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ABSTRACT

MODELING EUTROPHICATION IN LAKE HAMILTON

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The problem of eutrophication or excess productivity in a lake has long been of interest to limnologists. In this thesis project, WASP4 eutrophication model was used to simulate the productivity of Lake Hamilton. The calibrated results then were compared with the measured data of 1987, and were found to be in close agreement for dissolved oxygen, soluble reactive phosphorus, organic phosphorus, chlorophyll a, and ammonia nitrogen. Modifications were suggested when it was felt that the capabilities of WASP4 model could be improved. The model also simulated the transformations and processes in the lake sediments. The response of the lake to long term reduction in external phosphorus loading was evaluated. Sensitivity analysis was performed on hypolimnetic dissolved oxygen and peak epilimnetic chlorophyll a for a range of values of sediment oxygen demand, settling rate of phytoplankton, phosphorus loading reduction, and decomposition rate. The model indicated that the hypolimnetic dissolved oxygen was most sensitive to the sediment oxygen demand. The productivity of Lake Hamilton was most dependent on the external phosphorus loadings. It was concluded that the WASP4 eutrophication model would be of great value in developing and implementing management decisions for improving the trophic status of lakes.

TO MY PARENTS

Who sacrificed so much in life

to give us an excellent education

ACKNOWLEDGEMENTS

I have had the privilege of associating myself with my advisor Dr. Scott Martin, who initiated my interest in modeling and limnology, and who has been a continuous source of encouragement throughout my graduate program. My sincere thanks to Dr. Lauren A. Schroeder, for enduring my persistent doubts concerning the limnological processes, and for serving on my thesis committee. The faculty and staff of Civil Engineering Department have been indispensable by providing the necessary facilities for my thesis.

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INTRODUCTION

1.1 Background of Lake Hamilton

Lake Hamilton is one of the series of reservoirs on Yellow Creek. Lake Hamilton was constructed in 1905 to provide water to the steel industry and population in the Mahoning Valley. This was in response to rapid expansion of the steel industry which was accompanied by increased population, development and mining during the early twentieth century. Since then the demand for industrial water has been drastically reduced due to the decline in the steel industry. Today, Lake Hamilton is owned by Ohio Water Service Co. and supplies water to a few industries and the City of Campbell.

Lake Hamilton has had many problems associated with its water quality. It receives a high loading of nutrients from Yellow Creek which results in heavy algal blooms and prolonged anoxia in the hypolimnion during the summer stratification period. Being a highly productive lake, its large algal blooms make the water less attractive as a source of recreation and drinking water. Furthermore, the presence of high concentrations of algae, reduced chemical species such as hydrogen sulfide, and associated tastes and odors may result in poor raw water quality during mid and late summer.

1.2 Goals of Project

The initial aim of this project was to determine the applicability of EUTRO4E (Bierman et al., 1992), a recent modification of the USEPA's WASP4 eutrophication model (EUTRO4), to Lake Hamilton. Models may serve as management tools in making scientifically sound regulatory decisions. Modeling can assist in evaluating alternative methods of meeting water quality goals. The model applied in this study describes the following:

1) Dissolved Oxygen (DO) depletion in the hypolimnion;
2) Phosphorus (P) dynamics, including concentrations of soluble reactive phosphorus (SRP) and organic phosphorus (OP) in the epilimnion, hypolimnion and bottom sediments of the lake;
3) Nitrogen (N) dynamics, including concentrations of nitrate (NO_3-N), ammonia (NH_4-N), and orgnanic nitrogen (ON) in the lake;
4) Chlorophyll a concentrations (a measure of algal biomass) in the lake;
5) Relationships among nutrients (P and N), chlorophyll a, and dissolved oxygen in the lake.

The ultimate goal of this study was to calibrate the WASP4/EUTRO4E model to serve as an effective management tool for Lake Hamilton. The model was used to estimate the potential impact of nutrient loading reductions on the trophic status of Lake Hamilton.

LITERATURE REVIEW

2.1 Eutrophication in Lakes

2.1.1 Problems Caused by Eutrophic Conditions

The term "eutrophic" means well nourished; thus, "eutrophication" refers to natural or artificial addition of nutrients to bodies of water and to the effects of added nutrients (Hutchinson, 1957).

Eutrophication of lakes is a natural process that can be greatly accelerated by humans. Human activities, which introduce excess nutrients, along with other pollutants, into lakes, streams, and estuaries, are causing significant changes in aquatic environments. The excess nutrients greatly accelerate the process of eutrophication. Accelerated eutrophication causes changes in plants and animal life - changes that often interfere with the use of water, detract from natural beauty, and reduce property values. A common change is excessive growth of algae and larger aquatic plants. Such growth chokes the open water, may make it nonpotable, and may increase the cost of filtration.

Most of the literature about eutrophication puts the emphasis on the production of algal blooms and odor nuisances. But there are other aspects of high productivity that cause problems. One of these is in lakes used for supply of drinking water; unsatisfactory tastes can be generated by biological conditions that are otherwise acceptable. Another feature of productive lakes is the great abundance of insects. During periods of emergence, the adults may occur in such numbers as to interfere with various recreational or other outdoor activities, and masses of floating vegetation may be objectionable to swimmers and boaters.

2.1.2 Lake Trophic Status Classifications

Lakes are usually classified based on the nutrient concentrations, dissolved oxygen deficits, secchi depth, chlorophyll concentrations, and such trophic state indices as oligotrophic, eutrophic or mesotrophic. Oligotrophic lakes are characterized by low rates of productivity, clear waters regulated to a large extent by low input of inorganic nutrients from external sources (Wetzel, 1975). The low production of organic matter, resultant low rates of decomposition, and oxidizing hypolimnetic conditions result in relatively low nutrient release from the sediments.

Eutrophic lakes are characterized by high rates of productivity, usually resulting from increased loading of phosphorus. As the rates of photosynthetic energy fixation and productivity increase, the cyclic interactions of regeneration of inorganic nutrients and organic compounds accelerate. An increase in the decomposition rate of organic matter exerts a high oxygen demand in the hypolimnion, creating reducing conditions and facilitating recycling of nutrients from sediments. Mesotrophic lakes have the characteristics of being in transition between the oligotrophic and eutrophic lakes.

2.1.3 Determination of Lake Trophic Status

Most of the early methods for determining lake trophic status were empirical in nature. In recent years deterministic models have received increased attention. Empirical methods are usually simple to use and are often quite useful as lake management aids. A few of the important methods for trophic status classification are described in this section.

One of the earliest methods developed merely involved an observed relationship between the rate of development of areal hypolimnetic dissolved oxygen deficit and the apparent trophic status of lakes. Hutchinson (1957) set limits of 0.017 $mg/cm^2/day$ as the upper limit of oligotrophy and 0.033 $mg/cm^2/day$ as the lower limit of eutrophy. Mortimer (1941) set similar limits of 0.025 $mg/cm^2/day$ for oligotrophy and 0.055 $mg/cm^2/day$ for eutrophy.

Others have used nutrient concentrations to classify the trophic status of lakes. Sawyer (1966) suggested limits on inorganic N and P as a means of differentiating between "well behaved" and "nuisance" lakes, with "well behaved" lakes having inorganic phosphorus < 0.015 mg/l, and inorganic nitrogen < 0.3 mg/l at spring turnover. Vollenweider (1968) related the productivity of lakes to average total phosphorus concentration in the epilimnion as follows (Wetzel, 1975):

Ultra-oligotrophic	< 5 ug/l
Oligo-mesotrophic	5-10 ug/l

Meso-eutrophic	10-30 ug/l
Eutrophic	30-100 ug/l
Hypereutrophic	> 100 ug/l

USEPA (1974) set the following limits to represent the trophic status of lakes (Thomann and Mueller, 1987):

Total Phosphorus (ug/l)	< 10	Oligotrophic
	10-20	Mesotrophic
	> 20	Eutrophic
Chlorophyll <u>a</u> (ug/l)	< 4	Oligotrophic
	4-10	Mesotrophic
	> 10	Eutrophic
Secchi depth (m)	> 4	Oligotrophic
	2-4	Mesotrophic
	< 2	Eutrophic
Hypolimnetic Oxygen (% saturation)	> 80	Oligotrophic
	10-80	Mesotrophic
	< 10	Eutrophic

Carlson (1977) proposed Trophic State Index (TSI) equations based on various trophic parameters, with TSI varying from 0 (very clean) to 100 (eutrophic) (Martin, 1979).

$$TSI = 10[\,6 - \log_2(S.D)\,] \tag{2-1}$$

$$TSI = 10[\,6 - \frac{(2.04 - 0.68\ln(Chl\underline{a})}{ln2}\,] \tag{2-2}$$

$$TSI = 10 \left[6 - \frac{\ln 48}{(TP)(\ln 2)} \right] \qquad (2\text{-}3)$$

where:

S.D = Secchi depth, m.

Chl$\underline{a}$ = Chlorophyll $\underline{a}$ concentration, ug/l.

TP = Total phosphorus concentration, ug/l.

2.2 The Phosphorus Cycle in Lakes

Before modeling eutrophication in a lake, it is necessary to understand the various processes occurring in the aquatic system that can influence its trophic status. These include the phosphorus cycle, the nitrogen cycle, phytoplankton kinetics, and the dissolved oxygen balance. In comparison to the rich natural supply of all major nutritional and structural components of the biota, phosphorus is the least abundant, and most commonly limits biological productivity (Wetzel, 1975). Thus, interactions involving phosphorus are described in more detail in this section.

2.2.1 Sources and Forms of Phosphorus

Phosphorus is supplied to lakes in various forms and amounts from numerous sources. Natural sources include direct precipitation on the surface of the lake, precipitation runoff from the surrounding watershed area, animal wastes, vegetation deposits, and groundwater influxes. Human sources include domestic and industrial wastewaters, agricultural runoff, urban runoff, septic tank leachate, and landfill drainage. Also, phosphorus is supplied through recycling from sediments.

The following are the categories of phosphorus in limnology (Hutchinson, 1957):

1) Soluble inorganic phosphate (PO_4^{-3});
2) Acid-soluble sestonic phosphorus, consisting of inorganic phosphorus, mostly as ferric and calcium phosphates, becoming soluble phosphate under acidic conditions;
3) Organic soluble phosphorus consisting of phosphorus present in organic excretions;
4) Organic sestonic phosphorus consisting of phosphorus mostly associated with living and dead plants and animals.

A very large proportion, greater than 90%, of the phosphorus in lake water is bound in organic phosphates and cellular constituents of living and dead plankton (Wetzel, 1975). Of the total organic phosphorus, about 70% or more is within the particulate organic material (Wetzel, 1975), and the remainder is present as dissolved and colloidal organic phosphorus.

2.2.2 Phosphorus Dynamics Within Lakes

Phosphorus can enter a lake in various forms as explained earlier. Soluble inorganic phosphates are readily taken up by littoral vegetation and phytoplankton for growth. Organic matter, meanwhile, must undergo decomposition before the phosphorus present in it can be utilized. This is partly accomplished by the heterotrophic bacteria that use organic matter as a source of carbon and energy. Soluble organics, which come from the runoff of partially decomposed plants and other materials, are decomposed in the water column. Insoluble organic matter is only partially decomposed before settling to the lake bottom. Inorganic phosphorus compounds often make up less than 10% of total phosphorus in water columns, which is very inadequate to support the algal cells during blooms. This justifies the importance of nutrient cycling in supplying nutrients for biological growth.

Hutchinson (1957) has postulated seven mechanisms important in the cycling of phosphorus in lakes:

1) Liberation of phosphorus into the epilimnion from the littoral zone, due to decay of littoral vegetation; excretions from living littoral plants may also act as a source of phosphorus (Wetzel, 1975);
2) Uptake of phosphorus from water by littoral vegetation;
3) Uptake of liberated phosphorus by phytoplankton;
4) Loss of phosphorus as a soluble compound from phytoplankton;
5) Sedimentation of phytoplankton and other phosphorus containing particulates into the hypolimnion;
6) Liberation of phosphorus from the sedimenting seston in the epilimnion and hypolimnion by autolysis

and bacterial decomposition; and

7) Diffusion of phosphorus from the sediments into the water column under anoxic conditions. A portion of the phosphorus in the sediments is present as phosphate absorbed on and complexed with ferric oxides and hydroxides and as phosphate coprecipitated with iron and manganese. When the overlying waters are aerated, oxygen will penetrate a few centimeters into the sediments. This oxidized microzone reduces the transport of phosphorus into the overlying waters. However, if the dissolved oxygen content of the hypolimnion is greatly reduced as a result of bacterial decomposition of organic matter, the thickness of this oxidized microzone may be decreased considerably. Under such anaerobic conditions, ferric iron Fe^{+3} is reduced to ferrous iron Fe^{+2} and Mn^{+3} to Mn^{+2}, resulting in the release of phosphates into the water (Wetzel, 1975).

2.3 Modeling Eutrophication with WASP4 and EUTRO4E

2.3.1 Introduction to Water Quality Modeling

Since the early 1900's, decision makers, engineers, and scientists have continued to seek more rigorous means for assessing the effectiveness of environmental control actions. The effect of such action is measured by the attainment of a water quality standard and of a concomitant expected water use associated with that water quality. The aim is to achieve such water quality and water use objectives through a control plan, where the benefits would exceed the costs. Decision makers who assess which environmental control plans to implement are wary of two possibilities (Thomann & Mueller, 1987):

1) reducing waste inputs to a water body and observing little or no improvement in water quality; and
2) implementing control actions that are excessively costly, with an associated poor return in water use benefits.

Mathematical modeling of water quality arose out of the need to treat these two possibilities as the questions became more complex, and the economic consequences of making a wrong decision increased markedly (Thomann and Mueller, 1987).

In today's world it is not feasible to call for removal of inputs and then wait to see what happens. Such methods have been used in the past history of water quality management. Presently it is necessary that an attempt be made to assess the outcomes expected of water quality controls before the implementation of those controls, and to continue to monitor the effectiveness of the controls by both field monitoring efforts and mathematical modeling analyses. Thus, modeling is essentially a tool for predicting the consequences of a range of potential control actions to evaluate the advantages and disadvantages of various alternatives.

The modeling of surface water quality has a twofold result (Thomann and Mueller, 1987):

1) a better understanding of the mechanisms and

interactions that give rise to various types of water quality behavior; and

2) a more rational basis for making water quality control decisions.

The mathematical model of the water quality system basically gives the relationship between waste load input and the resulting response. The development and application of such a model involve a variety of considerations including the specification of parameters and model conditions. Figure 2-1, shows the principal components of a mathematical modeling framework. The upper two steps enclosed within the dashed line box, namely "Theoretical Construct" and "Numerical Specification", constitute what is considered a mathematical model. This is to differentiate between the writing of equations for a model, and the assignment of a set of representative numbers to inputs and parameters.

Modeling includes the following tasks (Thomann and Mueller, 1987):

1) Model Development: the theoretical construction of equations together with assignment of numerical values to model parameters, incorporating some prior observations drawn from field and laboratory data;
2) Model Calibration: the first stage testing or tuning of a model to a set of field data;
3) Model Verification: subsequent testing of a

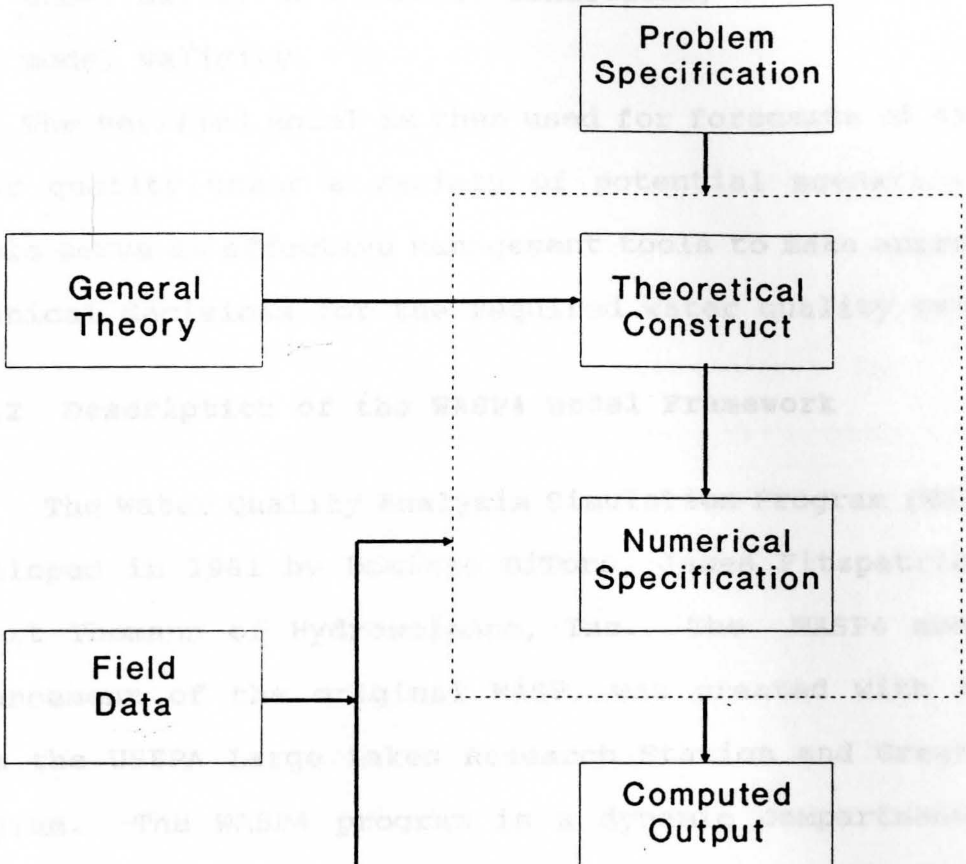


Figure 2-1. Components of Modeling Framework (Thomann and Mueller, 1987).

calibrated model to additional field data, preferably under different external conditions, to further examine model validity.

The verified model is then used for forecasts of expected water quality under a variety of potential scenarios. Thus models serve as effective management tools to make appropriate technical decisions for the required water quality response.

2.3.2 Description of the WASP4 Model Framework

The Water Quality Analysis Simulation Program (WASP) was developed in 1981 by Dominic DiToro, James Fitzpatrick, and Robert Thomann of Hydroscience, Inc. The WASP4 model, an enhancement of the original WASP, was created with funding from the USEPA Large Lakes Research Station and Great Lakes Program. The WASP4 program is a dynamic compartment model system for the water column and underlying sediments. Time varying processes like advection, dispersion, point and diffuse mass loading, and boundary exchange are represented in the model (Ambrose, et al; 1988) .

The WASP4 modeling system consists of two programs, DYNHYD4 and WASP4, that can be used together or separately. The hydrodynamic program, DYNHYD4, simulates the movement of water and the water quality program, WASP4, simulates the movement and interactions of pollutants within the water. The USEPA supplies two kinetic sub-models that can run with the WASP4 program. These simulate two of the major types of water quality problems - conventional pollution (dissolved oxygen, biochemical oxygen demand, nutrients and eutrophication) and toxic pollution (organic chemicals, heavy metals, and sediment), and are named EUTRO4 and TOXI4, respectively (Ambrose, et al., 1988).

The WASP4 modeling system is designed for analyzing water quality problems in a variety of water bodies, including large branching rivers, reservoirs, estuaries, ponds, streams, lakes, and coastal waters. The flexibility offered by the WASP4 program permits the user to structure one, two, and three dimensional models; allows the specifications of time-variable exchange coefficients, advective flows, waste loads and water quality boundary conditions; and permits structuring of the kinetic processes.

The equations solved by WASP4 are based on the principle of the conservation of mass. WASP4 traces each water quality constituent from the point of spatial and temporal input to its final point of export. To perform the mass balance computations, the user must supply WASP4 with input data defining seven important characteristics (Ambrose, et al., 1988):

1) simulation and output control;
2) model segmentation;
3) advective and dispersive transport;
4) boundary concentrations;
5) point and diffuse source waste loads;
6) kinetic parameters, constants, and time functions;
7) initial concentrations.

2.3.2.1 Model Segmentation

The model network is a set of control volumes, or "segments", that represent the physical configuration of the water body. Figure 2-2 illustrates the division of a water body laterally and vertically as well as longitudinally. Benthic segments can be included along with water column segments. Segments in WASP4 can be of four types, as specified by the input variable ITYPE. A value of 1 indicates the epilimnion, 2 indicates hypolimnion, 3 indicates an upper benthic layer, and 4 indicates lower benthic layers. Concentrations of water quality constituents are calculated in each segment. Transport rates of water quality constituents are calculated across the interface of adjoining segments (Ambrose, et al., 1988).

2.3.2.2 General Mass Balance Equations

The model input data, together with the general WASP4 mass balance equations and the specific chemical kinetics equations, define an unique, system-specific set of water quality equations. These are numerically integrated by WASP4 as the simulation proceeds in time. A mass balance equation for dissolved constituents in a body of water accounts for all the material entering and leaving through direct and diffuse loading; advective and dispersive transport; and physical, chemical, and biological transformations. Using x to represent the longitudinal coordinate and assuming lateral (y

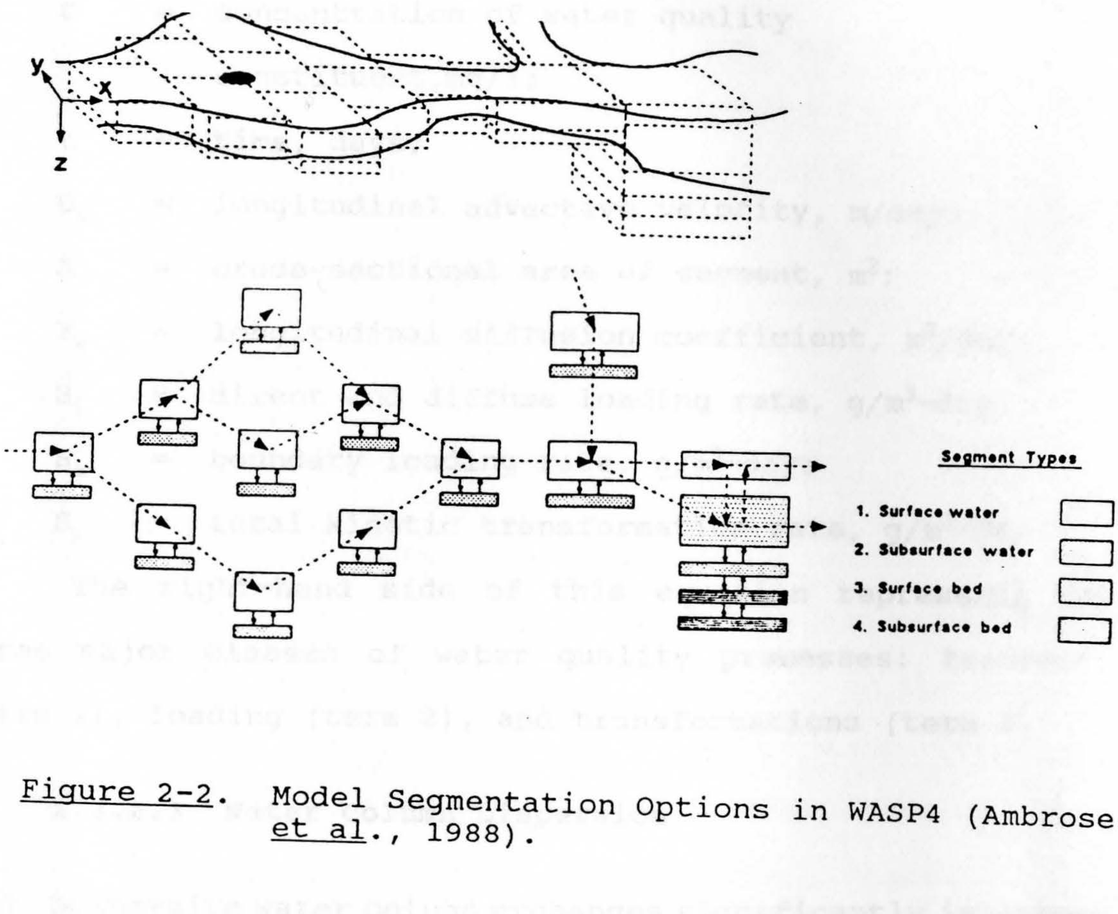


Figure 2-2. Model Segmentation Options in WASP4 (Ambrose, et al., 1988).

direction) and vertical (z direction) homogeneity, the mass balance equation is (Ambrose, <u>et al</u>., 1988):

$$\frac{\partial (AC)}{\partial t} = \frac{\partial \left(-U_X A C + E_X A \frac{\partial C}{\partial X}\right)}{\partial X} + A\,(S_L + S_B) + A S_K \tag{2-4}$$

where:

C = concentration of water quality constituent, mg/l;

t = time, days;

U_x = longitudinal advective velocity, m/day;

A = cross-sectional area of segment, m^2;

E_x = longitudinal diffusion coefficient, m^2/day;

S_L = direct and diffuse loading rate, g/m^3-day;

S_B = boundary loading rate, g/m^3-day;

S_K = total kinetic transformation rate, g/m^3-day.

