D R A F T - 10/2/2001

CHAPTER 12: MASS-BALANCE MODELING

12.1 INTRODUCTION

The development and structure of a mass-balance modeling framework for Onondaga Lake is described in the 1999 lake monitoring report (Ecologic, 2000). The associated software facilitates computation and analysis of mass balances for nutrients and other water-quality components using hydrologic and water quality data collected in the Lake and its tributaries since 1986 (Figure 12-1). Computed phosphorus and nitrogen mass-balances are linked to en empirical model network for predicting eutrophication-related water quality variables (Figure 12-2). These models provide a basis for predicting summer-average lake responses to reductions in external phosphorus and nitrogen loads resulting from future implementation of point-source and nonpoint-source control measures.

This chapter updates the mass-balance framework to include 1986-2000 data. Recent mass balances for key water quality components are summarized. Long-term trends in total loads (point, nonpoint), inflow concentrations, and outflow concentrations are documented. The eutrophication model network is recalibrated to 1996-2000 data. Data from 1986-1995 are used for model testing. To enable forecasting of lake outflow concentrations for use in Seneca River modeling, the model network is augmented to include predictions of organic nitrogen, inorganic nitrogen, organic carbon, and conservative water-quality components (e.g., chloride, sodium).

12.2 REFINEMENTS TO MASS-BALANCE FRAMEWORK

The mass-balance software (Figure 12-1) computes lake outflow loads using flows estimated from a water balance and three alternative sources of concentration data (Outlet

2-ft, Outlet 12-ft, and Lake South Epilimnion[1]). Detailed comparisons of 1991-2000 data from these three sources have been performed in preparing datasets for use in the Seneca River modeling effort (Walker, 2001). Good correlations are apparent between the Lake South Epilimnion and Outlet 12-ft samples for all major water quality components. Figure 12-3 shows results for chloride, total phosphorus, and ammonia nitrogen. Samples collected between 0 and 3 meters are assumed to represent the upper mixed layer, which is typically used and to approximate the epilimnion average. Concentrations in the Outlet 2-ft samples are frequently below those in the 12-ft and Lake South samples, apparently because of backflows from the River. The Outlet 12-ft samples are collected year-round and are therefore more suitable than the Lake South samples for annual budget calculations. Based upon these results, mass-balances are reported below using the Outlet 12-ft samples to compute outflow loads. For comparison purposes, results using the other data sets are also reported in the summary output (e.g., Tables 12-2, 3, & 4).

The existing framework does not consider exchange between the Lake and River as a component of the lake mass balance. Depending upon whether river concentrations are greater than or less than lake concentrations, hydraulic exchange would represent an additional net input or output from the Lake, respectively. Based upon concentration differences shown in Figure 12-3 and assuming that Outlet 2-foot samples are influenced by the River, the exchange term would represent an additional net outflow from the Lake in the case of chloride and ammonia nitrogen, but have little influence on the lake phosphorus budget under 1991-2000 conditions. With future reductions in lake

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[1] Although labeled “epilimnion” the Lake South values are the averages of 0 to 3 meter samples. These provide estimates of concentrations in the upper mixed layer, which are typically used in empirical eutrophication models (Walker, 1996). Computation of the true epilimnetic average would require consideration of variations in thermocline depth with sampling date. The 0-3 m averages approximate the epilimnetic averages to the extent that vertical variations in concentration above the thermocline are small.

phosphorus concentrations, however, exchange with the River may become a more important source of phosphorus.

Lack of long-term data on the magnitude of the exchange flow and year-round variations in River concentrations currently precludes consideration of the exchange term in the existing mass-balance software. Exchange would be sensitive to density differences, wind, lake elevations, and river elevations. The River hydraulic model currently under development (Chapter 11) may provide a basis for estimating exchange flows. Future analysis of the magnitude and potential significance of this term is recommended.

12.3 LOADING & CONCENTRATION TRENDS

The following figures show trends in each water quality component over the entire period of record (1986-2000):

Figure 12-6	Total Inflow & Outflow Concentrations
Figure 12-7	Total Inflow & Outflow Loads
Figure 12-8	Total NonPoint & Total Metro Loads

Ten-year (1991-2000) trends in concentration and load for each mass-balance term and water quality component are summarized in Table 12-1. Trends are tested using a linear regression of flow-weighted-mean concentration or load against year. Trend slopes that are significantly different from zero ($p < .10$) are listed.

For total inflows, decreasing trends in concentration and/or load are indicated for alkalinity, calcium, ammonia, nitrite, soluble reactive phosphorus, total Kjeldahl nitrogen, total organic carbon, total inorganic carbon, and total phosphorus, while an increasing trend is indicated for nitrate nitrogen. Corresponding results for the Metro and Total Municipal (Metro+Bypass) terms suggest that Metro improvements are primarily responsible for the long-term trends in total inflows to the Lake. For the lake outflow, significant decreasing trends in concentration and/or load are indicated for alkalinity, calcium, 5-Day BOD, ammonia nitrogen, total organic carbon, total inorganic carbon, total nitrogen, and total phosphorus.

Flows for Crucible Steel (Trib 5A) increased by about a factor of five in 2000, relative to values reported in previous five years (mean = 3.7 cfs vs. 0.7 cfs). The increase was apparently associated with a change in flow measurement methodology. Flows prior to 2000 were based upon reports provided by the industry. Flows in 2000 were metered directly by the County. It is unclear whether this discrepancy reflects an actual change in flows, errors in the historical values, or errors in the metered flows. This issue should be resolved because it influences the accuracy of the mass balances, model calibrations, and lake outflows used in the Seneca River modeling effort.

12.4 CHLORIDE BALANCES

The 1996-2000 average mass balance for chloride is listed in Table 12-2. Calculations have been performed using procedures described in the 1998 and 1999 annual reports. The average outflow chloride load in Water Years 1996-2000 exceeded the inflow load by 16 ± 3 %. In contrast, inflow and outflow loads for 1995-1999 (as presented in the 1999 Monitoring Report) differed by 1%. The divergence occurs when the 12-foot Outlet (or Lake Epilimnion) samples are used to compute outflow loads, instead of the Outlet 2-foot samples, as assumed in the 1999 Report. For reasons discussed above, the 12-foot Outlet samples are now considered to be more representative of flows leaving the lake. Figure 12-4 compares yearly inflow and outflow (12-ft) loads for chloride, sodium, and calcium for the 1986-2000 period. When evaluated on a yearly basis (Figure 12-4), outflow loads exceed inflow loads by ~10-20% in most years for chloride and sodium, but not for calcium. Results suggest the existence of an additional source of chloride and sodium that is not considered in the existing mass-balance framework.

Given the consistent year-to-year pattern and the precision of the load estimates, it is unlikely that the deviations reflect random variations in sampling and load computations for individual monitored streams. It is possible that loads from the ungauged portion of the watershed (~5% of the total drainage area) are under-estimated. Ungauged loads are estimated by multiplying the gauged nonpoint loads by the ratio of the ungauged to the gauged drainage areas. This procedure assumes that unit area loading rates (reflecting land use, etc.) are uniform across the watershed. Given the greater intensity of development around the shore of the Lake, as compared with the watershed as a whole, it is possible that this procedure under-estimates ungauged loads for some water quality components.

Variations in the drainage area estimates for each tributary is another factor contributing to uncertainty in ungauged loadings. Drainage areas reported by the USGS at stream gauging stations are not entirely consistent with results derived from recent GIS databases (see Table 1.2). For example, the USGS reports a drainage area of 115 km^2 at the Ninemile Creek flow gauge at Lakeland, as compared with 110 km^2 reported in Table 1.2 for the entire watershed. Given the potential importance of nonpoint loads in evaluating existing and future scenarios for the Lake, refinements to the procedure for estimating ungauged loads are recommended. Placing the existing monitoring network (flow & water quality stations) on a GIS layer would enable delineation of drainage areas (and corresponding land uses) above and below each monitoring point. This would permit more accurate estimation of ungauged flows & loads.

It is possible that chloride loads resulting from application of deicing salts to roads and parking lots in the urbanized areas around the lake shoreline may not be reflected in the existing estimates. Chloride spikes occasionally observed in the Metro effluent, Ley Creek, & Harbor Brook during winter and early spring months may reflect road salt contributions. Significant spikes may escape detection under the biweekly sampling program. Regardless of sampling frequency, the unit loads of road salts from areas below the monitoring gauge on each watershed may be higher because of the greater density of roads and parking lots. The potential importance of deicing salts could be further evaluated by compiling local data on application rates and road/parking lot surfaces in each subwatershed.

Ungauged groundwater inputs could also contribute to the divergence in the sodium and chloride budgets. This explanation is consistent with the existence of a saline groundwater wedge flowing north in the Onondaga Creek watershed, as documented by the USGS (ref, ???). In Water Years 1996-2000, the unit area chloride load for the Onondaga Creek watershed between the Dorwin Avenue and Kirkpatrick/Spencer monitoring stations was 702 mtons/km^2/yr, as compared with 59 mtons/km^2-yr above Dorwin Ave and (Table 12-2). Corresponding values for sodium are 459 mtons/km^2-yr and 35 mtons/km^2-yr, respectively. The ratio of sodium to chloride inputs in this river reach (0.65) is similar to the Na/Cl ratio of sodium chloride (0.66). Future analysis of USGS results may provide a basis for estimating groundwater inflows and associated sodium chloride loads potentially resulting from this mechanism. Consideration of groundwater inputs in the mass-balance framework would require monitoring of groundwater quality.

12.5 EUTROPHICATION MODEL

This section describes refinements and updates to the empirical eutrophication models described in the 1999 Lake Monitoring Report (Ecologic, 2000). To support the Seneca River modeling effort, the model network is expanded to include predictions of organic carbon, organic nitrogen, and inorganic nitrogen (Figure 12-2). Data from the last 5 years (1996-2000) are used for model calibration. Hindcasts of 1986-1995 data are used for model testing. Average phosphorus and nitrogen balances during the model calibration period are listed in Tables 12-3 and 12-4, respectively. Relevant input and observed data listed in Table 12-5. Updated model coefficients and equations are listed in Table 12-6. Model derivations and assumptions are described in the 1999 Lake Monitoring Report (Ecologic, 2000).

The model network is driven by hydrologic and nutrient loading time series formulated on a water-year basis (Figure 12-5). Total precipitation in WY 2000 (33.1 inches) was slightly below the 15-year average (37.7 inches). Total phosphorus loads generally declined over the 1986-2000 period, with the exception of 1993, when Metro bypass flows were relatively high. Total nitrogen loads declined steadily over the 1996-2000 period. As discussed above, Metro improvements were primarily responsible for reductions in phosphorus & nitrogen loads.

Empirical eutrophication models generally assume that algal growth is limited by phosphorus. Figure 12-9 shows total and soluble reactive phosphorus (SRP) concentrations in the epilimnion (July-September means, 0-6 m, Lake South) between 1986 and 2000. Relatively high SRP concentrations prior to ~1996 indicate that phosphorus was not limiting algal growth. It is likely that factors such as light and zooplankton grazing were controlling. The Lake approached a phosphorus-limited condition in recent years as the concentration of total phosphorus reached 50-60 ppb and SRP levels dropped below 5 ppb (< 2 ppb in 1999-2000). Given the increasingly P-limited conditions, it is likely that trophic state indicators (chlorophyll-a, transparency) will respond to future P reductions more dramatically than they have to historical P reductions.

By using data from 1996-2000 for calibration, the model network is tuned to a phosphorus-limited condition. When applied to data from years prior to ~1996, concentrations of chlorophyll-a, organic nitrogen, organic carbon, and oxygen depletion rate tend to be over-predicted (and transparency, under-predicted) because factors other than phosphorus were limiting algal growth. This does not restrict use the models to evaluate management strategies, however, because the Lake is expected to become increasing phosphorus limited with further reductions in phosphorus loads associated with future scenarios. Given the empirical nature of the models, periodic recalibration will be appropriate as the degree of phosphorus limitation increases with continued improvements in lake water quality.

Model equations and parameter estimates are updated in Table 12-6. Observed & predicted values of variables previously included in the model network shown in the following figures:

12-10 Observed & Predicted Time Series – All Variables
12-11 Observed & Predicted Annual Outflow Total P Concentrations
12-12 Observed & Predicted Summer Total P Concentrations
12-13 Observed & Predicted Annual Outflow Total N Concentrations
12-14 Observed & Predicted Summer Total N Concentrations
12-15 Observed & Predicted Mean Chlorophyll-a
12-16 Algal Bloom Frequencies vs. Observed Mean Chlorophyll-a
12-17 Algal Bloom Frequencies vs. Predicted Total Phosphorus
12-18 Algal Bloom Frequencies vs. Year
12-19 Calibration of Secchi Depth Model
12-20 Observed & Predicted Secchi Depths
12-21 Secchi Interval Frequencies vs. Mean Secchi
12-22 Observed & Predicted Frequency of Secchi < 1.2 meters
12-23 Observed & Predicted Frequency of Secchi < 2 meters
12-24 Observed & Predicted Hypolimnetic Oxygen Depletion Rate

Generally, recalibration to 1996-2000 data has relatively small effects on the model coefficients, relative to the previous 1995-1999 calibrations (Ecologic, 2000). Reductions in the phosphorus settling rate from 22.9 to 19.9 m/yr (Figure 12-11) and in the total nitrogen settling rate from 24.0 to 14.2 m/yr (Figure 12-13) primarily reflect switching from 2-foot to 12-foot samples as measures of lake outflow concentration. With this change, the standard error of summer epilimnetic total nitrogen concentration decreases from 0.10 to 0.05 (Figure 12-14), while the standard error of total phosphorus concentration is unchanged (0.08, Figure 12-12).

Concentrations of organic nitrogen and organic carbon in the epilimnion reflect direct inputs from the watershed and primary productivity within the lake. The latter converts inorganic nutrients to organic nutrients associated with live & dead algal cells, zooplankton, detritus, dissolved organics, etc. Predictions based upon phosphorus concentrations or loads assume direct inputs from the watershed are relatively constant or small relative to inputs from lake primary productivity (Walker, 1983; 1985; 1996). The importance of external inputs would depend upon the their removal rates (sedimentation, decomposition) relative the flushing rate of the epilimnion during the summer (~0.01 day $^{-1}$). It is likely that the lake outflow contains both watershed-derived forms (e.g., dissolved or colloidal species relatively resistant to decomposition), as well as dissolved and particulate species generated as a result of primary production within the Lake. The relative importance of the latter can be assessed based upon correlations with chlorophyll-a and/or total phosphorus. Consistent with other trophic response variables, correlations with total phosphorus would apply after 1995, when the lake approached a phosphorus-limited condition.

Figure 12-25 plots organic carbon and organic nitrogen concentrations against chlorophyll-a concentrations predicted by the model network (Figure 12-2). Linear regressions explain 92% and 54% of the variance in the 1996-2000 data, with residual standard errors of 4% and 22%, respectively. The data are compared with regression models previously calibrated to various nationwide data sets (Walker, 1983; 1985; 1996). Results are also compared with estimated organic nutrient fractions associated with algal cells using typical algal stoichiometry (Redfield ratios) reported by Chapra (2001). The 1996-2000 regression slopes are near the upper ends of ranges expected based upon algal stoichiometry. This is consistent with the fact that portions of the organic nutrient pools are associated with algal detritus, zooplankton, and decomposition products that reflect algal productivity but are not directly associated with algal cells.

Lake organic nitrogen concentrations in recent years are reasonably consistent with predictions of an empirical model derived a nationwide reservoir dataset (Walker, 1985). TOC levels are significantly below predictions of a model derived from a different nationwide dataset (Walker, 1983). This suggests that levels of autochthonous (watershed-derived) organic carbon in Onondaga Lake are low relative to the latter dataset, which was derived primarily from reservoirs. It is possible that higher reservoir TOC levels reflect higher average flushing rates (lower hydraulic residence times) and/or regional factors.

Observed and predicted organic carbon and nitrogen values are plotted against predicted total phosphorus and time in Figures 12-26 and 12-27, respectively. For consistency with the plot formats used for other response variables, Organic C and N regressions against chlorophyll-a have been re-expressed as functions of predicted total phosphorus concentrations. As observed for the other trophic response variables, the models tend to over-predict organic nutrient concentrations in years prior to 1996, when factors other than phosphorus limited algal growth.

Summer epilimnetic total inorganic nitrogen (TIN) concentrations (Figure 12-28) can be predicted by linking the total nitrogen model (Figures 12-13 & 14) and organic nitrogen (Figure 12-27) models. Results explain 38% of the variance in the TIN levels observed in 1996-2000, with a residual standard error of 22%. Observed ammonia nitrogen levels are also plotted against time in Figure 12-27. With increased nitrification at Metro, ammonia levels in the Lake South epilimnion decreased significantly over the 1996-2000 period. In July-September 2000, mean total inorganic nitrogen levels consisted of 84% nitrate, 7% nitrite, and 9% ammonia. With future reductions in Metro and/or nonpoint ammonia loads, further decreases in Lake nitrite & ammonia levels would be expected. Thus, inorganic nitrogen levels predicted by the model network under future scenarios will primarily reflect nitrate nitrogen.

12.6 MODEL IMPLEMENTATION

The model workbook has been updated to reflect the recalibration and enhancements (Table 12-7). Predictions are driven by lake outflow volume, inflow total phosphorus load, and inflow total nitrogen load, each referenced to a specified hydrologic period of record.

The predicted response of each trophic state indicator to variations in phosphorus load is shown in Figure 12-29. Results are for average 1996-2000 hydrologic conditions (outflow volume = 435 hm^3/yr). The 80% prediction interval (10th, 50th,90th percentiles) is shown for each response variable. These intervals reflect the combined influences of sampling variations (uncertainty in loads and measured responses) and model error.

The following table updates (vs. Ecologic, 2000) projected lake phosphorus concentrations for various management scenarios involving combinations of Metro effluent P levels & nonpoint source load reductions:

	Total P Concentrations (ppb)				
	Assumed Inflow Concs.		Predicted Lake Conc.		
Scenario	Metro	NonPoint	Mean	10 %	90 %
Existing (1996-2000)	429	78	52	46	60
April 2006	120	78	30	26	34
April 2006 + 20% NPS	120	62	26	22	29
Dec 2012	20	78	22	20	26
Dec 2012 + 20% NPS	20	62	18	16	21
Metro Diversion	0	78	25	21	28
Diversion + 20% NPS	0	62	20	17	23

Lake P levels approach the 20 ppb criterion for management scenarios involving control of Metro load (either by diversion or by achieving the 2012 effluent P level of 20 ppb) and ~20% reduction in nonpoint load. These projections differ only slightly from those derived from the previous calibration of the model (Ecologic, 2000).

12.7 CONCLUSIONS & RECOMMENDATIONS

Conclusions based upon the above analysis are summarized below:

1. Primarily as a consequence of Metro improvements, loadings and in-lake concentrations of total phosphorus and total nitrogen in 2000 were the lowest observed in the 1986-2000 period of record.

2. Over the last 10 years (1991-2000), decreasing trends in the total lake inflow concentration and/or load are indicated for alkalinity, calcium, ammonia, nitrite,

soluble reactive phosphorus, total Kjeldahl nitrogen, total organic carbon, total inorganic carbon, and total phosphorus, while an increasing trend is indicated for nitrate nitrogen. Significant decreasing trends in lake outflow concentration and/or load are indicated for alkalinity, calcium, 5-Day BOD, ammonia nitrogen, total organic carbon, total inorganic carbon, total nitrogen, and total phosphorus.

3. As a consequence of cumulative reductions in phosphorus load, phosphorus limitation has become increasingly important as a factor controlling algal growth in the Lake. Summer epilimnetic soluble reactive phosphorus concentrations averaged <5 ppb in 1996-1998 and <2 ppb in 1999-2000. Chlorophyll-a, transparency, organic nitrogen, and hypolimnetic oxygen depletion rates approached levels that are consistent with predictions of empirical models calibrated to data from other phosphorus-limited lakes. Calibration of the model network to recent years with increased phosphorus limitation improves accuracy and precision for predicting responses to further reductions in phosphorus load.

4. Based upon analysis of outlet and epilimnetic time series, samples collected at 12 feet are considered to be more representative of flows leaving the lake, as compared with samples collected at 2 feet previously used to calibrate the annual phosphorus and nitrogen balance models. Calibration to 12-foot samples reduces the standard errors of predicted annual outflow and summer epilimnetic total nitrogen concentrations, but has little influence on the standard errors of predicted phosphorus concentrations.

5. When 12-foot outlet samples are used in formulating the lake chloride budget, outflow loads exceeded inflow loads by 16 ± 3% over the 1996-2000 period. This may reflect inputs from ungauged portions of the watershed, including road salt application to roads and parking lots in urban areas around the lakeshore that are below the tributary monitoring sites or drain directly into the Lake. Ungauged inputs of saline groundwater from the Onondaga Creek watershed documented by

the USGS are also likely to contribute to apparent errors in the chloride and sodium budgets.

6. The empirical eutrophication model has been expanded to predict organic carbon, and organic nitrogen as a function of chlorophyll-a, in turn predicted from phosphorus loading. In 1996-2000, levels of allochthonous organic carbon in the Lake epilimnion appear to be lower to average values estimated from other lake and reservoir data sets, while levels of allochthonous organic nitrogen appear to be similar.

7. Coupling of the total nitrogen and organic nitrogen models enables prediction of inorganic nitrogen concentrations. Nitrate nitrogen accounted for 84% of the summer epilimnetic inorganic nitrogen concentrations. This percentage is expected to increase with further reductions in Metro ammonia load.

Recommendations for future enhancement of the mass-balance framework and empirical eutrophication model include:

1. Resolution of errors in the chloride budget and implications for the lake water budget. This would include quantitative evaluation of road salt inputs and potential groundwater inputs from the Onondaga Creek watershed.

