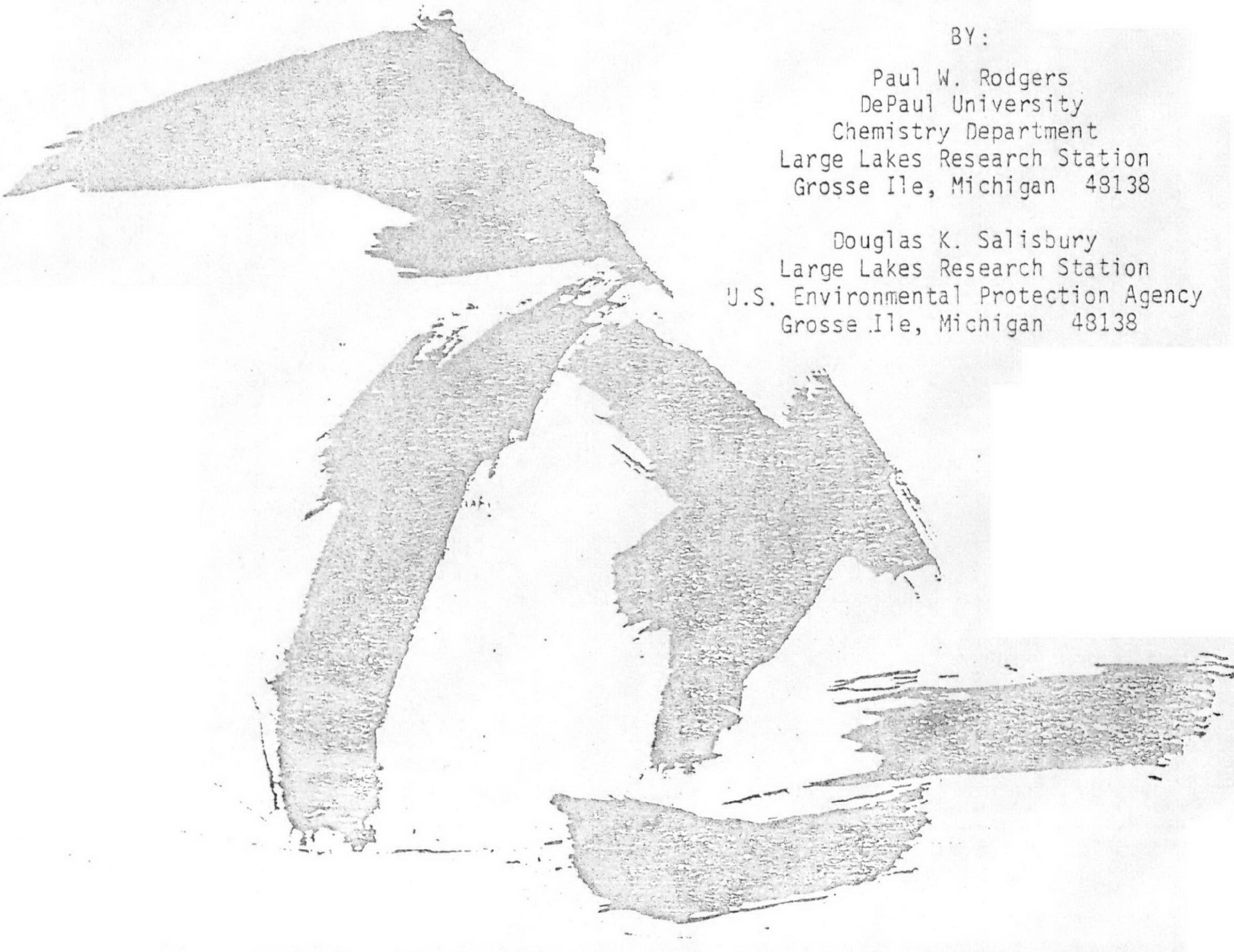
MODELING OF WATER QUALITY IN LAKE MICHIGAN AND THE EFFECT OF THE ANOMALOUS ICE COVER OF 1976-1977



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ABSTRACT

An intensive survey of water quality parameters was conducted on Lake Michigan during 1976 and 1977. A nutrient-phytoplankton model (MICH1) was developed and calibrated to data from 1976. MICH1 was then applied to data from 1977 in an attempt to simulate an observed phosphorus depletion of up to 3 μg-P/ℓ. In order to account for this rapid phosphorus loss an implicit representation of the extreme ice cover which separated these survey years was necessary. This procedure included increasing the apparent settling rate eight fold during ice cover. A time variable total phosphorus model (TPM) was used in a hindcasting application which produced a reasonable recreation of historical phosphorus concentrations. Two empirical models were compared to the forecasting results of MICH1 and TPM. The forecasts generally indicate a steady-state total phosphorus concentration of about 7 μg-P/ℓ, given a target load recommended by the 1978 Water Quality Agreement, which reflects a point source standard. The projected response time by MICH1 is 7-14 years for obtaining 95% of steady-state concentrations.

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MODELING OF WATER QUALITY IN LAKE MICHIGAN AND THE EFFECT OF THE ANOMALOUS ICE COVER OF 1976-1977

SECTION 1

INTRODUCTION

Lake Michigan is the only member of the Laurentian Great Lakes to lie entirely within the borders of the United States. Even so, Lake Michigan is included in the Great Lakes International Surveillance Plan (GLISP) as recommended to the International Joint Commission in 1974 by the Water Quality Board. The reason for having Lake Michigan as part of GLISP was attributed to the outflow contributing to the loading of Lake Huron. During 1976 and 1977, Region V of the U.S. Environmental Protection Agency and the University of Michigan, supported by the Large Lakes Research Station, undertook an intensive study, which was part of the first phase of the GLISP. The next such study is scheduled for 1985.

The field data obtained during the 1976-77 survey reflects the water quality status of the system and provides the basis for analyzing nutrient load responses. An analysis which includes deterministic modeling can assess kinetic processes affecting chemical and biological behavior as well as evaluate remedial programs. A challenging fact of this pursuit is for the scientific community to distinguish between the influences of natural processes upon chemical and biological dynamics and the concurrent impact of remedial programs. This insight would have special import to the management community. Ecological modeling has demonstrated the ability in the past to evaluate these influences. For example, Dolan and Clark (1981) were able to conclude that the reductions in flow to Saginaw Bay between 1974-1979 was of near equal importance in phosphorus load reduction as the phosphorus removal by municipalities. By the end of the study there was about an 11 μg/ℓ reduction in chlorophyll-a evident during the late summers. In analyzing the 1975 Lake Erie data set, DiToro and Connolly (1980) were able to attribute reduction in the anoxic zone of the central basin to changes in the onset of thermal stratification and not load reductions. In this study the concurrent effects of a phosphorus load reduction in 1977 and a climatically induced ice cover is examined for relative importance. The ice cover is hypothesized to enhance net phosphorus losses by isolating the lake from wind induced mixing and sediment resuspension.

The application of ecological models to the Lake Michigan basin was the central focus of this research. A modified version of a deterministic model, Lake 1 (Thomann et al. 1975), was first calibrated to the 1976 Lake Michigan results. An attempt to simulate the 1977 data was the first application of this calibrated Lake Michigan model, MICH1. During this verification phase additional modifications in the model became necessary. Specifically, attempts were made to implicitly reflect the effects that the extensive ice cover observed during the winter of 1976-77 might have had. The final application of MICH1 was to forecast lake response given several loading scenarios.

Additional models were used in making long term simulations. A time variable total phosphorus model was also used in forecasting as well as in hindcasting simulation. This total phosphorus model, similar to the Lorenzen (1976) model, provided valuable comparisons to MICH1 results. Two empirical models, the loading plot model by Vollenweider (1976) and the Dillon and Rigler (1975) model, were used for forecasting in order to gain more insight. By using a variety of models of varying complexity a contrast was made evident based on their performance versus their requirements.

SECTION 2

CONCLUSIONS

The efforts of this study enabled the following conclusions to be made:

1. A dynamic phytoplankton simulation model (MICH1) proved applicable to Lake Michigan for simulating field data.
2. MICH1 also proved useful, because of its versatility, in approaching new problems. Specifically, the hypothesis that an extraordinary ice cover may have enhanced an observed loss of phosphorus from the water column was investigated.
3. Changes in model forcing functions that may have been affected by an ice cover (incident light, vertical exchange, and ambient temperature) proved inadequate in providing a sufficient loss of particulate phosphorus.
4. The apparent settling rate had to be increased eight fold (to 1.6 m/day) during the ice cover period (the winter separating the 1976-77 survey years) in order to simulate the substantial phosphorus loss observed in the Southern Basin of Lake Michigan.
5. A case that an extraordinary ice cover may have enhanced removal of particulates from the water column was made in this investigation. If the mechanism for this influence is the isolation of the lake from wind induced circulation and sediment resuspension then these rapid losses in phosphorus may create rich deposits available for subsequent reintroduction into the lake.

6. A time variable total phosphorus model (TPM) was able to achieve an historical simulation of total phosphorus in Lake Michigan from 1800 to 1980 which "predicted" peak concentrations of total phosphorus during the early-1960's as well as the levels observed in the 1976 survey.

7. Two empirically derived models, the Vollenweider loading plot model and the Dillon and Rigler model, proved applicable to Lake Michigan for forecasting responses to various steady-state loading scenarios. The Vollenweider model suggested that long term loadings equivalent to 1976 loads (6671 MT/yr) would result in marginally mesotrophic conditions, whereas the long term target load recommended by the 1978 Water Quality Agreement (5553 MT/yr) would result in oligotrophic conditions. The Dillon and Rigler model predicted higher concentration responses than did MICH1 or TPM.

8. MICH1 and TPM forecasting results were similar regarding total phosphorus response. The recommended GLISP load results in an in-lake steady-state concentration of approximately 7 μg-P/ℓ. The observed 95% response time was eight to fourteen years.

9. MICH1 forecasted in-lake chlorophyll concentrations less than 4 μg/ℓ for all three future loading scenarios. Nearshore responses were not modeled.

SECTION 3

RECOMMENDATIONS

Based on the results and conclusions of this study the following recommendations are made:

1. Studies which are designed to assess the influence of major ice cover events may be a necessity in modeling lakes on a temporal scale.

2. If, indeed, ice cover can influence short term particle dynamics then there is a strong case for at least limited winter sampling.

3. Predictions of long term lake response should incorporate significant meteorological events by utilizing their frequency of occurrence as a stochastic model input.

4. An increased resolution of particle dynamics may be desirable. This would include improved representation of horizonal sediment and erosion transfer as well as resuspension phenomena.

5. A close look at the attainability of the GLISP recommended load over the long term is appropriate given that it is based on point source standards and appears to omit consideration of population and industrial growth.

6. Certain difficulties encountered in model calibration and application suggest the need for monitoring fundamental variables (e.g., temperature, conductivity, etc.) on a more regular basis. This change in sampling strategy would provide a basis for identifying the timing and magnitude of

water exchange processes. This sampling should occur seasonally at specific "master stations" on the major lakes, thereby establishing continuity in reporting general lake status.

SECTION 4

DATA PRESENTATION

4.1 HYDROLOGY AND PHYSICAL DEFINITION

Lake Michigan is the second largest of the Great Lakes in terms of volume and is the only one to lie entirely within the boundary of the United States. The shores of Lake Michigan fall within Wisconsin, Illinois, Indiana and Michigan. The drainage basin area for Lake Michigan is the largest among the Great Lakes. For a summary of the physical characteristics of Lake Michigan refer to Table 4-1. There are 25 major tributaries to Lake Michigan and the outlet to Lake Huron is through the Straits of Mackinac. The hydrology for Lake Michigan is summarized in Table 4-2. Projected hydraulic detention times based only on each year's flow are also reported. The values presented in these tables were obtained from a variety of sources and data from other sources may differ somewhat, but should be essentially similar. Note that the annual flows for 1975-1978 have been highly variable. The high flow year was in 1976 followed by the low flow year of 1977. A 66% reduction in annual flows was observed in this short period. This variation in flow and the projected detention times indicates that flows measured or computed during any given year may not be representa-

TABLE 4-1. LAKE MICHIGAN PHYSICAL CHARACTERISTICS

	Drainage Area* (km^2)	Lake Surface Area (km^2)	Mean Depth (m)	Volume (km^3)
Lake Michigan	117410	57800	86.1	4976.0
Green Bay	43670	4213	16.0	67.2
Main Lake	73740	53587	91.6	4908.8

*Does not include lake surface.

TABLE 4-2. LAKE MICHIGAN HYDROLOGY (cfs)

	1975	1976	1977	1978	Long Term
Northern Basin					
1. Gaged Flow*	14580	14784	9144	14726	14094
2. Adjusted Flow**	20935	21228	13130	21145	20238
3. Net Precipitation***	10888	12980	-713	8729	6941
4. Infiltration	200	200	200	200	200
Sub-Total (2+3+4)	32023	34408	12617	30074	27379
Southern Basin					
1. Gaged Flow	13764	15520	8057	11597	10514
2. Adjusted Flow	20822	23479	12189	17544	15906
3. Net Precipitation	11044	13166	-723	8854	7031
4. Infiltration	200	200	200	200	200
Sub-Total	32066	36845	11666	26598	23137
Total Inflow	64089	71253	24283	56672	50516
Projected Detention Time (yrs.)	87.0	78.2	229.5	98.3	110.3

*Approximately 78% of the basins were gaged.

**Adjusted for ungaged area plus additional flow to river mouth (1.12 in North and 1.18 in South).

***Precipitation minus evaporation estimates (refer to Philips and McCulloch, 1972).

tive of long term averages. This water balance does not consider possible deep layer return flows at the Straits of Mackinac discussed by Quinn (1977). Quinn further noted the variability in annual flow by calculating a 26% variation in the mean for the years 1950-1966.

