D R A F T - 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 1998 lake monitoring report (Ecologic, et al, 1999). Interactive 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 (Figure 12-1). Predictive models for annual outflow and summer lake total phosphorus and total nitrogen concentrations use simple first-order rate expressions to represent nutrient retention within the Lake.

This chapter updates the mass-balance framework to include 1986-1999 data. Total phosphorus and total nitrogen models are refined and recalibrated. The phosphorus balance is linked to a network of empirical models for predicting trophic state indicators including chlorophyll-a, transparency, and hypolimnetic oxygen depletion rate (Figure 12-2). These models provide a basis for predicting seasonally averaged lake responses to reductions in external phosphorus loads resulting from future implementation of point-source and nonpoint-source control measures.

12.2 DATABASE UPDATES

Mass-balance tables have been updated to include 1999 data using methods and assumptions described in the 1998 annual report. Ten-year trends in concentration and load for each source and water quality component are summarized in Tables 12-1 and12-2, respectively. Five-year-average mass-balances for chloride, total phosphorus, and total nitrogen are listed in Tables 12-3, 4, & 5, respectively. Accuracies of the water balance and load computation framework are supported by the fact that chloride inputs and output differ by ~1% over the 1995-1999 period.

In the previous report, total phosphorus loads for the 1985-1989 period (when TP was not measured) were estimated by applying TP/TIP ratios to the measured TIP loads for each tributary. The ratios were calibrated to data from subsequent years when both TP and TIP were measured. These estimates have been refined by developing a TP vs. TIP regression model for each tributary and the lake epilimnion. The model includes both a slope and an intercept, whereas the previous procedure assumed an intercept of zero. In addition, each model has been calibrated to paired TP and TIP measurements (vs. annual loads).

Figure 12-3 shows yearly variations in total precipitation, lake inflow volumes and loads of total phosphorus and total nitrogen over the 1986-1999 period. Inflow volumes and nutrient loads were relatively low in 1999, primarily because of low precipitation (31 inches vs. average of 37 inches for 1986-1998). Total phosphorus loads generally declined over the 1986-1999 period. Trend analysis results for 1990-1999 (Tables 12-1 & 12-2) indicate significant decreasing trends in phosphorus load and concentration for Onondaga Creek and Metro. When adjusted for variations in flow, however, only the Metro trend (-5% per year) is significant. For this particular time period, the adjustment procedure may over-compensate for flow effects because the time series starts with a wet year (1990) and ends in a dry year (1999). When this occurs, it is difficult to distinguish effects of flow from a long-term trend. For this reason, the declining trend in Onondaga Creek may in fact be significant, even though the regression indicates otherwise. Total nitrogen loads decreased steadily over the 1996-1999 period. This is attributed primarily to reductions in ammonia nitrogen load resulting from increased nitrification at Metro.

Yearly phosphorus and nitrogen balances are listed in Tables 12-6 and 12-7, respectively. Other data used for calibration and testing of the eutrophication model network are summarized in Table 12-8. These data have been derived from the mass-balance framework and historical lake water quality files.

12.3 TOTAL PHOSPHORUS MODEL

The structure of the phosphorus balance model is identical to that described in the 1998 annual report (Figure 12-2, Table 12-9). Flows and phosphorus loads used for model calibration and testing are listed in Table 12-6. The annual flow-weighted-mean outflow concentration is predicted from outflow volume and inflow load using a first-order settling velocity to predict net sedimentation within the Lake (Vollenweider, 1969; Chapra, 1975). Because the mass-balance is used to predict both annual outflow concentration and summer epilimnetic P concentration, it is formulated on a water-year basis (October thru September). A calendar-year basis would be less appropriate because loads between October and December could not influence lake conditions in summer of the same calendar year.

The settling velocity (22.9 m/yr) is calibrated to data from the last 5 water years (1995-1999). Hindcasts of 1986-1994 data provide a basis for model testing. Observed and predicted outflow P concentrations are plotted in Figure 12-4. Within the calibration period, the model explains 73 % of the variance in the observed outflow concentration with a residual standard error of 11%. There is a tendency for the model to over-predict outflow concentrations in earlier years (1986, 1989, 1991, 1992). This may reflect:

1. positive correlation between net settling rate and concentration or load, as embodied in other empirical phosphorus models developed from lake or reservoir data sets (Canfield & Bachman 1981; Walker, 1985; Sas,1989);
2. non-steady-state conditions in the Lake owing to feedback of sediment phosphorus during this period of declining external phosphorus loads; and/or
3. anomalies in sampling of the lake outlet owing to backflows from the Seneca River.

Development of a dynamic P balance model that accounts for sediment P storage and recycling may help to determine whether the second mechanism is important. Because the reasons cannot be specifically identified and because predictions of summer epilimnetic P concentrations do not show the same pattern (see below), modification of the model to simulate outflow concentrations in these early years does not seem appropriate. Future mass-balance results will determine whether the apparent pattern of a declining net settling rate computed from lake outflow concentrations continues.

Summer epilimnetic total phosphorus concentrations at the Lake South station drive predictions of other trophic state indicators (Figure 12-5). For reasons described below, summer epilimnetic concentrations are computed from samples collected between July and September at the Lake South station at depths ranging from 0 to 3 meters. Summer P values are predicted by applying a constant ratio to the annual flow-weighted-mean outflow concentration predicted by the mass-balance model (Sas, 1989). This ratio (0.55, calibrated to 1995-1999 data) accounts for seasonal and, to a lesser extent, spatial variations. Within the calibration period, the model explains 29% of the variance in the observed lake P concentration with a residual standard error of 9%. The low r^2 value reflects low variability in the observed concentration during this period; the validity of the model is supported by the low residual standard error, well below the ~20% level typical of empirical phosphorus balance models (Walker, 1985,1996). Model performance statistics for the entire 1986-1999 period are r^2 = 88% and CV =13%.

Summer epilimnetic P concentrations respond quickly to year-to-year variations in external load (Figure 12-5). This suggests that feedback of sediment phosphorus deposited historically is not significantly delaying the recovery of the lake during this period of declining phosphorus loads, at least within the concentration ranges achieved to date. Long-term trends in average inflow and outflow concentrations and loads (Figure 12-6) are also consistent with a rapid lake response to reductions in external load.

12.4 TOTAL NITROGEN MODEL

The structure of the nitrogen balance model is identical to that described in the 1998 annual report (Table 12-9, Figure 12-2). The annual flow-weighted-mean outflow concentration is predicted from inflow volume and load using a first-order settling velocity to predict net sedimentation within the Lake. Flows and nitrogen loads used for model calibration and testing are listed in Table 12-7. As for phosphorus, the nitrogen model is calibrated to water-year time series.

The nitrogen settling velocity (24 m/yr) is calibrated to data from the last 5 water years (1995-1999). Hindcasts of 1986-1994 data are used for model testing. Observed and predicted outflow N concentrations are plotted in Figure 12-7. Within the calibration period, the model explains 75% of the variance in the observed outflow concentration with a residual standard error of 8 %. Corresponding values for the entire 1986-1999 period are 61% and 7%, respectively.

Summer epilimnetic total nitrogen concentrations at the Lake South station (Figure 12-8) are predicted by applying a constant ratio to the annual flow-weighted-mean outflow concentration predicted by the mass-balance model. This ratio (1.15, calibrated to 1995-1999 data) accounts for seasonal and, to a lesser extent, spatial variations. Apparently because of the importance of point-source nitrogen loadings, summer nitrogen levels in the lake epilimnion are 15% greater than annual, flow-weighted-mean outflow concentrations. Within the calibration period, the model explains 71% of the variance in the observed lake total N concentration with a residual standard error of 10%. Corresponding statistics for the entire 1986-1999 period are 53% and 11%, respectively.

12.5 TROPHIC RESPONSE MODELS

A network of empirical models has been assembled from the literature to provide a basis for predicting variations in the following trophic state indicators from summer epilimnetic Total P concentrations:

- Mean Chlorophyll-a
- Algal Bloom Frequencies (percent of time Chl-a exceeds 10, 20, 30, and 40 ppb)
- Mean Secchi Depth
- Secchi Frequencies (percent of time Secchi is less than 1.2 meters [4 feet bathing standard] and 2 meters)

- Hypolimnetic Oxygen Depletion Rate & Duration of Anoxic Conditions

The linkage of variables in the model network is shown in Figure 12-2. Calibration data are listed in Table 12-8. Model equations and calibration results are listed in Table 12-9.

Generally, these models were originally developed and calibrated to data from phosphorus-limited lakes (lakes in which algal productivity is limited by phosphorus concentrations). Historically, phosphorus concentrations in Onondaga Lake have been well in excess of growth-limiting levels. It is likely that factors such as light and zooplankton grazing have been controlling. Figure 12-9 shows total and ortho (~soluble reactive) phosphorus concentrations in the epilimnion (July-September means, 0-6 m, Lake South) between 1986-1999. Excess Ortho P is present in the Lake when Total P concentrations exceed ~50-60 ppb. The plots show that the Lake has approached a phosphorus-limited condition in recent years as the concentration of total phosphorus has reached 50-60 ppb. 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.

As borne out by the data presented below, phosphorus-based models would be expected to over-predict historical concentrations of chlorophyll-a and other trophic state indicators. As phosphorus concentrations have declined and approached growth-limiting levels in recent years, observations and model predictions have converged. Attempting to adapt the models to simulate historical conditions may be futile and is not necessary to forecast responses to future reductions in phosphorus load. Accordingly, the calibration strategy is to focus in recent years (1995-1999). High R^2 values are not expected within this period, given the limited number of years and range of data. In some situations, the models are adopted without re-calibration because observed concentrations are not significantly different from model predictions. If necessary, the models can be recalibrated to match observed responses as phosphorus levels decrease future years. The key assumption in using the models in a forecast mode is that phosphorus will remain limiting and that the Lake will respond to reductions in phosphorus in a manner that is reflected in the cross-sectional data sets derived from other phosphorus-limited lakes.

For each year, trophic state indicators are computed from samples collected between July and September at the Lake South station at depths ranging from 0 to 3 meters. Figure 12-10 shows average seasonal variations in total phosphorus, chlorophyll-a, and transparency based upon 0-3 meter samples at the Lake South station. Chlorophyll-a concentrations tend to be significantly lower in June and transparencies, significantly higher, as compared with the rest of the summer. This probably reflects clearing events driven by zooplankton activity. The precise timing of these events varies from year to year and introduces considerable variability in the summer means computed from June-September or June-August data. Summarizing the data on a July-September basis excludes the highly variable conditions in June and provides greater precision in the modeled response variables. These months represent “worst-case” conditions for chlorophyll-a and transparency.

12.5.1 Chlorophyll-a

Summer mean chlorophyll-a concentrations are modeled as a log-linear function of summer phosphorus concentration (Figure 12-11). The regression model developed by Jones & Bachman (1976) has been calibrated to 1996-1999 data by adjusting the intercept from 0.081 to 0.076. The model is similar to others developed from other lake data sets (Dillon & Rigler, 1994; Carlson, 1977; Walker, 1979).

Figure 12-11 shows 80% prediction intervals (10th, 50th, and 90th percentiles) in relation to observed mean chlorophyll-a concentrations between 1986 and 1999. Prediction intervals are computed from the residual standard error for the 1996-1999 period (CV = 24%). A variety of chlorophyll-a sampling methods were used over the 1986-1999 (discrete depths, epilimnetic composite, photic zone composite). These results have been pooled and averaged by date before computing summer means. Figure 12-11 shows observed mean values plus or minus one standard error. Standard errors are computed from the number of sampling dates and the standard deviation of the mean concentration across dates. The residual CV in 1996-1999 (24%) is similar to the standard error of the observed mean values (averaging 23%). This suggests that sampling variability alone could account for a significant fraction of the difference between observed and predicted concentrations.

As expected, the model significantly over-predicts chlorophyll-a concentrations in the years prior to 1995 when phosphorus was not limiting. Predictions and observations converge as phosphorus concentration decrease in later years.