The right-hand side of this equation represents the three major classes of water quality processes: transport (term 1), loading (term 2), and transformations (term 3).

2.3.2.3 Water Column Dispersion

Dispersive water column exchanges significantly influence the transport of dissolved and particulate pollutants in lakes, reservoirs, and estuaries. In WASP4, water column dispersion is calculated from interfacial area, a characteristic mixing length, and concentrations in the segments between which the exchange takes place. The actual dispersive exchange between segments i and j at time t is given by (Ambrose, et al., 1988):

$$\frac{\partial M_i}{\partial t} = \frac{E_{ij}(t)\,A_{ij}}{L_{cij}}\,(C_j - C_i) \qquad (2\text{-}5)$$

where:

M_i = Mass of chemical in segment i, g;

C = Total chemical concentration, mg/l;

$E_{ij}(t)$ = Dispersion coefficient time function for exchange between segments i and j, m^2/day;

A_{ij} = Interfacial area between segments i and j, m^2;

L_{cij} = Characteristic mixing length between segments i and j, m;

2.3.2.4 Pore Water Diffusion

Bottom sediment pore water diffusion can significantly influence benthic and water column pollutant concentrations, particularly for soluble chemicals. Depending on the concentration gradient of dissolved species, pore water diffusion may be a source or sink of pollutants for the overlying water column. The diffusive exchange between benthic segments i and j at time t is given by (Ambrose, <u>et al</u>., 1988):

$$\frac{\partial M_i}{\partial t} = \frac{E_{ij}(t)\,A_{ij} n_{ij}}{L_{cij}/n_{ij}}\,(f_{Dj} C_j / n_j - f_{Di} C_i / n_i) \qquad (2\text{-}6)$$

where:

F_{Di}, F_{Dj} = Dissolved fraction of chemical in i and j;

n_{ij} = Average porosity at interface "ij";

$E_{ij}(t)$ = Diffusion coefficient time function for exchange "ij", m^2/day;

A_{ij} = Interfacial area shared by segments i and j, m^2;

L_{cij} = Characteristic mixing length between segments i and j, m;

2.3.2.5 Water Column Transport

Both dissolved and particulate substances are transported between segments by advection. The user must specify all inflows and the routing pattern followed by each in the input data set. In addition, solids and particulate chemicals in the water column can settle to lower water segments and deposit to upper benthic segments. Particulate transport velocities may vary both in time and space, and are multiplied by surface areas and water column concentrations to obtain mass loss rates to the sediments.

2.3.2.6 Benthic Deposition and Resuspension

Benthic exchange of sediment and particulate chemicals is driven by the wind induced resuspension and deposition velocities, and is given by the equation:

$$W_{BS} = A_{ij} \; (\; W_R S_i \; - \; W_D S_j \;) \qquad (2\text{-}7)$$

where:

W_{Bs} = Net sediment flux rate, g/day;

S = Sediment concentration, g/m^3;

W_D = Deposition velocity, m/day;

W_R = Scour velocity, m/day;

A_{ij} = Benthic surface area, m^2;

i = Benthic segment;

j = Water segment.

These are the main transport mechanisms of pollutants in a water body incorporated in the WASP4 program. The other remaining mechanisms are well described in the "WASP4, Model Theory, User's Manual, and Programmer's Guide" (Ambrose, et al., 1988).

2.3.3 Description of EUTRO4E

The eutrophication model, EUTRO4, is a simplified version of the Potomac Eutrophication Model, PEM (Thomann and Fitzpatrick, 1982). EUTRO4 was further modified for Green Bay (Lake Michigan) eutrophication modeling by Bierman et al. (1992), and came to be known as EUTRO4E. The eight systems, or state variables, described by this model are:

1) Ammonia Nitrogen
2) Nitrate Nitrogen
3) Orthophosphate Phosphorus
4) Phytoplankton Carbon
5) Carbonaceous BOD
6) Dissolved Oxygen

7) Organic Nitrogen

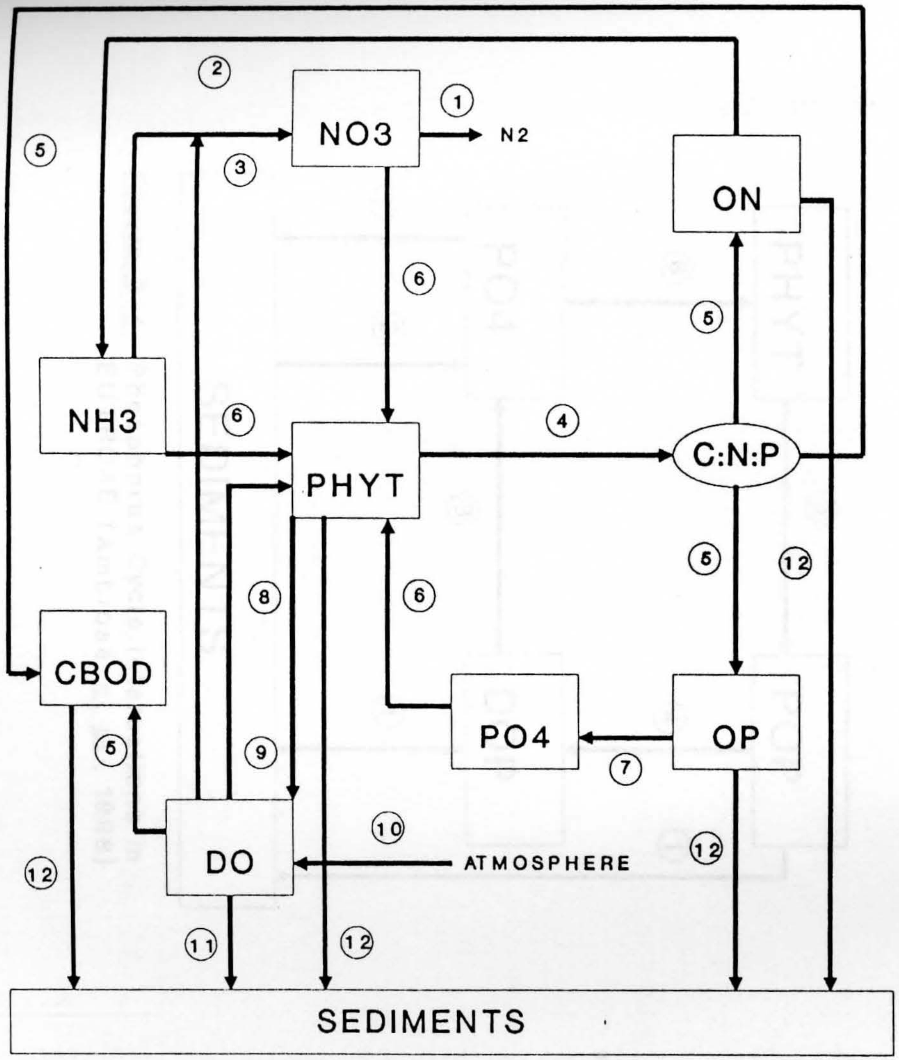
8) Organic Phosphorus

Several physical-chemical processes can affect the transport and interaction among the nutrients, phytoplankton, carbonaceous material, and dissolved oxygen in the aquatic environment. Figure 2-3 illustrates the principal kinetic interactions accounted for in EUTRO4E.

2.3.3.1 The Phosphorus Cycle

Two phosphorus state variables are modeled in the WASP4 eutrophication model - organic phosphorus and inorganic (orthophosphate) phosphorus. Phytoplankton phosphorus is also calculated by dividing phytoplankton carbon by a C:P ratio. Organic phosphorus is divided into particulate and dissolved concentrations. Inorganic phosphorus also is divided into particulate and dissolved concentrations. A fraction of the phosphorus released during phytoplankton respiration and death is in the inorganic form and readily available for uptake by other algal cells. The remaining fraction released is in the organic form and must undergo decomposition and mineralization into inorganic phosphorus before utilization by phytoplankton. A summary of the phosphorus cycle in EUTRO4E is illustrated in Figure 2-4 (Ambrose, et al., 1988).

The mass balance equation for phytoplankton phosphorus is given by:



NH3 - AMMONIA NITROGEN

NO3 - NITRATE NITROGEN

ON - ORGANIC NITROGEN

PHYT - PHYTOPLANKTON

OP - ORGANIC PHOSPHORUS

PO4 - ORTHOPHOSPHATE PHOSPHORUS

DO - DISSOLVED OXYGEN

CBOD - CARBONACEOUS BIO-CHEMICAL OXYGEN DEMAND

N2 - NITROGEN GAS

1 - DENITRIFICATION

2 - AMMONIFICATION

3 - NITRIFICATION

4 - ENDOGENOUS RESPIRATION

5 - DECOMPOSITION

6 - UPTAKE FOR GROWTH

7 - MINERALIZATION

8 - PHOTOSYNTHESIS

9 - RESPIRATION

10 - AERATION

11 - SEDIMENT OXYGEN DEMAND

12 - SETTLING

Figure 2-3. EUTRO4E State Variable Interactions (Ambrose, et al., 1988).

PHYT - PHYTOPLANKTON

POP - PARTICULATE ORGANIC PHOSPHORUS

DOP - DISSOLVED ORGANIC PHOSPHORUS

PO4 - ORTHOPHOSPHATE PHOSPHORUS

1 - SETTLING

2 - DIFFUSION AND FLUX

3 - MINERALIZATION

4 - DECOMPOSITION

5 - ENDOGENOUS RESPIRATION

6 - UPTAKE FOR GROWTH

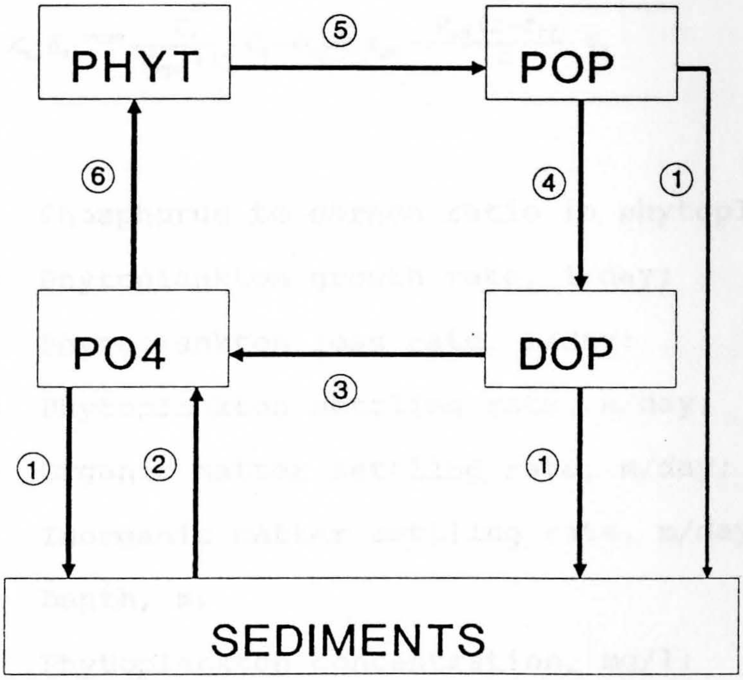


Figure 2-4. Phosphorus Cycle Interactions in EUTRO4E (Ambrose, et al., 1988)

$$\frac{\partial (C_4 a_{pc})}{\partial t} = (G_{Pl} - D_{Pl} - \frac{V_{s4}}{D})\, C_4 a_{pc} \tag{2-8}$$

The mass balance equation for organic phosphorus is given by:

$$\frac{\partial C_8}{\partial t} = D_{Pl} C_4 a_{pc} - K_{83} \theta_{83}{}^{T-20} \frac{C_4}{K_{mpc} + C_4} C_8 - \frac{V_{s3}(1 - f_{D8})}{D} C_8 \tag{2-9}$$

The mass balance equation for orthophosphate phosphorus is given by:

$$\frac{\partial C_3}{\partial t} = K_{83} \theta_{83}{}^{T-20} \frac{C_4}{K_{mpc} + C_4} C_8 - G_{Pl} C_4 a_{pc} - \frac{V_{s5}(1 - f_{D3})}{D} C_3 \tag{2-10}$$

where:

a_{pc} = Phosphorus to carbon ratio in phytoplankton;

G_{Pl} = Phytoplankton growth rate, 1/day;

D_{Pl} = Phytoplankton loss rate, 1/day;

V_{s4} = Phytoplankton settling rate, m/day;

V_{s3} = Organic matter settling rate, m/day;

V_{s5} = Inorganic matter settling rate, m/day;

D = Depth, m;

C_4 = Phytoplankton concentration, mg/l;

C_8 = Organic phosphorus concentration, mg/l;

C_3 = Orthophosphate phosphorus concentration,mg/l;

K_{83} = Dissolved organic phosphorus mineralization rate at 20°C, 1/day;

O_{83} = Temperature coefficient;

K_{mpc} = Half saturation constant for phytoplankton limitation of phosphorus, mg/l;

T = Temperature, °C;

f_{D8} = Fraction dissolved organic phosphorus;

f_{D3} = Fraction dissolved inorganic phosphorus.

2.3.3.2 The Nitrogen Cycle

The EUTRO4E nitrogen cycle is shown in Figure 2-5. The kinetics of the nitrogen species are fundamentally similar to the phosphorus system. Ammonia and nitrate are used by phytoplankton for growth. The rate at which each is taken up is proportional to its concentration relative to the total inorganic nitrogen available. Nitrogen is returned from the algal biomass and follows pathways that are similar to phosphorus. Organic nitrogen is converted to ammonia at a temperature dependent rate, and ammonia is then converted to nitrate (nitrification) at a temperature and oxygen dependent rate. Nitrate may be converted to nitrogen gas (denitrification) in absence of oxygen and at a temperature dependent rate (Ambrose, et al., 1988).

2.3.3.3 Phytoplankton Kinetics

The EUTRO4E phytoplankton kinetics are illustrated in Figure 2-6. Phytoplankton kinetics assume a central role in eutrophication, affecting all other systems as shown in Figure 2-6. The reaction term of phytoplankton is expressed as a

NO3 - NITRATE NITROGEN
NH3 - AMMONIA NITROGEN
ON - ORGANIC NITROGEN
N2 - NITROGEN GAS
PHYT - PHYTOPLANKTON

1 - UPTAKE FOR GROWTH
2 - NITRIFICATION
3 - DENITRIFICATION
4 - ENDOGENOUS RESPIRATION
5 - AMMONIFICATION

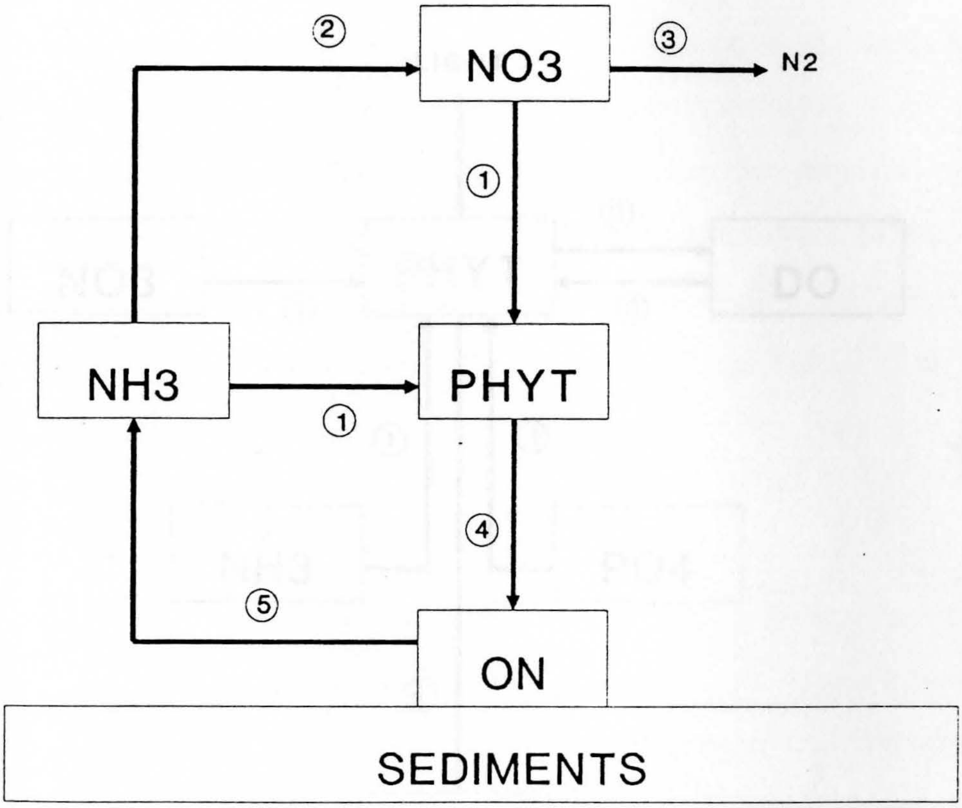
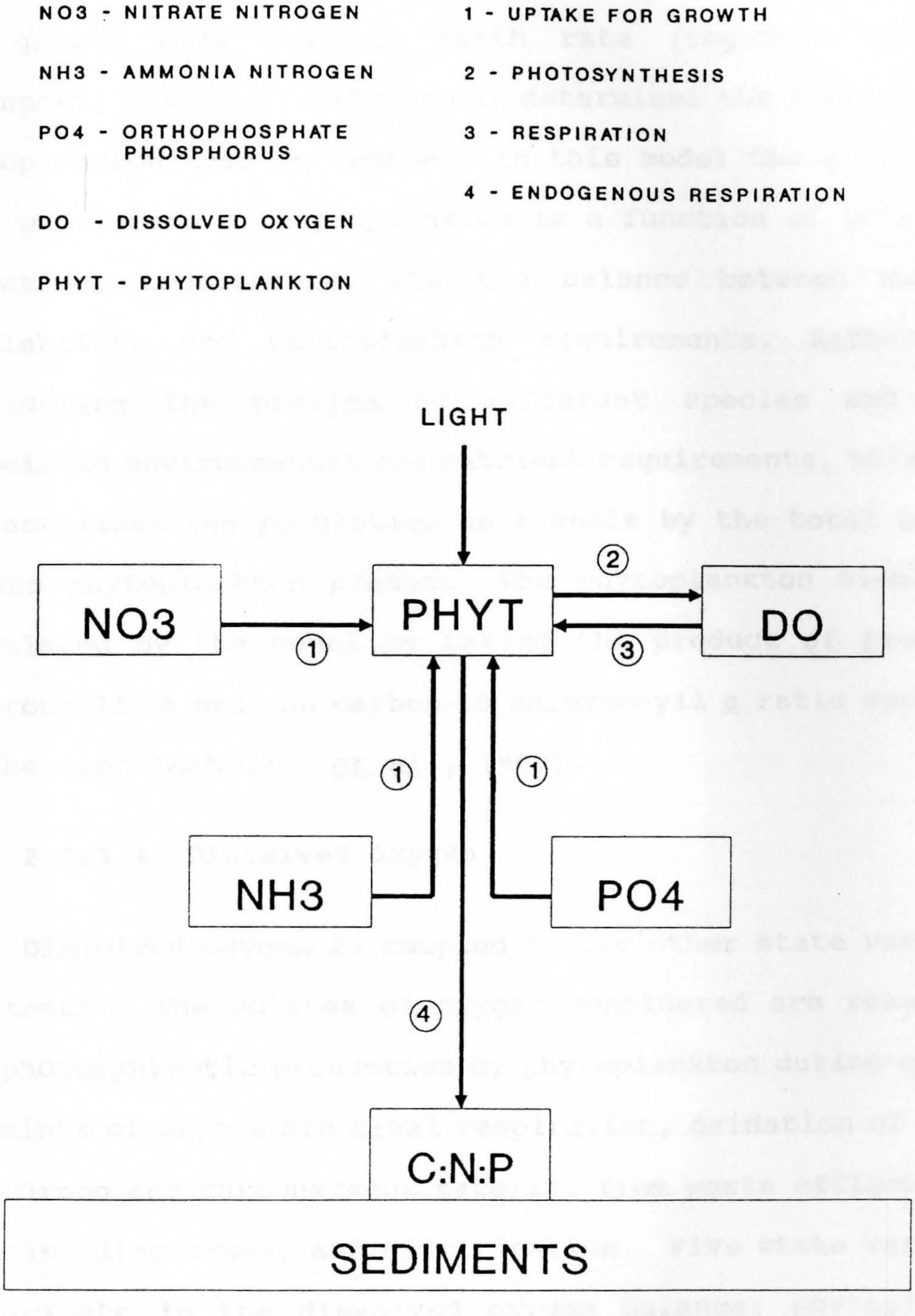


Figure 2-5. The Nitrogen Cycle in EUTRO4E (Ambrose, *et al*., 1988).



NO3 - NITRATE NITROGEN
NH3 - AMMONIA NITROGEN
PO4 - ORTHOPHOSPHATE PHOSPHORUS
DO - DISSOLVED OXYGEN
PHYT - PHYTOPLANKTON

1 - UPTAKE FOR GROWTH
2 - PHOTOSYNTHESIS
3 - RESPIRATION
4 - ENDOGENOUS RESPIRATION

Figure 2-6. Phytoplankton Interactions in EUTRO4E (Ambrose, et al., 1988).

difference between the growth rate of phytoplankton and their death and settling rates. The balance between the magnitude of the growth rate and the death rate (together with the transport, settling, and mixing) determines the rate at which phytoplankton mass is created. In this model the growth rate of a population of phytoplankton is a function of solar radiation, temperature, and the balance between nutrient availability and phytoplankton requirements. Rather than considering the problem of different species and their associated environmental and nutrient requirements, this model characterizes the population as a whole by the total biomass of the phytoplankton present. The phytoplankton biomass is calculated by the model by taking the product of predicted Chlorophyll a and the carbon to chlorophyll a ratio specified by the user (Ambrose, et al., 1988).

2.3.3.4 Dissolved Oxygen

Dissolved oxygen is coupled to the other state variables (systems). The sources of oxygen considered are reaeration and photosynthetic production by phytoplankton during growth. The sinks of oxygen are algal respiration, oxidation of detrital carbon and carbonaceous material from waste effluents and nonpoint discharges, and nitrification. Five state variables participate in the dissolved oxygen balance: phytoplankton carbon, ammonia, nitrate, carbonaceous biochemical oxygen demand, and dissolved oxygen. The reduction of dissolved oxygen is a consequence of the aerobic respiratory precesses in the water column and the anaerobic processes in the underlying sediments. A summary of the oxygen balance is illustrated in Figure 2-7.

2.3.3.5 Simulation Options

EUTRO4E can be operated at various levels of complexity to simulate some or all of the state variables and interactions. The six levels of complexity are (Ambrose, et al., 1988):

1) Streeter-Phelps
2) Modified Streeter-Phelps
3) Full Linear DO Balance
4) Simple Eutrophication Kinetics
5) Intermediate Eutrophication Kinetics
6) Intermediate Eutrophication Kinetics with Benthos

Streeter-Phelps: This is the simplest dissolved oxygen balance. It just solves the well known Streeter-Phelps (Streeter and Phelps, 1925) BOD-DO equations.

Modified Streeter-Phelps: The modified Streeter-Phelps equations divide the biochemical oxygen demand into carbonaceous (CBOD) and nitrogenous (NBOD) fractions.

Full Linear DO Balance: The full DO balance equations divide the NBOD into mineralization and nitrification, and add the effects of photosynthesis and respiration from given phytoplankton levels.

