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Resurrection of the Lake Michigan Eutrophication Model, MICH1

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ABSTRACT. *The Lake Michigan model, MICH1, was developed more than 30 years ago. This framework was evaluated using field data collected in 1976 and was later applied to predict total phosphorus and phytoplankton concentrations in Lake Michigan during the 1980s and early 1990s. With a renewed interest in the interaction of phytoplankton with toxics and the applicability to Total Maximum Daily Load studies, several new models have been developed and older models have been revived. As part of our interest in plankton dynamics in Lake Michigan, the MICH1 model was resurrected. The model was evaluated over the 1976–1995 period, with a surprisingly good model fit to lake-wide average total phosphorus (TP) field data. However, the model was less successful in mimicking the chlorophyll-a measurements, especially in the hypolimnion. Given the results, the model was applied to perform a few long-term TP model simulations. Using the model with average 1994–95 phosphorus loadings, a steady state was reached within approximately 20 years, and the lakewide phosphorus concentration was below the International Joint Commission water quality guideline of 7 μg/L. This exercise demonstrated that a relatively simple, four-segment model was able to mimic the TP lake-wide data well. However, this model was less suitable to predict future chlorophyll-a concentrations due to the limitation in the representation of the foodchain and the difficulty of the coarse segmentation of the model to capture the deep chlorophyll-a layer. Strengths and limitations of this model can guide future development of eutrophication models for Lake Michigan and the other Great Lakes.*

INDEX WORDS: *Lake Michigan, mathematical model, phosphorus, chlorophyll-a.*

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INTRODUCTION

Eutrophication models have traditionally been used to examine the relationship of phytoplankton production and standing crop with nutrients such as phosphorus, nitrogen, and silica (Thomann 1972, Thomann *et al.* 1975, DiToro *et al.* 1971). These models have been typically applied to the Great Lakes to evaluate the impact of existing and proposed phosphorus control measures on lake productivity and nutrient concentrations. The modeling has advanced from early studies that correlated phytoplankton (chlorophyll-a) concentrations with nutrient loadings and concentrations (Vollenweider 1969, Vollenweider and Dillon 1974, Rast and Lee 1978) to present day sophisticated three-dimensional multi-segment models which are driven by mechanistically derived hydrodynamic and sediment transport models that can simulate multiple types of phytoplankton and zooplankton as well as important carbon and nutrient forms (Cerco and Cole 1993, Bierman and Dolan 1981, Scavia 1980, Pauer *et al.* 2006).

Most Great Lakes models originate from the pioneering work done by researchers at Manhattan College and, in particular, from their development of the mathematical model, LAKE1 (Thomann *et al.* 1975). LAKE1, originally developed for Lake Ontario, is a deterministic model that simulates phytoplankton and nutrients and is driven by external loadings to the lake, hydrodynamics, and biochemical transformations within the lake. Several variations of LAKE1 have been applied to many of the lakes and bays of the Great Lakes region, with most undertaken in the 1970s and 1980s (DiToro and Matystik 1980, DiToro and Connolly 1980). One such LAKE1-based model is the Lake Michigan model known as MICH1, developed by Rodgers and Salisbury (1981a, 1981b). MICH1 was calibrated using field data from the intensive Lake Michigan survey of 1976–77 (Rockwell *et al.* 1980) and was used to forecast the lake's response to climatic events and changes in phosphorus loading (Rodgers and Salisbury 1981a, 1981b).

Concerns about water quality in the Great Lakes motivated the creation and implementation of the early models. The Great Lakes Water Quality Agreement (GLWQA) of 1978 emphasized the importance of the concept of overall lake water quality by establishing target trophic states for each lake, and defining lakewide phosphorus load and concentration limits required to reach or maintain these trophic states (Great Lakes Research Advisory Board 1978). The objective for Lakes Superior and Huron, with the exception of Saginaw Bay, was the maintenance of an oligotrophic state. For Saginaw Bay, a reversal of degradation to mesotrophic status was the desired objective. Phosphorus loading guidelines for Lake Michigan were established to allow a return of the lake to "its natural oligotrophic state" (Great Lakes Research Advisory Board 1978). For Lake Erie, phosphorus loads were established to provide for the recovery of the lake to mesotrophic status in the western basin and oligomesotrophic status in the central and eastern basins. The goal for Lake Ontario was to return the lake to an oligomesotrophic status.

While current eutrophication models still focus on the link between nutrients and phytoplankton, these models also have the ability to predict autochthonous organic carbon, which is necessary for toxic models to estimate the distribution of chemicals between dissolved and particulate phases. A high resolution state of the science eutrophication model known as LM3-Eutro was developed for Lake Michigan as part of the Lake Michigan Mass Balance Project (LMMBP) (Pauer *et al.* 2006). Contaminants, nutrients, biological, and other water quality variables were measured in Lake Michigan during 1994–1995 in support of this mass balance model that was used to predict the effects of regulatory action on contaminant concentrations in predator fish in the lake (Rossmann 2006). The LM3-Eutro model serves primarily as a means of generating phytoplankton carbon estimates for the LMMBP Polychlorinated Biphenyl (PCB) transport and fate model. LM3-Eutro will ultimately simulate water quality in a high resolution framework of the more than 44,000 grid cells of Lake Michigan. This will allow the model to be used for a number of new applications which previous models have been unable to address because of their coarse lake segmentation.