12.5.2 Algal Bloom Frequencies

Summer algal bloom frequencies (percent of the time that chlorophyll-a exceeds bloom criteria of 10, 20, 30, or 40 ppb) are predicted as a function of mean chlorophyll-a concentrations by modeling temporal variation in chlorophyll-a with a lognormal distribution (Walker, 1984). The temporal coefficient of variation (CV = 0.60) has been calibrated to 1986-1999 data. Chlorophyll-a levels of 10, 20, and 30 ppb correspond to “visible”, “nuisance”, and “severe nuisance” algal blooms, according to results of user surveys reported by Walmsley (1984). Figure 12-12 plots observed and predicted bloom frequencies against observed mean chlorophyll-a levels. These relationships typically show a threshold response that is useful for setting goals (Heiskary & Walker, 1988).

In a forecast mode, bloom frequencies would be estimated from predicted mean chlorophyll-a levels, in turn predicted from phosphorus levels. Observed and predicted algal bloom frequencies are plotted against predicted lake total phosphorus in Figure 12-13 and against year in Figure 12-14. Prediction intervals are computed directly from the prediction intervals for mean chlorophyll-a. As expected, the models tend to over-estimate bloom frequencies in earlier years when phosphorus concentrations were not limiting. Results suggest that the apparent reductions in severe bloom frequencies (30 or 40 ppb) in recent years can be at least partially attributed to reductions in phosphorus levels.

12.5.3 Secchi Depth

Secchi depths are predicted with a model that partitions light extinction into two components: an algal component (assumed to be proportional to chlorophyll-a concentration) and a non-algal component (attributed to color, inorganic particles, and non-algal organic particles) (Walker, 1985; 1996; Effler, 1994). The light extinction coefficient is assumed to be inversely proportional to the Secchi depth. Model coefficients are calibrated to Secchi and chlorophyll-a concentrations observed between 1990 and 1999 (Figure 12-15). There is a strong indication that non-algal turbidity was higher in years prior to 1990 (range 0.4-1.3 m^{-1} vs. average 0.3 m^{-1} in 1990-1999). This may reflect reductions in calcium, suspended solids, or other substances contributing to light extinction but independent of chlorophyll-a concentration. If further reductions in non-algal turbidity occur following implementation of additional source controls, it will be necessary to recalibrate the model by adjusting the non-algal turbidity term.

In a forecast mode, Secchi depths would be estimated from predicted mean chlorophyll-a levels, in turn predicted from phosphorus loads. Figure 12-16 plots observed mean Secchi depths against predicted lake phosphorus concentration and year. Prediction intervals are computed from the residual standard error over the 1995-1999 period (CV = 19%). As expected, transparency is under-predicted in earlier years when phosphorus concentrations were not limiting algal growth. Because of potential future reductions in non-algal turbidity unrelated to phosphorus controls, response of transparency to reductions in phosphorus load may be more dramatic than those predicted by the model as it is currently calibrated.

12.5.4. Secchi Frequencies

To recreational users, the average water transparency over a summer may have little meaning because of high variability experienced within the summer. The frequency of transparencies less than 1.2 meters (4 feet bathing standard) is of interest from a management perspective. Secchi interval frequencies (percent of time < 1.2 meters and < 2 meters) are predicted using a model analogous to that described above for algal bloom frequencies. Temporal variations in transparency are simulated with a lognormal distribution and CV=0.32, calibrated to 1986-1999 data. Figure 12-17 plots observed and predicted Secchi interval frequencies against observed mean Secchi depths.

In a forecast mode, bloom frequencies would be estimated from predicted mean transparency, in turn predicted from chlorophyll-a and phosphorus loads. Observed and predicted Secchi frequencies are plotted against predicted total lake phosphorus and year in Figure 12-18 (<1.2 meters) and Figure 12-19 (< 2 meters). Prediction intervals are computed from the prediction intervals for mean transparency. Again, the models tend to over-predict frequencies in earlier years when phosphorus concentrations were not limiting. One exception is 1986, when non-algal turbidity levels in the Lake were apparently much higher than those present in subsequent years.

12.5.5 Hypolimnetic Oxygen Depletion Rate

The rate of oxygen depletion below the thermocline in the spring and early summer has been promoted as a useful index of trophic state (Mortimer, 1941). This rate reflects the combined effects of respiration and decomposition processes ultimately fueled by external and internal sources of nutrients and organic matter. This rate also has a strong influence on summer hypolimnetic oxygen levels that, in turn, can limit fish habitat and control nutrient cycling.

The HOD rate is typically expressed on an aerial basis (mg/m^2-day) and computed from temperature and dissolved oxygen profiles collected on dates when the water column is thermally stratified and before oxygen is depleted. The calculation assumes that HOD values are independent of dissolved oxygen concentration when the above conditions are met. In Onondaga and other productive lakes, depletion occurs rapidly and closely-spaced profiles (~weekly) are needed for accurate computation of HOD rates.

Table 12-8 lists computed HOD rates for Onondaga Lake based upon data collected at the Lake South station between 1986 and 1999. Computations are based upon temperature and dissolved oxygen measurements collected at 3-meter increments between 6 and 18 meters. Measurements collected at finer depth increments with HYDROLAB units may provide an improved basis for HOD calculations in recent years The 3-meter data have been used because they were reported consistently over the 1986 to 1999 period. Results indicate that the accuracy of HOD calculations is more likely to be controlled by temporal sampling frequency (biweekly) than by vertical spacing of the observations. While thermocline depths may vary somewhat from year to year, HOD rates are computed for each year based upon the change in volume-weighted-mean oxygen concentrations below 6 meters, a typical spring thermocline level for the Lake. The areal HOD rate is computed as the product of the volumetric depletion rate (mg/m^3-day) and the mean depth below the thermocline (8.3 meters for a thermocline depth of 6 meters).

As indicated in Table 12-8, computed HOD rates in 7 out of 14 years under-estimate actual values because of incomplete spring turnover and/or depletion of oxygen in a least part of the hypolimnion between the first and second stratified dates. HOD rates are positively correlated with hypolimnetic mean dissolved oxygen concentration at the end of the calculation period in years when that concentration is less than ~ 4 mg/liter. In other years with reasonably reliable HOD estimates, rates ranged from 1500 to 2400 mg/m^2-day, as compared with a range of 1100 to 1900 mg/m^2-day reported by Effler (1994). These values are well within the “eutrophic” range proposed by Mortimer (1941) (> 550 mg/m^2-day).

Walker (1979) developed relationships between HOD rates and other trophic state indices (phosphorus, chlorophyll-a, transparency) in northern temperate lakes. When apparent morphometric effects (represented by mean depth) were also considered, the model explained 91% of the variance in reported HOD values for 30 lakes with a residual standard error of 23%. For a lake with a fixed mean depth (in this case, 10.9 meters), the model equations can be condensed to a log-linear function of summer epilimnetic P concentration (Table 12-9, $HOD = 42.3 P^{0.94}$).

Observed and predicted HOD rates are plotted against predicted total phosphorus and year in Figure 12-20. Prediction intervals are computed from the residual standard error for the 1995-1999 period (CV = 21%). This standard error is similar to that computed from the model development data set (CV = 23%, Walker,1979). As for other trophic state indicators, the model tends to over-predict HOD rates in earlier years when phosphorus concentrations exceeded ~100 ppb and were not limiting algal growth.

As indicated in Table 12-9, HOD rates can be translated into other useful measures of oxygen status. The "Days of Oxygen Supply" (T_{DO}, Walker, 1979) is computed from the HOD rate, oxygen concentration at the onset of stratification (typically 12 ppm) and the mean hypolimnetic depth (in this case, 8.3 meters for a 6-meter thermocline depth). The T_{DO} value represents the theoretical number of days between the onset of stratification and depletion of all oxygen stored in the hypolimnion. Oxygen levels at the bottom of the hypolimnion are usually depleted before this occurs. The duration of the anoxic period (T_{ANOXIC}) is estimated by the difference between TDO and the duration of the stratified period (T_{STRAT} ~ 183 days, April 15 – October 15).

12.6 MODEL IMPLEMENTATION

The model network can be programmed on a single page of an Excel™ workbook (Table 12-10). Variable categories include model parameter values (generally constant across simulated cases), input values, and output values. Once calibrated, the entire network is driven by three input variables that describe the year and/or management scenario being evaluated (lake outflow volume, inflow total phosphorus load, and inflow total nitrogen load). Nitrogen loads are used to predict total nitrogen concentrations only and do not influence predictions of other trophic state indicators.

Predicted responses of each trophic state indicator to variations in phosphorus load are shown in Figure 12-21. Results are for average 1986-1999 hydrologic conditions (outflow volume = 399 hm^3/yr). The 80% prediction interval (10^{th}, 50^{th},90^{th} 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.

12.7 CONCLUSIONS & RECOMMENDATIONS

1. Lake phosphorus concentrations have responded quickly to historical reductions in external phosphorus load. Despite these reductions, the trophic response of the lake has been muted because algal growth has been limited by factors other than phosphorus. Because lake total and ortho phosphorus concentrations have approached growth-limiting levels in recent years, it is expected that algal growth, transparency, and related water quality conditions will more responsive to future load reductions.

2. The empirical model network developed above can be used to forecast responses to future load reductions, assuming that relationships among lake phosphorus concentration, chlorophyll-a concentrations, and other trophic state indicators are similar to those characteristic of other phosphorus-limited lakes. Depending upon the magnitude of lake water quality improvements, periodic recalibration of the model may be necessary to track responses.

3. Model residual errors are similar to or below those expected based upon statistical analysis of other lake and reservoir datasets.

Potential areas for future enhancement of the model include:

1. An error analysis to partition lake time series and model residuals into measurement error, model error, and background year-to-year variability.

2. Extension of the model scope to include organic nutrient species (phosphorus, nitrogen, carbon), which have been shown to be correlated with phosphorus and

chlorophyll-a concentrations in phosphorus-limited lakes and reservoirs (Walker, 1985;1996).

3. Coupling of the phosphorus balance model with a simplified watershed model that allows prediction of lake phosphorus loads as a function of land use and non-point source control measures.

4. Development of software to facilitate evaluation of management scenarios involving implementation of alternative point-source and non-point-source control measures under a range of hydrologic conditions.

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Table 12-1: 10-Year Trends in Concentration

Concentration Trends (% / yr) **Period: 1990 to 1999** **Period: Year**

Term	ALK	BOD5	CA	CL	FCOLI	NA	NH3N	NO2N	NO3N	ORTHOP	TIC	TKN	TN	TOC	TP	TSS
Metro			-2%			3%			16%	-11%				-4%	-6%	-4%
Bypass		-5%														
Allied	-3%				-21%	2%	-10%	-14%	-6%	7%	-2%	-9%	-10%		3%	
Crucible			2%			3%		-8%	-5%	20%			-5%			
Harbor/Hiawatha	-1%	6%				3%										
Ley/Park														-5%		
Ninemile/Rt48	-1%	6%														
Onond./Kirkpatrick	-1%	8%				6%					-1%	3%			-6%	
Harbor/Velasko	-6%							-65%		-24%	-6%					
Onondaga/Dorwin	-2%					4%	10%		2%		-2%		3%		-8%	
Total Gauged	-1%		-1%			3%			7%	-8%	-1%				-4%	
NonPoint Gauged	-1%										-1%				-5%	
Ungauged	-1%										-1%				-5%	
Total NonPoint	-1%										-1%				-5%	
Total Industrial	-3%	-3%			-28%		-20%	-25%	-8%		-3%	-17%	-15%	-4%		
Total Municipal			-2%			3%			16%	-12%					-6%	
Total External	-1%		-1%			3%			7%	-8%	-1%				-4%	
Total Inflow	-1%		-1%			3%			7%	-8%	-1%				-4%	
Total Outflow	-2%		-2%								-1%			-3%		-8%
Outlet2	-2%		-2%								-1%			-3%		-8%
Outlet12	-1%		-1%			3%					-1%			-3%		
Outlet Avg	-1%		-1%								-1%			-3%		-6%
South Epil.	-1%					3%					-1%			-2%		

Flow-Adjusted Concentration Trends (% / yr)

