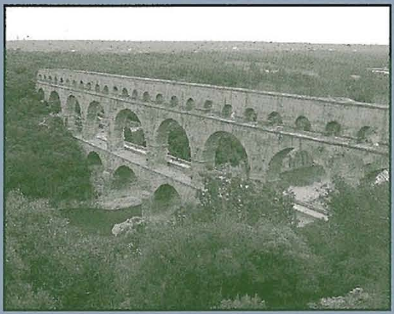
ASCE
AMERICAN SOCIETY OF CIVIL ENGINEERS

September / October 2010 • Volume 136, Number 5
ISSN 0733-9496 • CODEN: JWRMD5



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Phosphorus Budget and Remediation Plan for Big Platte Lake, Michigan

Raymond P. Canale[1]; Todd Redder[2]; Wilfred Swiecki[3]; and Gary Whelan[4]

Abstract: This paper presents a phosphorus budget and modeling case study for Big Platte Lake Michigan and the Platte River watershed. These analyses are a necessary component of a credible total maximum daily load (TMDL) for Big Platte Lake and may be more broadly applicable to similar systems and other water quality management issues. A calibrated Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) model is used to simulate total phosphorus loads from the watershed. A nonsteady state lake model is developed to predict total phosphorus concentrations in both the water column and the sediments. Temperature and dissolved oxygen models are used to predict the anoxic periods in the lake hypolimnion to facilitate calculation of the internal phosphorus loading due to sediment release. Following calibration, the models were used to determine allowable total phosphorus loads for Big Platte Lake for typical hydraulic conditions. Current measured total phosphorus loads exceed model calculated allowable loads. Therefore various nonpoint remediation alternatives were evaluated as a means to reduce the excess loading. The credibility of the analyses was enhanced because of the availability of laboratory measurements of sediment phosphorus release rates and an extraordinarily comprehensive database of current and historical lake and tributary water quality measurements.

DOI: 10.1061/(ASCE)WR.1943-5452.0000071

CE Database subject headings: Phosphorus; Water quality; Hydraulic models; Lakes; Michigan.

Author keywords: Phosphorus; Nonpoint loading; TMDL; Water quality model; BASINS.

Background

The Platte River watershed is located in the northwest region of the Lower Peninsula of Michigan and has a total drainage area of approximately 495 km^2 (see Fig. 1). The drainage is dominated by deep glacial outwash deposits and the watershed soils are predominantly sand. Big Platte Lake (Lake) is the largest lake in the lower watershed. It has a volume of 83.5 million m^3, a mean depth of 8.2 m, a maximum depth of 28 m, and a mean hydraulic retention time of about 0.75 years. The Platte River (River) is the major source of water inflow to the Lake. The discharge of the River has been measured by the USGS (USGS Gauge #04126740) near Honor, Michigan since 1990 (see Fig. 1 for the location of the gauge station). The mean discharge of the River is 3.5 m^3/s over the period of measurement, and most of this flow is from groundwater sources. The largest tributary of the River is the North Branch, which enters the main tributary approximately 0.6 km upstream of the inlet to Big Platte Lake.

Phosphorus limits the growth of algae in Big Platte Lake. Phosphorus enters the Lake water column from point, nonpoint, and internal sources. The only significant point source of phosphorus in the watershed is the Platte River State Fish Hatchery (Hatchery) operated by the Michigan Department of Natural Resources (MI DNR). This facility produces Coho and Chinook salmon for the Great Lakes fishery. The Hatchery uses surface water to culture fish, and this water becomes enriched with phosphorus from fish fecal pellets, urine, and unconsumed feed. The outflow from the Hatchery discharges into the Platte River 17.7 km upstream of Big Platte Lake. The maximum Hatchery phosphorus loading was estimated to be 1,960 kg/year in 1974. Today, the mean net loading from the Hatchery is only about 79 kg/year. This reduction was attained by upgrading the solids handling technology at the facility and by using low phosphorus fish feed. The Hatchery contributes approximately 3% of the total phosphorus load that enters the Lake and is currently compliant with National Pollutant Discharge Elimination System (NPDES) requirements. Most of the remaining phosphorus load originates from nonpoint sources associated with groundwater flow, watershed runoff, and precipitation. The Lake also has internal phosphorus loads that result from release of phosphorus from the bottom sediments during anoxic periods and from the death and subsequent decay of migrating salmon.

The applicable water quality standard requires that the annual average volume-weighted total phosphorus concentration of Big Platte Lake be maintained below 8.0 mg/m^3 95% of the time. This standard is a court-ordered directive that was prescribed sub-

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Note. This manuscript was submitted on May 15, 2009; approved on December 15, 2009; published online on August 13, 2010. Discussion period open until February 1, 2011; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Water Resources Planning and Management***, Vol. 136, No. 5, September 1, 2010. ©ASCE, ISSN 0733-9496/2010/5-576–586/$25.00.

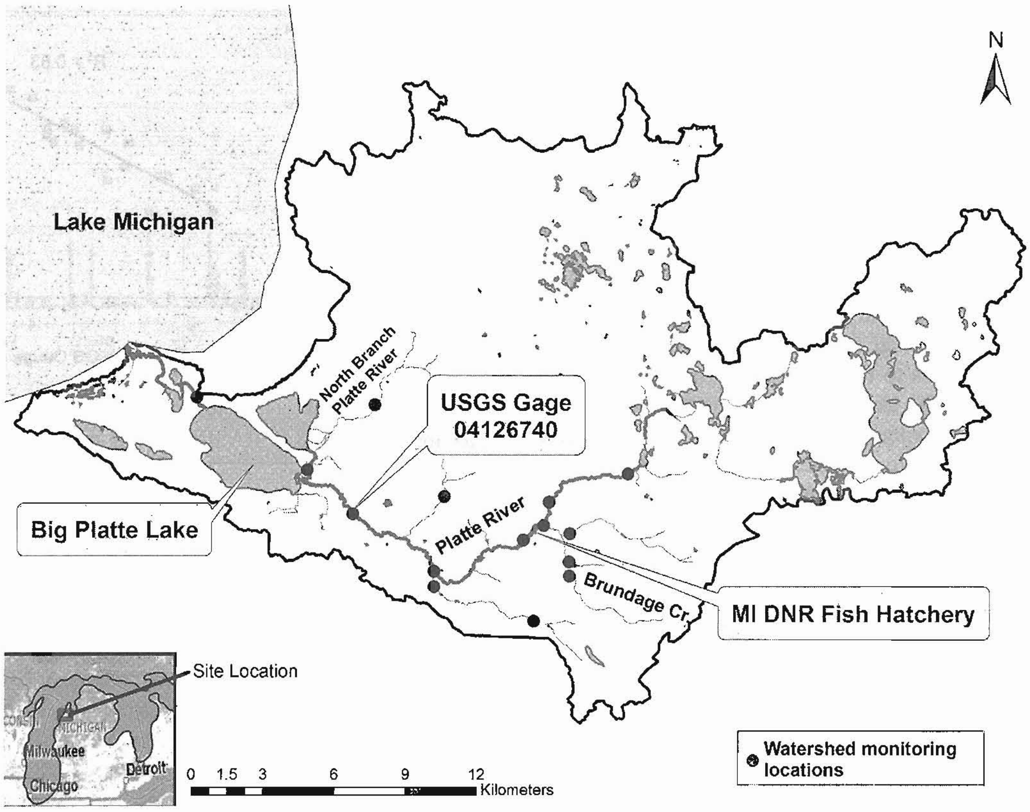


Fig. 1. Big Platte Lake and Platte River watershed

sequent to legal actions taken by residents of the Lake against the MI DNR as fully described in Canale et al. (2004). Currently the volume-weighted annual average Lake total phosphorus (TP) concentration typically varies between 7 and 9 mg/m^3 and has not complied with the water quality standard in recent years.