The decision to reexamine MICH1 came from a desire to better understand the previous modeling efforts for Lake Michigan while developing LM3-Eutro. Familiarity with MICH1 operations and predictions ensured that LM3-Eutro represents an advancement in the field of water quality modeling rather than a reiteration of existing modeling capability. In this paper the strengths and weaknesses of the original MICH1 model were evaluated over an extended time period (originally calibrated for only 1 year) and under lower phosphorus conditions than were present when the model was developed. The ability of MICH1 to represent the field data over a

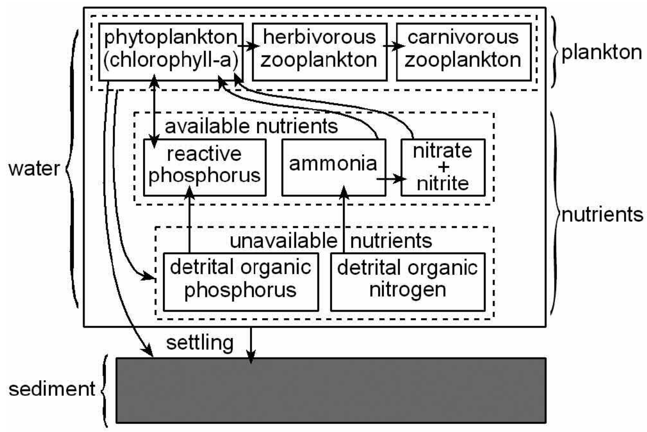

FIG. 1. Schematic of MICH1 model compartments and kinetic interactions.

longer time-period determines its usefulness as a predictive screening-level model. However, the comparison will also provide insight into which processes and equations are still relevant given changes in the foodweb of Lake Michigan, and what is needed to be changed or added to improve MICH1 and future eutrophication models. This study will therefore not only help with our ongoing eutrophication modeling effort in Lake Michigan but also with future eutrophication models for the Great Lakes and other systems.

HISTORICAL MODEL DEVELOPMENT

MICH1 was developed as part of the International Joint Commission's (IJC) Great Lakes International Surveillance Plan. The model framework was constructed by Rodgers and Salisbury (1981a, 1981b) based on the Great Lakes model LAKE1. A brief discussion of the model is presented here; a detailed description of the framework, kinetics and model coefficients can be found elsewhere (Rodgers and Salisbury 1981a, 1981b; Lesht 1984a, Thomann *et al.* 1975).

The model framework consists of four water column segments defined by the epilimnion and hypolimnion of the northern and southern basin. It excludes Green Bay and the sediment bed. The model simulates eight state variables that include a single phytoplankton class (expressed as chlorophyll-a), two zooplankton classes, and particulate (which are referred to in the original MICH1 document as "Non-living Organic" nutrients) and dissolved nutrients. It does not simulate diatoms or silica. A schematic diagram of the state variables and transformation reactions is shown in Figure 1. Table 1 shows the specific kinetic reactions in the MICH1 model. With the exception of a few small changes, the kinetic equations are the same as those used in LAKE1. The most important kinetic change is the replacement of the phytoplankton decomposition equation with a function that relates decomposition rate of the algae to the trophic status in the lake. For the original 1976 calibration, hydrodynamic parameters such as advective flows and vertical and horizontal exchange coefficients were calculated based on measurements and literature values and were then adjusted during model calibration (Rodgers and Salisbury 1981b). Best estimates from available field data were used for the initial conditions and boundary conditions (Rodgers and Salisbury 1981a, 1981b). Phosphorus loadings for 1976 and 1977 were based on the estimates made by the IJC (Vallentyne and Thomas 1978, International Joint Commission 1978, Sonzogni *et al.*1979). Rodgers and Salisbury attempted to verify the model using 1977 field data but discovered that the model was not able to simulate the unexpected low levels of total phosphorus in the lake. They postulated that the low total phosphorus values

TABLE 1. Kinetic reactions used in the MICH1 Model.

State Variable	Sources	Sinks
Chlorophyll-a (phytoplankton)	Growth	Mortality/predation
Herbivorous zooplankton	Grazing	Mortality/predation
Carnivorous zooplankton	Grazing	Mortality/predation
Non-living organic phosphorus (NLOP)	Plankton mortality	Hydrolysis/mineralization
Available phosphorus	NLOP hydrolysis/mineralization plankton excretion	Phytoplankton uptake
Non-living organic nitrogen (NLON)	Plankton mortality	Hydrolysis
Ammonia	Hydrolysis of NLON Plankton mortality	Phytoplankton uptake Nitrification
Nitrate-nitrite	Nitrification	Phytoplankton Uptake

were due to ice cover caused by a severe winter. The ice cover was thought to increase phosphorus settling during the winter. By increasing the model settling rate eight fold, they were able to obtain a reasonable fit to 1977 data (Rodgers and Salisbury 1981a, 1981b). Rodgers and Salisbury also used MICH1 to determine steady state phosphorus levels and the length of time required to reach those levels under several loading scenarios.