Term	ALK	BOD5	CA	CL	FCOLI	NA	NH3N	NO2N	NO3N	ORTHOP	TIC	TKN	TN	TOC	TP	TSS
Metro									16%	-8%				-4%	-5%	
Bypass																
Allied																
Crucible																
Harbor/Hiawatha		5%														
Ley/Park																
Ninemile/Rt48	-1%		-2%								-1%					
Onond./Kirkpatrick	-1%	7%									-1%					
Harbor/Velasko	-6%							-65%		-24%	-6%					
Onondaga/Dorwin	-2%						10%		3%		-2%		3%			
Total Gauged			-1%													
NonPoint Gauged	-1%		-2%								-1%					
Ungauged	-1%		-2%								-1%					
Total NonPoint	-1%		-2%								-1%					
Total Industrial																
Total Municipal																
Total External			-1%													
Total Inflow			-1%													
Total Outflow	-1%		-2%													
Outlet2	-1%		-2%													
Outlet12	-1%		-1%													
Outlet Avg	-1%		-1%													
South Epil.			-1%													

Table 12-2: 10-Year Trends in Load

Load Trends (% / yr) **Period: 1990 to 1999** **Period: Year**

Term	ALK	BOD5	CA	CL	FCOLI	NA	NH3N	NO2N	NO3N	RTHOP_F	TIC	TKN	TN	TOC	TP	TSS
Metro	-3%		-4%				-5%		15%	-12%	-3%	-5%		-5%	-7%	-5%
Bypass																
Allied	-35%	-35%	-33%	-34%	-36%	-32%	-39%	-42%	-38%	-23%	-35%	-38%	-39%	-33%	-30%	-37%
Crucible	-12%	-11%	-9%	-10%	-17%	-7%	-10%	-19%	-17%		-12%	-10%	-17%	-13%		
Harbor/Hiawatha	-7%		-5%						-7%		-7%		-6%	-7%		
Ley/Park	-7%		-5%	-6%				-10%	-7%	-11%	-6%	-7%	-7%	-10%		
Ninemile/Rt48	-8%		-8%	-8%		-9%	-5%				-7%	-7%	-6%	-9%	-12%	
Onond./Kirkpatrick	-6%		-4%								-6%				-11%	
Harbor/Velasko																
Onondaga/Dorwin															-12%	-10%
Total Gauged	-6%		-6%	-5%			-5%	-7%		-12%	-6%	-5%	-4%	-7%	-9%	
NonPoint Gauged	-7%		-6%	-5%				-7%			-6%	-5%	-5%	-7%	-10%	
Ungauged	-7%		-6%	-5%				-7%			-6%	-5%	-5%	-7%	-10%	
Total NonPoint	-7%		-6%	-5%				-7%			-6%	-5%	-5%	-7%	-10%	
Total Industrial	-27%	-27%	-24%	-26%	-36%	-24%	-38%	-42%	-32%	-19%	-27%	-36%	-36%	-26%	-25%	-26%
Total Municipal	-3%		-4%	-3%			-5%		14%	-13%	-3%	-5%	-3%		-8%	
Total External	-6%		-6%	-5%			-5%	-7%		-12%	-6%	-5%	-4%	-7%	-9%	
Total Inflow	-6%		-6%	-5%			-5%	-6%		-11%	-6%	-5%	-4%	-7%	-9%	
Total Outflow	-6%	-7%	-7%	-5%					-6%		-6%		-6%	-8%	-8%	-12%
Retention								-14%	47%	-340%	-6%	-5%			-9%	
Outlet2	-6%	-7%	-7%	-5%					-6%		-6%		-6%	-8%	-8%	-12%
Outlet12	-6%	-6%	-6%								-6%		-4%	-7%	-8%	
Outlet Avg	-6%	-6%	-6%	-4%							-6%		-5%	-8%	-8%	-10%
South Epil.	-6%	-6%	-6%	-3%					-5%		-6%		-5%	-7%		-9%

Flow-Adjusted Load Trends (% / yr)

Term	ALK	BOD5	CA	CL	FCOLI	NA	NH3N	NO2N	NO3N	RTHOP_F	TIC	TKN	TN	TOC	TP	TSS
Metro									16%	-8%				-4%	-5%	
Bypass																
Allied																
Crucible																
Harbor/Hiawatha																
Ley/Park														-3%		
Ninemile/Rt48	-1%		-2%								-1%					
Onond./Kirkpatrick	-1%	8%									-1%					
Harbor/Velasko																
Onondaga/Dorwin	-2%					3%	10%		3%		-2%		3%			
Total Gauged			-1%					-4%								
NonPoint Gauged	-1%		-1%								-1%					
Ungauged	-1%		-1%								-1%					
Total NonPoint	-1%		-1%								-1%					
Total Industrial																
Total Municipal																
Total External			-1%					-4%								
Total Inflow			-1%					-4%								
Total Outflow	-1%		-2%													
Outlet2	-1%		-2%													
Outlet12	-1%		-1%													
Outlet Avg	-1%		-1%													
South Epil.			-1%													

Table 12-3: Chloride Balance for 1995-1999

Variable: **Chloride** **Average for Years:** **1995** **thru** **1999** **Season:** **Year**

							Percent of Total Inflow			Drain.		Export
Term	**Flow 10^6 m3**	**Load mtons**	**Std Error mtons**	**Conc ppm**	**RSE %**	**Samp. Count**	**Flow %**	**Load %**	**Error %**	**Area km2**	**Runoff cm**	**mtons/ km2**
Metro Effluent	89.77	27780	1411	309	5%	26	22%	19%	19%			
Metro Bypass	1.70	811	193	476	24%	6	0%	1%	0%			
East Flume	0.29	130	5	443	4%	27	0%	0%	0%			
Crucible	0.61	190	3	310	2%	27	0%	0%	0%			
Harbor Brook	7.74	1762	82	228	5%	28	2%	1%	0%	29.3	26.4	60.2
Ley Creek	32.03	9461	569	295	6%	27	8%	6%	3%	77.5	41.3	122.1
Ninemile Creek	115.99	55486	1814	478	3%	27	29%	38%	32%	298.1	38.9	186.1
Onondaga Creek	130.56	45810	2000	351	4%	28	32%	31%	39%	285.1	45.8	160.7
Nonpoint Gauged	286.32	112519	2761	393	2%	110	71%	76%	74%	690.0	41.5	163.1
Nonpoint Ungauged	15.37	6039	831	393	14%	0	4%	4%	7%	37.0	41.5	163.1
NonPoint Total	301.69	118557	2883	393	2%	110	75%	80%	80%	727.0	41.5	163.1
Industrial	0.90	320	6	354	2%	53	0%	0%	0%			
Municipal	91.47	28592	1424	313	5%	32	23%	19%	20%			
Total External	394.07	147468	3216	374	2%	195	97%	100%	100%	727.0	54.2	202.8
Precipitation	10.52	11	1	1	9%	0	3%	0%	0%	11.7	89.9	0.9
Total Inflow	404.59	147479	3216	365	2%	195	100%	100%	100%	738.7	54.8	199.6
Evaporation	8.86						2%			11.7	75.7	
Outflow	395.73	145838	3485	369	2%		98%	99%	117%	738.7	53.6	197.4
Retention	0.00	1641	4742		289%		0%	1%				
Alternative Estimates of Lake Output												
Outlet 12 Feet	395.73	176957	2445	447	1%	24	98%	120%	58%	738.7	53.6	239.5
Outlet 2 Feet	395.73	145838	3485	369	2%	24	98%	99%	117%	738.7	53.6	197.4
Outlet Average	395.73	161397	3010	408	2%	24	98%	109%	88%	738.7	53.6	218.5
Lake Epil	395.73	176545	1907	446	1%	20	98%	120%	35%	738.7	53.6	239.0
Upstream/Downstream Contrast- Harbor Brook												
Upstream - Velasko	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	25.9	#N/A	#N/A
Downstream - Hiawatha	7.74	1762	82	228	5%	28	2%	1%	0%	29.3	26.4	60.2
Local Inflow	#N/A	#N/A	#N/A	#N/A	#N/A		#N/A	#N/A	#N/A	3.4	#N/A	#N/A
Upstream/Downstream Contrast - Onondaga Creek												
Upstream - Dorwin	100.85	12677	403	126	3%	29	25%	9%	2%	229.4	44.0	55.3
Downstream - Kirkpatrick	130.56	45810	2000	351	4%	28	32%	31%	39%	285.1	45.8	160.7
Local Inflow	29.72	33133	2040	1115	6%		7%	22%	40%	55.7	53.3	594.5

Lake Overflow Rate 33.82 m/yr Calib. Settling Rate 0.4 m/yr RSE % = Relative Std. Error of Load & Inflow Conc. Estimates
Lake Residence Time 0.32 years Calib. Retention Coef. 1% Error % = Percent of Variance in Total Inflow Load Estimate

Table 12-4: Total Phosphorus Balance for 1995-1999

Variable: Total Phosphorus Average for Years: 1995 thru 1999 Season: Year

Term	Flow 10^6 m3	Load kg	Std Error kg	Conc ppb	RSE %	Samp. Count	Percent of Total Inflow Flow %	Percent of Total Inflow Load %	Percent of Total Inflow Error %	Drain. Area km2	Runoff cm	Export kg / km2
Metro Effluent	89.77	39685	464	442	1%	365	22%	60%	8%			
Metro Bypass	1.70	2515	102	1477	4%	42	0%	4%	0%			
East Flume	0.29	64	2	218	3%	26	0%	0%	0%			
Crucible	0.61	43	2	70	5%	27	0%	0%	0%			
Harbor Brook	7.74	631	173	82	27%	28	2%	1%	1%	29.3	26.4	21.5
Ley Creek	32.03	4119	649	129	16%	27	8%	6%	15%	77.5	41.3	53.2
Ninemile Creek	115.99	7174	959	62	13%	26	29%	11%	33%	298.1	38.9	24.1
Onondaga Creek	130.56	10860	1065	83	10%	28	32%	16%	41%	285.1	45.8	38.1
Nonpoint Gauged	286.32	22785	1583	80	7%	110	71%	34%	90%	690.0	41.5	33.0
Nonpoint Ungauged	15.37	1223	199	80	16%	0	4%	2%	1%	37.0	41.5	33.0
NonPoint Total	301.69	24008	1595	80	7%	110	75%	36%	92%	727.0	41.5	33.0
Industrial	0.90	107	3	118	3%	53	0%	0%	0%			
Municipal	91.47	42201	475	461	1%	407	23%	63%	8%			
Total External	394.07	66315	1664	168	3%	570	97%	100%	100%	727.0	54.2	91.2
Precipitation	10.52	316	28	30	9%	0	3%	0%	0%	11.7	89.9	27.0
Total Inflow	404.59	66630	1664	165	2%	570	100%	100%	100%	738.7	54.8	90.2
Evaporation	8.86						2%			11.7	75.7	
Outflow	395.73	40310	1582	102	4%		98%	60%	90%	738.7	53.6	54.6
Retention	0.00	26320	2296		9%		0%	40%				
Alternative Estimates of Lake Output												
Outlet 12 Feet	395.73	44717	1599	113	4%	24	98%	67%	92%	738.7	53.6	60.5
Outlet 2 Feet	395.73	40310	1582	102	4%	24	98%	60%	90%	738.7	53.6	54.6
Outlet Average	395.73	42514	1590	107	4%	24	98%	64%	91%	738.7	53.6	57.5
Lake Epil	395.73	43011	1827	109	4%	21	98%	65%	120%	738.7	53.6	58.2
Upstream/Downstream Contrast- Harbor Brook												
Upstream - Velasko	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	25.9	#N/A	#N/A
Downstream - Hiawatha	7.74	631	173	82	27%	28	2%	1%	1%	29.3	26.4	21.5
Local Inflow	#N/A	#N/A	#N/A	#N/A	#N/A		#N/A	#N/A	#N/A	3.4	#N/A	#N/A
Upstream/Downstream Contrast - Onondaga Creek												
Upstream - Dorwin	100.85	6138	708	61	12%	29	25%	9%	18%	229.4	44.0	26.8
Downstream - Kirkpatrick	130.56	10860	1065	83	10%	28	32%	16%	41%	285.1	45.8	38.1
Local Inflow	29.72	4723	1279	159	27%		7%	7%	59%	55.7	53.3	84.7