NH3 - AMMONIA NITROGEN

NO3 - NITRATE NITROGEN

DO - DISSOLVED OXYGEN

CBOD - CARBONACEOUS BIO-CHEMICAL OXYGEN DEMAND

PHYT - PHYTOPLANKTON

1 - NITRIFICATION

2 - AERATION

3 - SEDIMENT OXYGEN DEMAND

4 - PHOTOSYNTHESIS

5 - RESPIRATION

6 - SETTLING

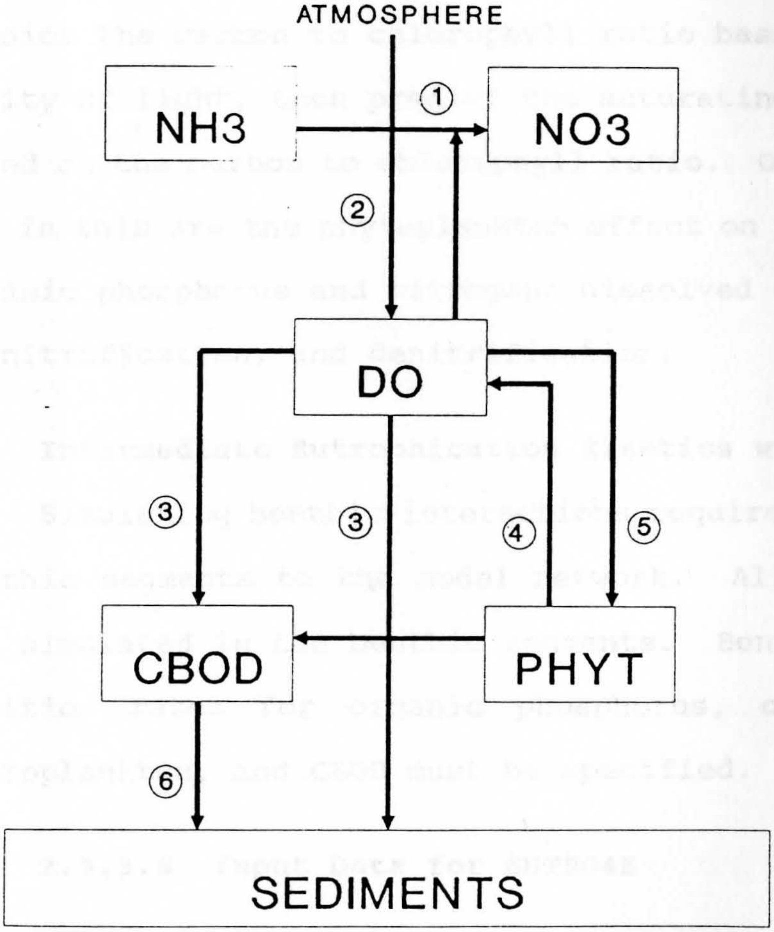


Figure 2-7. Oxygen Balance Interactions in EUTRO4E (Ambrose, et al., 1988).

Simple Eutrophication Kinetics: The simple eutrophication kinetics option simulates the growth and death of phytoplankton, with its effects on the nutrient cycles and DO balance. Growth can be limited by the availability of inorganic nitrogen, inorganic phosphorus, and light.

Intermediate Eutrophication Kinetics: The intermediate eutrophication kinetics add certain nonlinear terms and functions to the simple eutrophication kinetics. These equations predict the carbon to chlorophyll ratio based on the availability of light, then predict the saturating light intensity based on the carbon to chlorophyll ratio. Other terms included in this are the phytoplankton effect on mineralization of organic phosphorus and nitrogen; dissolved oxygen limitation on nitrification; and denitrification.

Intermediate Eutrophication Kinetics with Benthos: Simulating benthic interactions requires the addition of benthic segments to the model network. All state variables are simulated in the benthic segments. Benthic layer decomposition rates for organic phosphorus, organic nitrogen, phytoplankton, and CBOD must be specified.

2.3.3.6 Input Data for EUTRO4E

The data required to run EUTRO4E is divided into 10 groups, A through J:

A - Model identification and simulation control

B - Exchange coefficients

C - Volumes

D - Flows

E - Boundary conditions

F - Waste loads

G - Environmental parameters

H - Chemical constants

I - Time functions

J - Initial conditions

Data Group A is for model identification and contains simulation control options. The number of segments, number of systems, time steps and print intervals are specified here.

Data Group B contains dispersive exchange information, including interface areas, characteristic lengths, and time series of bulk dispersion coefficients.

Data Group C contains segment volumes and mean depths.

Data Group D contains information on flow and sediment transport between segments, including inflows, flow routing patterns, and settling and resuspension velocities. Flows can be constant or variable with time.

Data Group E contains concentration for each system at the external boundaries of the water body. Concentrations must be supplied for all state variables at each boundary.

Data Group F defines the waste loads and segments that receive waste loads for both point and diffuse sources.

Data Group G contains the required environmental characteristics of the water body. These include the segmental multipliers for the environmental and kinetic time functions in data group I.

Data Group H contains required chemical characteristics or constants, including phytoplankton growth and respiration parameters and other stoichiometric and kinetic factors describing nutrient cycling.

Data Group I contains required environmental or kinetic time functions. These are multiplied by the segmental multipliers in data group G to determine parameters like temperature, nutrient fluxes, extinction coefficients, and flow velocities, for each segment. This data group also contains additional time functions for daily solar radiations, daylight fractions, wind velocity, and herbivorous zooplankton populations.

Data Group J contains the initial concentration of each state variable in each segment (Ambrose, <u>et al</u>., 1988).

2.3.3.7 EUTRO4E Simulation Output

EUTRO4E simulations produce several output files with file names identical to the name of the input data set, but with unique extensions. Output files with the following extensions are generated:

1) *. DMP (where P = 1,2,...8)
2) *. OUT
3) *. TRN
4) *. MSB

where * = Input data set file name

The most important of these are the **DMP** files, which contain all kinetic "display" variables for each segment and system at each print interval throughout the simulation. These variables include concentrations, certain calculated variables, and some rates. A post-processor program named WPOST was developed by Limno-Tech, Inc. (LTI, personnal communication, 1991) to permit graphical display of the variables contained in DMP files.

The **OUT** file contains a record of the input data plus any simulation error messages that may have been generated. The **TRN** file contains a set of transport associated variables for each segment at each print interval throughout the simulation. These variables include the time step, calculated maximum time steps, segment volumes, segment flows, flow changes, time constants for segment flow, segment exchange flows, the time constant for segment exchanges, the segment dispersion coefficient, and the numerical dispersion coefficient.

The **MSB** file contains a mass balance record for one designated system in the model network as a whole. For each print interval, this file records the accumulated mass in from advection, dispersion, and loading; the accumulated mass out through advection, dispersion, burial, and kinetic transformation; total resident mass; and the residual mass.

DATA REDUCTION AND MODEL CALIBRATION

3.1 Collection of Data for Lake Hamilton

Much of the data needed to apply WASP4/EUTRO4E to Lake Hamilton was obtained from a monitoring study conducted in 1987. The lake was sampled during spring, summer and early fall of 1987 on twenty five dates by S. Martin and B. Abbas of Youngstown State University. The sampling sites are shown in Figure 3-1. At the sampling sites, dissolved oxygen and temperature readings were taken at every half meter depth. Transparency of the water was also measured with a Secchi disk. At the deepest site, samples were collected at four depths (usually 1m, 4m, 8m and 12m) for determining total phosphorus, total soluble phosphorus (TSP), soluble reactive phosphorus (SRP) or orthophosphate phosphorus, chlorophyll a (Chl a), nitrate nitrogen (NO_3), and ammonia nitrogen (NH_3) concentrations. Additional samples for these parameters were also collected in Yellow Creek at the inlet and outlet of Lake Hamilton (S.Martin, Youngstown State University, personnal communication, 1992). The analytical methods used will be described by Abbas (1992). This monitoring program provided a detailed calibration data set, as well as information on nutrient loadings and environmental conditions.

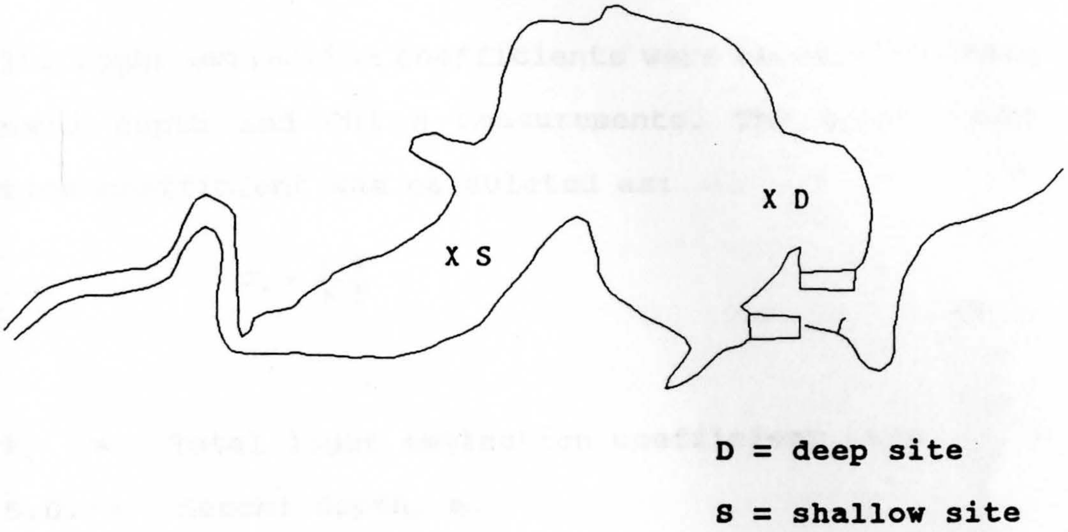


Figure 3-1. Lake Hamilton Sampling sites.

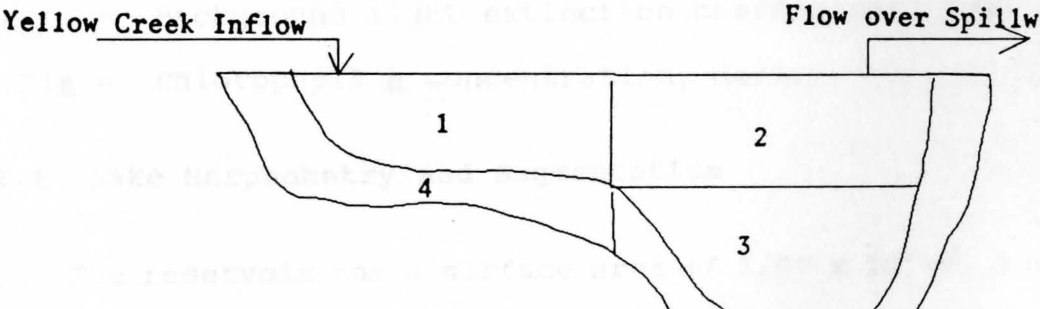


Figure 3-2. Lake Hamilton Segmentation.

3.2 Model Input and Calibration Data

3.2.1 Light Extinction Coefficients

The Light extinction coefficients were calculated using the secchi depth and Chl a measurements. The total light extinction coefficient was calculated as:

$$K_e = \frac{1.9}{S.D} \tag{3-1}$$

Where:

K_e = Total light extinction coefficient, 1/m.
S.D. = Secchi depth, m.

The background light extinction coefficient was calculated by using the equation (Thomann and Mueller, 1987):

$$K_{eb} = K_e - 0.0088(Chla) - 0.054(Chla)^{0.66} \tag{3-2}$$

Where:

K_{eb} = Background light extinction coefficient, 1/m.
Chla = Chlorophyll a concentration, ug/l.

3.2.2 Lake Morphometry and Segmentation

The reservoir has a surface area of 3.97×10^5 m^2, volume of 2.74×10^6 m^3 and a maximum depth of 17 meters. The reservoir has a mean depth of nearly one-third of its maximum depth and a shoreline development of 1.8, which is indicative of steep slopes (Schroeder and Farran, 1989).

For the purpose of modeling, the lake was divided into five segments as shown in Figure 3-2. Segments 1 and 2 are the surface water (epilimnion) segments. Segment 1 has a depth of 5 m, and segment 2 has a depth of 5.5 m. Segment 3 is the hypolimnion extending below segment 2, with a total depth of 11.5 m. Segments 4 and 5 are the upper sediment segments, with an assumed thickness of 4 centimeters each, underlying segments 1 and 3 respectively. The volumes and surface areas for the segments are tabulated in Table 3-1.

In the water column, characteristic mixing lengths were taken as the distances between geometric centers of adjacent segments. Values of 703.4 m and 5.735 m were used for the segment 1/2 and 2/3 interfaces, respectively. Interfacial areas between adjacent segments were estimated from a bathymetric map of Lake Hamilton to be 360 m^2 for segments 1/2 and 1.49×10^5 m^2 for segments 2/3. Since field data show relatively small horizontal gradients between segments 1 and 2, a fairly large lateral dispersion coefficient of 20 m^2/s was specified for this segment pair. For dispersion (or diffusion) between the bottom sediments and overlying water, the characteristic length was taken as 0.04 m; the thickness of the sediment layer.

3.2.3 Vertical Diffusivity Coefficients

The vertical diffusivity coefficients between segments 2 and 3 were determined from the temperature profiles based on a method by Jassby and Powell (1974).

Table 3-1. Volumes and Areas for the Segments of Lake Hamilton.

Segment Number	Area (m^2)	Volume (m^3)
1	2.248×10^5	1.038×10^6
2	1.488×10^5	7.964×10^5
3	1.488×10^5	9.099×10^5
4	2.248×10^5	9.132×10^3
5	1.488×10^5	5.952×10^3

A computer program to calculate the diffusivity coefficients was developed and is shown in Appendix B (Table B-1).

The computed values of the diffusivity coefficients varied between 1.0 x 10^{-4} m^2/s and 1.16 x 10^{-7} m^2/s, which agree well with the literature values. The Jassby and Powell equation used for calculating the vertical diffusivity coefficient is:

$$K_z = \frac{\left(\frac{T_{h1} - T_{h2}}{t}\right) \frac{V_H}{A_{th}}}{TGT_1 - TGT_2} \tag{3-3}$$

Where:

K_z = Vertical diffusivity coefficient, m^2/day.

T_{h1} = Average temperature in hypolimnion on day 1, °C.

T_{h2} = Average temperature of hypolimnion on next sampling date, °C.

t = Time between the two sampling dates, days.

V_H = Volume of hypolimnion, m^3.

A_{th} = Area at thermocline, m^2.

TGT1 = Maximum temperature gradient in thermocline on day 1, °C/m.

TGT2 = Maximum temperature gradient in thermocline on next sampling date, °C/m.

The maximum temperature gradient in the lake was frequently observed at 5.5 meters from the surface; hence, the thermocline depth was fixed at 5.5 meters for these calculations. The calculated values of vertical diffusivity coefficients were then assigned to the day midway between the two consecutive sampling dates. The results are presented in Table 3-2.

3.2.4 Volume-Weighted Average Concentrations

The computations of volume-weighted average concentrations for each state variable in the epilimnion and the hypolimnion required the division of the lake into a number of layers, with each layer having a thickness of one half meter. The location of the thermocline was fixed at a depth of 5.5 meters between segments 2 and 3 using temperature profiles as explained in section 3.2.3.

The value of the concentration for the state variable in any given layer was taken as the measured concentration at the closest point possible to the center of the layer. A computer program developed by S. Martin and D. Wallace at Youngstown State University was used for calculating the volume-weighted average concentrations for the epilimnion and hypolimnion. The layer thicknesses and their volumes, estimated from hypsographic curves (S.Martin, Youngstown State University, unpublished data) are tabulated in Appendix A (Table A-1).

The volume-weighted average concentrations in the epilimnion and hypolimnion were calculated using the equations:

Table 3-2. Computed Values of Vertical Diffusivity Coefficients for Lake Hamilton.

Date	Julian Day	Diffusivity Coefficient (M^2/S)
4/3/87	93	6.713E-06
4/16/87	106	3.820E-06
4/27/87	117	1.146E-05
5/4/87	124	4.630E-06
5/12/87	132	3.370E-06
5/18/87	138	3.700E-07
5/25/87	145	9.840E-07
6/1/87	152	7.990E-07
6/8/87	159	1.227E-06
6/14/87	165	1.640E-06
6/20/87	171	2.770E-07
6/28/87	179	1.470E-06
7/3/87	184	3.704E-07
7/10/87	191	5.324E-07
7/17/87	198	7.870E-07
7/24/87	205	9.840E-07
7/31/87	212	8.330E-07
8/7/87	219	4.510E-07
8/16/87	228	1.160E-07
8/27/87	239	1.320E-06
9/9/87	252	8.330E-06
9/23/87	266	8.450E-07
10/8/87	281	1.610E-06
10/27/87	300	7.520E-05

$$C_e = \frac{\sum_{i=1}^{m} (C_i V_i)}{\sum_{i=1}^{m} (V_i)} \quad \text{and} \quad C_h = \frac{\sum_{i=m+1}^{n} (C_i V_i)}{\sum_{i=m+1}^{n} V_i} \qquad (3\text{-}4)$$

Where:

C_e, C_h = Volume-weighted average concentrations in epilimnion and hypolimnion.

C_i = Concentration assigned to layer i, mg/l.

V_i = Volume of layer i, m^3.

A summary of the calculated volume-weighted average concentrations for all state variables is given in Table 3-3. All of these parameters were measured directly on Lake Hamilton water samples except organic phosphorus (OP). OP was calculated from the relationship:

$$OP = TP - SRP - Chl\underline{a}\ (P{:}Chl\underline{a}\ ratio) \qquad (3\text{-}5)$$

Where:

TP = Total Phosphorus, ug/l.

SRP = Soluble Reactive Phosphorus, ug/l.

Chl<u>a</u> = Chlorophyll <u>a</u>, ug/l.

This is consistent with the EUTRO4E definition of OP, which excludes phytoplankton phosphorus. A value of 0.6 was used for the P:Chl <u>a</u> ratio in phytoplankton.

3.2.5 Flows and Loadings to the Lake

The inflow data for 1987 was obtained from the Ohio Water Service Company. The flow into and out of the reservoir was computed as the sum of the water sales and the flow over

Table 3-3. Volume Weighted Average Concentrations for Lake Hamilton, 1987.

JULIAN DAY	DATE	DO(mg/l)		SRP(ug/l)		OP(ug/l)		TP(ug/l)		CHLa(ug/l)		NH3(ug/l)		NO3(ug/l)	
		SEG.2	SEG.3	SEG.2	SEG.3	SEG.2	SEG.3	SEG.2	SEG.3	SEG.2	SEG.3	SEG.2	SEG.3	SEG.2	SEG.3
86	3/27	13.6	9.3	3.95	2.09	37.59	32.28	53.92	43.37	20.63	14.99				
99	4/9	11.7	8.6	3.12	1.53	61.85	40.1	72.5	50.06	12.55	14.04	9.2	284.24	1087.5	566.06
113	4/23	13.1	7	2.42	1.87	33	42.27	49.29	53.32	23.11	15.3	11.6	11.6	0	241.63
120	4/30	11.2	6	3.4	2.8	42.2	39.15	54.19	47.37	14.31	9.02	20.4	302.71	201.8	201.8
128	5/8	11.5	4.8	1.8	3.52	39.12	33.05	49.41	39.32	14.14	4.59	29.97	302.72	151.85	411.42
135	5/15	10.4	2.4	2.11	4.49	17.86	16.29	30.26	24.45	17.14	6.11	10.24	289.91	69.92	358.41
141	5/21	8.1	2	3.58	9.73	31.28	39.6	45.81	53.37	18.24	6.73	27.92	308.97	415.42	308.81
148	5/28	9.3	1	5.58	19.34	24.1	36.17	31.74	58.03	3.46	4.2	7.38	330.72	106.63	270.16
155	6/4	9.1	1.3	3.15	30.57	20.6	27.58	25.87	60.81	3.55	4.43	26.95	403.43	139.29	238.72
163	6/12	10.7	1.7	3.02	41.22	20.93	24.72	27.85	70.15	6.49	7.02	20.26	395.04	167.27	52.94
168	6/17	9.8	1.6	3.21	52.38	38.43	37.82	48	96.88	7.27	11.13	56.7	601.69	185.76	64.92
174	6/23	8.3	1.7	3.01	67.12	22.66	23.86	39.01	94.92	22.23	6.56	49.39	586.9	113.73	29.03
183	7/2	6.8	1.7	4.91	21.41	56.19	29.31	80.76	54.47	32.76	6.25				
188	7/7	9.2	0.7	8.03	75.48	44.22	33.08	77.87	110.02	42.69	2.42	63.36	453.57	1018.6	136.02
195	7/14	6	0.3	2.11	153.28	28.6	40.03	36.28	195.98	9.24	4.45	108.59	742.12	477.71	78
202	7/21	6.6	0.04	2.07	176.01	32.85	22.07	56.28	204.53	35.59	10.74	18.47	716.8	650.72	99.02
208	7/27	7.95	0	0.76	183.45	35.14	56.63	58.27	246.74	37.27	11.1	1.58	797.34	384.62	51.96
216	8/4	9.66	0	1.79	183.22	66	118.85	81.11	305.6	22.27	5.88	71.6	1061.17	119.55	31.08
222	8/10	4.88	0	4.34	174.86	33.98	58.48	57.58	235.47	32.1	3.54	82.18	722.75	43.94	10.21
233	8/21	6.7	0	0	218.2	65.01	67.13	68.25	286.71	5.39	2.3	16.75	549.43	17.9	0
244	9/1	7.51	0	0	163.38	44.21	69.05	52.09	233.61	13.13	1.96	62.45	1125.93	0	0
259	9/16	7.22	0	0.75	225.54	26.22	55.3	33.58	281.17	11.01	0.88	126.65	1353.09	87.41	25.19
273	9/30	10.82	0.86	1.06	171.46	27.9	30.96	36.69	207.5	12.92	8.46	54.18	735.5	2.06	0.54
289	10/16	9.26	5.98	5.26	213.31	92.53	44.91	102.43	259.08	7.73	1.43				
310	11/6	10.86	9.99	24.21	2.73	43.23	79.23	68.11	81.28	1.11	1.28				

the spillway. The total flow into the reservoir in 1987 was 6150 Mgal, with 385.7 Mgal being the sales and 5764 Mgal being the flow over the spillway. Daily values of flow over the spillway were available, while the average daily sale was computed from the monthly sale figures. The time variable flows were entered in Data Group D of the input data set, presented in Appendix C .

The water samples at the inlet to the lake were analyzed for total phosphorus, total soluble phosphorus, soluble reactive (orthophosphate) phosphorus, nitrate nitrogen, and ammonia nitrogen. A summary of these measured concentrations is given in Table 3-4. Organic phosphorus which is a state variable in the WASP4 model was computed using Equation 3-5.

A constant value of 5 ug/l was assumed for chlorophyll _a_ in the inflow to the lake. Saturation dissolved oxygen in Yellow Creek was determined based on the estimated temperature of the inflowing water. The inflow concentrations are specified as boundary conditions for segment 1 in the input data set. The model calculates the external loading to segment 1 by taking the product of flow and the inflow concentration.

3.3 Approach to Model Calibration

Calibration of EUTRO4E to the conditions observed in Lake Hamilton in 1987 was accomplished by adjusting key kinetic and stoichiometric coefficients within the ranges of values appearing in the scientific literature (Bowie, _et al_., 1985). An attempt was made to simulate the transformations

Table 3-4. Concentrations in Yellow Creek at Inlet to Lake Hamilton, 1987.

