Consideration of Variability & Uncertainty in Developing Phosphorus TMDL's for Lakes & Reservoirs

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Workshop: Water Quality Management & Restoration

Using Settling Basins, Wetlands, & Other Watershed BMPs

St. Paul, Minnesota

July 11, 2001

???   Total Maximum Daily Load   ???

Iterative TMDL Process

Define Management/Use Objectives

Identify Water Quality Standards

Monitor & Model

Estimate TMDL's

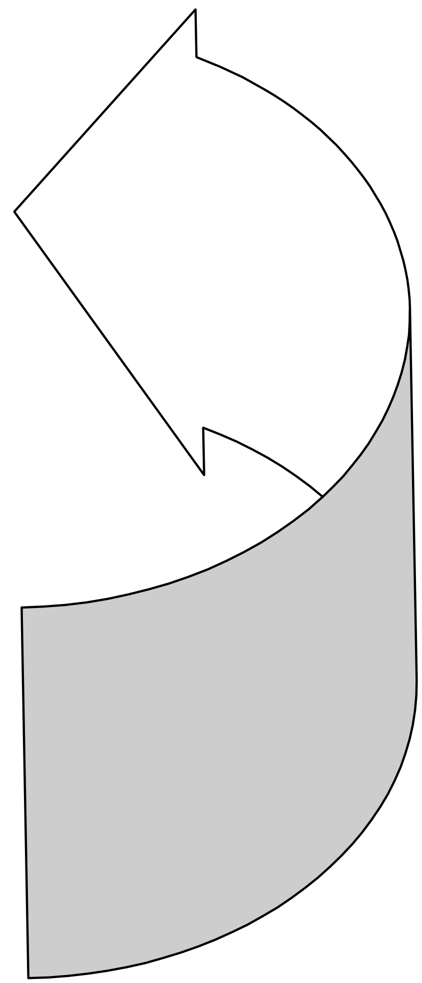
Evaluate Controls

Develop Load Allocations

Implement Controls

Monitor Results

Objectives Achieved ?



~ 5-10 years?

T M D L   Equations

Watershed Mass Balance:

$$TMDL = \Sigma\, LAs + \Sigma\, WLAs + Background + MOS$$

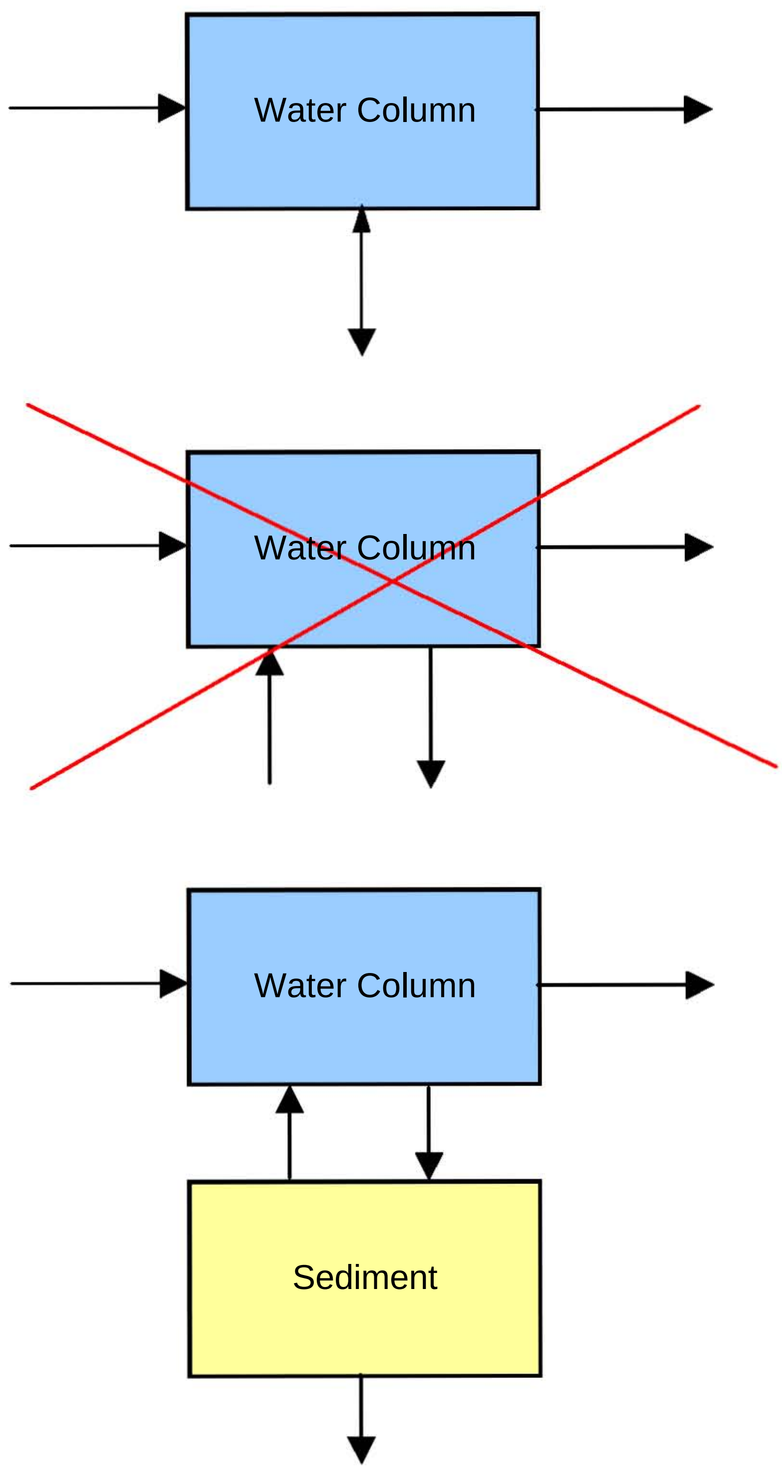
TMDL	Σ LAs	Σ WLAs	Background	MOS
Total Maximum Daily Load	Non-Point Sources	Point Sources	Natural or Unregulated	Margin of Safety

Lake/Reservoir Mass Balance:

$$TMDL = Q_O\ P^* + K_{NET}\ A\ P^* + L_I$$

TMDL	$Q_O\ P^*$	$K_{NET}\ A\ P^*$	L_I
Input	Flushing	Net Retention	"Internal Load"

Alternative Mass Balance Models



Quantifying Variability & Uncertainty
Benefits

Provides Realistic Assessment

Provides Rational Basis for MOS

Helps to Define Lake Goal

- Numerical Value "Target" or "Limit"?
- Spatial & Temporal Averaging
- Compliance Rate

Identifies Important Sources of Uncertainty

Provides Incentive for Continued Data Collection & Modeling

- More Data --?-> Lower MOS --?--> Higher Load Alloc

Increases Probability of Success

Quantifying Variability & Uncertainty Difficulties

Vague & Difficult Concepts

Limited Guidance Provided in TMDL Regulations

Frequency Concepts Rarely Built into WQ Standards

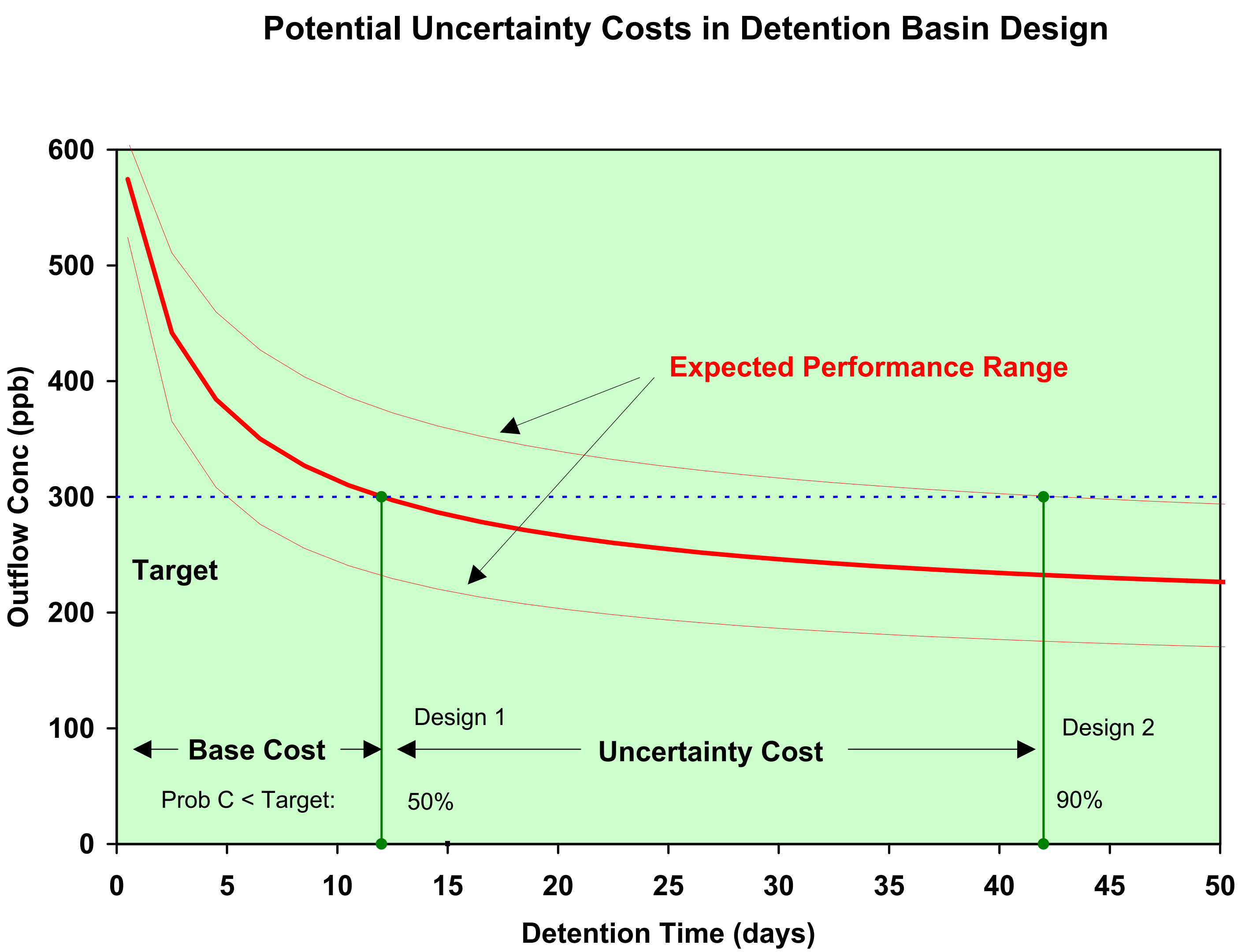
Load Allocations Sensitive to Assumptions:

- **Compliance Rate (e.g., % of yrs <= target)**
- **Confidence Level (~probability of success)**

Uncertainty Costs (MOS) Can Be Large

Can Backfire & Retard Restoration Efforts

Uncertainty Estimates are Uncertain


Potential Uncertainty Costs in Detention Basin Design
Expected Performance Range
Target
Design 1
Design 2
Base Cost
Uncertainty Cost
Prob C < Target:
50%
90%
Outflow Conc (ppb)
Detention Time (days)
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40
45
50

