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An Introduction to Lake and Reservoir Water Quality Modeling

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AN INTRODUCTION TO LAKE AND RESERVOIR WATER QUALITY MODELING

A Short Course Presented at the Arkansas Water Resources Center Annual Spring Conference March 25, 1996

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MSC-198

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Topics

Introduction and overview; objectives and outline for lecture (questions and discussion encouraged)

2. What's the problem? What do we care about? ==> objectives and attributes

3 Assessment and prediction - scientific analysis in support of decision making ==> models

4. Model selection criteria

Mechanistic models (WASP5)

6. Bathtub model

7. Statistical/empirical models (Vollenweider loading criterion; Eutromod)

8 Special topics (as time permits: embayment modeling, uncertainty, trend analysis)

Useful Internet and E-mail Addresses

US EPA (WASP5)
Center for Exposure Assessment Modeling (Athens, GA)
    ftp://ftp.epa.gov/epa_ceam/wwwhtml/ceamhome.htm

US Army Corps of Engineers
Waterways Experiment Station (Vicksburg, MS)
    http://www.wes.army.mil/Welcome2.html
Bathtub Model: contact Dr. Robert Kennedy at: kennedr@ex1.wes.army.mil

Eutromod
North American Lake Management Society (NALMS)
    http://www.nalms.org/bkstore/bkstore.htm
K. Reckhow
    http://www2.ncsu.edu/ncsu/CIL/WRRI/ken's_page.html
    ken_reckhow@ncsu.edu
    reckhow@duke.edu

General
Old Dominion University, Department of Civil and Environmental Engineering
    (Dr. Jaewan Yoon)
    http://www.cee.odu.edu/cee/model/model.html

Model Selection Criteria

- the model is appropriate and comprehensive
- prediction uncertainty is acceptable
- cost and ease of use are reasonable

Model Descriptors/Approaches

- *Mechanistic (process oriented)*

Conservation of mass (mass balance):

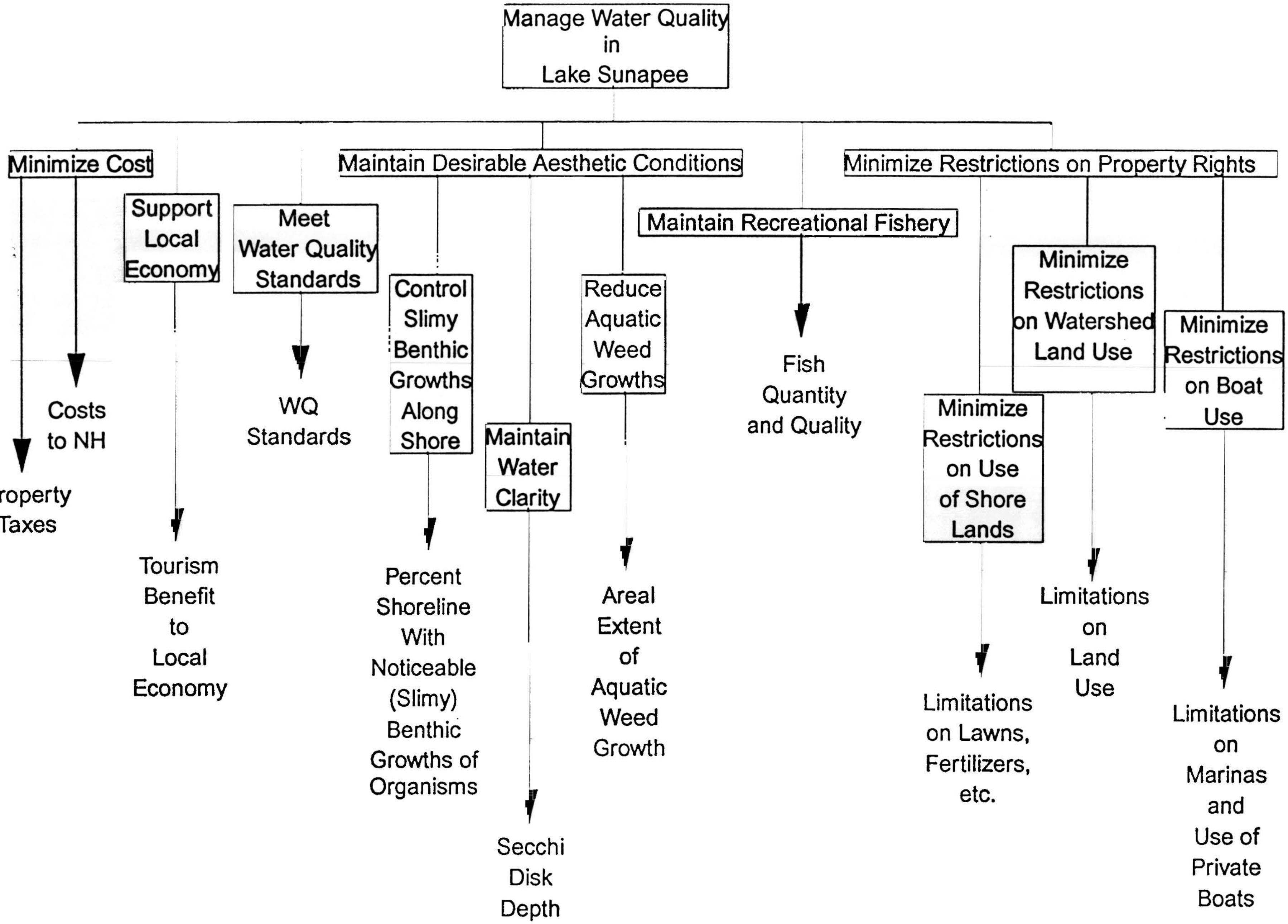
Accumulation = Inputs - Outputs ±Reactions