DATE	JULIAN DAY	TP (ug/l)	SRP (ug/l)	OP (ug/l)	NO3 (ug/l)	NH3 (ug/l)
3/27/87	86	23.90	2.80	21.10		
4/9/87	99	57.70	1.90	55.80		
4/23/87	113	41.10	1.00	40.10		
4/30/87	120					
5/8/87	128	47.10	2.40	44.70	57.30	2.60
5/15/87	135	127.00	11.40	115.60	647.80	85.10
5/28/87	148	219.70	51.60	168.10	559.70	102.20
6/12/87	163	93.20	36.80	56.40	625.80	55.10
6/17/87	168	89.60	58.70	30.90	454.90	102.30
6/23/87	174	126.40	105.70	20.70	48.10	104.80
6/30/87	181				1077.80	160.00
7/2/87	183		64.80			
7/7/87	188	54.90	17.70	37.20	710.00	0.00
7/14/87	195	166.10	62.70	103.40	567.30	68.50
7/21/87	202	36.20	15.50	20.70	243.50	17.00
7/27/87	208	41.60	14.20	27.40	461.50	0.00
8/4/87	216	113.80	21.20	92.60	54.60	31.30
8/10/87	222	88.30	24.20	64.10	630.50	0.00
8/21/87	233	59.60	31.50	28.10	118.00	22.00
9/1/87	244	114.60	31.70	82.90	415.70	620.70
9/16/87	259	59.70	19.70	40.00	574.60	20.10
9/30/87	273	78.90	60.50	18.40	333.00	17.40
10/16/87	289	40.00	26.60	13.40		
11/6/87	310	67.50	41.70	25.80		
No. of Obs.		21	22	21	17	17
Mean		83.19	32.01	52.73	445.89	82.89
Std. Deviation		47.11	25.80	38.63	270.66	142.13

going on in all the segments of the lake. Some of the important parameters and processes that were found to affect the model calibration are summarized below:

1. Release of orthophosphate phosphorus from the sediments when hypolimnetic anoxia begins;
2. Orthophosphate phosphorus loss to the sediments when oxygen appears in the hypolimnion;
3. Ammonification when the hypolimnion goes anoxic;
4. Termination of the ammonification process when the hypolimnion becomes aerobic;
5. Spatial and temporal variability of phytoplankton settling rate;
6. Dispersion between surface water segments 1 and 2;
7. Initial conditions for state variable concentrations in the bottom sediments;
8. Sediment oxygen demand (SOD) in the hypolimnion during summer stratification;
9. Permanent loss of state variables (deep burial) in sediments;
10. Phytoplankton growth and death rate;
11. Decomposition of organic matter in sediments to account for recycling of nutrients;
12. Pore water dispersion at the sediment-water interfacial area;

The values used for these parameters and processes are listed in the input data set in Appendix C, and are discussed further in Chapter 4.

CALIBRATED RESULTS OF MODEL AND DISCUSSION

4.1 Comparison of Calibrated and Measured Concentrations

The model was calibrated and simulation was performed for the year 1987. The comparison of the calibrated results and the measured data is shown graphically in Figures 4-1 to 4-12. Plots are not shown for segment 1, since model results are nearly identical to segment 2. Note that Julian Day 1 corresponds to January 1, 1987. A discussion on the comparison is provided below.

4.1.1 Dissolved oxygen

The calibrated results for the epilimnion compare well, on average, with the observed data as indicated by Figure 4-1a. Up to day 150, the variability is only 1.0-1.5 mg/l. The model does not reproduce the dramatic short-term fluctuations in DO due to algal photosynthesis and respiration. During the summer stratification, there is a significant difference between the calibrated results and measured data, with the model values being much higher. This is due to the assumption of a constant depth of epilimnion. Low DO levels were sometimes observed above 5.5 m depth, lowering the calculated volume-weighted average concentrations significantly.

Close agreement between the simulation and the data was observed for dissolved oxygen (DO) in the hypolimnion, particularly at the critical summer stratification in Figure 4-1b. The simulated anoxic period extended beyond the observed

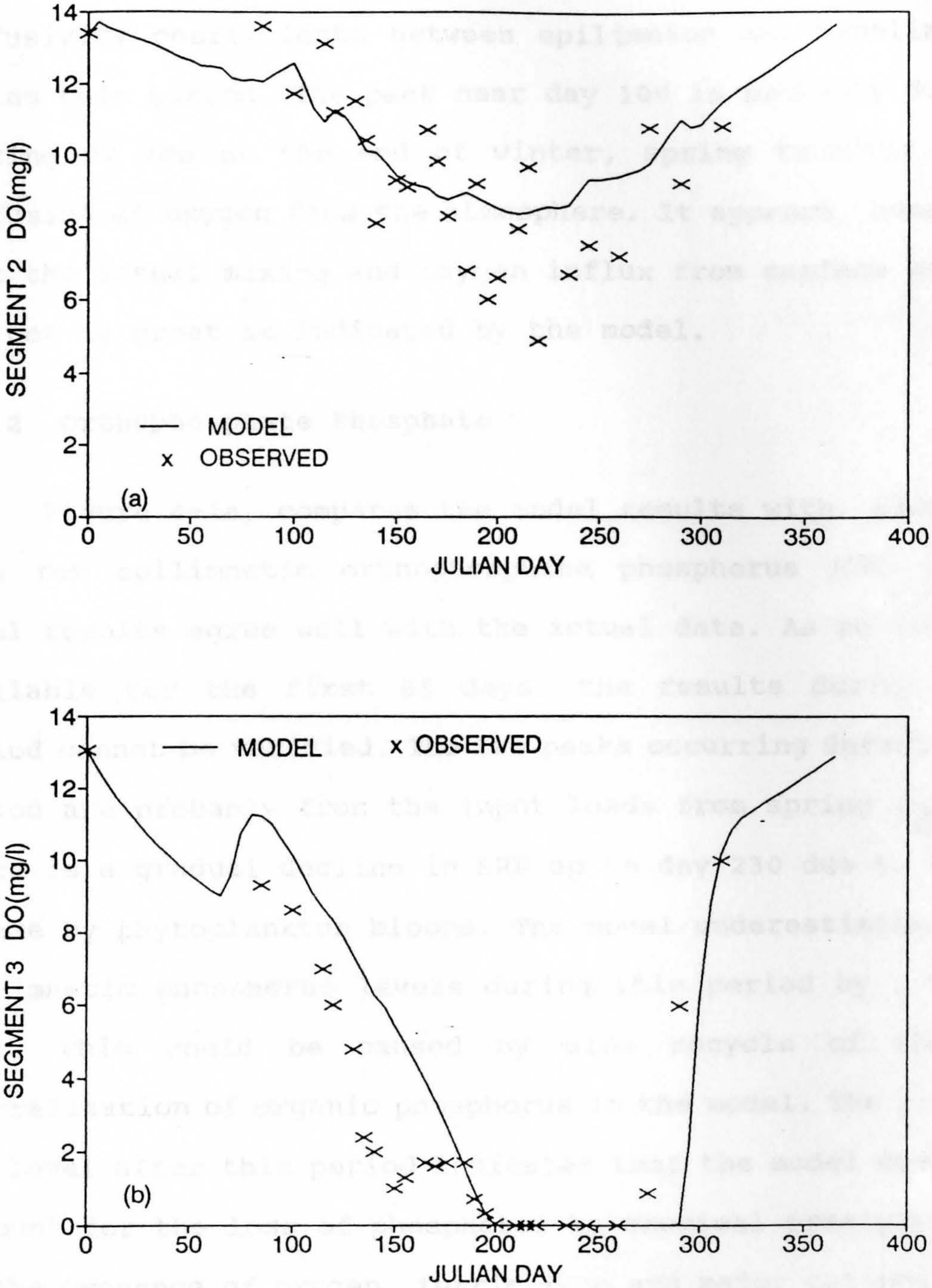


Figure 4-1. Calibrated Model Results, 1987, of: (a) Epilimnetic Dissolved Oxygen; and (b) Hypolimnetic Dissolved Oxygen.

period. This could be due to late turnover as indicated by low diffusivity coefficients between epilimnion and hypolimnion during this period. The peak near day 100 is probably due to melting of ice at the end of winter, spring turnover, and diffusion of oxygen from the atmosphere. It appears, however, that the actual mixing and oxygen influx from surface waters was not as great as indicated by the model.

4.1.2 Orthophosphate Phosphate

Figure 4-2a, compares the model results with measured data for epilimnetic orthophosphate phosphorus (SRP). The model results agree well with the actual data. As no data is available for the first 85 days, the results during this period cannot be verified. The two peaks occurring during that period are probably from the input loads from spring inflow. There is a gradual decline in SRP up to day 230 due to rapid uptake by phytoplankton blooms. The model underestimates the epilimnetic phosphorus levels during this period by 1.0-3.0 ug/l. This could be caused by slow recycle of SRP by mineralization of organic phosphorus in the model. The rise in SRP level after this period indicates that the model does not account for the loss of phosphates by chemical precipitation in the presence of oxygen, ferric iron and major cations like calcium. The last peak due to dispersion from the hypolimnion, is simulated well, but a little early .

The calibrated SRP profile for the hypolimnion (Figure 4-2b) also compares well with the measured data, except for

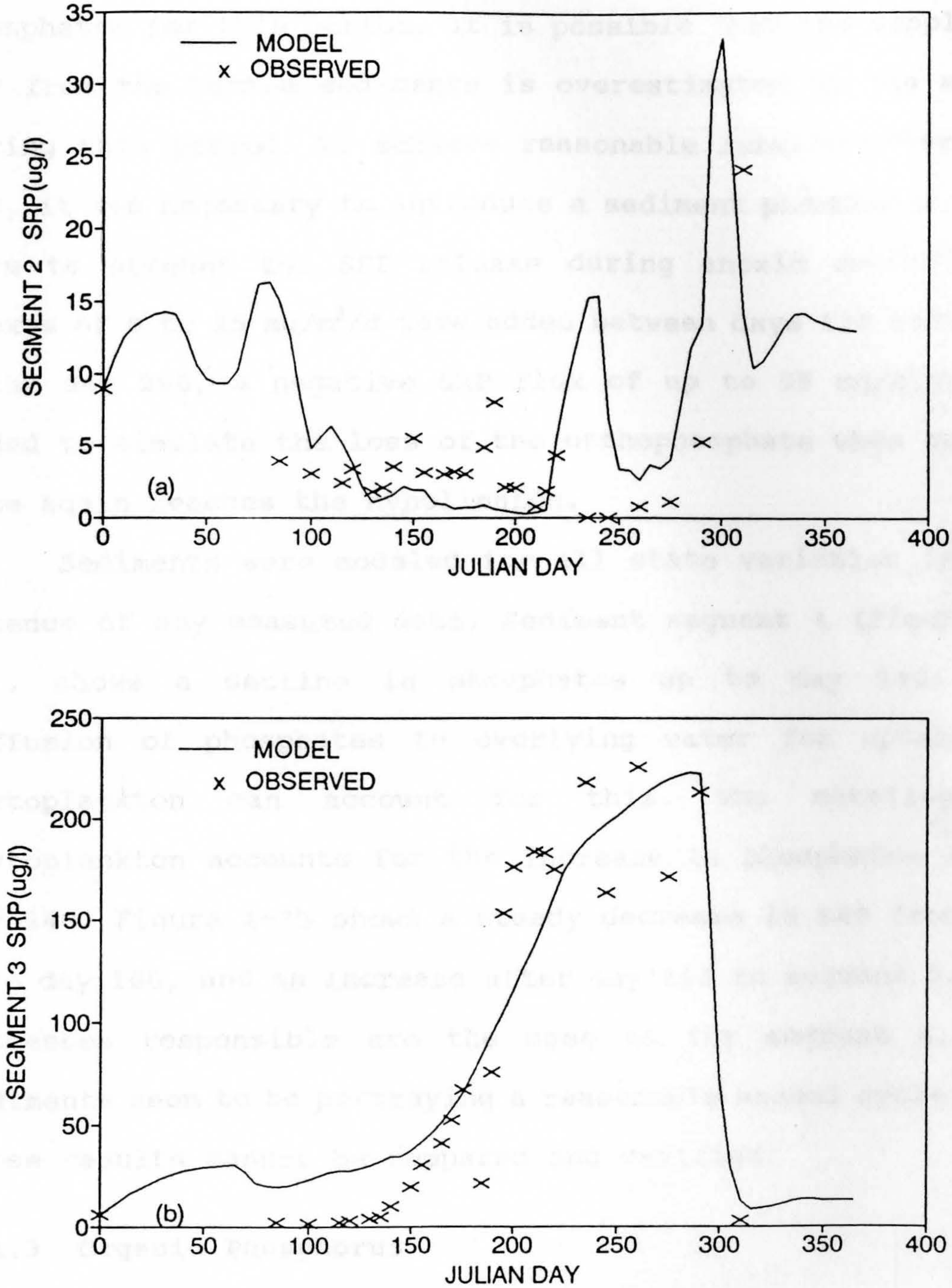


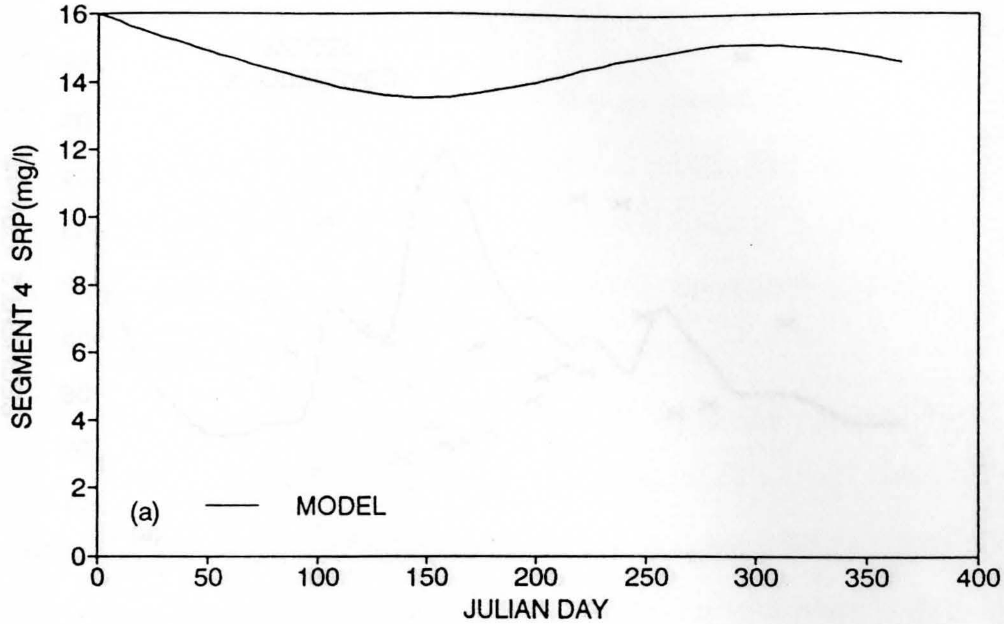
Figure 4-2. Calibrated Model Results, 1987, of: (a) Epilimnetic Soluble Reactive Phosphorus; and (b) Hypolimnetic Soluble Reactive Phosphorus.

the period up to day 140. The model shows higher levels of phosphates for this period. It is possible that the supply of SRP from the bottom sediments is overestimated by the model during this period. To achieve reasonable results after day 150, it was necessary to introduce a sediment phosphorus flux term to account for SRP release during anoxic conditions. Fluxes of 0 to 15 mg/m^2/d were added between days 130 and 290. After day 290, a negative SRP flux of up to 55 mg/m^2/d was added to simulate the loss of the orthophosphate when oxygen once again reaches the hypolimnion.

Sediments were modeled for all state variables in the absence of any measured data. Sediment segment 4 (Figure 4-3a), shows a decline in phosphates up to day 140. The diffusion of phosphates to overlying water for uptake by phytoplankton can account for this. The settling of phytoplankton accounts for the increase in phosphates after day 140. Figure 4-3b shows a steady decrease in SRP from day 0 to day 160, and an increase after day 160 in segment 5. The processes responsible are the same as for segment 4. The sediments seem to be portraying a reasonable annual cycle, but these results cannot be compared and verified.

4.1.3 Organic Phosphorus

Figure 4-4a compares the model results and the data for organic phosphorus in the epilimnion. The observed peak on day 290 is not consistent with the other data points and therefore was not considered for calibration. While the model results



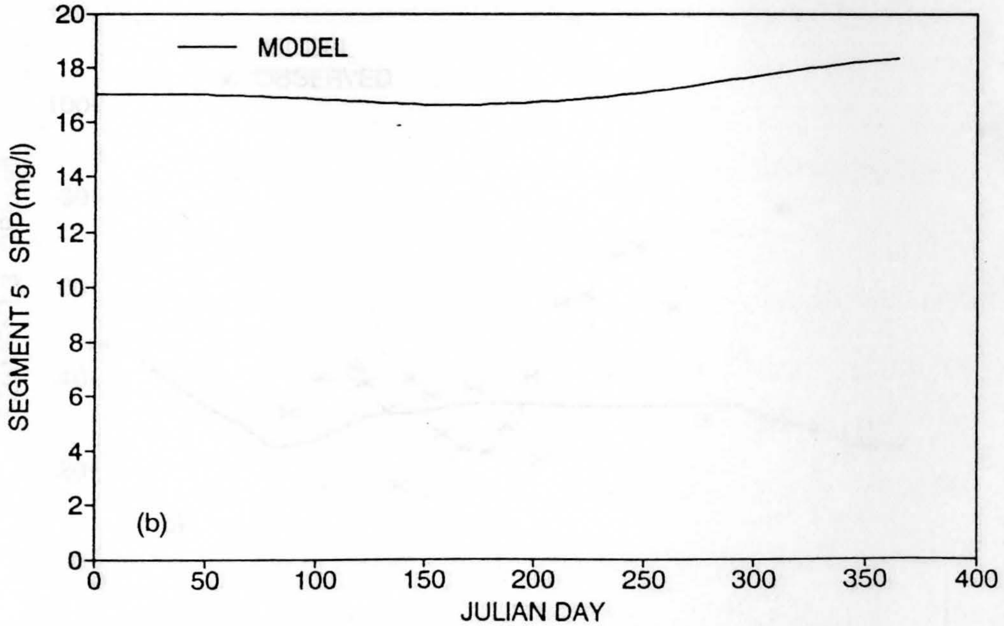


Figure 4-3. Calibrated Model Results, 1987, of: (a) Segment 4 Soluble Reactive Phosphorus; and (b) Segment 5 Soluble Reactive Phosphorus.

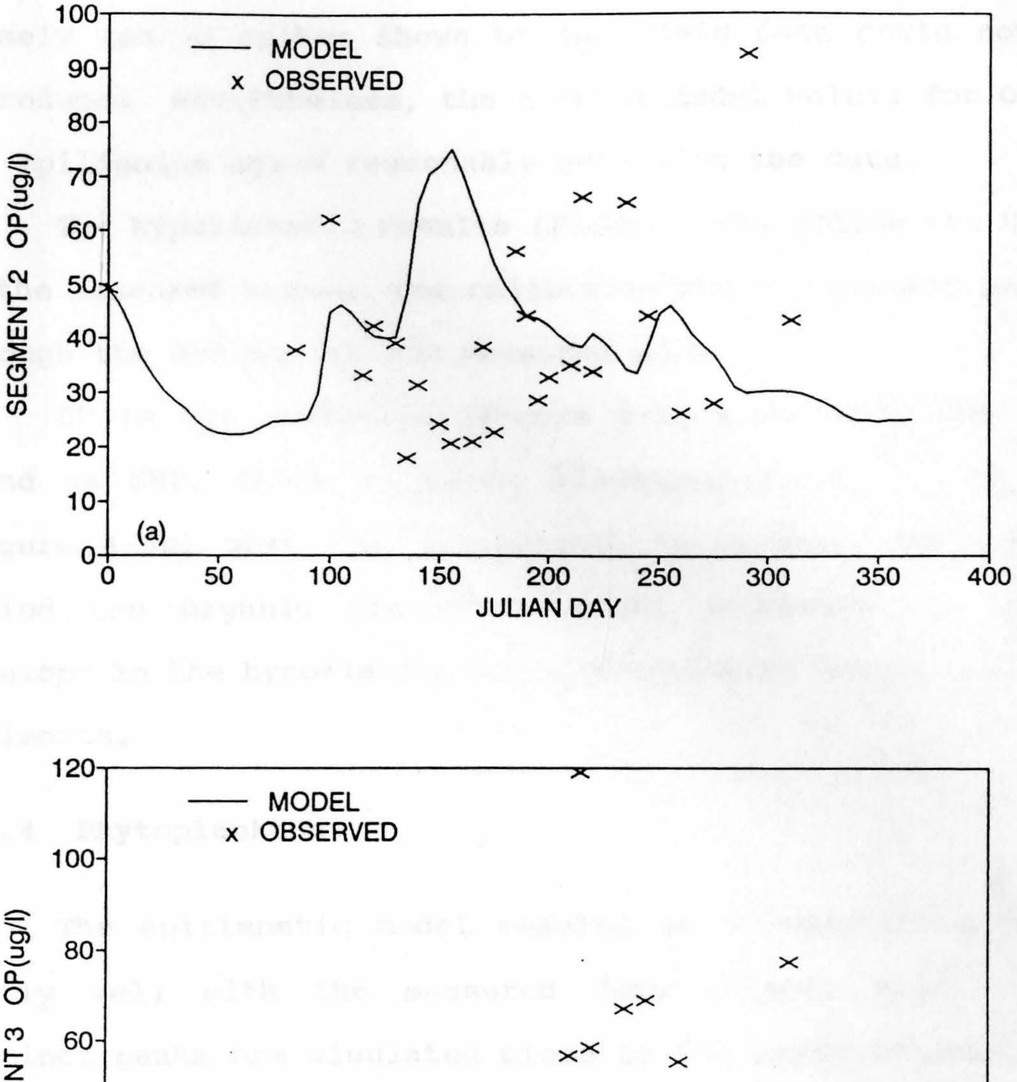


Figure 4-4. Calibrated Model Results, 1987, of: (a) Epilimnetic Organic Phosphorus; and (b) Hypolimnetic Organic Phosphorus.

show considerable seasonal variability in OP, the series of closely spaced spikes shown by the field data could not be reproduced. Nevertheless, the average model values for OP in the epilimnion agree reasonably well with the data.

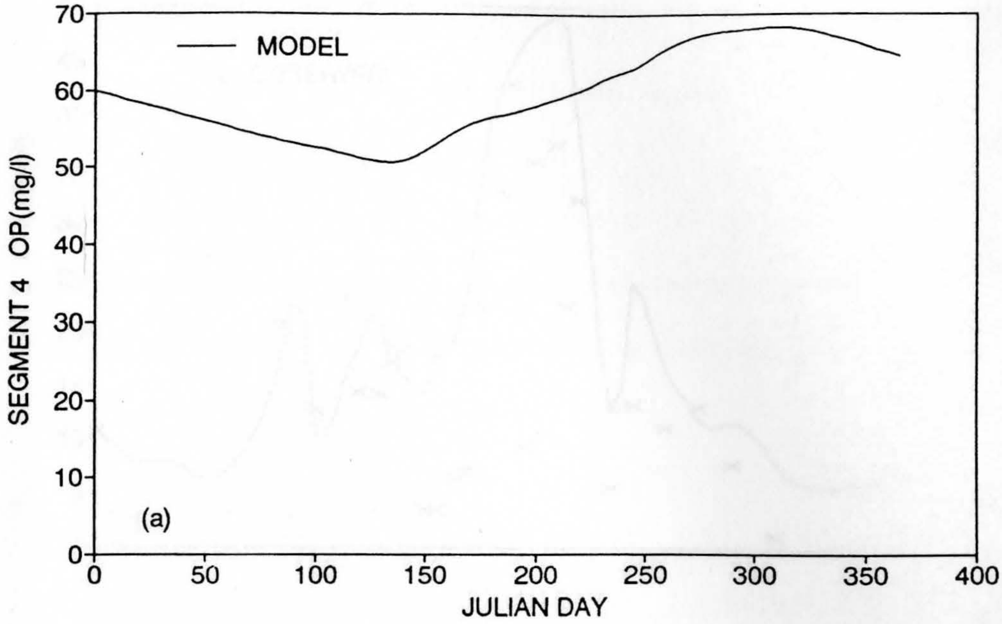
The hypolimnetic results (Figure 4-4b) follow the trend of the measured values. The calibrated profile roughly passes through the average of the measured data.

OP in the sediments (Figure 4-5a & b) shows the same trend as SRP. There is rapid decomposition up to day 150 (Figure 4-5b) when the hypolimnion is aerobic. After this period the organic phosphorus level increases as anoxia develops in the hypolimnion and phytoplankton settle onto the sediments.

4.1.4 Phytoplankton

The epilimnetic model results of chlorophyll a agree fairly well with the measured data (Figure 4-6a). Four distinct peaks are simulated close to the measured ones. The model did not accurately simulate abrupt declines (or "crashes") in chlorophyll a around days 150, 195, and 240. This is probably because the model does not account for changes in dominant phytoplankton species, and assumes that kinetic coefficients for phytoplankton growth and death are constant.