Modeling Variability & Uncertainty
Stochastic Approach

Expected Long-Term Average Mass-Balance:

$$P_M = L_M \; / \; (K_{NET} + Q_S)$$

Accounting for Uncertainty:

$$P_{MU} = P_M \; \exp (d_u)$$

d_u = random error term, mean = 0, std dev = s_u

s_u ~ 0.1 - 0.5

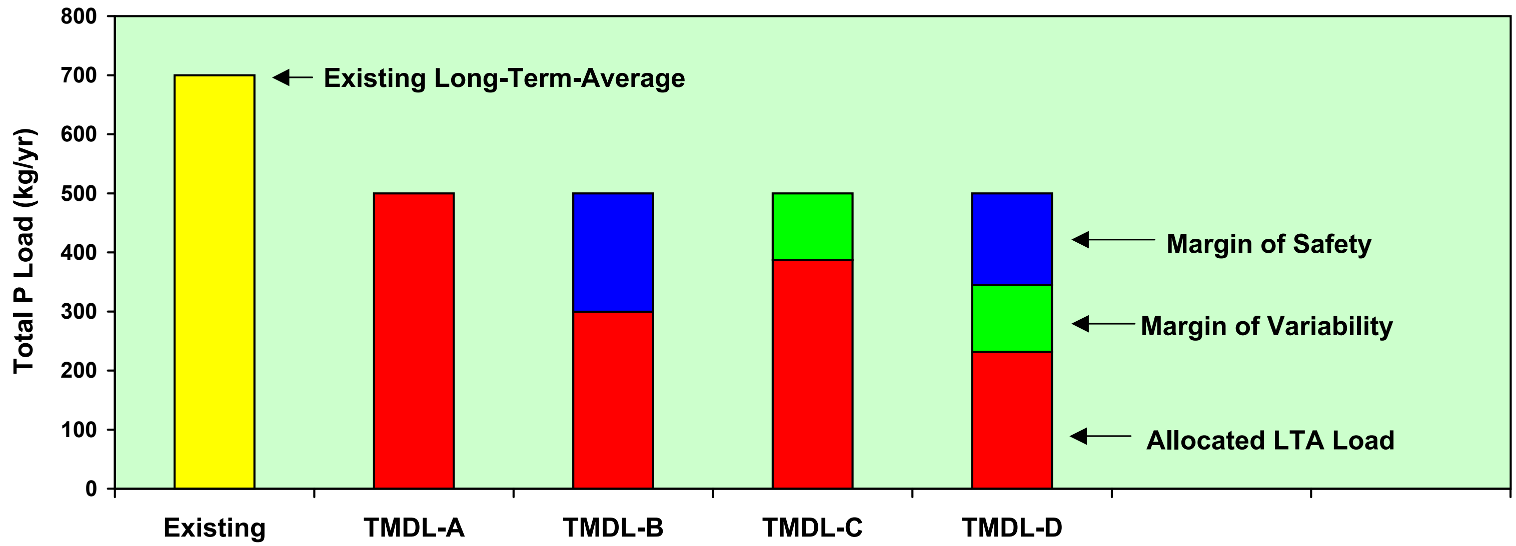
Accounting for Uncertainty & Variability:

$$P_{MUY} = P_M \; \exp (d_u + d_y)$$

d_y = random yr-to-yr variation, mean = 0, std dev = s_y

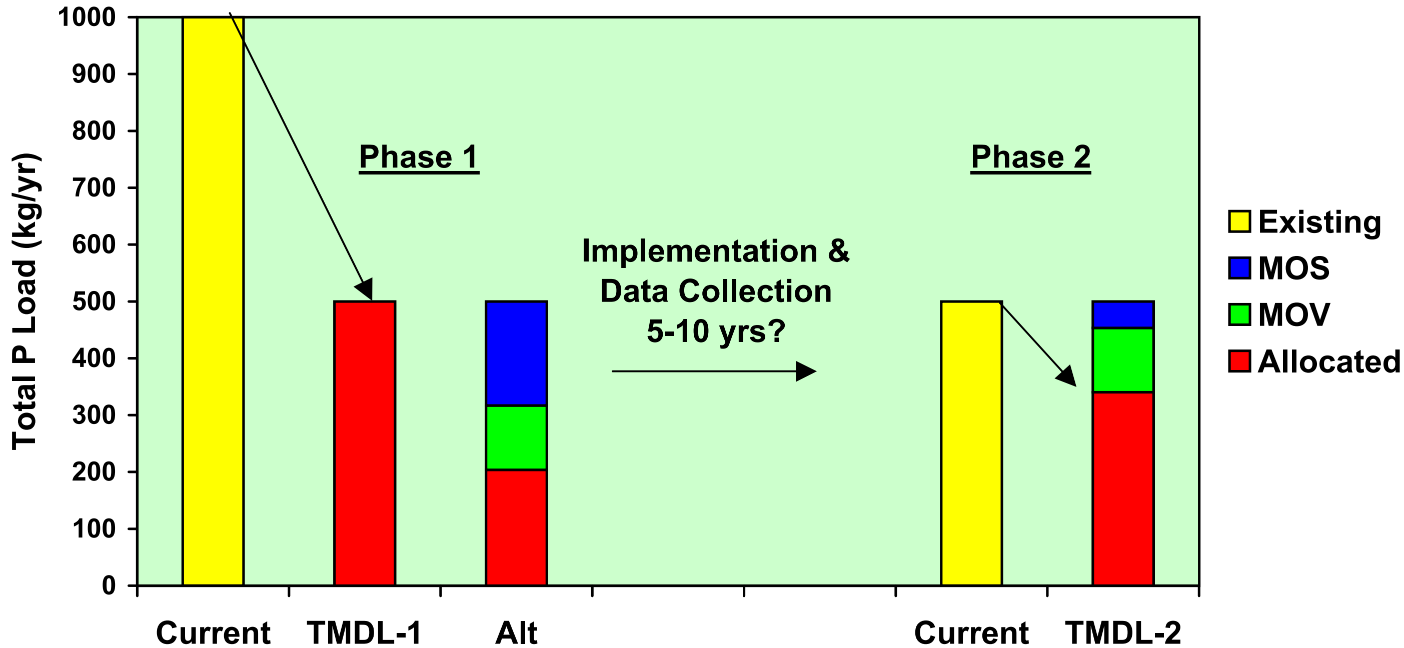
s_y ~ 0.1 - 0.3

Alternative TMDL Formulations



Lake P Target	**LT-Avg**	**LT-Avg**	**10-Yr Max**	**10-Yr Max**
Uncertainty Considered	**No**	**Yes**	**No**	**Yes**
Variability Considered	**No**	**No**	**Yes**	**Yes**
Confidence Level --->MOS	**50%**	**90%**	**50%**	**90%**
Compliance Freq --> MOV	**50%**	**50%**	**90%**	**90%**
Model Error Std Dev	**0.4**	**0.4**	**0.4**	**0.4**
Temporal Std Dev	**0.2**	**0.2**	**0.2**	**0.2**
Allocated Load	**500**	**299**	**387**	**232**
Load Reduction	**29%**	**57%**	**45%**	**67%**
Uncertainty Cost		**29%**		**22%**

Phased Approach to T M D L Implementation



	TMDL-1	Alt		TMDL-2
Confidence Level	50%	90%		90%
Compliance Freq	50%	90%	Uncertainty Reduction	90%
Model Error Std Dev	0.5	0.5	→	0.1
Temporal Std Dev	0.2	0.2		0.2
Allocated Load	500	204		340
Load Reduction	50%	80%		66%

TMDL = Allocated Long-Term Average Load + MOV + MOS
MOV = Margin of Variability
MOS = Margin of Safety