$$V\frac{dP}{dt} \quad W \quad QP \quad \sigma PV$$

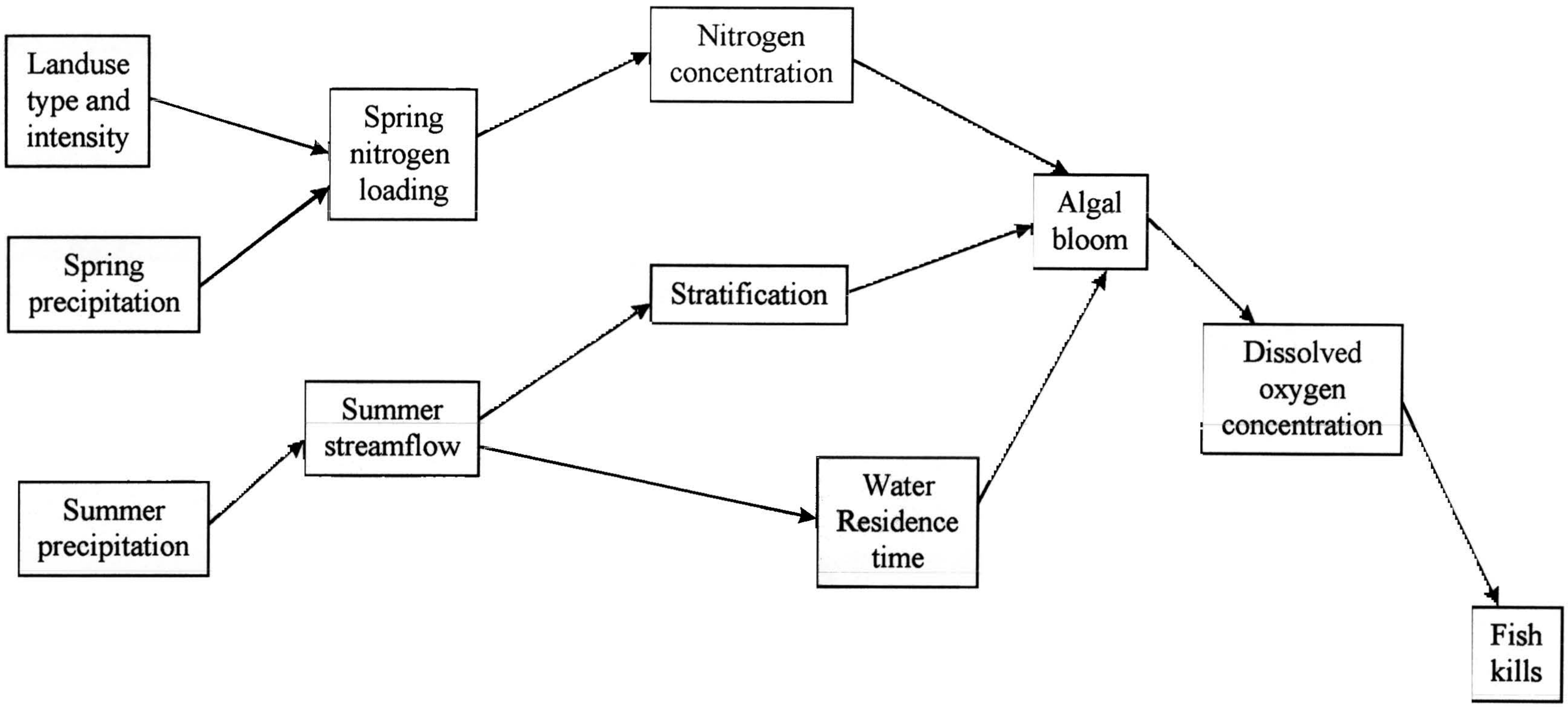
- *Empirical (statistical)*

Statistical (parameter) estimation (e.g., regression)

$$Chla = 0.0731P^{1.449}$$



Manage Water Quality in Lake Sunapee
Minimize Cost
Property Taxes
Costs to NH
Support Local Economy
Tourism Benefit to Local Economy
Meet Water Quality Standards
WQ Standards
Maintain Desirable Aesthetic Conditions
Control Slimy Benthic Growths Along Shore
Percent Shoreline With Noticeable (Slimy) Benthic Growths of Organisms
Maintain Water Clarity
Secchi Disk Depth
Reduce Aquatic Weed Growths
Areal Extent of Aquatic Weed Growth
Maintain Recreational Fishery
Fish Quantity and Quality
Minimize Restrictions on Property Rights
Minimize Restrictions on Use of Shore Lands
Limitations on Lawns, Fertilizers, etc.
Minimize Restrictions on Watershed Land Use
Limitations on Land Use
Minimize Restrictions on Boat Use
Limitations on Marinas and Use of Private Boats


Landuse type and intensity
Spring precipitation
Spring nitrogen loading
Nitrogen concentration
Summer precipitation
Summer streamflow
Stratification
Water Residence time
Algal bloom
Dissolved oxygen concentration
Fish kills