Lake Overflow Rate	33.82 m/yr	Calib. Settling Rate	22.1 m/yr	RSE % = Relative Std. Error of Load & Inflow Conc. Estimates
Lake Residence Time	0.32 years	Calib. Retention Coef.	40%	Error % = Percent of Variance in Total Inflow Load Estimate

Table 12-5: Total Nitrogen Balance for 1995-1999

Variable: **Total Nitrogen** **Average for Years:** **1995** **thru** **1999** **Season:** **Year**

							Percent of Total Inflow					
Term	**Flow 10^6 m3**	**Load kg**	**Std Error kg**	**Conc ppb**	**RSE %**	**Samp. Count**	**Flow %**	**Load %**	**Error %**	**Drain. Area km2**	**Runoff cm**	**Export kg/ km2**
Metro Effluent	89.77	1580852	27322	17610	2%	26	22%	74%	57%			
Metro Bypass	1.70	27107	17070	15915	63%	6	0%	1%	22%			
East Flume	0.29	2330	82	7948	4%	26	0%	0%	0%			
Crucible	0.61	1620	92	2653	6%	27	0%	0%	0%			
Harbor Brook	7.74	15442	403	1996	3%	26	2%	1%	0%	29.3	26.4	527.2
Ley Creek	32.03	57352	5549	1791	10%	24	8%	3%	2%	77.5	41.3	740.0
Ninemile Creek	115.99	213886	12322	1844	6%	26	29%	10%	12%	298.1	38.9	717.5
Onondaga Creek	130.56	205516	8005	1574	4%	27	32%	10%	5%	285.1	45.8	720.8
Nonpoint Gauged	286.32	492196	15711	1719	3%	104	71%	23%	19%	690.0	41.5	713.3
Nonpoint Ungauged	15.37	26415	3812	1719	14%	0	4%	1%	1%	37.0	41.5	713.3
NonPoint Total	301.69	518611	16167	1719	3%	104	75%	24%	20%	727.0	41.5	713.3
Industrial	0.90	3951	123	4370	3%	53	0%	0%	0%			
Municipal	91.47	1607959	32216	17578	2%	32	23%	75%	80%			
Total External	394.07	2130521	36045	5406	2%	188	97%	99%	100%	727.0	54.2	2930.4
Precipitation	10.52	19993	1795	1900	9%	0	3%	1%	0%	11.7	89.9	1708.8
Total Inflow	404.59	2150514	36090	5315	2%	188	100%	100%	100%	738.7	54.8	2911.0
Evaporation	8.86						2%			11.7	75.7	
Outflow	395.73	1274847	28020	3221	2%		98%	59%	60%	738.7	53.6	1725.7
Retention	0.00	875667	45690		5%		0%	41%				
Alternative Estimates of Lake Output												
Outlet 12 Feet	395.73	1489835	23345	3765	2%	24	98%	69%	42%	738.7	53.6	2016.7
Outlet 2 Feet	395.73	1274847	28020	3221	2%	24	98%	59%	60%	738.7	53.6	1725.7
Outlet Average	395.73	1382341	25789	3493	2%	24	98%	64%	51%	738.7	53.6	1871.2
Lake Epil	395.73	1537519	20489	3885	1%	20	98%	71%	32%	738.7	53.6	2081.2
Upstream/Downstream Contrast- Harbor Brook												
Upstream - Velasko	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	25.9	#N/A	#N/A
Downstream - Hiawatha	7.74	15442	403	1996	3%	26	2%	1%	0%	29.3	26.4	527.2
Local Inflow	#N/A	#N/A	#N/A	#N/A	#N/A		#N/A	#N/A	#N/A	3.4	#N/A	#N/A
Upstream/Downstream Contrast - Onondaga Creek												
Upstream - Dorwin	100.85	152976	6095	1517	4%	26	25%	7%	3%	229.4	44.0	666.9
Downstream - Kirkpatrick	130.56	205516	8005	1574	4%	27	32%	10%	5%	285.1	45.8	720.8
Local Inflow	29.72	52540	10061	1768	19%		7%	2%	8%	55.7	53.3	942.8

Lake Overflow Rate	33.82 m/yr	Calib. Settling Rate	23.2 m/yr	RSE % = Relative Std. Error of Load & Inflow Conc. Estimates	
Lake Residence Time	0.32 years	Calib. Retention Coef.	41%	Error % = Percent of Variance in Total Inflow Load Estimate	

Table 12-6

Yearly Total Phosphorus Balances

Water Years 1986-1999

Water	Outflow	Inflow Load		Metro+Bypass Load		Inflow Conc	Outflow Conc @ 2 ft		Lake South Epil. June-Sept, 0-6 m Concentration	
Year	106 m3	kg	RSE%	kg	RSE%	ppb	ppb	RSE%	ppb	RSE%
1986	483.5	174968	5%	121740	6%	362	134	5%	136	5%
1987	440.5	145808	4%	104222	4%	331	198	10%	120	4%
1988	341.8	116002	3%	89279	4%	339	208	8%	127	5%
1989	426.7	120874	6%	74729	5%	283	108	9%	96	11%
1990	602.3	139838	6%	73460	9%	232	155	13%	88	14%
1991	536.7	103589	9%	61088	12%	193	93	10%	61	9%
1992	476.1	86216	6%	55830	7%	181	92	9%	62	18%
1993	563.7	156070	5%	112279	6%	277	172	6%	132	12%
1994	478.2	81034	8%	61232	10%	169	98	10%	87	11%
1995	296.7	70431	8%	47372	3%	237	134	15%	72	13%
1996	474.2	89570	5%	52661	3%	189	120	9%	68	10%
1997	444.9	61725	3%	40422	2%	139	99	10%	60	10%
1998	466.2	70668	7%	41068	2%	152	79	9%	55	8%
1999	312.5	51366	5%	34174	2%	164	89	9%	54	10%
95-99	398.9	68752	6%	43140	3%	172	103	11%	62	10%

RSE = relative standard error = standard error / mean

Table 12-7

Yearly Total Nitrogen Balances

Water Years 1986-1999

									Lake South Epil.	
						Inflow	Outflow Conc		June-Sept, 0-6 m	
Water	Outflow	Inflow Load		Metro+Bypass Load		Conc	@ 2 ft		Concentration	
Year	106 m3	kg	RSE%	kg	RSE%	ppb	ppb	RSE%	ppb	RSE%
1986	483.5	2740662	3%	1709557	3%	5668	3461	7%	3640	6%
1987	440.5	2781108	3%	1970213	4%	6314	4526	7%	4379	6%
1988	341.8	2631519	3%	2058390	4%	7698	4583	5%	5479	3%
1989	426.7	2793577	3%	2111344	4%	6546	4216	5%	4274	5%
1990	602.3	2614438	3%	1725019	4%	4340	3168	3%	3661	4%
1991	536.7	2598964	3%	1777828	4%	4843	3098	5%	4197	3%
1992	476.1	2568401	3%	1873839	3%	5395	3793	5%	4493	7%
1993	563.7	2762308	3%	2011697	3%	4900	3248	5%	3673	3%
1994	478.2	2448586	3%	1818246	4%	5121	3274	4%	4080	5%
1995	296.7	2146274	3%	1800917	4%	7233	3354	8%	5055	6%
1996	474.2	2634024	3%	1924330	3%	5555	3696	4%	3834	5%
1997	444.9	2377383	2%	1762833	2%	5343	3172	6%	3631	5%
1998	466.2	2183767	4%	1550049	5%	4684	3032	4%	3604	6%
1999	312.5	1613254	3%	1219387	4%	5162	2747	4%	3330	5%
95-99	398.9	2190940	3%	1651503	4%	5492	3224	5%	3891	5%

RSE = relative standard error = standard error / mean

Table 12-8
Model Calibration Data

Phosphorus Balance

Water Year	Net Inflow hm3	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	174968	8339	64961	3216	361.9	17.2	134.4	6.7	146.0	11.3
1987	440.5	145808	5619	87270	9112	331.0	12.8	198.1	20.7	118.2	6.2
1988	341.8	116002	3906	71035	5864	339.4	11.4	207.8	17.2	120.5	14.7
1989	426.7	120874	6817	46070	4035	283.3	16.0	108.0	9.5	80.9	11.8
1990	602.3	139838	8048	93253	11692	232.2	13.4	154.8	19.4	95.5	23.0
1991	536.7	103589	9702	49826	4808	193.0	18.1	92.8	9.0	64.7	6.5
1992	476.1	86216	4939	43974	3947	181.1	10.4	92.4	8.3	61.7	15.4
1993	563.7	156070	7536	96799	5640	276.8	13.4	171.7	10.0	109.0	13.1
1994	478.2	81034	6850	47006	4778	169.5	14.3	98.3	10.0	79.1	12.6
1995	296.7	70431	5456	39743	5889	237.4	18.4	133.9	19.8	65.0	9.0
1996	474.2	89570	4898	56980	4869	188.9	10.3	120.2	10.3	60.9	3.8
1997	444.9	61725	1922	44172	4517	138.7	4.3	99.3	10.2	52.8	5.9
1998	466.2	70668	5204	36933	3387	151.6	11.2	79.2	7.3	50.9	4.2
1999	312.5	51366	2339	27909	2608	164.4	7.5	89.3	8.3	53.9	7.8

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

Secchi Depth July - September, Lake South Station **Hypol. Oxygen Depletion Rate** below 6 meters

Water Year	Sample Dates	Mean m	Std Dev m	SE m	Freq < 1.2 -	Freq < 2.0 -	HOD mg/m2-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

SE = Standard Error of Mean

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

Table 12-9 – Model Equations

Predicted Trophic Response Variables:

Po = Water Year Flow-Wtd-Mean Outflow Total P (ppb)
P = July-Sept Surface (0-3 m) Mean Total P (ppb)
No = Water Year Flow-Wtd-Mean Outflow Total N (ppb)
N = July-Sept Surface (0-3 m) Mean Total N (ppb)
B = June-Sept Epilimnetic Mean Chlorophyll-a (ppb)
S = June-Sept Mean Secchi Depth (m)
HOD = Hypolimnetic Oxygen Depletion Rate (mg/m^2-day)

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 = 22.9 m/yr

Calibrated to 1995-1999

Period	95-99	86-99
Residual CV	0.11	0.28
R^2	0.73	0.25

Lake South Epilimnetic Total P:

Reference: Walker (1978), Sas (1989)

$P = F_P P_O$

F_P = 0.55 Calibrated to 1995-1999

Period	95-99	86-99
Residual CV	0.09	0.13
R^2	0.29	0.88

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 = 24.0 m/yr

Calibrated to 1995-1999

Period	95-99	86-99
Residual CV	0.07	0.08
R^2	0.61	0.75

Lake South Epilimnetic Total N:

$N = F_N No$

F_N = 1.15 Calibrated to 1995-1999

Period	95-99	86-99
Residual CV	0.10	0.11
R^2	0.71	0.53

Table 12-9: Model Equations (ct.)

Lake South Chlorophyll-a:

Reference: Jones & Bachman (1976)

$B = k P^{1.46}$

$k =$ 0.076 calibrated to 1996-1999 Data

DataSet	J& B	96-99
Residual CV	-	0.24
R^2	0.90	0.66

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 = 0.600

Calibrated to 1986-1999 Data

Lake South Secchi Depth:

Reference: Walker (1985,1996)

S = exp (S_S^2) / (a + b B)

Calibrated to Sample Dates, 1996-1999

a = 0.381 1/m

b = 0.016 m^2/mg

From Predicted Chla

Period	96-99	86-99
Residual CV	0.19	0.40
R^2	0.39	0.00

Table 12-9: Model Equations (ct.)