Including a Margin of Safety in TMDL's

Conservative Water Quality Criteria/Standard

Conservative Phosphorus Goal

Conservative Modeling Assumptions

Conservative Effluent Limits / Discharge Permits

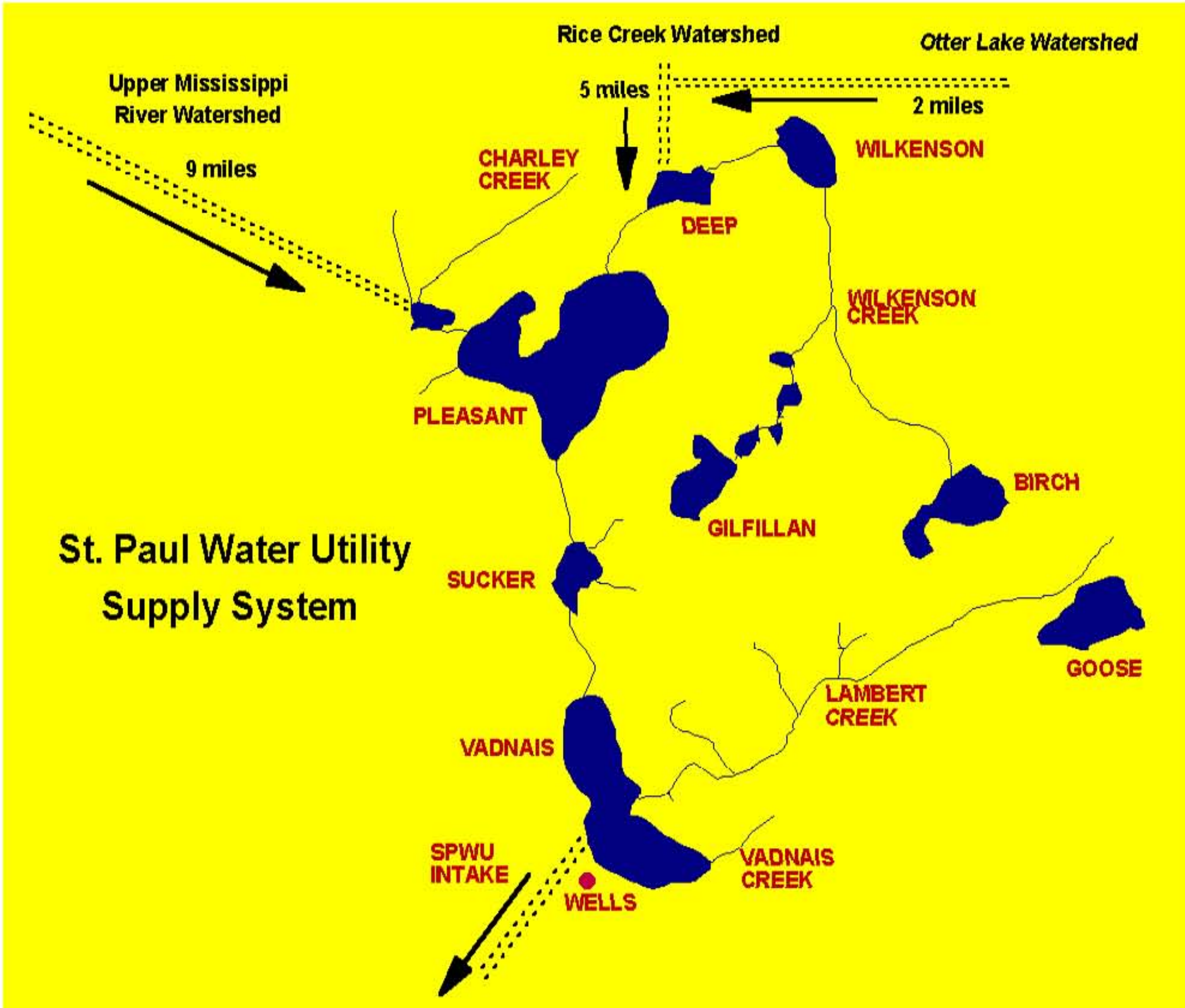
Conservative Facility Designs

Conservative Growth Projections

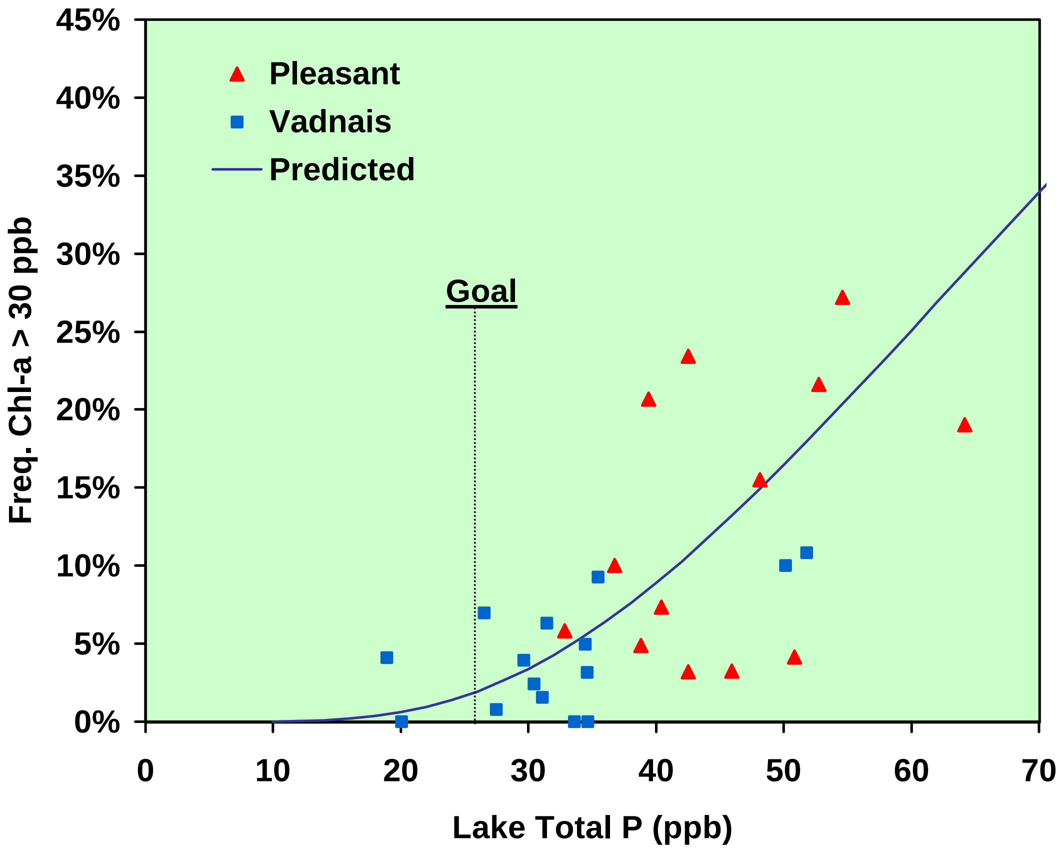
Shell Game

Examples of Phosphorus TMDL's & Similar Control Programs

Lake/Reservoir	Klamath	Cherry Creek	Vadnais	Onondaga	Okeechobee	Everglades Phase I	Everglades Phase II
State	Oregon	Colorado	Minnesota	New York	Florida	Florida	Florida
Concern	pH, Blooms, DO	Blooms	Taste & Odor	Blooms, Transparency	Blooms	Ecosystem Imbalance	Ecosystem Imbalance
Numerical Criterion	pH < 9	Chl-a < 15 ppb	Chla < 20 ppb	Secchi > 4 ft	Chla < 40 ppb	Tech-Based	TP < 10 ppb
Time Scale	Daily	Summer	Daily	Daily	Daily	Long-Term	Long-Term
Compliance Rate	90%	90%	90%	?	90%	50%	50%
P Balance Model	Dynamic	Dynamic	Steady State	Steady-State	Dynamic	Steady-State	Dynamic
Phosphorus Goal	Spring	Summer	Summer	Summer	Long-Term	Long-Term Flow-Wtd	Long-Term Geometric
Historical P (ppb)	60	60	60	58	87	170	50
Target P (ppb)	20	35	25	20	40	50	10
Conc Reduction	67%	42%	58%	66%	54%	71%	80%
Other Factors	Background		Treatment Costs	State P Criterion		Technology-Based	Background

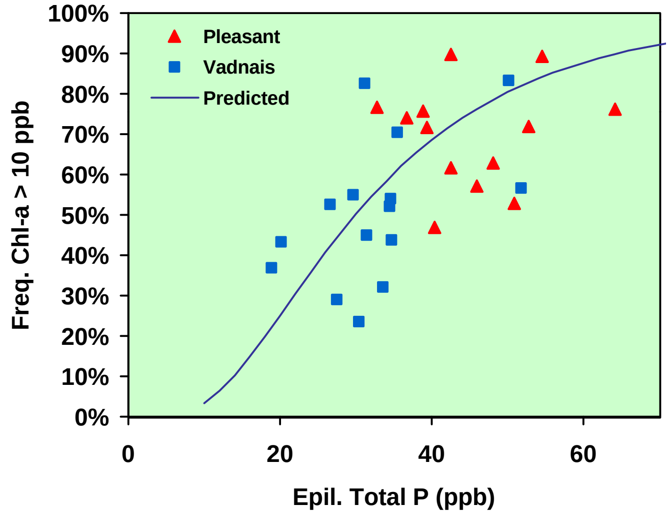

Rice Creek Watershed
Otter Lake Watershed
Upper Mississippi
River Watershed
5 miles
2 miles
9 miles
CHARLEY
CREEK
WILKENSON
DEEP
WILKENSON
CREEK
PLEASANT
BIRCH
GILFILLAN
St. Paul Water Utility
Supply System
SUCKER
GOOSE
LAMBERT
CREEK
VADNAIS
SPWU
INTAKE
WELLS
VADNAIS
CREEK

Algal Bloom Frequency vs. Total Phosphorus



Bloom Frequencies from daily samples at Vadnais Intake & Pleasant Gatehouse
Total Phosphorus concentrations measured in Lake Epilimnion (0- 6 m)
April-September Means for Each Year

Algal Bloom Frequencies vs. Total Phosphorus



Model:

B_a = k P

B_g = B_a / exp (S^2 / 2)

Z* = ln (B* / B_g) / S

Freq (B > B*) = 1 - NORMSDIST (Z*)

Coefficients:

k = 0.4

S = 0.6

Variables:

P = april-sept. epilimnetic mean total p (ppb)

B_a = arithmetic mean chl-a (ppb)

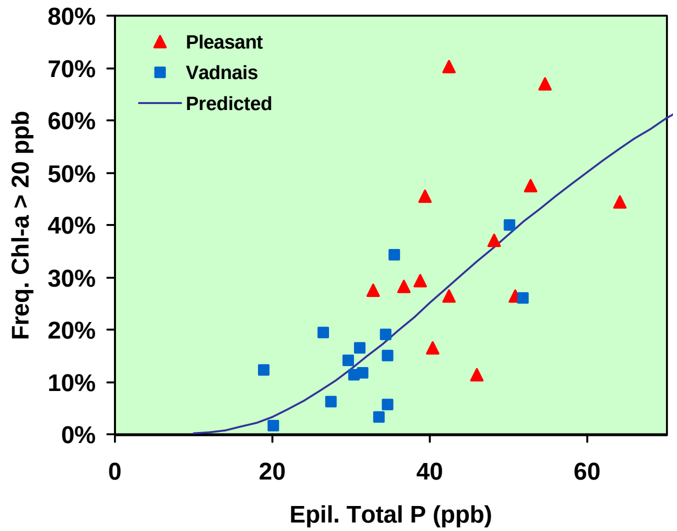
B_g = geometric mean chl-a (ppb)

B* = bloom criterion (ppb)

S = standard deviation of ln(Chl-a)

Z* = standard normal deviate

NORMSDIST = cumulative normal distrib. (Excel)



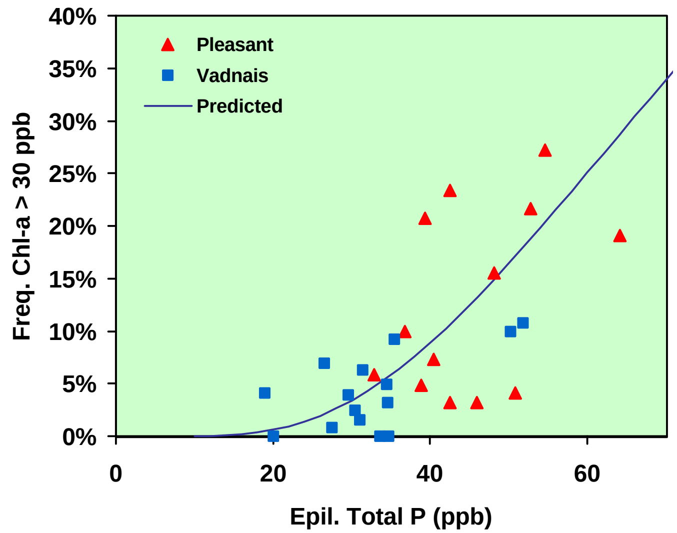
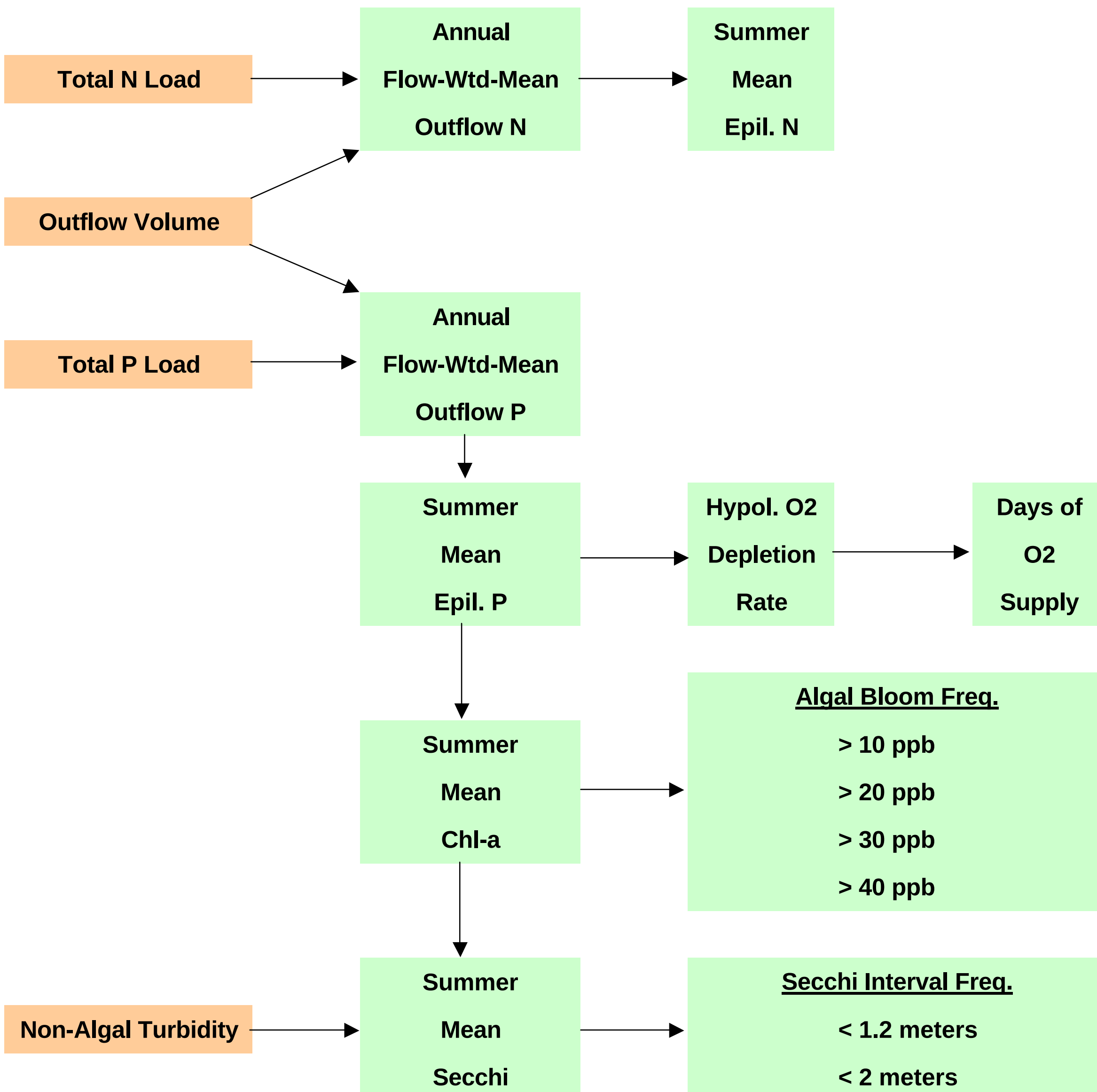
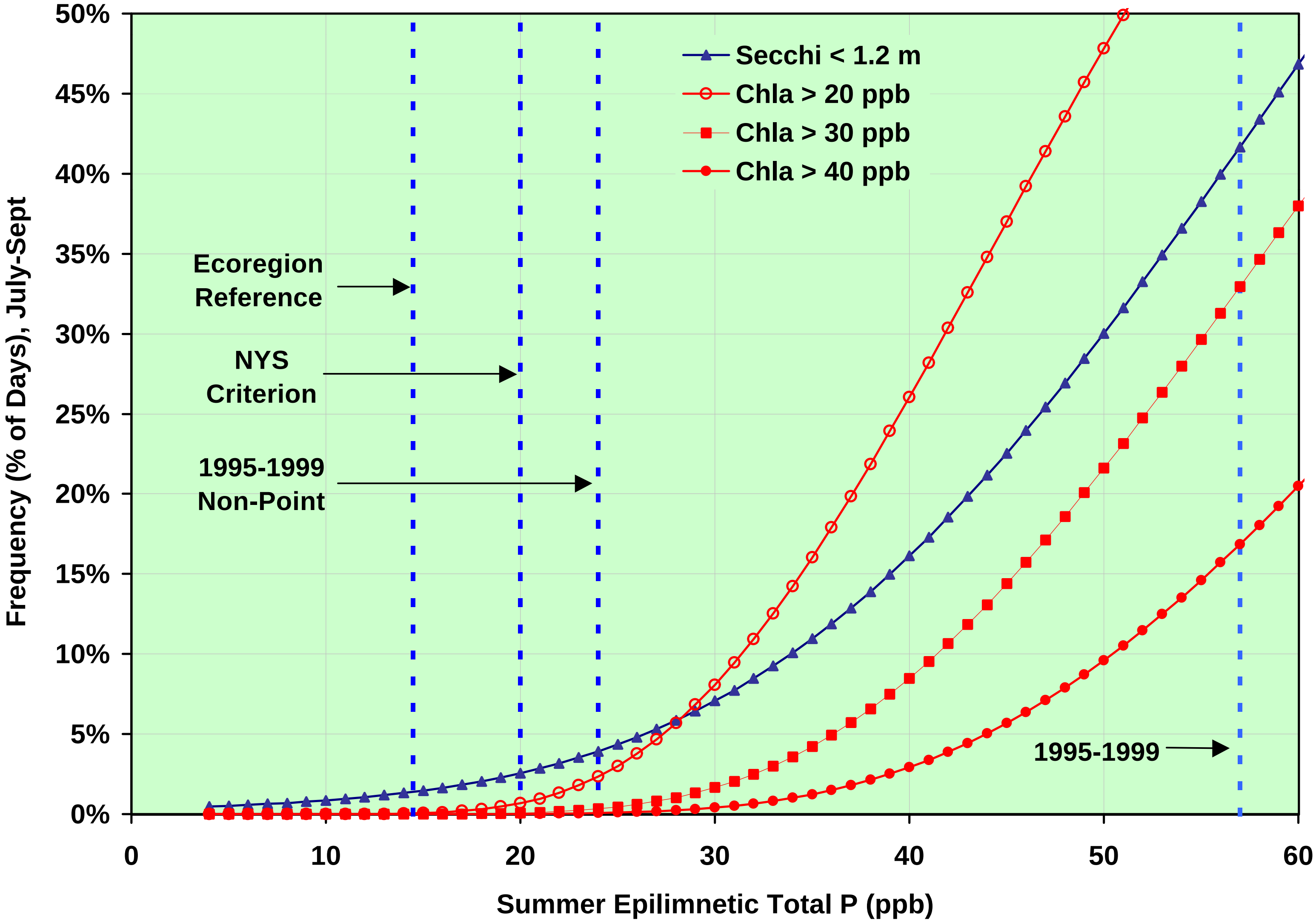