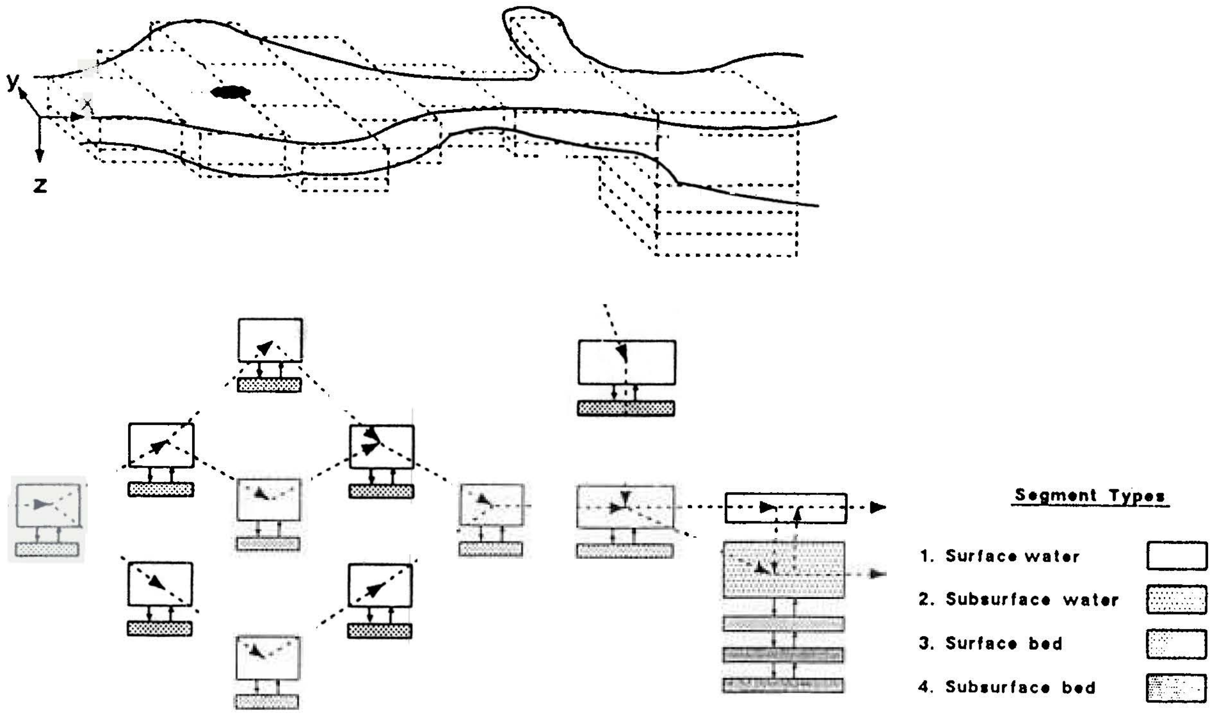


Figure 1.3.2. Model segmentation

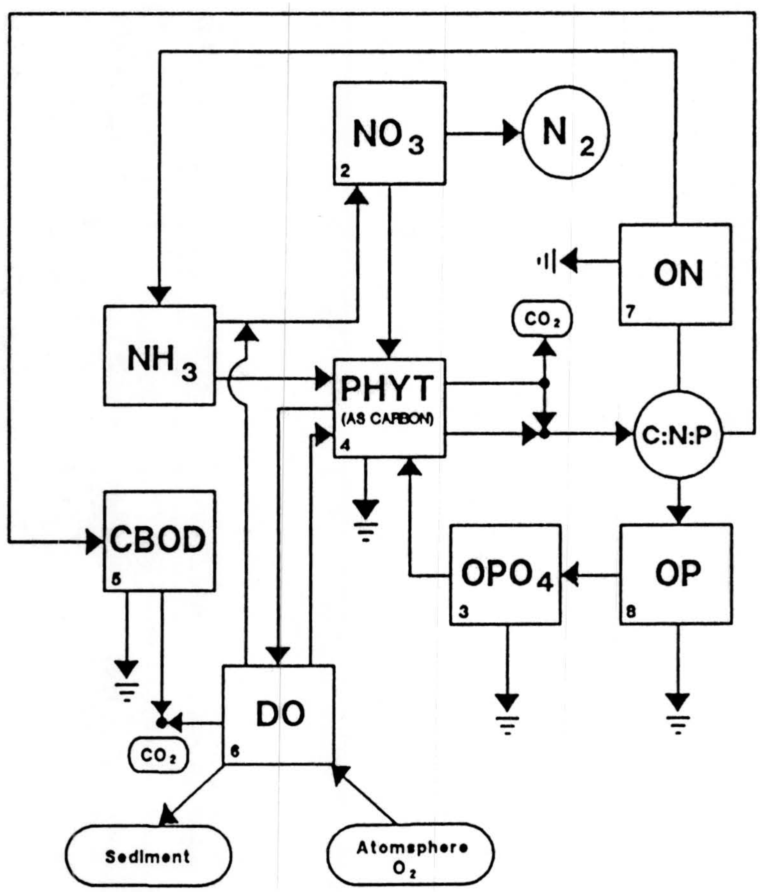


Figure 1.4.1 EUTRO4 state variable interactions

WASP5 Phytoplankton Growth Equations

$$Growth\ Rate = G_{max,Temp} G_{Nutrients} G_{Light} = G_{1max}(T) G(I,t) G(N)$$

$$G_{1max}(T) = G_{1max}(20\ °C)\ \theta_1^{(T-20)}$$

where:

θ_1 = temperature coefficient, unitless

$$G(I,t) = \frac{e}{K_e D} [\exp\left\{ \frac{I_o}{I_s} \exp(-K_e D) \right\} - \exp(- \frac{I_o}{I_s}) \qquad 1.4.6$$

where

$$I_s = \frac{G_{1max}(T)\ \theta_c\ e}{\Phi_{max}\ K_c\ f_u} \qquad 1.4.7$$

where

D = the average segment depth, m

Φ_{max} the quantum yield, mg carbon fixed per mole of light quanta absorbed

K_e the total extinction coefficient, computed from the sum of the non-algal light attenuation, K_e', and the self-shading attenuation due to ambient phytoplankton population, m^{-1}

K_c the extinction coefficient per unit of chlorophyll, m^2/mg chlorophyll a

f_u = units conversion factor (0.083, assuming 43% inciden light is visible and 1 mole photons is equivalent to 52,000 cal) mole photons/m^2-ly

I_o = the incident light intensity just below the surface, assusmed to average 0.9 I, ly/day

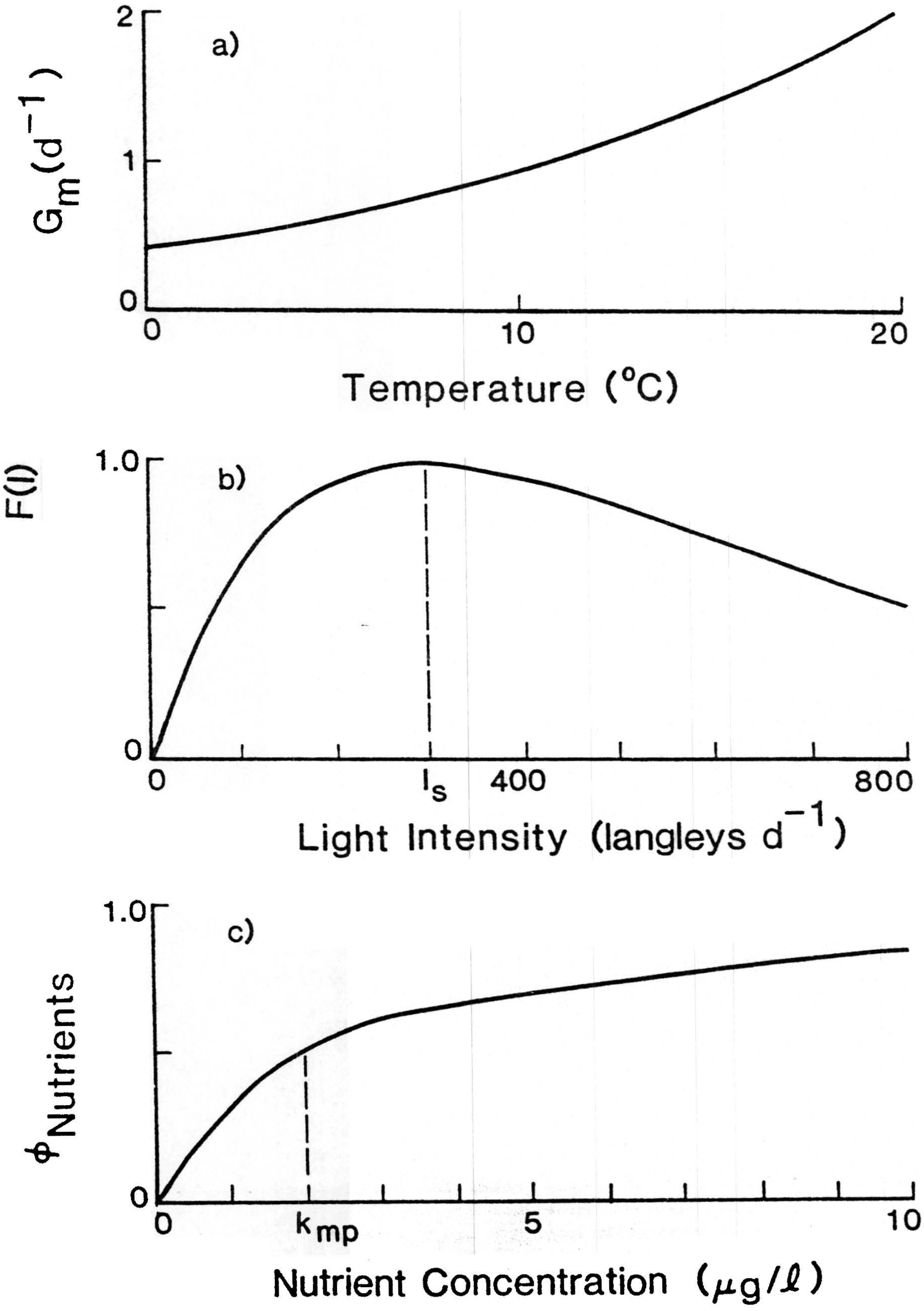
I_s = the saturating light intensity of phytoplankton, ly/day

θ_c the ratio of carbon to chlorophyll in the phytoplankton, (mg carbon/mg chlorophyll a)

e = the base of natural logarithms (2.71828), unitless

$$G(N) = Min\ (\frac{DIN}{K_{mN} + DIN}\quad \frac{DIP}{K_{mP} + DIP}$$

DIN, DIP = dissolved nutrient concentrations
K_{mN}, K_{mP}=Michael-Menten parameters


a)
$G_m(d^{-1})$
2
1
0
0
10
20
Temperature (°C)
b)
F(I)
1.0
0
0
I_s
400
800
Light Intensity (langleys d^{-1})
c)
$\phi_{Nutrients}$
1.0
0
0
k_{mp}
5
10
Nutrient Concentration ($\mu g/\ell$)