In the hypolimnion, a spring peak in Chlorophyll a is simulated very well as shown by Figure 4-6b. However, for the rest of the year, the model generally overestimates the



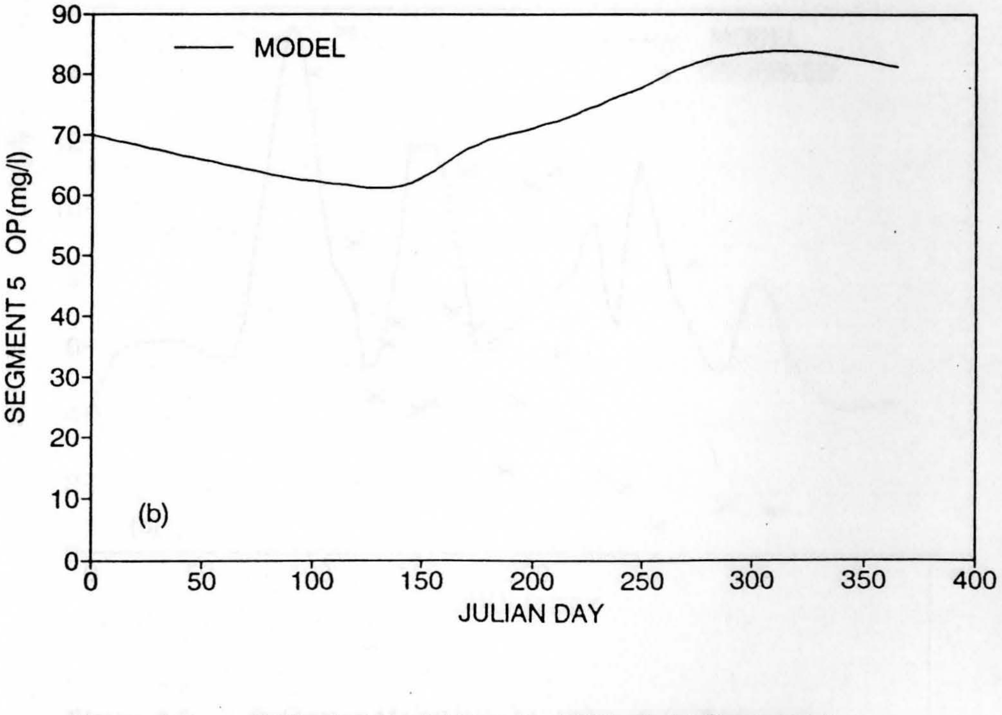


Figure 4-5. Calibrated Model Results, 1987, of: (a) Segment 4 Organic Phosphorus; and (b) Segment 5 Organic Phosphorus.

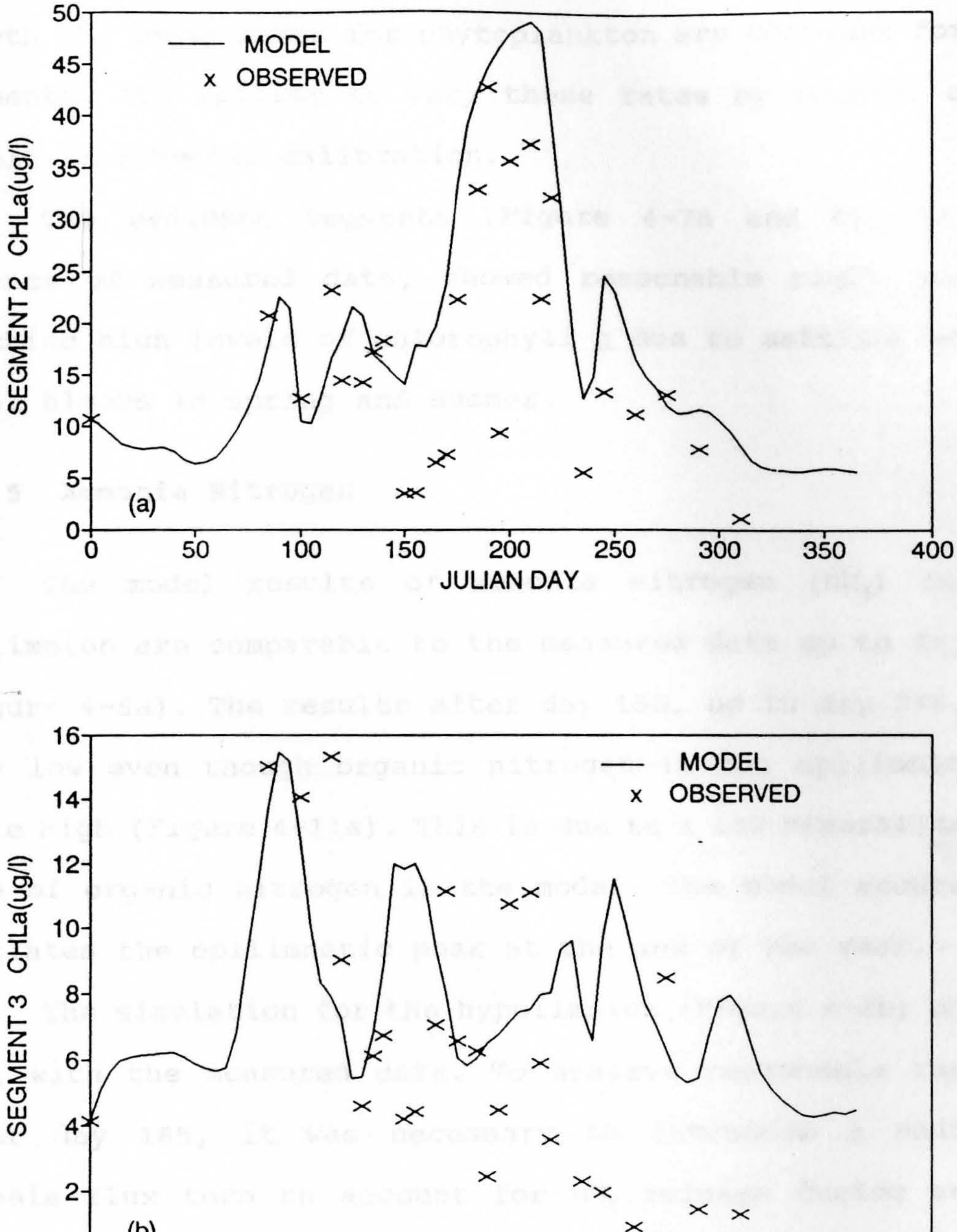


Figure 4-6. Calibrated Model Results, 1987, of: (a) Epilimnetic Chlorophyll a; and (b) Hypolimnetic Chlorophyll a.

data. The overestimation is probably due to the fact that the growth and death rates for phytoplankton are constant for all segments. The ability to vary these rates by segment could result in a better calibration.

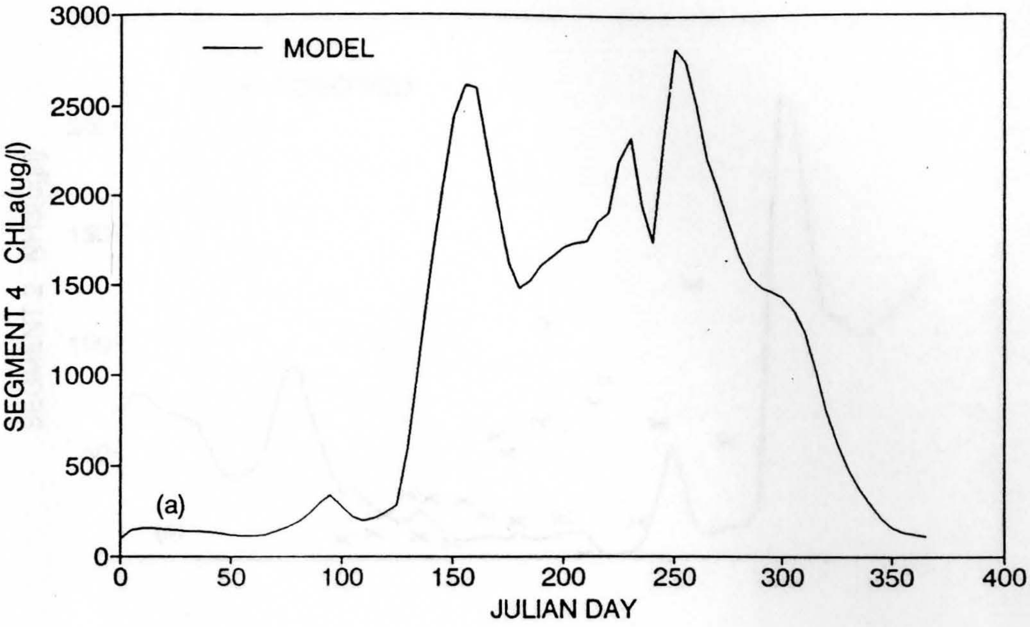
The sediment segments (Figure 4-7a and b), in the absence of measured data, showed reasonable right trends, reaching high levels of chlorophyll a due to settling of the algal blooms in spring and summer.

4.1.5 Ammonia Nitrogen

The model results of ammonia nitrogen (NH_3) in the epilimnion are comparable to the measured data up to day 150 (Figure 4-8a). The results after day 150, up to day 275, are very low even though organic nitrogen in the epilimnion is quite high (Figure 4-11a). This is due to a low mineralization rate of organic nitrogen in the model. The model accurately simulates the epilimnetic peak at the end of the year.

The simulation for the hypolimnion (Figure 4-8b) agrees well with the measured data. To achieve reasonable results after day 185, it was necessary to introduce a sediment ammonia flux term to account for NH_3 release during anoxic conditions. Fluxes of 0 to 35 $mg/m^2/d$ were added between days 185 and 290. After day 290, the flux was terminated when oxygen appears in the hypolimnion.

The sediments (Figure 4-9a & b), in the absence of measured data, show reasonable trends. There is a decrease in ammonia (Figure 4-9a) up to day 150, which can be explained by



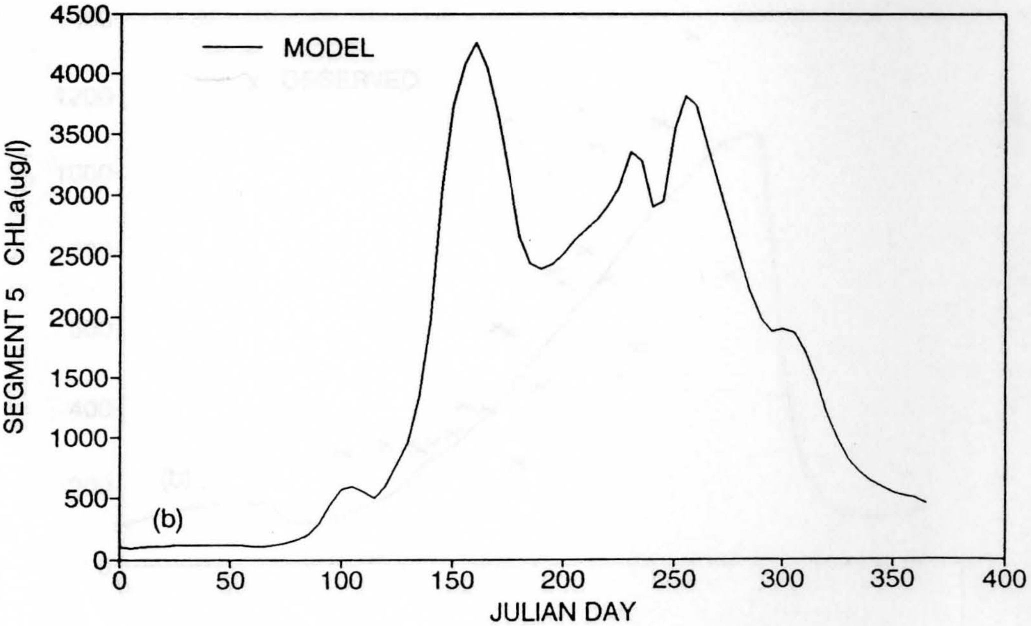


Figure 4-7. Calibrated Model Results, 1987, of: (a) Segment 4 Chlorophyll a; and (b) Segment 5 Chlorophyll a.

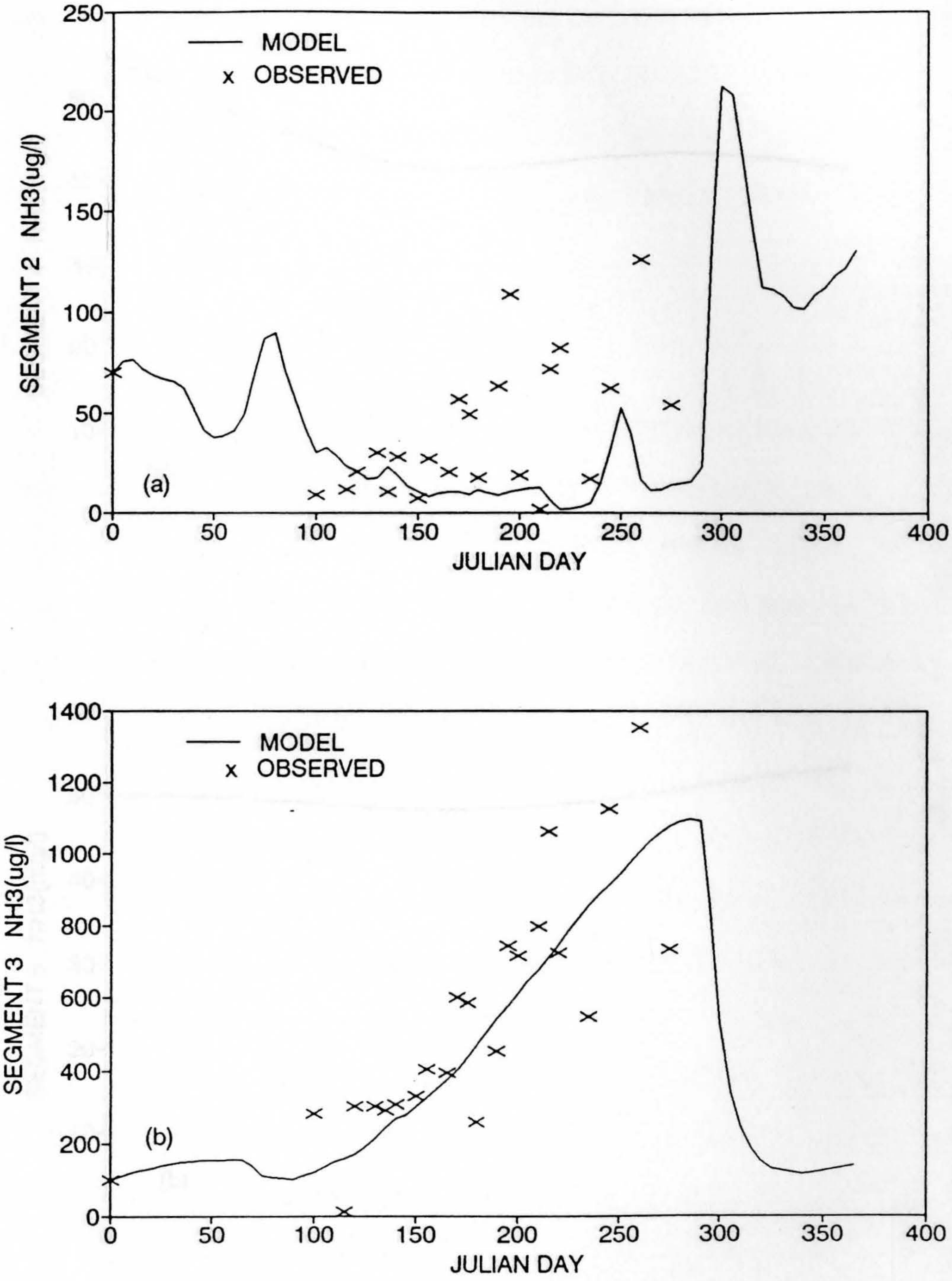


Figure 4-8. Calibrated Model Results, 1987, of: (a) Epilimnetic Ammonia Nitrogen; and (b) Hypolimnetic Ammonia Nitrogen.

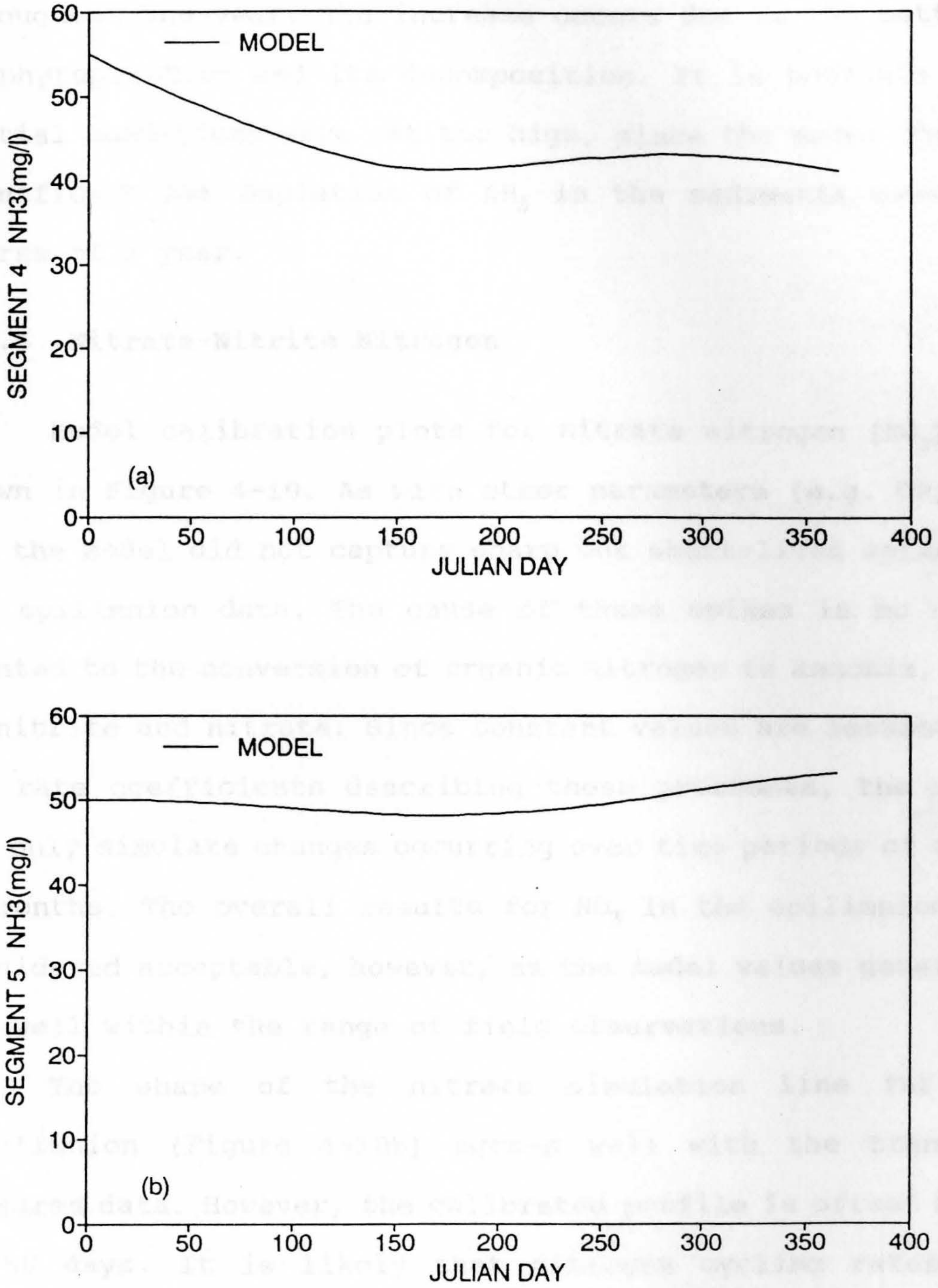


Figure 4-9. Calibrated Model Results, 1987, of: (a) Segment 4 Ammonia Nitrogen; and (b) Segment 5 Ammonia Nitrogen.

nitrification in the presence of oxygen in segment 1 throughout the year. The increase occurs due to the settling of phytoplankton and its decomposition. It is possible that initial conditions were set too high, since the model shows a significant net depletion of NH_3 in the sediments over the course of a year.

4.1.6 Nitrate-Nitrite Nitrogen

Model calibration plots for nitrate nitrogen (NO_3) are shown in Figure 4-10. As with other parameters (e.g. OP, Chl a), the model did not capture sharp but short-lived spikes in the epilimnion data. The cause of these spikes is no doubt related to the conversion of organic nitrogen to ammonia, then to nitrite and nitrate. Since constant values are assumed for the rate coefficients describing these processes, the model can only simulate changes occurring over time periods of weeks or months. The overall results for NO_3 in the epilimnion are considered acceptable, however, as the model values generally lie well within the range of field observations.

The shape of the nitrate simulation line for the hypolimnion (Figure 4-10b) agrees well with the trend in measured data. However, the calibrated profile is offset by 20 to 50 days. It is likely that nitrogen cycling rates are faster in the bottom sediments than in the water column. However, the model uses the same kinetic coefficients for all segments. Thus, the response of the hypolimnion to conversions in the bottom sediments is delayed somewhat.

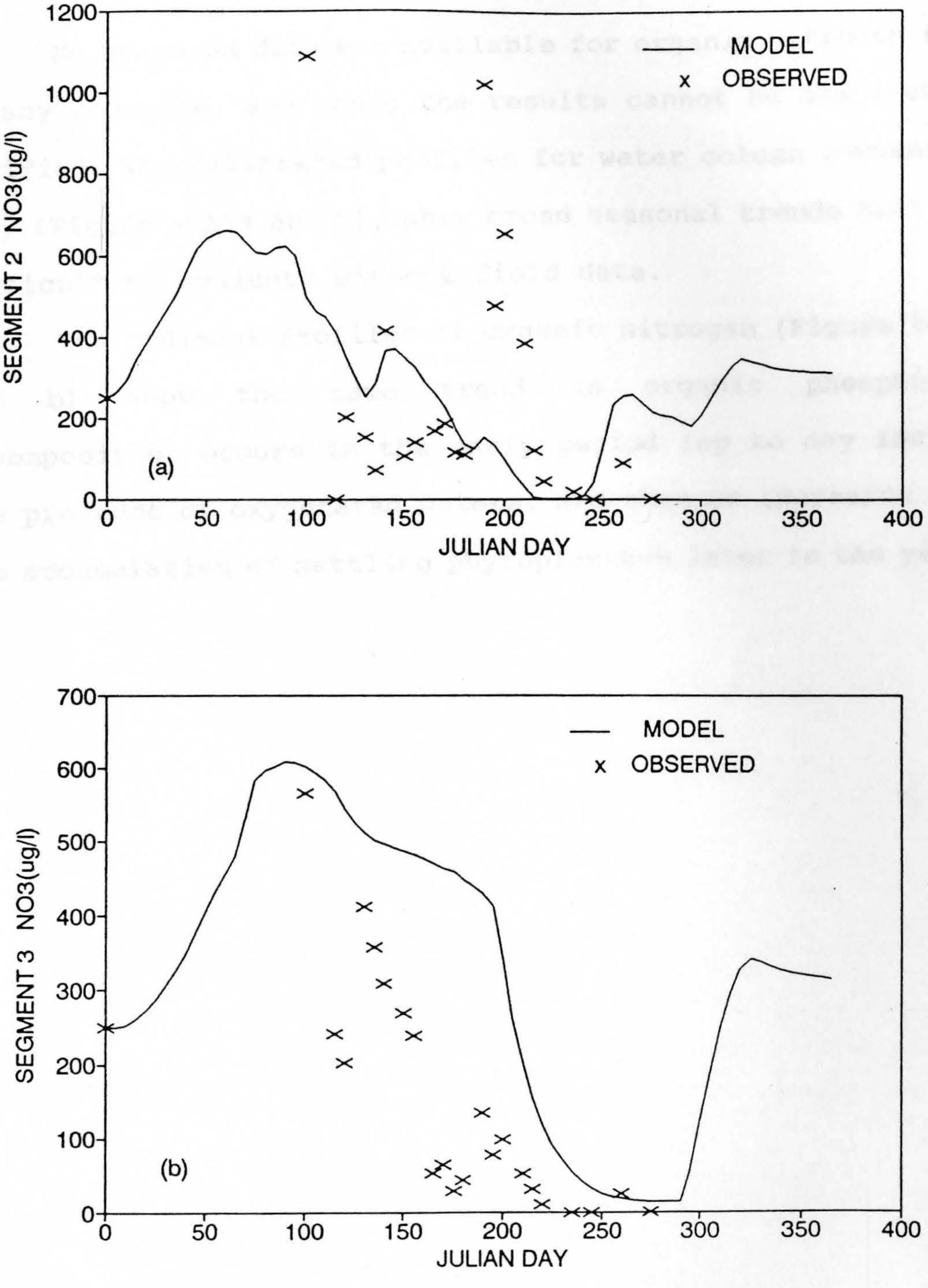
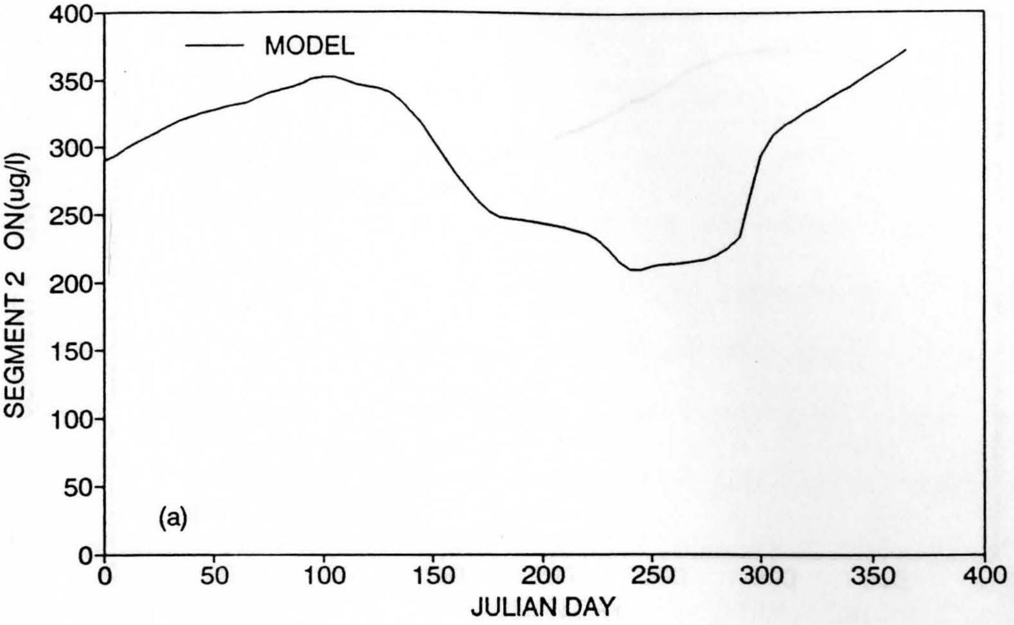


Figure 4-10. Calibrated Model Results, 1987, of (a) Epilimnetic Nitrate Nitrogen; and (b) Hypolimnetic Nitrate Nitrogen.