2. Resolution of the ~5-fold increase in flows reported for the Crucible Steel discharge in 2000, relative to values reported in 1986-1999. Revision of current and/or historical water and mass balances to reflect any errors identified in these flows.

3. Refinements to the estimates of drainage area and land uses above and below the monitoring points on each tributary. This will improve the accuracy and precision of estimated loadings from ungauged portions of the watershed.

4. Daily nutrient budgets could be formulate using the same datasets compiled to support annual and seasonal mass balances. This would provide an improved basis for predicting the effects of within-year flow and load variations and time series to support mechanistic modeling of the Lake and Seneca River.

5. Other recommendations detailed in the 1999 Lake Monitoring report also stand. These include (a) improvements to the error analysis; (b) software for forecasting lake responses to a given loading scenario under a range of hydrologic conditions; (c) coupling with a simple watershed loading model; (d) prediction of near-shore transparencies; (e) integration of data from other regional lakes for comparison purposes; and (f) evaluation of the effects of nutrient load speciation (organic vs. inorganic) on model performance and trophic response; and (g) consideration of hydraulic exchanges with the Seneca River as an additional input and/or output term in the lake mass balance.

6. Addition of volume-days of anoxia as an additional response variable that appears to be correlated with lake phosphorus levels (Figure 6-6).

7. Blank samples for total phosphorus averaged 0.008 mg/liter (8 ppb) in the year 2000 lake monitoring program (Chapter 3). This relatively high value could have significant effects on the calibration of the phosphorus mass balance model and on forecasts of future lake conditions relative to the 20 ppb guidance value. Continued refinement of sampling techniques is recommended to identify and eliminate sources of sample contamination.

12.8 REFERENCES

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Table 12-7
Model Inputs & Outputs

Model Parameters	Units	Input Value
Lake Area	km^2	11.7
P Settling Rate	m/yr	18.92
Epil P / Outflow P	-	0.513
Outflow P Error CV	-	0.146
Lake P Error CV	-	0.088
Chla/P Slope	-	1.460
Chla/P Intercept	-	0.078
Chl-a Error CV	-	0.217
Chla Temporal CV	-	0.61
Non-Algal Turbidity	1/m	0.285
Secchi/Chla Slope	m^2/mg	0.018
Secchi Error CV	-	0.168
Secchi Temporal CV	-	0.320
HOD Intercept	-	42.4
HOD Slope		0.94
HOD Error CV		0.230
Spring DO Conc	ppm	12.0
Hypol. Depth	m	8.340
Stratified Period	days	183.0
Total N Setting Rate	m/yr	14.2
Outflow N CV	-	0.065
Epil N / Outflow N	-	0.917
Epil N CV	-	0.047
Organic N Slope	-	30.4
Organic N Intercept	ppb	113.9
Organic N CV	-	0.217
TOC Slope	-	0.102
TOC Intercept	ppm	2.356
TOC CV	-	0.041
Inorgn CV	-	0.12

Scenario			
Outflow Volume	hm^3/yr	435	1996-2000 Average
Inflow P Load	kg/yr	67143	1996-2000 Average
Inflow N Load	kg/yr	2112700	1996-2000 Average

Predicted Reponses		Units	Mean	Low (10%)	High (90%)
Outflow P Conc		ppb	102	82	128
Lake P Conc		ppb	52	46	60
Mean Chlorophyll-a		ppb	25	18	35
Algal Bloom Frequencies					
	>	10	0.92	0.78	0.98
	>	20	0.56	0.33	0.77
	>	30	0.28	0.12	0.51
	>	40	0.14	0.05	0.31
Mean Secchi Depth		m	1.48	1.80	1.19
Secchi Interval Frequencies					
	<	1.2	0.30	0.13	0.57
	<	2	0.87	0.69	0.96
Oxygen Depletion Rate		mg/m^2-day	1754	1232	2497
Days of O2 Supply		days	57	81	40
Anoxic Period		days	126	102	143
Outflow N		ppb	3512	3179	3881
Lake N		ppb	3219	2995	3460
Organic N		ppb	888	636	1239
Inorganic N		ppb	2331	1938	2804
Organic C		ppb	4.95	4.65	5.27

Figure 12-1

Framework for Mass-Balance Calculations

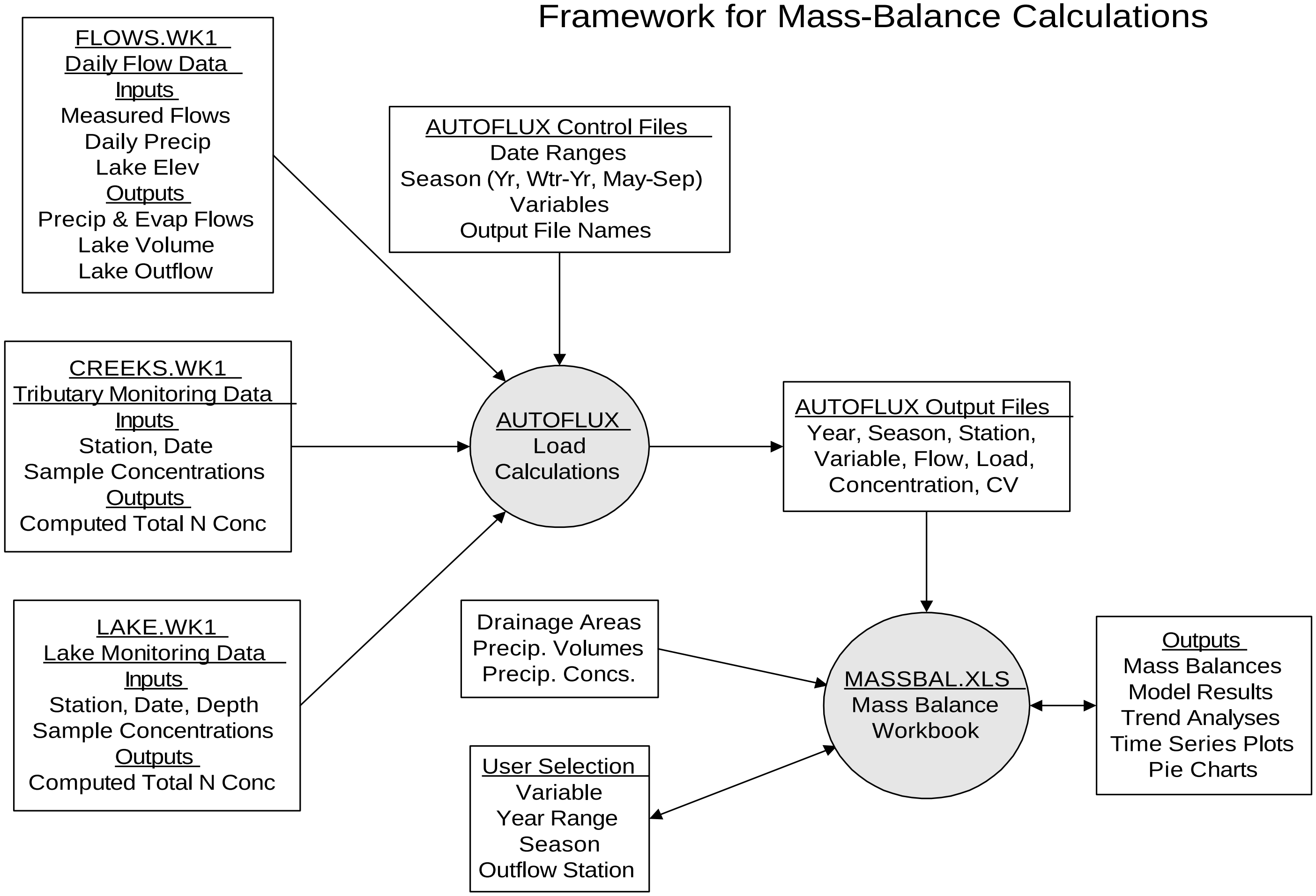


Figure 12-2

Eutrophication Model Network for Onondaga Lake

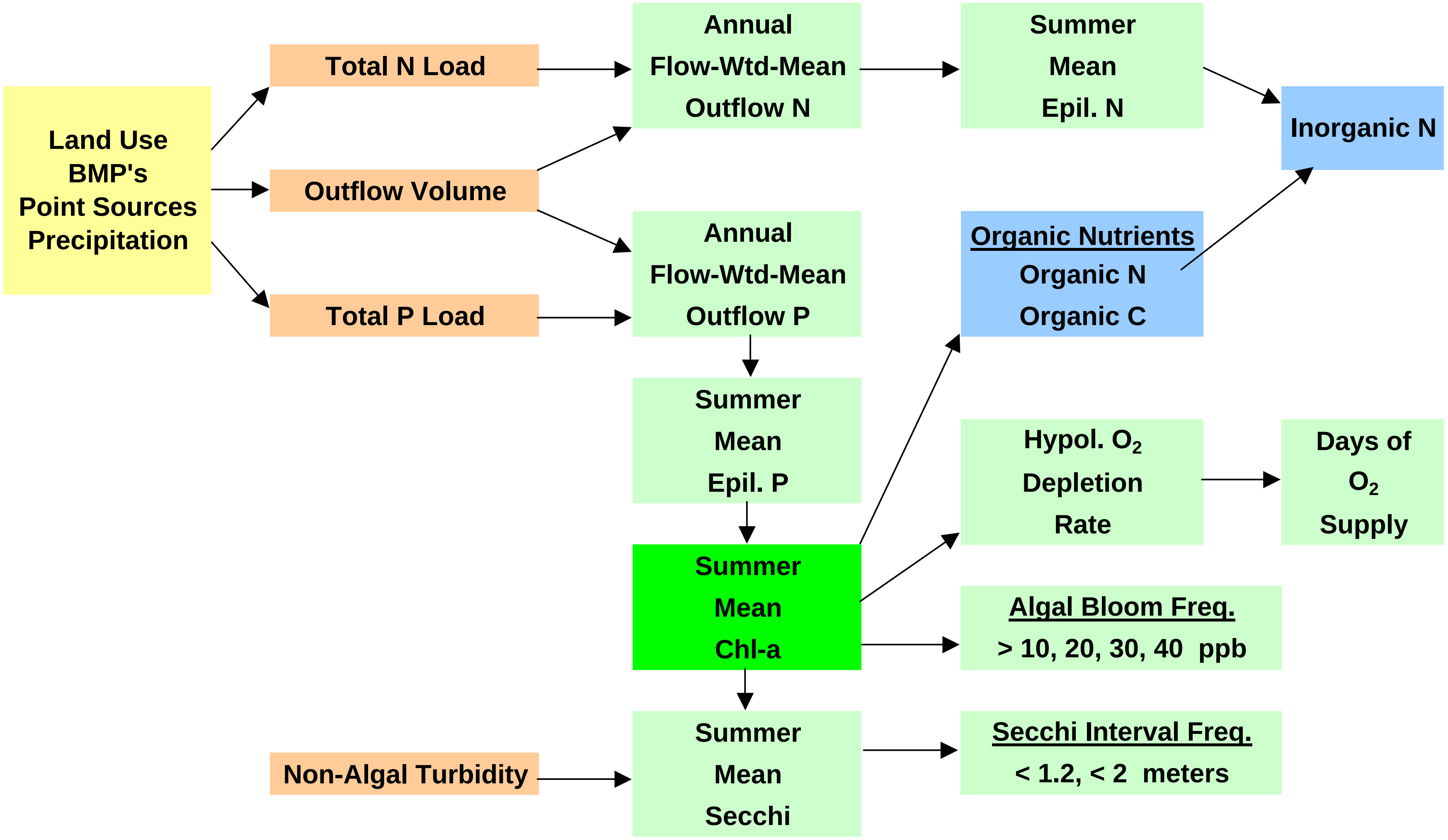


Figure 12-3
Lake Outflow Time Series

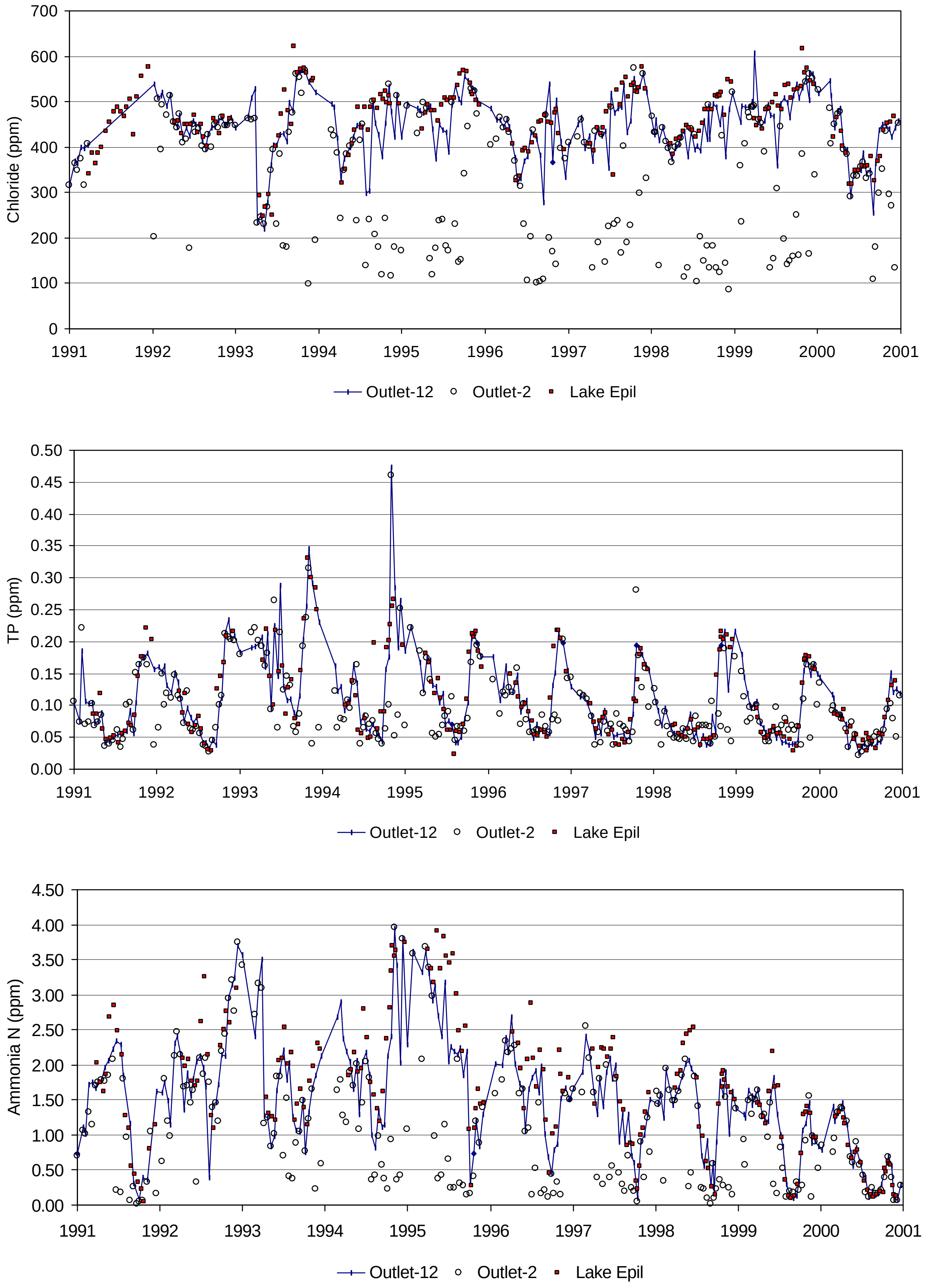
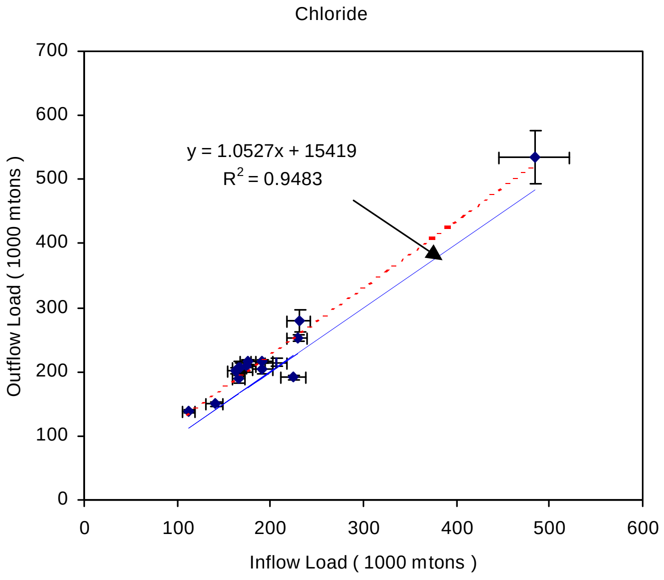


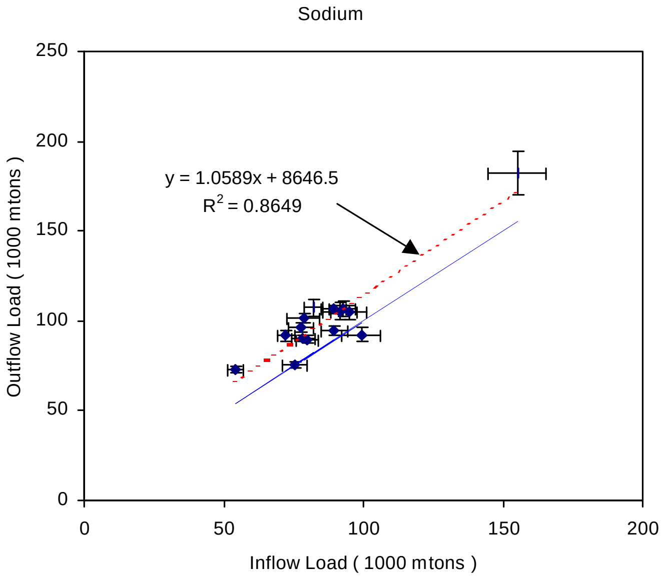
Figure 12-4
Outflow Loads vs. Inflow Loads
Water Years 1986-2000