4.2 1976-1977 IN-LAKE DATA

During 1976 and 1977, Region V of the U.S. Environmental Protection Agency and the University of Michigan undertook an intensive survey which was part of the first phase of the Great Lakes International Surveillance Plan. The next such study is scheduled for 1985. The stations sampled and the cruise dates are presented in Figure 4-1. There were about forty in-lake stations in the Southern Basin and seventy in the Northern Basin, although not all stations were sampled on every cruise. An extensive sampling of water quality parameters included physical, chemical, and biological measurements. Those parameters relevant to this modeling effort include water and air temperature, transparency, chlorophyll-a, primary productivity, total phosphorus, soluble reactive phosphorus, total Kjeldahl nitrogen, ammonia, nitrite + nitrate nitrogen, chloride, and zooplankton biomass. The time variable results for the most important of these parameters will be evident in the model comparison figures presented in "Calibration to 1976 Data," Section 6, and "Application to 1977 Data," Section 7. In the subsequent years since those data were collected the results have been reported by Rockwell et al. (1980) and separately by Bartone and Schelske (1980). A more extensive treatment of the data will soon be available from the E.P.A. (Region V).

The inspection of this data has revealed the status of Lake Michigan as compared to historical samples from less intensive surveys. Comparison of the 1976-77 data to historical conditions in Lake Michigan reveals degradation of these waters as evidenced by an increase in chloride and sulfate concentrations (conservative ions), increasing phytoplankton populations, and decreased reactive silica concentrations (Rockwell et al. 1980). An analysis of anthropogenic phosphorus loads to the Great Lakes basin by Chapra (1977) indicates that as much as two-thirds of recent loads to Lake Michigan have been related to human influences within the basin.

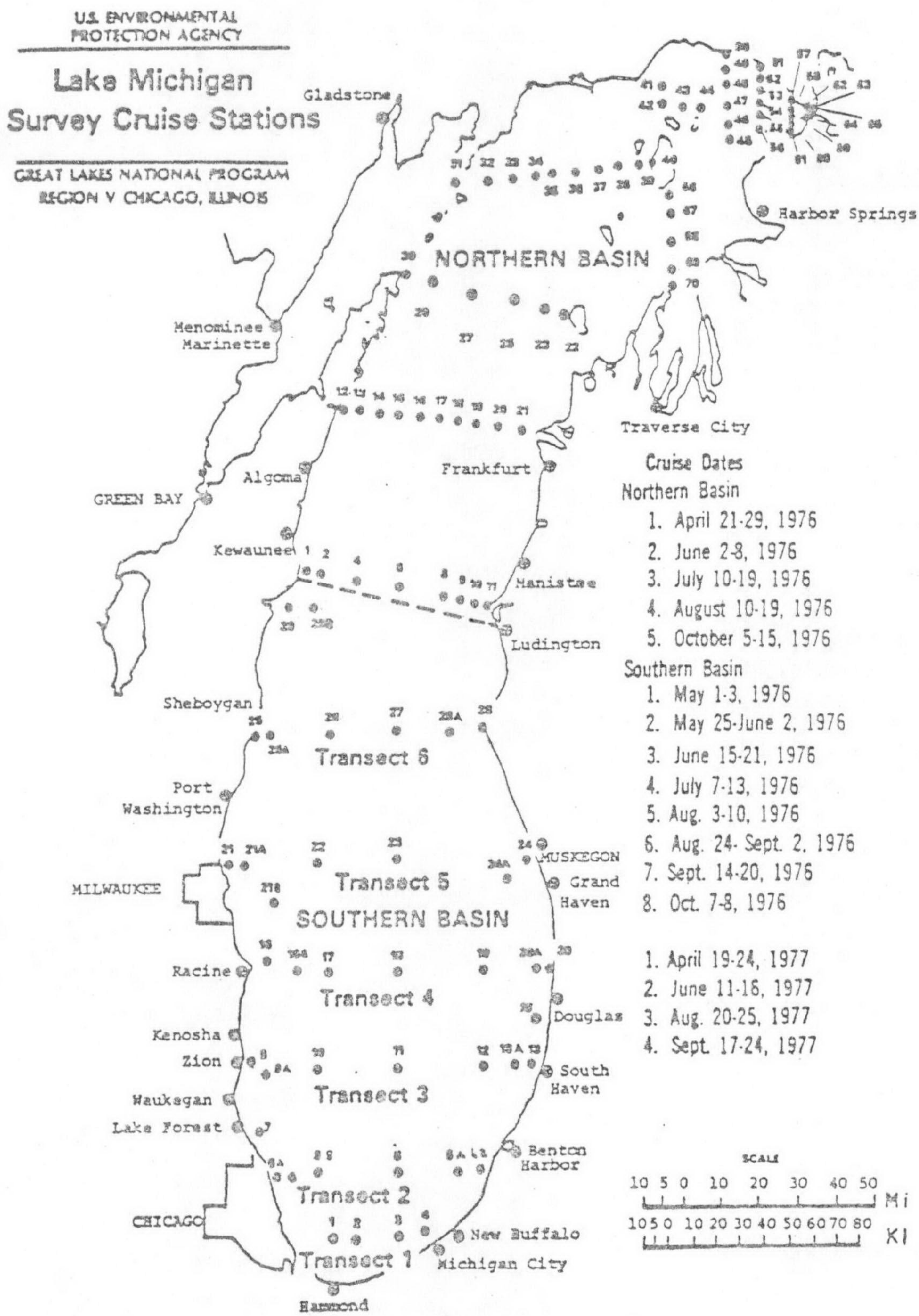

Figure 4-1. Lake Michigan station grid and cruise dates.

This cultural impact upon phosphorus loads has resulted in increased phosphorus levels in nearshore zones (Rockwell et al. 1980) and throughout the lake (IJC-Surveillance Subcommittee 1978). As a result Lake Michigan has been identified as presently being on the borderline between oligotrophic and mesotrophic conditions (Rast and Lee 1978). Since phosphorus has been identified as the growth limiting nutrient throughout most of Lake Michigan (Schelske et al. 1974; Rast and Lee 1978) the increased phosphorus loads are no doubt the stimulus for the observed phytoplankton related water quality problems. Confirming these observations is the trend in silica depletion accompanied by a shift from diatom dominance to an increase in blue-green phytoplankton abundance (Schelske and Stoermer 1971; Rockwell et al. 1980). A linear increase in conservative ions over the past 100 years has also been suggested as a cause for this shift to blue-greens (Stoermer and Tuchman 1980).

The data from the two cruise seasons further indicated substantial changes in important water quality parameters between 1976 and 1977 values. A conclusive comparison of 1976 data to 1977 data is hampered because of the reduction in sampling in 1977. As indicated in Figure 4-1, there were only four cruises in 1977 and the Northern Basin was not sampled. However, the data strongly indicates decreases in phosphorus, ammonia, chlorophyll-a and phytoplankton cell counts, and increased silica concentrations in 1977 when compared to the 1976 results (Rockwell et al. 1980). The magnitude of the phosphorus reduction is particularly striking and is evident in Figure 4-2. The data indicates approximately 6,500 metric tonnes of phosphorus were removed from the water column in one year's time. Yet the reduction in loading to that basin was only about 1,100 metric tonnes. Therefore, even if an immediate response to the load reduction is assumed nearly 83% of the phosphorus loss from the water column remains to be accounted for via other influences.

4.3 HISTORICAL DATA

There exists no historical water quality data set for Lake Michigan comparable to that of the intensive survey of 1976-77. Previous to this time there were no organized attempts to obtain a comprehensive analysis of

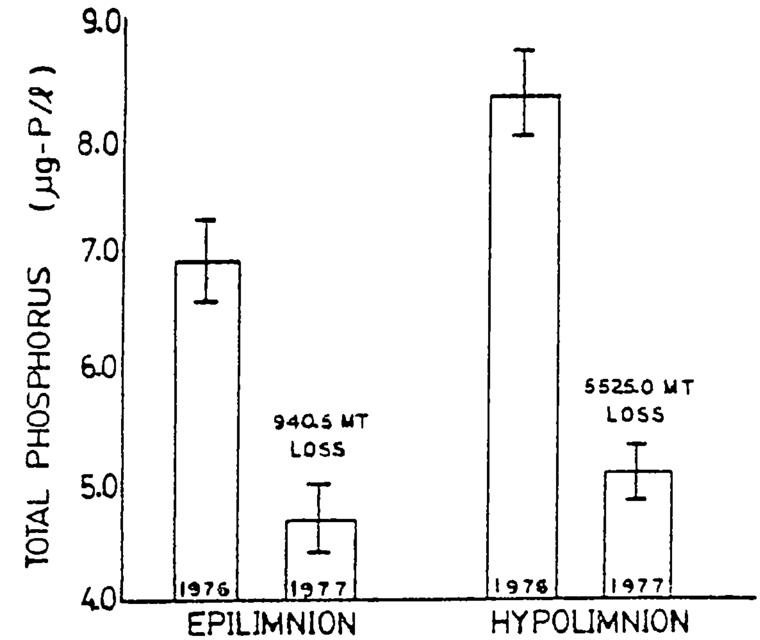

Figure 4-2. Phosphorus concentration during days 260-263 in the Southern Basin for the 1976-1977 survey years.

the Lake Michigan waters. Instead, the historical data is the combined product of many research efforts in localized areas. This data usually reflects a relatively limited number of parameters collected for a short term by single investigative efforts. The only consecutive long term data available usually has been obtained from the routine sampling of water treatment plant intakes. A synopsis of data sources and trends in biological and chemical composition can be found in a series entitled, "Environmental Status of the Lake Michigan Region," available from the National Technical Information Service.

An advantageous application of models is to attempt the simulation of the aquatic system over the dynamic historical period (that time frame when nutrient loads were increasing due to anthropogenic influences). An important requirement for this application is to reconstruct the nutrient loading during the historical period. If the model accurately reflects the lake response to these loads then it should "predict" present day conditions. To aid in the historical simulation a summary of historical loading estimates was gathered from a variety of sources and is graphically presented in Figure 4-3. The absence or presence of atmospheric loading was

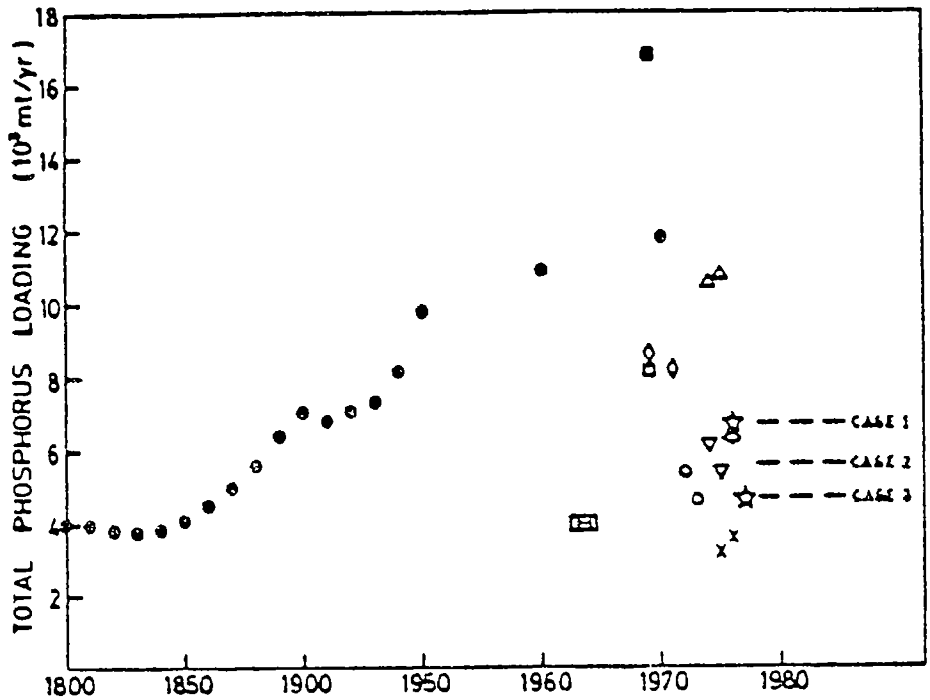

Figure 4-3. Historic and future total phosphorus loading estimates to Lake Michigan (10^3 metric tonnes/yr). Solid symbols represent historical loading model estimates:

● - Chapra (1977)
▣ - Patalas (1972).

Open symbols represent estimated loads based on field measurements:

△ - Eisenreich et al. (1977)
▽ - IJC (1978)
◊ - Lee (1974)
X - Sonzogni et al. (1978)
□ - Zar (1974)
○ - GLWQB (1974)
☆ - IJC (1978),
◇ - PLUARG (1978)
⊟ - U.S. Dept. HEW (1963)

Dashed lines (--) represent the three loading cases presented in Table 4-3 and used in forecasting.

normally found to be the difference in reported values within a particular year. These loads are used as model input in Section 8.2, "Historical Simulation Results."

4.4 FUTURE LOADING SCENARIOS

Three representative phosphorus loads were used for observing steady state response from various water quality models. Table 4-3 presents these loads on a whole lake basis. These loads are also indicated in

TABLE 4-3. TOTAL PHOSPHORUS LOADINGS TO LAKE MICHIGAN IN METRIC TONNES PER YEAR

	CASE 1	CASE 2	CASE 3
	1976 Load[1]	1976 Load with 1 mg/ℓ effluent standard[1]	1977 Load[2]
Atmospheric	1690	1690	1690
Point Sources	2268	1150	1623
Diffuse Sources	2713	2713	1353
TOTAL[3]	6671	5553	4666

[1]Reported in Fifth Year Review of Canada-United States Great Lakes Water Quality Agreement, eds. J.R. Vallentyne and N.A. Thomas, a Report of Task Group III, IJC, 1978.

[2]Total load reported in Great Lakes Water Quality, Sixth Annual Report, Appendix B, IJC, 1978. Allocation between point and diffuse sources for 1977 is only an estimate based on the mid 1970's portions reported in Critical Assessment of U.S. Land Derived Pollutant Loadings to the Great Lakes, Sonzogni et al., IJC, 1979.

[3]Total does not include shoreline erosion or re-entry from sediments.