4.1.7 Organic Nitrogen

No measured data was available for organic nitrogen (ON) in any segments, and hence the results cannot be compared or verified. The calibrated profiles for water column segments 2 & 3, (Figure 4-11a and b), show broad seasonal trends that are difficult to evaluate without field data.

The sediment profiles of organic nitrogen (Figure 4-12a and b) show the same trend as organic phosphorus. Decomposition occurs in the early period (up to day 150) in the presence of oxygenated waters, and then ON increases from the accumulation of settling phytoplankton later in the year.



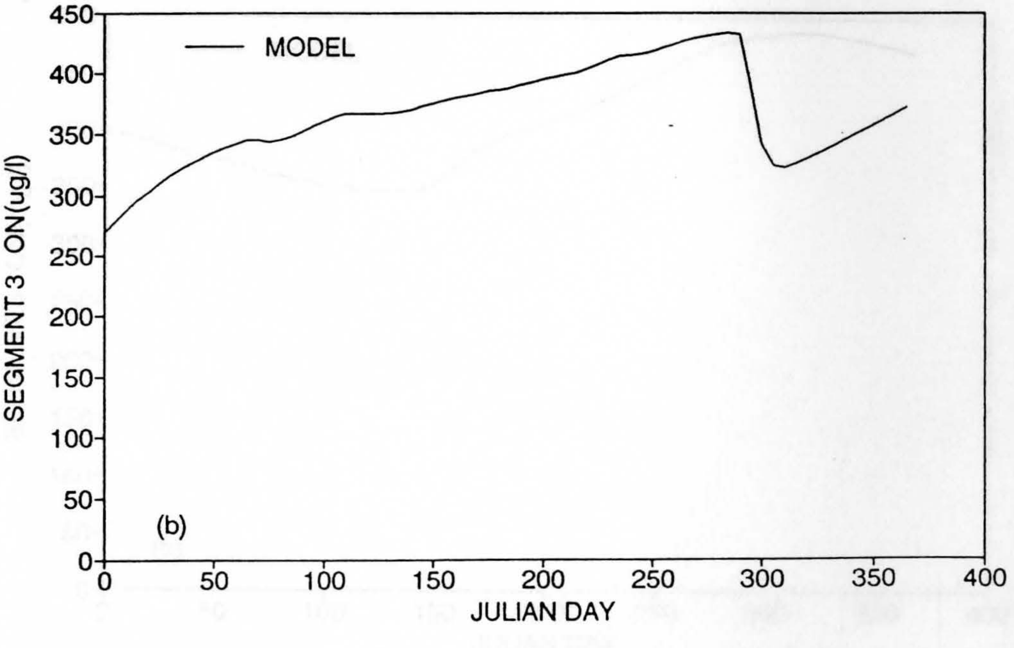


Figure 4-11. Calibrated Model Results, 1987, of: (a) Epilimnetic Organic Nitrogen; and (b) Hypolimnetic Organic Nitrogen.

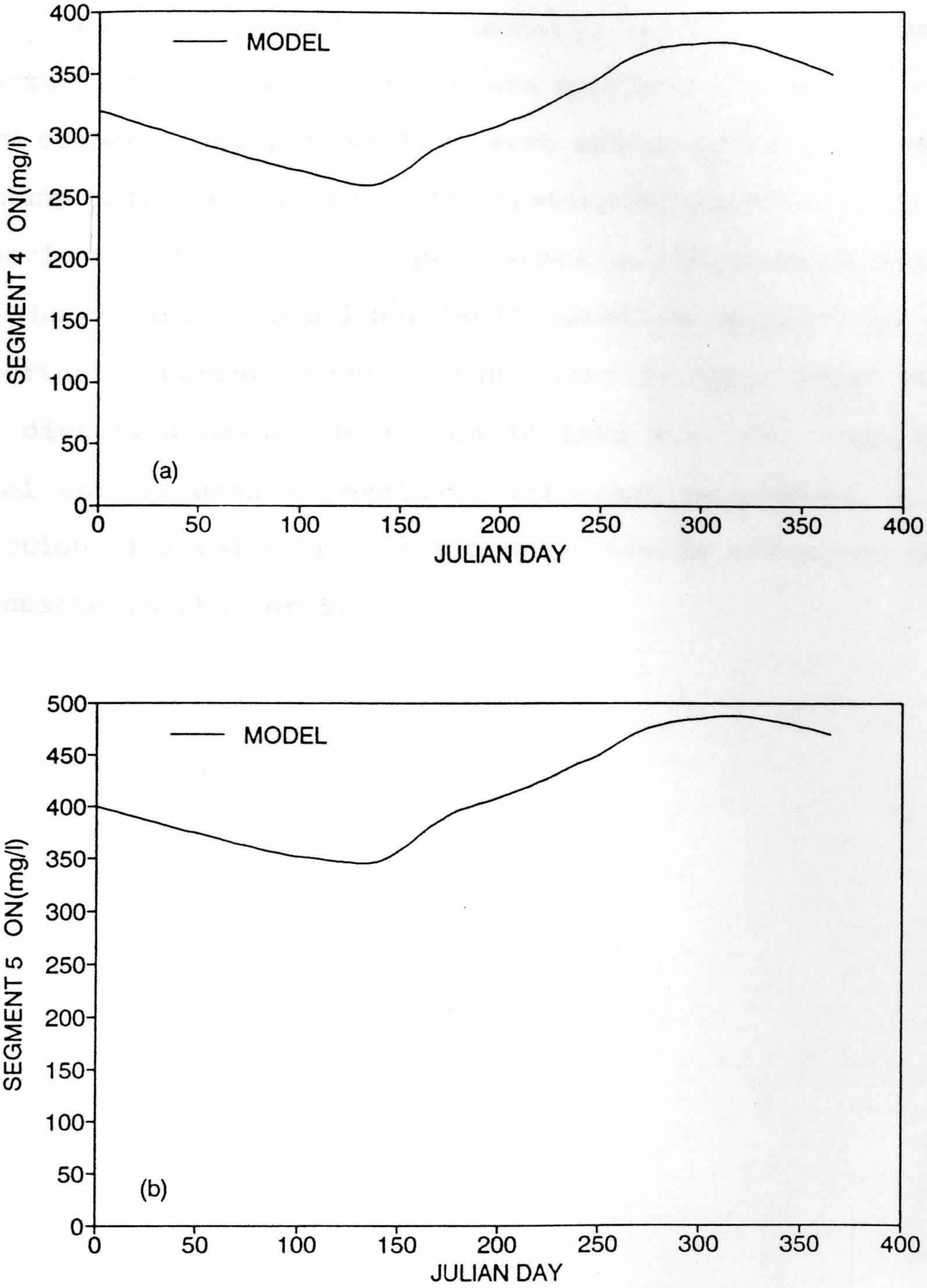


Figure 4-12. Calibrated Model Results, 1987, of: (a) Segment 4 Organic Nitrogen; and (b) Segment 5 Organic Nitrogen.

4.1.8 Summary

The model provided a reasonable simulation of seasonal fluctuations for many of the state variables. However, short-term changes (daily to weekly) were not accurately reproduced in many cases. A summary of calibration values for several key kinetic and stoichiometric parameters is presented in Table 4-1. The calibrated model has facilitated the identification of important processes governing nutrient cycling, algal growth and dissolved oxygen depletion in Lake Hamilton. Before the model can be used to evaluate different management options (Sections 4.2 and 4.3), certain enhancements are necessary as discussed in Chapter 5.

Table 4-1. Calibration Values of Selected Model Coefficients.

Coefficient	Calibration Value		
	Epilimnion	Hypolimnion	Sediments
Sediment Oxygen Demand, g/sq.m-day			2.66
Nitrification Rate, 1/day	0.2	0.2	
Denitrification Rate, 1/day	0.1	0.1	
Saturation Light Intensity for Phytoplankton, Langleys/day	100	100	
Carbon to Chlorophyll a Ratio	15	15	
N:C Ratio in Phytoplankton	0.25	0.25	
P:C Ratio in Phytoplankton	0.04	0.04	
Phosphorus Half Saturation Constant for Phytoplankton, mgPO4-P/l	0.003	0.003	
Nitrogen Half Saturation Constant for Phytoplankton, mg-N/l	0.015	0.015	
Saturated Phytoplankton Growth Rate, 1/day	2.00	2.00	
Endogenous Respiration Rate of Phytoplankton, 1/day	0.01	0.01	
Non-Predatory Mortality rate of Phytoplankton, 1/day	0.007	0.007	
Phytoplankton Settling Rate, m/day	0.1-1.5	0.1-2.0	
Decomposition Rate For Phytoplankton in Sediments, 1/day			0.5
Decomposition Rate for Organic Nitrogen in Sediments, 1/day			0.002
Decomposition Rate for Organic Phosphorus in Sediments, 1/day			0.004
Mineralization Rate of Dissolved Organic Nitrogen, 1/day	0.02	0.02	0.02
Mineralization Rate of Dissolved Organic Phosphorus, 1/day	0.02	0.02	0.02

4.2 Prevention of Anoxic Conditions in the Hypolimnion

During mid-summer, water supplied from Lake Hamilton may sometimes contains reduced chemical species such as hydrogen sulfide when anoxia reaches the water intake level. The calibrated model was used to investigate the alternatives to prevent the anoxia in the hypolimnion. The objective was established of maintaining a minimum volume-weighted average DO of 2.0 mg/l in the hypolimnion throughout the summer.

First, total external phosphorus loading in the inflow was reduced by 90% with all other 1987 inputs held constant. The model predicted no major change in the hypolimnetic oxygen profile. The only improvement was a reduction in duration of the total anoxic period by 10 days (Figure 4-13a). Next, sediment oxygen demand (SOD) was reduced by 56% (1.16 $g/m^2/day$), and the model predicted an aerobic hypolimnion with a minimum oxygen concentration of 2.2 mg/l (Figure 4-13b). This emphasized the sensitivity of dissolved oxygen in the hypolimnion to the sediment oxygen demand. It should be noted that a reduction in phosphorus loading will ultimately result in a decrease in SOD as well, since the amount of organic matter (algae) reaching the bottom sediments will decrease. However, the EUTRO4E model does not contain a mechanistic expression for SOD, so the amount of decrease must be estimated by the user.

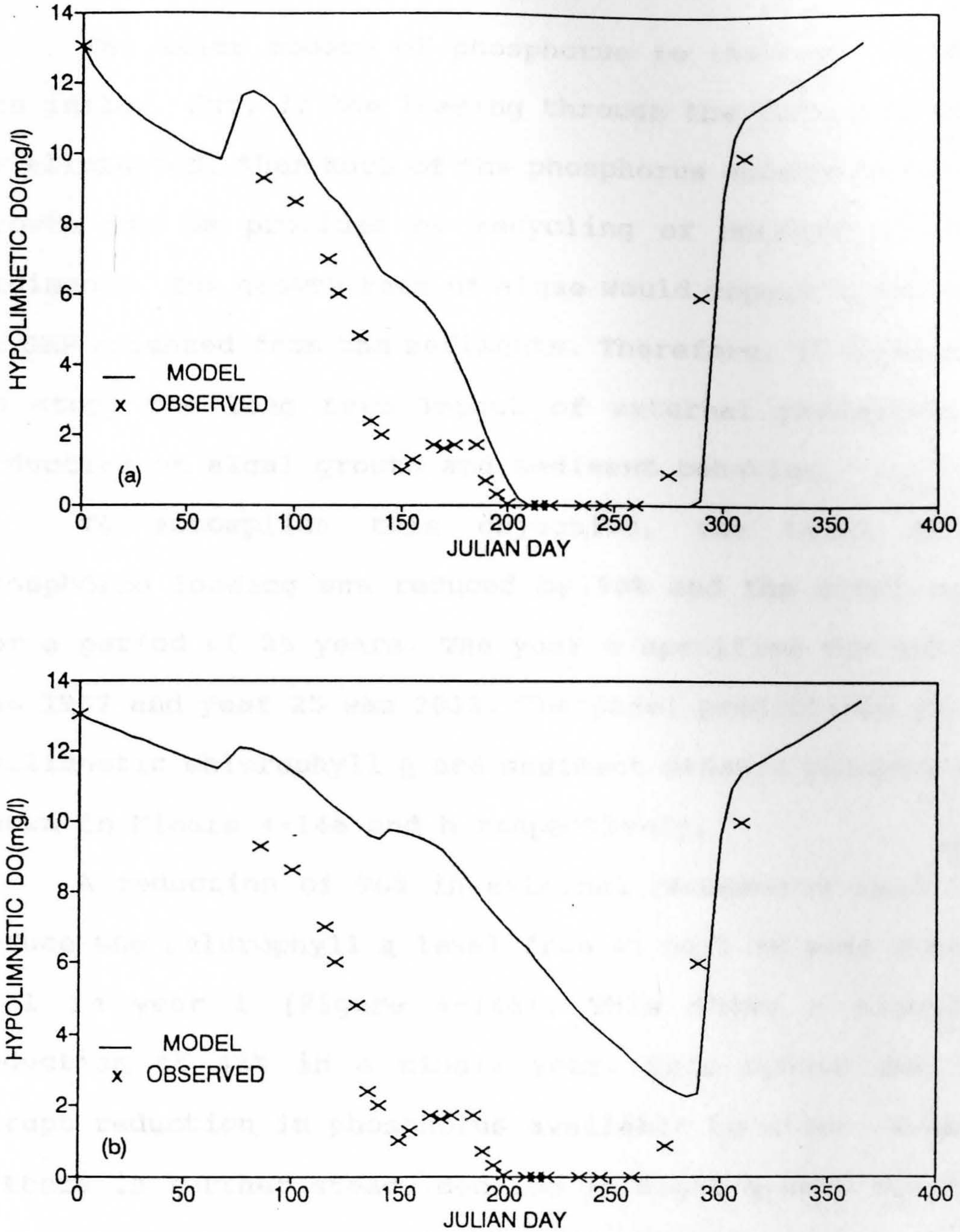


Figure 4-13. Calibrated Model Predictions, of: (a) Hypolimnetic Minimum Dissolved Oxygen with 90% Reduction in Phosphorus loads; and (b) Hypolimnetic Minimum Dissolved Oxygen with 56% Reduction in Sediment Oxygen Demand.

4.3 Long-Term Impact of Phosphorus Loading Reduction

The major source of phosphorus to the lake is through the inflow. But, if the loading through the inflow is reduced or eliminated, then much of the phosphorus necessary for algal growth may be provided by recycling of nutrients from the sediments. The growth rate of algae would depend on the amount of SRP released from the sediments. Therefore, it is necessary to study the long term impact of external phosphorus load reduction on algal growth and sediment behavior.

To accomplish this objective, the total external phosphorus loading was reduced by 90% and the model was run for a period of 25 years. The year 0 specified for the model was 1987 and year 25 was 2012. The model predictions for peak epilimnetic chlorophyll a and sediment organic phosphorus are shown in Figure 4-14a and b respectively.

A reduction of 90% in external phosphorus loads would reduce the chlorophyll a level from 43 ug/l in year 0 to 22.5 ug/l in year 1 (Figure 4-14a). This shows a significant reduction of 48% in a single year. This occurs due to an abrupt reduction in phosphorus available to algae. From year 1 there is further steady decline in algal growth reaching a constant level of 21 ug/l in year 10. The phosphorous required to support the algae is available mostly from the sediments, and a small fraction from the reduced phosphorus loading. The chlorophyll a concentration then stays at a constant level of 21 ug/l up to year 25. This indicates an equilibrium between

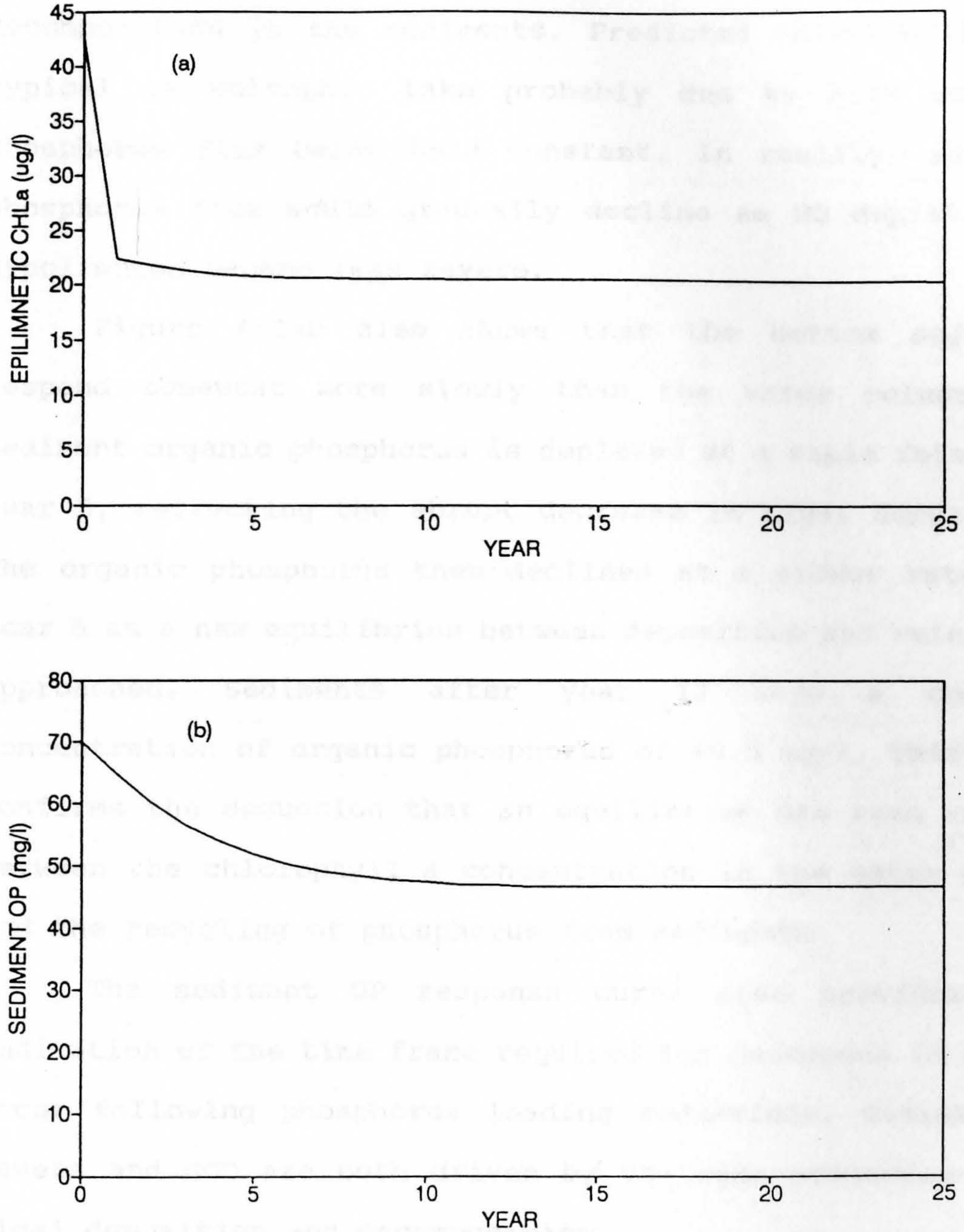


Figure 4-14. 25 Year Model Predictions with 90% Reduction in Phosphorus loads, of: (a) Epilimnetic Chlorophyll a; and (b) Sediment Organic Phosphorus.

the algal deposition and release of nutrients due to its decomposition in the sediments. Predicted chlorophyll a is typical of eutrophic lake probably due to high sediment phosphorus flux being held constant. In reality, sediment phosphorus flux would gradually decline as DO depletion in hypolimnion became less severe.

Figure 4-14b also shows that the bottom sediments respond somewhat more slowly than the water column. The sediment organic phosphorus is depleted at a rapid rate up to year 5, reflecting the abrupt decrease in algal deposition. The organic phosphorus then declines at a slower rate from year 5 as a new equilibrium between deposition and release is approached. Sediments after year 13 show a constant concentration of organic phosphorus of 46.5 mg/l. This again confirms the deduction that an equilibrium has been reached between the chlorophyll a concentration in the water column and the recycling of phosphorus from sediments.

The sediment OP response curve also provides some indication of the time frame required for decreases in SOD to occur following phosphorus loading reductions. Sediment OP levels and SOD are both driven by the same processes- i.e. algal deposition and decomposition.

4.4 Sensitivity Analysis

A sensitivity analysis was performed to determine the relative influence of variability in several important input parameters on model predictions of dissolved oxygen and chlorophyll a. The parameters varied were phytoplankton settling rate, total phosphorus loading, sediment oxygen demand, and decomposition rate of organic matter in sediments. The variability of these parameters was within the range of published literature values. The results of the sensitivity analysis are summarized in Table 4-2.

4.4.1 Phytoplankton Settling Rate

As indicated in Table 4-2, phytoplankton is most sensitive to its settling rate. An increase of 50% in settling rate reduced the peak phytoplankton population in epilimnion by 38%, while a 50% reduction in settling rate increased the peak epilimnetic phytoplankton by 38%. The values of settling rates used are well within the literature range of 0-4.0 m/day. The variability in settling rates did not affect the minimum dissolved oxygen in the hypolimnion.

4.4.2 External Phosphorus Loading

Phosphorus loading directly affects the phytoplankton kinetics as shown by Figure 4-14a. An increase of 50% in

Table 4-2. Sensitivity of Model Predictions to Selected Parameters.

Parameter	Value	Minimum Hypolimnetic D.O.(mg/l)	Epilimnetic peak Chlorophyll a (ug/l)
Settling rate (m/day)	0.15	0	68.65
	0.3[a]	0	49.6
	0.45	0	30.76
Phosphorus load	0.5A	0	39.2
	1.0A	0	49.6
	1.5A	0	54.8
Sediment Oxygen Demand (g/m2/day)	1.33	0.93	49.6
	2.66[b]	0	49.6
	4.00	0	49.6
Decomposition Rates in Sediments[c] (1/day)	0.5C	0	47.1
	1.0C	0	49.6
	1.5C	0	50.8

[a] Calibration value
[b] Calibration value
A=Actual external phosphorus loading
C=Calibration value
[c] Phytoplankton decay, OP decomposition, and ON decomposition rates were all varied by the same factor.

loading resulted in an increase of 10.5% in peak epilimnetic chlorophyll a, and a 50% reduction in loading reduced the peak by 21%. The minimum dissolved oxygen in the hypolimnion was not affected by varying the phosphorus loading.