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 1986-1999 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)	96-99
Residual CV	0.23	0.21
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

Table 12-10
Model Inputs & Outputs

Model Parameters	Units	Value
Lake Area	km2	11.7
P Settling Rate	m/yr	22.873
Epil P / Outflow P	-	0.550
Outflow P Error CV	-	0.112
Lake P Error CV	-	0.089
Chla/P Slope	-	1.460
Chla/P Intercept	-	0.076
Chl-a Error CV	-	0.241
Chla Temporal CV	-	0.600
Non-Algal Turbidity	1/m	0.381
Secchi/Chla Slope	m2/mg	0.016
Secchi Error CV	-	0.193
Secchi Temporal CV	-	0.320
HOD Intercept	-	42.400
HOD Slope		0.940
HOD Error CV		0.230
Spring DO Conc	ppm	12.000
Hypol. Depth	m	8.340
Stratified Period	days	183.000

Scenario			
Outflow Volume	hm3/yr	399	1995-1999 Average
Inflow Load	kg/yr	68752	1995-1999 Average

Predicted Reponses		Units	Mean	Low	High
Outflow P Conc		ppb	103	87	123
Lake P Conc		ppb	57	49	65
Mean Chl-a		ppb	28	19	40
Algal Bloom Frequencies					
	>	10	0.94	0.81	0.99
	>	20	0.62	0.36	0.83
	>	30	0.33	0.14	0.59
	>	40	0.17	0.05	0.39
Mean Secchi Depth		m	1.34	1.61	1.08
Secchi Interval Frequencies					
	<	1.2	0.42	0.22	0.69
	<	2	0.92	0.80	0.98
Oxygen Depletion Rate		mg/m2-day	1887	1326	2686
Days of O2 Supply		days	53	75	37
Anoxic Period		days	130	108	146

