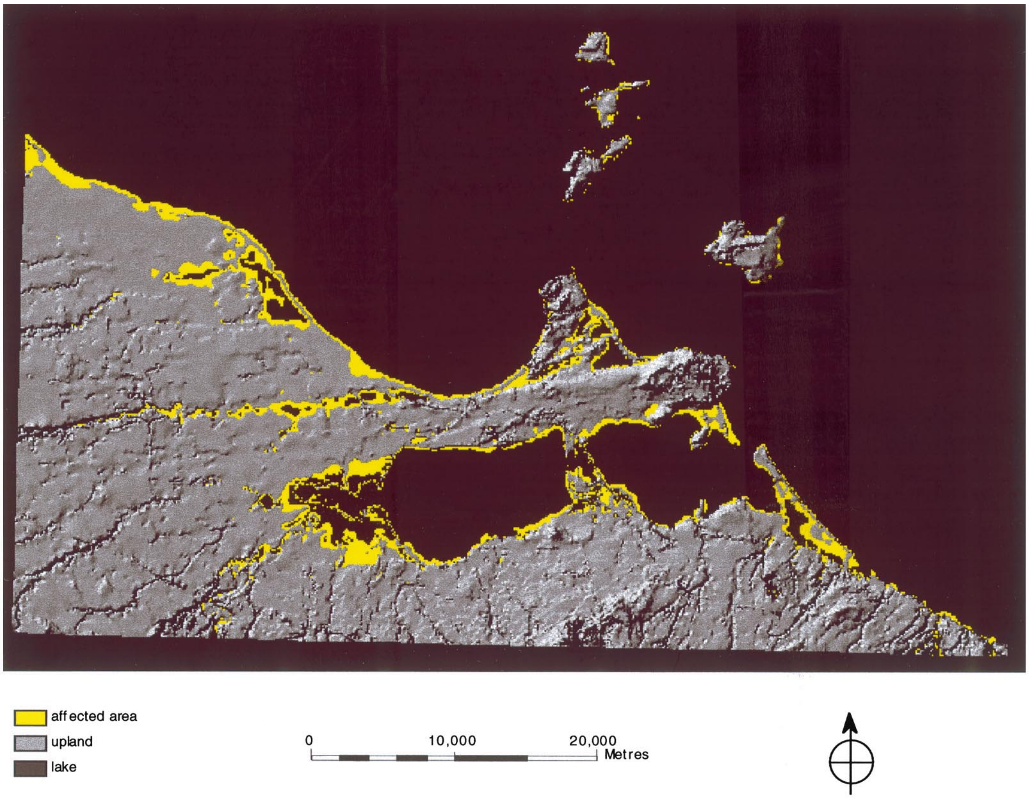
The original classification used included: not flooded, intermittently flooded, shallow marsh; deep marsh, and open water. Over the 95-year simulation, the elevation at which marsh wetlands (estimated to be deep marsh, shallow marsh, and intermittently flooded combined) are found more than 50% of the years is in a narrow 80 cm elevation range of 173.5–174.3 m amsl (Fig. 10b and Fig. 11). Deep marsh is the most likely type of marsh in this range. On either side of this elevation range, either open water or not flooded occurs more than half the time. Overall, simulations of 95 years illustrated that 1432 ha of marshes were possible more than 50% of the time while there were 2235 ha where open water was possible more than 50% of the time (Fig. 10b). Most of these wetland elevations are currently diked wetlands (2100 ha) that could be hydrologically restored. This GIS simulation indicates that removing the dikes would essentially remove marsh vegetation in large parts of this study area.

4. Conclusions

To meet two major resource goals of the Great Lakes—restoring wetland habitat and controlling pollution entering the lakes—coastal restoration projects on the Great Lakes should have dual success criteria of wildlife enhancement and improvement of water quality. The application of coastal wetland restoration at certain locations can result in both. The best strategy for wetland restoration to maximize nutrient reduction appears to be designing restored wetlands to receive upstream river or runoff water. In some cases this involves the conversion of flooded agricultural lands back to wetlands; in other cases the dikes that 'protect' wildlife protection wetlands might have to be breached.

In the spatial and temporal models we attempted to describe variables such as wetland extent and water quality enhancement in relatively simple approaches that cover longer time spans and larger areas than those covered in individual restoration projects. While our models are limited by assumptions, they can be used to predict the behavior of systems prior to restoration rather than relying on the current approaches from individual case studies. The wetland distribution model demonstrated that spatial data bases, when coupled with other readily available data bases

(a)



(b)