4.4.3 Sediment Oxygen Demand

Dissolved oxygen was observed to be most sensitive to the variability of sediment oxygen demand. The high values of sediment oxygen demand used are not uncommon for lakes like Hamilton, which have high organic matter loading to the sediments. A reduction in sediment oxygen demand by 50% showed an increase in minimum hypolimnetic oxygen to 0.93 mg/l. The variability of sediment oxygen demand had no effect on peak chlorophyll a concentrations in the epilimnion.

4.4.4 Decomposition of Organic Matter in Sediments

The model predictions show no change in minimum hypolimnetic DO due to the variability of decomposition rates. Also, the decomposition rate variations had only a small impact on phytoplankton predictions. An increase of 50% in decomposition rate resulted in an increase of 2% in epilimnetic chlorophyll a, and a reduction in decomposition rate by 50% reduced the epilimnetic chlorophyll a by 5.0%. This supports the deduction from section 4.3 that the phytoplankton kinetics are most sensitive to external phosphorus loading.

4.5 Applicability of WASP4 Eutrophication Model

The WASP4 eutrophication model EUTRO4E was found to be quite credible in modeling eutrophication in Lake Hamilton. A detailed discussion of model calibration results is provided in section 4.1. Here a brief overview of the model's predictions and its shortcomings are discussed.

Temporal dissolved oxygen distribution in epilimnion and hypolimnion agreed well with the measured data. Although the timing of the decline in hypolimnetic DO was slightly off, the length of the anoxic period was very accurately simulated by the model. A constant sediment oxygen demand has to be specified by the user to the model to simulate the depletion of hypolimnetic DO. A more dynamic model would exert a sediment oxygen demand depending on the decomposition rate and amount of organic matter present in the sediments.

The phytoplankton kinetics were well simulated and were in close agreement with the measured values. The model only provides for inputing constant values of growth and death rates for phytoplankton in the whole lake. Although EUTRO4E accounts for variations due to temperature and light conditions, changes due to the seasonal successions of phytoplankton species are not accounted for. Therefore, spatial and temporal variability in these rates would generate more accurate profiles.

Even though the orthophosphate phosphorus predictions were comparable to the actual data, some weaknesses in the model were noticed. The fact that ferrous (Fe^{+2}) iron is released from sediments during hypolimnetic anoxia and is precipitated as ferric oxides and phosphates in the presence of oxygen is not accounted for in the model. These two processes are major sources and sinks of phosphorus in the hypolimnion. However, the timing and magnitude of phosphate flux from sediments in the presence of anoxia are left with the user. It is desirable that the model should start and shut of the flux from the sediments depending on the oxic state of overlying water column. A mechanistic approach to this problem would probably require adding iron as a state variable. An empirical approach would be, at best, only a slight improvement over the present model.

Much needs to be done about the ammonification, nitrification, and denitrification processes in the model as shown by the predicted results. Similar to phosphorus, the ammonia flux from bottom sediments should be generated by the model instead of by the user's depending on the oxygen content of the water column. The model does not seem to simulate well the ammonification and nitrification processes in the epilimnion as indicated by the figures 4-8a & 4-10a.

All these considerations indicate the necessity far more dynamic sediment behavior in the WASP4 eutrophication model to more precisely simulate actual eutrophication in highly productive lakes.

CONCLUSION AND SCOPE OF FURTHER WORK

The calibrated model simulated quite well the eutrophication kinetics in Lake Hamilton for 1987. The model results agreed well for dissolved oxygen, orthophosphate phosphorus, organic phosphorus, and chlorophyll a in all the segments. Also, the calibrated results were comparable for ammonia and nitrates.

The calibration of the model was done based on 1987 data from Lake Hamilton. This calibrated model should be verified for the same lake under different external conditions. The verification part of model application was beyond the scope of this thesis. But, the credibility of the calibration rests with the verification. So, the model should be verified with data from another year if possible.

The calibrated model indicated that the hypolimnetic DO was most sensitive to the sediment oxygen demand. Reducing the sediment oxygen demand by 56% makes the hypolimnion aerobic during the summer stratification period. Running the calibrated model for 25 years with 90% reduction in phosphorus loading, the peak chlorophyll a level in epilimnion dropped from 43 ug/l to 21 ug/l over a period of 10 years. The actual reduction would probably be greater as sediment phosphorus flux would also decline with time. Also, the organic phosphorus in sediments gradually decreased over a period of 13 years. This confirmed the dependency of phytoplankton on external phosphorus loading and recycling of SRP from sediments.

Sensitivity analysis predicted chlorophyll a to be very sensitive to the phytoplankton settling rate and phosphorus loading. Hypolimnetic DO was predicted to be significantly affected by sediment oxygen demand.

Several improvements can be made in calibration of the model itself. Water column sampling under the ice during winter could provide important data for more precise calibration. Sediment data, particularly for orthophosphate phosphorus, organic phosphorus, organic nitrogen, iron species and sediment oxygen demand could prove to be of much value. Data on herbivorous zooplankton can also be incorporated in the model for calibration.

There are several important modifications that could be made in the EUTRO4E program code. Some of these are summarized below:

1) The algal growth and death rates could be made variable in space and time.
2) Modeling of sediments could be made more dynamic with the model controlling the phosphate and ammonia fluxes depending on the oxic state of overlying water column.
3) The boundary between the epilimnion and hypolimnion could be determined by the model based on the temperature profiles specified for these segments. This will account for the movement of thermocline in the water column depending on temperature profiles.

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APPENDIX A

Table A-1. Volumes and Depths of Layers in Lake Hamilton for Computing Volume-Weighted Average Concentrations.

Layer depth (m)	Volume(m^3)	Layer Depth (m)	Volume(m^3)
0.5	196190	9.0	56988
1.0	191440	9.5	52863
1.5	186680	10.0	47688
2.0	181930	10.5	42338
2.5	177160	11.0	36813
3.0	172390	11.5	31275
3.5	165210	12.0	25725
4.0	155640	12.5	21450
4.5	145950	13.0	18450
5.0	136150	13.5	15750
5.5	126340	14.0	13350
6.0	116150	14.5	10950
6.5	104350	15.0	8550
7.0	89850	15.5	6287.5
7.5	77350	16.0	4162.5
8.0	66850	16.5	2325
8.5	60063	16.75	387.5

APPENDIX B

Table B-1. BASIC Computer Program to calculate vertical diffusivity coefficients based on a method by Jassby and Powell (1974).

```
SCREEN 0
2 KEY OFF
5 COLOR 6,15
6 CLS
10 LPRINT TAB(13);"THIS PROGRAM IS TO CALCULATE VERTICAL DIFFUSIVITY COEFFICIENT"
15 LPRINT TAB(13);"-------------------------------------------------------------
20 LPRINT TAB(13);"BASED ON THE METHOD OF JASSBY & POWELL FOR LAKE HAMILTON"
25 LPRINT TAB(13);"-------------------------------------------------------"
30 DIM Z1(40),Z2(40)
40 DIM T1(40),T2(40)
45 DIM TA1(40),TA2(40)
50 DIM V(40),SA(40),Z(40)
70 REM DATA FOR LAKE HAMILTON,OHIO
80 DATA 196190,387600,0.5,191440,378100,1.0
81 DATA 186680,368600,1.5,181930,359100,2.0
82 DATA 177161,349600,2.5,172390,340000,3.0
83 DATA 165210,320800,3.5,155640,301700,4.0
84 DATA 145950,282100,4.5,136150,262500,5.0
85 DATA 126340,242800,5.5,116150,223200,6.0
86 DATA 104350,194200,6.5,89850,165200,7.0
87 DATA 77350,144200,7.5,66850,123200,8.0
88 DATA 60063,117000,8.5,56988,110900,9.0
89 DATA 52863,100600,9.5,47688,90200,10.0
90 DATA 42338,79100,10.5,36813,68100,11.0
91 DATA 31275,57000,11.5,25725,45900,12.0
92 DATA 21450,39900,12.5,18450,33900,13.0
93 DATA 15750,29100,13.5,13350,24300,14.0
94 DATA 10950,19500,14.5,8550,14700,15.0
95 DATA 6287.5,10400,15.5,4162.5,6200,16.0
96 DATA 2325,2060,16.5,387.5,0,16.75
97  FOR I=1 TO 34
100 READ V(I),SA(I),Z(I)
110 NEXT I
115 PLAY "MB A B C D E F G E F G G F E D C B A B C D E F G"
120 INPUT "NUMBER OF INPUT DATA FOR DEPTH & TEMPERATURE=";N
130 INPUT "DATE FOR DAY 1 :";D1$
140 INPUT "DATE FOR DAY 2 :";D2$
150 INPUT "INTERVAL BETWEEN THE TWO DATES(DAYS)=";DAYS
160 INPUT "D=DAY FOR WHICH DATA IS TO BE ENTERED:TYPE 1,2,OR 0:D=";D
170 IF D=2 GOTO 230
180 IF D=0 GOTO 270
190 FOR I=1 TO N
200 INPUT "ENTER DEPTH(M) & TEMPERATURE(C) DATA FOR DAY 1:Z1,T1:";Z1(I),T1(I)
210 NEXT I
220 GOTO 160
230 FOR I=1 TO N
240 INPUT "ENTER DEPTH(M) & TEMPERATURE(C) DATA FOR DAY 2:Z2,T2:";Z2(I),T2(I)
250 NEXT I
260 GOTO 160
270 LPRINT
280 INPUT "DEPTH OF BOUNDARY/CENTER OF THERMOCLINE(M)=";C
290 INPUT "THERMOCLINE THICKNESS(M)=";TT
300 LET P=(2*C)-1
310 LET Q=(2*C)+1
320 REM CALCULATION OF TEMPERATURE GRADIENT IN THERMOCLINE ON DAY 1 (TGT1)
330 TGT1=ABS((T1(P)-T1(Q))/(TT))
```

Table B-1 Continued:

```
340 REM CALCULATION OF TEMPERATURE GRADIENT IN THERMOCLINE ON DAY 2 (TGT2)
350 TGT2=ABS((T2(P)-T2(Q))/(TT))
360 REM AVERAGE TEMPERATURE GRADIENT IN THERMOCLINE FOR THE GIVEN TWO DAYS
370 TGT=(TGT1+TGT2)/2
380 REM CALCULATION OF VOLUME OF HYPOLIMNION(Vh)
390 VH=0
400 FOR I=((2*C)+1) TO 34
410 VH=VH + V(I)
420 NEXT I
430 REM CALCULATION OF AVERAGE TEMPERATURE FOR HYPOLIMNION FOR DAY 1 USING       VOLUME WEIGHTED
AVERAGES
440 FOR I= 2*C TO (N-1)
450 TA1(I)=(T1(I)+T1(I+1))/2
460 NEXT I
470 VT1=0
480 FOR I= 2*C TO (N-1)
490 VT1=VT1 + (V(I+1))*(TA1(I))
500 NEXT I
510 TH1=VT1/VH
520 REM CALCULATION OF AVERAGE TEMPERATURE FOR HYPOLIMNION FOR DAY 2 USING       VOLUME WEIGHTED
AVERAGES
530 FOR I= 2*C TO (N-1)
540 TA2(I)=(T2(I)+T2(I+1))/2
550 NEXT I
560 VT2=0
570 FOR I=2*C TO (N-1)
580 VT2= VT2 + (V(I+1))*(TA2(I))
590 NEXT I
600 TH2=VT2/VH
610 TH= ABS((TH1-TH2)/DAYS)
620 REM CALCULATION OF VERTICAL DIFFUSIVITY COEFFICIENT(Kz)
630 KZ=(TH)*(VH/(SA(2*C)))/(TGT)
640 LPRINT
650 LPRINT TAB(20);D1$;TAB(55);D2$
660 LPRINT TAB(20);"-------";TAB(55);"-------"
670 LPRINT
680   LPRINT   TAB(12);"DEPTH(M)";TAB(27);"TEMPERATURE(C)";TAB(47);"DEPTH(M)";
TAB(62);"TEMPERATURE(C)"
690 LPRINT TAB(12);"-----------------------------------------------------------------"
700 LPRINT
710 FOR I=1 TO N
720 LPRINT USING "               ##.##             ##.#              ##.##
##.#";Z1(I),T1(I),Z2(I),T2(I)
730 NEXT I
740 LPRINT
750 LPRINT
760 LPRINT TAB(11);"DEPTH OF BOUNDARY/CENTER OF THERMOCLINE=";C;" M"
770 LPRINT
780 LPRINT TAB(11);"THERMOCLINE THICKNESS=";TT;" M"
790 LPRINT
800 LPRINT USING "          TEMPERATURE GRADIENT AT THERMOCLINE ON DAY 1=##.## CELSIUS/M";TGT1
810 LPRINT
820 LPRINT USING "          TEMPERATURE GRADIENT AT THERMOCLINE ON DAY 2=##.## CELSIUS/M";TGT2
830 LPRINT
840 LPRINT USING "          AVERAGE TEMPERATURE GRADIENT AT THERMOCLINE=##.## CELSIUS/M";TGT
850 LPRINT
860 LPRINT USING "          TOTAL VOLUME OF HYPOLIMNION=#######.## cu.m ";VH
870 LPRINT
880 LPRINT USING "          AVERAGE TEMPERATURE OF HYPOLIMNION ON DAY 1=##.#  CELSIUS";TH1
890 LPRINT
900 LPRINT USING "          AVERAGE TEMPERATURE OF HYPOLIMNION ON DAY 2=##.#  CELSIUS";TH2
910 LPRINT
920 LPRINT USING "          VERTICAL DIFFUSIVITY COEFFICIENT=Kz=##.### sq.m/day ";KZ
930 END
```

APPENDIX C

Table C-1. Calibration Input Data Set For Lake Hamilton

```
 LAKE HAMILTON 5 SEGMENT MODEL 8/15/92: ADVISOR DR. SCOTT C. MARTIN
HAMS4.INP  1987 EUTROPHICATION WITH FIVE SEGMENTS
NCHM NSOL NSEG ICFL MFLG JMAS NSLN INTY ADFC   DD HHMM ** A: MODEL OPTIONS **
   8    0    5    0    0    1    0    1  0.0   01 0000    3    2    3      1.0
   1
   0.200       365.0
   2
    5.00         5.0        5.00      400.0
   0    0    0    0    0    0    0    0  System By-Passes (0=model, 1=Bypass)
   3                 ***** B:EXCHANGE COEFFICIENTS*****
   2     1.000      1.000
   1                          LATERAL DISPERSION COEFFICIENTS [SQ.M/SEC.]
 3.601E02 703.38          1    2
   2
  20.00        0.0       20.00     365.0
   1                          VERTICAL DISPERSION COEFFICIENTS [SQ.M/SEC.]
 1.488E05  5.735          2    3
  31
 0.1E-04       0.0    0.10E-04    1.0   0.10E-04       59.0     0.1E-04   65.0
 1.0E-04      75.0    6.71E-06   93.0   3.82E-06      106.0     1.15E-05 117.0
 4.63E-06    124.0    3.37E-06  132.0   3.70E-07      138.0     9.84E-07 145.0
 7.99E-07    152.0    1.23E-06  159.0   1.64E-06      165.0     2.77E-07 171.0
 1.47E-06    179.0    3.70E-07  184.0   5.32E-07      191.0     7.87E-07 198.0
 9.84E-07    205.0    8.33E-07  212.0   4.51E-07      219.0     1.16E-07 228.0
 1.32E-06    239.0    8.45E-07  252.0   8.45E-07      266.0     1.61E-06 289.0
 7.25E-05    300.0    1.00E-04  310.0   1.00E-04      365.0
   2     1.000      1.000          PORE WATER DISPERSION COEFFICIENTS
   1
 2.248E05    2.145        1    4
   2
 5.00E-9       0.0    5.00E-9   365.0
   1
 1.488E05    3.065        3    5
   2
5.000E-9       0.0    5.00E-9   365.0
   0     1.000      1.000    SEDIMENT DISPERSION COEFFICIENTS
   0    0    0    0    0    0    0    0  System bypass  (1=Bypass,0=Model)
   1    0      0.200    +    *    +    *    +    *    +       ** C: VOLUMES **
    1.00        1.00               Volume(cu m)     a          b           c       d
       1           4             1 1.038E+06      0.00       0.00        4.27    0.00
       2           3             1 7.964E+05      0.00       0.00        5.35    0.00
       3           5             2 9.099E+05      0.00       0.00        6.11    0.00
       4           0             3 9.132E+03      0.00       0.00        0.04    0.00
       5           0             3 5.952E+03      0.00       0.00        0.04    0.00
   1    5                   (Calculated from daily flow meas.) ** D: FLOWS **
   1       1.0        1.0
   3                                          Yellow Creek 1987 Piece-wise Flows
     1.0     0    1         1.0     1    2          1.0    2    0
  71
 2.54E-01      0.0    2.20E-01    1.0       7.46E-01    2.0         2.20E-01    5.0
 1.36E+00      9.0    1.37E+00   32.0       5.48E+00   47.0         1.37E+00   51.0
 5.48E+00     54.0    2.11E+00   58.0       2.10E+00   60.0         1.36E+00   61.0
 2.20E-01     65.0    7.46E-01   68.0       2.20E-01   72.0         2.20E-01   91.0
 1.36E+00     93.0    6.97E+00   96.0       2.10E+00  100.0         1.36E+00  103.0
 7.46E-01    106.0    2.20E-01  111.0       2.10E+00  114.0         1.36E+00  117.0
 7.47E-01    121.0    1.36E+00  124.0       7.47E-01  128.0         2.21E-01  131.0
 2.10E+00    135.0    7.47E-01  138.0       2.21E-01  148.0         7.49E-01  152.0
 2.23E-01    156.0    4.80E-02  159.0       2.23E-01  163.0         4.80E-02  166.0
 2.23E-01    173.0    4.80E-02  177.0       4.47E-02  182.0         7.46E-01  187.0
 2.20E-01    191.0    4.47E-02  198.0       4.41E-02  213.0         7.45E-01  215.0
```

Table C-1 Continued:

```
4.41E-02   219.0    2.20E-01  223.0     4.41E-02 226.0       2.20E-01 236.0
7.45E-01   240.0    7.48E-01  244.0     1.36E+00 251.0       7.48E-01 254.0
2.22E-01   257.0    7.48E-01  261.0     2.22E-01 264.0       4.69E-02 268.0
4.50E-02   274.0    2.20E-01  275.0     7.46E-01 282.0       2.20E-01 285.0
4.50E-02   289.0    5.07E-02  305.0     1.36E+00 334.0       1.36E+00 337.0
7.47E-01   338.0    2.22E-01  341.0     7.47E-01 345.0       2.22E-01 352.0
7.47E-01   355.0    2.22E-01  361.0     2.22E-01 365.0
  0       1.0       1.0       Pore Water Field
  1       1.0 1.1574E-5    Solids Trans- Field 3(BOD,ON,OP) [m/d to m/s]
  2         Sedimentation (Deep Burial)
2.248E05     4   0  1.488E05    5    0
  2
 6.00E-6     0.0     6.00E-6   365.0
  3       1.0 1.1574E-5        Solids Trans-Field 4(Phyto) [m/d to m/s]
  2
2.248E05     1   4  1.488E05    2    3
 20
   0.10      0.0      0.10       1.0      0.10      120.0     0.10     125.0
   1.0     140.0      1.50     150.0      1.00      160.0     0.30     175.0
   0.30    185.0      0.30     200.0      0.30      210.0     0.40     220.0
   1.00    230.0      1.00     240.0      1.00      275.0     0.80     290.0
   0.80    310.0      0.40     325.0      0.10      345.0     0.10     365.0
  1
1.488E05     3   5
 20
   0.10      0.0      0.10       1.0      0.1        85.0     0.30     100.0
   0.30    115.0      2.00     140.0      2.0       150.0     2.0      180.0
   2.00    200.0      2.0      220.0      2.0       240.0     2.00     260.0
   2.00    280.0      1.5      295.0      1.00      310.0     0.7      325.0
   0.7     340.0      0.6      350.0      0.6       360.0     0.4      365.0
   2
2.248E05     4   0  1.488E05    5    0
  2
 6.00E-06    0.0    6.00E-06   365.0
  1       1.0 1.1574E-5        Solids Trans- Field 5(NH3,NO3,PO4,DO)
  2     SEDIMENTATION (DEEP BURIAL)
2.248E05     4   0  1.488E05    5    0
  2
 6.00E-06     0.0     6.00E-06   365.0
  0   0     0   0     1   0     1   0  System By-Passes (1=Bypass,0=Model)
     5                             *** System 1  - NH3 mg N/L  ** E: BCs **
    1.0       1.0
  1   28
  0.0218       0.0   0.0218        1.0    0.0208       32.0    0.0154     86.0
  0.0157      99.0   0.01147     113.0    0.0026      128.0    0.0851    135.0
  0.1022     148.0   0.0551      163.0    0.1023      168.0    0.1048    174.0
  0.1602     181.0   0.1144      183.0    0.0         188.0    0.0685    195.0
  0.017      202.0   0.0         208.0    0.0313      216.0    0.0       222.0
  0.022      233.0   0.6207      244.0    0.0201      259.0    0.0174    273.0
  0.0252     289.0   0.0254      310.0    0.0256      335.0    0.0246    365.0
  2   28
  0.0          0.0   0.0           1.0    0.0          32.0    0.0        86.0
  0.0         99.0   0.0         113.0    0.0         128.0    0.0       135.0
  0.0        148.0   0.0         163.0    0.0         168.0    0.0       174.0
  0.0        181.0   0.0         183.0    0.0         188.0    0.0       195.0
  0.0        202.0   0.0         208.0    0.0         216.0    0.0       222.0
  0.0        233.0   0.0         244.0    0.0         259.0    0.0       273.0
  0.0        289.0   0.0         310.0    0.0         335.0    0.0       365.0
  3   28
  0.0          0.0   0.0           1.0    0.0          32.0    0.0        86.0
  0.0         99.0   0.0         113.0    0.0         128.0    0.0       135.0
  0.0        148.0   0.0         163.0    0.0          168.0    0.0       174.0
  0.0        181.0   0.0         183.0    0.0         188.0    0.0       195.0
  0.0        202.0   0.0         208.9    0.0         216.0    0.0       222.0
  0.0        233.0   0.0         244.0    0.0         259.0    0.0       273.0
```