Solid Lines: Y = X

Dashed Lines: Linear Regressions

Symbols = Observed Values +/- 1 Standard Error





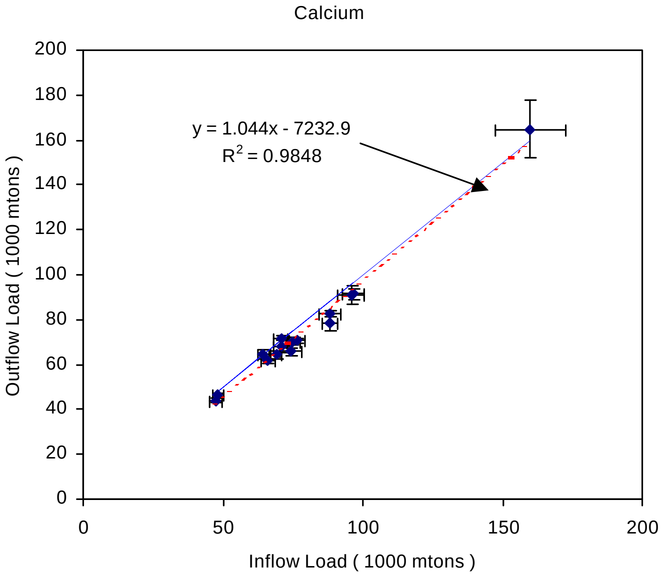


Figure 12-5
Lake Inflow Time Series

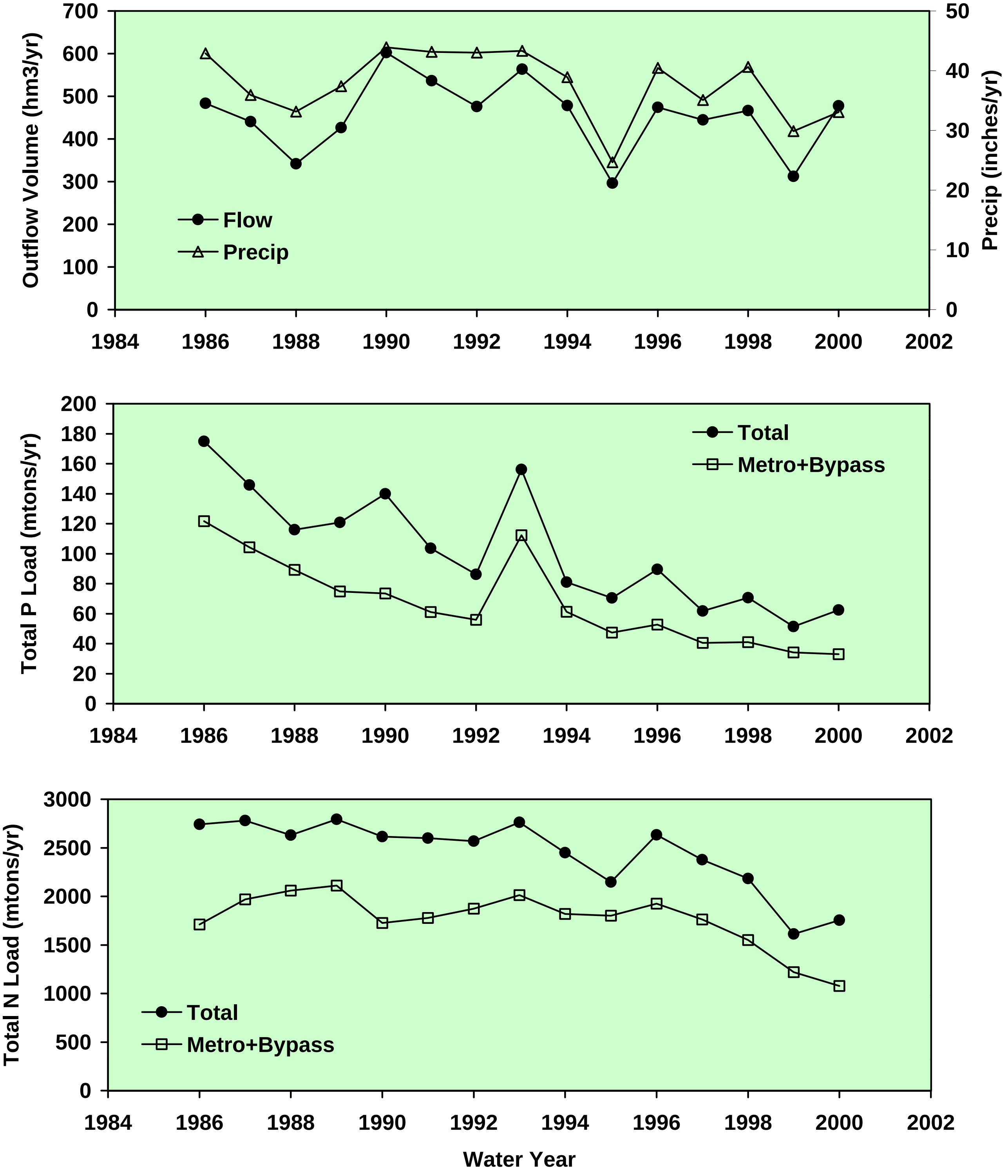
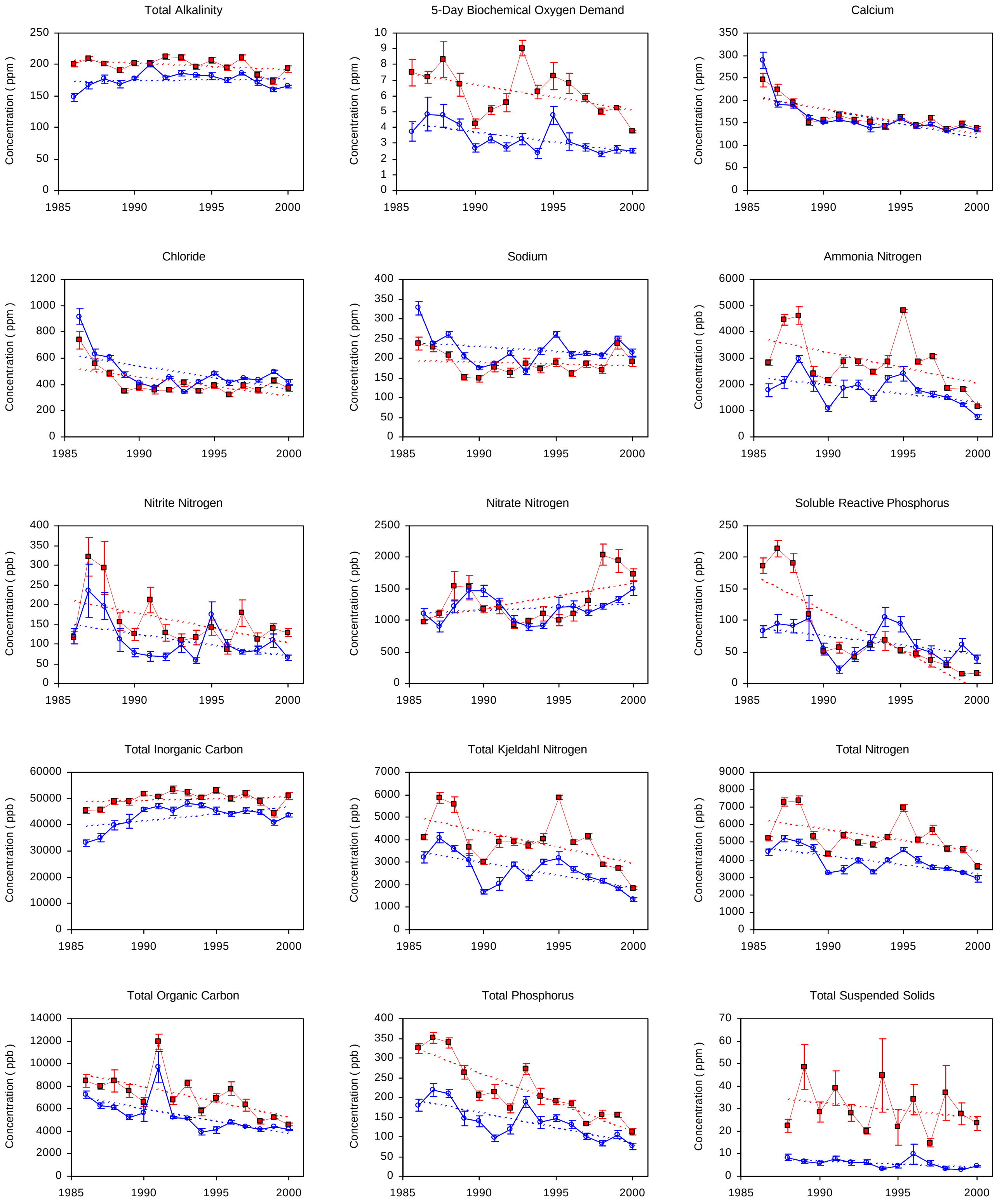
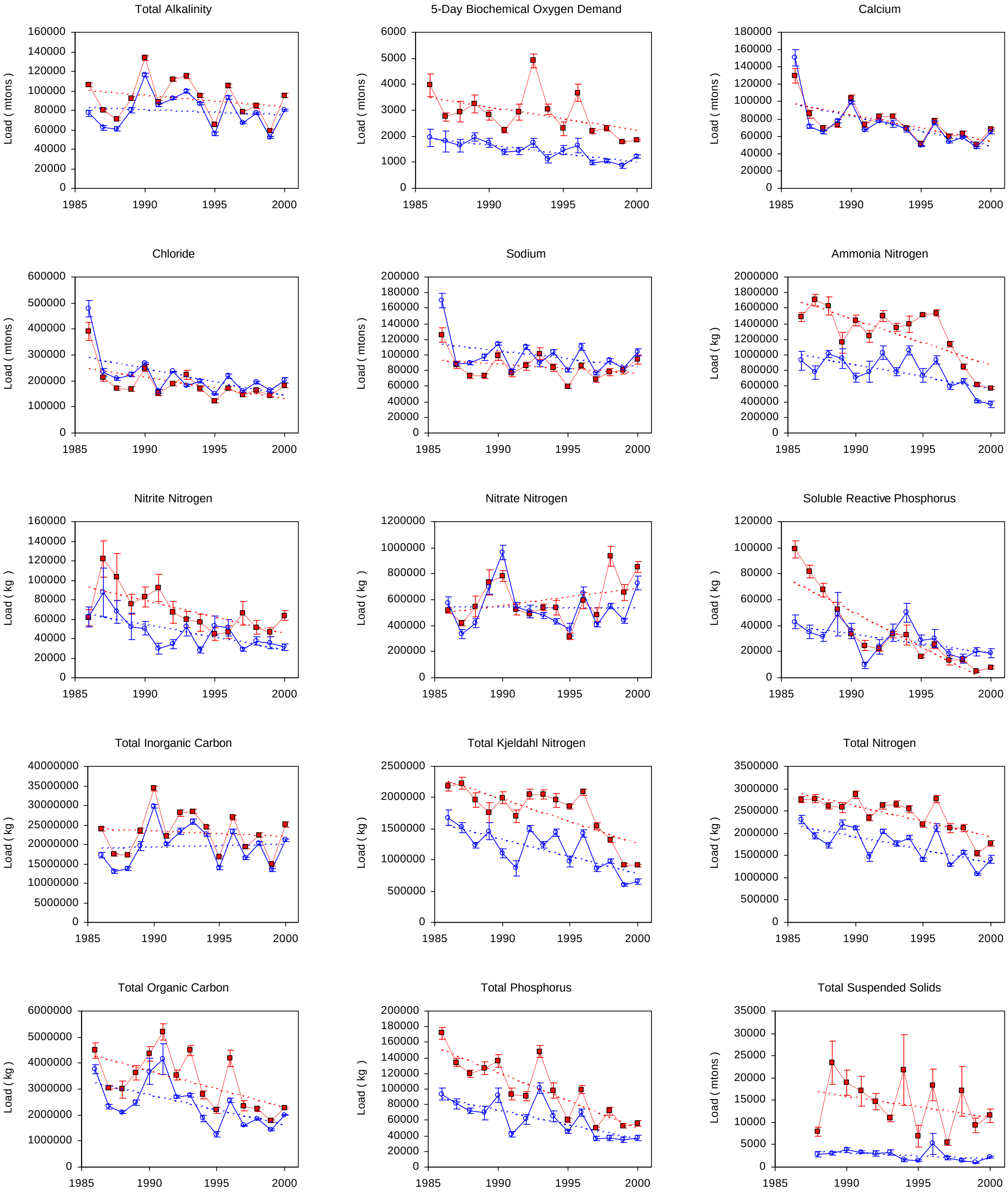


Figure 12-6
Long-Term Trends in Total Inflow & Outflow Concentrations



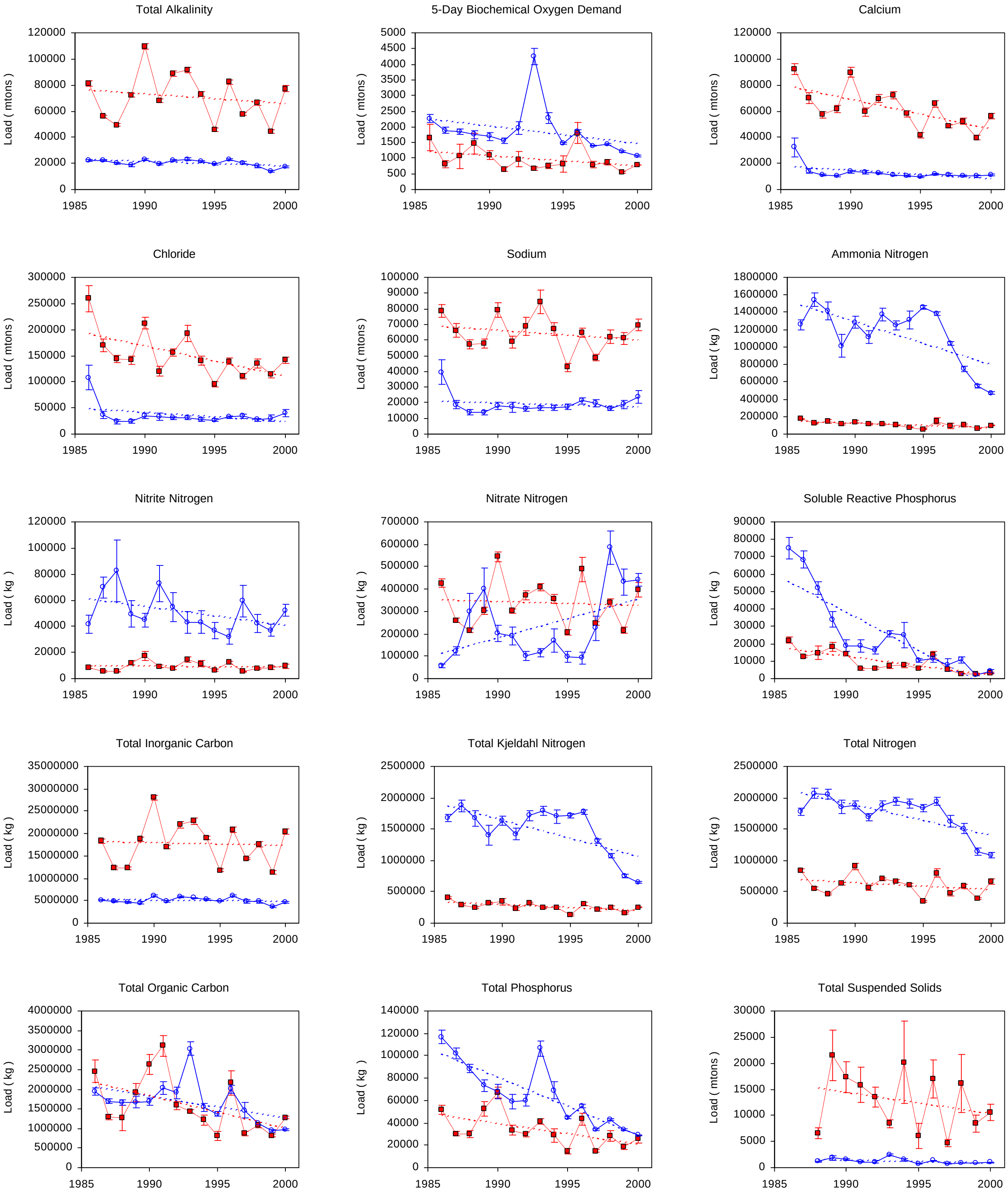
Squares = Inflow, Circles = Outflow   Error Bars = +/- 1 Standard Error   Dotted Lines = Linear Trends   X-Axis = Calendar Year

Figure 12-7
Long-Term Trends in Total Inflow & Outflow Loads



Squares = Inflow, Circles = Outflow   Error Bars = +/- 1 Standard Error   Dotted Lines = Linear Trends   X-Axis = Calendar Year

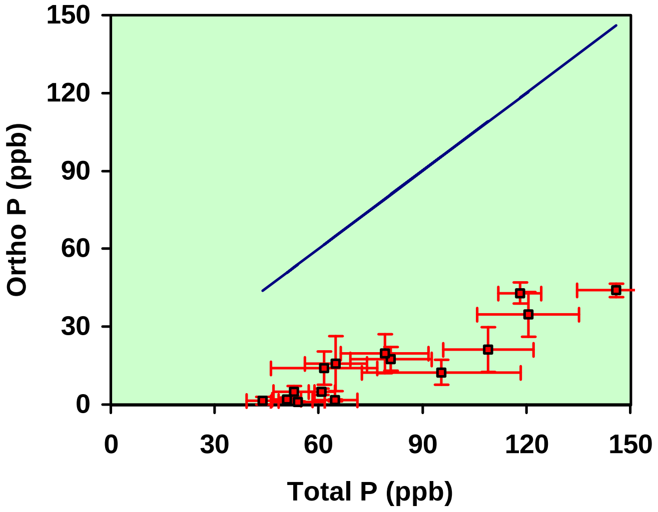
Figure 12-8
Long-Term Trends in NonPoint & Metro Loads

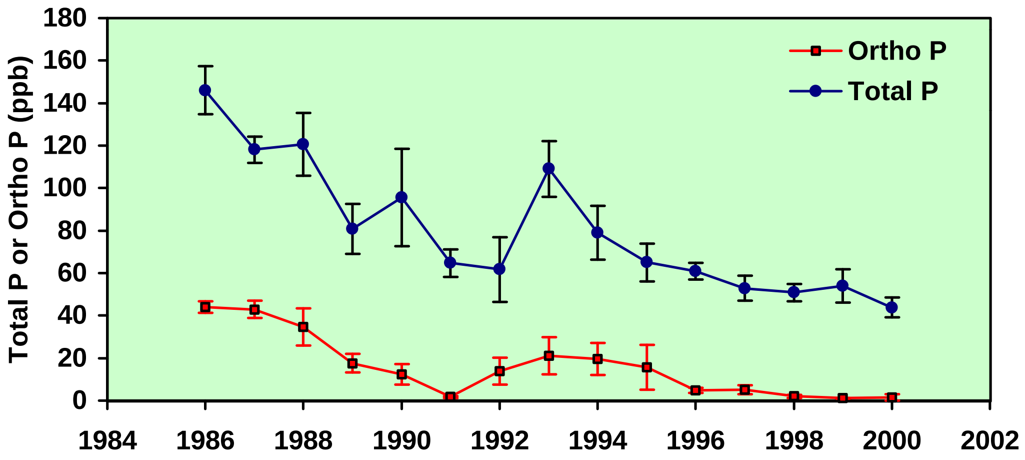


Squares = NonPoint, Circles = Metro+Bypass   Error Bars = +/- 1 Standard Error   Dotted Lines = Linear Trends   X-Axis = Calendar Year

Figure 12-9

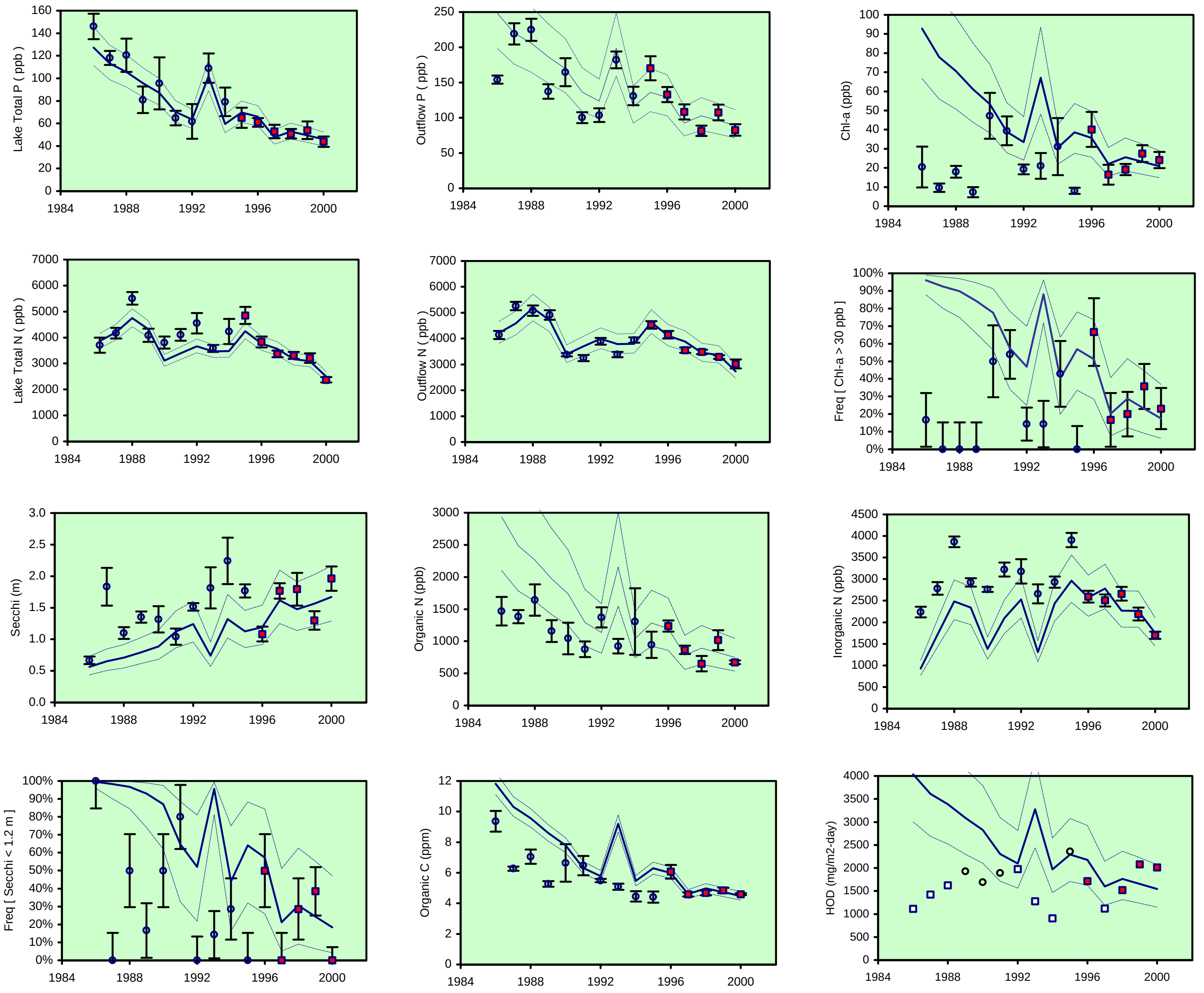
Ortho P vs. Total P Concentrations





July-September Means, 0-3 meters, Lake South Station
Error bars show mean +/- 1 standard error ~ P Limited ----->