The Clean Water Act of 1972 mandates that analyses be performed to determine allowable phosphorus loads from point and nonpoint sources that are consistent with the water quality standards. This allowable loading is called a total maximum daily load (TMDL). The purpose of this paper is to present the results of technical analyses that are necessary to develop a credible TMDL for Big Platte Lake and may be more broadly applicable to similar systems. The approach uses a model for the phosphorus loading from the watershed and a model for the annual average total phosphorus concentration of Big Platte Lake. These two models will be applied to determine an allowable phosphorus loading to the Lake and quantify the annual average phosphorus load reduction needed to meet the water quality standards. This reduction most logically must be achieved exclusively through control of nonpoint sources because the Hatchery is currently a minor component of the overall loading. Finally, the models will be used to analyze the effectiveness of various nonpoint phosphorus control measures.

Sampling Program

The phosphorus loading reduction needed to meet the water quality standards for Big Platte Lake will affect public policy and expenditures, local zoning, and the attitudes and behaviors of private citizens. Thus, it is imperative that the calculations for the required phosphorus loading reduction be credible and defensible. This requires that the watershed phosphorus loading and lake water quality models be carefully calibrated using local water quality data. The Big Platte Lake and Platte River watershed monitoring program is quite comprehensive, and the details of the effort have evolved and expanded over time. The description below summarizes the current program.

Big Platte Lake has been sampled at the deepest location (approximately 28 m) at eight discrete depths every 2 weeks since 1993 except when ice conditions restrict access. Three replicate samples are taken at each depth and analyzed for total and dissolved phosphorus and turbidity. In addition, surface composite samples are collected using a 10 m vertical tube. Composite samples are analyzed for total and dissolved phosphorus, nitrate, nitrite, chlorophyll *a*, turbidity, alkalinity, phytoplankton, total dissolved solids, and calcium. Vertical net hauls are used to collect zooplankton. Other measurements include Secchi depth and vertical profiles of dissolved oxygen, temperature, pH, and light intensity.

Total phosphorus, nitrate, nitrite, turbidity, and flow have been measured at several Platte River and tributary locations every 2 weeks since 1990 (Fig. 1). The baseline flow data have been supplemented with measurements taken during more than 100 storm events between 2003 and 2007. Total phosphorus, turbidity, and flow were measured during these events using automated sampling equipment.

Hatchery discharge flow and phosphorus concentrations have been measured regularly since 1981. The current program collects samples two times per week from both the discharge and input locations to the Hatchery to permit calculation of the net loading as specified by NPDES regulations. Phosphorus concentrations are also obtained from the fish food used at the Hatchery and on sludge solids trucked away from the Hatchery. Periodic measurements of salmon tissue phosphorus also are taken to allow estimates of the amount of phosphorus in fish transported from the Hatchery. These measurements account for all of the inputs and outputs of phosphorus to and from the Hatchery and serve as the basis of a mass balance and bioenergetic model for fish production currently under development. The purpose of this model is to predict the phosphorus loading from the Hatchery as a function of the number and size of the fish produced and the efficiency of various facility waste treatment operations.

Other measurements complement the routine Lake, River, tributary, and Hatchery monitoring efforts. Rain water has been collected and analyzed for total phosphorus, nitrate, and nitrite concentrations over 40 times to facilitate estimation of the atmospheric loading to the Lake. A hydroacoustic survey was conducted to determine the density and percent coverage of macrophytes in Big Platte Lake in 2002. Macrophyte tissue phosphorus measurements were also taken to permit calculation of the mass of phosphorus associated with the plant biomass in the Lake. The phosphorus content of shoreline buffer zone plant material and debris was measured to permit estimates of the effectiveness of shoreline maintenance efforts. Migrating salmon are restricted from entering Big Platte Lake except during times when weir gates located downstream of the Lake are opened to allow upstream passage. All fish are individually counted as they enter the Lake and when they eventually arrive at an upstream collection facility located at the Hatchery. Fish counts at both the downstream and upstream locations, as well as size and tissue phosphorus measurements, allow calculation of the potential internal phosphorus loading to the Lake through the decay of spawning salmon biomass. Undisturbed sediment core samples were collected in 2004 and 2005 for laboratory measurement of sediment oxygen demand (SOD) and aerobic and anaerobic phosphorus sediment release rates. These measurements are the basis of estimates of the internal phosphorus loading from the sediments to the lake water column during periods of low bottom water dissolved oxygen concentrations. Finally, an ongoing study is being conducted to measure biologically available phosphorus from the Hatchery and various River and tributary locations using algal bioassay methodologies.

Watershed Phosphorus Loading Model

The purpose of the watershed model is to predict the flow and nonpoint loading of phosphorus into Big Platte Lake from the Platte River as a function of land use in the watershed for various hydrologic and hydraulic conditions. This task was accomplished by using the Hydrologic Simulation Program—FORTRAN (HSPF) model found within the overall EPA BASINS model framework (Bicknell et al. 2001). The HSPF framework has wide acceptability and is commonly used to simulate watershed hydrology, runoff, and instream nutrient transport. As a notable example, HSPF serves as the watershed component of the modeling framework developed to support the Chesapeake Bay Program (U.S. EPA, "Chesapeake Bay Phase 5 Community Watershed Model," in preparation, 2008). Recent and ongoing nutrient TMDL evaluations for the Minnesota River (MN) and the Truckee River (NV) are also based on HSPF model applications (Butcher et al. 2004; Peternel-Staggs et al. 2008). The model is capable of simulating daily stream flows, as well as instream total phosphorus and total suspended solids concentrations at various locations within the watershed. However, these impressive model capabilities alone do not guarantee credible predictions without careful calibration and validation using large amounts of local terrestrial, stream flow, water quality, and meteorological data.