Figure 12-2

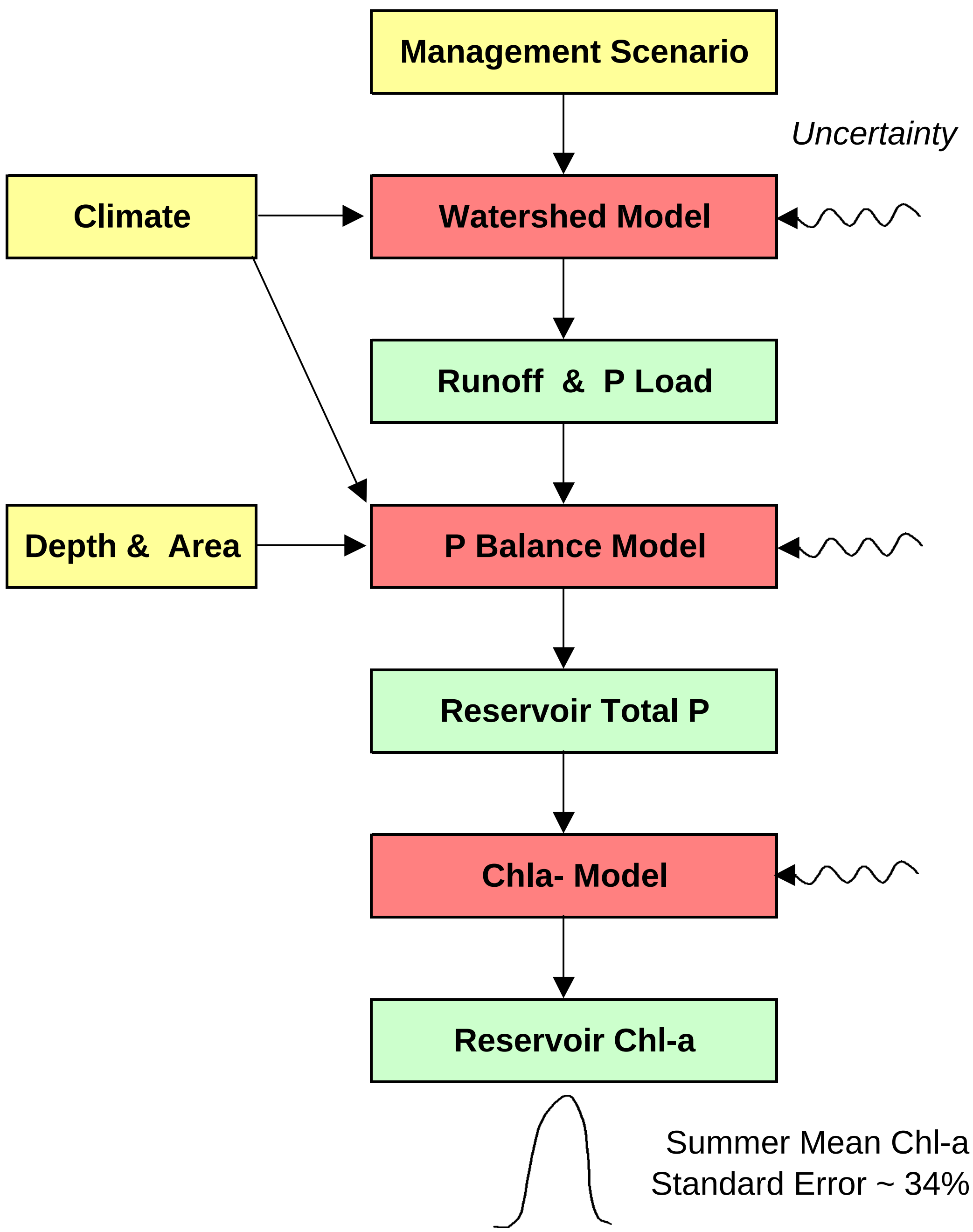
Eutrophication Model Network for Onondaga Lake



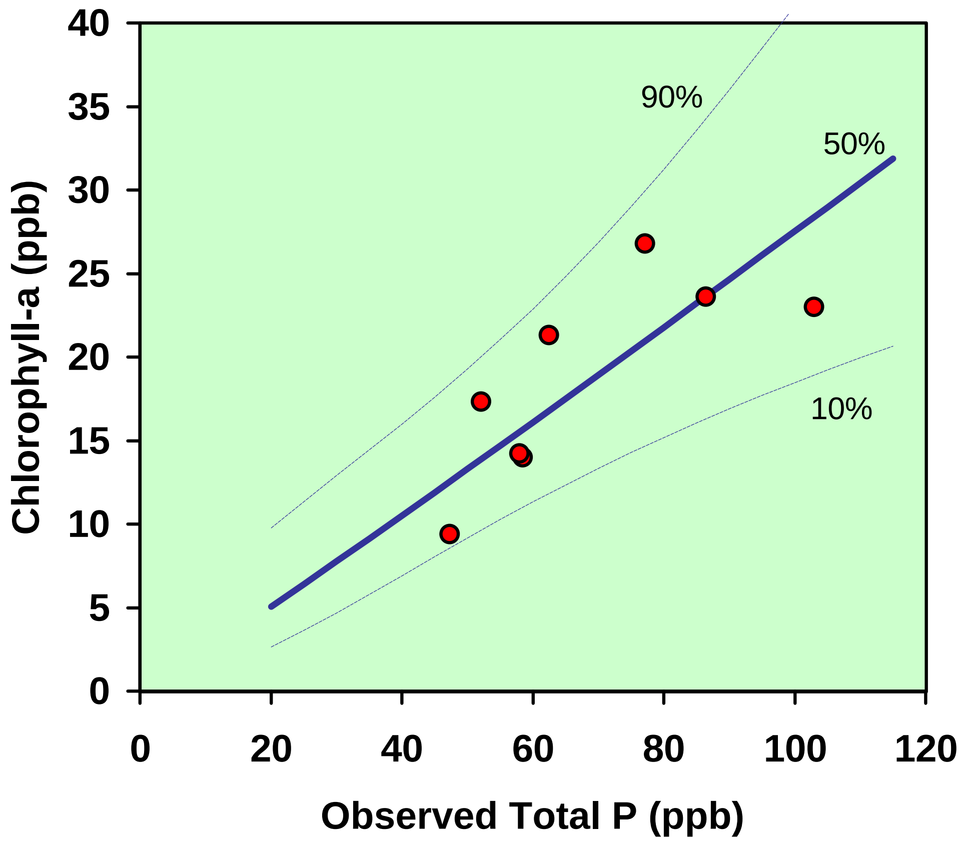
Phosphorus Criteria for Onondaga Lake



Linkage of Models Used to Forecast Reservoir Chlorophyll-a Levels



Prediction Intervals for Chlorophyll-a based upon Observed Total P



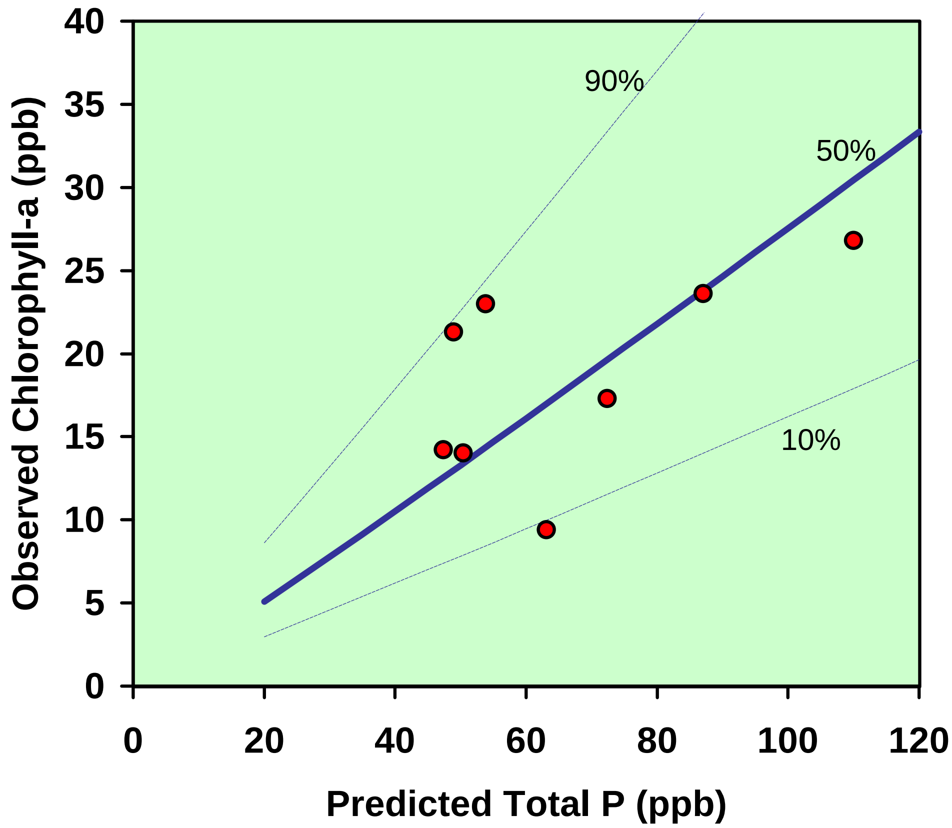
Symbols = Measured July-Sept.mean Chl-a, 1992-1999