Figure 12-10
Observed & Predicted Time Series - All Variables



Square Symbols = Calibration Period; Observed Means +/- 1 Std Error

Lines = 80% Prediction Intervals

Figure 12-11
Observed & Predicted Annual Outflow P Concentrations

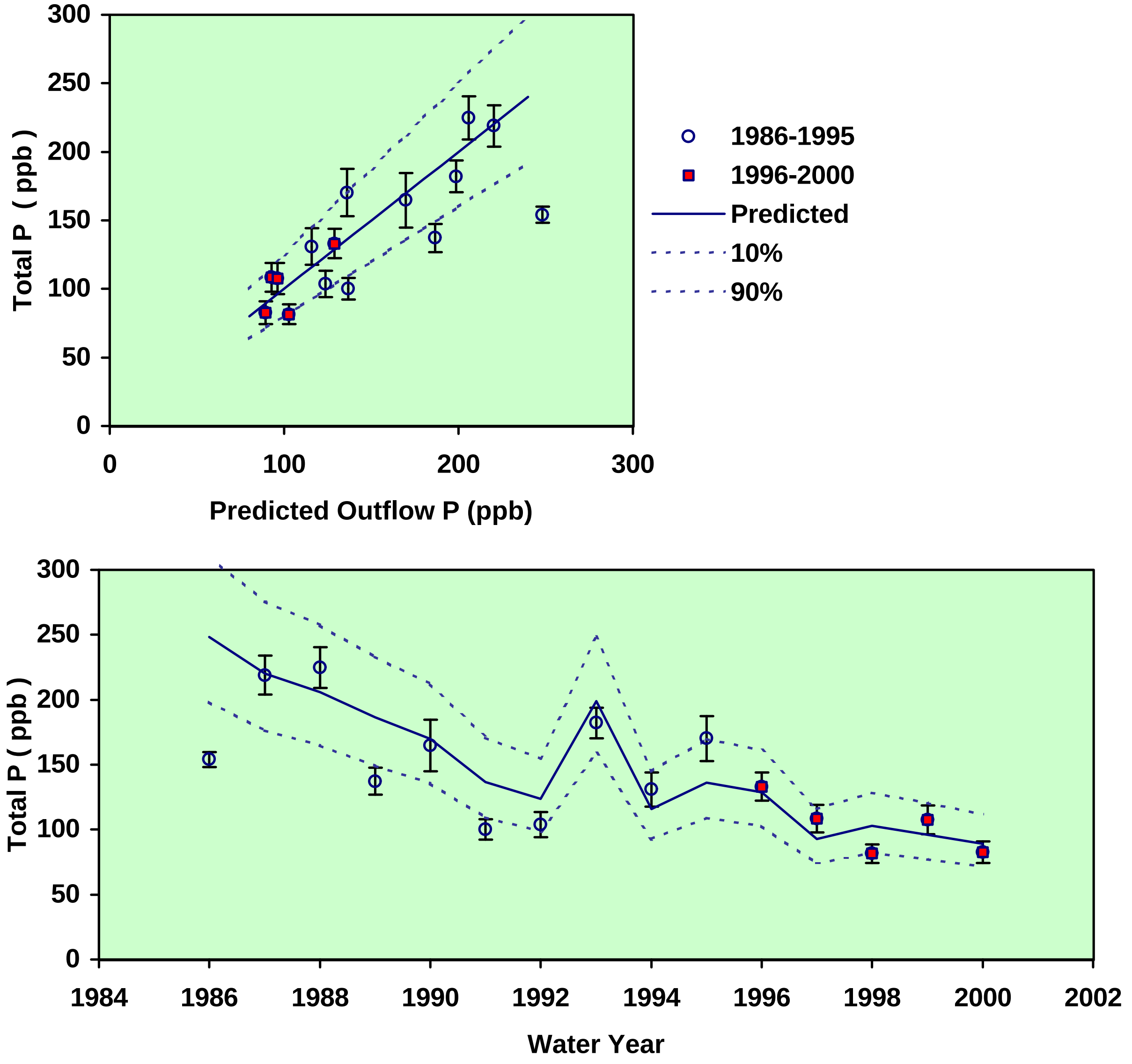
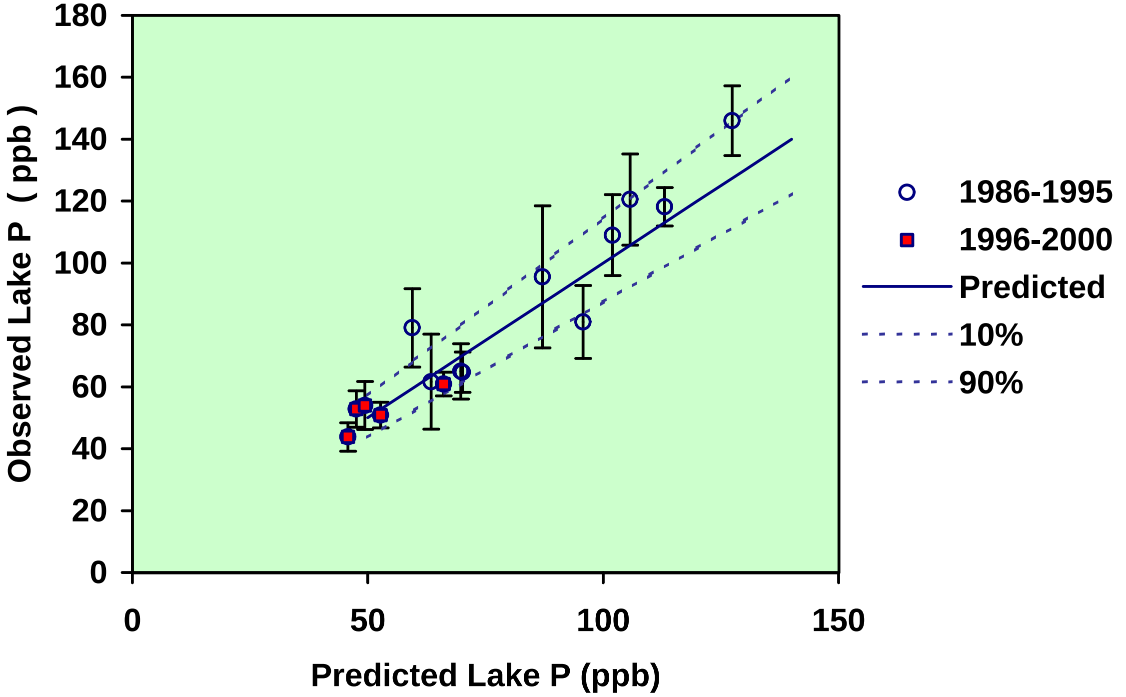


Figure 12-12
Observed & Predicted Summer Epilimnetic P Concentrations



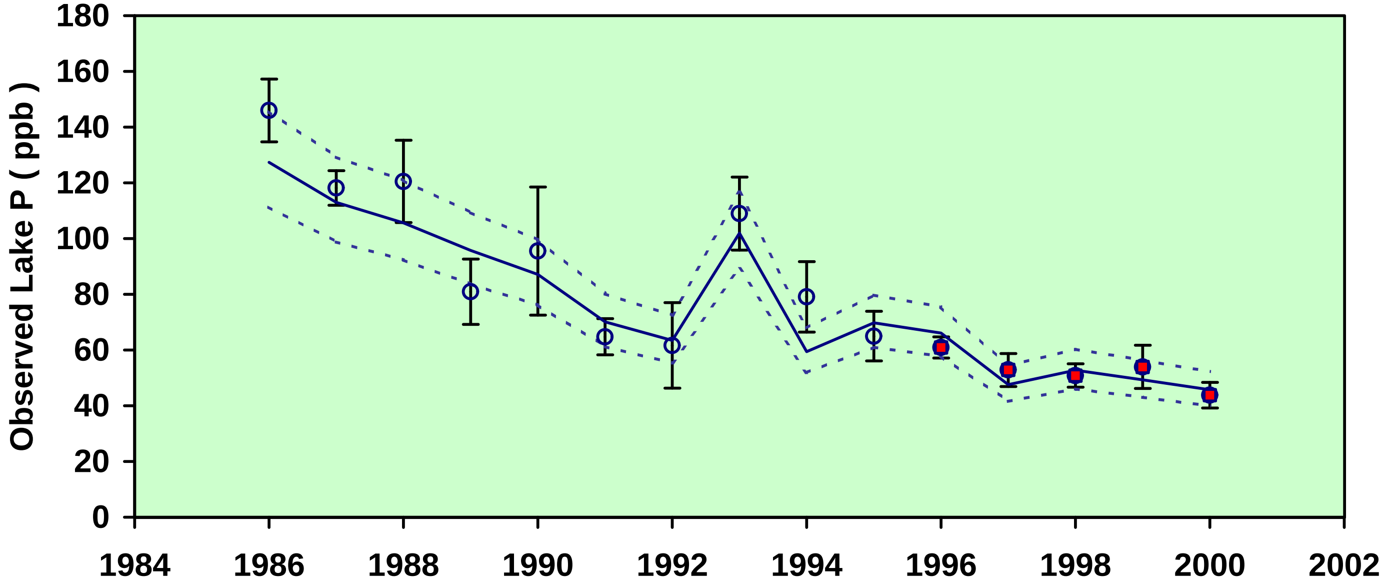
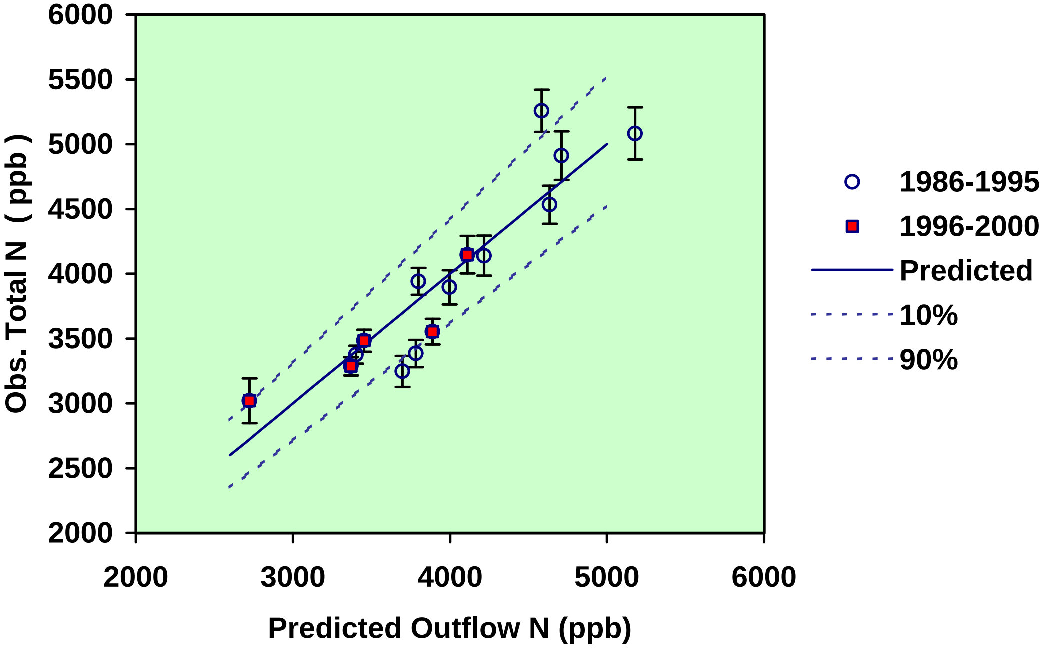
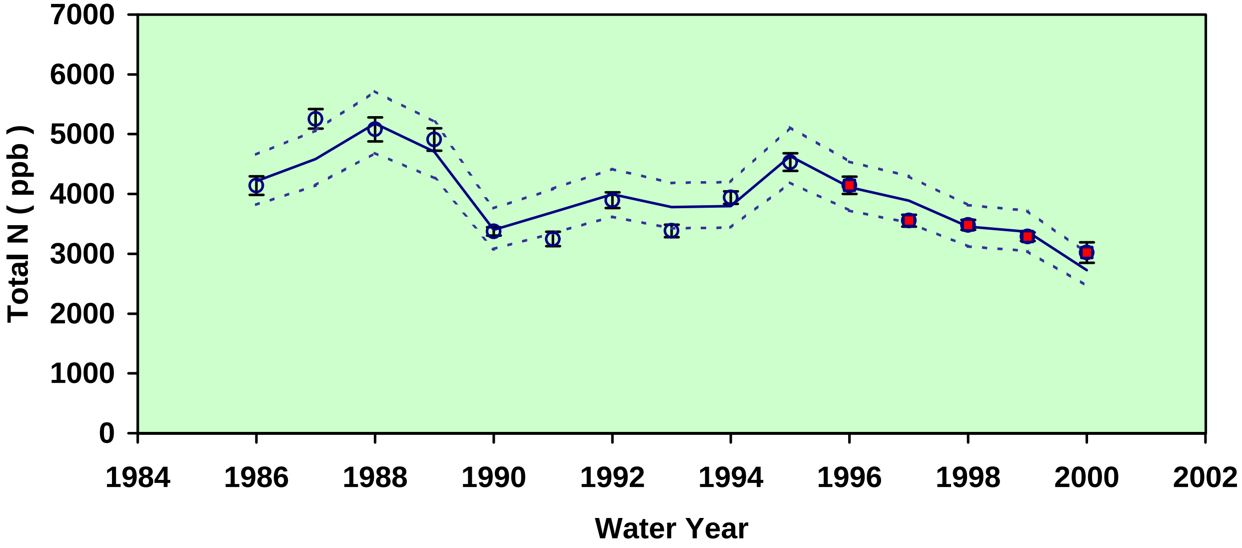


Figure 12-13
Observed & Predicted Annual Outflow N Concentrations





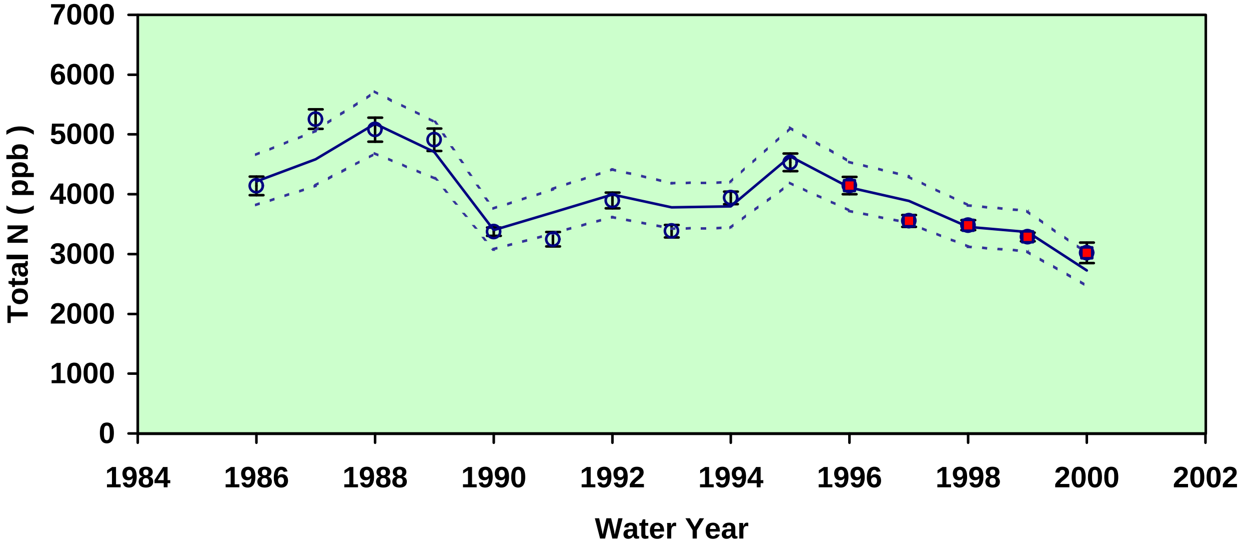
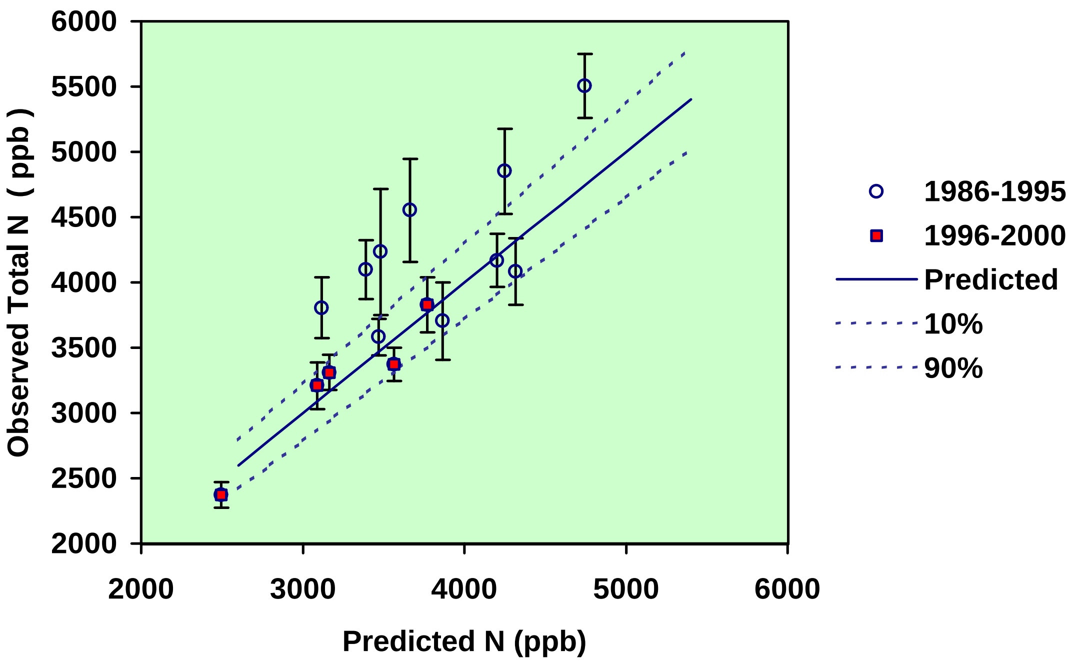

Total N (ppb)
7000
6000
5000
4000
3000
2000
1000
0
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
Water Year