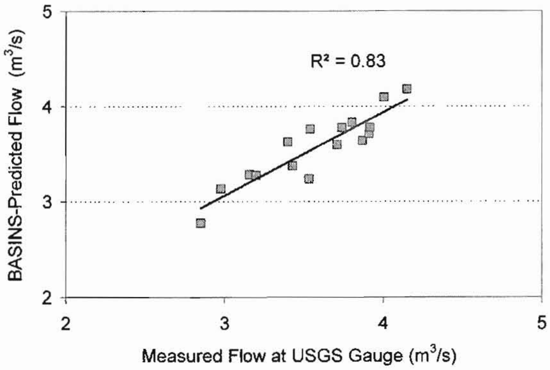


Fig. 2. Measured total annual flow of the Platte River at USGS gauge location compared to BASINS model predictions for various years

Hydrologic and hydraulic calibration of the BASINS-HSPF model was based on comparisons between model predictions and observed flows for the Platte River at the USGS gauge. Fig. 2 compares the measured and model-predicted annual average flows for 1990 through 2005 (R^2=0.83, slope=0.99). These results indicate that the model adequately simulates the long-term hydrologic response of the watershed and the variations in flow volume across dry and wet years. The model also closely matches observed trends in mean monthly flows (R^2=0.77, slope=0.94) and mean daily flows (R^2=0.71, slope=1.04) at the USGS gauge during the 16-year calibration period. Statistical error metrics, including RMS error (RMSE) and mean absolute relative error (MRE), also compare favorably for mean monthly (RMSE =8.9 cfs, MRE=5.4%) and mean daily (RMSE=14.4 cfs, MRE=6.4%) results during this period. Collectively, these statistical comparisons illustrate that the model accurately captures the seasonal and daily hydrologic response of the watershed. Overall, the annual, seasonal, and daily flow trends and patterns measured at the USGS location are consistent with model predictions as discussed in more detail in Canale et al. (2004).

The calibration of the BASINS-HSPF model for total phosphorus focused on comparisons between predicted and measured total phosphorus concentrations and estimated annual average loads at several River and tributary locations within the watershed. The total phosphorus calibration proceeded in a two-step iterative process. Model sediment and nutrient input parameters affecting total phosphorus runoff were configured to achieve unit area loads (UALs) consistent with ranges reported in the literature. Next, the model parameters were adjusted to compute diffuse loadings to match observed concentration and loading measurements at the USGS gauge station and other River and tributary locations. Fig. 3 shows an example of hourly model predictions compared to discrete measured total phosphorus concentrations in the Platte River at the USGS gauge station for 2005. The model results compare favorably to concentration measurements taken during both baseline and wet weather flow conditions (R^2=0.62 for 2005). Similar comparisons have been made for other locations and time periods as discussed in Canale et al. (2004). In addition, the model achieves good agreement with data-based estimates of the annual total phosphorus loading for the Platte River at the USGS gauge station (Fig. 4) (MRE =16%) and at various other locations in the watershed (Fig. 5). The favorable daily concentration and annual loading comparisons between the model output and data-based estimates provide

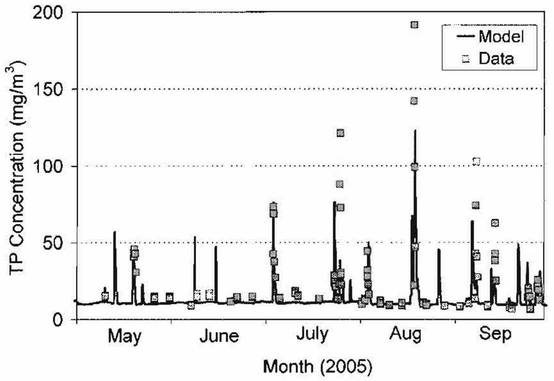


Fig. 3. Measured total phosphorus concentrations (squares) and BASINS model predictions (line) for 2005 at the Platte River USGS gauge location

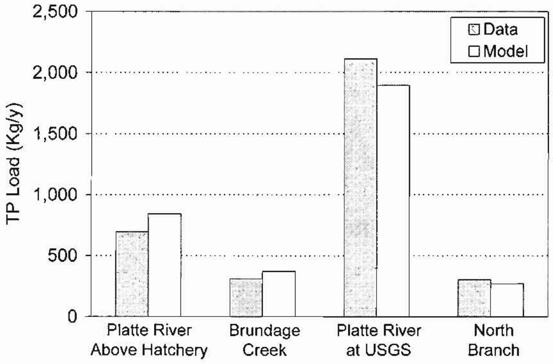


Fig. 5. Measured total annual total phosphorus loads (shaded bars) and BASINS model predictions (open bars) for 2005 at various watershed locations

confidence that the model can be used not only to reproduce recently measured watershed phosphorus loading, but also to reliably predict future loadings under various hydrologic and hydraulic conditions of interest.

Lake Water Quality Model

Overall Approach

The objective of this section is to develop reliable and practical models to predict long-term changes in total phosphorus concentrations in Big Platte Lake and to identify an allowable loading consistent with the water quality standards. Upon first consideration one might think that the preferred way to proceed would be to use a model that simulates a wide array of chemical and biological components of the ecosystem everywhere in the Lake and sediments at all times. Such a model would have several forcing functions such as flow, phosphorus loading, temperature, light intensity, and other meteorological variables. The model might have detailed horizontal and vertical resolution in the water column and sediments, dozens of dependent variables, and hundreds of coefficients to define the chemical and biological kinetics and the mass transport processes, perhaps on an hourly time scale to simulate diurnal changes.

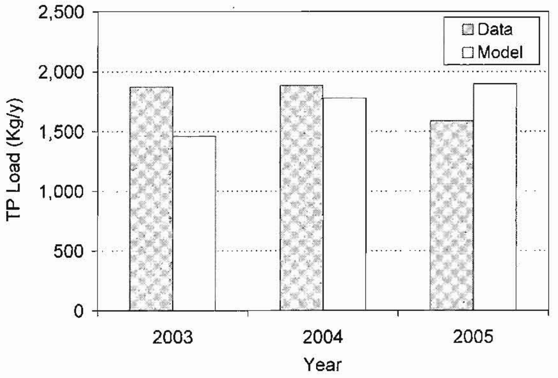


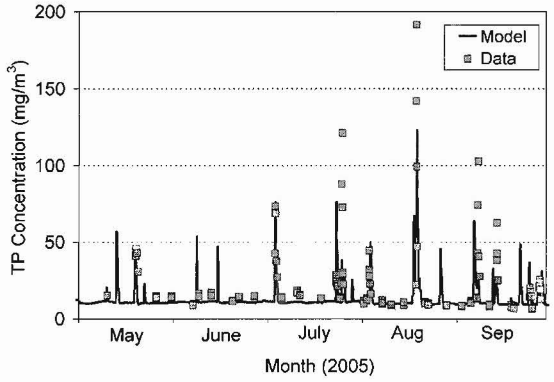
Fig. 4. Measured total annual total phosphorus loads (shaded bars) and BASINS model predictions (open bars) for various years at the Platte River USGS gauge location

However, as a practical matter, the coefficients and forcing functions of any model can never be known with exact certainty. Errors in the model coefficients and forcing functions propagate through the structure of the defining differential equations and expand in magnitude as the equations are integrated through space and time. As a result, the overall reliability of models can decrease as the number and uncertainty of the model variables, coefficients, and inputs increases. These issues have been extensively examined from both deterministic and stochastic perspectives (Seo and Canale 1996; Canale and Seo 1996). These analyses suggest that it may be most appropriate to use simple models for planning applications that are consistent with the availability of supporting lake and tributary water quality measurements. The downside of such an approach is that models with frameworks that are too simple may not be able to realistically simulate all of the important water quality parameters. Therefore, it is important to explore and test the effectiveness of models with an intermediate level of framework complexity because models that are either too simple or too complex may be unreliable and subject to scientific and legal challenge.