MICH1 was subsequently used by Lesht (1984a, 1984b) in the mid-1980s to perform forecasts and hindcasts for Lake Michigan. He performed a 5-year hindcast simulation (1976–1981) using a slightly modified MICH1 model (model parameters were used as reported by Rodgers and Salisbury 1981a, b) and compared it to limited field data. He included a function that relates the fraction of lake ice cover to enhanced winter settling (he termed it enhanced winter removal) for each year. With limited field data, he was unable to determine whether the ice-cover function improved the accuracy of the model predictions. However, he believed that the exclusion of this poorly understood process from the model construct can increase the uncertainty in the prediction.

Since the late 1970s, there have been several changes in the ecosystem of Lake Michigan, such as shifts in the phytoplankton and zooplankton species composition (Fahnenstiel and Scavia 1987a, Makarewicz *et al.* 1998) and the introduction of invasive species (Kraft 1993, Fleischer *et al.* 2001). MICH1, however, has not been modified to account for changes in the foodweb structure or other perturbations to the lake system that have occurred since then.

HISTORICAL DATA

Lake Michigan field data collected from 1976–1995 were used to evaluate the model validity for a period of 20 years. Detailed chlorophyll-a and phosphorus concentration data for Lake Michigan were available for the time periods of 1976–1977, 1983–1984, and 1994–1995. Open lake 1976–1977 data were collected as part of the USEPA GLNPO Lake Michigan Intensive Survey of 1976–1977 and obtained from the USEPA's Storage and Retrieval database, STORET, and published reports (Rockwell *et al.* 1980). The 1983–1984 data were also collected by GLNPO as part of an intensive lake survey and obtained from STORET and data reports (Lesht and Rockwell 1985, 1987). Data from 1994–1995 were collected by GLNPO in support of the LMMBP (GLNPO 2004).

Figure 2 shows a map of Lake Michigan with the sampling station locations for each of the six years, while Table 2 provides a summary of the sample start dates, end dates, and sampling frequency for each of the 6 years. With the exception of 1977, where only the southern basin of the lake was sampled, all other years have representative sampling locations across the lake. The lake was more frequently sampled during the years of 1976, 1994, and 1995. The 1983–1984 data were collected from paired offshore stations running the north/south length of the lake, with the total number of stations around 20. No attempt was made to match up stations from different years, and a simple mathematical mean and standard deviation were used to estimate an average value and variation in the lake for the individual years.

While historical data are commonly used to evaluate model accuracy, there are inherent limitations that must be taken into account when comparing field data and MICH1 model predictions. One general limitation is locating datasets that specify all of the information needed for comparison to MICH1, including sample date, depth, and location. Data sets with data available from multiple seasons are preferable, although it is more difficult to locate Lake Michigan data collected during winter

TABLE 2. Summary of Total Phosphorus samples collected in Lake Michigan.

Year	Start date	End date	Number of cruises	Number of samples
1976	April	October	8	2,587
1977	April	October	4	1,673
1983	April	October	3	592
1984	February	December	4	546
1994	April	November	4	515
1995	January	October	4	401