Table C-1 Continued:

```
0.0       289.0    0.0      310.0    0.0      335.0    0.0      365.0
4   28
0.0         0.0    0.0        1.0    0.0       32.0    0.0       86.0
0.0        99.0    0.0      113.0    0.0      128.0    0.0      135.0
0.0       148.0    0.0      163.0    0.0      168.0    0.0      174.0
0.0       181.0    0.0      183.0    0.0      188.0    0.0      195.0
0.0       202.0    0.0      208.0    0.0      216.0    0.0      222.0
0.0       233.0    0.0      244.0    0.0      259.0    0.0      273.0
0.0       289.0    0.0      310.0    0.0      335.0    0.0      365.0
5   28
0.0         0.0    0.0        1.0    0.0       32.0    0.0       86.0
0.0        99.0    0.0      113.0    0.0      128.0    0.0      135.0
0.0       148.0    0.0      163.0    0.0      168.0    0.0      174.0
0.0       181.0    0.0      183.0    0.0      188.0    0.0      195.0
0.0       202.0    0.0      208.0    0.0      216.0    0.0      222.0
0.0       233.0    0.0      244.0    0.0      259.0    0.0      273.0
0.0       289.0    0.0      310.0    0.0      335.0    0.0      365.0
  5                         *** System 2  - NO2+NO3 mg N/L
   1.0      1.0
1   28
0.350       0.0    0.409      1.0    0.6337    32.0    0.7605    86.0
0.418      99.0    0.244    113.0    0.0573   128.0    0.6478   135.0
0.560     148.0    0.6258   163.0    0.455    168.0    0.0481   174.0
1.0778    181.0    0.9727   183.0    0.710    188.0    0.567    195.0
0.2435    202.0    0.4615   208.0    0.0546   216.0    0.630    222.0
0.118     233.0    0.4157   244.0    0.5746   259.0    0.333    273.0
0.320     289.0    0.309    310.0    0.310    335.0    0.310    365.0
2   28
0.0         0.0    0.0        1.0    0.0       32.0    0.0       86.0
0.0        99.0    0.0      113.0    0.0      128.0    0.0      135.0
0.0       148.0    0.0      163.0    0.0      168.0    0.0      174.0
0.0       181.0    0.0      183.0    0.0      188.0    0.0      195.0
0.0       202.0    0.0      208.0    0.0      216.0    0.0      222.0
0.0       233.0    0.0      244.0    0.0      259.0    0.0      273.0
0.0       289.0    0.0      310.0    0.0      335.0    0.0      365.0
3   28
0.0         0.0    0.0        1.0    0.0       32.0    0.0       86.0
0.0        99.0    0.0      113.0    0.0      128.0    0.0      135.0
0.0       148.0    0.0      163.0    0.0      168.0    0.0      174.0
0.0       181.0    0.0      183.0    0.0      188.0    0.0      195.0
0.0       202.0    0.0      208.0    0.0      216.0    0.0      222.0
0.0       233.0    0.0      244.0    0.0      259.0    0.0      273.0
0.0       289.0    0.0      310.0    0.0      335.0    0.0      365.0
4   28
0.0         0.0    0.0        1.0    0.0       32.0    0.0       86.0
0.0        99.0    0.0      113.0    0.0      128.0    0.0      135.0
0.0       148.0    0.0      163.0    0.0      168.0    0.0      174.0
0.0       181.0    0.0      183.0    0.0      188.0    0.0      195.0
0.0       202.0    0.0      208.0    0.0      216.0    0.0      222.0
0.0       233.0    0.0      244.0    0.0      259.0    0.0      273.0
0.0       289.0    0.0      310.0    0.0      335.0    0.0      365.0
5   28
0.0         0.0    0.0        1.0    0.0       32.0    0.0       86.0
0.0        99.0    0.0      113.0    0.0      128.0    0.0      135.0
0.0       148.0    0.0      163.0    0.0      168.0    0.0      174.0
0.0       181.0    0.0      183.0    0.0      188.0    0.0      195.0
0.0       202.0    0.0      208.0    0.0      216.0    0.0      222.0
0.0       233.0    0.0      244.0    0.0      259.0    0.0      273.0
0.0       289.0    0.0      310.0    0.0      335.0    0.0      365.0
  5                     *** System 3  - PO4 mg P/L
   1.0      1.0
1   28
0.0085      0.0    0.0085     1.0    0.0085    32.0    0.0028    86.0
  0.0019      99.0    0.0019    113.0    0.0024    128.0    0.0114   135.0
0.0516    148.0    0.0368   163.0    0.0587   168.0    0.1057   174.0
0.0600    181.0    0.0648   183.0    0.0177   188.0    0.0627   195.0
```

Table C-1 Continued:

```
 0.0155     202.0    0.0142    208.0    0.0212     216.0    0.0242   222.0
0.0315      233.0    0.0317    244.0    0.0197     259.0    0.0605   273.0
0.0266      289.0    0.0417    310.0    0.0219     335.0    0.0109   365.0
2   28
0.0           0.0    0.0         1.0    0.0         32.0    0.0       86.0
0.0          99.0    0.0       113.0    0.0        128.0    0.0      135.0
0.0         148.0    0.0       163.0    0.0        168.0    0.0      174.0
0.0         181.0    0.0       183.0    0.0        188.0    0.0      195.0
0.0         202.0    0.0       208.0    0.0        216.0    0.0      222.0
0.0         233.0    0.0       244.0    0.0        259.0    0.0      273.0
0.0         289.0    0.0       310.0    0.0        335.0    0.0      365.0
3   28
0.0           0.0    0.0         1.0    0.0         32.0    0.0       86.0
0.0          99.0    0.0       113.0    0.0        128.0    0.0      135.0
0.0         148.0    0.0       163.0    0.0        168.0    0.0      174.0
0.0         181.0    0.0       183.0    0.0        188.0    0.0      195.0
0.0         202.0    0.0       208.0    0.0        216.0    0.0      222.0
0.0         233.0    0.0       244.0    0.0        259.0    0.0      273.0
0.0         289.0    0.0       310.0    0.0        335.0    0.0      365.0
4   28
0.0           0.0    0.0         1.0    0.0         32.0    0.0       86.0
0.0          99.0    0.0       113.0    0.0        128.0    0.0      135.0
0.0         148.0    0.0       163.0    0.0        168.0    0.0      174.0
0.0         181.0    0.0       183.0    0.0        188.0    0.0      195.0
0.0         202.0    0.0       208.0    0.0        216.0    0.0      222.0
0.0         233.0    0.0       244.0    0.0        259.0    0.0      273.0
0.0         289.0    0.0       310.0    0.0        335.0    0.0      365.0
5   28
0.0           0.0    0.0         1.0    0.0         32.0    0.0       86.0
0.0          99.0    0.0       113.0    0.0        128.0    0.0      135.0
0.0         148.0    0.0       163.0    0.0        168.0    0.0      174.0
0.0         181.0    0.0       183.0    0.0        188.0    0.0      195.0
0.0         202.0    0.0       208.0    0.0        216.0    0.0      222.0
0.0         233.0    0.0       244.0    0.0        259.0    0.0      273.0
0.0         289.0    0.0       310.0    0.0        335.0    0.0      365.0
    5                          **** System 4  - Chl a  ug/L
  1.0         1.0
1   28
5.0           0.0    5.0         1.0    5.0         32.0    5.0       86.0
5.0          99.0    5.0       113.0    5.0        128.0    5.0      135.0
5.0         148.0    5.0       163.0    5.0        168.0    5.0      174.0
5.0         181.0    5.0       183.0    5.0        188.0    5.0      195.0
5.0         202.0    5.0       208.0    5.0        216.0    5.0      222.0
5.0         233.0    5.0       244.0    5.0        259.0    5.0      273.0
5.0         289.0    5.5       310.0    5.0        335.0    5.0      365.0
  2       28
  0.0           0.0    0.0         1.0    0.0         32.0    0.0       86.0
0.0          99.0    0.0       113.0    0.0        128.0    0.0      135.0
0.0         148.0    0.0       163.0    0.0        168.0    0.0      174.0
0.0         181.0    0.0       183.0    0.0        188.0    0.0      195.0
0.0         202.0    0.0       208.0    0.0        216.0    0.0      222.0
0.0         233.0    0.0       244.0    0.0        259.0    0.0      273.0
0.0         289.0    0.0       310.0    0.0        335.0    0.0      365.0
3   28
0.0           0.0    0.0         1.0    0.0         32.0    0.0       86.0
0.0          99.0    0.0       113.0    0.0        128.0    0.0      135.0
0.0         148.0    0.0       163.0    0.0        168.0    0.0      174.0
0.0         181.0    0.0       183.0    0.0        188.0    0.0      195.0
0.0         202.0    0.0       208.0    0.0        216.0    0.0      222.0
0.0         233.0    0.0       244.0    0.0        259.0    0.0      273.0
0.0         289.0    0.0       310.0    0.0        335.0    0.0      365.0
```

Table C-1 Continued:

```
4   28
0.0           0.0    0.0          1.0    0.0           32.0    0.0       86.0
0.0          99.0    0.0        113.0    0.0          128.0    0.0      135.0
0.0         148.0    0.0        163.0    0.0          168.0    0.0      174.0
0.0         181.0    0.0        183.0    0.0          188.0    0.0      195.0
0.0         202.0    0.0        208.0    0.0          216.0    0.0      222.0
0.0         233.0    0.0        244.0    0.0          259.0    0.0      273.0
0.0         289.0    0.0        310.0    0.0          335.0    0.0      365.0
5   28
0.0           0.0    0.0          1.0    0.0           32.0    0.0       86.0
0.0          99.0    0.0        113.0    0.0          128.0    0.0      135.0
0.0         148.0    0.0        163.0    0.0          168.0    0.0      174.0
0.0         181.0    0.0        183.0    0.0          188.0    0.0      195.0
0.0         202.0    0.0        208.0    0.0          216.0    0.0      222.0
0.0         233.0    0.0        244.0    0.0          259.0    0.0      273.0
0.0         289.0    0.0        310.0    0.0          335.0    0.0      365.0
    0                ******NO BOUNDARY CONDITIONS FOR SYSTEM 5*****
    5                           *** System 6  - DO mg/L
  1.0         1.0
1   28
12.37         0.0    12.37        1.0    12.37         32.0    10.92     86.0
10.92        99.0    10.20      113.0     9.76        128.0     9.76    135.0
8.18        148.0     8.18      163.0     8.18        168.0     8.84    174.0
8.84        181.0     8.53      183.0     8.00        188.0     8.00    195.0
8.00        202.0     8.00      208.0     8.00        216.0     8.00    222.0
8.00        233.0     8.00      244.0     8.53        259.0     9.18    273.0
9.56        289.0    10.43      310.0    11.47        335.0    12.37    365.0
2   28
0.0           0.0     0.0         1.0     0.0          32.0     0.0      86.0
0.0          99.0     0.0       113.0     0.0         128.0     0.0     135.0
0.0         148.0     0.0       163.0     0.0         168.0     0.0     174.0
0.0         181.0     0.0       183.0     0.0         188.0     0.0     195.0
0.0         202.0     0.0       208.0     0.0         216.0     0.0     222.0
0.0         233.0     0.0       244.0     0.0         259.0     0.0     273.0
0.0         289.0     0.0       310.0     0.0         335.0     0.0     365.0
3   28
0.0           0.0     0.0         1.0     0.0          32.0     0.0      86.0
0.0          99.0     0.0       113.0     0.0         128.0     0.0     135.0
0.0         148.0     0.0       163.0     0.0         168.0     0.0     174.0
0.0         181.0     0.0       183.0     0.0         188.0     0.0     195.0
0.0         202.0     0.0       208.0     0.0         216.0     0.0     222.0
0.0         233.0     0.0       244.0     0.0         259.0     0.0     273.0
0.0         289.0     0.0       310.0     0.0         335.0     0.0     365.0
4   28
0.0           0.0     0.0         1.0     0.0          32.0     0.0      86.0
0.0          99.0     0.0       113.0     0.0         128.0     0.0     135.0
0.0         148.0     0.0       163.0     0.0         168.0     0.0     174.0
0.0         181.0     0.0       183.0     0.0         188.0     0.0     195.0
0.0         202.0     0.0       208.0     0.0         216.0     0.0     222.0
0.0         233.0     0.0       244.0     0.0         259.0     0.0     273.0
0.0         289.0     0.0       310.0     0.0         335.0     0.0     365.0
5   28
0.0           0.0     0.0         1.0     0.0          32.0     0.0      86.0
0.0          99.0     0.0       113.0     0.0         128.0     0.0     135.0
0.0         148.0     0.0       163.0     0.0         168.0     0.0     174.0
0.0         181.0     0.0       183.0     0.0         188.0     0.0     195.0
0.0         202.0     0.0       208.0     0.0         216.0     0.0     222.0
0.0         233.0     0.0       244.0     0.0         259.0     0.0     273.0
0.0         289.0     0.0       310.0     0.0         335.0     0.0     365.0
    0                ****No BC'S for System 7  - ON mg N/L
    5                            *** System 8  - OP mg P/L
  1.0         1.0
1   28
0.0225        0.0    0.0225       1.0    0.0215        32.0    0.0211    86.0
0.0558       99.0    0.0392     113.0    0.0447       128.0    0.1156   135.0
0.1681      148.0    0.0564     163.0    0.0309       168.0    0.0207   174.0
```

Table C-1 Continued:

```
0.0361     181.0    0.0313     183.0    0.0372      188.0    0.1034  195.0
0.0207     202.0    0.0274     208.0    0.0926      216.0    0.0641  222.0
0.0281     233.0    0.0839     244.0    0.040       259.0    0.0184  273.0
0.0134     289.0    0.0258     310.0    0.019       335.0    0.024   365.0
2   28
0.0          0.0    0.0          1.0    0.0          32.0    0.0      86.0
0.0         99.0    0.0        113.0    0.0         128.0    0.0     135.0
0.0        148.0    0.0        163.0    0.0         168.0    0.0     174.0
0.0        181.0    0.0        183.0    0.0         188.0    0.0     195.0
0.0        202.0    0.0        208.0    0.0         216.0    0.0     222.0
0.0        233.0    0.0        244.0    0.0         259.0    0.0     273.0
0.0        289.0    0.0        310.0    0.0         335.0    0.0     365.0
3   28
0.0          0.0    0.0          1.0    0.0          32.0    0.0      86.0
0.0         99.0    0.0        113.0    0.0         128.0    0.0     135.0
0.0        148.0    0.0        163.0    0.0         168.0    0.0     174.0
   0.0        181.0    0.0        183.0    0.0         188.0    0.0     195.0
0.0        202.0    0.0        208.0    0.0         216.0    0.0     222.0
0.0        233.0    0.0        244.0    0.0         259.0    0.0     273.0
0.0        289.0    0.0        310.0    0.0         335.0    0.0     365.0
4   28
0.0          0.0    0.0          1.0    0.0          32.0    0.0      86.0
0.0         99.0    0.0        113.0    0.0         128.0    0.0     135.0
0.0        148.0    0.0        163.0    0.0         168.0    0.0     174.0
0.0        181.0    0.0        183.0    0.0         188.0    0.0     195.0
0.0        202.0    0.0        208.0    0.0         216.0    0.0     222.0
0.0        233.0    0.0        244.0    0.0         259.0    0.0     273.0
0.0        289.0    0.0        310.0    0.0         335.0    0.0     365.0
5   28
0.0          0.0    0.0          1.0    0.0          32.0    0.0      86.0
0.0         99.0    0.0        113.0    0.0         128.0    0.0     135.0
0.0        148.0    0.0        163.0    0.0         168.0    0.0     174.0
0.0        181.0    0.0        183.0    0.0         188.0    0.0     195.0
0.0        202.0    0.0        208.0    0.0         216.0    0.0     222.0
0.0        233.0    0.0        244.0    0.0         259.0    0.0     273.0
0.0        289.0    0.0        310.0    0.0         335.0    0.0     365.0
     2                  F: NH3 (LOADS AND SINKS FROM SEDIMENTS KG/DAY)
  1.0         1.0
 1   10
  0.0        0.0       0.0        70.0         0.0      135.0     0.0     140.0
  0.0      150.0       0.0       200.0         0.0      230.0     0.0     250.0
  0.0      310.0       0.0       365.0
 2   10
  0.0        0.0       0.0        70.0         0.0      100.0     0.0     140.0
 00.0      165.0      00.0       200.0        00.0      220.0     0.0     260.0
  0.0      310.0       0.0       365.0
     2              NO3
  1.0         1.0
 1   9
  0.0        0.0       0.0       100.0      0.0      120.0     00.0      160.0
  0.0      175.0       0.0       210.0      0.0      235.0      0.0      300.0
  0.0      365.0
 2   9
  0.0        0.0       0.0       100.0      0.0      120.0      0.0      160.0
     0.0      190.0       0.0       200.0      0.0      220.0      0.0      300.0
  0.0      365.0
     2              PO4 LOADS FROM SEDIMENTS (KG/DAY)
  1.0         1.0
 1   16
  0.00       0.0       0.00       85.0      0.00     120.0      0.00     155.0
  0.00     170.0       0.00      180.0      0.00     195.0      0.00     205.0
  0.00     215.0       0.0       230.0      0.0      250.0      0.0      265.0
  0.0      275.0       0.0       310.0      0.00     320.0      0.0      365.0
```

Table C-1 Continued:

```
    2    16
   0.0      0.0       0.0     140.0     0.0      180.0     0.0     210.0
   0.0    230.0       0.0     240.0     0.0      245.0     0.0     250.0
   0.0    255.0       0.0     260.0     0.0      270.0     0.0     280.0
   0.0    285.0       0.0     290.0     0.0      300.0     0.0     365.0
     0            CHLA
     0            CBOD
     0            DO
     0            ON
     0            OP
     0            NO NPS LOADS
    13      Number of parameters                         ** G: PARAMETERS **
VELFN    1     1.0   SAL     2       1.0TMPSG     3     1.00TMPFN    4      1.0
 KESG    5     1.0  KEFN     6       1.0 FNH4     7      1.0 FPO4    8      1.0
SOD1D    9    3.13 RLGHT    10       1.0SODTA    11     1.08ITLIM   12      1.0
ICELT   13    0.2
         1
VELFN    1     0.0   SAL     2       1.0TMPSG     3      1.0TMPFN    4      1.0
 KESG    5     1.0  KEFN     6       1.0 FNH4     7      0.0 FPO4    8      0.5
SOD1D    9    0.85 RLGHT    10       1.0SODTA    11     1.00ITLIM   12      1.0
ICELT   13    1.0
         2
VELFN    1     0.0   SAL     2       1.0TMPSG     3      1.0TMPFN    4      1.0
 KESG    5     1.0  KEFN     6       1.0 FNH4     7     0.05 FPO4    8      0.1
SOD1D    9    0.00 RLGHT    10       1.0SODTA    11     1.00ITLIM   12      1.0
ICELT   13    1.0
         3
VELFN    1     0.0   SAL     2       1.0TMPSG     3      1.0TMPFN    4      2.0
 KESG    5     1.0  KEFN     6       1.0 FNH4     7     0.75FPO4     8      0.9
SOD1D    9    0.85 RLGHT    10       1.0SODTA    11     1.00ITLIM   12      1.0
ICELT   13    1.0
         4
VELFN    1     0.0   SAL     2       1.0TMPSG     3      0.3TMPFN    4      1.0
 KESG    5     1.0  KEFN     6       1.0 FNH4     7      0.0 FPO4    8      0.0
SOD1D    9    0.00 RLGHT    10       1.0SODTA    11     1.00ITLIM   12      1.0
ICELT   13    1.0
         5
VELFN    1     0.0   SAL     2       1.0TMPSG     3      0.1TMPFN    4      2.0
 KESG    5     1.0  KEFN     6       1.0 FNH4     7      0.0 FPO4    8      0.0
SOD1D    9    0.00 RLGHT    10       1.0SODTA    11     1.00ITLIM   12      1.0
ICELT   13    1.0
Kinetics for Level 6 Eutrophication                       ** H: CONSTANTS **
Globals        1
general        1
    WTYPE      1      2.0
NH3            1
nitrificat     3
    K1320C    11      0.20    K1320T       12      1.07
      KNIT    13      2.0
NO3            1
denitrific     3
     K140C    21      0.10    K140T        22      1.045
      KNO3    23      0.10
PO4            0
PHYT           4
growth         2
       K1C    41      2.00      K1T        42      1.07
light          3
    LGHTSW    43       1.0     CCHL        46      15.0
       IS1    47     100.0
nutrients      5
     KMNG1    48     0.015    KMPG1        49     0.003
```

Table C-1 Continued:

```
      NCRB       58     0.250        PCRB         57      0.04
    NUTLIM       54       0.0
death             6
      K1RC       50     0.010        K1RT         51      1.07
       K1D       52     0.007       KPZDC         55      0.50
     KPZDT       56      1.07         K1G         53      0.0
CBOD              1
deoxygenat        5
       KDC       71     0.030         KDT         72       1.07
      KDSC       73     0.002        KDST         74       1.08
      KBOD       75       0.1
DO                1
ratio             1     note: not using K2 at the moment
      OCRB       81      2.67          K2         82       2.00
ON                2
mineralize        2
    K1013C       91      0.02      K1013T         92       1.08
bed decomp        2
     KONDC       93    0.0020       KONDT         94       1.08
OP                2
mineralize        2
      K58C      100    0.020         K58T        101       1.07
bed decomp        2
KOPDC           102    0.0040       KOPDT        103       1.08
        16                                             ** I: TIME FUNCTIONS **
TEMP1   27     1      Segment 1 & 2 & 4
       2.0       0.0      7.24      86.0      4.86      99.0       11.62      113.0
      9.74     120.0     11.64     128.0     15.16     135.0       15.21      141.0
     18.12     148.0     19.61     155.0     19.79     163.0       21.08      168.0
     22.13     174.0     20.64     183.0     21.26     188.0       22.70      195.0
     23.59     202.0     24.18     208.0     23.97     216.0       22.72      222.0
     23.12     233.0     18.89     244.0     18.17     259.0       16.71      273.0
     10.77     289.0      8.25     310.0     2.0       365.0
TEMP2   27     2      Segments 3 & 5
       3.0       0.0      3.33      86.0      3.43      99.0        4.51      113.0
      4.99     120.0      5.41     128.0      5.75     135.0        5.85      141.0
          5.97      148.0       6.34      155.0       6.89    163.0         7.47      168.0
      7.79     174.0      9.18     183.0      9.04     188.0        9.43      195.0
      9.86     202.0     10.16     208.0     10.67     216.0       10.95      222.0
     10.88     233.0     11.88     244.0     12.28     259.0       12.50      273.0
      9.82     289.0      8.15     310.0     3.0       365.0
 ITOT   14     5                                                 units of LY/day
    50.0       0.0      70.0      15.0     150.0      45.0     250.0     75.0
   393.0     105.0     458.0     135.0     487.0     165.0     477.0    195.0
   424.0     225.0     345.0     255.0     258.0     285.0     162.0    315.0
   123.0     345.0     123.0     365.0
PHOTO   14     6
    0.375      0.0     0.400      15.0     0.450      45.0     0.500     75.0
    0.560    105.0     0.615     135.0     0.645     165.0     0.630    195.0
    0.585    225.0     0.500     255.0     0.400     285.0     0.400    315.0
    0.350    345.0     0.350     365.0
 WIND    5     7
     0.00      0.0      0.00      75.0      0.15     80.0        0.15    290.0
     0.00    365.0
  KE1   23     8      Segment 1  2
    1.730      0.0     1.530      86.0     2.310      99.0     1.480     113.0
    1.280    120.0     0.0       141.0     0.250     148.0     0.200     155.0
    0.220    163.0     0.140     168.0     0.430     174.0     1.070     183.0
    0.700    188.0     0.410     195.0     0.0       202.0     0.0       208.0
    0.730    216.0     0.640     222.0     0.650     233.0     0.700     244.0
    0.700    273.0     0.620     289.0     1.500     365.0
TFNH4    8    13
     0.00      0.0      0.00     100.0     35.0      130.0     40.0      200.0
    40.00    260.0      5.00     290.0      0.0      295.0      0.0      365.0
TFPO4   11    14
     0.00      0.0      0.00     100.0      0.0      130.0     10.0      185.0
```

Table C-1 Continued:

```
     15.00       220.0      6.00       230.0     2.0      290.0     -55.0     295.0
     -7.00       315.0     -6.00       330.0    -4.0      365.0
VELN1   2     15
      0.00         0.0      0.00       365.0
VELN2   2     16
      0.00         0.0      0.00       365.0
VELN3   2     17
      0.00         0.0      0.00       365.0
VELN4   2     18
      0.00         0.0      0.00       365.0
ZOO     2     19
     0.000         0.0     0.000       365.0
SALIN   2     20
      0.0        0.0       0.0       365.0
ATEMP   2     21
      15.0         0.0      15.0       365.0
ICECV   9     22
       0.8         0.0       0.8        45.0     0.8       90.0       1.0     135.0
       1.0       180.0       1.0       225.0     1.0      270.0       1.0     315.0
          0.8      365.0
NH3                                         3    1.0      1.0E08  ** J: ICs **
   1:      0.07        1.0   2:       0.070      1.0   3:   0.100          1.0
   4:     55.00        1.0   5:       50.00      1.0
NO3                                         5    1.0      1.0E08
   1:     0.250        1.0   2:       0.250      1.0   3:   0.250          1.0
   4:     0.40         1.0   5:       0.40       1.0
PO4                                         5    1.0      1.0E08
   1:  0.00896         1.0   2:  0.00896         1.0   3:   0.00586        1.0
   4:     16.00        1.0   5:         17.00    1.0
CHLa                                        4    1.0      1.0E08
   1:     10.70        0.0   2:   10.70          0.0   3:       4.13       0.0
   4:    100.0         0.0   5:  100.0             0.0
CBOD                                        3    1.0      1.0E08
   1:      0.0        0.22   2:       0.000     0.22   3:       0.00      0.22
   4:      0.0        0.22   5:       0.000     0.22
DO                                          5    1.0      1.0E08
   1:     13.40        1.0   2:     13.40        1.0   3:      13.05       1.0
   4:      0.50        1.0   5:         0.5      1.0
ON                                          3    1.0      1.0E08
   1:      0.290       0.5   2:       0.290      0.5   3:     0.270        0.5
   4:    320.00        0.3   5:       400.0      0.3
OP                                          3    1.0      1.0E08
   1:   0.04926       0.30   2:   0.04926       0.30   3:   0.0472         0.3
   4:     60.00       0.10   5:       70.00     0.10
```