Two separate water quality modeling approaches are being developed simultaneously for Big Platte Lake to accommodate these considerations. The water quality standard for Big Platte Lake is based on whole lake volume-weighted annual average total phosphorus concentrations. Therefore, the primary approach as described here involves a model designed to predict annual average total phosphorus concentrations. This phosphorus model needs an associated seasonal dissolved oxygen model because the rate of phosphorus release from the lake bottom sediments depends on the hypolimnetic dissolved oxygen concentration. The overall model has relatively simple mechanisms and is easy to use, but it does not provide insight into the fine points of the chemical and biological dynamics of the Lake. The second approach uses a more complex ecosystem model that can provide more detailed information when needed. This latter model has multiple phosphorus components, dependent variables for the phytoplankton and zooplankton populations, and can simulate water clarity as described in more detail in Canale et al. (2004).

Model Description

Fig. 6 illustrates the total phosphorus model for Big Platte Lake and the lake bottom sediments used for this case study. The model has single water and sediment layers that are assumed to be completely mixed in both the horizontal and vertical directions. The



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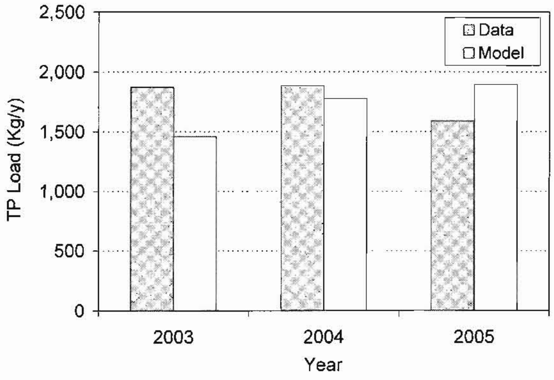

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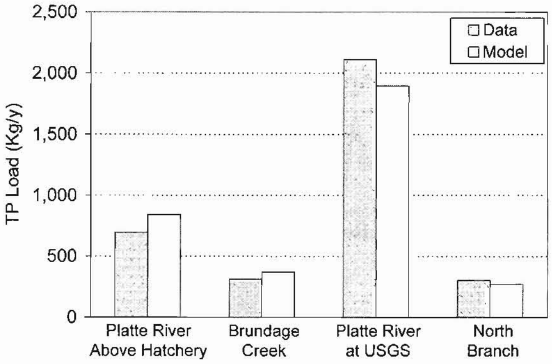

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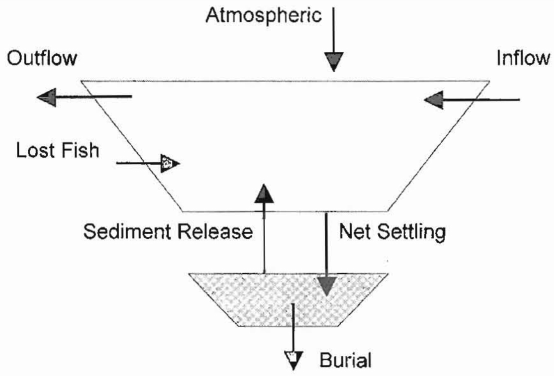

Fig. 6. Two-layer Big Platte Lake water and sediment model and components

phosphorus model mechanisms include point and nonpoint external loads, discharge through the lake outlet, settling losses to the bottom sediments, internal loading due to release from the sediments, and sediment burial. The nonsteady state mass balance equations are similar to those used by Chapra and Canale (1991) and Seo and Canale (1996) and are given by

$$V_w \frac{dP_w}{dt} = W - QP_w - v_s A_s P_w + v_r A_r P_s \quad (1)$$

$$V_s \frac{dP_s}{dt} = v_s A_s P_w - v_r A_r P_s - v_b A_r P_s \quad (2)$$

where A_r=phosphorus release area (m^2); A_s=settling area (m^2); P_s=sediment total phosphorus concentration (mg/m^3); P_w =water total phosphorus concentration (mg/m^3); Q=hydraulic flow rate (m^3/year); t=time (years); v_b=sediment burial rate velocity (m/year); v_r=phosphorus release rate velocity (m/year); v_s=settling rate velocity (m/year); V_s=volume of lake sediments (m^3); V_w=volume of lake water (m^3); and W=total annual external phosphorus loading (mg/year).

Significant phosphorus release from the bottom sediment of Big Platte Lake occurs only when the sediments are anaerobic. These conditions occur when the average concentration of dissolved oxygen in the hypolimnion is less than about 2 mg/L (Michigan Department of Natural Resources 1990). Thus it is necessary to have a model that predicts the seasonal variation of the hypolimnetic dissolved oxygen concentrations to permit calculation of the fraction of the year when significant sediment release occurs. The hypolimnetic dissolved oxygen model mechanisms include hydraulic exchange between the epilimnion and hypolimnion and the hypolimnetic oxygen demand rate. Eq. (3) is the basis of the dissolved oxygen component of the Lake model.

$$V_h \frac{d\mathrm{DO}_h}{d\tau} = v_e A_e(\mathrm{DO}_e - \mathrm{DO}_h) - A_r(\mathrm{HOD}) \quad (3)$$

where A_e=area of the thermocline (m^2); DO$_e$=epilimnion dissolved oxygen concentration (mg/L); DO$_h$=hypolimnion dissolved oxygen concentration (mg/L); HOD=hypolimnetic oxygen demand rate (gm/m^2/day); τ=time (days); v_e=exchange rate velocity between epilimnion and hypolimnion (m/day); and V_h =volume of hypolimnion (m^3).

Eqs. (1)–(3) represent a simple yet robust nonsteady state model that can simulate long-term changes in lake water and sediment total phosphorus. Similar models have been successfully used in a wide variety of applications (for example, Lung and Canale 1977; Seo and Canale 1999).