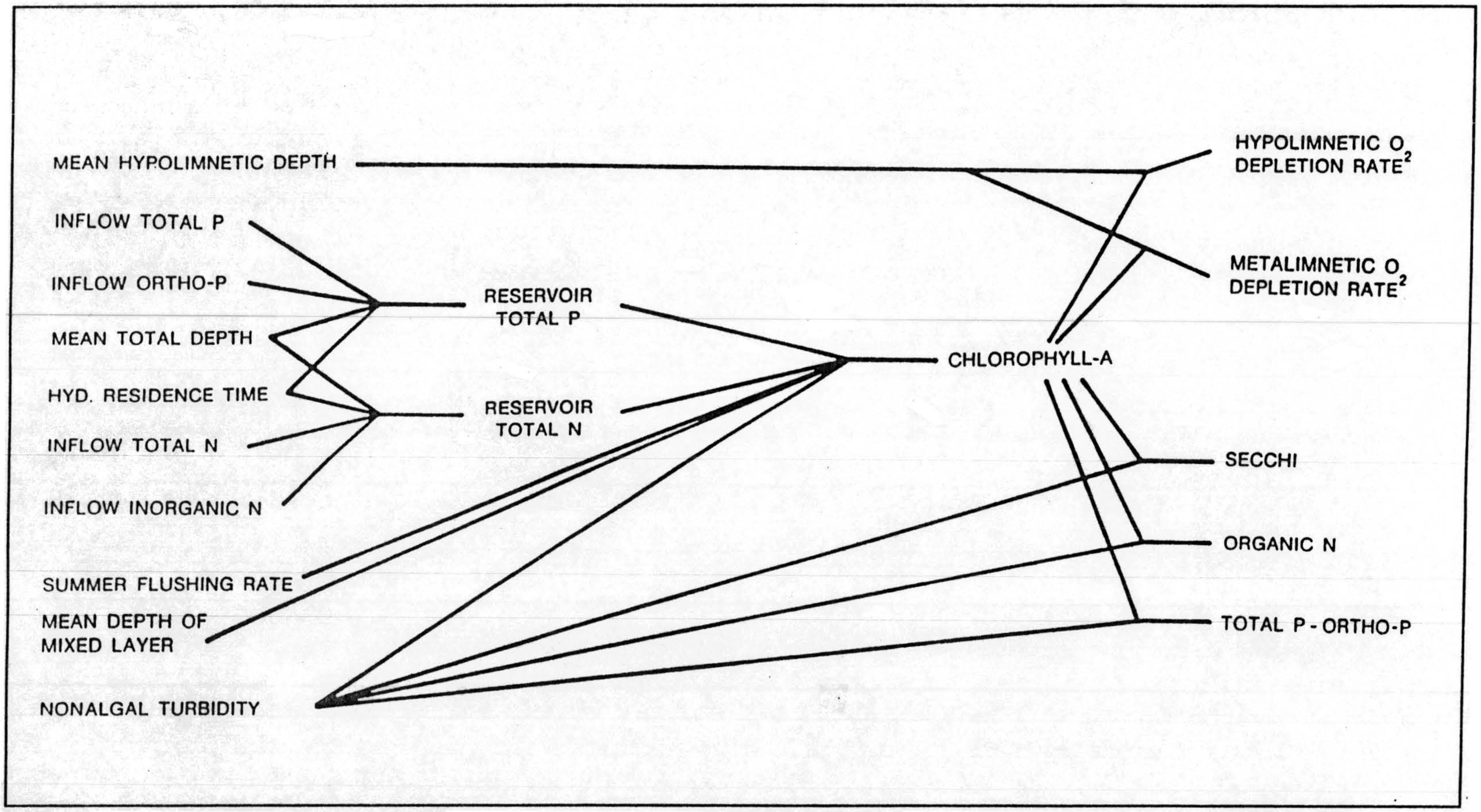
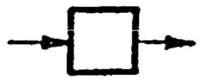


Figure 4.2. Control pathways in empirical eutrophication models developed for CE reservoir applications

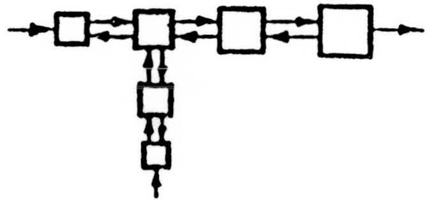
SCHEME 1.

SINGLE RESERVOIR, SPATIALLY AVERAGED



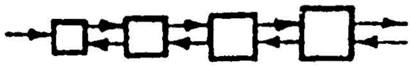
SCHEME 2.

SINGLE RESERVOIR, SEGMENTED



SCHEME 3.

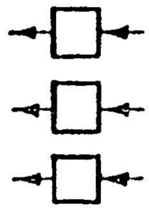
PARTIAL RESERVOIR OR EMBAYMENT, SEGMENTED



SCHEME 4.

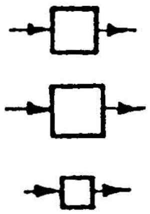
SINGLE RESERVOIR, SPATIALLY AVERAGED,

MULTIPLE LOADING REGIMES



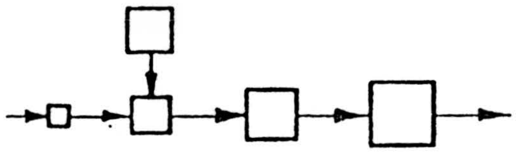
SCHEME 5.