X- Axis = Observed July-Sept mean Total P

Lines = Chl-a prediction interval using regression model

Residual Standard Error = 23%

Prediction Intervals for Chlorophyll-a using Coupled Mass-Balance & Regression Models



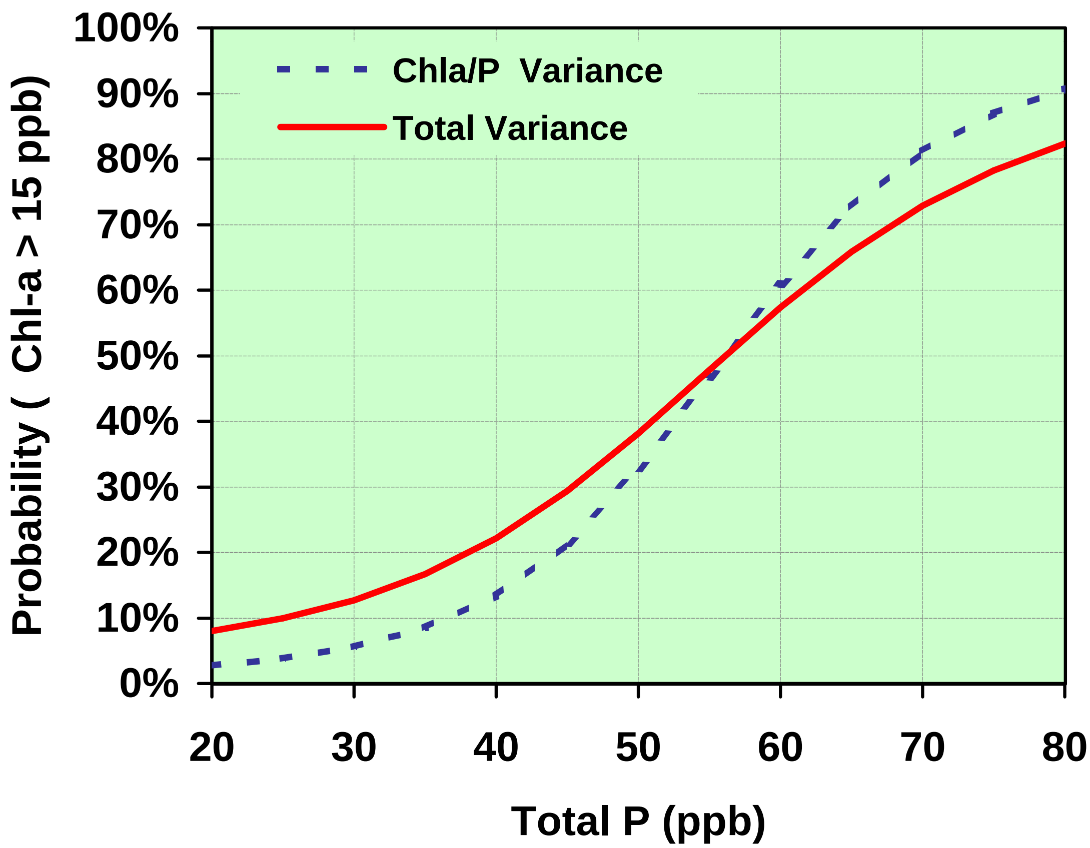
Symbols = Measured July-Sept. Mean Chl-a, 1992-1999

X- Axis = Total P predicted from mass-balance model used in TMDL analysis (Appendix K, Table 2)

Predicted = Chl-a predicted from coupled mass-balance & Chl-a vs. TP regression models

Residual Standard Error = 38%

Risk of Exceeding 15 ppb Chl-a vs. Total P in Any Year

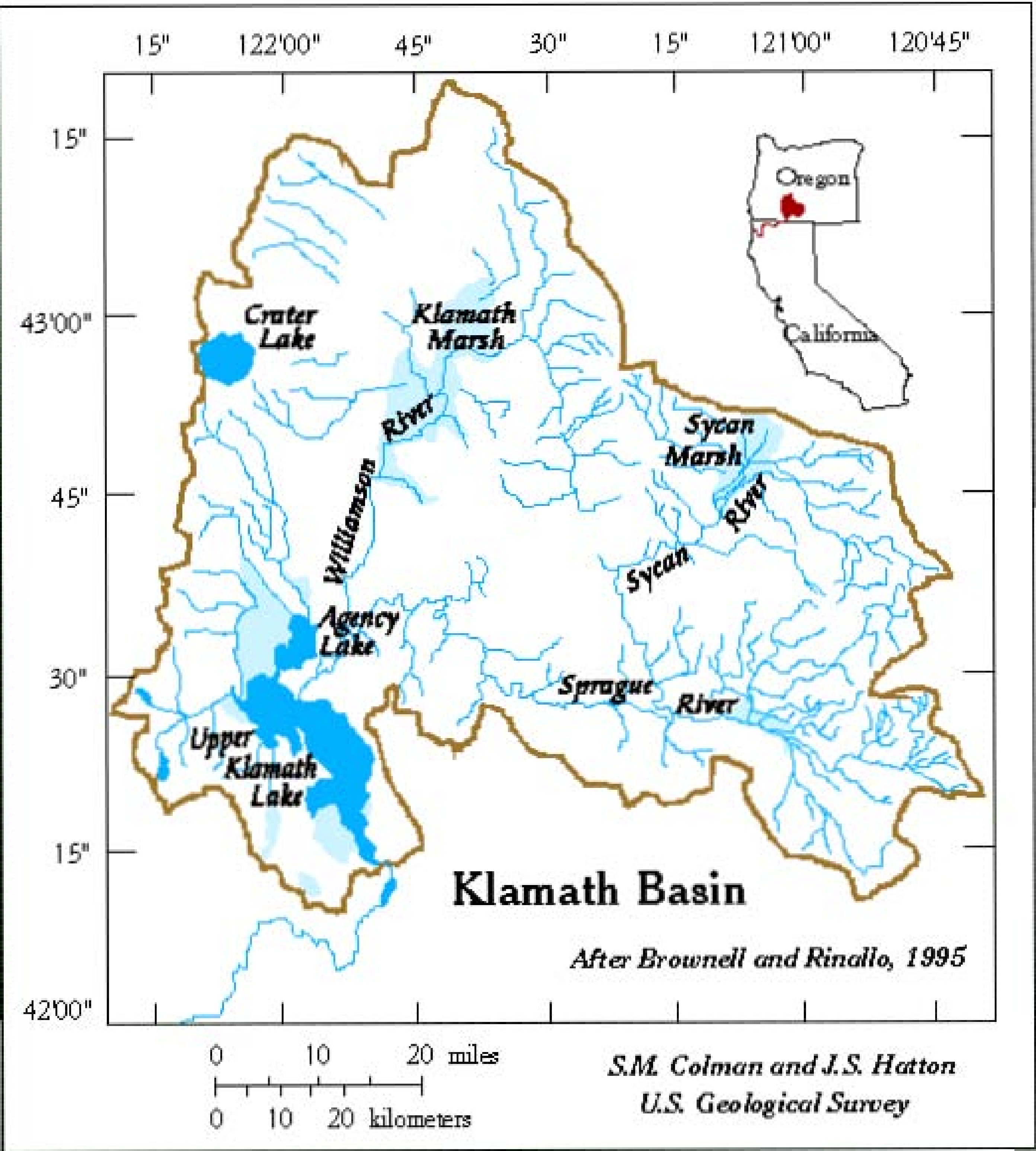


Y-Axis: Probability (July-Sept. Mean Chl-a > 15 ppb)

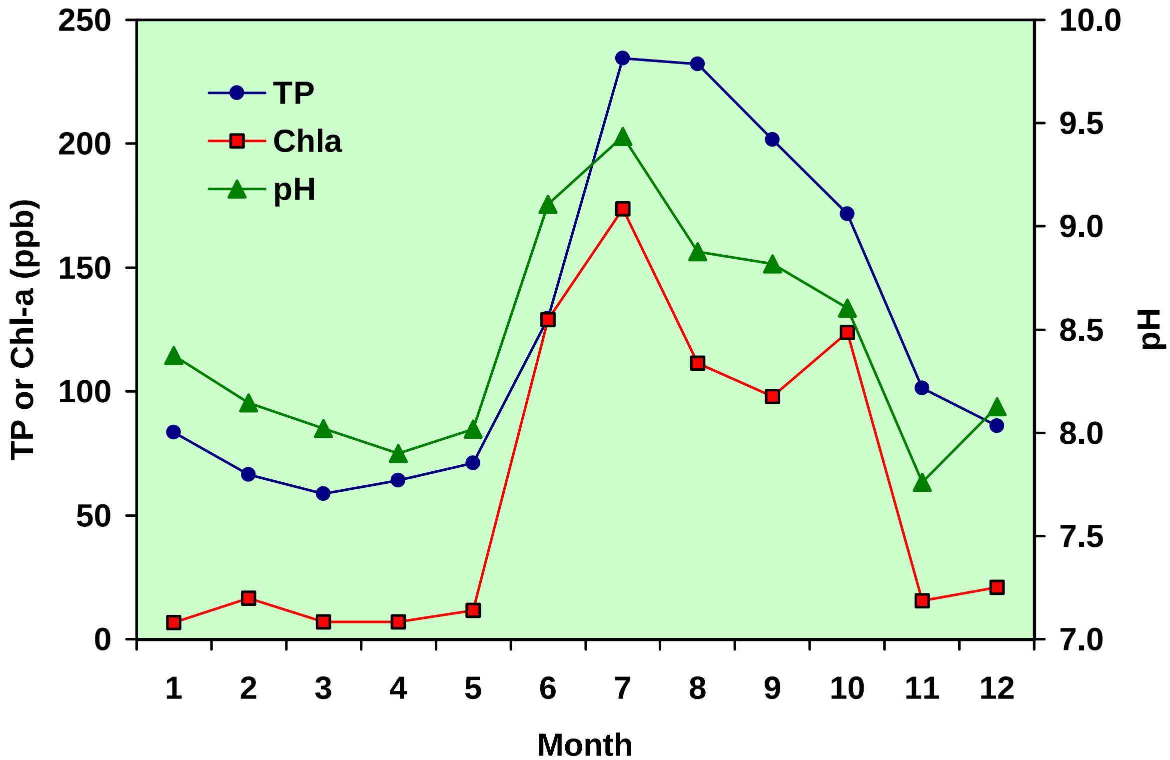
Uncertainty Sources:

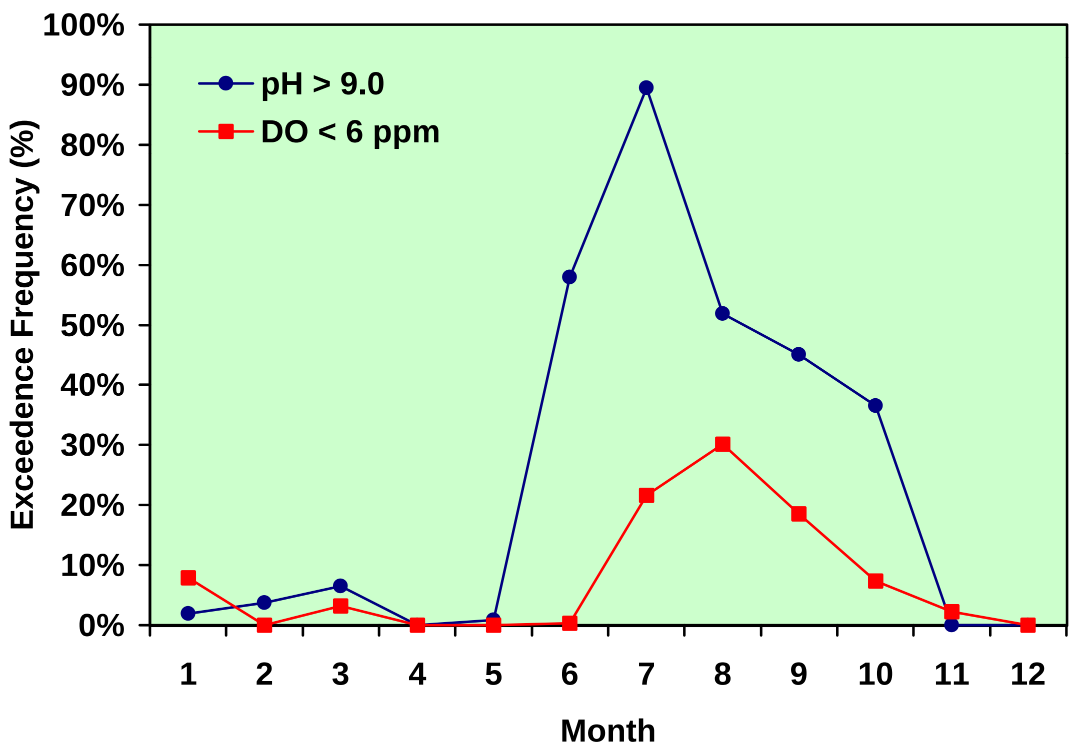
Chl-a/P	Chlorophyll-a vs. Total P Regression
Total	Coupled Mass-Balance Model & Chl-a vs. TP Regression

X-Axis: July-Sept Mean Total P

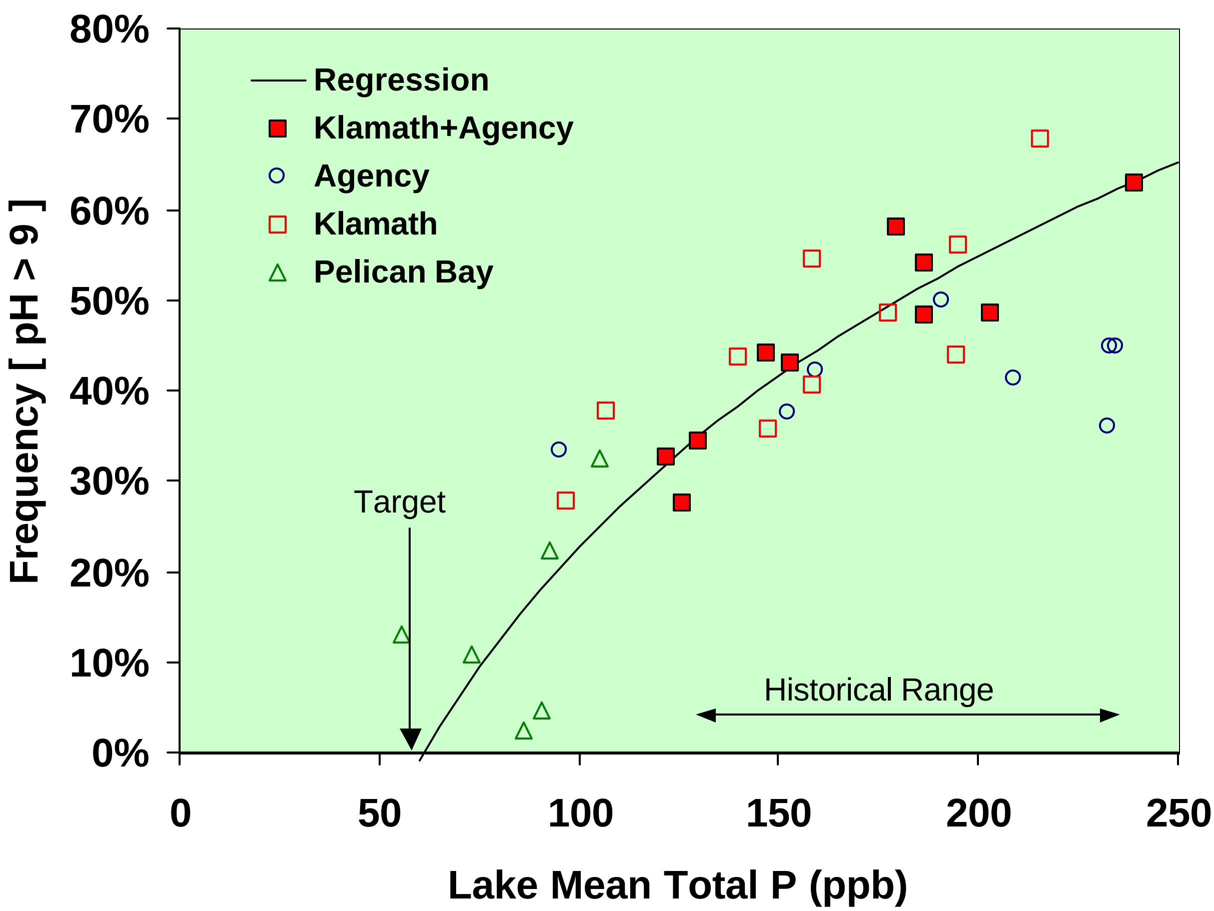

15"
122'00"
45"
30"
15"
121'00"
120'45"
15"
43'00"
45"
30"
15"
42'00"
Oregon
California
Crater Lake
Klamath Marsh
Williamson River
Sycan Marsh
Sycan River
Agency Lake
Upper Klamath Lake
Sprague River
Klamath Basin
After Brownell and Rinallo, 1995
0 10 20 miles
0 10 20 kilometers
S.M. Colman and J.S. Hatton
U.S. Geological Survey

Seasonal Variations - Upper Klamath Lake





Derivation of Phosphorus Target for Upper Klamath Lake for Compliance with pH Standard