Figure 12-14
Observed & Predicted Summer Total N Concentrations



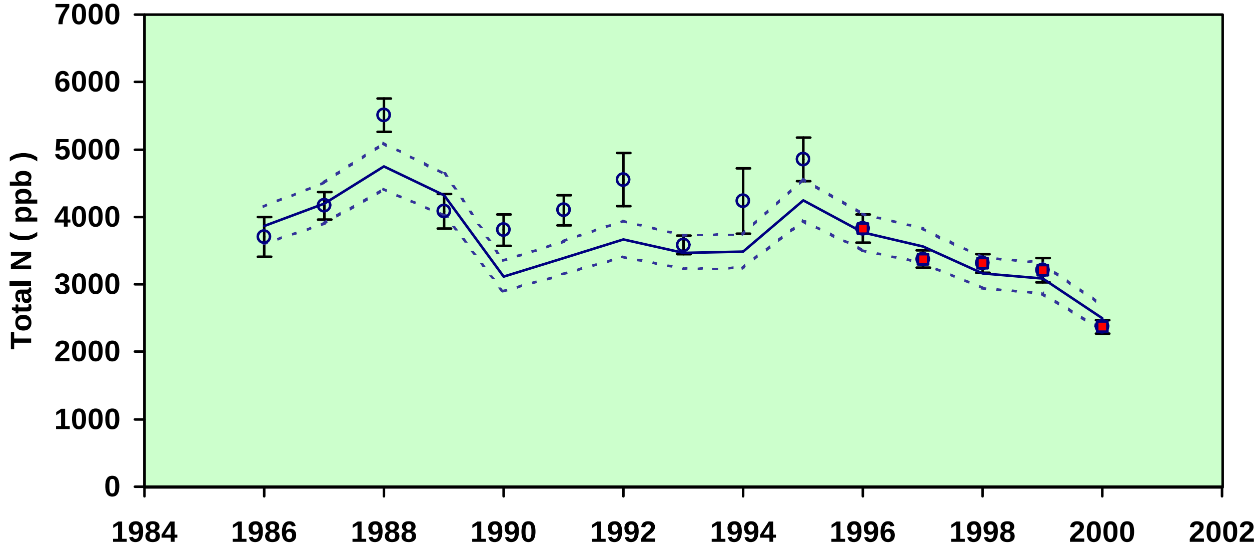


Figure 12-15
Observed & Predicted Mean Chlorophyll-a

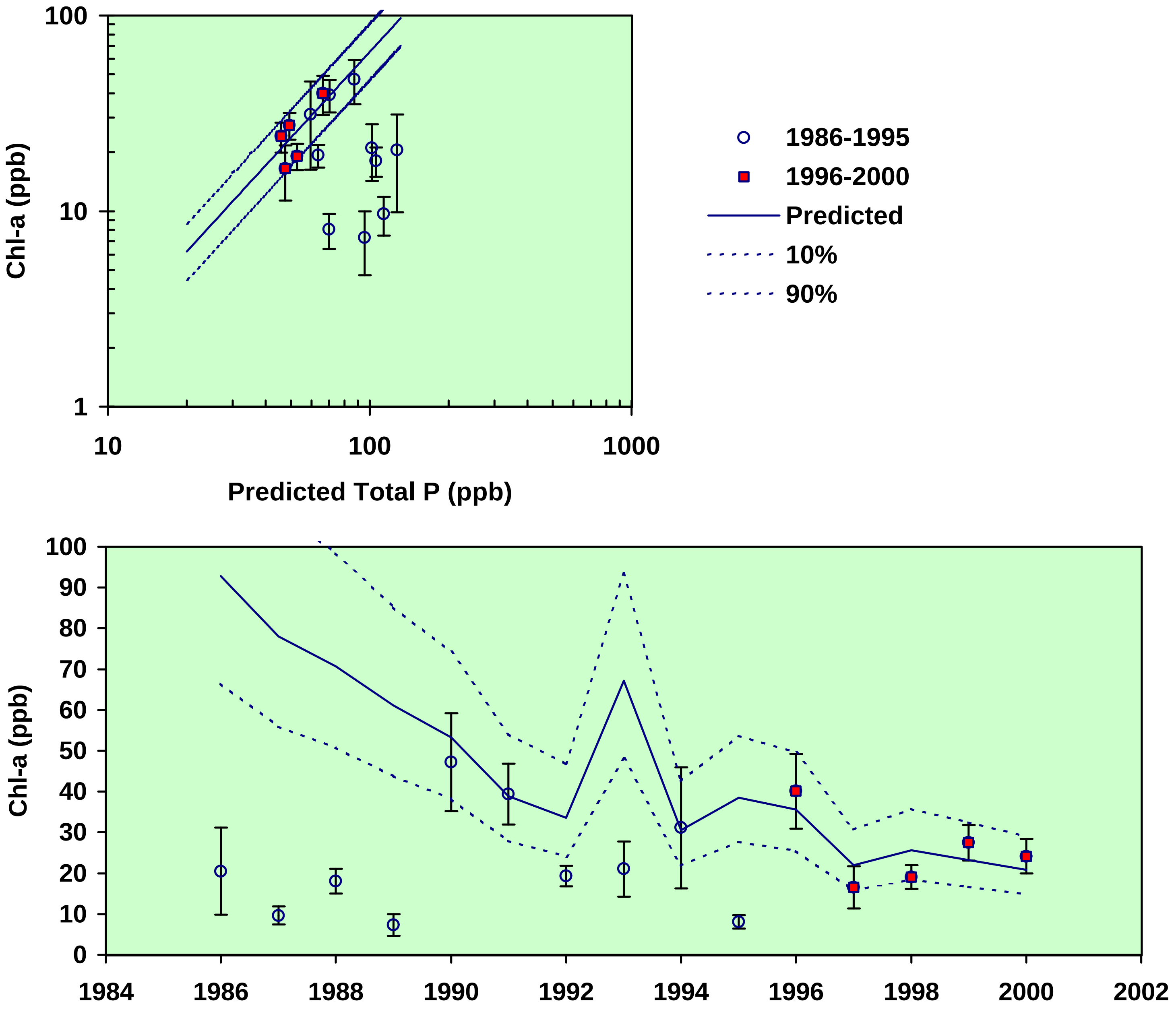


Figure 12-16
Algal Bloom Frequencies vs. Observed Mean Chlorophyll-a

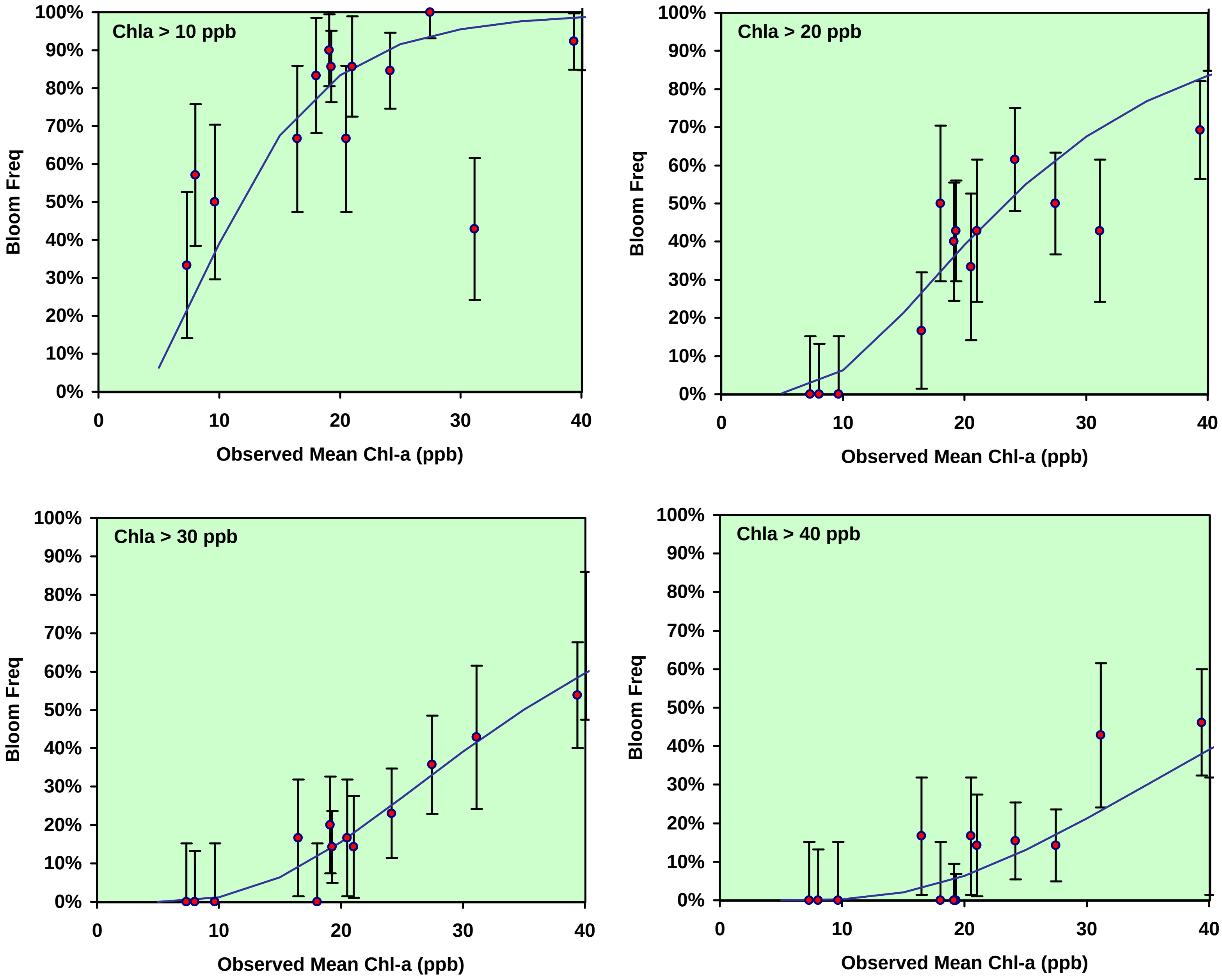


Figure 12-17
Algal Bloom Frequencies vs. Predicted Total Phosphorus

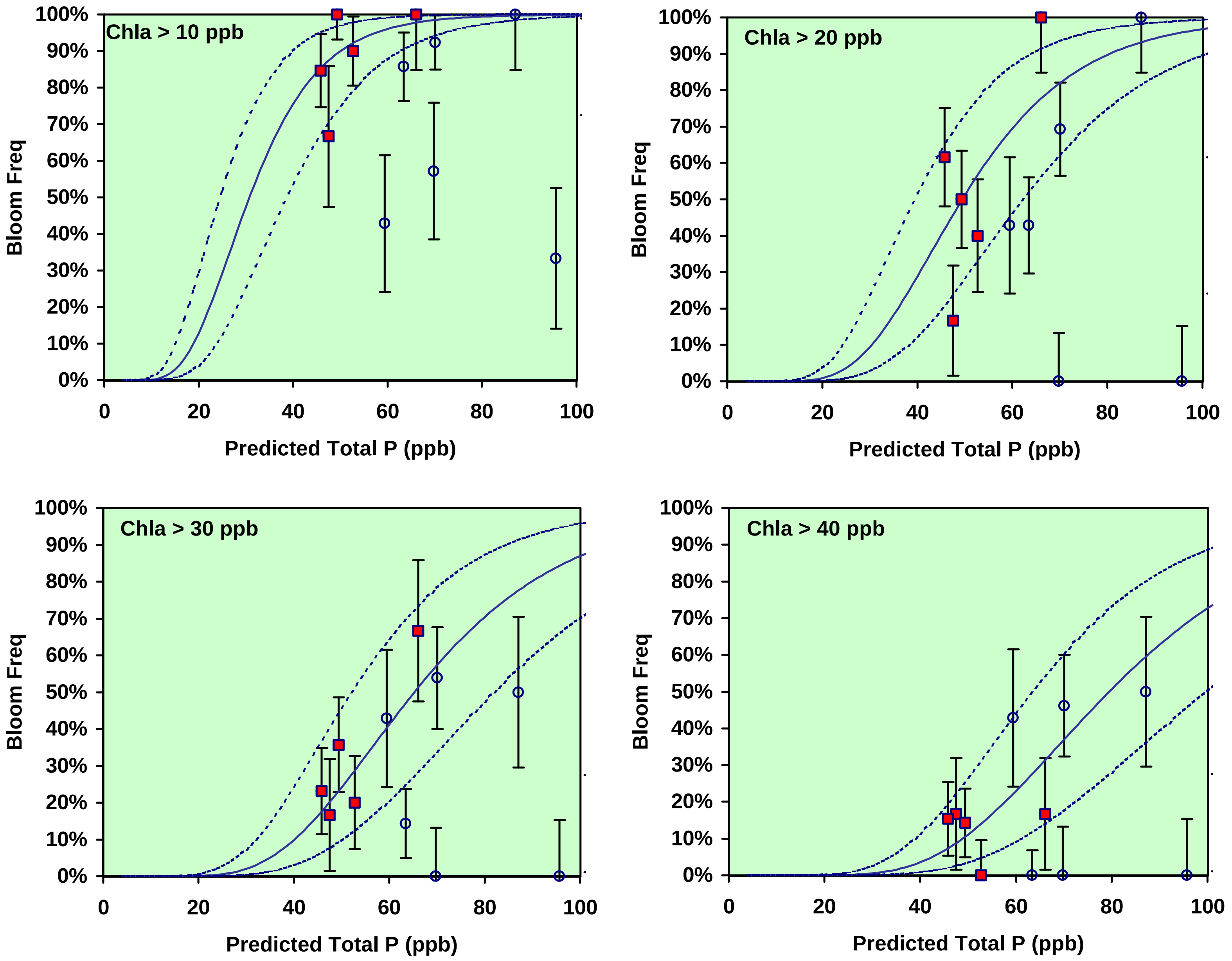


Figure 12-18
Algal Bloom Frequencies vs. Year

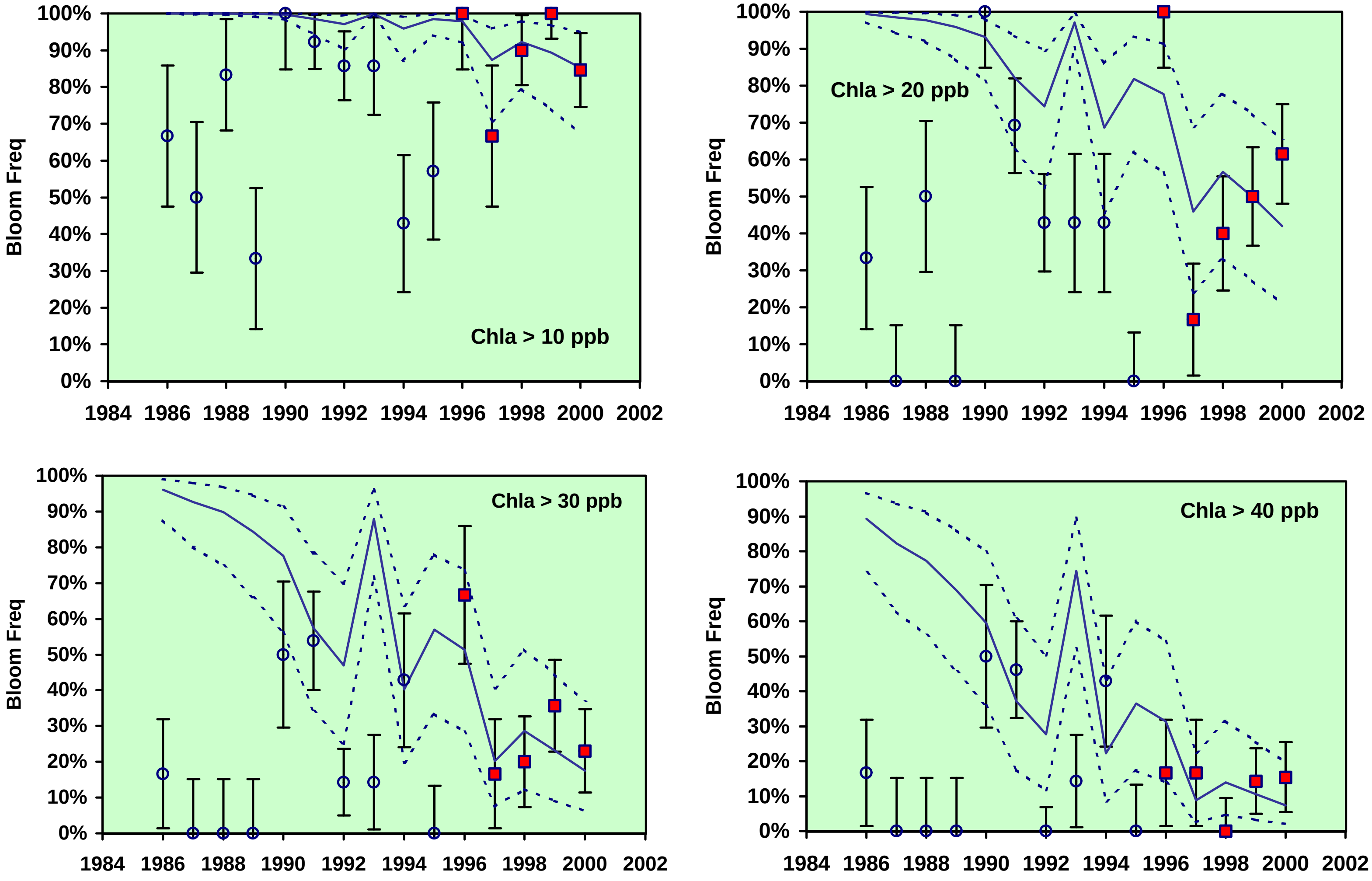
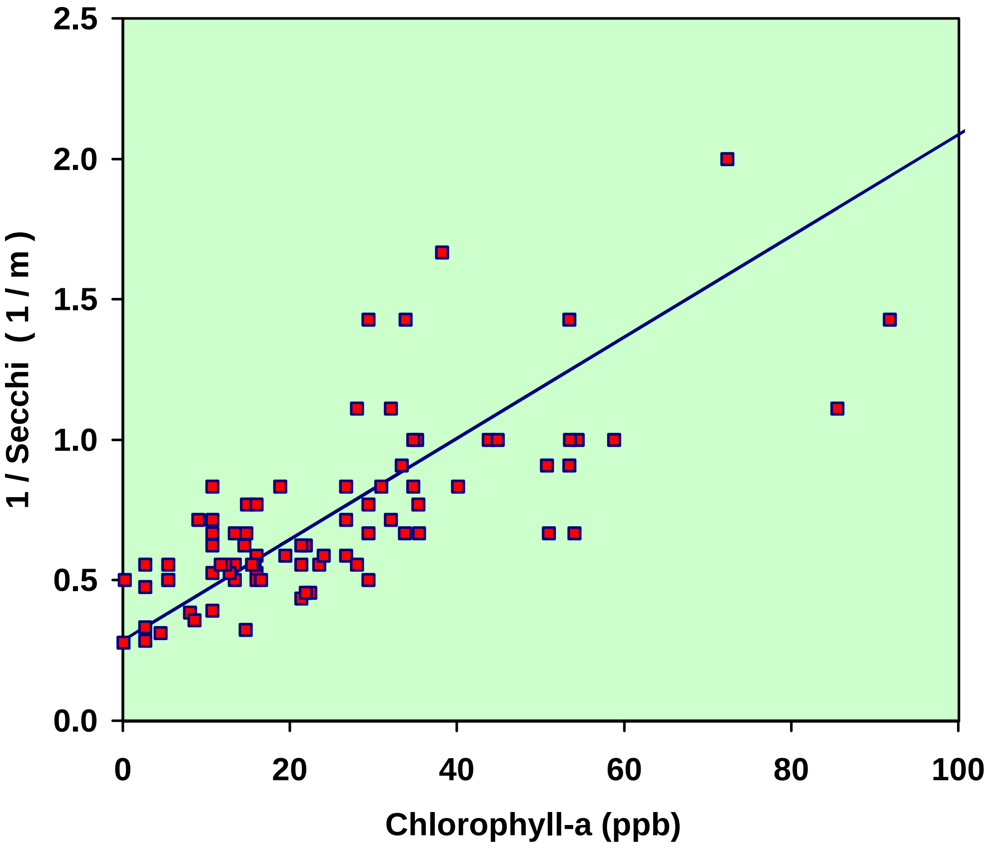


Figure 12-19
Calibration of Secchi Depth Model



Lake South Epilimnion Samples, 0-3 m, July-September, 1996-2000
Regression:

Y =	0.285	+	0.018	X
R^2 =	0.52	SE =	0.25	

Figure 12-20
Observed & Predicted Secchi Depth

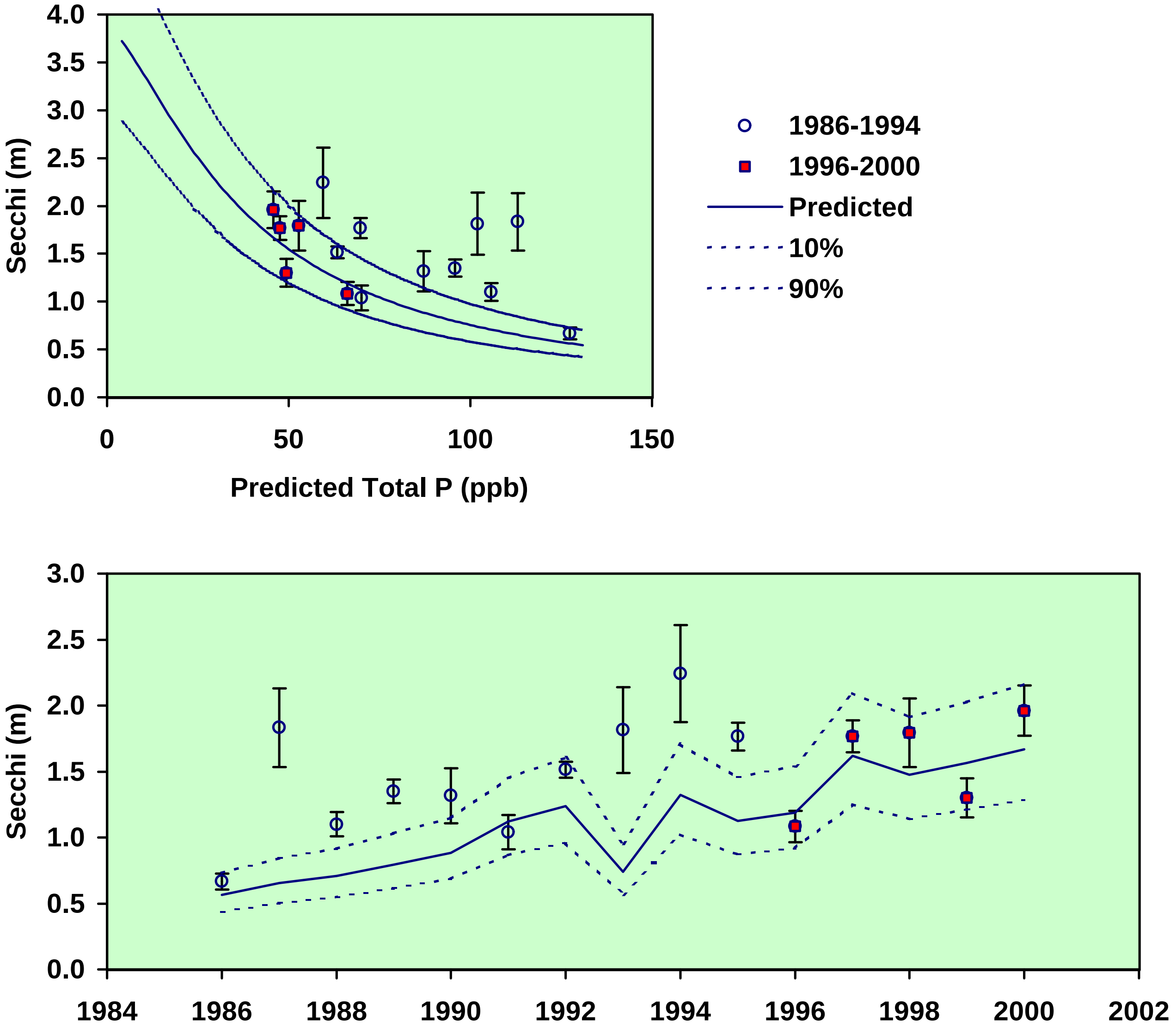
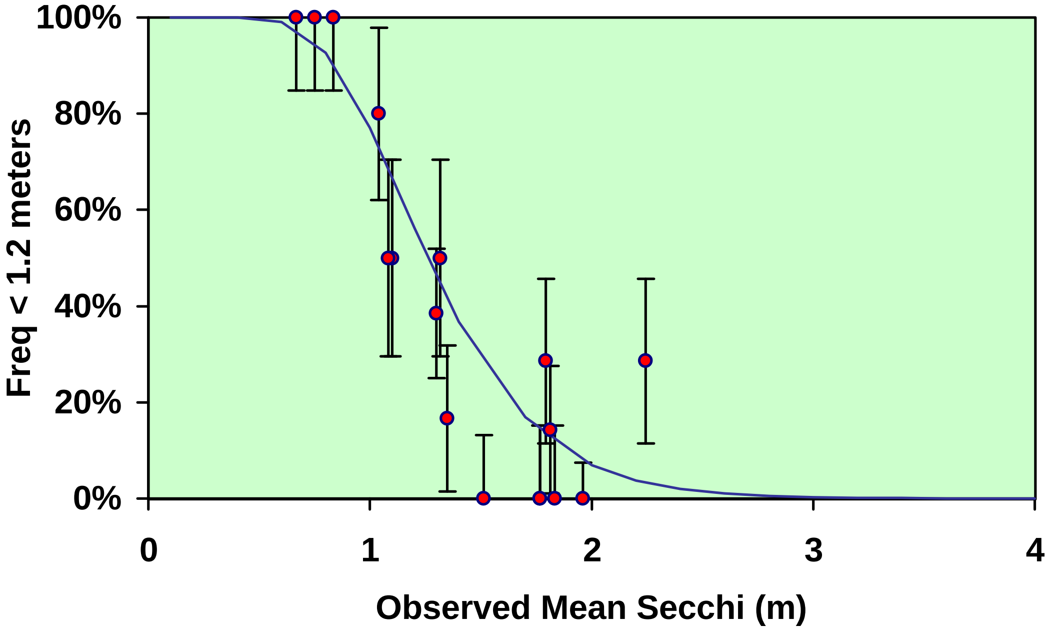