List of Figures - Chapter 12

Figure 12-1

Framework for Mass-Balance Calculations

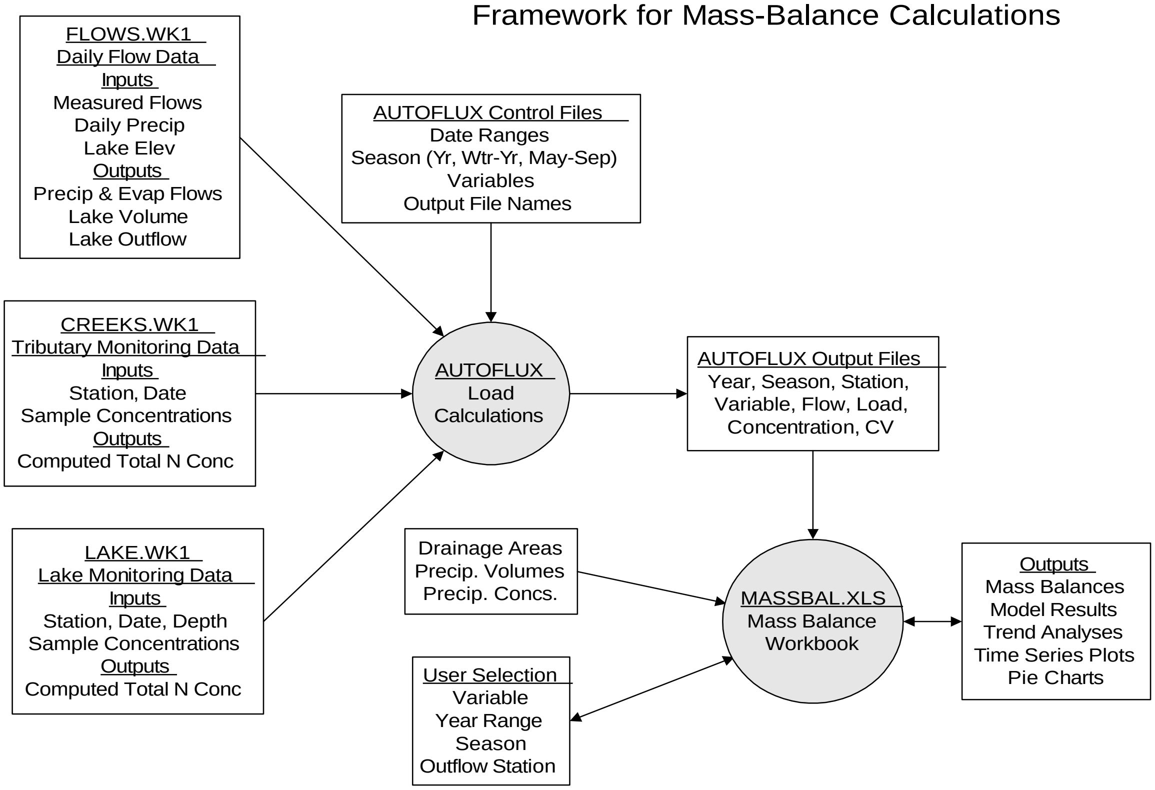


Figure 12-2

Eutrophication Model Network for Onondaga Lake

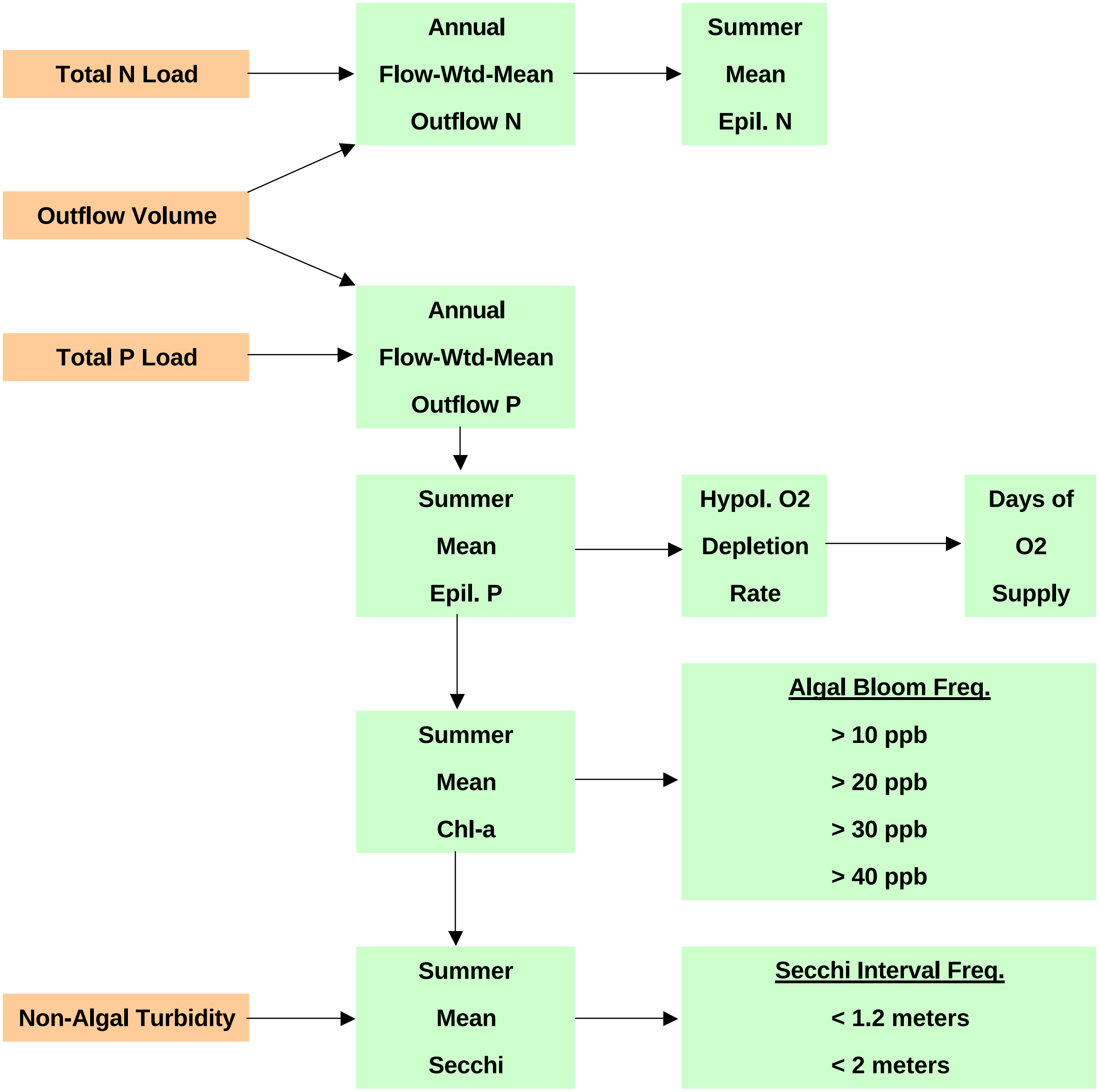


Figure 12-3
Lake Inflow Time Series

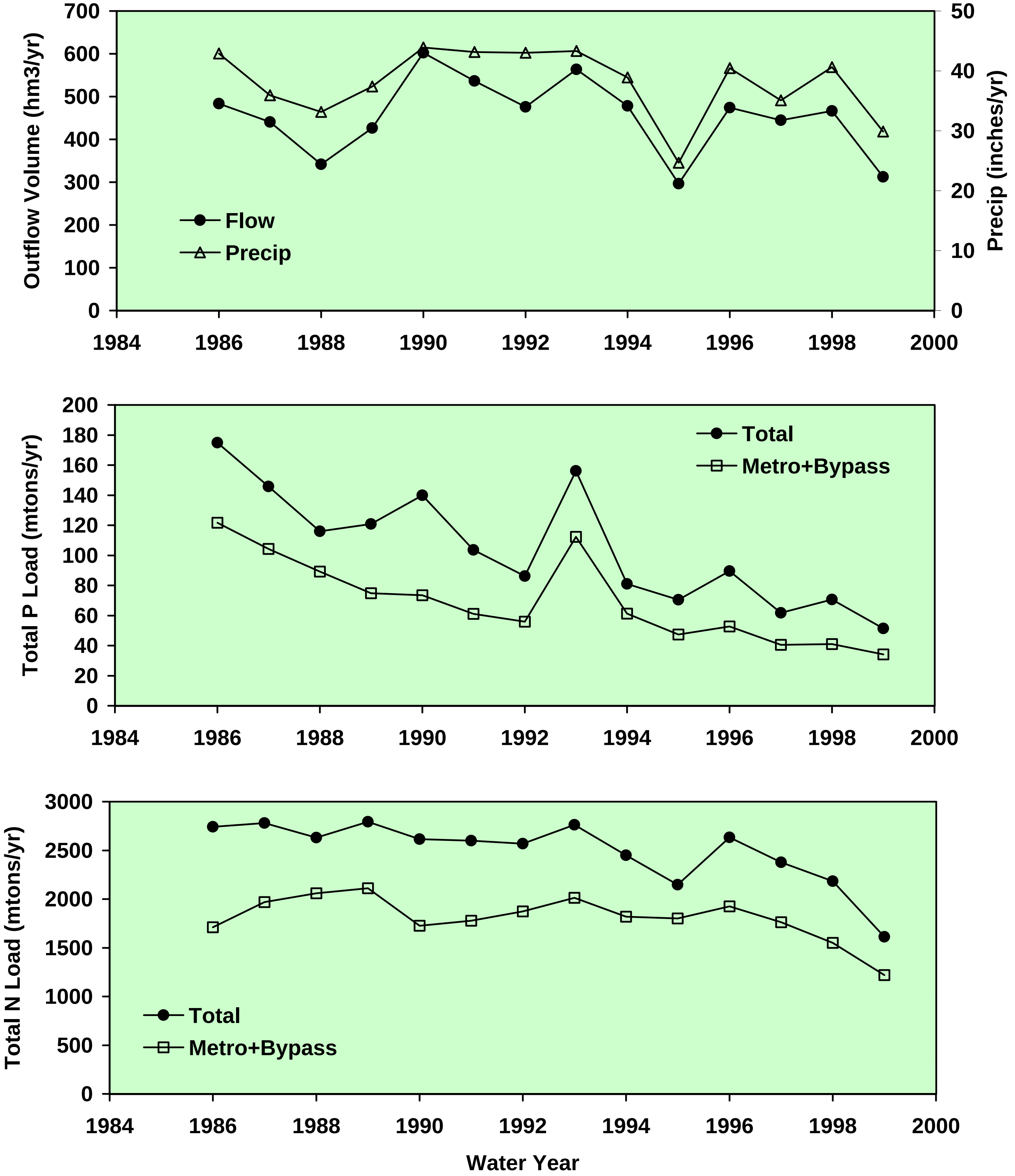


Figure 12-4
Observed & Predicted Annual Outflow P Concentrations

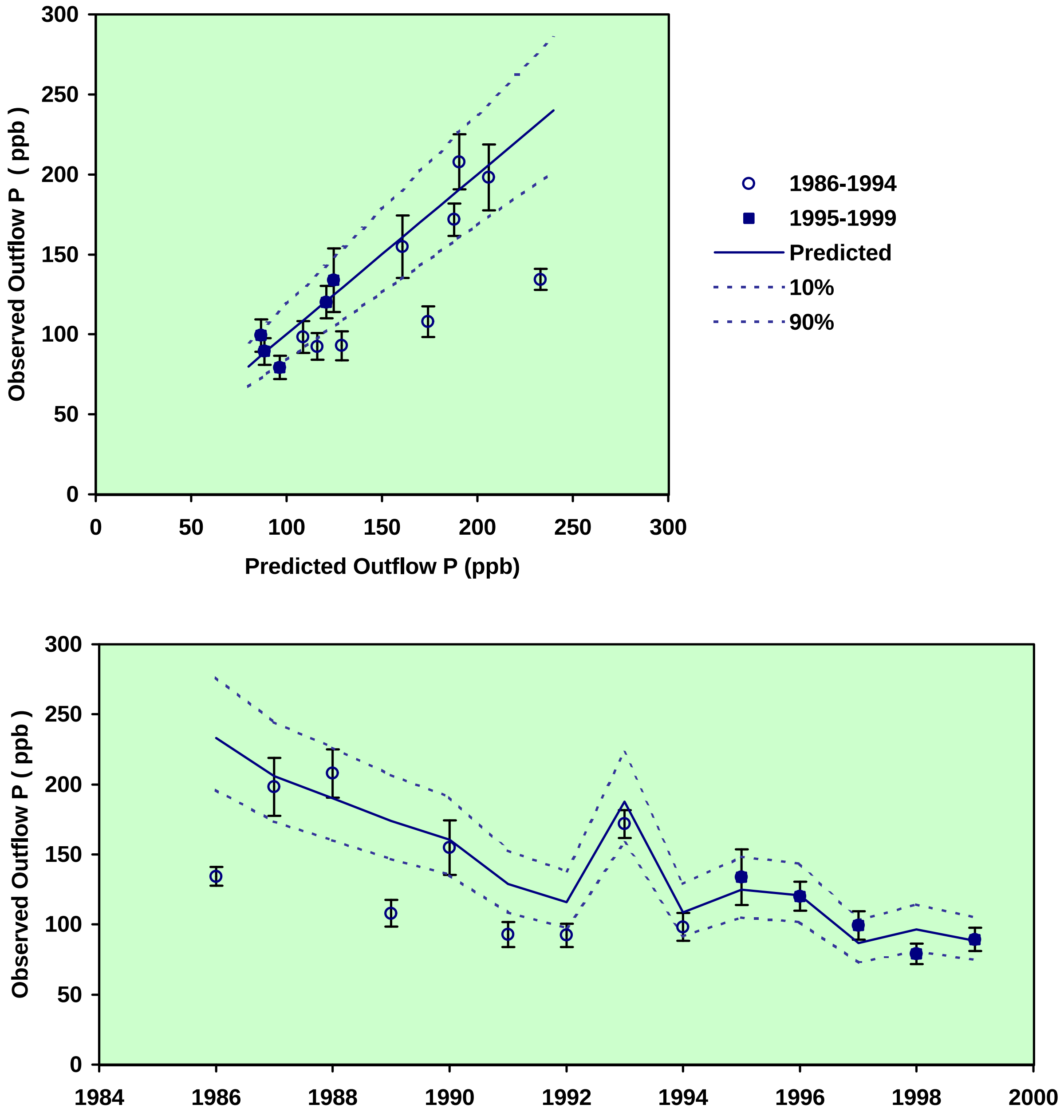


Figure 12-5
Observed & Predicted Summer Epilimnetic P Concentrations

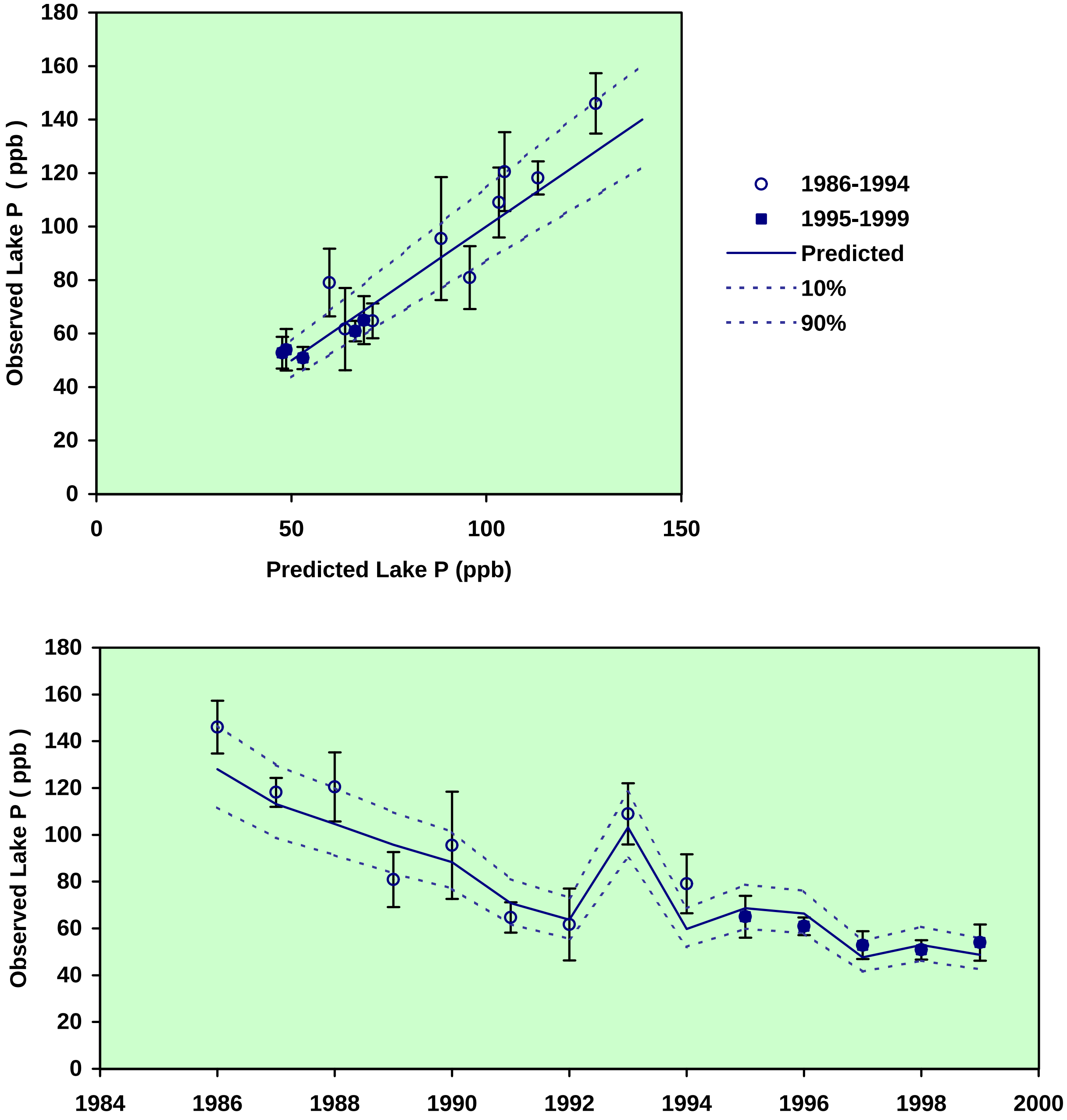


Figure 12-6
Long-Term Trends in Phosphorus Concentration & Load

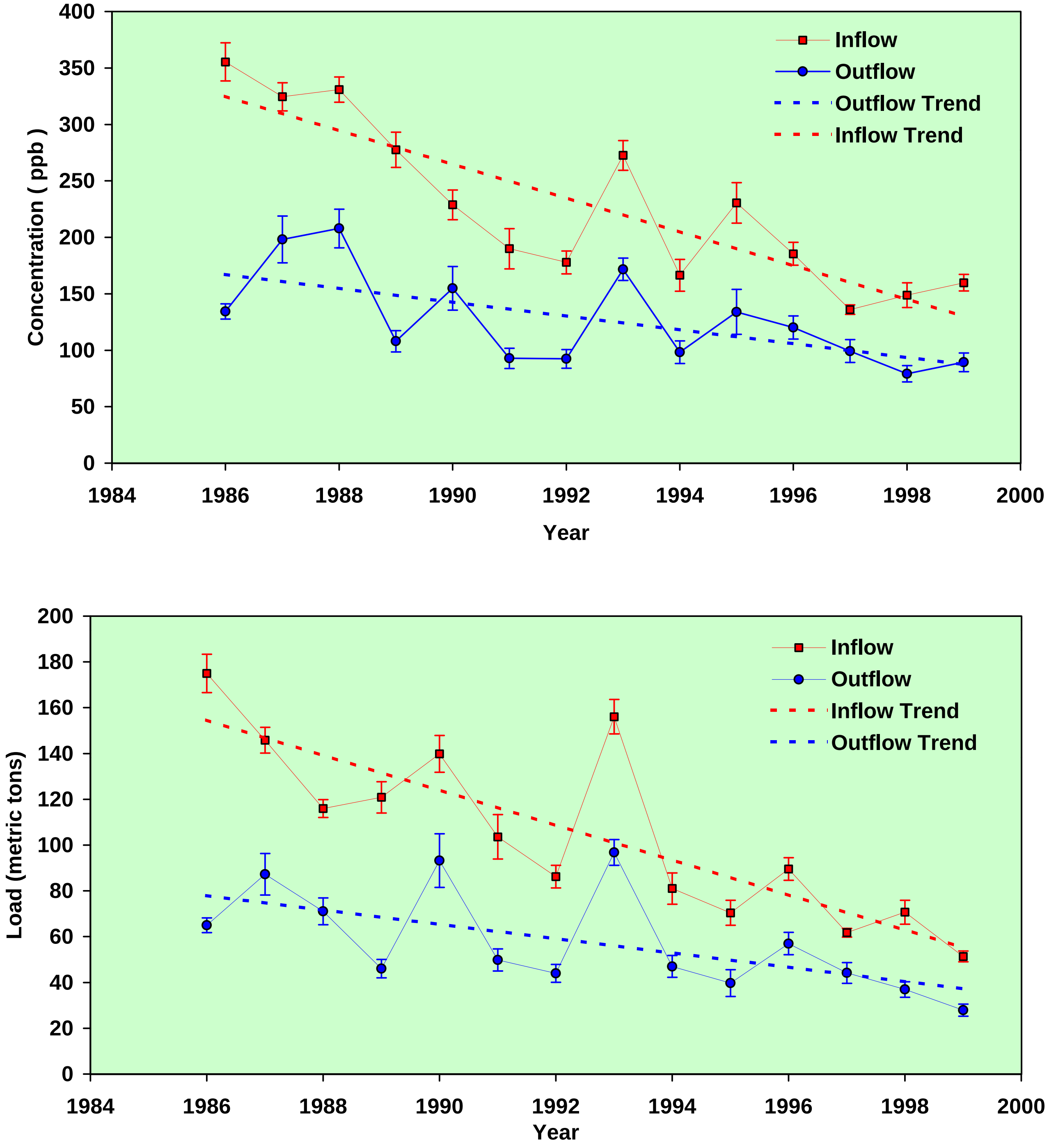
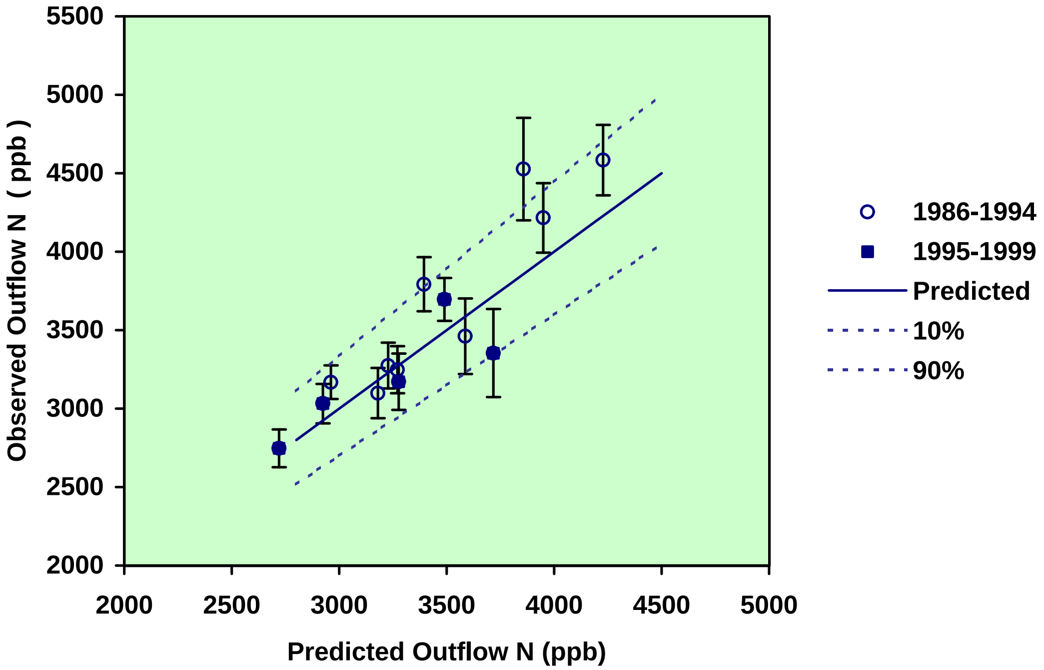