Figure 4-3. Case 1 reflects the high flow, high load condition of 1976. Case 2 is the target load recommended by Task Group III in 1978 (Vallentyne and Thomas 1978). This load was considered achievable through a 1 mg/ℓ effluent standard applied to Case 1. The Task Group felt that this load would result in the in-lake phosphorus concentration being held to 7 μg-P/ℓ or less. Case 3 represents the low end of the loading spectrum by reflecting the extreme low flow, low loading condition observed in 1977. Note that the atmospheric loading accounts for 25-36% of the total and that erosion inputs are not included. When applying these loads to the water quality models a steady input commencing in 1978 was assumed. No attempt to predict changes in loading due to industrial, agricultural, or population changes within the basin was made. The use of the three loading scenarios proved sufficient for demonstrating critical load and response sensitivity of Lake Michigan (Section 8.3).

SECTION 5

MODEL DEVELOPMENT AND REQUIREMENTS

5.1 MODEL TYPES AND REQUIREMENTS

A modified version of the Lake 1 model, MICH1, was used to evaluate the 1976-1977 Lake Michigan conditions. Lake 1 was chosen as the basic framework on the basis of its proven application flexibility. Lake 1 was originally developed for Lake Ontario (Thomann et al. 1975) and modified versions have since been applied to Lake Huron (DiToro and Matystik 1980) and Lake Erie (DiToro and Connolly 1980). The physical segmentation in MICH1 utilizes the horizontal division between the Northern and Southern Basins as depicted in Figure 4-1, but includes only the in-lake portion greater than 15 meters in depth. Green Bay is also excluded from model representation. The mathematical representation of Lake Michigan further segments each of the two basins into two vertical layers at 20 meters in order to represent summer thermal stratification. This segmentation scheme, depicted in Figure 5-1, succeeds in modeling over ninety-five percent of the Lake Michigan volume without requiring the detailed data and segmentation necessary for nearshore modeling.

The framework of MICH1 simulates both biological and chemical parameters as state variables. There are three biological trophic levels represented. Corrected chlorophyll-a represents phytoplankton biomass and equivalent carbon reflects the two zooplankton trophic levels. In addition there are six chemical or nutrient state variables. These include two phosphorus compartments, total and soluble reactive phosphorus. The three nitrogen compartments simulated are total nitrogen, ammonia, and nitrite + nitrate nitrogen. Chloride is modeled as a conservative substance and served as a quantity of predictable behavior during the calibration phase.

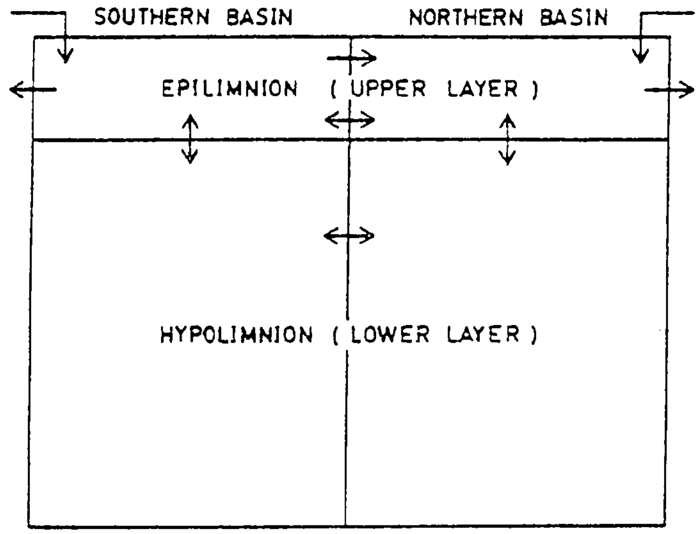

Figure 5-1. Schematic of segmentation used by MICH1.
Flow (→) Water Exchange (↔)

In addition to MICH1 several additional models were applied to the Lake Michigan ecosystem. A total phosphorus model (TPM) was chosen to possibly corroborate the phosphorus simulations observed in MICH1. Empirical models by Vollenweider (1976) and Dillon and Rigler (1975) were also applied to Lake Michigan for further general comparisons. TPM, a time variable model of total phosphorus, is conceptually similar to that developed by Lorenzen (1976) for use on Lake Washington and is numerically similar to a variety of total phosphorus models (Rumer 1978; Dolan and Bierman 1980). In essence this model invisions phosphorus as one compartment subject to one kinetic loss, settling. However, the phosphorus in the sediments are made available for reintroduction into the water column via resuspension or diffusion and may be permanently loss to deeper unavailable sediments.

The Vollenweider model is empirical in its development, although the relationship between areal loading (mass/area/time) and the overflow rate (depth/time) can be derived from steady-state solutions to a mixed reactor mass balance model (Vollenweider 1975). The Dillon and Rigler model (1975) is a mathematical formulation based on empirical observation and correlation. However, its mathematical formulation can be derived from a steady-state solution of a simplistic phosphorus model having only one kinetic loss term.

5.2 MICH1 Model Kinetics

For the most part MICH1 is a specific application of the Lake 1 model (Thomann et al. 1975) to the Lake Michigan system. The interaction of the nutrient and biological state variables is shown in Figure 5-2. Note that the chloride compartment is not included in this kinetic representation due to its non-dynamic conservative nature. Whereas, all other compartments which comprise MICH1 interact with one or more additional compartments. In addition, these compartments are subject to inter-segment mixing. The unavailable nutrients and the phytoplankton chlorophyll are also subject to sinking from the water column to the sediments.

The major kinetic change included in MICH1 as compared to the original Lake 1 framework is a parameterization of phytoplankton decomposition followed by a similar representation for phosphorus recycle. This change was made to give the modeling framework an ability to be applied to lakes of various trophic status. DiToro and Matystik (1979) observed that similar models, when applied to lakes exhibiting a range of trophic states, required more rapid phosphorus recycle as the trophic state increased. This observation was inconsistent with a genuine first order recycle mechanism and they therefore hypothesized a recycle rate that is a saturating function of chlorophyll (an indicator of trophic status).

Recent experimental results by Rodgers (1979) suggests an explanation for the above observation by DiToro and Matystik (1979). These laboratory results indicated that making recycle rates a function of chlorophyll concentration is probably an implicit representation of bacterial metabolic activity responding to lake trophic status and, therefore, organic content. Rodgers (1979) also demonstrated that the degradation rate of phytoplankton biomass is enhanced when the physiological status of phytoplankton is stressed. The saturation function representing phytoplankton decomposition in Equation 1 is therefore proportional to an indicator of trophic status (e.g., biomass concentration) and inversely proportional to an indicator of phytoplankton physiology (e.g., growth rate).

$$DR = \theta^{(T-20)} \left(K_e + K_{max} \frac{A/\mu}{K + A/\mu}\right) \qquad (1)$$

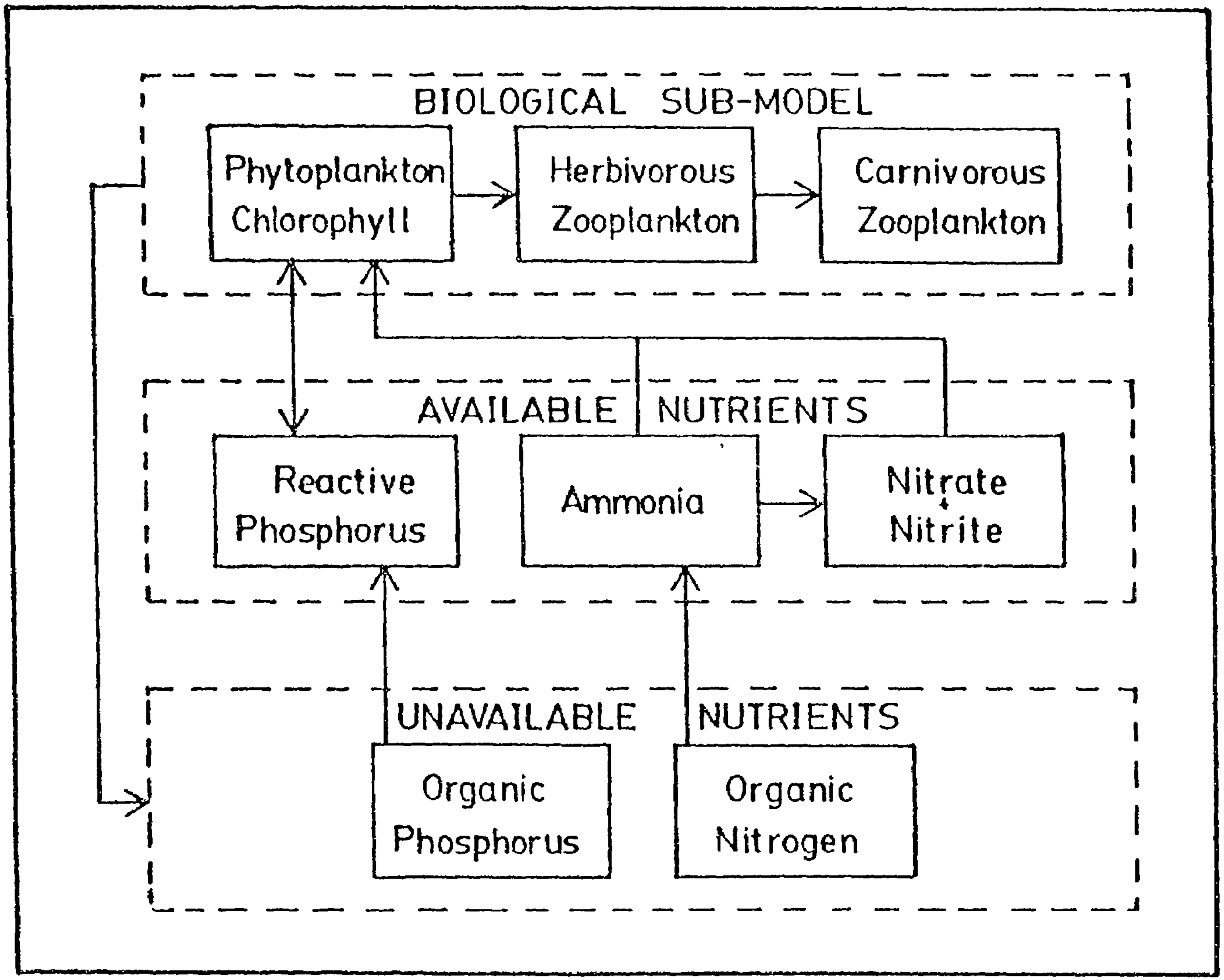

Figure 5-2. Schematic of MICH1 model compartments and kinetic interactions.

where,

CR	= specific first order phytoplankton decomposition rate	(day^{-1})
T	= ambient temperature	(°C)
θ	= Arrhenius coefficient	-
K_e	= endogenous respiration rate necessary for cell maintenance at 20°C	(day^{-1})
K_{max}	= theoretical maximum first order decomposition rate due to heterotrophic activity at 20°C	(day^{-1})
A	= chlorophyll biomass concentration	($\mu g/\ell$)
μ	= calculated growth rate	(day^{-1})
k	= half-saturation coefficient	($\frac{\mu g \cdot day}{\ell}$)

5.3 Model Requirements

The Great Lakes Environmental Planning Study (1978) has pointed out the need for model requirement summaries. Such a summary of requirements necessary for MICH1, TPM, the Vollenweider loading plot model, and the Dillon and Rigler model is found in Table 5-1. MICH1 has the most extensive requirements and its data are single system intensive. This investment of data collection yields more detailed model output than do the other models. Not only are nine water quality state variables tracked in time, but MICH1 has the versatility of representing the desired three dimensional segmentation. The versatility of MICH1 is due to foresight in the Lake 1 development (Thomann et al. 1975). TPM is less sophisticated than MICH1 in its representation of a complex system. Yet, TPM is a dynamic, time variable model whose conceptual framework has succeeded in simulating a number of lakes. The simplified framework and reduced model requirements of TPM lends itself to more widespread application. The output of TPM, however, yields no information regarding the nutrient fractions or the biological responses of a lake. The mixing characteristics of a lake are also not represented by TPM.

The last two total phosphorus models, Vollenweider's loading plot model and Dillon and Rigler's empirical model are both based on steady-state

TABLE 5-1. SUMMARY OF MODELS APPLIED TO LAKE MICHIGAN

Model	Model Type	Program Language	Input Data	No of Coefficients	Time Scale	Spatial Segmentation	Model Output
MICH1	Deterministic phytoplankton and nutrient model	Fortran	Lake hydrology and morphometry, incident light, segment exchange coefficients, loading and initial conditions for nine state variables (two phosphorus and three nitrogen fractions, two zooplankton trophic levels, chlorophyll-a, and chloride)	30-40	Time variable, daily, seasonally, or annually	Horizonal and vertical (4 segments)	Graphics of state variables vs. time and comparison with field data for each spatial segment
TPM	Dynamic mass balance model	Fortran	Lake hydrology and morphometry, loading and initial conditions for total phosphorus	3	Time variable, annually	Horizonal (2 segments)	Total phosphorus concentration in the water column and sediments
Dillon and Rigler	Empirical total phosphorus loading model	Mathematical equations	Empirical interpretation of areal total phosphorus loading, overflow rate, and in-lake total phosphorus concentration for numerous lakes	1	Steady-state assumptions	None (basin separation possible)	Total phosphorus concentration in the water column
Vollenweider	Loading plot model	None	Plot of areal phosphorus load vs overflow rate and the trophic status for numerous lakes	none	Steady-state assumptions	None	Judgement of permissable or dangerous total phosphorus loads for a given lake

assumptions. The data required for the empirical development of these models must come from many lakes of similar geo-physical and climatic classification. Normally data from over 30 lakes and sometimes in excess of 100 lakes are utilized in empirical formulation. Although the application of these models are comparatively easy, the predictions of lake response to phosphorus loading has considerable uncertainty. The cautions regarding the interpretation of results hinges on their empirical development. Their application is best suited to yielding general indications of lake response for lakes that are similar to the lakes for which the empirical relationships were developed. No direct indication of transition concentrations or response times are available from these models.