Yearly Means by Lake Region, April-October

Frequency = % of Measurements (All Stations & Depths) Exceeding pH 9

DRAFT

Figure 11
Model Structure

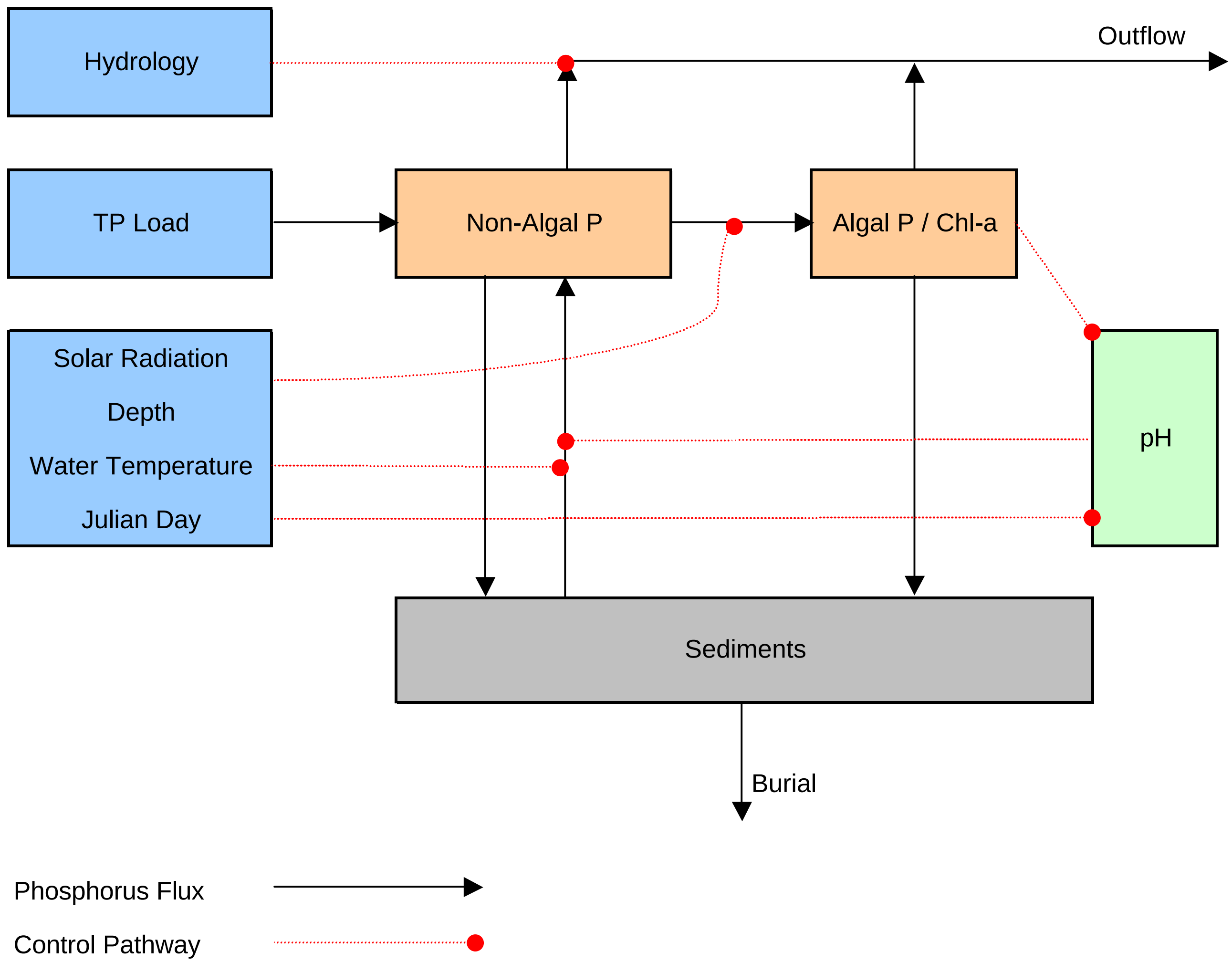
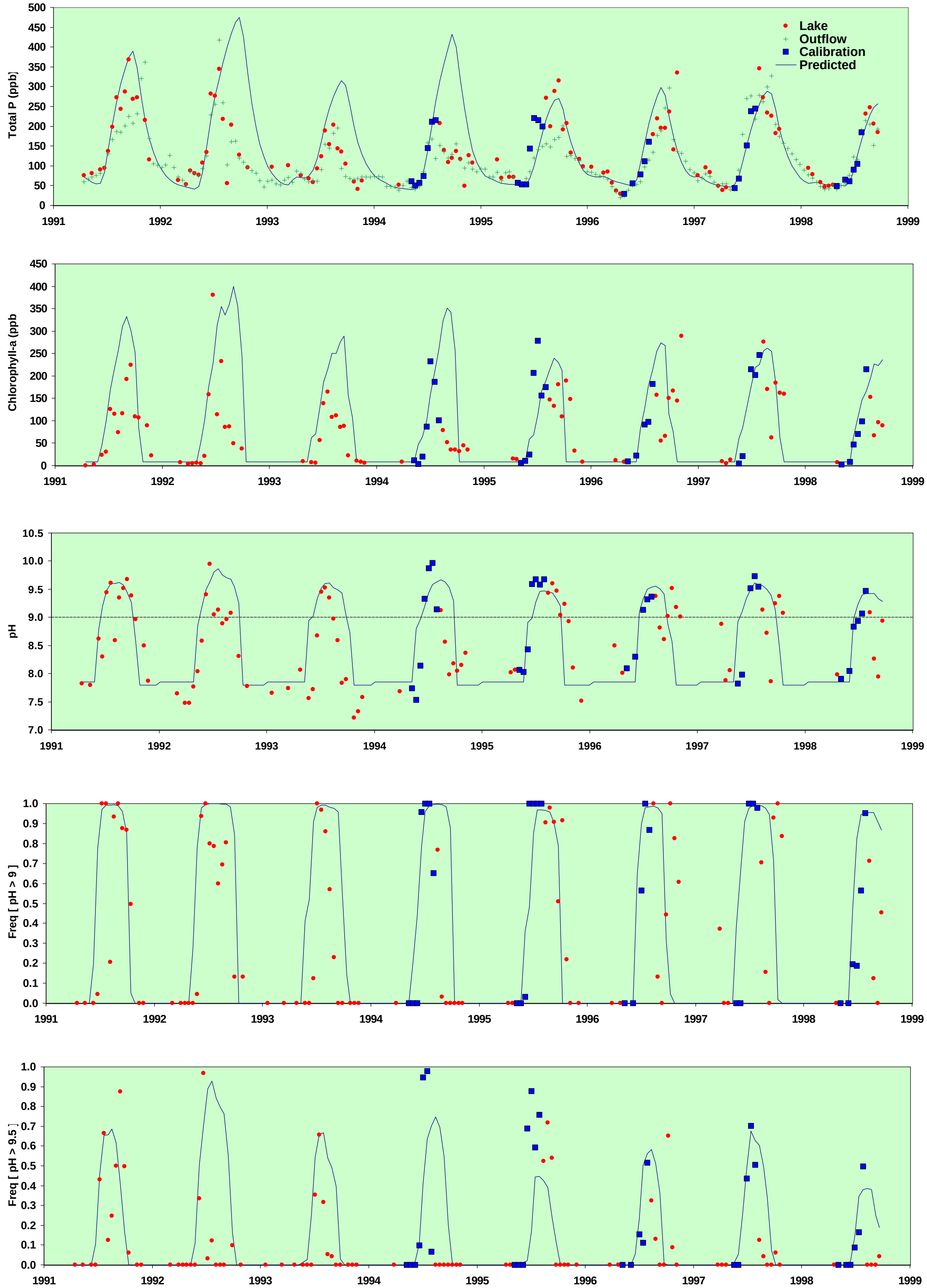
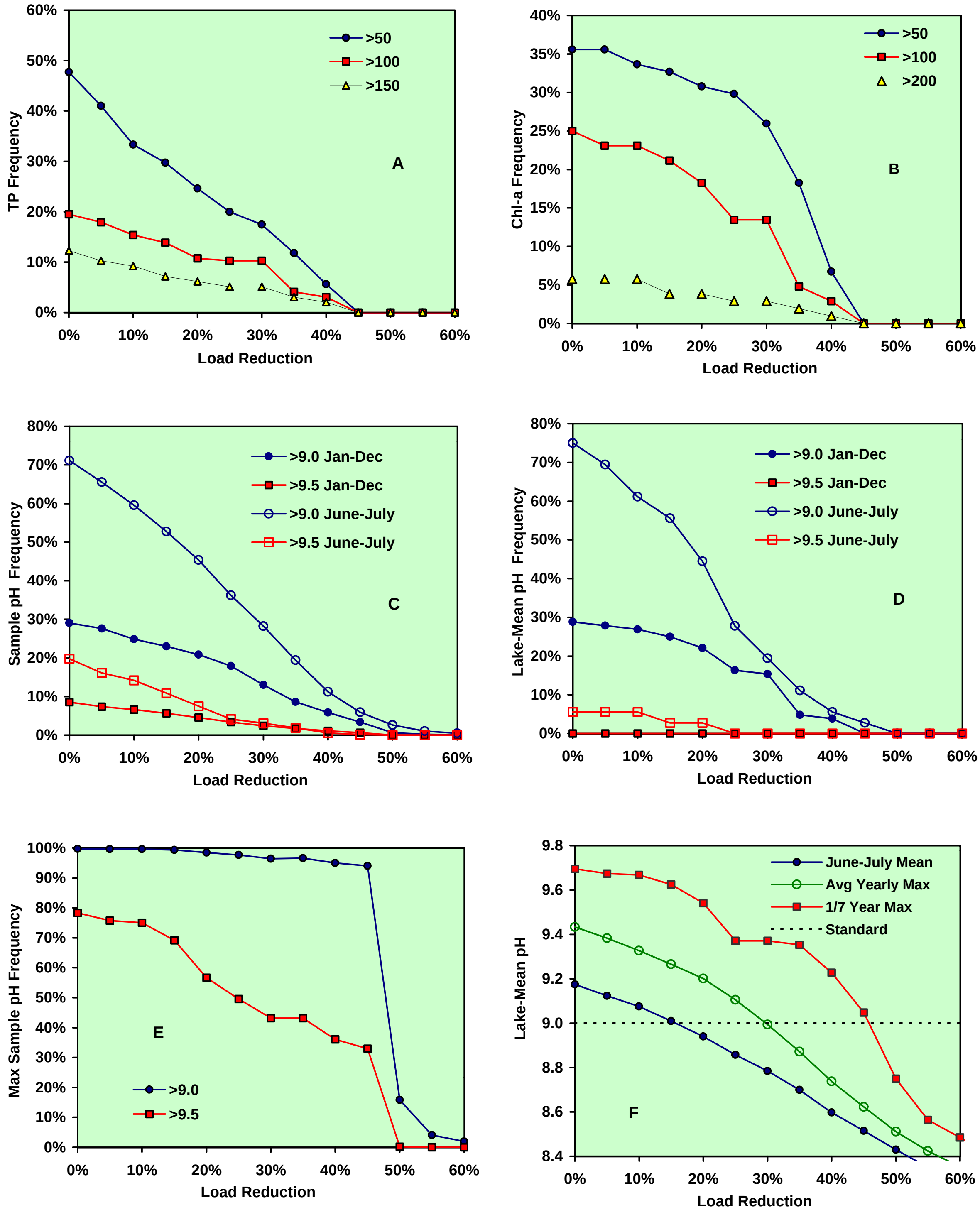


Figure 20
Observed & Predicted Time Series Driven by Phosphorus Loads



Top: Observed Lake P & Outlet P concentrations
Lines: TP, Chl-a, pH, & pH Frequency predicted from external P loads & other controlling factors (light, temp., depth, flushing, etc.)
Squares: Observed values used for model calibration (May-July, 1994-1999)
Circles: Observed values used for model testing

Figure 24
Excursion Frequencies vs. Phosphorus Load Reduction



A,B: Total P & Chl-a Frequencies for January-December, Averaged over 7 Years

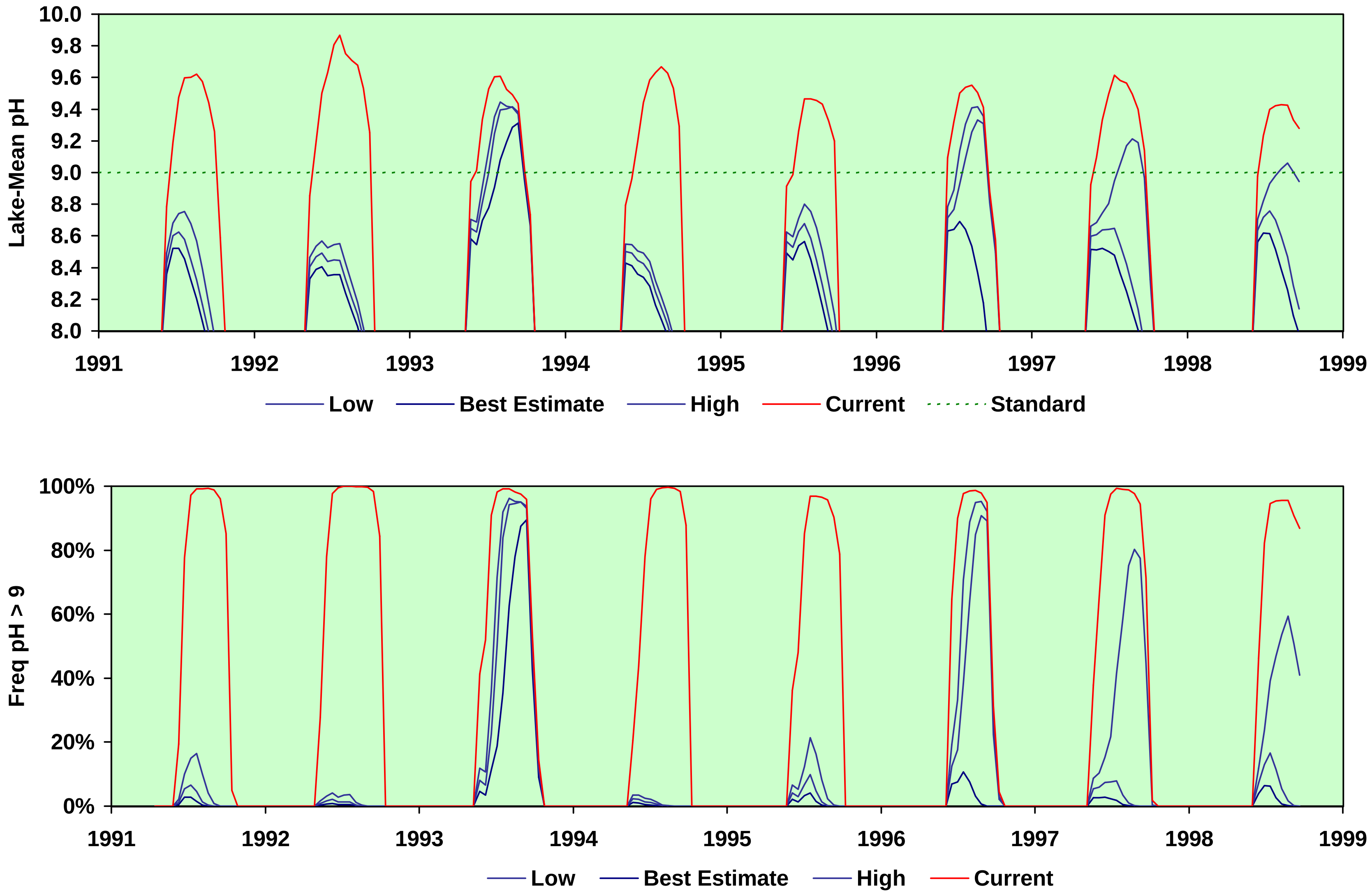
C: % of pH Measurements, Averaged Over 7 Years, For Jan-Dec & June-July