Figure 12-21
Secchi Interval Frequencies vs. Mean Secchi



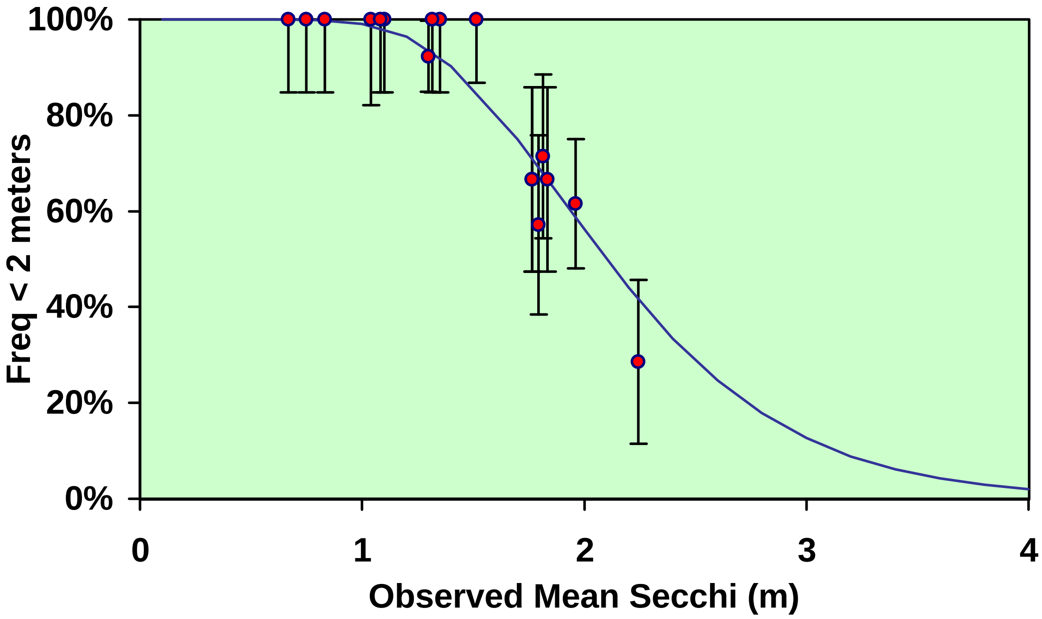


Figure 12-22
Observed & Predicted Frequency of Secchi < 1.2 meters

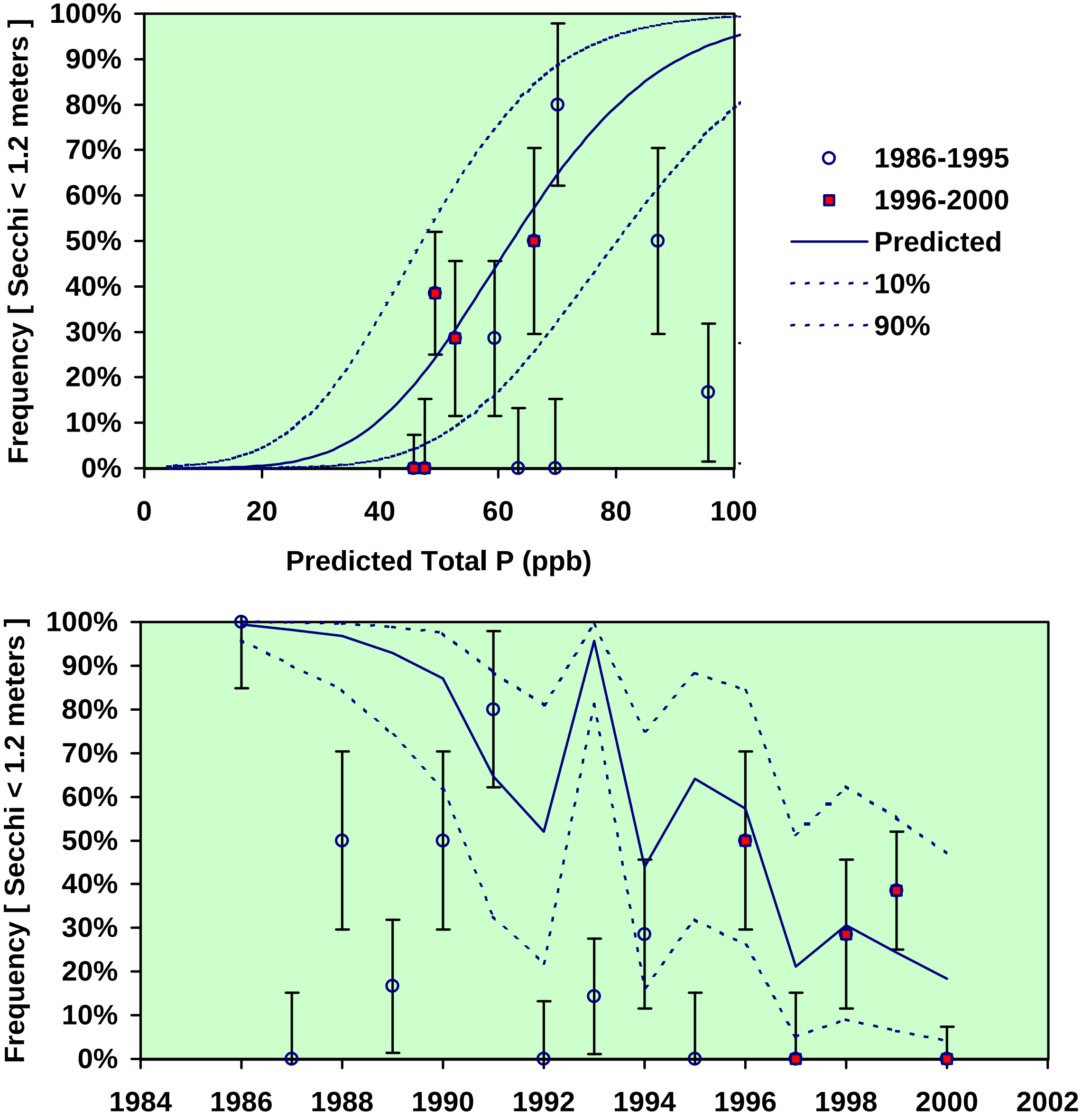
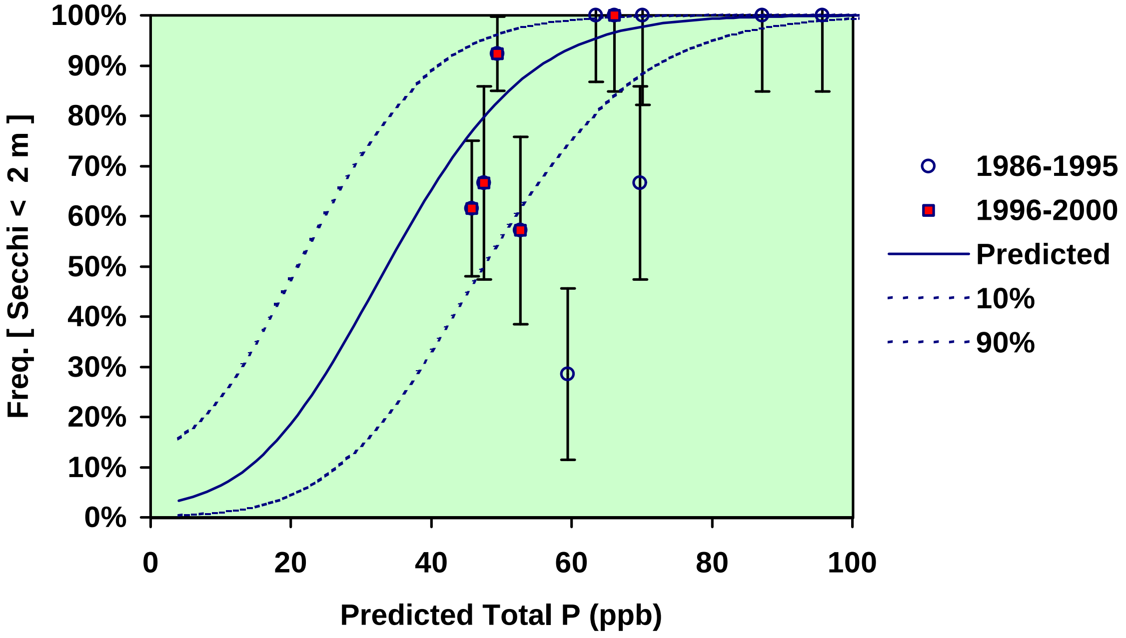


Figure 12-23
Observed & Predicted Frequency of Secchi < 2 meters



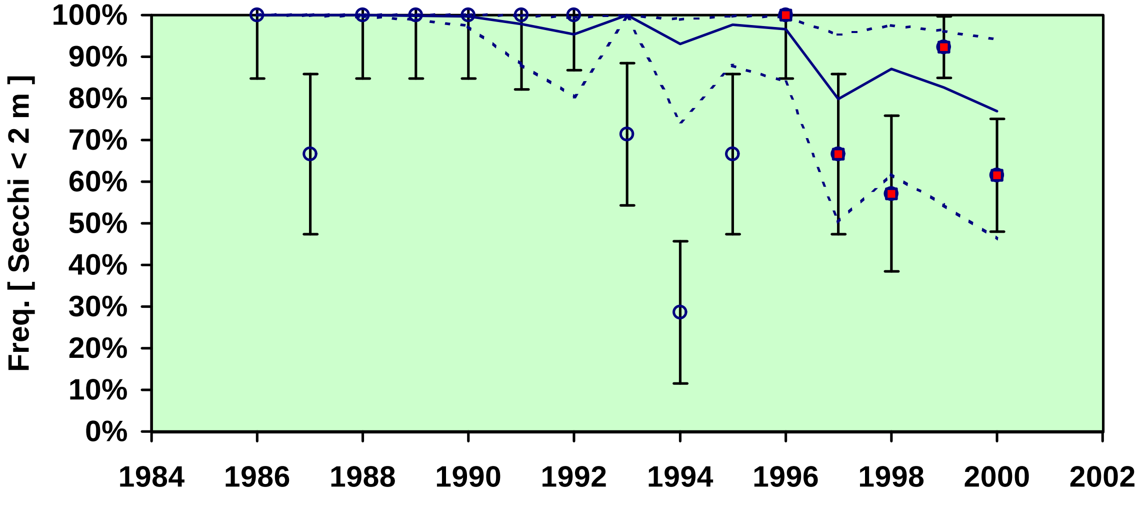
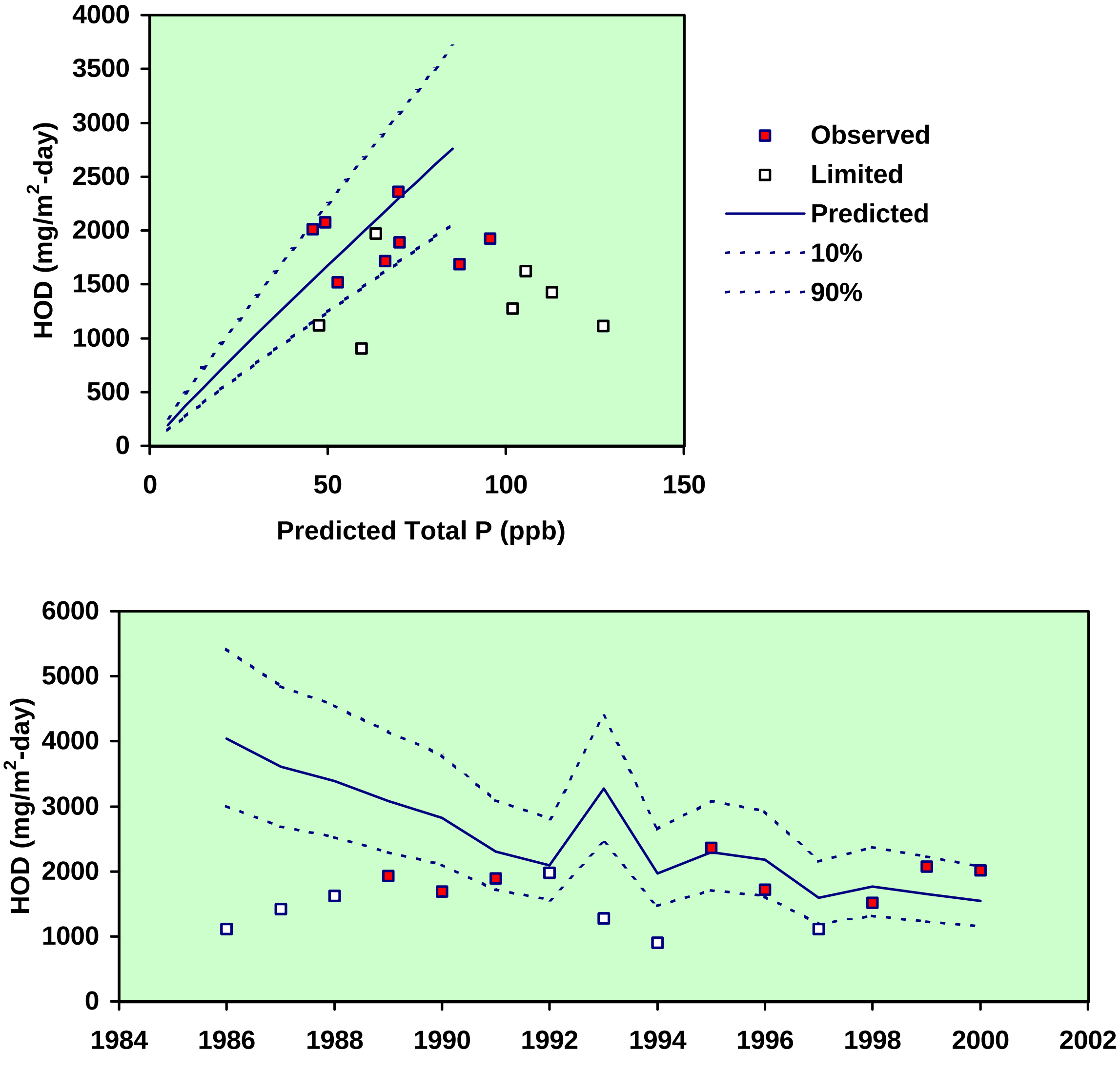
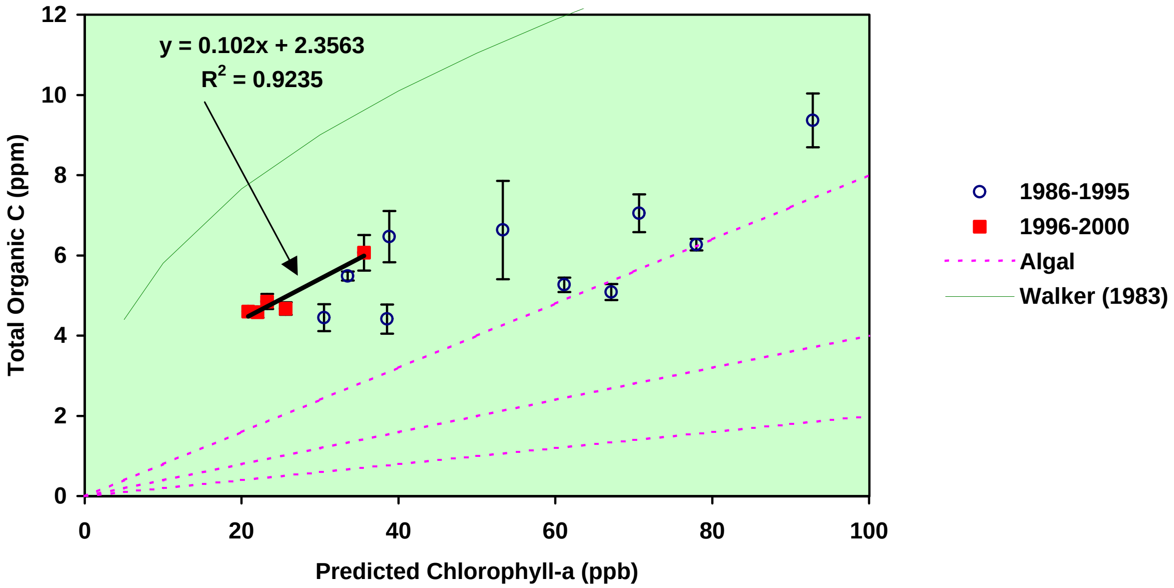


Figure 12-24
Observed & Predicted Hypolimnetic Oxygen Depletion Rates

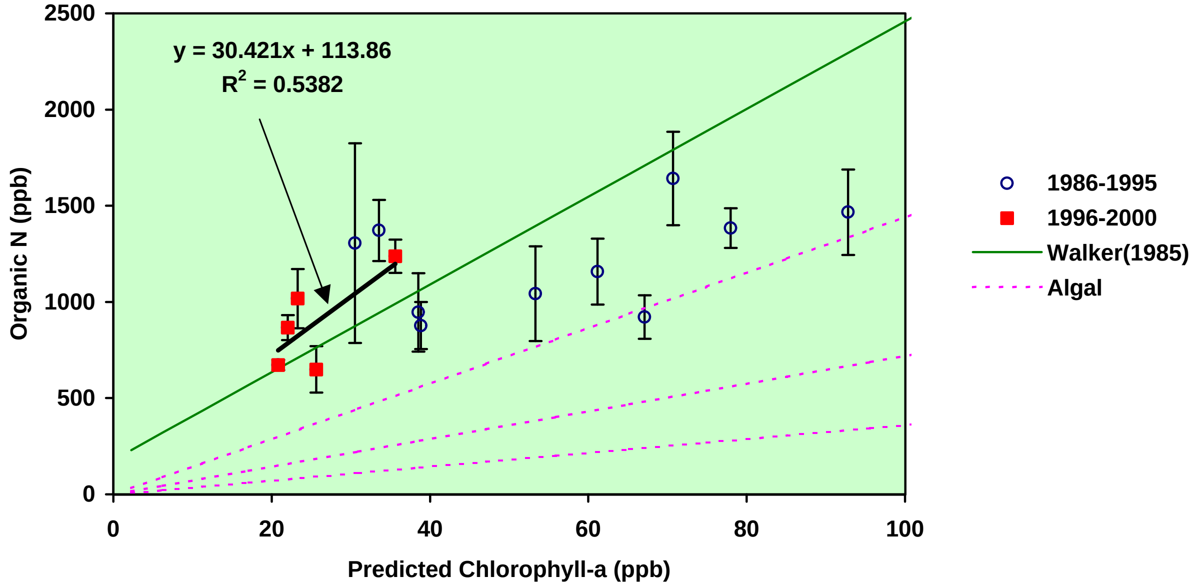


Limited = observed value limited by incomplete spring turnover or partial depletion of oxygen; lower limit of actual value

Figure 12-25
Calibration of Organic Carbon & Organic Nitrogen Models



X-Axis	Chlorophyll-a Predicted by Model Network (Figure ?)
Walker (1983)	Regression Analysis of Data from 20 Lakes & Reservoirs, Nationwide Database
Algal	Algal Organic Carbon Predicted Using Carbon/Chl-a Ratios of 20, 40, & 80 g/g (Chapra, 2001)
Regression	Regression of Onondaga Lake 1996-2000 Data



X-Axis	Chlorophyll-a Predicted by Model Network (Figure ?)
Walker (1985)	Regression Analysis of Data from 62 Reservoirs, Nationwide Database
Algal	Algal Organic N Predicted Using Organic N/Chl-a Ratios of 3.6, 7.2, & 14.4 g/g (Chapra, 2001)
Regression	Regression of Onondaga Lake 1996-2000 Data