SECTION 6

CALIBRATION OF MICH1 TO THE 1976 DATA

6.1 CALIBRATION APPROACH

There are three primary topics to be addressed when calibrating a specific model to a given lake. First the mass loads that the model requires must be measured or estimated. The total phosphorus load to Lake Michigan in 1976 was represented by Case 1 in Table 4-3. In MICH1, however, there are additional loads which must be quantified for an accurate representation of the system. The nutrient and chemical loads required by MICH1 are presented in Table 6-1. The total loads are also divided between Southern and Northern Basins, as the model requires. Note that loads for the biological state variables are not included. This is because the primary source of chlorophyll-*a* is autochthonous generation within the euphotic zone followed by responses in the zooplankton community.

TABLE 6-1. NUTRIENT AND CHEMICAL LOADS TO LAKE MICHIGAN IN 1976.
(Metric Tonnes/Yr.)

	Unavailable Organic Phosphorus	Available Phosphorus	Organic Nitrogen	Ammonia Nitrogen	Nitrate + Nitrite Nitrogen	Chloride*
Southern Basin	2686	895	24211	10126	26804	489700
Northern Basin	2317	773	20869	8729	23104	221900
Total	5003	1668	45080	18855	49908	711600

*Total does not include direct industrial and municipal load of approximately 116000 metric tonnes/yr.

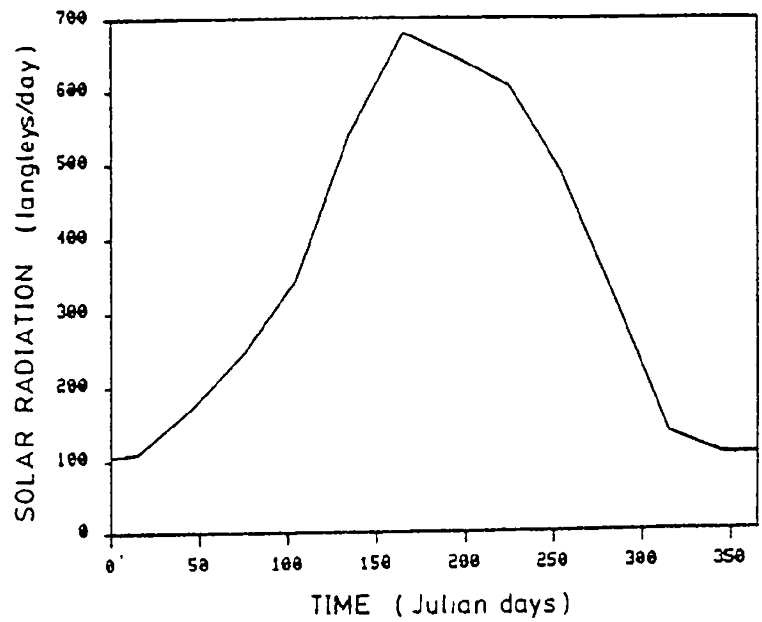

Figure 6-1. Incident light input to MICH1.

Secondly, the field data has to be reduced and organized to fit the spatial segmentation of the model. This step includes characterizing additional forcing functions such as incident light and temperature as well as representing the status of the state variables. The time series for incident light used in the 1976 calibration is reported in Figure 6-1. These values are similar to those developed by Thomann et al. (1975). In this study, volume-weighted averages for the state variables were computed (Yui 1978), but since these values proved to be the same (within the variance of the data) as the arithmetic averages the latter means were used. These data, once prepared, are later compared to the model output, both graphically and statistically.

The last primary responsibility in calibrating the model is to adjust the model coefficients within realistic value ranges so that the model output of state variables will best simulate the observed data. The coefficients which govern the simulation of biological and chemical processes within the water column depend upon known relationships which are characterized through extensive field and laboratory experimentation. There are nearly forty coefficients in MICH1. Although many coefficients are reasonably well determined, others require calibration runs where coefficients are adjusted and model output is compared to field data in order to calibrate acceptable values. The state of the art knowledge of the processes serve as a guideline which fixes the range within which the coefficients must be calibrated. Therefore, a continuing effort must be made by the modeler to not only mathematically simulate the state variables but to maintain external consistency.

6.2 CALIBRATION COEFFICENTS

A preliminary requirement of MICH1 is the characterization of water exchange rates between adjacent segments. The vertical dispersion between model layers, previously indicated in Figure 5-1, is time dependent. Conservative substances are often used when calibrating exchange coefficients. However, there are no large gradients to be found in the open waters of Lake Michigan for chloride (Rockwell et al. 1980). In order to calibrate the dispersion between the vertical layers, conceptually equivalent to the epilimnion and hypolimnion, it is necessary to simulate the temperature dynamics. This process can be accomplished by directly evaluating the heat flux (DiToro and Matystik 1980). Unfortunately, sufficient data to properly utilize this approach does not exist for Lake Michigan. This heat flux can instead be modeled implicitly by using the upper 5 meter layer as a boundary layer. The water and its associated heat can be mixed until the model output fits the measured temperature throughout the year. The water is first mixed into the remaining epilimnion and then into the hypolimnion. The results of calibrating vertical exchange coefficients are presented graphically in Figure 6-2 for the Southern and Northern Basin.

Note that the onset of stratification in the Northern Basin lags behind that of the Southern Basin and that it is not as complete in the North. The magnitude of vertical dispersion is also generally higher in the North than in the South. These results are due to the more inclement weather in the Northern sector mediating colder temperatures and greater mixing from the winds. This calibrated dispersion set is very influential in predicting the timing and magnitude of the first phytoplankton bloom and should be an essential step in calibrating any new aquatic system.

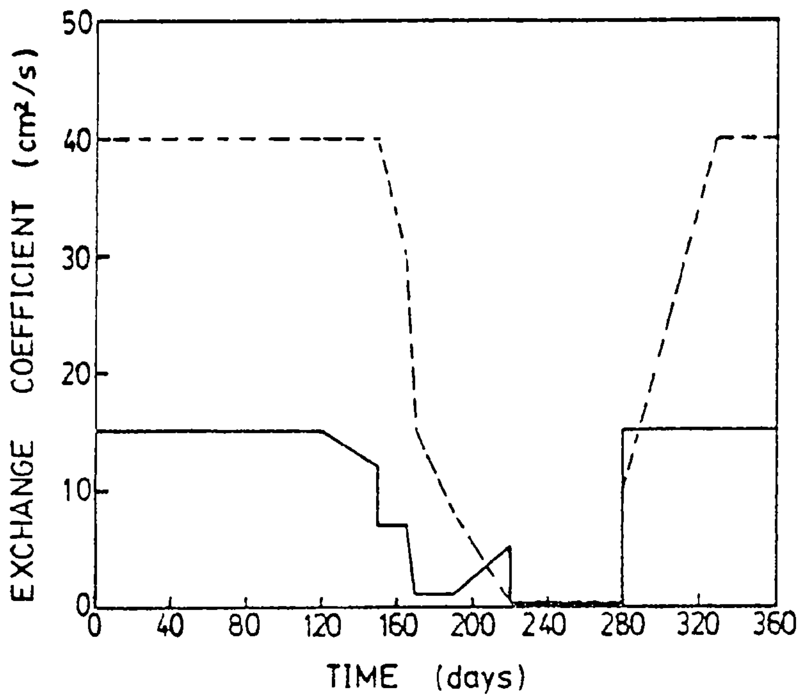

Figure 6-2. Vertical exchange coefficient from temperature calibration.
- Southern Basin -- Northern Basin

The horizontal exchange coefficients were set at constant values of 1000 cm^2/sec between the epilimnetic segments and 100 cm^2/sec between the hypolimnetic segments. Similar coefficients have been utilized for other large systems.

The principal model coefficients are listed in Table 6-2. Many of the values associated with these coefficients required a calibration process. The general approach and guidelines to this calibration process have already been discussed here and elsewhere (Thomann et al. 1975, Bierman et al. 1981). However, the specific details regarding the calibration of several of these coefficients is appropriate.

Nutrient to Chlorophyll Ratios: There are four cellular components which MICH1 must simulate, chlorophyll (Chl), phosphorus (P), nitrogen (N), and carbon (C). The framework of MICH1 kinetically simulates chlorophyll, but tracks the cellular nutrients by assigning constant nutrient to chlorophyll ratios. This approach lacks accurate representation of known nutrient kinetics. Namely, nutrient ratios are known to vary depending on phyto-

TABLE 6-2. PRINCIPLE COEFFICIENTS

Name	Description	Value	Units
K1C	Maximum Growth Rate	2.10	$days^{-1}$
K1T	Arrhenius Temperature Coefficient for Growth	1.08	none
IS	Saturating Light Intensity	125	langleys/day
CCHL	Carbon to Chlorophyll Ratio	50	μg-C/μg-chl-a
NCHL	Nitrogen to Chlorophyll Ratio	12.5	μg-N/μg-chl-a
PCHL	Phosphorus to Chlorophyll Ratio	0.5	μg-P/μg-chl-a
KMP	Half-Saturation Coefficient for P Limited Growth	0.5	μg-P/ℓ
K_e	Biomass Loss Rate due to Endogenous Respiration	0.03	$days^{-1}$
K_{max}	Maximum Biomass Loss Rate Due to	0.3	$days^{-1}$
k	Half-Saturation Coefficient for Microbial Biomass Loss	500	μg-chl-a day/ℓ
K2T	Arrhenius Temperature Coefficient for Biomass Loss	1.08	none
RHO	Available Fraction of Respired Phytoplankton	0.6	none
KC	Nutrient Mineralization Rate	0.03	$days^{-1}$
KT	Arrhenius Temperature Coefficient for Mineralization	1.08	none
KMR	Half-Saturation Coefficient for Mineralization	8.0	μg-chl-a/ℓ
SVEL	Settling Rate for all Particulates	0.2	m/day

plankton species, nutrient limitation status, external nurient concentrations, and past population history. For a thorough discussion of these influences and their incorporation in a phytoplankton model see Bierman et al. (1981). In general, large ratios correspond to excess nutrients and small ratios to a limiting nutrient situation. The stoichiometry chosen should therefore reflect the phosphorus limited conditions of Lake Michigan. The calibrated nutrient to chlorophyll ratios in Table 6-2 suggest a C:N:P ratio of 100:25:1. Literature values of phytoplankton stoichiometry, reported in Table 6-3, provide a standard guideline for which the calibrated nutrient ratios can be compared. The C/dry wt. ratio of 0.39 reflected a range of phytoplankton functional groups and therefore should reflect a mixed field population. An expected Chl/dry wt. ratio is calculated by dividing the C/dry wt. ratio by the calibrated C/Chl ratio. This calculation yields 0.0078 as the expected Chl/dry wt. ratio and is within the range reported in Table 6-3. Furthermore, the product of this Chl/dry wt. ratio and the calibrated P/Chl ratio (0.5) provides a P/dry wt. ratio of .004, again within the range of observed data. A check on the external consistency of nutrient ratios calibrated for similar models (Thomann et al. 1978; DiToro and Connolly 1980; DiToro and Matystik 1980) does not yield a consistent result. Their C/Chl ratio of 100 suggests a Chl/dry wt. ratio of .0039 and a P/Chl ratio of 0.002. Both ratios are at or below the extreme minimum reported in Table 6-3.

Phytoplankton Decomposition Coefficients: Equation 1 in Section 5 represents a sub-model describing the decomposition of phytoplankton. This decomposition sub-model represented the observation that nutrients recycle more rapidly when the trophic status of a system increases. The first order decay rate was parameterized in a saturation function which is proportional to an indicator of trophic status and inversely proportional to the physiological state of the phytoplankton. MICH1 uses this proposed sub-model and the required coefficients, as calibrated, are also reported in Table 6-2. The calibration of these coefficients should be considered provisional. Refinements in deterministic models which are made for rendering that model acceptable to lakes of various trophic status are best calibrated when applied to multiple systems. A single system like Lake Michigan is not diverse enough to test the performance of this type of sub-model.

TABLE 6-3. REPORTED PHYTOPLANKTON STOICHIOMETRY

Ratio Description	Value Range	Reference
$\frac{\text{Carbon}}{\text{Dry wt.}}$	0.15-0.67 (0.39)*	Bierman (1981)
$\frac{\text{Chlorophyll-a}}{\text{Dry wt.}}$	0.005-0.015 (0.01)	Dolan et al. (1978), Rodgers (1979)
$\frac{\text{Phosphorus}}{\text{Dry wt.}}$	0.002-0.050 (0.006)	Sawyer (1973), Rodgers (1979), MacKenthun et al. (1978)
$\frac{\text{Nitrogen}}{\text{Phosphorus}}$	4-80 (10-40)	Rhee and Gotham (1981)

*Typical value.

The calibrated coefficients, if accurate, do have ecological significance. The endogenous respiration rate, K_e, of 0.03 day^{-1} is applicable to the phytoplankton community without bacterial mediation. This loss is a result of normal cell maintenance requirements. However, K_{max} represents that loss due to microbial activity and is an order of magnitude higher. Although, K_{max} is only realized under the worse conditions of cell maintenance. The half-saturation coefficient (k) which characterizes the controlling saturation function is of particular interest. Its calibrated value means that as long as the ratio of chlorophyll biomass (A) to growth rate (μ) is less than 500 the phytoplankton decomposition rate is a linear function. Most useful lakes exhibit chlorophyll concentrations between 1 and 50 μg-chl/ℓ and the growth rate of algae in natural settings is commonly between 0.05 and 0.5 days^{-1}. Therefore, the A/μ ratio frequently ranges from 2 to 1000. Even when this ratio is at its upper range only two-thirds of the maximum decay rate is operative. For non-eutrophic lake conditions and during active growth periods the specific decay rate is about 20 per cent or less of the maximum rate, K_{max}. Temperatures less than 20°C would additionally impair the magnitude of the specific decay rate.