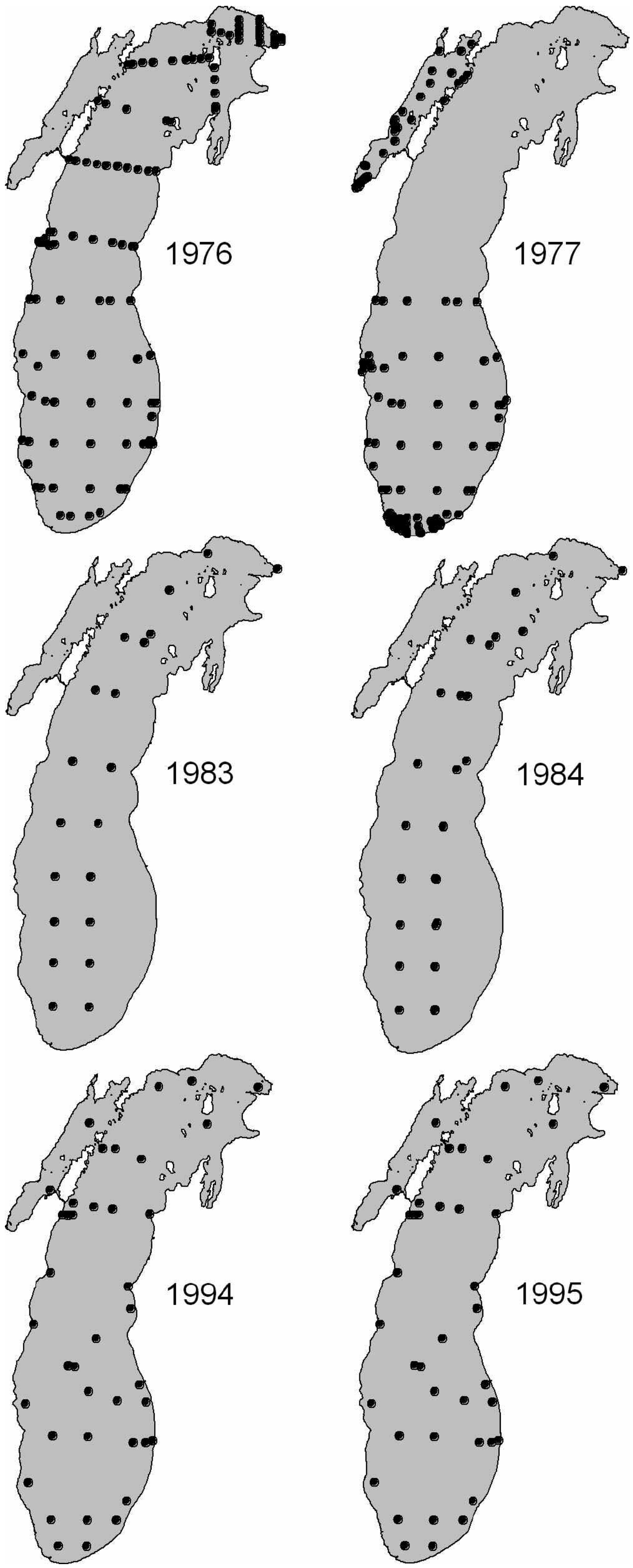

FIG. 2. Lake Michigan sampling locations for the time periods of 1976–1977, 1983–1984, and 1994–1995.

months. Fortunately, the availability of data from large scale sampling programs for Lake Michigan provided an adequate amount of suitable data for comparison to MICH1.

MODEL EVALUATION

In order to see how well MICH1 performed over a longer simulation period, it was run for a 20-year period (1976–1995). No modifications were made to the original MICH1 code, initial conditions, or model coefficients. The 1976 flows and exchanges were repeated to generate a 20-year hydrodynamic file; likewise, the time dependent forcing functions such as incident solar radiation and temperature were also repeated. A continuous record of annual total phosphorus loads for 1976–1995 (Fig. 3) was constructed based on loading estimates made by the IJC, loads reported in the literature, and loadings measured during the Lake Michigan Mass Balance project (Lesht *et al.* 1991, Johengen *et al.* 1994, McGucken 2000, Pauer *et al.* 2006).

The model output was compared to the total phosphorus (TP) and chlorophyll-a field data. Because very little information was available on the breakdown of the historical phosphorus loads to the northern and southern basin, it was decided to combine the two surface segments to represent the epilimnion, and the two subsurface segments to represent the hypolimnion. The segments were also averaged using volume weighting in order to represent TP for the whole lake. Time series plots of model output of total phosphorus and chlorophyll-a

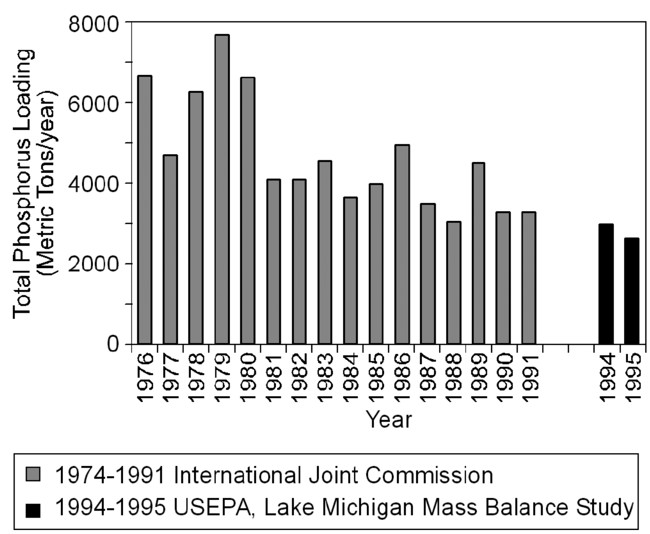

FIG. 3. Historical total phosphorus loading to Lake Michigan between 1976 and 1995.

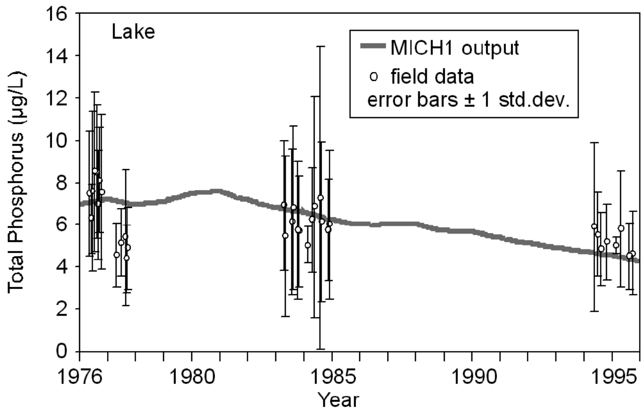

FIG. 4. Model results and field measurements of the average lakewide total phosphorus concentration in Lake Michigan from 1976 to 1995.

versus field data comparisons are shown in Figures 4 and 5 respectively. Due to the large seasonal chlorophyll-a changes, it was difficult to evaluate how well the model was fitting the field data over the multi-year period (Fig. 5). In order to clarify these comparisons, a plot of model prediction versus field data was also generated (Fig. 6).