Figure 12-26
Observed & Predicted Total Organic Carbon Concentrations

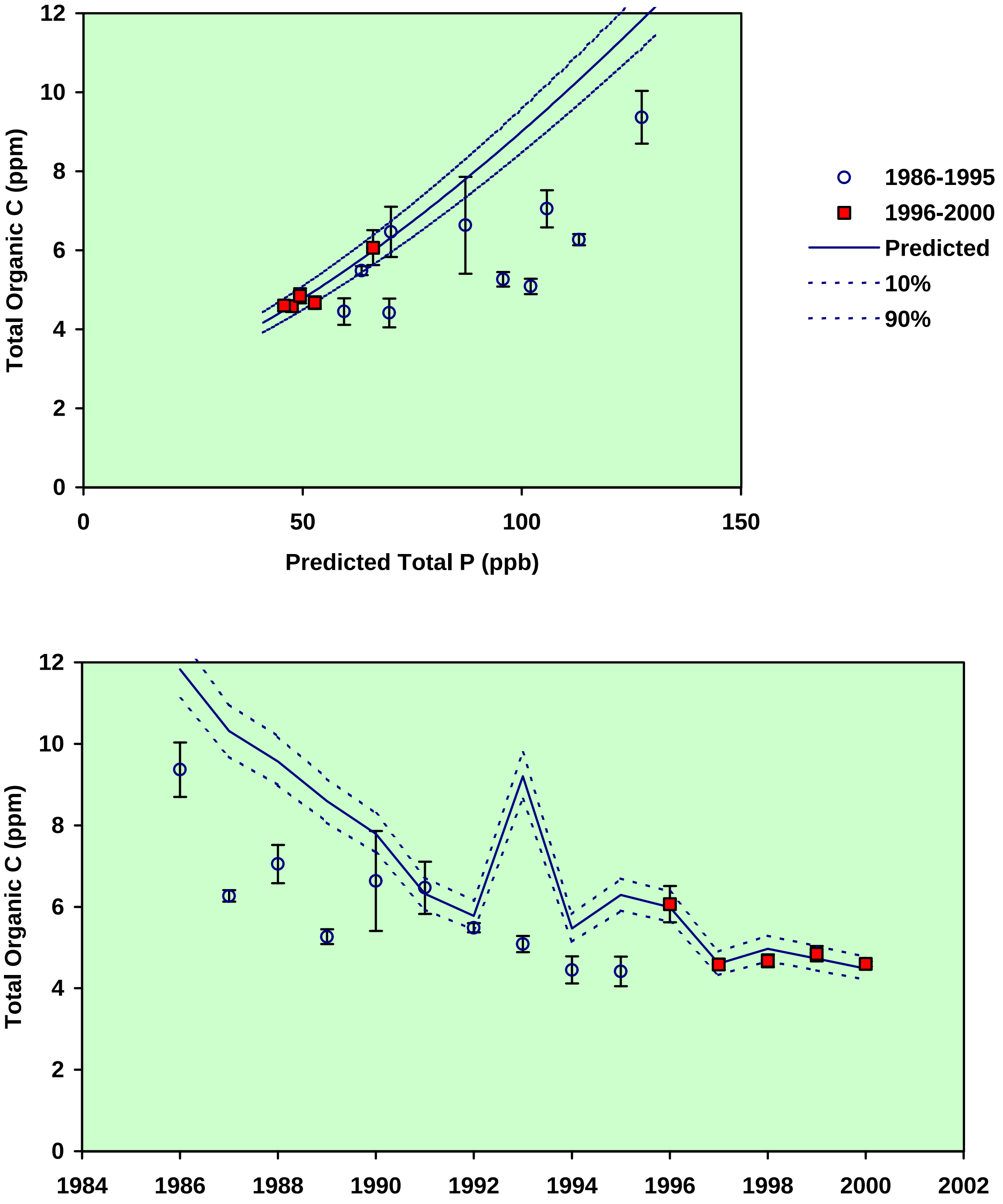


Figure 12-27
Observed & Predicted Organic Nitrogen Concentrations

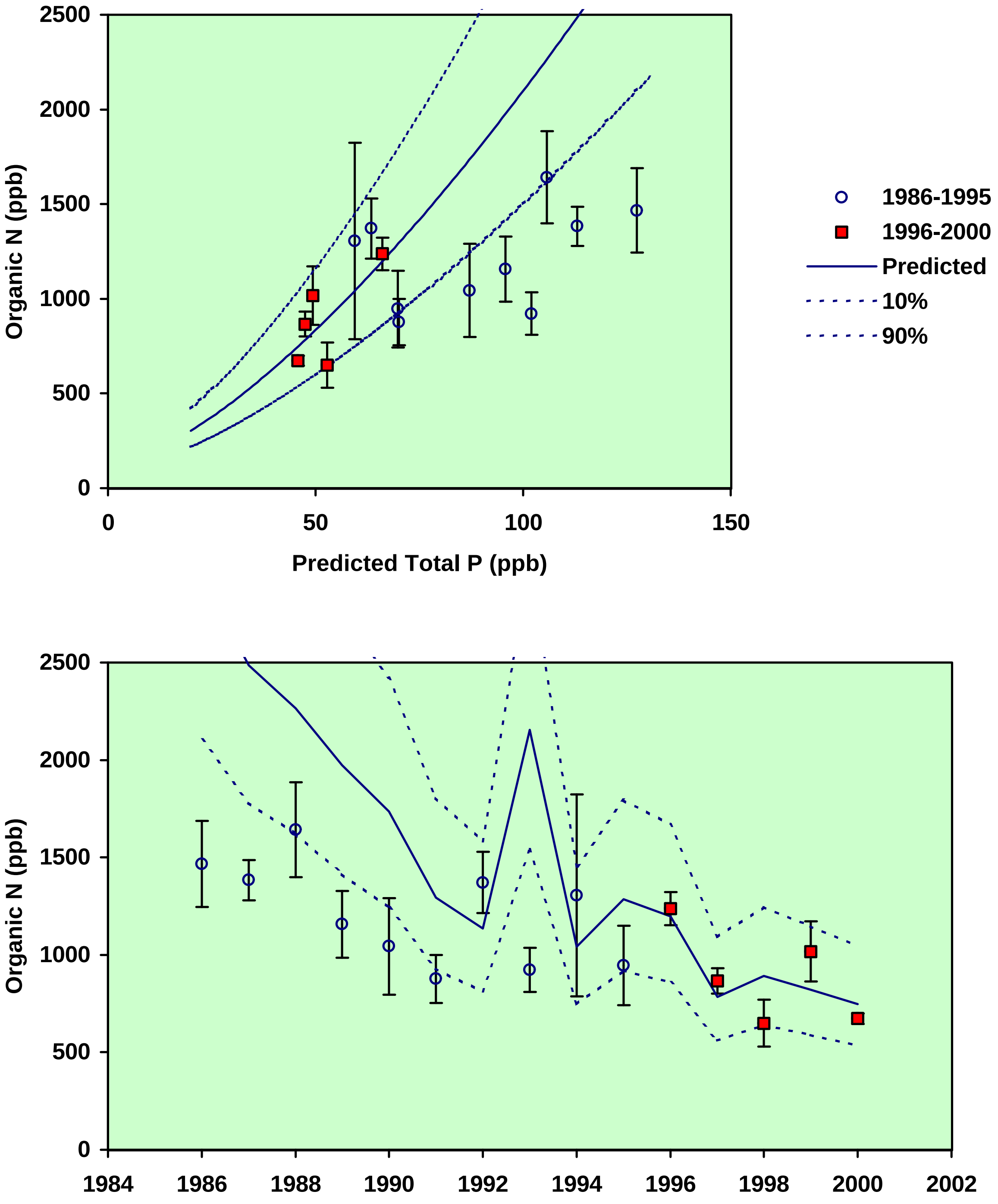


Figure 12-28
Observed & Predicted Inorganic Nitrogen Concentrations

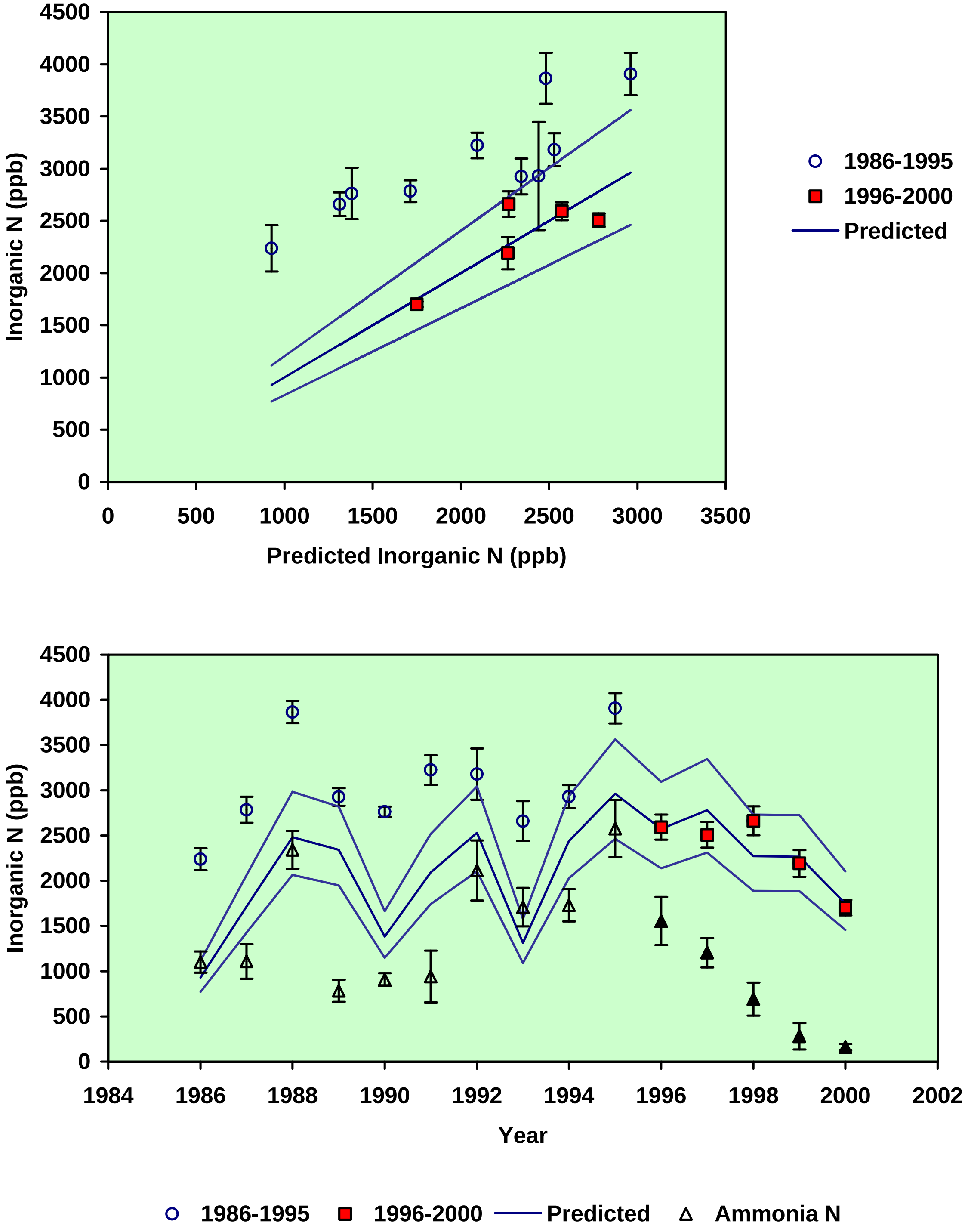
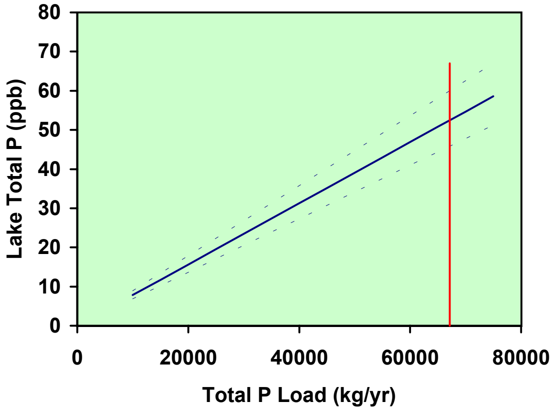


Figure 12-29

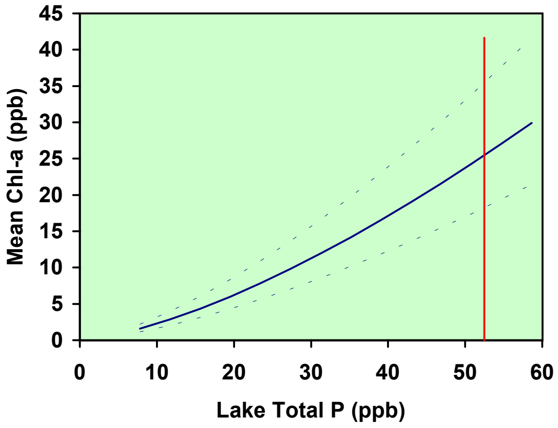


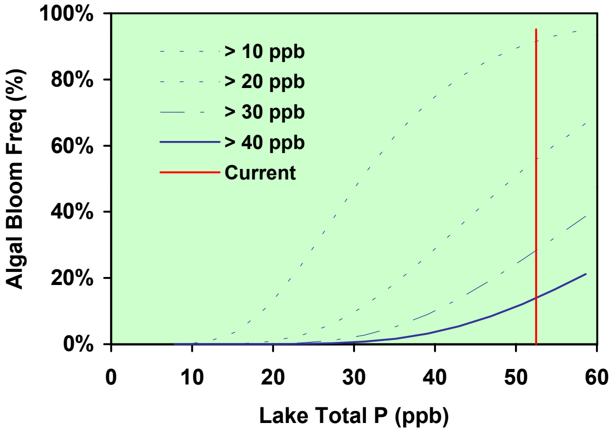
Predicted Lake Responses to Reductions in Phosphorus Load

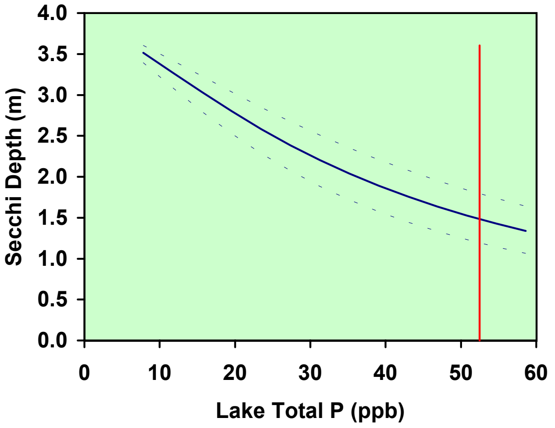
Base Conditions (1996-2000):

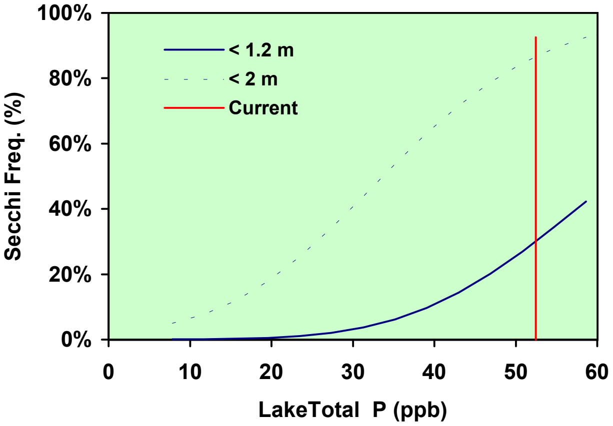
Average Outflow = 435 hm^3/yr
Total P Load = 67143 kg/yr
Total N Load = 2112700 kg/yr

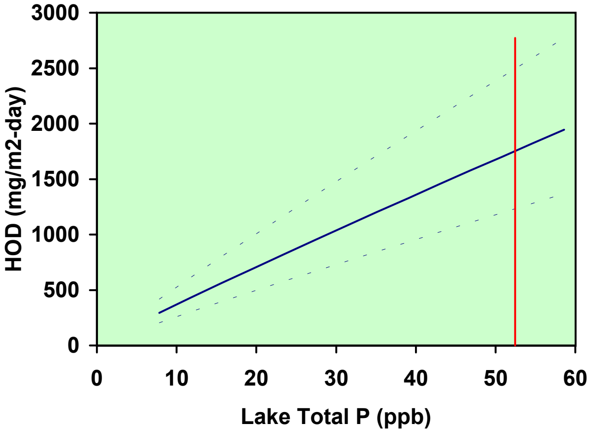
Dashed lines show 80% prediction intervals
Vertical Line = 1996-2000 Average Load

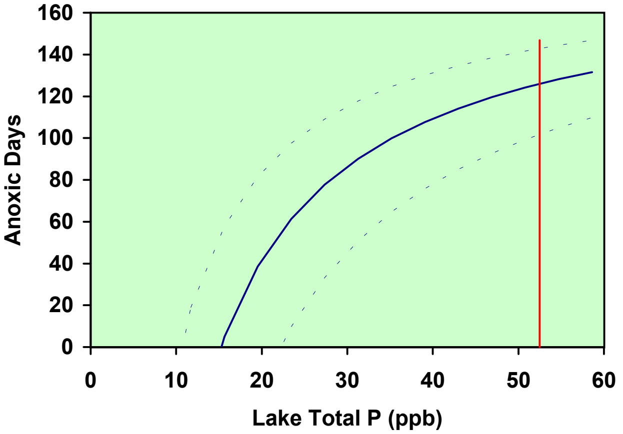












List of Tables - Chapter 12

Table 12-1: 10-Year Trends in Load & Concentration

Load Trends (% / yr) **Period: 1991 to 2000** **Period: Year**

Term	ALK	BOD5	CA	CL	FCOLI	NA	NH3N	NO2N	NO3N	ORTHOP	TIC	TKN	TN	TOC	TP	TSS
Metro		-5%				4%	-8%		18%	-14%		-7%	-4%	-7%	-8%	
Bypass																
Allied	-30%	-29%	-27%	-27%	-46%	-24%	-40%	-35%	-29%		-29%	-40%	-38%	-30%	-20%	
Crucible										36%						
Harbor/Hiawatha														-13%		
Ley/Park												-7%	-6%			
Ninemile/Rt48			-5%	-5%		-6%								-12%		
Onond./Kirkpatrick																
Harbor/Velasko						19%			25%							
Onondaga/Dorwin																
Total Gauged			-3%				-8%		7%	-13%		-7%	-4%	-10%	-8%	
NonPoint Gauged			-4%											-10%		
Ungauged			-4%											-10%		
Total NonPoint			-4%											-10%		
Total Industrial					-45%		-36%	-35%				-35%	-31%			
Total Municipal	-3%					3%	-8%		17%	-16%	-3%	-8%	-5%	-9%	-10%	
Total External			-3%				-8%		7%	-13%		-7%	-4%	-10%	-8%	
Total Inflow			-3%				-8%		6%	-13%		-7%	-4%	-10%	-8%	
Total Outflow		-4%					-8%					-6%		-9%		
Retention									34%	32%		-9%	-6%	-12%	-10%	
Outlet2		-5%					-7%					-7%		-9%		-9%
Outlet12		-4%					-8%					-6%		-9%		
Outlet Avg		-5%					-8%					-7%		-9%		
South Epil.		-4%	-3%				-8%					-7%	-4%			

Concentration Trends (% / yr)

Term	ALK	BOD5	CA	CL	FCOLI	NA	NH3N	NO2N	NO3N	ORTHOP	TIC	TKN	TN	TOC	TP	TSS
Metro	-2%	-5%				4%	-8%		18%	-14%	-2%	-7%	-4%	-7%	-8%	
Bypass	-2%	-5%							14%	-13%					-5%	
Allied	-3%				-31%	2%	-13%	-9%			-3%	-13%	-10%	-4%		
Crucible		-4%	3%			3%		-9%	-5%	24%			-5%	-7%	12%	
Harbor/Hiawatha		5%		5%		4%								-11%		
Ley/Park																
Ninemile/Rt48	-1%	5%				-3%										
Onond./Kirkpatrick	-2%	7%									-1%	2%			-4%	
Harbor/Velasko					-33%		-13%	-56%	7%	-26%						
Onondaga/Dorwin	-2%	5%						9%	3%		-2%		4%			-9%
Total Gauged	-1%		-2%						8%	-12%	-1%	-5%		-8%	-6%	
NonPoint Gauged	-1%													-9%		
Ungauged	-1%													-9%		
Total NonPoint	-1%													-9%		
Total Industrial	-3%	-4%			-38%		-21%	-20%	-6%	7%	-2%	-19%	-15%	-6%		
Total Municipal	-2%					4%	-8%		18%	-16%	-2%	-7%	-4%	-9%	-9%	
Total External	-1%		-2%						8%	-12%	-1%	-5%		-8%	-6%	
Total Inflow	-2%		-2%						8%	-12%	-1%	-5%		-8%	-6%	
Total Outflow	-2%		-1%				-6%		3%		-1%	-4%		-7%		
Outlet2	-2%	-4%	-2%				-5%		3%		-1%	-5%	-3%	-7%		-7%

Table 12-2: Chloride Balance for 1996-2000

Variable: **Chloride** **Average for Years:** **1996** **thru** **2000** **Season:** **Year**

							Percent of Total Inflow					
Term	**Flow 10^6 m3**	**Load mtons**	**Std Error mtons**	**Conc ppm**	**RSE %**	**Samp. per yr**	**Flow %**	**Load %**	**Error %**	**Drain. Area km2**	**Runoff cm**	**Export mtons/ km2**
Metro Effluent	91.07	31605	2138	347	7%	26	21%	20%	34%			
Metro Bypass	1.90	883	194	464	22%	6	0%	1%	0%			
East Flume	0.36	167	7	459	4%	27	0%	0%	0%			
Crucible	1.15	454	18	394	4%	27	0%	0%	0%			
Harbor Brook	8.43	2071	98	246	5%	29	2%	1%	0%	29.3	28.8	70.7
Ley Creek	34.10	10272	564	301	5%	28	8%	6%	2%	77.5	44.0	132.5
Ninemile Creek	129.70	56559	1760	436	3%	27	29%	35%	23%	298.1	43.5	189.7
Onondaga Creek	146.17	52623	2157	360	4%	29	33%	33%	35%	285.1	51.3	184.6
Nonpoint Gauged	318.40	121525	2842	382	2%	112	72%	75%	60%	690.0	46.1	176.1
Nonpoint Ungauged	17.09	6522	893	382	14%	0	4%	4%	6%	37.0	46.1	176.1
NonPoint Total	335.49	128047	2979	382	2%	112	76%	79%	66%	727.0	46.1	176.1
Industrial	1.52	621	19	409	3%	54	0%	0%	0%			
Municipal	92.98	32488	2146	349	7%	32	21%	20%	34%			
Total External	429.99	161156	3672	375	2%	198	97%	100%	100%	727.0	59.1	221.7
Precipitation	12.49	12	1	1	9%	0	3%	0%	0%	11.7	106.8	1.1
Total Inflow	442.48	161168	3672	364	2%	198	100%	100%	100%	738.7	59.9	218.2
Evaporation	8.86						2%			11.7	75.7	
Outflow	433.62	187716	3007	433	2%		98%	116%	67%	738.7	58.7	254.1
Retention	0.00	-26548	4746		18%		0%	-16%				
Alternative Estimates of Lake Output												
Outlet 12 Feet	433.62	187716	3007	433	2%	24	98%	116%	67%	738.7	58.7	254.1
Outlet 2 Feet	433.62	158049	3667	364	2%	25	98%	98%	100%	738.7	58.7	213.9
Lake Epil	433.62	183268	2191	423	1%	20	98%	114%	36%	738.7	58.7	248.1
Upstream/Downstream Contrast- Harbor Brook												
Upstream - Velasko	6.51	1418	55	218	4%	23	1%	1%	0%	25.9	25.1	54.7
Downstream - Hiawatha	8.43	2071	98	246	5%	29	2%	1%	0%	29.3	28.8	70.7
Local Inflow	1.92	654	112	341	17%		0%	0%	0%	3.4	56.9	194.0
Upstream/Downstream Contrast - Onondaga Creek												
Upstream - Dorwin	114.19	13488	441	118	3%	29	26%	8%	1%	229.4	49.8	58.8
Downstream - Kirkpatrick	146.17	52623	2157	360	4%	29	33%	33%	35%	285.1	51.3	184.6
Local Inflow	31.98	39135	2202	1224	6%		7%	24%	36%	55.7	57.4	702.2