6.3 CALIBRATION RESULTS AND DISCUSSION

Results: The coefficients presented and discussed in Section 4.2 were calibrated by observing their ability to simulate the field data of 1976 and guided by knowledge of lake processes. The results of this simulation, in its totality, would reflect the time dependent behavior of nine state variables as well as observing the concurrent behavior of model functions. The two major state variables for the purpose of this research, are phytoplankton biomass (chlorophyll-a) and total phosphorus. The model output for chlorophyll-a for the four segments of the lake is presented graphically in Figure 6-3. This figure plots the model output as a continuous line over the observed data. The solid squares denote the arithmetic mean of data collected for a particular cruise within a lake segment. These means are each bounded by one standard deviation. Similar plots are output by each run of the model for each state variable of interest. The model does simulate chlorophyll-a within the more biologically active epilimnion

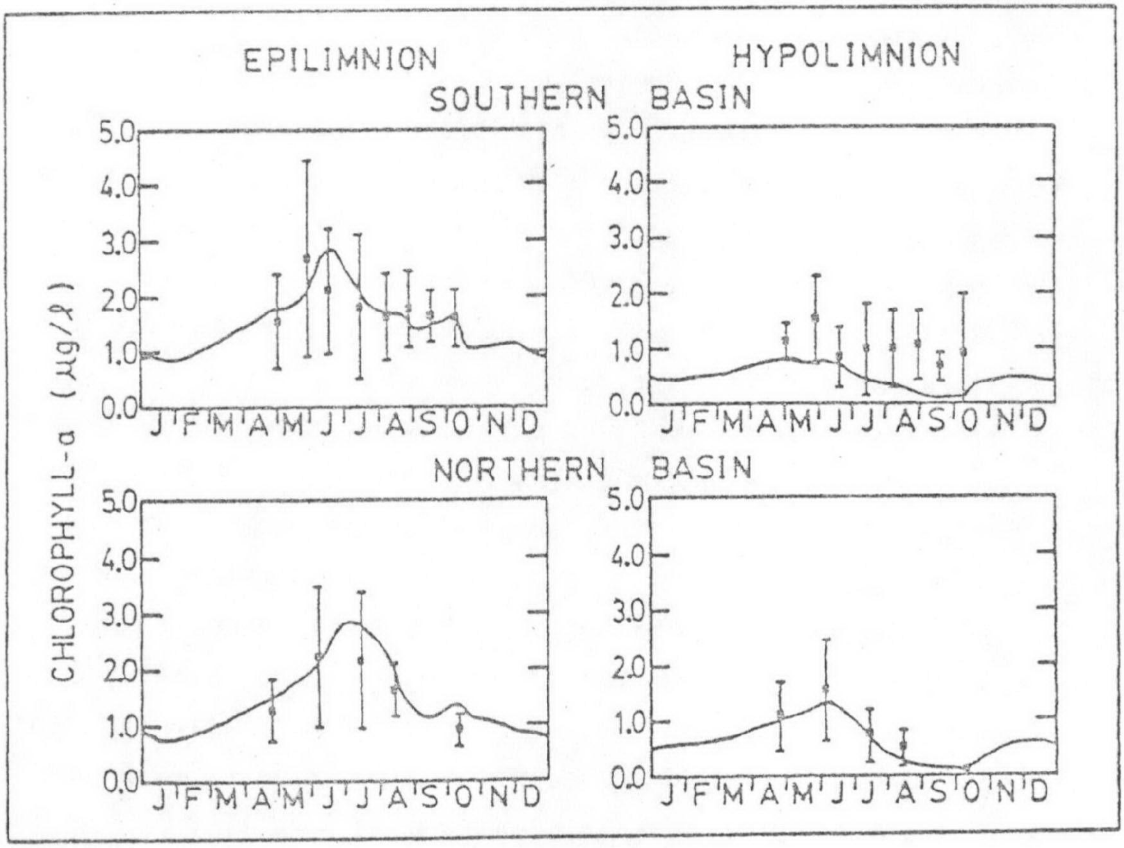

Figure 6-3. Model calibration results for chlorophyll-a during 1976.

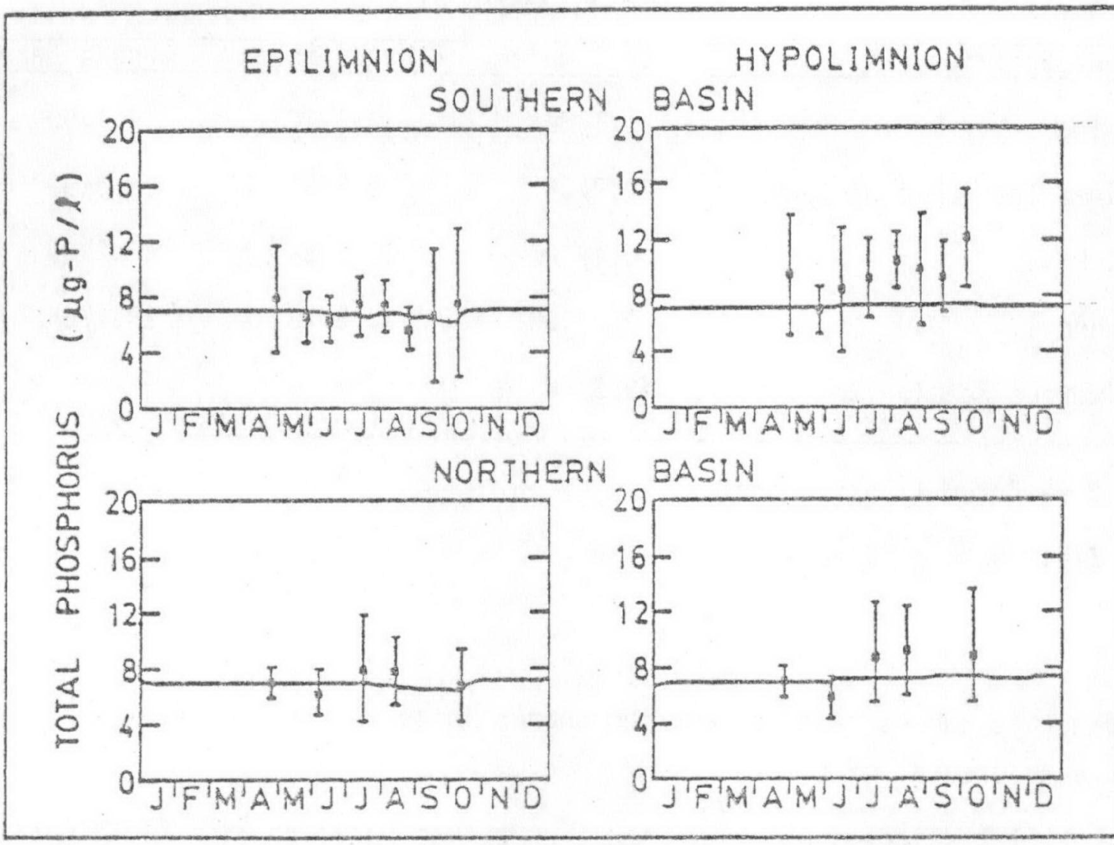

Figure 6-4. Model calibration results for total phosphorus during 1976.

both in respect to trend and magnitude. The model produces the observed peak in phytoplankton as reflected by chlorophyll-a in late May to late June. The peak in the North lags somewhat behind that of the Southern Basin due to greater dispersion and colder ambient temperatures. The model does not simulate the chlorophyll-a concentrations of the hypolimnion segments quite as effectively.

The calibration to the 1976 data for total phosphorus is presented in Figure 6-4. It is evident that the model simulates total phosphorus as relatively non-dynamic over short periods. This is to be expected in a lake having a detention time of 69-100 years. This output of total phosphorus results is a representative simulation throughout most of the lake. However, the output for the hypolimnion of the Southern Basin fails to simulate the dynamic increase observed in the late summer and early fall. If these data are accurate then the model would have to account for approximately

TABLE 6-4. 1976 CALIBRATION STATISTICS

Segment Grouping	Epilimnion	Hypolimnion	Whole Lake
Chloride	1.1/80*	1.1/100	1.1/90
Combined Inorganic Nitrogen	29.7/56	9.5/45	4.6/89
Total P	6.1/100	19.8/89	16.9/89
Chlorophyll-a	19.3/100	42.5/78	28.4/67
Herbivorous Zooplankton	42.3/80	**	**

*Relative Error/T-test Score.

**No field data available.

6,800 metric tonnes of temporary phosphorus influx during low flow months to produce an accurate fit.

Statistical analysis of model output compared to 1976 field data provided an objective judgement of the model's simulation. The T-test and relative error analyses yield a standard quantitative comparison (Thomann et al. 1979) and the resulting statistical scores for select state variables are reported in Table 6-4. The higher the T-test scores the more often the model output lies within plus or minus one standard error of the cruise mean. This evaluation ascribes the same error flexibility to the model as that calculated for the mean of each data point. The relative error score is an indication of model adequacy and ideally should approach zero. Relative error evaluation has a number of problems associated with its interpretation. The error in the data mean is not taken into account. The evaluation is poor at relatively low data values when there are large differences in model output and data values. This statistical technique, however, is used in model comparison and in fine tuning of coefficients.

Discussion of Calibration: When evaluating the calibration of a deterministic model there exists a myriad of relevant considerations. Certainly, it is fundamental that the model simulate the state variables within desired limits both in time and space. In achieving that goal, an equally important concern is the model's accurate representation of dominant processes. This representation should reflect the goals of the model as well as the state of the art knowledge. The final calibration results do not represent a best fit to field data, but instead reflect a most appropriate fit. When model output deviates from available field data or calibrated coefficients appear not to lie within reported ranges then a re-evaluation of either available knowledge or of the modeling framework may be appropriate. A model must maintain this flexibility in order to interact with current thought and approach new problems.

The problem encountered in Figure 6-3 where the model does not accurately simulate the mean chlorophyll in the hypolimnion may be due to the existence of deep chlorophyll layers (DCL). The phenomenon of DCL is well documented as observed high concentration layers of chlorophyll in the vicinity of or just below the thermocline (Fee 1976, Talling 1966, Ichimura et al. 1978, Steele and Yentsch 1960). Fee (1976) concluded that the DCL reflected a species specific light adaptive mechanism for growth. The inability of the present modeling framework to consistently simulate DCL has previously been noted (DiToro and Matystik 1980).

Although light adaptation may be a partial explanation for the DCL, especially when the species composition of these layers are unique to the water column, there exists two other processes which undoubtedly influence the occurrence of DCL. Steele and Yentsch (1960) concluded that the DCL near the compensation depth in the Atlantic Ocean was controlled by decreased sinking rates. There is little doubt that during stratified conditions the thermocline would reduce the apparent settling of phytoplankton originating in the upper waters (Hutchinson 1967) and thereby result in observed deep layers of biomass. Another explanation for DCL recognizes the variability in the ratio between chlorophyll-a and other biomass indicators (Dolan et al. 1978). Talling (1966) demonstrated variability in chlorophyll content when he found a range between 0.8 and 2.0 mg of chlorophyll-a per 10^9 Asterionella cells, the higher values clearly associated with samples from deeper layers. To a large extent this variability is probably due to a concurrent change in the physiological state of the phytoplankton. Chlorophyll-a content per cell generally increases with increasing growth rates

(Rhee 1981, Rodgers 1979), yet is comparably high for very low growth rates (Rodgers 1979) and for cells grown at low light illuminance (Steemann Nielson 1962). These observations probably reflect a physiological response to stress conditions and may be referred to as chlorophyll compensation.

Recall that during late summer and early fall of 1976 the field data, evident in Figure 6-4, indicated an increase in total phosphorus concentration in the hypolimnion of the Southern Basin which the model output failed to simulate. The question arises as to where and by what means does this total phosphorus enter the hypolimnion during this time period. Three potential sources of this hypolimnetic total phosphorus are 1) Vertical resuspension of sediment phosphorus; 2) Sedimentation of epilimnetic phosphorus; and 3) Horizontal transport of phosphorus which had been resuspended in the nearshore zone. Resuspension of a sufficient amount of sediment phosphorus to account for the observed increase in phosphorus mass seems unlikely in a lake having a mean depth of approximately 92 meters. The energy sources required to create the stress necessary to accomplish resuspension diminish exponentially with lake depth (Sheng and Lick 1979). As a result, resuspension of in-lake sediments can be considered minimal. The hypothesis that the observed mass of phosphorus could have originated from epilimnetic waters appears even more unlikely. The entire mass of total phosphorus present in the Southern Basin's epilimnion constitutes only about one-third of the mass required to produce the concentration increase in the hypolimnion.

The location and timing of this increase in total phosphorus concentrations may indicate that its origin was from nearshore zones. The sediment distribution in Lake Michigan indicates that there has been nonhomogeneous deposition of sediments and that the southeastern sector has served as a sediment sink over the long term (Edgington and Robbins 1976). The source of these sediment deposits are not only the particulates generated in the overlying water column, but most likely reflect sediment transfer from adjacent segments and from the nearshore zone. The nearshore zones of Southern Lake Michigan have substantial resuspension and erosion activity. Chesters and Delfino (1978) characterized Lake Michigan's nearshore resuspension as having the highest mean number of potential days of resuspension conditions for all the Great Lakes and ranked it a close second behind Lake Superior for amount resuspended on a nearshore areal basis. In fact, the southeastern nearshore area of Lake Michigan proved to have the highest areal resuspension potential of any of the Great Lakes' twenty-eight nearshore zones studied. In addition, Lake Michigan has also been identified as having the highest erosion rate per kilometer of shoreline of the Great Lakes (Sonzogni et al. 1979). The combined processes of nearshore resuspension and shoreline erosion suspend large masses of sediment and associated nutrients into the water column of Lake Michigan. The high seasonal winds may succeed in mixing some of these sediments horizontally. Lower layer velocities of 3-7 cm/sec (Kizlauskas and Katz 1973) would be sufficient for the timely transfer of nearshore sediments to in-lake hypolimnetic stations. Turbulence created by thermocline oscillation would assist in prolonging suspension of these sediments and their associated nutrients. The turbidity in the southern hypolimnion also doubled during this time period and may support the contention of horizontal transfer of nearshore sediments. The absence of similar observations in the epilimnion could be a result of its depth being less, resulting in particle retention being several times shorter than in the hypolimnion. The sediment dynamics may therefore result in a loss of sediments from the epilimnion by the time in-lake locations are reached by horizontal mixing.