Although low for hypolimnetic chlorophyll-a, the model predictions overall agreed rather well with the field data. On a whole lake basis, TP predictions agreed favorably with the 1976, 1983, and 1984 field data (Mean Error = –0.14; Absolute Error = 0.89 and Relative Error = 15%). Model output was

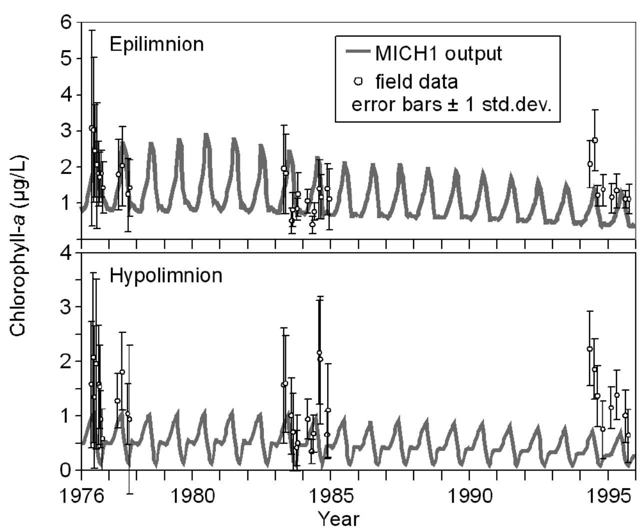

FIG. 5. Model results and field measurements of the average epilimnion and hypolimnion chlorophyll-a concentrations in Lake Michigan from 1976 to 1995.

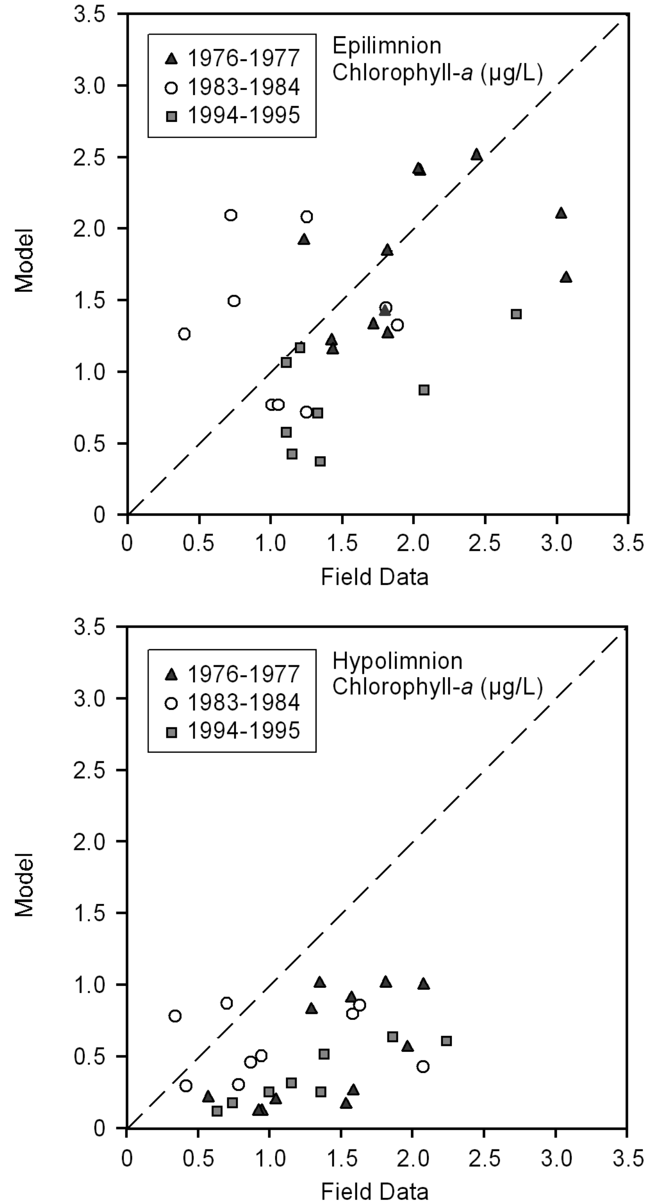

FIG. 6. Model output versus field data of chlorophyll-a in the epilimnion and hypolimnion of Lake Michigan. The dashed line represents the 1:1 relationship.

within 7% of the field data for each of these years. However, the model TP results were lower than the 1994 and 1995 field data (model output was ~12% lower than field data) and 46% higher than the 1977 field data (Fig. 4). Although lower than the 1994 field observations, model predictions appear to fit the epilimnetic chlorophyll-a field data (Figs. 5–6) with a mean error of 0.20, indicating that the model output is slightly lower than field data. The absolute

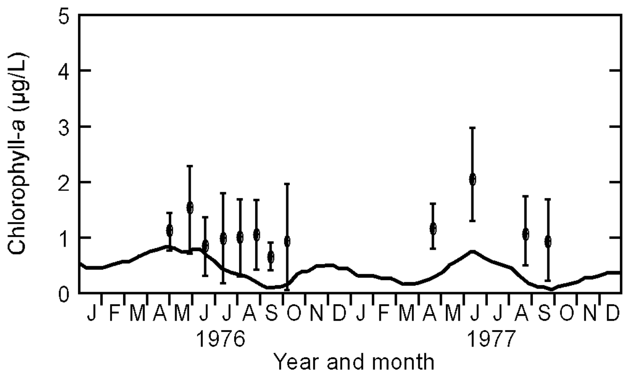

FIG. 7. Two year chlorophyll-a simulation for Lake Michigan hypolimnion (lower layer) redrawn from Rodgers and Salisbury, 1981b.