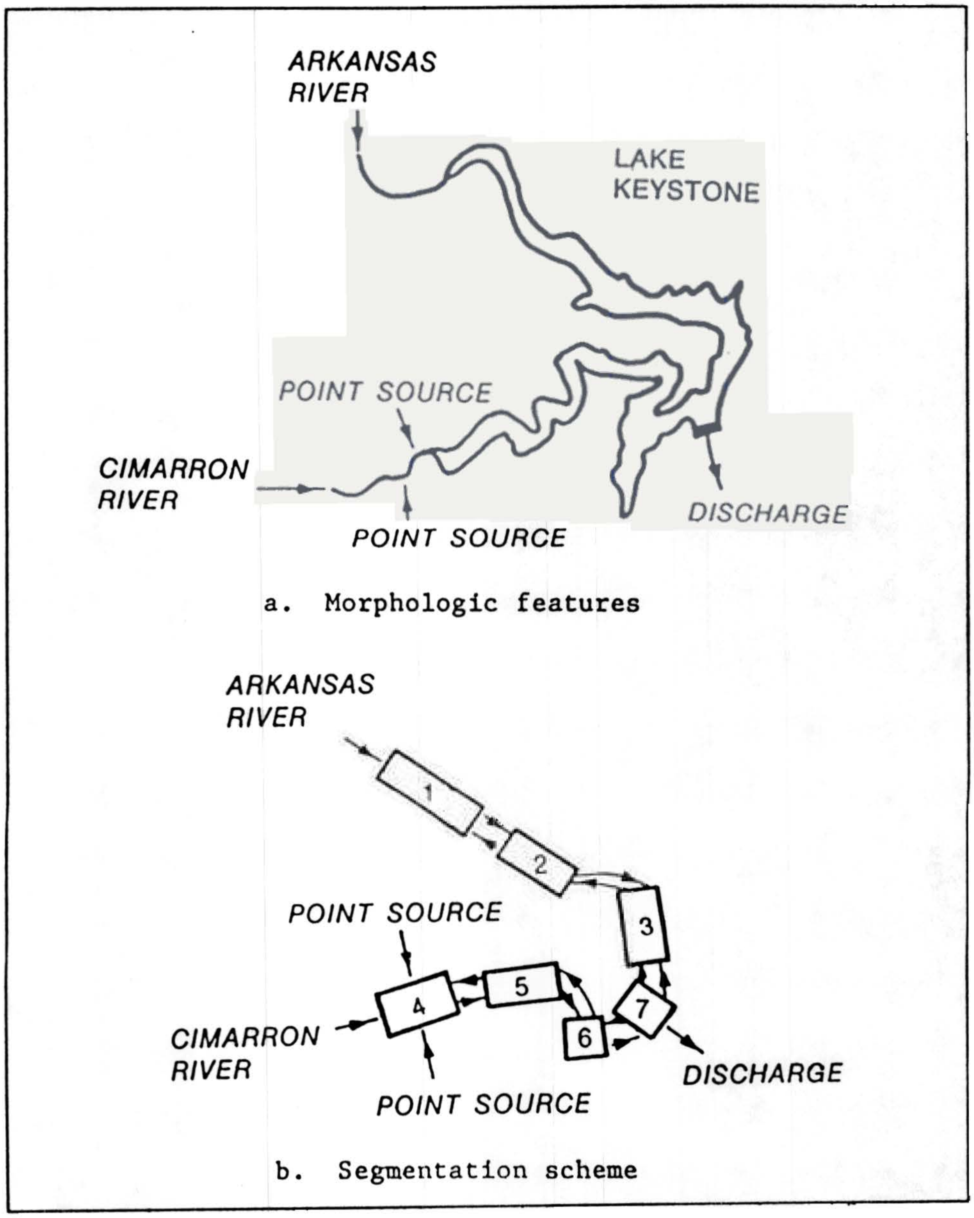
COLLECTION OF RESERVOIRS, SPATIALLY AVERAGED



SCHEME 6.

NETWORK OF RESERVOIRS, SPATIALLY AVERAGED





a. Morphologic features

b. Segmentation scheme

Figure 4.9. Model segmentation for Lake Keystone, Oklahoma, application

BATHTUB Chlorophyll Equations

Model 1: N, P, Light, Flushing Rate

$Xpn = [P^{-2} + ((N-150)/12)^{-2}]^{-0.5}$

$Bx = Xpn^{1.33} / 4.31$

$G = Zmix\ (0.14 + 0.0039\ Fs)$

$B = CB\ Bx / [(1 + 0.025\ Bx\ G)\ (1 + Ga)]$

Model 2: P, Light, Flushing Rate [default]

$Bp = P^{1.37} / 4.88$

$G = Zmix\ (0.19 + 0.0042\ Fs)$

$B = CB\ Bp / [(1 + 0.025\ Bp\ G)\ (1 + Ga)]$

Model 3: P, N, Low-Turbidity

$B = CB\ 0.2\ Xpn^{1.25}$

Model 4: P, Linear

$B = CB\ 0.28\ P$

Model 5: Jones and Bachman (1976)

$B = CB\ 0.081\ P^{1.46}$

where:

B = chlorophyll *a* concentration (ug/l)
P = total phosphorus concentration (ug/l)
N = total nitrogen concentration (ug/l)
CB = calibration factor for chlorophyll *a*
Zmix = mean depth of mixed layer (m)
Fs = summer flushing rate (yr^{-1})
a = nonalgal turbidity (m^{-1})

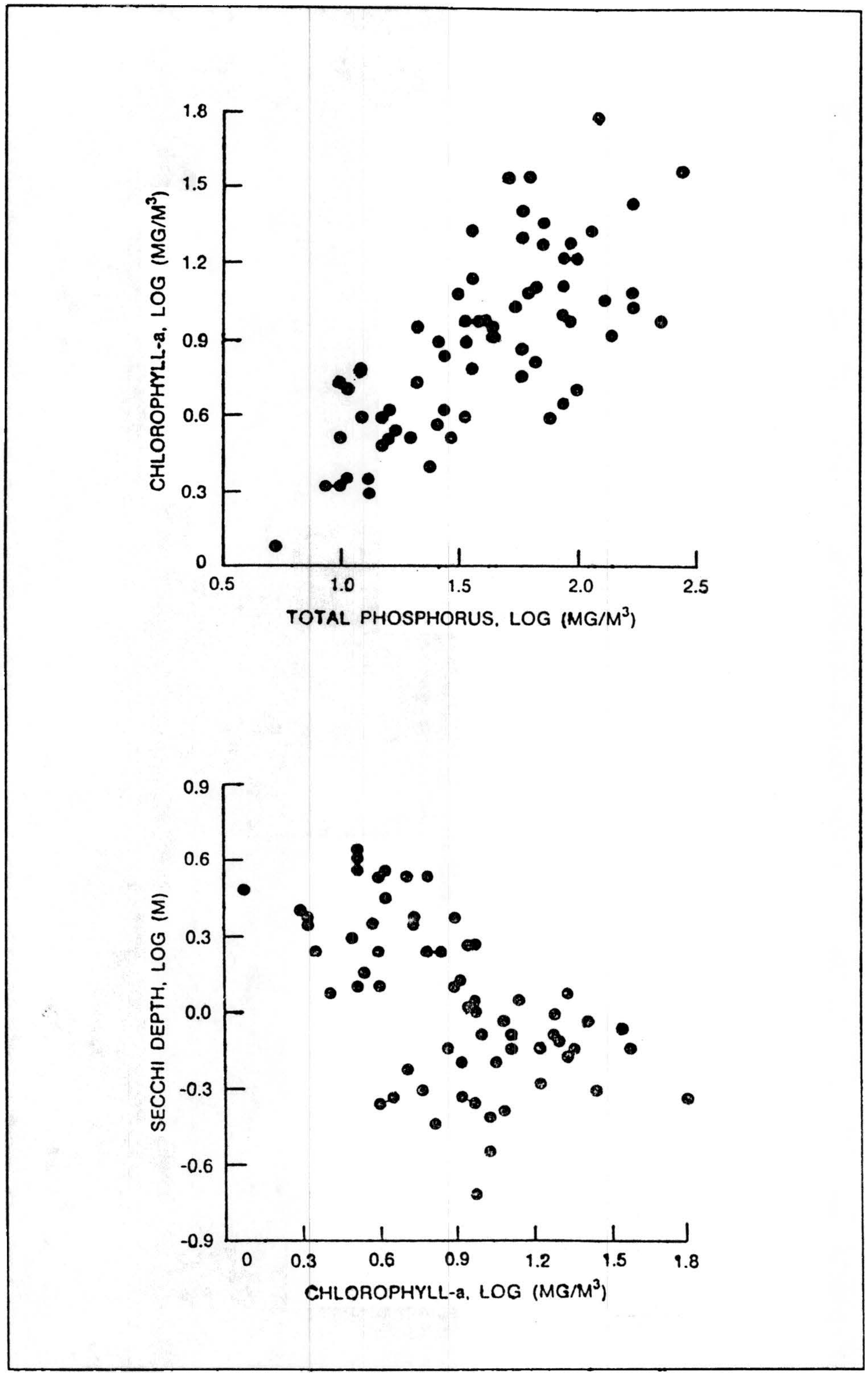


Figure 4.7. Phosphorus, chlorophyll *a*, and transparency relationships for CE reservoirs

FIG. 8. Chlorophyll and Total Phosphorus Concentrations in the Lake Okeechobee Littoral Zone (May - October Data).