Calibration Procedure

The first step toward calibration of the model is to define the annual average hydraulic and total phosphorus loadings to the Lake. The flow rates into the Lake for 1990 through 2008 are based on USGS measurements extrapolated to include the entire watershed. Nonpoint phosphorus loads for the Platte River watershed were calculated using flow and total phosphorus measurements and results from the BASINS model. The Hatchery point load is based on direct measurements and estimates using fish production at the facility (Canale et al. 2004). An internal phosphorus load results from losses of fish that migrate through the Lake. The phosphorus loading is calculated as the difference between the fish that enter the Lake and those that are collected at the Hatchery multiplied by the percent phosphorus in the fish flesh. This estimated internal load is an upper bound because some fish may be taken by anglers before they reach the Hatchery. The atmospheric phosphorus loading (0.10 kg/ha/year) is estimated by multiplying the annual rainfall by the surface area of the Lake and the average of measured phosphorus concentrations. This estimate is roughly twice the wet deposition rate estimated by Miller et al. (2000) for Lake Michigan in 1994–1995, and it is similar to the total phosphorus deposition rate estimated by Delumyea and Petel (1978) for Lake Huron. Therefore, the calculated deposition rate of 0.10 kg/ha/year was taken to be representative of total atmospheric deposition of phosphorus for the purpose of calibrating the Lake model.

The model coefficients are the sediment release rate velocity, the settling velocity, the deep sediment burial rate velocity, the exchange rate between the epilimnion and hypolimnion, and the hypolimnetic oxygen demand rate. It is desirable to obtain approximate numerical values for each of these coefficients to the extent possible using independent data sets rather than performing multiple degree of freedom calibrations. The simple structure of the model and the robust field and laboratory data for Big Platte Lake allow such an approach in this case.

Holmes (M. Holmes, "Relationship between Phosphorus Release and Sediment Characteristics in Big Platte Lake, Benzie Co., MI," unpublished 2005 summary report, 2005) collected undisturbed cores from several bottom locations in Big Platte Lake and conducted laboratory experiments to measure sediment phosphorus release rates and SOD rates. These results, along with accompanying measurements of P_s, can be used to develop a first-cut estimate of v_r. With this value for v_r now available, Eq. (1) can be used to calculate v_s because W is known from the BASINS model calibration, and extensive measurements are available for Q and P_w. With v_r and v_s known, Eq. (2) can be used to determine v_b. Minor adjustments in the values of these coefficients can now be made following inspection of the long-term changes in model calculated and measured Lake water and sediment total phosphorus concentrations and the annual phosphorus release from the sediments.

The seasonal dynamics of the depletion of dissolved oxygen concentrations in the hypolimnion depend on the transfer of oxygen from the epilimnion to the hypolimnion, and the hypolimnetic oxygen demand rate. Oxygen transfer to the hypolimnion from the epilimnion depends on hydraulic exchange rates (v_e) that vary seasonally with spring and fall mixing and summer thermal stratification. The exchange rates can be estimated by employing a

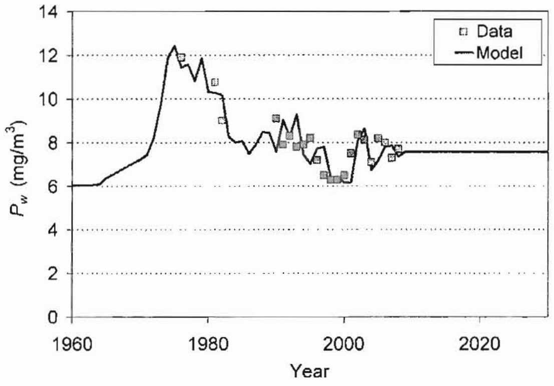

Fig. 7. Measured annual average total phosphorus concentrations (squares) for Big Platte Lake and model predictions (line) for various years

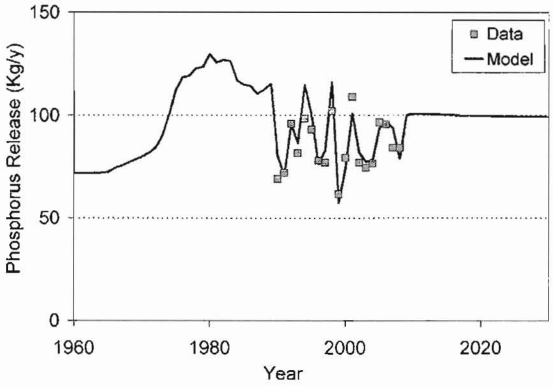

Fig. 9. Measured total annual release of total phosphorus from Big Platte Lake sediments (squares) and model predictions (line) for various years

two-layer temperature model that uses the measured epilimnion temperature as a forcing function and the hypolimnion temperature as the dependent variable. With the exchange rates thus determined, the HOD is calculated from Eq. (3) using measured dissolved oxygen data.

Calibration Results

Figs. 7–9 show measured data and model output for the annual average water total phosphorus concentration (MRE=8.5%), sediment phosphorus concentration (MRE=5.0%), and the total annual release of phosphorus from the sediments (MRE=6.2%). The calculations beyond 2009 are projections that will be discussed in a subsequent section of this paper. Fig. 10 shows measured dissolved oxygen data and the model calibration for 2005 (MRE=7.2%). Note the winter oxygen depletion that is a consequence of ice cover that is present for the first 45 days of the year. The major role of the dissolved oxygen model is to provide the capability to determine the number of days of low hypolimnetic dissolved oxygen as a function of changes in the external phosphorus loading and the Lake water phosphorus concentration. Fig. 11 shows the measured number of days when the dissolved oxygen in the hypolimnion is less than 2 mg/L compared to model calculations for 1990–2008. The physical dimensions of the system and a summary of the final calibrated values of the model coefficients are shown in Table 1.

The calibrated value for HOD is 0.89 gm/m^2/day for 2005. Similar calibrations were performed for other years using measured temperature and dissolved oxygen vertical profiles. Fig. 12 shows a plot of calibrated HOD values as a function of the measured annual average volume-weighted water total phosphorus concentration for 1990–2008. A power function least-squares fit of the data are given by Eq. (4)

$$\text{HOD} = 0.41 P_w^{0.425} \quad (R^2 = 0.31) \tag{4}$$

Note the correlation is not strong and the curvilinear relationship is not apparent because the range in total phosphorus concentration is rather small. Despite these limitations, the exponent in the Eq. (4) is similar to other published values. Chapra and Canale (1991) gave the exponent as 0.478, and Rast and Lee (1978) gave 0.467. On the other hand, the overall magnitude of the HOD for Big Platte Lake is about five times larger than that in these previous studies. Note, however, that most published values for HOD are based on observed decreases of dissolved oxygen concentrations in the hypolimnion that implicitly include transfer across the thermocline. The HOD values determined here by model calibration recognize and account for oxygen transfer across the thermocline and are subsequently higher than HOD values determined simply by calculating the slope of the hypolimnetic dissolved oxygen depletion curve. In addition, it is important to note that the HOD of any lake depends on the volume and depth of the hypolimnion as well as the phosphorus concentration in the

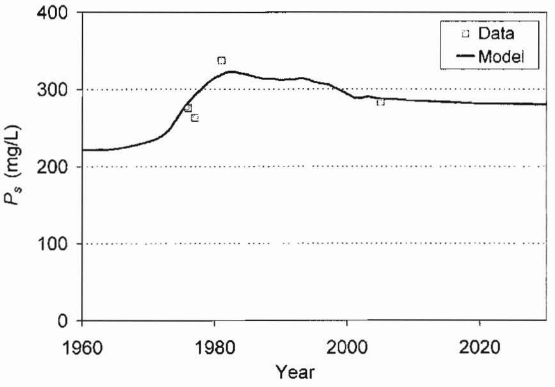

Fig. 8. Measured total phosphorus concentrations for Big Platte Lake sediments (squares) and model predictions (line) for various years