Figure 12-7
Observed & Predicted Annual Outflow N Concentrations



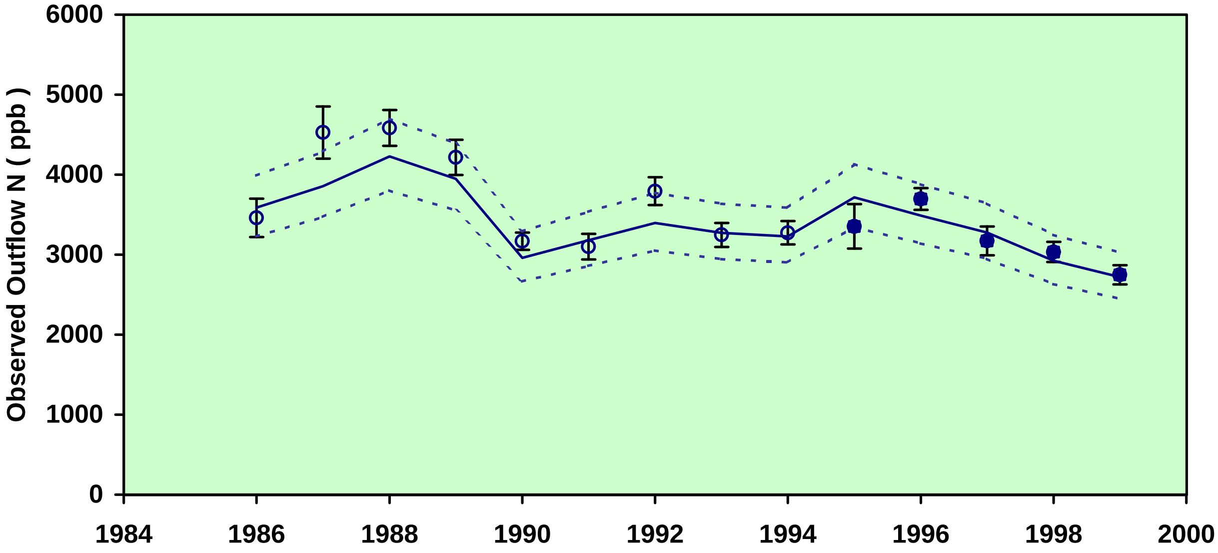
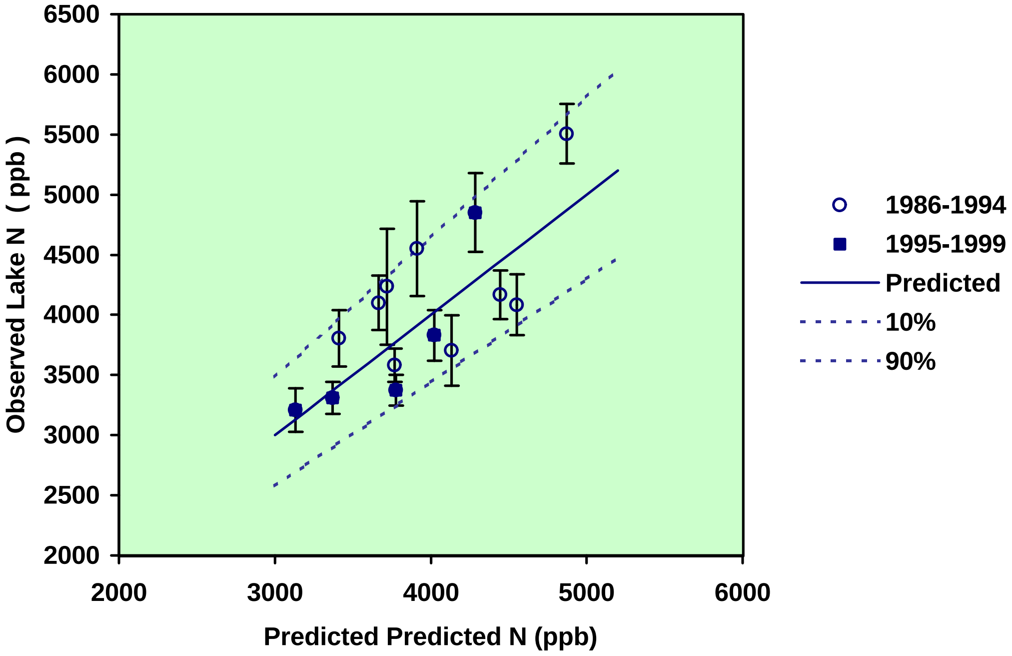


Figure 12-8
Observed & Predicted Summer Total N Concentrations



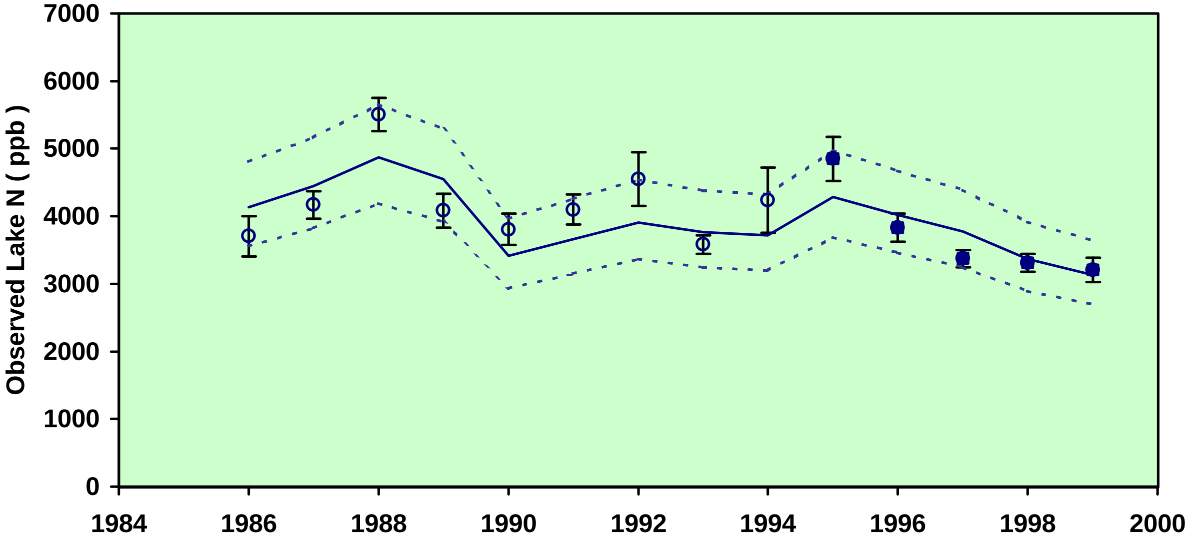
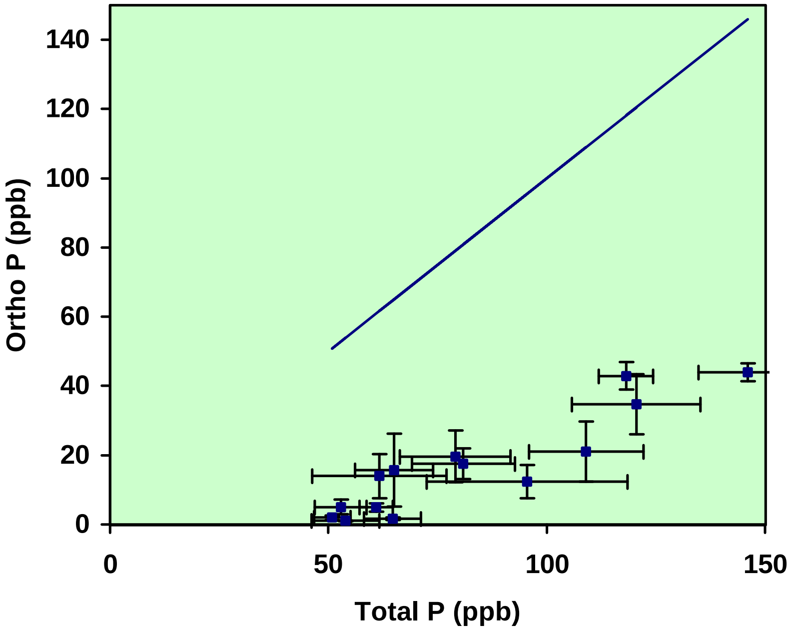
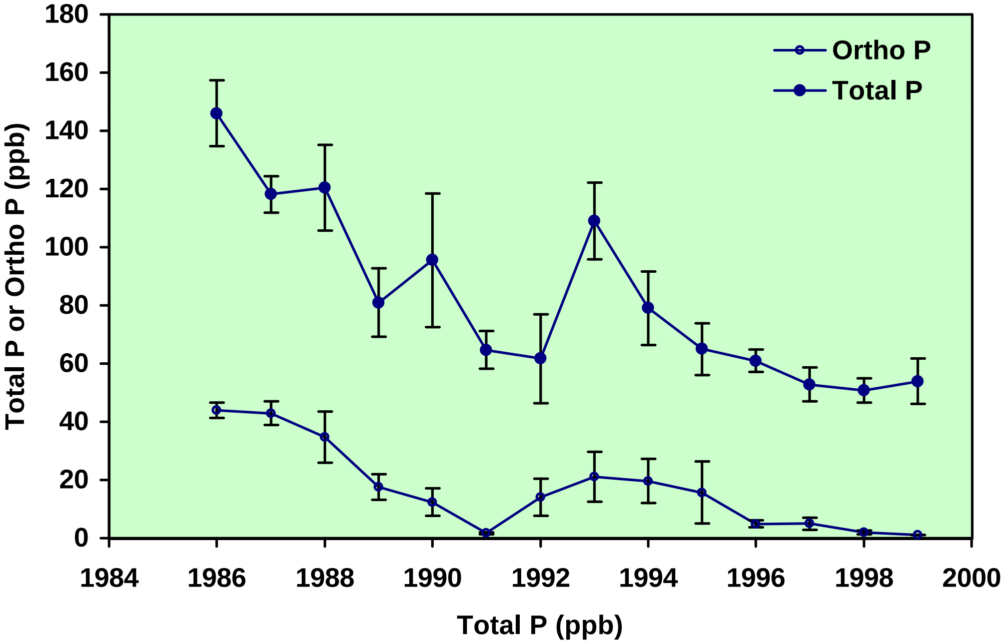