D: % of Lake-Mean pH Values, Averaged Over 7 Years, For Jan-Dec & June-July

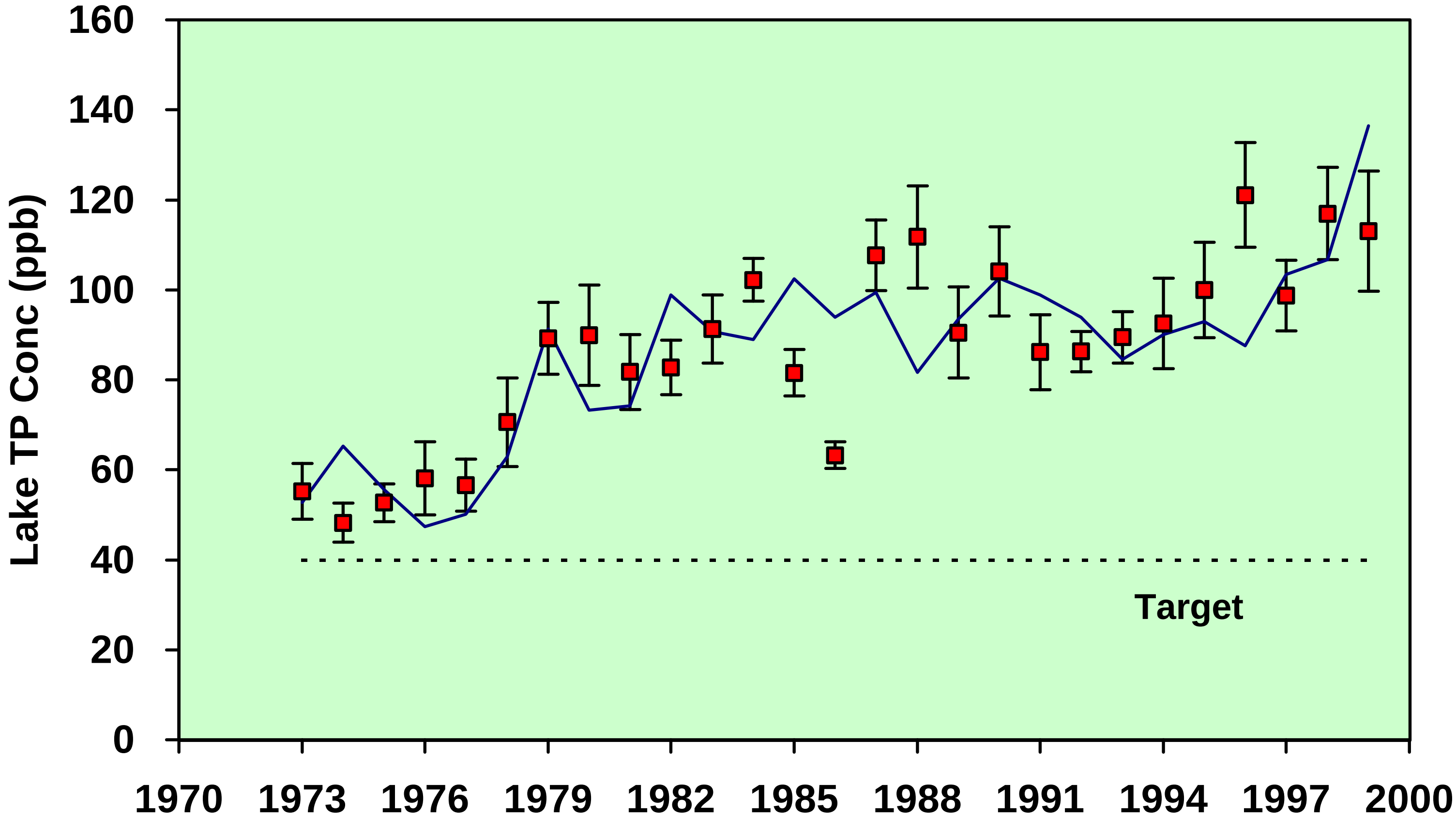
E: Maximum% of Measurements in Any 2-Week Period, All Seasons & Years (i.e., worst-case)

F: Lake Mean pH for June-July (Mean, Mean Yearly Maximum, 1/7 Year Maximum)

Figure 25
pH Simulations with Estimated Background Loads

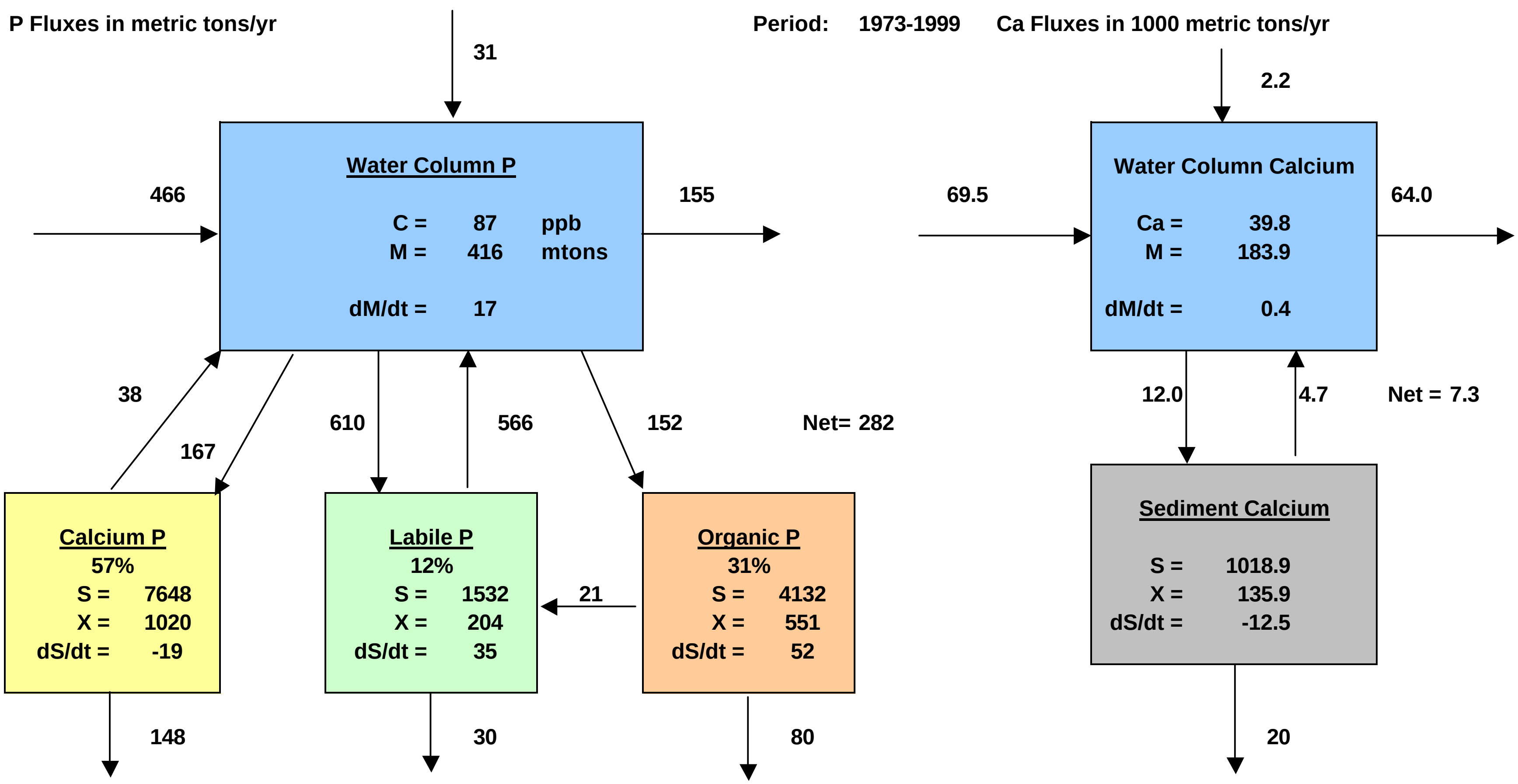


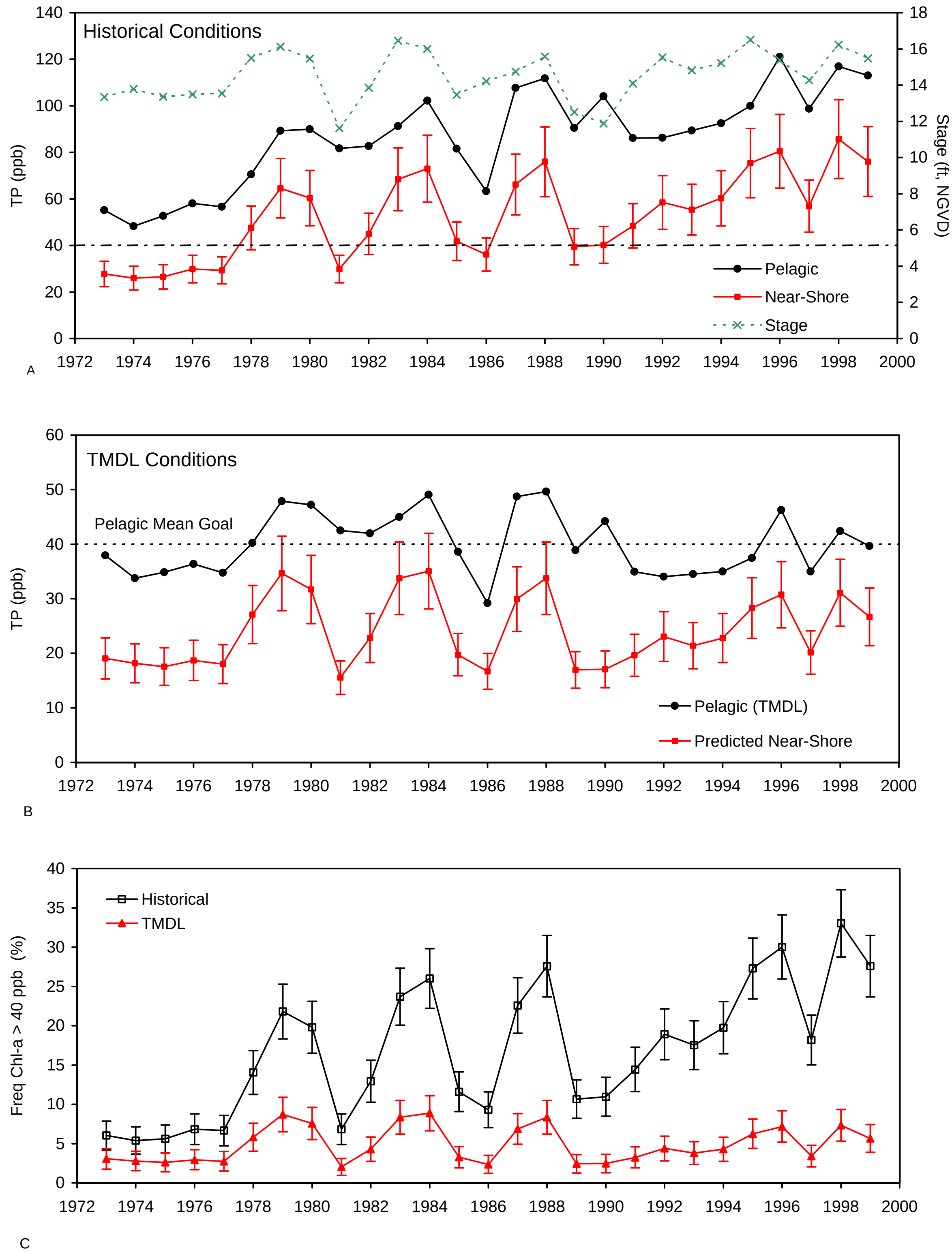
Low, Best Estimate, High = Approximate 80% Confidence Interval for Estimated Background Inflow Concentration (55, 63, & 70 ppb)
Corresponding to Reductions of 33%, 40%, & 47% in 1992-1998 Watershed P Loads



Mass Balance: $dM / dt = L - Q\,C - K_{NET}\,A\,C$

Phosphorus & Calcium Balances





Historical Conditions
TP (ppb)
Stage (ft, NGVD)
Pelagic
Near-Shore
Stage
A
TMDL Conditions
Pelagic Mean Goal
TP (ppb)
Pelagic (TMDL)
Predicted Near-Shore
B
Historical
TMDL
Freq Chl-a > 40 ppb (%)
C