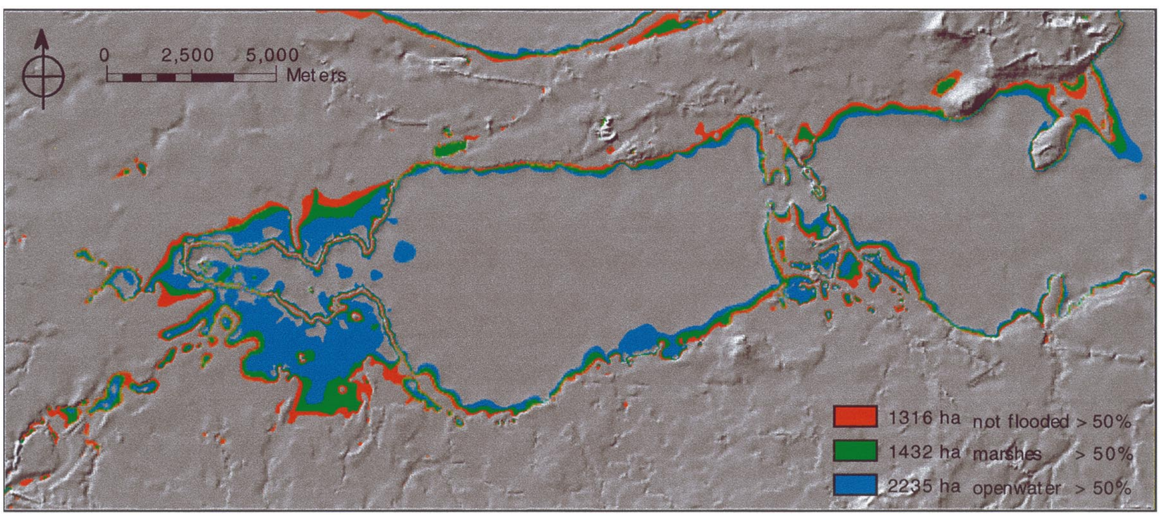


Fig. 10. Sandusky Bay digital elevation model results showing: (a) area that would be affected by highest and lowest lake water levels; and (b) nearshore areas that have more than 50% chance of being one of the transitional zones — open water, marsh, and not flooded — over the last 95 years.

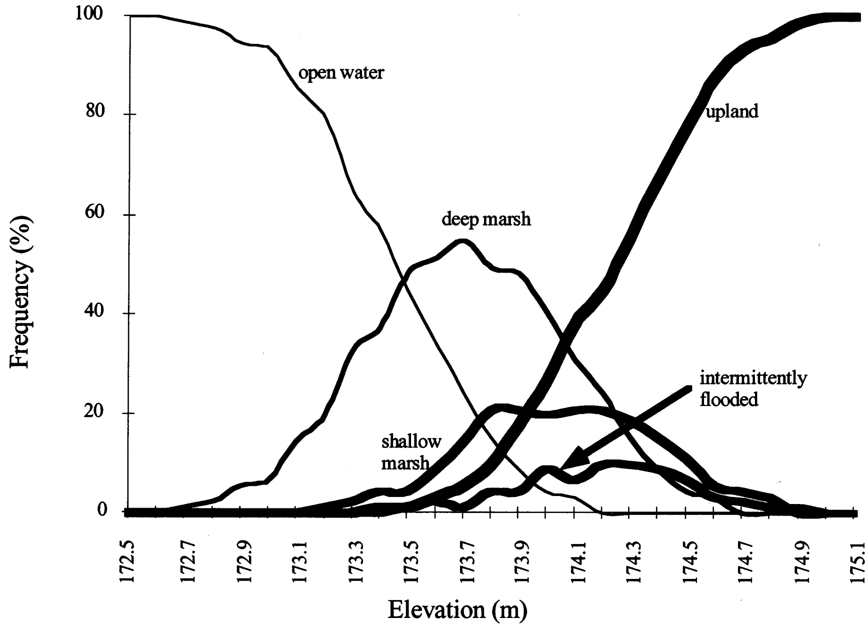


Fig. 11. Frequencies of each wetland type occurring under natural conditions at different elevations of Sandusky Bay study area over the period 1900–1995.

such as historic lake levels, can provide an effective means for identifying sites along the Great Lakes coastline where the potential for largescale wetland restoration would be highest.

4.1. Will Great Lakes coastal wetland restoration occur

The coastlines of the Great Lakes are over managed; it is from this overuse that many of the problems in the lakes themselves are caused. The restoration of the coastline of the Great Lakes with ecosystems that connect the watersheds and the lakes is an optimum situation from an ecological perspective. But there are many stakeholders in the region, from those interested in hunting and fishing along the shoreline and those interested in having a lakeshore 'view' even at the expense of a natural shoreline, to those who see the lake in the perspective of swimming beaches and amusement parks. The shoreline of the Great Lakes is dynamic, a concept that is in direct conflict with our ideas of legal property boundaries.

Ultimately interest in coastal wetland restoration around the Great Lakes will manifest itself if enough public support is forthcoming as has occurred in areas such as the Florida Everglades, Chesapeake Bay, the Louisiana coastline, or Delaware Bay. The challenge, which needs to be assisted by systems approaches as demonstrated in this paper, is to be ready to provide accurate predictions on the implications and benefits of restoration. Then we can work toward a multifunctional shoreline with optimum connectivity between the uplands and the Great Lakes through nature's transition zones—wetlands.

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