Lake Overflow Rate 37.06 m/yr Calib. Settling Rate -5.2 m/yr RSE % = Relative Std. Error of Load & Inflow Conc. Estimates
Lake Residence Time 0.29 years Calib. Retention Coef. -16% Error % = Percent of Variance in Total Inflow Load Estimate

Table 12-3: Total Phosphorus Balance for 1996-2000

Variable: **Total Phosphorus** **Average for Years:** **1996** **thru** **2000** **Season:** **Year**

							Percent of Total Inflow			Drain.		Export
Term	**Flow 10^6 m3**	**Load kg**	**Std Error kg**	**Conc ppb**	**RSE %**	**Samp. per yr**	**Flow %**	**Load %**	**Error %**	**Area km2**	**Runoff cm**	**kg / km2**
Metro Effluent	91.07	36359	404	399	1%	365	21%	55%	5%			
Metro Bypass	1.90	2688	92	1411	3%	39	0%	4%	0%			
East Flume	0.36	78	6	215	7%	27	0%	0%	0%			
Crucible	1.15	123	4	106	4%	27	0%	0%	0%			
Harbor Brook	8.43	699	174	83	25%	29	2%	1%	1%	29.3	28.8	23.9
Ley Creek	34.10	4178	651	123	16%	27	8%	6%	14%	77.5	44.0	53.9
Ninemile Creek	129.70	7906	965	61	12%	27	29%	12%	31%	298.1	43.5	26.5
Onondaga Creek	146.17	12076	1180	83	10%	28	33%	18%	46%	285.1	51.3	42.4
Nonpoint Gauged	318.40	24860	1667	78	7%	111	72%	38%	93%	690.0	46.1	36.0
Nonpoint Ungauged	17.09	1334	211	78	16%	0	4%	2%	1%	37.0	46.1	36.0
NonPoint Total	335.49	26194	1680	78	6%	111	76%	40%	94%	727.0	46.1	36.0
Industrial	1.52	201	7	133	4%	54	0%	0%	0%			
Municipal	92.98	39047	415	420	1%	404	21%	59%	6%			
Total External	429.99	65442	1731	152	3%	569	97%	99%	100%	727.0	59.1	90.0
Precipitation	12.49	375	34	30	9%	0	3%	1%	0%	11.7	106.8	32.0
Total Inflow	442.48	65817	1731	149	3%	569	100%	100%	100%	738.7	59.9	89.1
Evaporation	8.86						2%			11.7	75.7	
Outflow	433.62	43023	1662	99	4%		98%	65%	92%	738.7	58.7	58.2
Retention	0.00	22794	2400		11%		0%	35%				
Alternative Estimates of Lake Output												
Outlet 12 Feet	433.62	43023	1662	99	4%	24	98%	65%	92%	738.7	58.7	58.2
Outlet 2 Feet	433.62	38797	1552	89	4%	25	98%	59%	80%	738.7	58.7	52.5
Lake Epil	433.62	40229	1805	93	4%	21	98%	61%	109%	738.7	58.7	54.5
Upstream/Downstream Contrast- Harbor Brook												
Upstream - Velasko	6.51	279	54	43	19%	23	1%	0%	0%	25.9	25.1	10.7
Downstream - Hiawatha	8.43	699	174	83	25%	29	2%	1%	1%	29.3	28.8	23.9
Local Inflow	1.92	421	182	219	43%		0%	1%	1%	3.4	56.9	124.9
Upstream/Downstream Contrast - Onondaga Creek												
Upstream - Dorwin	114.19	7383	800	65	11%	29	26%	11%	21%	229.4	49.8	32.2
Downstream - Kirkpatrick	146.17	12076	1180	83	10%	28	33%	18%	46%	285.1	51.3	42.4
Local Inflow	31.98	4692	1426	147	30%		7%	7%	68%	55.7	57.4	84.2

Lake Overflow Rate	37.06	m/yr	Calib. Settling Rate	19.6	m/yr	RSE % = Relative Std. Error of Load & Inflow Conc. Estimates
Lake Residence Time	0.29	years	Calib. Retention Coef.	35%		Error % = Percent of Variance in Total Inflow Load Estimate

Table 12-4: Total Nitrogen Balance for 1996-2000

Variable: **Total Nitrogen** **Average for Years:** **1996** **thru** **2999** **Season:** **Year**

							Percent of Total Inflow			Drain.		Export
Term	**Flow 10^6 m3**	**Load kg**	**Std Error kg**	**Conc ppb**	**RSE %**	**Samp. per yr**	**Flow %**	**Load %**	**Error %**	**Area km2**	**Runoff cm**	**kg/ km2**
Metro Effluent	91.07	1428326	25746	15683	2%	29	21%	69%	52%			
Metro Bypass	1.90	28960	17070	15207	59%	6	0%	1%	23%			
East Flume	0.36	2765	93	7597	3%	27	0%	0%	0%			
Crucible	1.15	2585	155	2244	6%	27	0%	0%	0%			
Harbor Brook	8.43	17202	428	2042	2%	27	2%	1%	0%	29.3	28.8	587.3
Ley Creek	34.10	60237	5460	1767	9%	25	8%	3%	2%	77.5	44.0	777.2
Ninemile Creek	129.70	240150	12726	1852	5%	27	29%	12%	13%	298.1	43.5	805.6
Onondaga Creek	146.17	235147	10298	1609	4%	27	33%	11%	8%	285.1	51.3	824.7
Nonpoint Gauged	318.40	552736	17263	1736	3%	105	72%	27%	23%	690.0	46.1	801.0
Nonpoint Ungauged	17.09	29664	4204	1736	14%	0	4%	1%	1%	37.0	46.1	801.0
NonPoint Total	335.49	582400	17767	1736	3%	105	76%	28%	25%	727.0	46.1	801.0
Industrial	1.52	5351	181	3529	3%	54	0%	0%	0%			
Municipal	92.98	1457286	30891	15673	2%	35	21%	70%	75%			
Total External	429.99	2045037	35636	4756	2%	193	97%	99%	100%	727.0	59.1	2812.8
Precipitation	12.49	23731	2136	1900	9%	0	3%	1%	0%	11.7	106.8	2028.3
Total Inflow	442.48	2068768	35700	4675	2%	193	100%	100%	100%	738.7	59.9	2800.4
Evaporation	8.86						2%			11.7	75.7	
Outflow	433.62	1492653	27433	3442	2%		98%	72%	59%	738.7	58.7	2020.5
Retention	0.00	576115	45023		8%		0%	28%				
Alternative Estimates of Lake Output												
Outlet 12 Feet	433.62	1492653	27433	3442	2%	24	98%	72%	59%	738.7	58.7	2020.5
Outlet 2 Feet	433.62	1323137	28945	3051	2%	25	98%	64%	66%	738.7	58.7	1791.1
Lake Epil	433.62	1519526	22491	3504	1%	21	98%	73%	40%	738.7	58.7	2056.9
Upstream/Downstream Contrast- Harbor Brook												
Upstream - Velasko	6.51	13018	300	2000	2%	23	1%	1%	0%	25.9	25.1	502.2
Downstream - Hiawatha	8.43	17202	428	2042	2%	27	2%	1%	0%	29.3	28.8	587.3
Local Inflow	1.92	4185	523	2181	12%		0%	0%	0%	3.4	56.9	1241.8
Upstream/Downstream Contrast - Onondaga Creek												
Upstream - Dorwin	114.19	181336	8707	1588	5%	26	26%	9%	6%	229.4	49.8	790.5
Downstream - Kirkpatrick	146.17	235147	10298	1609	4%	27	33%	11%	8%	285.1	51.3	824.7
Local Inflow	31.98	53812	13486	1683	25%		7%	3%	14%	55.7	57.4	965.6

Lake Overflow Rate 37.06 m/yr Calib. Settling Rate 14.3 m/yr RSE % = Relative Std. Error of Load & Inflow Conc. Estimates
Lake Residence Time 0.29 years Calib. Retention Coef. 28% Error % = Percent of Variance in Total Inflow Load Estimate
Lake Residence Time 0.32 years Calib. Retention Coef. 41% Error % = Percent of Variance in Total Inflow Load Estimate

Table 12-5
Model Calibration Data

Phosphorus Balance

Water Year	Net Inflow hm3	Metro+ Bypass kg	Total Load kg	SE kg	Outflow Load kg	SE kg	Inflow P P Conc ppb	SE ppb	Outflow P Conc ppb	SE ppb	July-Sept 0-3 m P Conc ppb	SE ppb
1986	483.5	121740	174968	8339	74508	2796	361.9	17.2	154.1	5.8	146.0	11.3
1987	440.5	104222	145808	5619	96439	6653	331.0	12.8	218.9	15.1	118.2	6.2
1988	341.8	89279	116002	3906	76868	5375	339.4	11.4	224.9	15.7	120.5	14.7
1989	426.7	74729	120874	6817	58577	4370	283.3	16.0	137.3	10.2	80.9	11.8
1990	602.3	73460	139838	8048	99223	11908	232.2	13.4	164.7	19.8	95.5	23.0
1991	536.7	61088	103589	9702	53830	4198	193.0	18.1	100.3	7.8	64.7	6.5
1992	476.1	55830	86216	4939	49383	4603	181.1	10.4	103.7	9.7	61.7	15.4
1993	563.7	112279	156070	7536	102672	6627	276.8	13.4	182.1	11.8	109.0	13.1
1994	478.2	61232	81034	6850	62614	6293	169.5	14.3	130.9	13.2	79.1	12.6
1995	296.7	47372	70431	5456	50507	5110	237.4	18.4	170.2	17.2	65.0	9.0
1996	474.2	52661	89570	4898	63094	5088	188.9	10.3	133.1	10.7	60.9	3.8
1997	444.9	40422	61725	1922	48247	4750	138.7	4.3	108.4	10.7	52.8	5.9
1998	466.2	41068	70668	5204	38013	3348	151.6	11.2	81.5	7.2	50.9	4.2
1999	312.5	34174	51366	2339	33627	3503	164.4	7.5	107.6	11.2	53.9	7.8
2000	477.9	32953	62386	3606	39538	3950	130.5	7.5	82.7	8.3	43.8	4.6

Nitrogen Balance

Water Year	Net Inflow hm3	Metro+ Bypass kg	Total Load kg	SE kg	Outflow Load kg	SE kg	Inflow P P Conc ppb	SE ppb	Outflow N Conc ppb	SE ppb	July-Sept 0-3 m N Conc ppb	SE ppb
1986	483.5	1709557	2740662	68830	2001359	74980	5668	142	4139	155	3704	295
1987	440.5	1970213	2781108	91737	2315259	71701	6314	208	5256	163	4168	204
1988	341.8	2058390	2631519	80553	1737374	68659	7698	236	5082	201	5507	246
1989	426.7	2111344	2793577	78436	2095994	80087	6546	184	4912	188	4083	253
1990	602.3	1725019	2614438	91045	2032496	41581	4340	151	3374	69	3806	234
1991	536.7	1777828	2598964	83851	1742457	64203	4843	156	3247	120	4100	226
1992	476.1	1873839	2568401	68474	1854635	62849	5395	144	3896	132	4552	395
1993	563.7	2011697	2762308	69379	1907806	58847	4900	123	3384	104	3581	138
1994	478.2	1818246	2448586	85229	1883996	49810	5121	178	3940	104	4234	483
1995	296.7	1800917	2146274	73875	1344905	43370	7233	249	4533	146	4851	325
1996	474.2	1924330	2634024	73836	1966103	68425	5555	156	4146	144	3829	210
1997	444.9	1762833	2377383	48233	1581144	43669	5343	108	3554	98	3373	128
1998	466.2	1550049	2183767	87845	1624155	39711	4684	188	3483	85	3311	135
1999	312.5	1219387	1613254	54959	1026854	21900	5162	176	3286	70	3208	180
2000	477.9	1077170	1755075	67796	1443324	82450	3672	142	3020	173	2373	99

Chlorophyll-a

July - September, Lake South Station, 0 to 3 meters

Water Year	Sample Dates	Mean ppb	Std Dev ppb	SE ppb	Freq > 10 -	Freq > 20 -	Freq > 30 -	Freq > 40 -	Freq > 60 -
1986	6	20.5	26.2	10.7	0.667	0.333	0.167	0.167	0.167
1987	6	9.7	5.3	2.2	0.500	0.000	0.000	0.000	0.000
1988	6	18.0	7.5	3.1	0.833	0.500	0.000	0.000	0.000
1989	6	7.3	6.4	2.6	0.333	0.000	0.000	0.000	0.000
1990	6	47.2	29.4	12.0	1.000	1.000	0.500	0.500	0.167
1991	13	39.4	27.0	7.5	0.923	0.692	0.538	0.462	0.154
1992	14	19.3	9.6	2.6	0.857	0.429	0.143	0.000	0.000
1993	7	21.0	17.8	6.7	0.857	0.429	0.143	0.143	0.000
1994	7	31.1	39.3	14.9	0.429	0.429	0.429	0.429	0.143
1995	7	8.0	4.4	1.6	0.571	0.000	0.000	0.000	0.000
1996	6	40.1	22.4	9.1	1.000	1.000	0.667	0.167	0.167
1997	6	16.5	12.7	5.2	0.667	0.167	0.167	0.167	0.000
1998	10	19.1	9.2	2.9	0.900	0.400	0.200	0.000	0.000
1999	14	27.5	16.2	4.3	1.000	0.500	0.357	0.143	0.071
2000	13	24.2	15.3	4.2	0.846	0.615	0.231	0.154	0.000

Secchi Depth July - September, Lake South Station **Hypol. Oxygen Depletion Rate**

Water Year	Sample Dates	Mean m	Std Dev m	SE m	Freq < 1.2 -	Freq < 2.0 -	below 6 meters mg/m^2-day
1986	6	0.667	0.151	0.061	1.000	1.000	1111 *
1987	6	1.833	0.731	0.299	0.000	0.667	1425 *
1988	6	1.100	0.228	0.093	0.500	1.000	1623 *
1989	6	1.350	0.217	0.089	0.167	1.000	1927
1990	6	1.317	0.512	0.209	0.500	1.000	1687
1991	5	1.040	0.288	0.129	0.800	1.000	1889
1992	7	1.514	0.157	0.059	0.000	1.000	1974 *
1993	7	1.814	0.857	0.324	0.143	0.714	1278 *
1994	7	2.243	0.971	0.367	0.286	0.286	904 *
1995	6	1.767	0.258	0.105	0.000	0.667	2358
1996	6	1.083	0.293	0.119	0.500	1.000	1714
1997	6	1.767	0.301	0.123	0.000	0.667	1116 *
1998	7	1.793	0.688	0.260	0.286	0.571	1519
1999	13	1.300	0.529	0.147	0.385	0.923	2077
2000	13	1.962	0.690	0.191	0.000	0.615	2013

Nutrients

July - September, Lake South Station, 0 to 3 meters

	Total Org. Carbon		Organic N		Ammonia N		SRP	
Water Year	Mean ppm	SE ppm	Mean ppb	SE ppb	Mean ppb	SE ppb	Mean ppb	SE ppb
1986	9.37	0.67	1467	222	1100	117	44.0	2.6
1987	6.27	0.14	1383	103	1108	191	42.9	4.0
1988	7.05	0.47	1642	243	2342	210	34.8	8.7
1989	5.27	0.18	1158	171	783	121	17.6	4.5
1990	6.63	1.23	1043	246	907	69	12.4	4.8
1991	6.47	0.64	877	122	941	285	1.7	0.4
1992	5.49	0.11	1372	158	2113	332	14.0	6.3
1993	5.09	0.20	922	113	1709	213	21.1	8.6
1994	4.45	0.33	1305	519	1728	178	19.6	7.5
1995	4.41	0.36	946	203	2577	314	15.7	10.6
1996	6.07	0.44	1237	86	1554	267	4.9	1.2
1997	4.58	0.14	867	65	1204	162	5.0	2.1
1998	4.67	0.16	649	120	692	182	2.0	0.6
1999	4.85	0.19	1018	154	280	147	1.1	0.1
2000	4.60	0.06	673	27	161	34	1.4	1.5

SE = Standard Error of Mean

* Lower limit of actual HOD because of incomplete spring turnover or loss of oxygen during calculation interval

Table 12-6
Model Equations

Predicted Trophic Response Variables:

Po = Water Year Flow-Wtd-Mean Outflow Total P (ppb)
P = Mean Total P (ppb) *
No = Water Year Flow-Wtd-Mean Outflow Total N (ppb)
N = Mean Total N (ppb) *
B = Mean Chlorophyll-a (ppb) *
S = Mean Secchi Depth (m) *
HOD = Hypolimnetic Oxygen Depletion Rate (mg/m^2-day)
TOC = Total Organic Carbon (ppm) *
TON = Total Organic Nitrogen (ppb) *
TIN Total Inorganic Nitrogen (ppb) *
* July-September, 0-3 meters, Lake South Station

Lake Outflow Total P:

Reference: Vollenweider (1969) , Chapra (1975), Sas (1989)
$P_O = W_P \;/\; (Q_O + U_P A)$
W_P = Inflow P Load (kg/yr)
Q_O = Outflow = External Inflow + Precip - ET (hm^3/yr)
A = Lake Surface Area = 11.7 km^2
U_P = P Settling Rate = 18.9 m/yr
Calibrated to 1995-1999

Period	1996-2000	1986-1995
Residual CV	0.15	0.24
R^2	0.51	0.45

Lake South Epilimnetic Total P:

Reference: Walker (1978), Sas (1989)
$P = F_P \; P_O$
F_P = 0.51 Calibrated to 1996-2000

Period	1996-2000	1986-1995
Residual CV	0.09	0.13
R^2	0.44	0.89

Lake Outflow Total N:

$N_O = W_N \;/\; (Q_O + U_N A)$
W_N = Inflow N Load (kg/yr)
U_N = N Settling Rate = 14.2 m/yr
Calibrated to 1995-1999

Period	1996-2000	1986-1995
Residual CV	0.07	0.07
R^2	0.70	0.84

Lake South Epilimnetic Total N:

$N = F_N \; No$
F_N = 0.92 Calibrated to 1996-200

Period	1996-2000	1986-1995
Residual CV	0.05	0.13
R^2	0.92	0.56

Lake South Chlorophyll-a:

Reference: Jones & Bachman (1976)
$B = k \; P^{1.46}$
k = 0.078

DataSet	J& B	1996-2000
Residual CV	-	0.22
R^2	0.90	0.64

Algal Bloom Frequencies:

Reference: Walker (1984)
F_X = 1 - Normal $[\; (\ln(X) - \ln(B) - 0.5 \, S_B^2) \; / \; S_B \;]$
S_B = $[\ln (1 + C_B^2)]^{1/2}$
X = Bloom Criterion (10, 20, 30 or 40 ppb)
F_X = Frequency of Chl-a > X
Normal Cumulative Normal Frequency Distribution
S_B = Standard Deviation of ln (Chl-a)
C_B = Within-Year Temporal CV = 0.61
Calibrated to 1996-2000 Data

Lake South Secchi Depth:

Reference: Walker (1985,1996)
$S = \exp (S_S^2) \;/\; (a + b \; B)$
Calibrated to Sample Dates, 1996-1999
a = 0.285419 1/m
b = 0.018 m^2/mg

Period	1996-2000
Residual CV	0.17
R^2	0.53

Secchi Interval Frequencies:

Reference: Walker (1984)
F_Y = Normal $[\; (\ln(Y) - \ln(S) - 0.5 \, S_S^2) \; / \; S_S \;]$
S_S = $[\ln (1 + C_S^2)]^{1/2}$ = 0.31
C_S = 0.32 Calibrated to 1986-2000 Data
Y = Secchi Criterion (1.2 or 2 m)
F_Y = Frequency of Secchi < Y
S_S = Standard Deviation of ln (Secchi)
C_S = Within-Year Temporal CV of Secchi Depth

Hypolimnetic Oxygen Depletion Rate:

Reference: Walker (1979)
Log HOD = -0.58 + 0.0204 I + 4.55 log Z -2.04 (Log Z)^2
I = Phosphorus Trophic Index = -15.6 + 46.1 log P
Z = Mean Depth = 10.90 m
HOD = 42.3 $P^{0.94}$ not recalibrated

DataSet	Walker(1979)	1996-2000
Residual CV	0.23	0.25
R^2	0.91	0.00

Days of Oxygen Supply in Hypolimnion:

Reference: Walker (1979)
$T_{DO} = 1000 \; DO_S \; Z_H \;/\; HOD$
$T_{ANOXIC} = T_{STRAT} - T_{DO}$
T_{DO} = Oxygen Supply at Spring Turnover (days)
T_{ANOXIC} = Duration of Anoxic Period (days)
DO_S = Oxygen at Spring Turnover = 12 ppm
Z_H = Mean Hypolimnetic Depth = 8.34 meters
for 6-meter Thermocline Depth
T_{STRAT} = Duration of Stratified Period = 183 days
April 15 - October 15

Lake South Total Organic Carbon:

Reference: Walker (1983)
TOC = a + b B
a = 2.36
b = 0.10

	1996-2000
Residual CV	0.04
R^2	0.90

Lake South Total Organic Nitrogen:

Reference: Walker (1985; 1996)
TON = a + b B
a = 113.9
b = 30.4

	1996-2000
Residual CV	0.22
R^2	0.38

Lake South Total Inorganic Nitrogen:

TIN = N - TON

	1996-2000
Residual CV	0.12
R^2	0.50