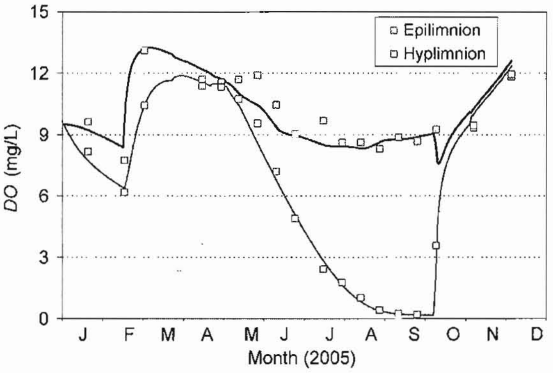

Fig. 10. Measured dissolved oxygen concentrations (squares) and model predictions (lines) for 2005 in the epilimnion and hypolimnion of Big Platte Lake

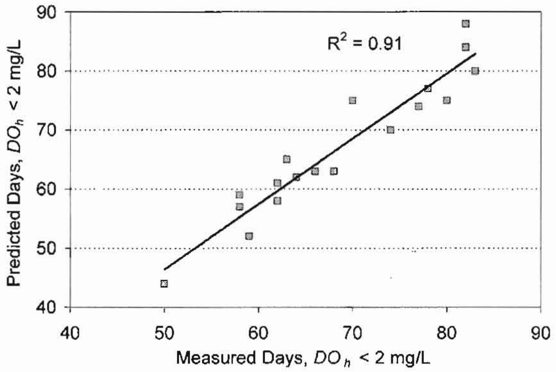

Fig. 11. Measured number of days the dissolved oxygen concentration in the hypolimnion of Big Platte Lake is less than 2 mg/L compared to model predictions for various years

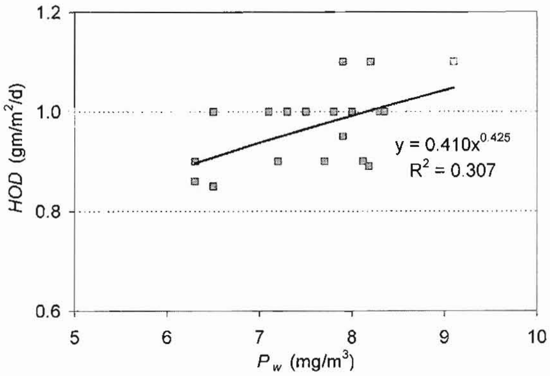

Fig. 12. Measured annual average total phosphorus concentration of Big Platte Lake versus model calibration values for HOD for various years

water column. The hypolimnion of Big Platte Lake is relatively small and is therefore expected to have a higher rate of oxygen depletion compared to a lake with a larger hypolimnion.

It is important to note that the empirical relationship between HOD and total phosphorus concentration has an implicit rational basis. The HOD is primarily a function of the SOD, bacterial respiration, and algal respiration that occurs under low light conditions in the hypolimnion. The algal and bacteria density and respiration are directly related to the phosphorus concentration of the water. SOD is related to the carbon deposition flux to the sediment, which is also proportional to the algal population. Complex mathematic models are available that can predict algal density and respiration rates in the hypolimnion, carbon deposition rates, and the resulting SOD (Di Toro et al. 1990; Chapra 1997) These models could certainly be used to circumvent the use of the empirical relationship given by Eq. (4). However, as discussed earlier in this paper, these complex models have important disadvantages associated with them, including greater resource requirements and the inclusion of model processes and coefficients that often cannot be parameterized using available data sets. Complex models are under development for Big Platte Lake and, when completed, will allow a quantitative evaluation and comparison of the merits and drawbacks of the empirical modeling approaches used here to estimate the HOD.

Holmes (M. Holmes, unpublished, 2005) determined that the average SOD of Big Platte Lake was 0.81 $gm/m^2/day$ in 2005 using undisturbed bottom sediment cores collected at several locations and depths. The difference between the calibrated value of the HOD and the measured SOD can be attributed to algal respiration. The apparent magnitude of the respiration component of the HOD was about 0.08 $gm/m^2/day$ in 2005. This estimate can be substantiated using 2005 measurements of hypolimnetic chlorophyll *a* and temperature. The average hypolimnetic chlorophyll *a* concentration was 2.0 mg/m^3 for 2005. An algal respiration rate of 0.07 per day was determined by preliminary calibration of the ecosystem model for the average measured hypolimnion temperature of 11°C. These measurements were used to calculate an average algal respiration depletion rate of about 0.1 $gm/m^2/day$ assuming a carbon to chlorophyll *a* ratio of 50. This value is close to the result estimated by subtracting the measured SOD from the calibrated value of the HOD. The above calculations indicate that the SOD is the dominant component of the HOD of Big Platte Lake and therefore would be a parameter of high priority in a more complex model.

Table 1. Calibration Values for Big Platte Lake Water Quality Model Coefficients

A_e	4.07×10^6	m^2
A_r	1.45×10^6	m^2
A_s	10.2×10^6	m^2
HOD (2005)	0.89	$gm/m^2/day$
v_b	0.0034	m/year
v_r (DO_h=<2 mg/L)	0.0011	m/year
v_e (summer)	0.0075	m/day
v_s	19.0	m/year
V_h	22.7×10^6	m^3
V_s	7.25×10^4	m^3
V_w	80.1×10^6	m^3

The annual amount of phosphorus released from the sediments is the product of the release rate velocity, the area of the sediment-water interface, the sediment phosphorus concentration, and the number of days of anoxia. The model calculations are compared to the measurements conducted by Holmes (M. Holmes, unpublished, 2005) in Fig. 9. This internal source is equivalent to an accumulation in the hypolimnion of about 3 mg/m^3 of phosphorus during the period of anoxia. This estimate is generally consistent with observations; however, the expected increase in concentration is relatively small, and the precision of the phosphorus measurements is limited in this low range. Therefore, any attempt to estimate the sediment release rate using increases in hypolimnetic total phosphorus concentrations in Big Platte Lake would be subject to unacceptably large errors. The anaerobic release rate velocity determined here is about 10 times smaller than that found in Shagawa Lake by Chapra and Canale (1991). This is not unexpected because the total phosphorus concentration of Shagawa Lake is an order of magnitude higher than Big Platte Lake. Furthermore, Big Platte Lake has high marl content and an alkalinity of about 150 mg/L compared to 25 mg/L for Shagawa Lake. These conditions suggest that the amount and mobility of the phosphorus in the sediments of Big Platte Lake is considerably less than that in Shagawa Lake.