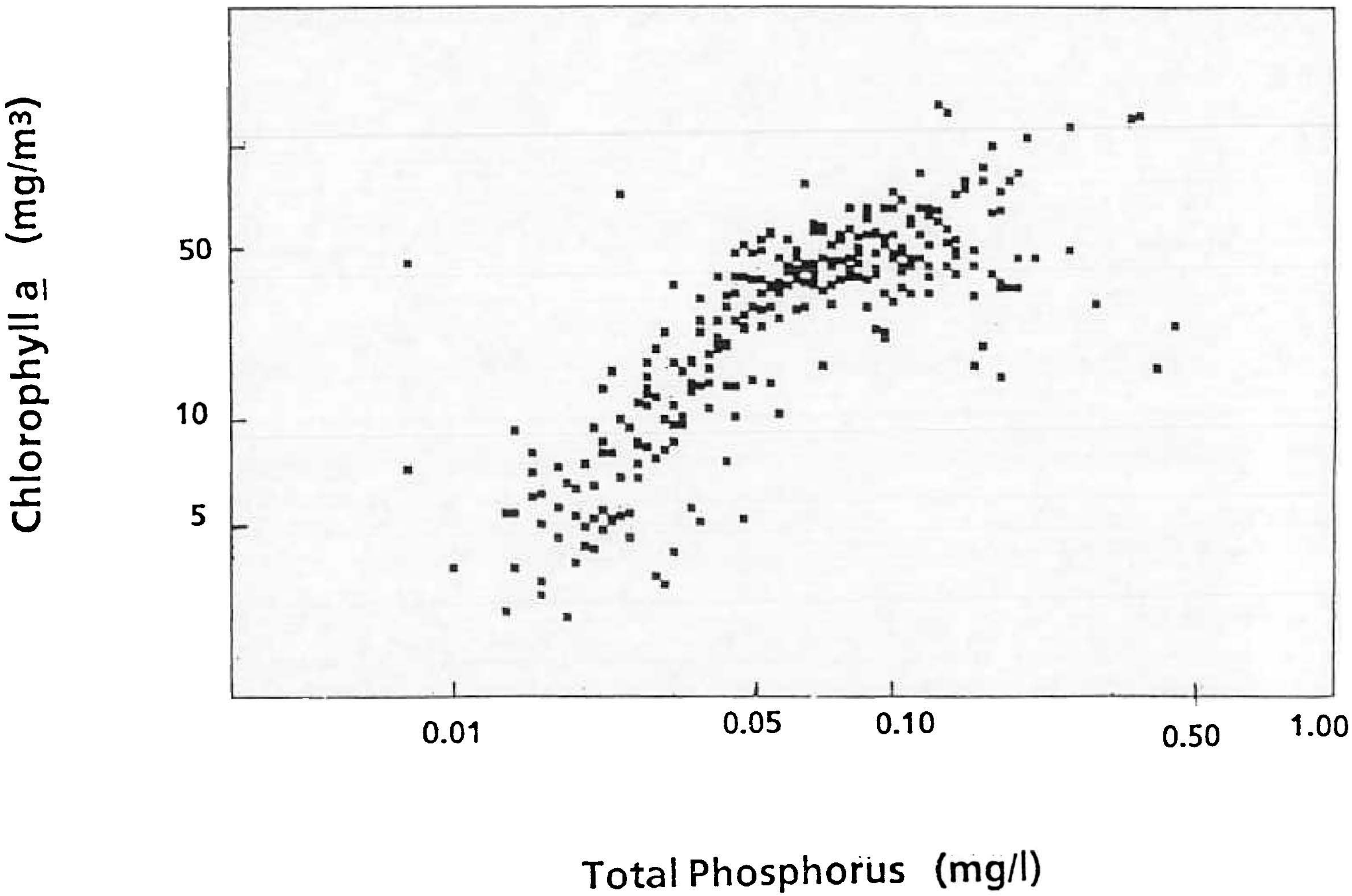
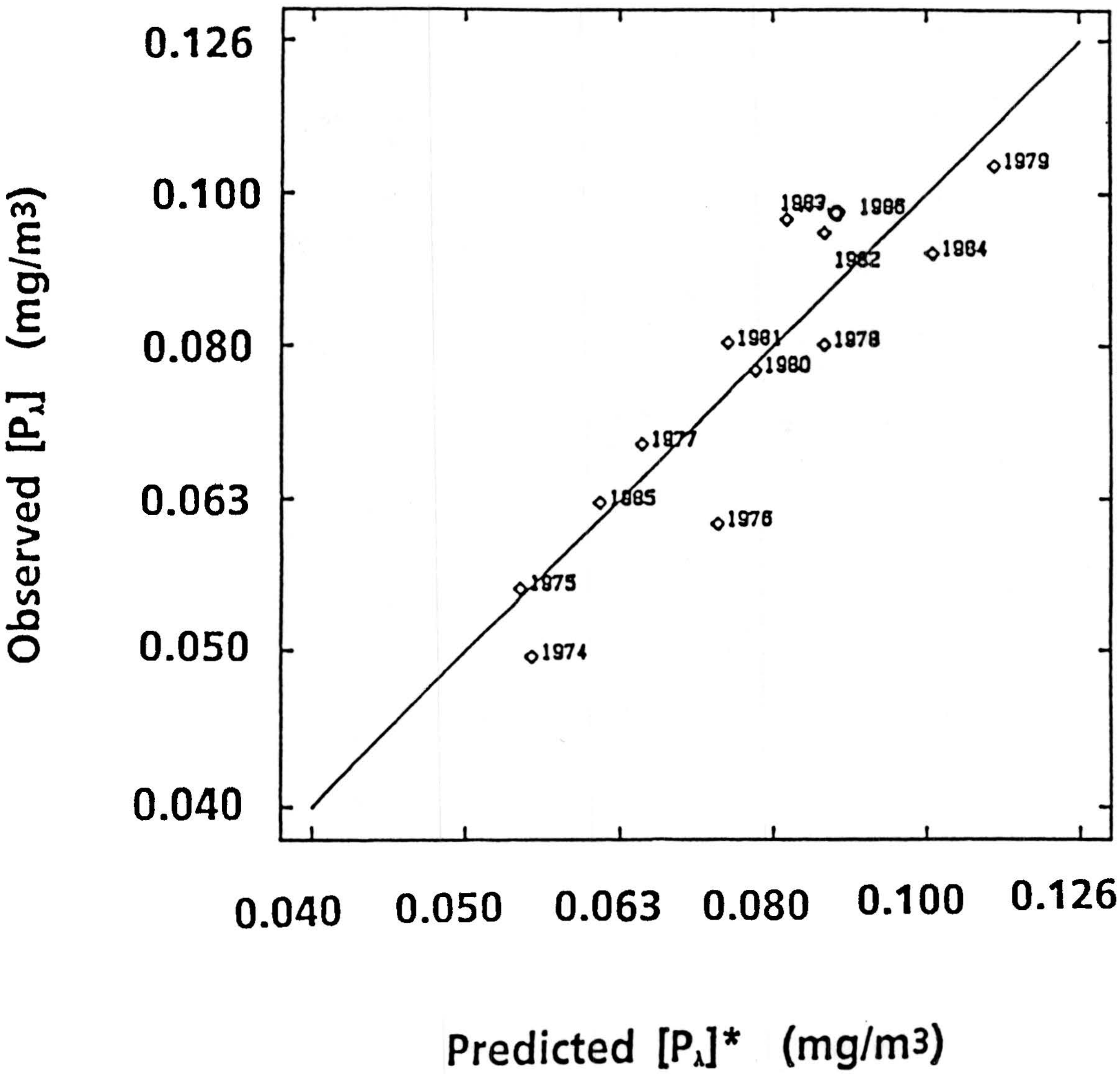
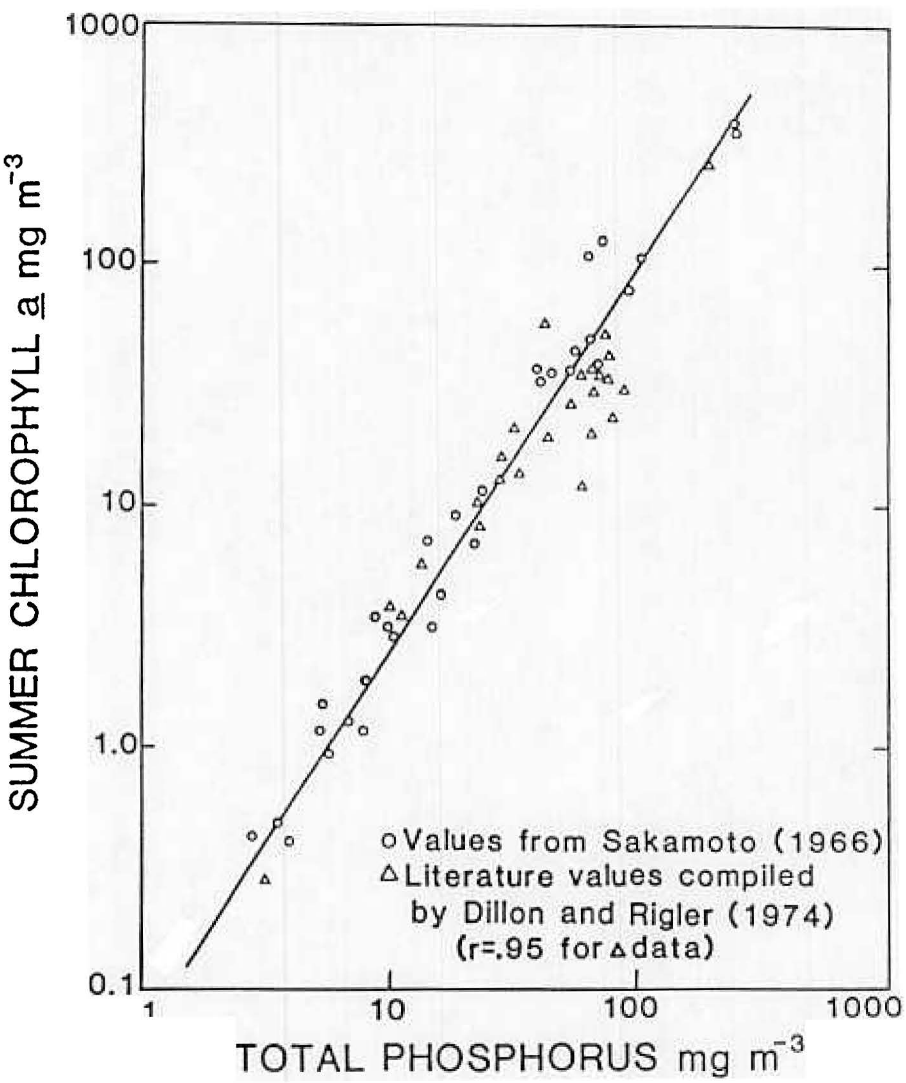