mean error and relative error of 0.58 and 37%, respectively, demonstrate the deviation between the model prediction and the field data. The hypolimnetic chlorophyll-a field data, however, were much higher than the predictions throughout the entire 20-year period (Figs. 5–6) with a mean error of 0.75, an absolute mean error of 0.79 and a relative error of 64%. These observations of fit between model predictions and field data are similar to the original observations of Rodgers and Salisbury for 1976–1977. The original MICH1 Rodgers and Salisbury calibration underpredicted hypolimnetic chlorophyll-a concentration (Fig. 7). They suggested that this discrepancy may be the result of the existence of a deep chlorophyll-a layer (Rodgers and Salisbury 1981a). Deep chlorophyll-a layers in Lake Michigan have been observed to occur at depths of 15 to 70 m, with concentrations running as high as 5–6 µg/L (Fahnenstiel and Scavia 1987b). Because the MICH1 hypolimnetic segments span from 20 m to the lake bottom, it is possible that the deep chlorophyll layer affects the fit of the model during the summer. Rodgers and Salisbury also hypothesized that the higher than expected hypolimnetic chlorophyll-a was due to higher chlorophyll-a to carbon ratios (MICH1 uses a constant chlorophyll-a to carbon ratio) that result from low light conditions present in deep waters. In addition to underpredicting hypolimnetic chlorophyll-a, MICH1 also overpredicted 1977 total phosphorus concentrations. Rodgers and Salisbury addressed the latter by using an enhanced settling rate, concluding that the extensive ice cover during the particularly severe winter of 1976–1977 greatly increased settling rates in the lake. The 1977 TP concentrations, however, stand out as abnormally low values when compared to field data from 1976 and 1983–1984 (Fig. 4).

MODEL DIAGNOSTICS

All of the simulations performed above were performed using original MICH1 model coefficients (Rodgers and Salisbury 1981a, 1981b). A limitation of the model is that it uses a net settling rate (the difference between settling and resuspension values) and does not have an explicit sediment recycle mechanism. It has been reported that a significant fraction of the nutrients are recycled in the water column before reaching the sediments (Conway *et al.* 1977, Meyers and Eadie 1993). This suggests that the model may underpredict TP in 1994–1995 because too much phosphorus is lost to the sediments. For this reason, the model was run using lower particulate nutrient settling rates which resulted in less phosphorus settled to, and buried within the sediment. Model simulations were performed using particulate nutrient settling rate decreases of 10%, 20%, and 50%. The best model fit to the data was obtained using a 20% reduction (particulate nutrient settling rate = 0.08 m/d), and the results are shown in Figure 8. This run yielded a very small TP difference for the calibration year of 1976 (less than a 2% difference in comparison with the original calibration). This is because the mass of phosphorus within the system is much higher than the phosphorus load (mass) entering the lake within a 1 year period. Although it is an improvement over the original model simulation for 1994–95 (model

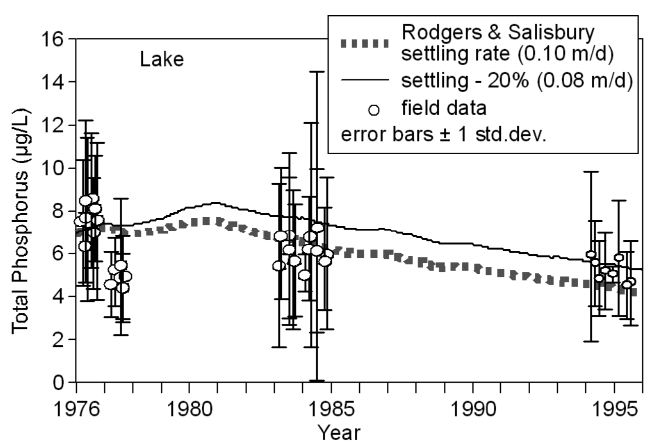

FIG. 8. Model results and field measurements of the average lakewide total phosphorus concentration in Lake Michigan from 1976 to 1995.

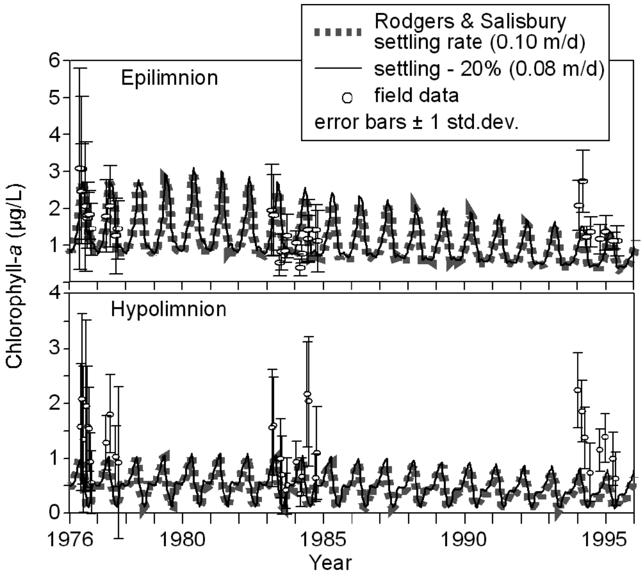

FIG. 9. Model results and field measurements of the average epilimnion and hypolimnion chlorophyll-a concentration in Lake Michigan from 1976 to 1995.