Nürnberg (1994) developed an empirical correlation between anaerobic sediment phosphorus release rates and sediment total phosphorus concentrations. This relationship and sediment phosphorus concentrations measured by Holmes (M. Holmes, unpublished, 2005) can be used to calculate an anaerobic phosphorus release rate of about 3.4 $mg/m^2/day$ for Big Platte Lake. This value is considerably higher than typical release rates of 0.85 $mg/m^2/day$ determined by Holmes (M. Holmes, unpublished, 2005) through field and laboratory measurements and model calibration. Sen et al. (2004) measured an average release rate of 0.57 $mg/m^2/day$ for eutrophic Beaver Lake (Arkansas), a value that is similar in magnitude to those determined for Big Platte Lake. On the other hand, Penn et al. (2000) measured sediment release rates in hypereutrophic Onondaga Lake (New York) that are about an order of magnitude larger than those measured in oligotrophic Big Platte Lake. It is apparent that the anaerobic sediment phosphorus release rate of a particular lake is dependent on both trophic status and sediment chemistry and is therefore not easily predicted from published studies for other systems. Therefore, it is recommended that sediment release rates be measured using intact cores as part of developing accurate phosphorus budgets for lakes where sediment-water interactions might be significant.

The sediment burial rate velocity determined by model calibration is 0.0034 m/year for Big Platte Lake (see Table 1). This is about five times higher than the rate found in Shagawa Lake by Chapra and Canale (1991). Again, this is not unexpected and is consistent with the differences in the hardness and alkalinity of the water in these lakes.

The annual average settling velocity for Big Platte Lake determined by model calibration is 19.0 m/year. The associated phosphorus retention is about 56%, an amount that is consistent with other oligotrophic lakes (Chapra 1997). Note, however, that the settling velocity is larger than the "apparent settling velocity" that would be estimated from models such as Vollenweider (1976) that do not explicitly include internal loading resulting from sediment release during anoxic periods. On the other hand, the settling velocity derived here acts on total phosphorus rather than on the particulate fraction alone. Only about 25% of the total phosphorus of Big Platte Lake is particulate; therefore, a settling velocity of 76 m/year would be required to deliver the same phosphorus and carbon flux to the sediments in a model that uses separate dependent variables for the dissolved and particulate components.

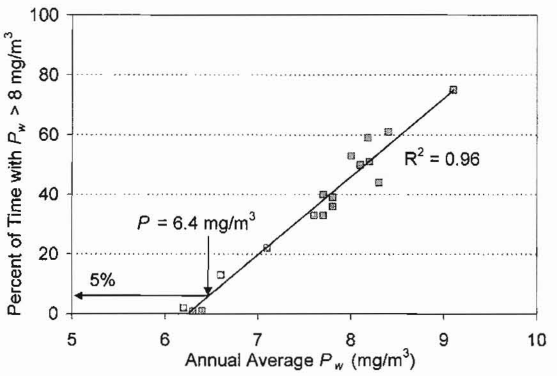

Fig. 13. Measured annual average total phosphorus concentration of Big Platte Lake versus the percent of the individual measurements that exceed 8 mg/m^3 for various years

Practical Applications

Design Conditions

The water quality models will now be used to calculate an allowable annual average total phosphorus load that will insure that the total phosphorus concentration of Big Platte Lake is below 8 mg/m^3 95% of the time. The first step is to determine the annual average Lake phosphorus concentration consistent with this objective. Fig. 13 shows a plot of the percent of time the concentration of phosphorus in Big Platte Lake exceeds 8 mg/m^3 during the year as a function of the annual average volume-weighted total phosphorus concentration. This plot is based on approximately 7,000 discrete phosphorus measurements collected over a period of 17 years. A linear fit of the data indicates that an annual average concentration of 6.4 mg/m^3 will insure compliance with the Lake total phosphorus standard.

The baseline calculations employ typical nonpoint phosphorus loads and lake inflow rates based on 2004 measurements and BASINS model results. The baseline total phosphorus load is 2,539 kg/year and includes 2,197 kg/year from diffuse, nonpoint watershed sources, 71 kg/year for lost fish, and 101 kg/year from atmospheric deposition. The calculations use the NPDES limit for the Hatchery loading of 79 kg/year. The internal phosphorus loading from sediment release is about 90 kg/year and is calculated by the model. This loading gradually varies with time because P_w, P_s, and HOD, as well as the duration of anoxia, all vary in response to changes in the phosphorus loading to the Lake. The phosphorus model coefficients were unchanged from the calibration values reported in Table 1.

The model projections beyond 2008 through 2030 shown in Figs. 7–9 were determined using the typical input conditions as described above. If no actions are taken to reduce phosphorus loading, the predicted annual average total phosphorus concentration of Big Platte Lake will be 7.6 mg/m^3, a value that violates the water quality standard (see Fig. 13). Simulations were performed using a series of stepwise reductions in phosphorus loading to determine an allowable total phosphorus load of 2,164 kg/year. These results show that the total phosphorus loading must be reduced by 375 kg/year to meet the water quality standards for the Lake. The projected total phosphorus concentrations and loading reduction requirements for other nonpoint loading and flow rate conditions are discussed in Canale et al. (2004).

Evaluation of Alternative Remedial Actions

The above model calculations have identified the need to reduce the nonpoint phosphorus loads to the lake, and now an action plan is needed to complete the task of attaining compliance with the water quality standards. This requires implementation of various watershed management practices that will reduce the nonpoint phosphorus loading. Although the BASINS and lake models discussed above cannot be used to determine the practicality or effectiveness of various abatement alternatives, the models can be used to determine incremental decreases in lake total phosphorus concentration if the functioning of these efforts can be estimated, prescribed, or specified as described below.

A local ordinance requires lakeside residents to construct retention basins to collect the runoff from all impervious surfaces to allow percolation into the groundwater. The calibrated BASINS model for the Platte River watershed estimates that the event mean concentration of such runoff has a total phosphorus concentration of approximately 250 mg/m^3 and that local groundwater has a concentration of about 6 mg/m^3. A maximum potential phosphorus reduction of about 86 kg/year could be attained if all 500 lakeside residents were to comply with the ordinance. This is equivalent to about 23% of the needed reduction in phosphorus loading to meet water quality standards.

Lake shore buffer zone ordinances are being considered to reduce the nonpoint phosphorus loads to the Lake. Although buffer zone vegetation reduces erosion, it is not considered effective for the removal of phosphorus over the long term because phosphorus retained by plants in the spring and summer is released with plant senescence in the fall. Therefore, lakeside residents have been asked to circumvent this natural recycling by collecting beach debris and cutting, harvesting, and removing excess buffer zone vegetation two to three times per year as suggested by Dillaha et al. (1986). Measurements indicate that typical shoreline debris material has a water content of about 75% and contains about 0.25% phosphorus by dry weight. Therefore, a total phosphorus loading reduction of about 70 kg/year could be attained if each lakeside property owner removed 225 kg of vegetative litter and beach debris (wet weight) from their property per year.