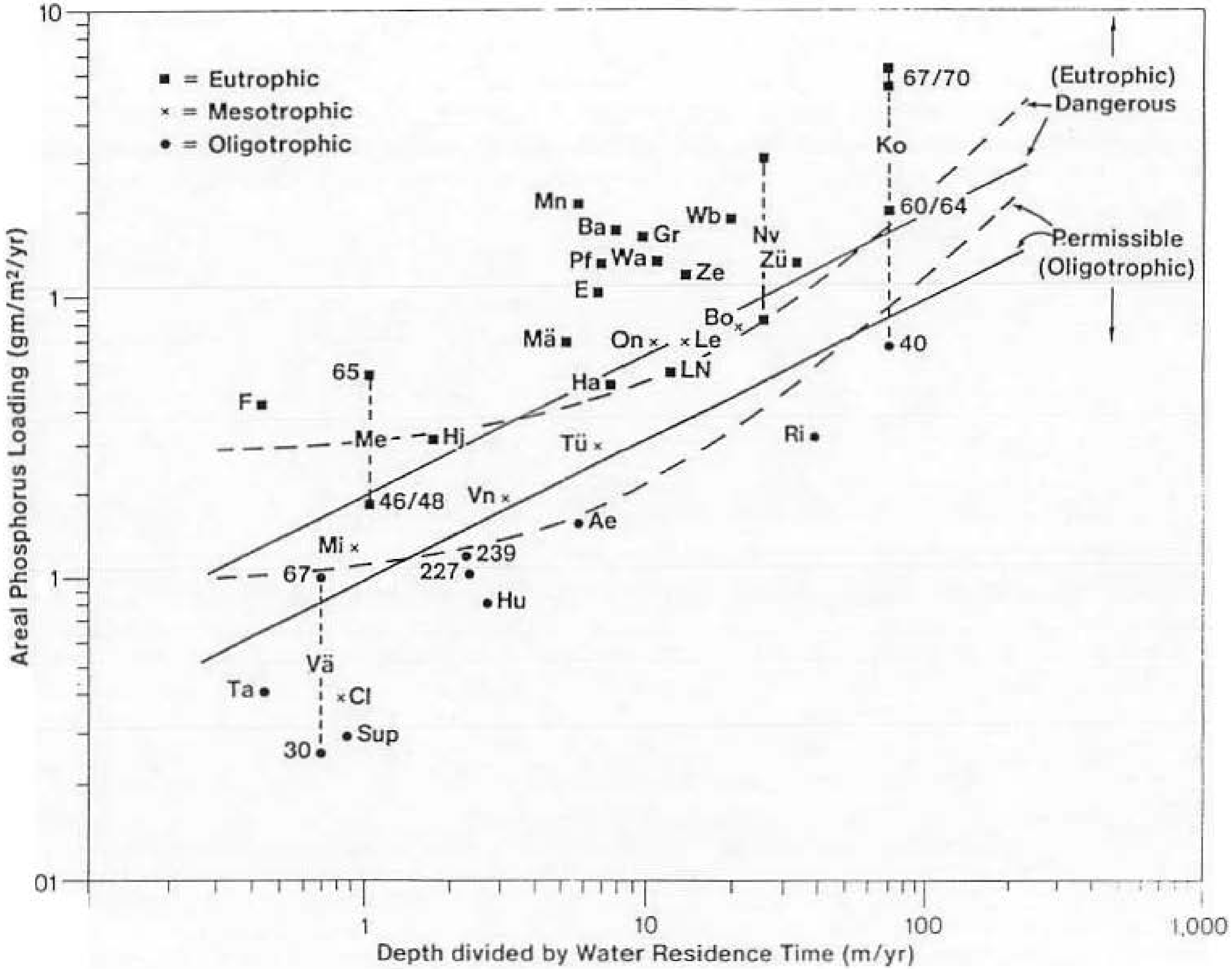
FIG. 3. Next year's mean lake [P] as a function of (P_1, T_w, z) for Okeechobee.