The inability of present models to track sediment movement and to include nearshore resuspension and shoreline erosion may not be of equal biological importance when compared to present model sources because of questions involving biological availability of associated nutrients (Lee et al. 1980, DePinto et al. 1980). However, these sediments no doubt play important roles in nearshore zones and quantification of their transport and biological role remains a research need.

SECTION 7

MODEL APPLICATION TO 1977 DATA

7.1 APPROACH AND RESULTS

The data gathered in 1977 indicated a substantial loss of total phosphorus from the Southern Basin when compared to the results of the 1976 survey (observed in Figure 4-2). Initially there may have been a temptation to attribute the improvement in water quality to active remedial programs. However, since the hydraulic detention of Lake Michigan approaches a century, and since our present understanding of long term sediment rates would suggest a loading response time on the order of years, then alternative loss mechanisms must be responsible for such a rapid depletion in total phosphorus. The main challenge in applying MICH1 to the 1977 data was to suggest a process by which such a rapid loss of total phosphorus could occur.

The approach to applying MICH1 to the 1977 Lake Michigan data was guided by the above realization. Initially, MICH1 would be run from 1976 through 1977 only changing the values of certain forcing functions as the model progressed into 1977. This included changing phosphorus loadings, flows, and ambient temperatures. If the model simulation failed to demonstrate the observed depletion of total phosphorus then the model structure would be inspected for the absence of a mechanism not included which might have been operative in Lake Michigan during the survey period.

Results: To run MICH1 for 1977 it was only necessary to link the initial conditions to the final output for 1976 and at the same time change the appropriate forcing functions. This attempt at direct verification, as seen in Figure 7-1, failed to simulate the substantial decrease in mean total phosphorus within the water column of the Southern Basin. The model responded to the 2000 metric ton decrease in phosphorus load with a maximum 0.35 μg-P/ℓ loss in concentration instead of the 3.1 μg-P/ℓ loss necessary

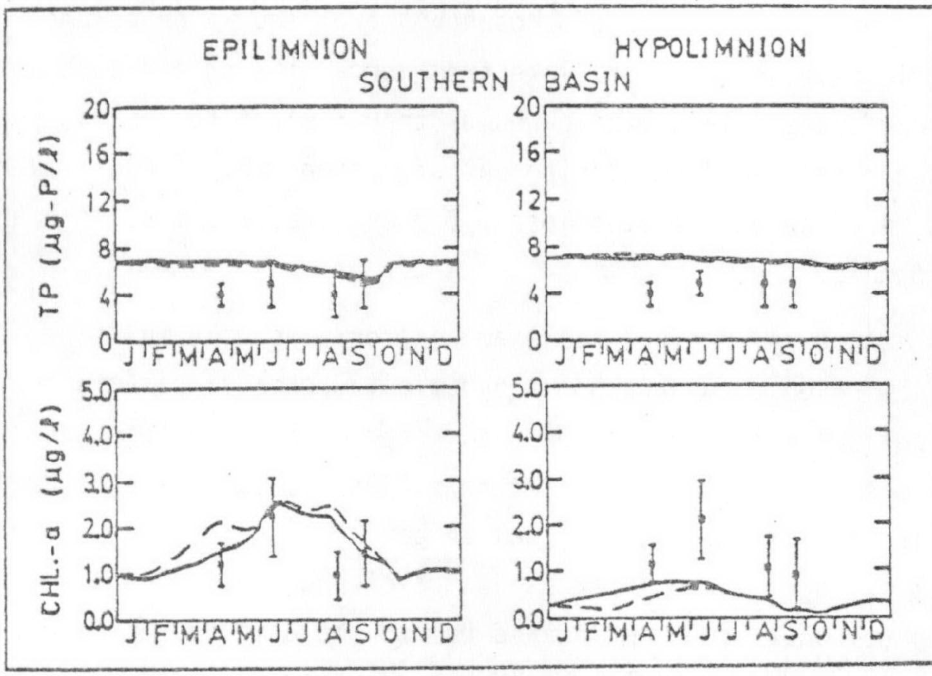

Figure 7-1. MICH1 application to 1977 data for total phosphorus and chlorophyll-a.

- Calibrated model using 1977 loads. Initial conditions linked to final output for 1976.

-- Model incorporating changes in forcing functions for representing ice cover effects. No change in settling rate coefficient.

to simulate the field data observed in the Southern Basin. Even though the phosphorus fit was awry the chlorophyll-a fit to the limited data was reasonable (Figure 7-1), which may suggest a possible inconsistency between the phosphorus data and the concurrent chlorophyll-a data. Although such an observation may also indicate that the biologically available phosphorus in the epilimnion was not radically affected by the dynamic total phosphorus depletion.

7.2 CONSIDERATION OF ICE COVER EFFECTS

As suggested previously, an explanation for not simulating the observed phosphorus loss is the absence of a particular loss mechanism not originally incorporated in the model structure which might have been operative in Lake Michigan. The extreme ice cover during the winter of 1976-77 (Quinn et al. 1978) presented a potential phenomenon that might be substantial enough to enhance the loss of phosphorus from the water column. The ice cover would have isolated the lake from normal mixing and turbulence due to wind driven forces. This mixing would otherwise act to inhibit particles and associated nutrients from sinking out of suspension. Such a severe climatic induction of an accelerated loss, if operative, would be rare and temporal in nature.

The structure of MICH1 was examined for ways of simulating the effect of the ice cover upon phosphorus dynamics. Vertical dispersion, incident light, and water temperature were adjusted with respect to per cent ice cover, available data, and expected effects. An ice cover was assumed to reduce wind induced mixing proportional to per cent ice cover for weekly periods. Estimating changes in transmission of photosynthetically active radiation was somewhat more complicated due to the observed effect of ice type on light transmission (Bolsenga 1978). However, its total attenuation is also influenced by per cent ice cover. These changes in the model structure represent an attempt to simulate a unique and significant climatic event without altering the calibrated coefficients or the structure of MICH1. Since this approach was based on deductive estimates, rather than actual data, the accuracy of the representation is subject to continued improvement based on measurement of pertinent parameters. The results of this approach are represented by the dashed line in Figure 7-1. The most influential change was the reduction in vertical dispersion, since vertical dispersion acts as a competitive parallel process to particulate sinking. Therefore, its reduction results in an increase in net (or apparent) sinking, thereby increasing the losses from the water column. By the end of the simulation year, this adjusted model exhibits a slight improvement but still fails to simulate the large phosphorus loss. Equally important is the observation that the response did not progress rapidly enough to simulate the total phosphorus concentration observed on the first cruise. In addition, the chlorophyll-a response to these dynamics did not fit the field data as well as it had previously.

The calibrated settling rate used in MICH1, and in many eutrophication models, reflects the net forces affecting the long term loss of particulate matter from the water column. Wind driven resuspension and intra-segment mixing no doubt affect this calibrated "apparent" settling rate. The present model structure cannot account directly for these component forces which may have been influenced by the ice cover. However, if it is assumed that the ice cover decreased these forces then net settling would have been further enhanced during this period. MICH1 was run while increasing the settling rate during ice cover until the model output simulated the first cruise total phosphorus concentration. The necessary settling rate proved to be 1.6 m/day, eight times the value from the 1976 calibration. After the ice cover receded significantly, the settling rate was returned to its previous calibrated value. The results of this approach can be seen in Figure 7-2 for total phosphorus, and in Figure 7-3 for chlorophyll-a simulations.

7.3 DISCUSSION OF 1977 SIMULATION

There are a number of potential explanations for the model and data not coinciding when 1977 was initially linked to the 1976 final conditions. For example, the phosphorus samples were stored up to 90 days (Rockwell et al. 1980), which exceeds the E.P.A. recommendation of a maximum storage time of 24 hours (U.S. E.P.A. 1974). Whether this storage practice influenced the analytical evaluation of the samples is difficult to ascertain. Also, the incomplete coverage in data collection in 1977, both in spatial coverage and cruise frequency, makes a thorough analysis additionally difficult.

This research approach accepted the validity of the data and examined the modeling framework for methods of simulating the potential influence of an extreme ice cover upon the dynamics of the particulates residing in the water column. When the initial attempt to simulate the 1977 data by simply altering the phosphorus load and certain other forcing functions failed there were two approaches devised for representing the influence of ice cover.

The first approach did not alter model structure but instead looked at present model inputs which might have been altered by a substantial ice cover. Model components which were changed included vertical dispersion and incident light. These components are normally time variable and, therefore, their adjustment required only assumptions in regard to the influence that

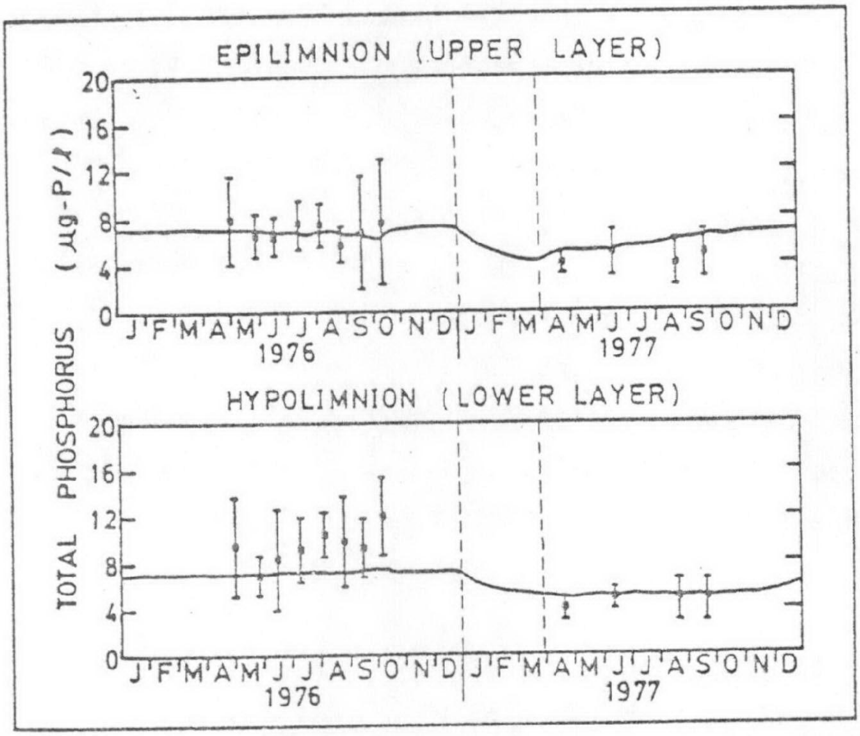

Figure 7-2. Two year total phosphorus simulation incorporating an eight fold increase in apparent net settling during the ice cover period (between dashed lines).

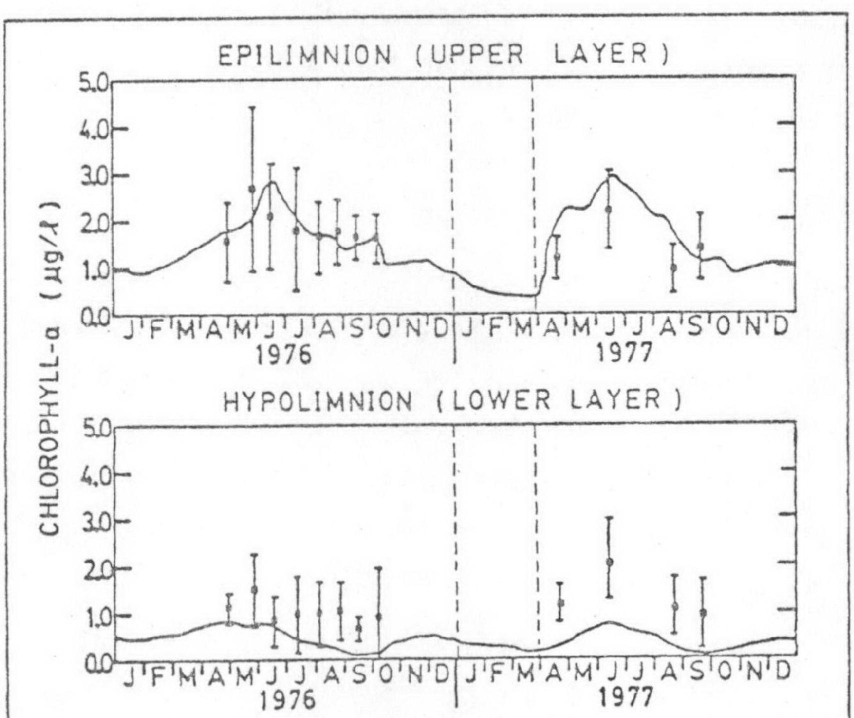

Figure 7-3. Two year chlorophyll-a simulation incorporating an eight fold increase in apparent net settling during the ice cover period (between dashed lines).

an extensive ice cover might have had. When this approach proved to fail at mediating a sufficient loss the alternative mechanism that net sedimentation is enhanced directly by the ice cover reducing wind induced intra-segment mixing, turbulence, and resuspension was then explored.

Analysis of the attempts to adjust the modeling framework to simulate the ice cover event suggests that if the phosphorus data is accurate then the net settling during ice cover is altered substantially. In order to fit the total phosphorus data and the chlorophyll-a data simultaneously it was necessary to make extensive alterations in the settling coefficient and the vertical dispersion between segment layers. This meant decreasing vertical dispersion and increasing the "apparent" settling rate during the period of ice cover. This final approach succeeded in simulating both the phosphorus and chlorophyll-a dynamics. Its implication is that the "apparent" settling rate, whose value is normally determined over the long term, can change dramatically in the short term due to rare and extreme climatic conditions. What role such climatic influences may have in long term responses to nutrient loading alternatives is a subject yet to be addressed. Perhaps the solution to such a problem lies in representing the frequency of occurrences on a statistical basis. These observations indicate that a more thorough analysis of ice cover events would be in order.