A typical 9 kg bag of lawn and garden fertilizer used in the area contains 10% phosphorus, or 0.9 kg per bag. A local ordinance is being considered that requires lakeside residents to use only phosphorus-free fertilizers. Detailed fertilizer sales volume and application rate data are not available for the local area; however, if 50% of the lakeside residences currently use one bag of fertilizer per year, a reduction of 227 kg of phosphorus loading could be attained through the use of phosphorus-free fertilizers.

It is important to note that the reductions in phosphorus loading estimated for the actions described above are a maximum because even without the remedial measures, some phosphorus from these sources would naturally percolate into the groundwater. It is not possible to quantitatively evaluate the actual phosphorus reduction achieved in practice compared to the potential reductions described in the previous paragraphs. In addition, note that the model calculations presented above do not account for increases in the nonpoint phosphorus loads that are expected from the future growth of population and commercial activities. Therefore, additional modeling and a long-term monitoring program should be carried out to confirm the effectiveness of the implemented corrective actions, to detect the effects of future watershed development, and to predict the benefits of future remedial efforts.

Discussion Items

TMDL applications of the watershed and lake phosphorus models developed in this paper require that a margin of safety (MOS) be established for load allocations to provide a degree of protection. The MOS can be expressed either explicitly by specifying unallocated assimilative capacity, or implicitly through the use of conservative assumptions in the TMDL analysis (Dilks and Freedman 2004). Various researchers have stressed the importance of defining an appropriate MOS based on modeling uncertainty analysis (Reckhow 2003; Walker 2003; Zhang and Yu 2002). The development of a meaningful MOS also requires that a desired level of protection be specified as a matter of policy. In practice, the MOS is often arbitrary in nature (Dilks and Freedman 2004).

Rigorous uncertainty analysis and development of a MOS for Big Platte Lake is beyond the scope of the present paper; however, some aspects of this issue will be discussed in this section. First, the internal phosphorus load due to bottom sediment release depends on the dissolved oxygen concentration in the hypolimnion, which is a function of the rate of mixing between the epilimnion and the hypolimnion. This mixing varies with wind speed and direction, both of which vary seasonally and annually. The allowable loads determined here are based on 2005 mixing conditions, which are more restrictive than typical mixing conditions. Fig. 9 shows that the projected sediment releases beyond 2009 are somewhat higher than the average of recent preceding years. Second, the loading requirements developed here assume that all fish not accounted for at the Hatchery constitute an internal phosphorus load. It is possible that some of the fish that enter the Lake are captured by anglers, but reliable estimates of the number of fish removed are not available. Finally, and most importantly, the water quality standard itself has an inherent safety factor because the allowable loads insure compliance with the Lake total phosphorus concentration standard 95% of the time. If no actions are taken to reduce the current total phosphorus loads, model calculations indicate that the Lake will attain a near steady state annual average total phosphorus concentration of 7.6 mg/m^3. This concentration is equivalent to 65% compliance with the 8 mg/m^3 standard rather than 95% as specified by the court order (see Fig. 13). Thus, the required nonpoint load reductions are a function of the statistical aspects of the numerical standard.

The intent of this case study was to demonstrate the utility of a model with an intermediate level of complexity to facilitate TMDL analyses and other planning applications for Big Platte Lake. It is also of interest to consider the utility of an even simpler approach. The nonpoint loads used to calibrate the above models were the result of dynamic simulations performed using the BASINS model. The calibrated BASINS model can also be used to derive site-specific UALs for each land-use type that characterizes the watershed. These UALs can be used in conjunction with the steady state solution of the model described by Eq. (1) to predict total phosphorus concentrations in Big Platte Lake and evaluate the effectiveness of alternative land-use assumptions and management options and scenarios. Field measurements can be used to estimate the number of days during the year when sediment release of phosphorus is significant. This steady state approach cannot reliably be used for cases where the sediment dynamics are important or where the nonpoint loads change in response to long-term watershed development. However, it can be a useful screening tool for cases where these long-term dynamic considerations are not important (for example, see case study by Litwack et al. 2006).

Conclusions

The experience gained through this case study indicates that a model with single water and sediment layers and one dependent variable (total phosphorus) can be used to perform reliable nutrient budget analyses for Big Platte Lake. The study suggests that this intermediate complexity model could be used to similar advantage for other lake systems. The model can be used with confidence when long-term sediment dynamics are significant or where long-term planning applications and projections are needed. The monitoring data for this study proved to be of critical importance to the efforts to achieve credible and defensible results. In addition to the typical components of a monitoring program such as stream flow, phosphorus loading, water total phosphorus concentrations, temperature, and dissolved oxygen concentrations; the laboratory measurements of sediment phosphorus release rates, SOD, and sediment total phosphorus concentrations proved to be particularly useful and are highly recommended to support other similar projects.

Additional insight into lake system dynamics may be provided by complex mechanistic models for HOD, but such efforts do not appear warranted for applications similar to Big Platte Lake.

Where additional analyses are necessary, SOD and algal respiration in the hypolimnion are the most important processes that must be quantified. However, care must be taken to avoid the propagation of large errors by minimizing the number and uncertainty of model coefficients and forcing functions.

UAL coefficients derived from the calibrated BASINS model and steady state versions of Eq. (1) may serve as a useful screening tool in cases for lakes where sediment dynamics and long-term trends are not important. In these cases, the internal loads due to sediment release may be considered constant with time, but sediment sampling and requisite laboratory measurements are necessary to correctly estimate their magnitude.

Acknowledgments

The writers wish to thank Jim Berridge of the Platte Lake Improvement Association (PLIA) for his efforts to develop and maintain the water quality database. Sylvia Heaton from the Michigan Department of Environmental Quality reviewed the manuscript and provided insights into the Michigan TMDL regulatory protocol. Steve Chapra from Tufts University and Mike Pattison (PLIA) reviewed the manuscript and provided useful comments and thoughtful suggestions.

Notation

The following symbols are used in this paper:

A_e = thermocline area (m^2);
A_r = phosphorus release area (m^2);
A_s = settling area (m^2);
DO_e = epilimnion dissolved oxygen concentration (mg/L);
DO_h = hypolimnion dissolved oxygen concentration (mg/L);
HOD = hypolimnetic oxygen demand rate ($gm/m^2/day$);
P_s = sediment total phosphorus concentration (mg/m^3);
P_w = water total phosphorus concentration (mg/m^3);
Q = hydraulic flow rate ($m^3/year$);
t = time (year);
V_h = volume of hypolimnion (m^3);
V_s = volume of lake sediments (m^3);
V_w = volume of lake water (m^3);
v_b = sediment burial rate velocity (m/year);
v_e = exchange rate velocity between epilimnion and hypolimnion (m/day);
v_r = phosphorus release rate velocity (m/year);
v_s = settling rate velocity (m/year);
W = total annual external phosphorus loading (kg/year); and
τ = time (days).

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0733-9496(201009/201010)136:5;1-4