*i.e., predicted from the three-factor multiple regression model

$$\text{Chl } a = 0.0731\text{P}^{1.449}$$




■ = Eutrophic
× = Mesotrophic
• = Oligotrophic
Areal Phosphorus Loading (gm/m²/yr)
Depth divided by Water Residence Time (m/yr)
10
1
1
01
1
10
100
1,000
(Eutrophic)
Dangerous
Permissible
(Oligotrophic)
67/70
Ko
60/64
40
Mn
Ba
Gr
Wb
Nv
Pf
Wa
Zü
Ze
E
Bo
Mä
On
Le
LN
Ha
65
F
Me
Hj
Tü
Ri
46/48
Vn
Ae
Mi
239
227
67
Hu
Vä
Ta
Cl
Sup
30

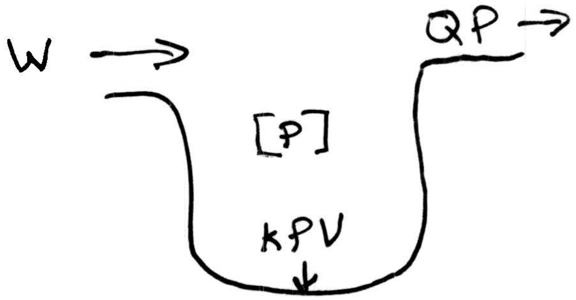
Lake Models

Input-Output Models for Nutrients

Mass balance (conservation of mass):

Accumulation = Inputs - outputs ± Reactions

for phosphorus:



$$V\frac{dP}{dt} = W - QP - kPV$$

solution:

$$P = \frac{W}{Q+kV}\left[1 - e^{-(\frac{1}{\tau}+k)t}\right] + P_i e^{-(\frac{1}{\tau}+k)t}$$

steady-state solution:

$$P = \frac{W}{Q+kV} = \frac{P_{in}}{1+k\tau}$$

other similar expressions:

$$P = \frac{L}{v_s+q_s} = P_{in}(1 - R_p)$$

V=lake volume
P=phosphorus concentration
W=phosphorus mass loading
Q=volumetric water load
k=first order reaction rate

τ=water residence time
P_{in}=influent p-concentration

v_s=apparent settling

Eutromod Equations for Arkansas Lakes

Total Phosphorus (mg/l)

$$\log_{10}(P) \quad \log_{10}\left[\frac{P_{in}}{1+k\tau}\right]$$

where: $k = 10.77\tau^{-0.61} z^{0.01} P_{in}^{0.82}$

Total Nitrogen (mg/l)

$$\log_{10}(N) = \log_{10}\left[\frac{N_{in}}{1+k\tau}\right]$$

where: $k = 0.46\tau^{-0.75} z^{0.22} N_{in}^{0.95}$

Chlorophyll a (ug/l)

$$\log_{10}(chla) = 1.99 + 0.5\log_{10}(\hat{P}) + 0.23\log_{10}(\tau) - 0.351\log_{10}(z)$$

Secchi Disk Depth (m)

$$\log_{10}(SD) = -1.32 - 0.66\log_{10}(\hat{P}) + 0.47\log_{10}(z)$$

where:

τ = water residence time

z = mean depth

^ ~ "predicted"

$_{in}$ ~ influent

EUTROMOD
Version 2.50
by
Kenneth H. Reckhow
Duke University
Durham, NC 27706
1991

A watershed/lake modeling procedure for eutrophication management, with region-specific models and with emphasis on uncertainty analysis.

Enter two letter (all caps) state postal code (e.g., NY) in box, identifying the location of the lake.

CO

Hit ALT-X to continue; this selects the region-specific lake models.

Figure A.

Eutromod:
Map of Screen Worksheets[1]

	A	J	T	AB
20	Surface water runoff Precipitation USLE	USLE	Land areas Septic tanks Treatment plants	Lake depth Detention time, etc. Water runoff
40	Phosphorus concentrations in inputs	Nitrogen concentrations in inputs	Attenuation zones for nutrient trapping	Calculation tables
60	Phosphorus-total loading by land use category	Nitrogen-total loading by land use category	Attenuation zones for nutrient trapping	Calculation tables
80	Lake response predictions (uncertainty due to hydrologic variability)	Lake response predictions (uncertainty due to model error)	Attenuation zones for nutrient trapping	Calculation tables
100	Allowable nutrient loading (chlor a goal)	Allowable nutrient loading (chlor a, P goals)	Calculations-dissolved nutrients	
120	Allowable nutrient loading (TSI goal)		Calculations-sediment-attached nutrients	
140			Calculations-total nutrients	

[1] Letters across the top of the table and numbers along the left side identify cells in the spreadsheet (e.g., the intersection of "T" and "60" is cell T60).

Figure A.2

Surface Water Runoff & Soil Loss

Figure A.3

Universal Soil Loss Equation

Land Use Category	LS factor	C factor	P factor	Xi
Agriculture1	0.3	0.2	0.5	5.263
Agriculture2	0.4	0.03	0.3	0.631
Agriculture3	0	0	0	0
Agriculture4	0	0	0	0
Agriculture5	0	0	0	0
Forest	0.9	0.001	0.2	0.031
Urban1				0
Urban2				0
Feedlots				0
Other1	0	0	0	0
Other2	0	0	0	0
Other3	0	0	0	0

X (total soil loss) =2.12098961 t/ha (area-weighted average)

Figure A.6

Phosphorus Concentration Estimates
Dissolved and Total in mg/l; Sed-Attached (Ci) in mg/kg]

Land Use Category	Dissolved	Sed-Attach	Total
Agriculture1	0.07	220	*****
Agriculture2	0.07	220	*****
Agriculture3	0	0	*****
Agriculture4	0	0	*****
Agriculture5	0	0	*****
Forest	0.008	220	*****
Urban1	*****	*****	0.2
Urban2	*****	*****	0.1
Feedlots	*****	*****	0
Other1	0	0	*****
Other2	0	0	*****
Other3	0	0	*****
Precipitation	*****	*****	0.05

P-enrichment ratio = 2

Figure A.7

Nitrogen Concentration Estimates
[Dissolved and Total in mg/l; Sed-Attached (Ci) in mg/kg]

Land Use Category	Dissolved	Sed-Attach	Total
Agriculture1	2.8	500	*****
Agriculture2	1.8	500	*****
Agriculture3	0	0	*****
Agriculture4	0	0	*****
Agriculture5	0	0	*****
Forest	0.19	500	*****
Urban1	*****	*****	1.5
Urban2	*****	*****	1.75
Feedlots	*****	*****	0
Other1	0	0	*****
Other2	0	0	*****
Other3	0	0	*****
Precipitation	*****	*****	0.1

N-enrichment ratio = 2

Phosphorus Loading Estimates - By Category

Loading (kg/yr)		Expected	
Agriculture		546.93439	
Forest		7.2419592	
Urban		19.635	
Feedlots		0	
Precipitation		37.6635	
Septic Tanks		24.375	
Point Sources		0	
Other		0	

Estimated Total = 635.849855 (kg/yr)

Nitrogen Loading Estimates - By Category

Loading (kg/yr)		Expected	
Agriculture		9847.0767	
Forest		145.88448	
Urban		158.6865	
Feedlots		0	
Precipitation		75.327	
Septic Tanks		216.125	
Point Sources		0	
Other		0	

Estimated Total = 10443.0997 (kg/yr)

Predicted Lake Trophic State Variables - Based on Model Uncertainties
(Median Values)

Variable (units)	-1 Std Err	Predicted	+1 Std Err
Total P-in (mg/l)		0.0805	
Total N-in (mg/l)		1.3226	
Total P (mg/l)	0.0259	0.0387	0.0577
Total N (mg/l)	0.6860	0.8899	1.1544
Chlor a (ug/l)		12.7905	
Secchi Depth (m)	1.4660	1.0826	0.8282
Prob Hypo Anoxia		0.3964	
Prob BG Dominant		0.5187	
THMs			
TSI			