SECTION 8

LONG TERM SIMULATIONS

8.1 RATIONALE AND APPROACH

Hindcasting or historical simulations, when successful, add credibility to the model structure. Through this exercise the behavior of the model for prolonged periods can be observed and the ability of the model to "predict" present conditions, given historical loadings, can be tested. To aid the historical simulation, a summary of historical loading estimates was gathered from a variety of sources and were graphically presented in Figure 4-3. Forecasting fulfills a primary motive of model development, the ability to make scientific cause and effect judgements to aid present management decisions concerned with resource preservation. Simulating lake response given the nature of a remedial program along with estimating the time necessary for that response is a valuable model application.

In Section 5-1 three models besides MICH1 were briefly described and in Table 5-1 a model requirement summary for all four models was presented. The time variable total phosphorus model (TPM) was the only model applied for historical simulation. TPM was chosen for this task because the loads during the simulation period (1800-1980) were variable, therefore a non-steady-state model was required. Secondly, the model requirements for running TPM during the historical period were considerably less than what would have been required by MICH1. All models were applied for forecasting simulations of steady-state loading scenarios.

8.2 HISTORICAL SIMULATION RESULTS

The historical loads resulting from Chapra's (1977) loading model, as presented in Figure 4-3, were used as an input to TPM from 1800 through 1960. Thereafter, an interpolation of the estimated loads were used through

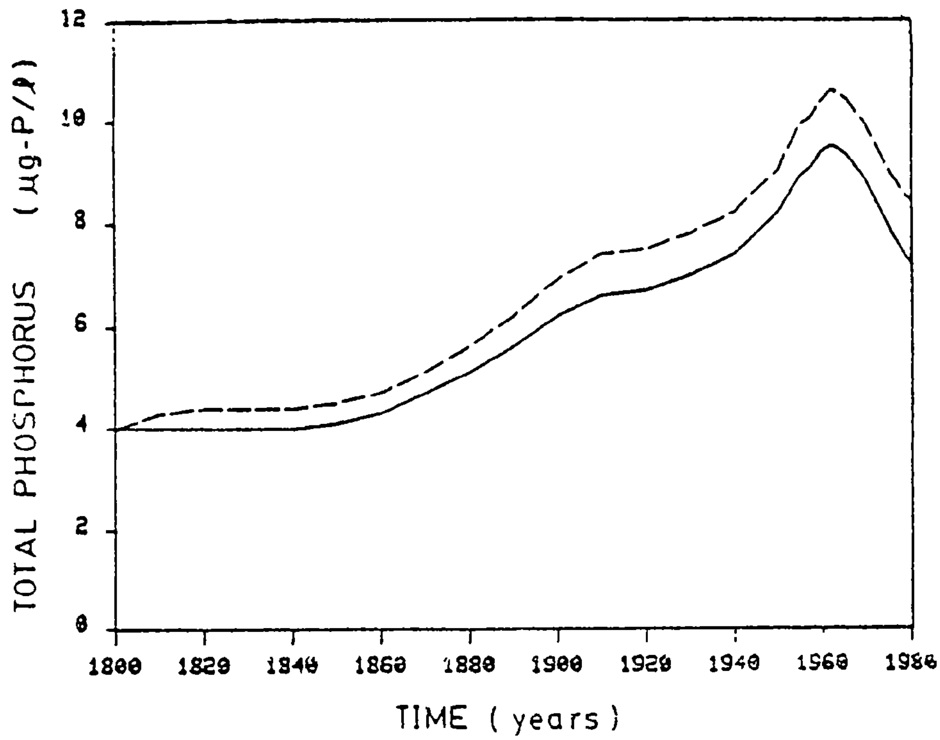

Figure 8-1. TPM historical simulation output for Lake Michigan for the years 1800-1980.
- Southern Basin -- Northern Basin

1980. Using this recreation of historical loads produced the TMP results evident in Figure 8-1. Note that the maximum total phosphorus concentrations, 9.5 and 10.6 μg-P/ℓ in the Southern and Northern basins, respectively, were during the early-1960's. These concentrations are within the range of values reported through the U.S. Department of the Interior (1966, 1968) and by Risley and Fuller (1965) for the years 1962-63. This entire range of 6.5 - 22.8 μg-P/ℓ is large due to the inclusion of nearshore stations, but the few in-lake stations appear to vary between 6.5 and 13.1 μg-P/ℓ. The 1976 concentration resulting from this historical simulation are 7.8 μg-P/ℓ in the south and 8.9 μg-P/ℓ in the north. This horizontally segmented total phosphorus model predicts slightly higher concentrations in the Northern Basin due to its shorter detention time and the loading of phosphorus this basin receives from the Southern Basin.

Recall that the loadings used in this historical simulation were primarily obtained from a loading model based on cultural activity and the physical characteristics of the drainage basin (Chapra 1977). These loadings were never verified due to a lack of appropriate data. TPM reflected the input loadings in a consistent manner and reflects the 1976 results within the error of the field data (compare with the values evident in Figure 6-4). The results do favor the high side of the data but the loads for the preceding years may be somewhat high. Even though the TPM model says nothing about the response in the biological community during this historical period its performance in regard to total phosphorus renders the model suitable for limited comparison with MICH1 forecasting results.

8.3 FORECASTING RESULTS

The three loads presented in Table 4-3 and noted in Figure 4-3 were utilized in applying the models for forecasting purposes. Case 1 reflects the high flow, high load condition of 1976. Case 2 is the value recommended by Task Group III (Vallentyne and Thomas 1978). At the lower end of the load spectrum, Case 3 represents the extreme low flow, low load condition of 1977.

The Vollenweider model (1975) makes use of an empirical observation. When the areal loading of many lakes are plotted versus their overflow rate, lakes classified as eutrophic generally group separately from the oligotrophic lakes. In the area in between these two groups reside mesotrophic lakes and some lakes from each category. Using whole lake loading and morphometry measurements the Vollenweider model suggests that Lake Michigan would fall within the mesotrophic range if long term loads equivalent to Case 1 are assumed. Application of this sort of model does not permit specific phosphorus concentrations to be obtained. Also, this "loading plot model" cannot indicate response times to load changes. A similar application, using Cases 2 and 3, reveals that these load reductions are barely sufficient to enable Lake Michigan to be within "permissable" loading limits and to reside in the oligotrophic zone.

These loading scenarios were applied to MICH1 (as calibrated to 1976), TPM and the Dillon and Rigler empirical model. Except for MICH1, forecasting was performed on a whole lake basis as well as for the two basin scheme. The input to these models assume, for the purpose of illustration,

TABLE 8-1. MODEL COMPARISONS OF FORECASTING RESULTS FOR STEADY-STATE TOTAL PHOSPHORUS CONCENTRATION (μg/ℓ)

	Loading Case*	MICH1	TPM	Dillon & Rigler
Whole Lake	1	-	7.7	12.7
	2	-	6.4	10.6
	3	-	5.4	8.8
			(10 yrs.)**	(29 yrs.)
Southern Basin	1	7.4	7.3	12.0
	2	6.6	6.1	10.1
	3	5.5	5.1	8.4
		(7 yrs.)	(8 yrs.)	(25 yrs.)
Northern Basin	1	9.0	8.2	13.4
	2	7.4	6.9	11.1
	3	6.7	5.8	9.3
		(14 yrs.)	(14 yrs.)	(30 yrs.)

*Whole lake loadings reported in Table 1.

**Response time for reaching > 95% steady-state.

a step change starting in 1978. Table 8-1 summarizes the results for easy comparison of the steady-state concentration of total phosphorus and the response time for each of the three models. Reference to Figure 4-2 provides a baseline comparison to the 1976 and 1977 observed concentrations.

For the most part these forecasting results produced similar loading responses. The Northern Basin consistently reaches steady-state concentrations for non-conservative substances which are somewhat higher than those in the Southern Basin. This concentration gradient may not be as evident in the actual case due to sedimentation in Green Bay of particulate phosphorus that is not represented in the models. However, since the Southern Basin receives the higher phosphorus load, these modeling forecasts suggest that the Southern Basin serves as a loading source to the Northern Basin. In a similar way, Lake Erie has been noted for being a loading source to Lake Ontario (Chapra 1977). In Lake Michigan, MICH1 finds that even the chloride concentration in the North, 12.7 mg/ℓ at steady-state, would only be 4.7 mg/ℓ were it not for the load from the Southern Basin. The shorter residence time in the Northern Basin also influences the model results from non-conservative state variables. Note that the whole lake responses are intermediate to the two basin results.

The Dillon and Rigler empirical model consistently predicts higher phosphorus concentration responses to the loading scenarios. The explanation for this deviation may lie in that model's loss term. Unfortunately, this loss term is very difficult to measure and, therefore, is normally estimated via data from many lakes (Kirchner and Dillon 1975) or from generalized assumptions derived from lake morphometry (Dillon and Rigler 1975). The value utilized for this loss term was 12.3 m/yr. after estimates made by Sonzogni et al. (1979). The uncertainty in this loss term and its inaccuracy in depicting a highly kinetic environment results in an equal uncertainty in results, especially when applied to a lake not used in the original empirical data base. Although the magnitude in the steady-state results for the Dillon and Rigler model are higher than the other two models, the general trends noted previously are similar for all model forecasts.

The response times, also indicated in Table 8-1, were obtained for the time variable models by observing the elapsed time required for greater than 95% equilibration. Conservative substances in Lake Michigan would be expected to have a response time of three times the hydraulic detention time of approximately 100 years. The net loss of total phosphorus to the sediments provides the mechanism for the predicted response times being considerably shorter. Due to the hydrology of the lake, the Northern Basin lags behind the response of the Southern Basin. The fourteen year response time in the north includes the seven to eight year response in the south. For the main lake portion to respond in eight to fourteen years in the kinetic models compares favorably with the estimate made by Chapra (1977) of sixteen years for the entire lake. A more optimistic response time of five years has been estimated and reported by Sonzogni et al. (1979). These response times should be regarded with caution because they assume well defined steady-state conditions and no resuspension events of sediments outside that included in the long term net settling rate.

Special note regarding the MICH1 forecasts should be made. These results indicate that if Lake Michigan were to receive a long term phosphorus load equivalent to the 1976 load (Case 1) then the in-lake concentration of total phosphorus would exceed the GLISP goal of 7.0 μg-P/ℓ for Lake Michigan. Even when a 1 mg/ℓ treatment standard is applied to this load (i.e., Case 2) the Northern Basin is forecast to exceed the goal by 0.4 μg-P/ℓ. However, on a whole lake basis Case 2 loading does result in phosphorus concentrations very close to the GLISP goal. These loading scenarios do not include probable increases in wastewater volume in the basin due to expected population growth.

Unlike the total phosphorus model, MICH1 can predict concurrent responses in chlorophyll-a when forecasting. The calibrated 1976 simulation of chlorophyll-a indicated a peak concentration of 2.8 μg/ℓ in the Southern Basin and 2.9 μg/ℓ in the Northern Basin, although the annual productivity is greater in the south due to a longer growing season. The forecast based on Case 1 loading only sees less than a 0.5 μg/ℓ increase in peak chlorophyll in the south and nearly a 1 μg/ℓ increase in the north. A 0.3 μg/ℓ decrease in peak chlorophyll-a for the south is predicted by the GLISP recommended phosphorus load, represented in Case 2. This same scenario finds a very slight increase in the north. Case 3 loading, on the other hand, would result in decreases in peak chlorophyll-a in both basins, 0.9 μg/ℓ in the south and 0.4 μg/ℓ in the north, when compared to the 1976 values. None of the forecast loadings results in dramatic shifts in chlorophyll-a. Obviously these concentrations of in-lake chlorophyll-a do not envision Lake Michigan as exhibiting eutrophic responses to these loading examples. However, Green Bay and the nearshore zones may indeed display such undesirable water quality problems.

SECTION 9

SUMMARY

The intensive surveys of 1976 and 1977 provided the data necessary for calibrating MICH1, a nutrient and phytoplankton model. These data also indicated a substantial total phosphorus decrease in 1977, when compared to 1976. A reflex explanation that short term remedial programs were responsible could not be accepted in light of known loss mechanisms and lake hydrology. In fact, because the flow decreased by 66% in 1977 compared to the high flow year of 1976 it is not clear that remedial programs affected the load decrease appreciably during these survey years.

MICH1 was first calibrated to the 1976 field data and then applied to the 1977 data. This application of the calibrated model overestimated the 1977 total phosphorus. In order to suggest an explanation for the observed phosphorus loss, a careful examination of the meteorological conditions separating the surveys was made. The winter of 1976-77 was the fifth coldest in 200 years. Record breaking low temperatures from mid-October to mid-February resulted in an extraordinary ice cover over the entire Great Lakes. The maximum extent of ice cover in Lake Michigan was over 90% (Quinn et al. 1978). This ice cover would have isolated the lake from wind induced mixing and resuspension. The result being enhanced sedimentation and loss of phosphorus from the water column. Based on this scenario of events, refinements were made to the MICH1 forcing functions to account for the expected effects of the observed ice cover. The final results of the 1977 refinement efforts indicated that the apparent settling rate would had to have been increased eight-fold during the ice cover to affect the loss in phosphorus mass observed. This increase in net apparent settling is in addition to reduced vertical dispersion, incident light, and ambient temperatures.

The application of MICH1 and the implicit incorporation of possible physical effects due to ice cover does not close the case on the validity of the survey data. However, it does suggest a possible loss mechanism not normally incorporated in long term ecological models. In addition, such a model application demonstrates how a modeling framework can be utilized in the difficult assessment of remedial programs, especially when such an evaluation is made difficult by concurrent physical and biological phenomena of a complex nature. The combined influence of dispersion, particle settling and resuspension is a major factor in determining the fate of particulates and associated parameters. The predicament encountered in interpreting the 1977 data is a strong case for at least limited winter sampling.