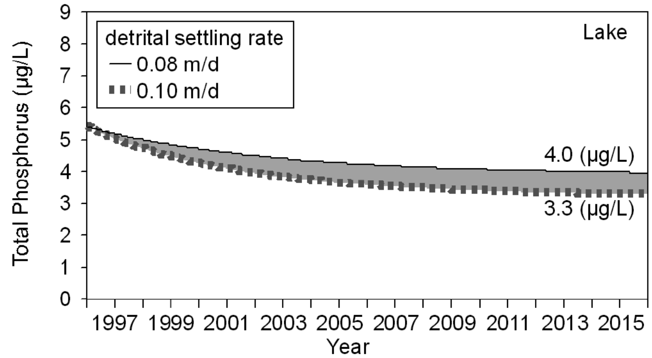

FIG. 10. Model predictions of lakewide average total phosphorus concentration in Lake Michigan (1996–2015) using the average 1994/95 total phosphorus loading. Shaded area represents the model predictive range and the values are the steady-state concentrations.

is approximately 6% higher than the field data for the 2 years) with a settling rate of 0.1 m/d, the model overpredicts the 1983 and 1984 TP field data (average of approximately 23% percent higher). The change in settling rate had only a very small effect on the long-term chlorophyll-a simulations, with the epilimnetic predictions fitting the data fairly well and hypolimnetic predictions lower than the field data (Fig. 9).

MODEL APPLICATION

Given the success of the model to mimic lakewide TP concentrations over the 1976–1995 period, it was decided to perform two long-term forecast scenarios of this screening level model to provide some insight into future TP concentrations. A simulation was performed using the same model coefficients, hydrodynamics, and forcing functions as used for model evaluation. A set of initial conditions was constructed for 1996 based upon the 1994–1995 Lake Michigan Mass Balance field data (Table 3). The average annual 1994–95 phosphorus loading was 2,788 metric tons (Pauer *et al.* 2006). The simulation was performed over a 20-year period using the original particulate nutrient settling rate (0.1 m/d) as well as a 20% reduction in the particulate nutrient settling rate (0.08 m/d) to provide a predicted range rather than a specific value. The model predictions appear to approach a steady state concentration for lakewide TP within the 20-year period (Fig. 10). The TP concentration decreased from the 1996 initial condition of 5.4 µg/L to between 3.3 µg/L and 4.0 µg/L. The 1994–1995 average phosphorus load of 2,788 metric tons used in the simulations was well below the 5,600 metric ton

TABLE 3. Model initial conditions based on 1994/95 Lake Michigan Mass Balance field data.

	Southern Epilimnion	Northern Epilimnion	Southern Hypolimnion	Northern Hypolimnion
Chlorophyll-a (µg/L)	1.36	1.48	1.10	1.09
Herbivorous Zooplankton (µg/L)	0.75	1.00	0.88	1.17
Carnivorous Zooplankton (µg/L)	0.14	0.19	0.16	0.22
Non-living Organic Nitrogen (µg/L)	41	70	51	61
Ammonia (µg/L)	43	17	34	23
Nitrate (µg/L)	323	226	316	245
Non-living Organic Phosphorus (µg/L)	3.80	3.80	4.20	4.50
Phosphate (µg/L)	0.60	0.46	0.62	0.55

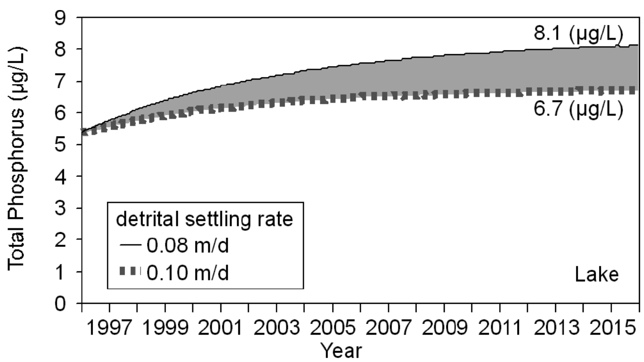

FIG. 11. Model predictions of lakewide average total phosphorus concentration in Lake Michigan (1996–2015) using the GLWQA total phosphorus loading of 5,600 MT/yr. The shaded area represents the model predictive range and the values are the steady-state concentrations.

guideline established in 1978 by the Great Lakes Water Quality Agreement (GLWQA) (International Joint Commission 1978).

A model simulation was also performed to determine the steady state TP and epilimnetic chlorophyll-a values using the GLWQA phosphorus loading goal of 5,600 metric tons. This phosphorus loading level was greater than a 100% increase over 1994–1995 average loads. The lakewide TP steady state value thus ranged between 6.7 µg/L and 8.1 µg/L (Fig. 11). The steady state lakewide TP concentration ranged from somewhat below the IJC TP concentration guideline of 7 µg/L using the original settling rate, to more than 1 µg/L higher than the guideline using the reduced settling rate (Great Lakes Research Advisory Board 1978).