There are important cautions in considering the observed phosphorus loss of 1977. If indeed a loss of this magnitude did occur there is no doubt that a short term reduction in load was not responsible for the bulk of the loss. Secondly, if resuspension of sediments or sediment transfer are important mechanisms in Lake Michigan then such a loss should not be considered entirely permanent, but rather as a phosphorus rich deposition available for subequent resuspension.

The Fifth-Year Review of Canada - United States Great Lakes Water Quality Agreement (Vallentyne and Thomas 1978) has recommended an annual load of 5553 metric tonnes of phosphorus as a target load for Lake Michigan. This load, reflected by Case 2, was considered achievable through a 1 mg/ℓ effluent standard and was projected at the time to result in approximately 7 μg-P/ℓ. MICH1 results indicate that the target load may result in slightly higher concentrations than the projections in the Northern Basin, but overall this work reaffirms their projections. Whether the target load can be maintained in light of population and industrial growth in the drainage basin under only a point source standard is open to question. The question of phosphorus availability of the high erosion inputs may also affect the attainability of the effective target load and resulting water quality.

REFERENCES

Ayers, J.C. 1970. Lake Michigan Environmental Survey. Univ. Michigan, Great Lakes Res. Div., Spec. Rep. No. 49, 97 pp.

Bartone, C.R., and Schelske, C.L. 1980. Limnological conditions in Lake Michigan based on analysis of 1976 surveillance data, submitted for pub., J. of Great Lakes Res.

Bierman, V.J., Jr., Stoermer, E.F. and Smith, V.E. 1980. The development and calibration of a spatially simplified multi-class phytoplankton model for Saginaw Bay, Lake Huron. A Great Lakes Environmental Planning Study (GLEPS) Report, Contribution No. 33.

Bolsenga, S.J. 1978. Photosynthetically active radiation transmission through ice. NOAA Technical Memorandum, ERL GLERL-18.

Chapra, S.C. 1977. Total Phosphorus Model for the Great Lakes. J. of the Env. Eng. Div. 103: 147-161.

Chesters, G. and Delfino, J.J. 1978. Frequence and Extent of Wind-Induced Resuspensin of Bottom Material in the U.S. Great Lakes Nearshore Waters. PLURG Technical Report, U.S. Task D, IJC, G.L.N.P.O., Windsor, Ontario, 111 p.

DePinto, J.V., Young, T.C. and Martin, S.C. 1980. Bioassay determination of algal-available phosphorus in suspended sediments of Great Lakes tributaries. Progress Report for EPA Grant #807155.

DiToro, D.M. and Connolly, J.P. 1980. Mathematical models of water quality in large lakes, Part 2: Lake Erie. EPA-600/3-80-065.

DiToro, D.M. and Matystik, W.F., Jr. 1979. Phosphorus recycle and chlorophyll in the Great Lakes. J. of Great Lakes Res. 5(3-4): 233-245.

DiToro, D.M. and Matystik, W.F., Jr. 1980. Mathematical models of water quality in large lakes, Part 1: Lake Huron and Saginaw Bay. EPA-600/3-80-056.

Dillon, P.J. and Rigler, F.H. 1975. A simple method for predicting the capacity of a lake for development based on lake trophic status. J. Fish. Res. Board Can. 32(9): 1519-1531.

Dolan, D.M., Bierman, V.J., Jr., Dipert, M.H., Geist, R.D. 1978. Statistical analysis of the spatial and temporal variability of ratio chlorophyll-a to phytoplankton cell volume in Saginaw Bay, Lake Huron. J. of Great Lakes Res. 4(1): 75-83.

Dolan, D.M., Bierman, V.J., Jr., Gonzales, P. and Paddy, B. 1980. Analysis of the effect of total phosphorus load reductions on phosphorus concentrations in Saginaw Bay. A paper presented at the 23rd Conference on Great Lakes Res., Kingston, Ont.

Dolan, D.M. and Clark, J.L. 1981. Analysis of the tributary phosphorus loading decrease to Saginaw Bay, Lake Huron and the associated by response. In Proc. of Envirometrics 81, Wash., D.C.

Edgington, D.N. and Robbins, J.A. 1976. Records of lead deposition in Lake Michigan sediments since 1800. Environ. Sci. Technol. 10(3): 266-274.

Eisenreich, S.J., Emmling, P.J. and Beeton, A.M. 1977. Atmospheric loading of phosphorus and other chemicals to Lake Michigan. J. Great Lakes Res. 3: 291-304.

Fee, E.J. 1976. The vertical and seasonal distribution of chlorophyll in lakes of the Experimental Lakes Area, Northwestern Ontario: Implications for primary production estimates. Limnol. Oceanogr. 21(6): 767-783.

Great Lakes Water Quality Board. 1974. Great Lakes Water Quality, Second Annual Report to the International Joint Commission. IJC, Windsor, Ont.

Hutchinson, G.E. 1967. A Treatise on Limnology, Vol. 2. New York: John Wiley and Sons.

Ichimura, S., Nagasawa, S. and Tanaka, T. 1968. On the oxygen and chlorophyll maxima found in the metalimnion of a mesotrophic lake. Bot. Mag. Tokyo. 81: 1-10.

International Joint Committee. 1976. Great Lakes Water Quality, Fourth Annual Report, Appendix B, Surveillance Subcommittee Report. IJC, Windsor, Ont.

International Joint Commission. 1978. Great Lakes Water Quality, Sixth Annual Report, Appendix B, Surveillance Subcommittee Report. IJC, Windsor, Ont.

Kirchner, W.B. and Dillon, P.J. 1975. An empirical method of estimating the retention of phosphorus in lakes. Water Resour. Res. 11: 182-183.

Kizlauskas, A.G. and Katz, P.L. 1973. A two-layer finite difference model for flows in thermally stratified Lake Michigan. In: Proc. Sixteenth Conf. Great Lakes Res., pp. 743-753. Int. Assoc. Great Lakes Res.

Lee, G.F. 1974. Phosphorus, water quality, and eutrophication of Lake Michigan. In Conf. in the matter of pollution of Lake Michigan and its tributary basin in the states of Wisconsin, Illinois, Indiana, and Michigan, 4th session, Chicago, Ill., 19-21 September 1972, Vol. 1. USEPA, U.S. Government Printing Office.

Lee, G.F., Jones, R.A. and Rast, W. 1980. Availability of phosphorus to phytoplankton and its implications for phosphorus management strategies. In Phosphorus Management Strategies for Lakes, ed. R.C. Loehr, C.S. Martin, W. Rast, pp. 259-310. Ann Arbor Science Publ.

Lorenzen, M.W., Smith, D.J. and Kimmel, L.V. 1976. A long-term phosphorus model for lakes: Application to Lake Washington. In Modeling Biochemical Processes in Aquatic Ecosystems, ed. R.P. Canale, pp. 75-92. Ann Arbor Science Publ.

MacKenthun, K.M., Keop, L.E. and Stewart, R.K. 1968. Nutrients and algae in Lake Sebasticock, Maine. J. Water Pollut. Control Fed. 40(2): R72-R81.

Monteith, T.J. and Sonzogni, W.C. 1976. U.S. Great Lakes shoreline erosion loadings. PLUAGR Tech. Report, IJC, GLNOP, Windsor, Ont.

Patalas, K. 1972. Crustacean plankton and the eutrophication of St. Laurentian Great Lakes. J. Fish. Res. Board Can. 29: 1451-1462.

Phillips, D.W. and McCulloch, J.A.W. 1972. The climate of the Great Lakes Basin, from climatological studies. Number 20, Environment Canada, Toronto.

PLUARG, Pollution From Land Use Activities Reference Group. 1978. Environmental management strategy for the Great Lakes system. IJC, Windsor, Ont.

Quinn, F.H., Assel, R.A., Boyce, D.E., Leshkevich, G.A., Snider, C.R. and Weisnet, D. 1978. Summary of Great Lakes weather and ice conditions, winter 1976-77. NOAA Technical Memorandum, ERL GLERL-20.

Quinn, F.H. 1977. Annual and seasonal flow variations through the Straits of Mackinac. Water Resour. Res. 13(1): 137-144.

Rast, W. and Lee, G.F. 1978. Summary analysis of the North American OECD Eutrophication Project: Nutrient loading-lake response relationships and trophic status indices. EPA-600/3-78-008.

Rhee, G. and Gotham, I.J. 1981. Effects of environmental factors and their interactions on nutrient kinetics of Great Lakes phytoplankton. Manuscript for publication.

Risley, C., Jr. and Fuller, F.D. 1965. Chemical characteristic of Lake Michigan. Proc. 8th Conference on Great Lakes Research. Great Lakes Research Div., Institute of Science and Tech., Univ. Michigan. Pub. #13, 168-174.

Rockwell, D.C., Marion, C.V., Palmer, M.F., DeVault, D.S. and Bowden, R.J. 1980. Environmental trends in Lake Michigan. In Phosphorus Management Strategies for Lakes, ed. R.C. Loehr, C.S. Martin, and W. Rast, pp. 91-132. Ann Arbor Science Publ.

Rodgers, P.W. 1979. Kinetic studies of phytoplankton decomposition. Ph.D. dissertation, Univ. of Michigan Publ., Ann Arbor, Michigan.

Rousar, D.C. and Beeton, A.M. 1973. Distribution of phosphorus, silica, chlorophyll-a, and conductivity in Lake Michigan and Green Bay. Wis. Acad. of Sciences, Arts, and Letters. 61: 117-140.

Rumer, R.R. 1978. Methodology for evaluating in-lake effect resulting from phosphorus management in the Lake Erie drainage basin. Prepared for LEWMS, U.S. Army Engr. District, Buffalo, N.Y.

Sawyer, C.N. 1973. Phosphorus and ecology. In Environmental Phosphorus Handbook, ed. E.J. Griffith, et al., pp. 633-648. New York: J. Wiley and Sons.

Schelske, C.L. 1974. Nutrient inputs and their relationship to accelerated eutrophication in Lake Michigan. In Biological Effects in the Hydrobiological Cycle, ed. E.J. Monke, pp. 59-81. Proc. 3rd International Symposium for Hydrology Professors, Purdue Univ., Dept. Agric. Eng.

Schelske, C.L. and Stoermer, E.F. 1971. Eutrophication, silica depletion, and predicted changes in algal quality in Lake Michigan. Science 173: 423-424.

Schelske, C.L., Rothman, E.D., Stoermer, E.F. and Santiago, M.A. 1974. Responses of phosphorus-limited lake Michigan phytoplankton to factorial enrichments with nitrogen and phosphorus. Limnol. Oceanogr. 19(3): 409-419.

Sheng, Y.P. and Lick, W. 1979. The transport and resuspension of sediments in a shallow lake. J. of Geophysical Res. 84(C4): 1809-1826.

Sonzogni, W.C., Monteith, T.J., Skimin, W.E., and Chapra, S.C. 1979. Critical assessment of U.S. land derived pollutant loadings to the Great Lakes, a summary U.S. Task D. PLUARG, IJC, Windsor, Ont.

Sonzogni, W.E., Monteith, T.J., Bach, W.N. and Hughes, V.G. 1978. U.S. Great Lakes tributary loadings. Great Lakes Basin Commission for IJC, Windsor, Ont.

Steele, J.H. and Yentsch, C.S. 1960. The vertical distribution of chlorophyll. J. Mar. Biol. Assoc. U.K. 39: 217-226.

Steeman Nielsen, E. 1962. Inactivation of the photochemical mechanism in photosynthesis as a means to protect the cells against too high light intensities. Physiol. Plant 15: 161-171

Stoermer, E.F. and Tuchman, M.L. 1980. Conservative ion effect on phytoplankton. A proposal to the USEPA, Great Lakes Res. Div., Ann Arbor, Michigan.

Surveillance Subcommittee Report. 1978. Great Lakes water quality 1977-Appendix B. IJC, Windsor, Ont.

Talling, J.F. 1966. The annual cycle of stratification and phytoplankton growth in Lake Victoria (East Africa). Int. Rev. Hydrobiol. 51: 545-621.

Thomann, R.V., DiToro, D.M., Winfield, R.P. and O'Connor, D.J. 1975. Mathematical modeling of phytoplankton in Lake Ontario, 1. Model development and verification. EPA-660/3-75-005.

Thomann, R.V., Winfield, R.P. and Segna, J.J. 1979. Verification analysis of Lake Ontario and Rochester embayment three dimensional eutrophication models. EPA-600/3-79-094.

U.S. Dept. HEW. 1963. Great Lakes-Illinois River Basins Project, Part 1 Text, Report on the Illinois River System, Water Quality Condition. A report by the Public Health Service, Division of Water Supply and Pollution Control.

U.S. Dept. Interior. 1966. FWPCA. Comprehensive Water Pollution Control Program. Lake Michigan Basin, Milwaukee Area.

U.S. Dept. Interior. 1968. FWPCA. Physical and chemical quality conditions. Water Quality Investigations, Lake Michigan Basin. 81 p.

U.S. EPA. 1974. Methods for chemical analysis of water and wastes. EPA-625/6-74-003, p. xi.

Vallentyne, J.R. and Thomas, N.A. 1978. Fifth year review of Canada-United States Great Lakes Water Quality Agreement. Report of Task Group III, a technical group to review phosphorus loadings, IJC, Windsor, Ont.

Vollenweider, R.A. 1975. Input - output models with special reference to the phosphorus loading concept in limnology, Schwizer. Z. Hydrol. 37: 53-84.

Vollenweider, R.A. 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. Mem. Ist. Ital. Idrobiol. 33: 53-83.

Yui, A.K. 1978. The VWA data base at the LLRS. System manual, Grosse Ile, MI.

Zar, H. 1974. Report of the Phosphorus Technical Committee to the Lake Michigan Enforcement Conf. In Conf. in the matter of pollution of Lake Michigan and its tributary basin in the states of Wisconsin, Illinois, Indiana and Michigan, 4th session, Chicago, Illinois, 19-21 September 1972, Vol. 1. U.S. EPA, U.S. Govt. Printing Office.