SUMMARY AND DISCUSSION

The original MICH1 eutrophication model was resurrected using historical model code and coefficients and a number of publications and reports. The model was evaluated over a 20-year period using historical data from three extensive sampling surveys in Lake Michigan. The model output compared well on a lake-wide basis with the total phosphorus, although the model somewhat underpredicted total phosphorus in the 1990s. A reasonable fit was obtained for the epilimnetic chlorophyll-a field data over this period; however, the model underpredicted the hypolimnetic chlorophyll-a throughout the 20 year period. Decreasing the particulate nutrient settling rate improved the TP fit of the model for 1994–1995, but it overpredicted the field measurements of 1983 and 1984. The lower settling rate also did not eliminate the poor model fit to the hypolimnetic chlorophyll-a data.

Given the success of the model in mimicking the TP data over the 1976–1995 period, the model was used to perform long-term lakewide TP scenarios using the original settling rate as well as a 20% reduction in particulate nutrient settling rate. A simulation was performed over a 20-year period using 1994–1995 average loads. The model approached steady state within the 20-year time frame. As expected, the predicted TP concentration range was well below the IJC water quality guideline of 7 µg/L. This was not surprising because the 1994–1995 average phosphorus loading of 2,788 MT was much lower than the GLWQA value of 5,600 MT. A second model simulation was performed using the GLWQA loading (5,600 MT) to see how this compared to the 7 µg/L IJC target lake-wide TP concentration in the lake. The model predicted a steady state concentration range between 6.7 µg/L and 8.1 µg/L.

It is remarkable that the MICH1 model prediction was able to fit the lakewide total phosphorus field data given the many changes in the phytoplankton and zooplankton communities, significantly decreased phosphorus loads, and introduction of invasive species such as zebra mussels that occurred in Lake Michigan since the model was originally developed. It is believed that the main reason for the overall good phosphorus results (fit between measured and model values on a whole lake basis) was because phosphorus in many ways acts like a conservative substance in Lake Michigan. With good estimates of the loads, the only process which plays an important role is the amount of phosphorus lost from the system due to settling. Because this model uses a net-settling that represents the difference between settling and sediment recycling (resuspension of particles and sediment fluxes of dissolved phosphorus), a good estimate of this value should provide an overall good fit. The shifts in phytoplankton species can be a possible explanation for why the model fit the TP field data well for 1983–84, but somewhat underpredicted the 1994–95 values (Fig. 4). Phytoplankton species changed from spring peaks dominated by diatoms through the 1980s to an increasingly higher number of flagellates after this period (Barbiero and Tuchman 2001). It is generally accepted that diatoms (and their detrital material) settle faster than most other algae (Bowie *et* *al.* 1985), which could explain why MICH1, which was calibrated in 1976, underpredicted the TP values in the 1994–95 period. Recalibration of the model using settling rates that represent present phytoplankton species composition will probably improve the accuracy of TP predictions. However, it is believed that the values used for net-settling of TP (original and 20% reduction in settling rate) in this study provide a reasonable range that represents the complex process of settling and sediment feedback over the 1976–1995 time-period.

The model was less successful at mimicking the chlorophyll-a data, especially the hypolimnetic chlorophyll-a concentrations. As described previously (see Model Evaluation section), part of the poor fit is due to the inability of this four box segment model to capture the deep chlorophyll-a layer. Higher resolution models with multiple vertical segments should be able to better represent the deep chlorophyll-a layer in Lake Michigan, and will likely produce improved hypolimnetic chlorophyll-a results.

In addition, changes in the phytoplankton community, as mentioned earlier, were not accounted for in MICH1 and could possibly have affected the phosphorus:chlorophyll-a ratios. This might explain why the model was able to reasonably mimic the TP in the lake, but underpredicted the chlorophyll-a levels, especially for the hypolimnion. The invasion and establishment of zebra mussels by the early 1990s (Fleischer *et al.* 2001) in the near-shore areas also affected chlorophyll-a levels and likely altered the species composition and ultimately the phosphorus:chlorophyll-a ratio. Including multi-class phytoplankton and zebra mussels in the model equations should enable this or newer models to better describe chlorophyll-a in the system.

However, it is believed that MICH1, with its limitations, is a useful screening level model that is able to provide reasonable estimate ranges of lakewide TP concentrations for Lake Michigan under different TP loading scenarios. The predicted ranges from the two model scenarios provide us with insight into future TP conditions in the lake and how TP concentration relates to the GLWQA loading of 5600 MT and the IJC target TP concentration of 7 μg/L.

Since the development of MICH1 and other first generation WASP-based models, improvements have been made in describing phytoplankton dynamics and interactions with nutrients, including formulation of multiple phytoplankton and zooplankton classes and invasive species. Due to the improved understanding of the system, incorporation of the most recent changes in the ecosystem, and the availability of powerful modern computers, the next generation of models such as LM3-Eutro will provide a better description of the lake water quality, especially for chlorophyll-a, and will enable us to make more accurate predictions of the system. These models will also have the ability to make predictions of water quality on a high-resolution framework to address specific regions in the lake such as bays and river confluences and distinguish between near shore and off shore regions of the lake.

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