Figure 12-9

Ortho P vs. Total P Concentrations

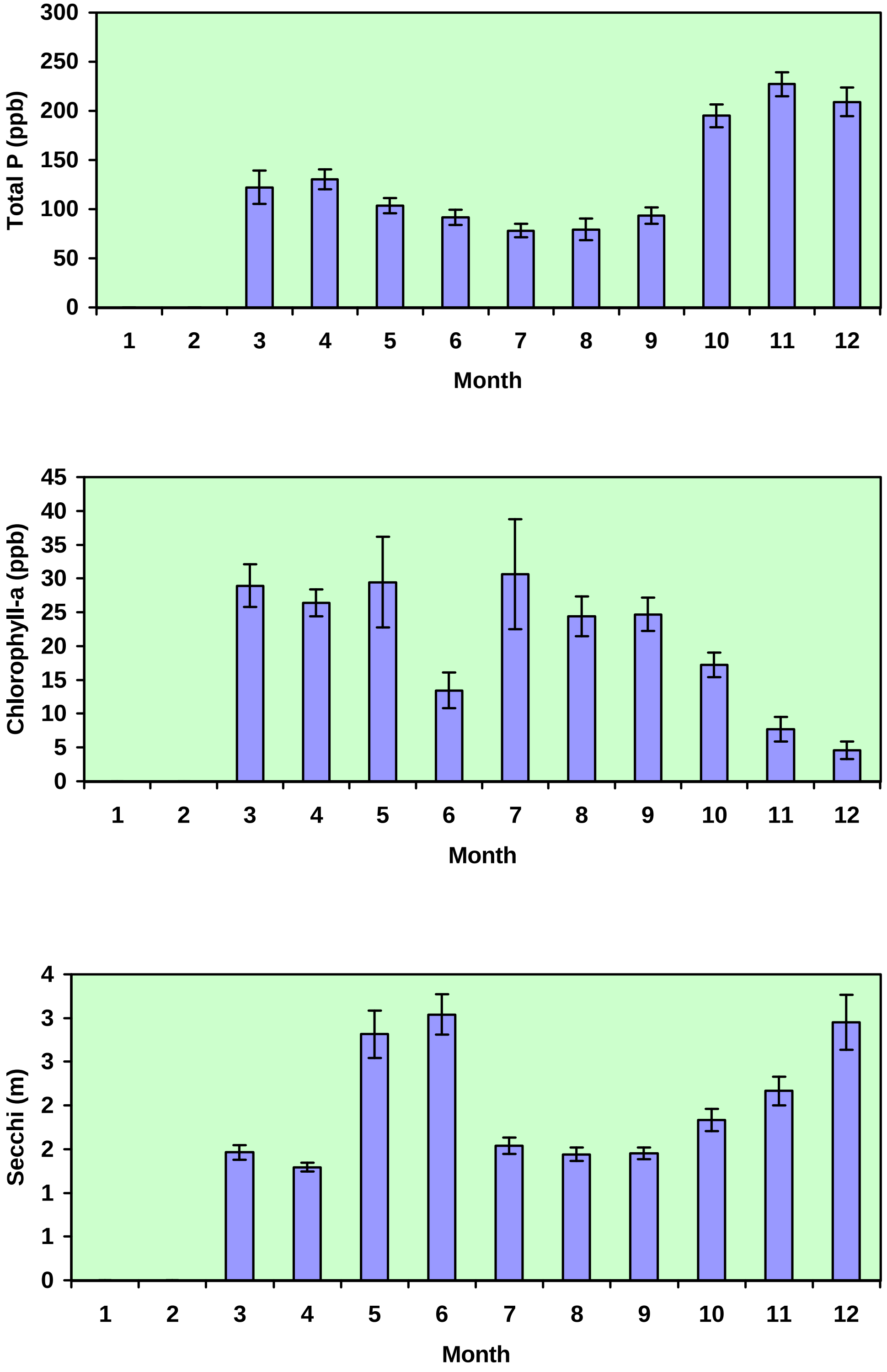
July-September Means, 0-3 meters, Lake South Station





Error bars show mean +/- 1 standard error

Figure 12-10
Season Variations in Trophic State Indicators



Means +/- 1 Standard Error, 1986-1999, 0-3 meters, Lake South

Figure 12-11
Observed & Predicted Mean Chlorophyll-a

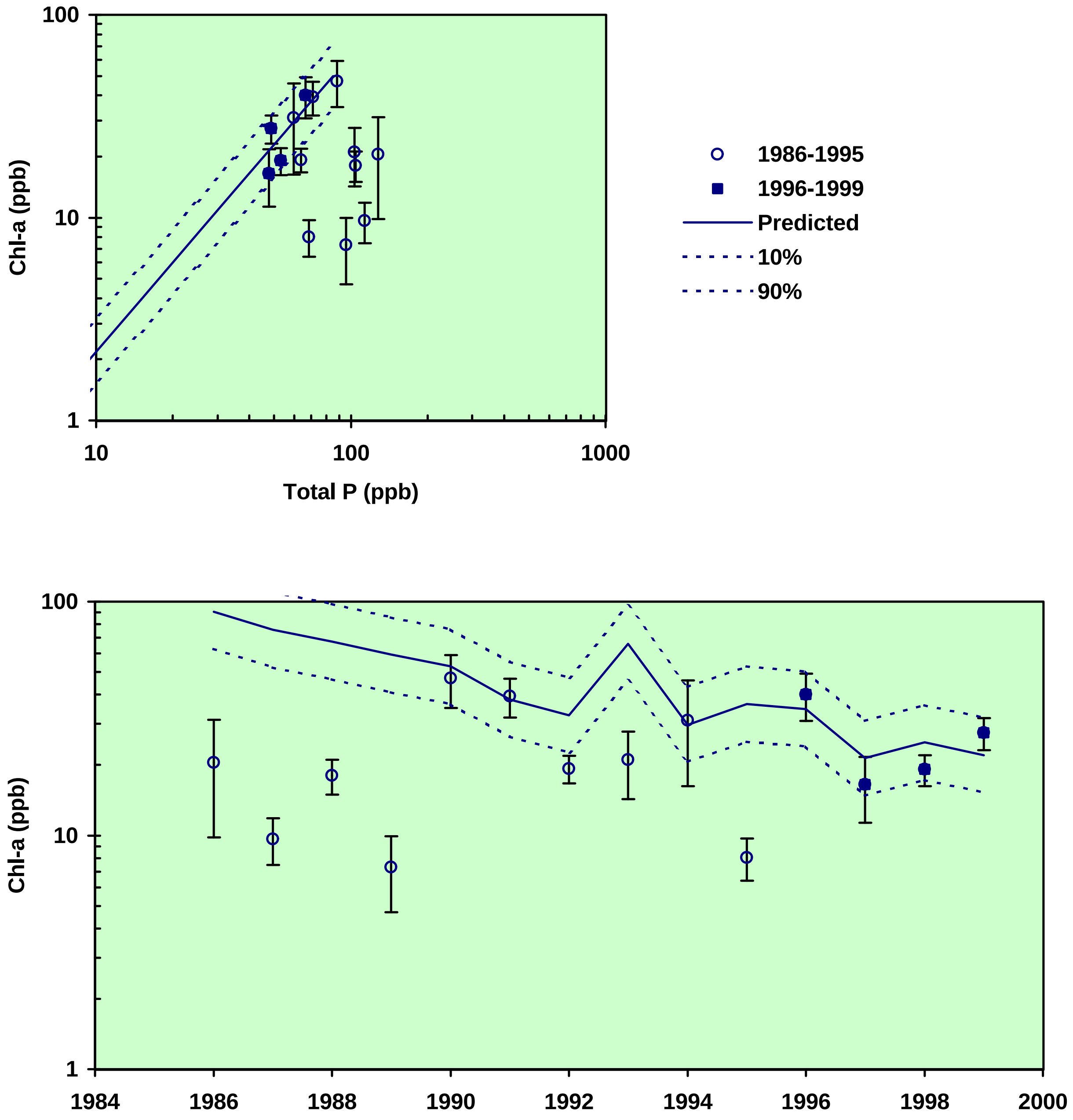


Figure 12-12
Algal Bloom Frequencies vs. Observed Mean Chlorophyll-a

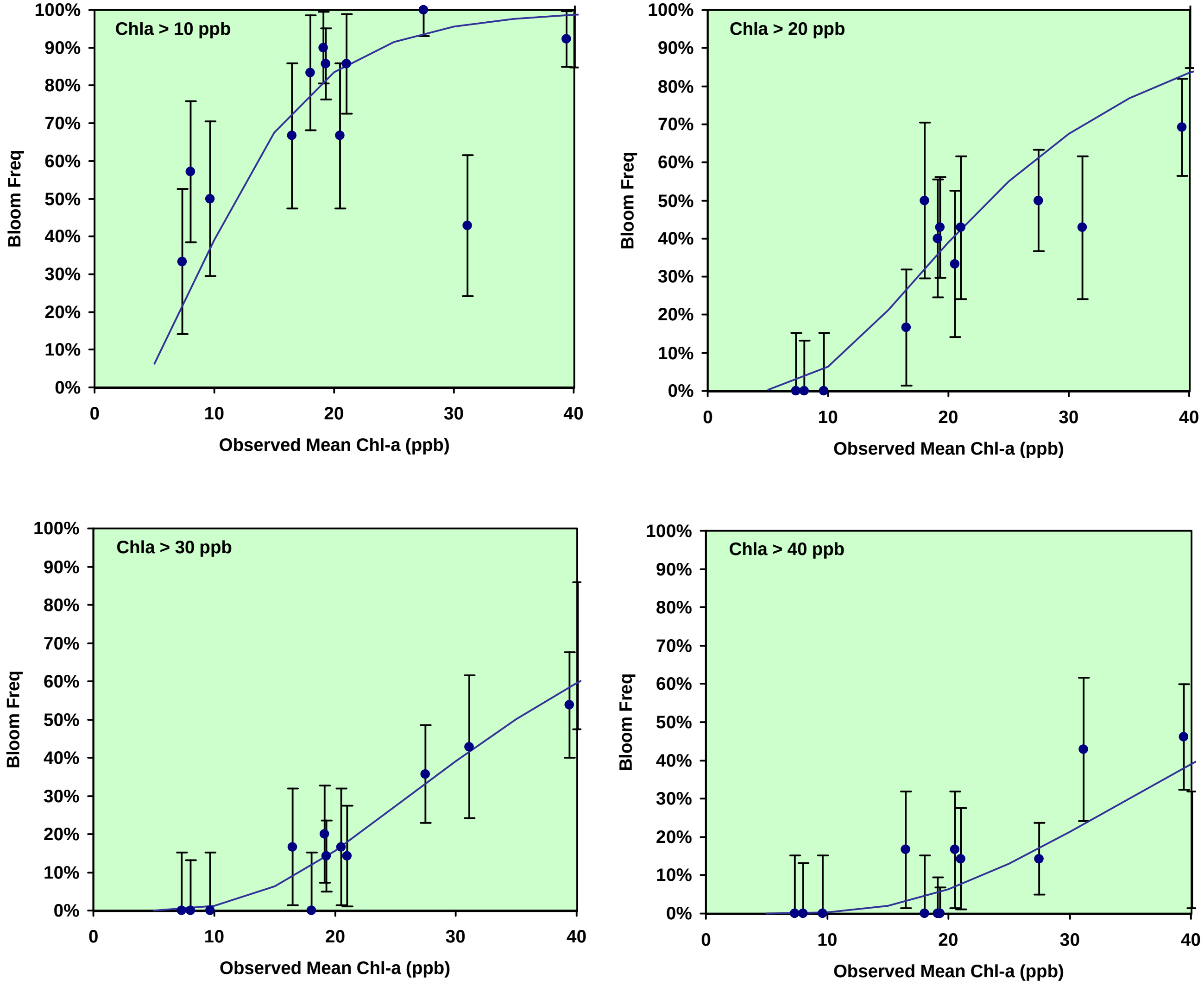


Figure 12-13
Algal Bloom Frequencies vs. Predicted Total Phosphorus

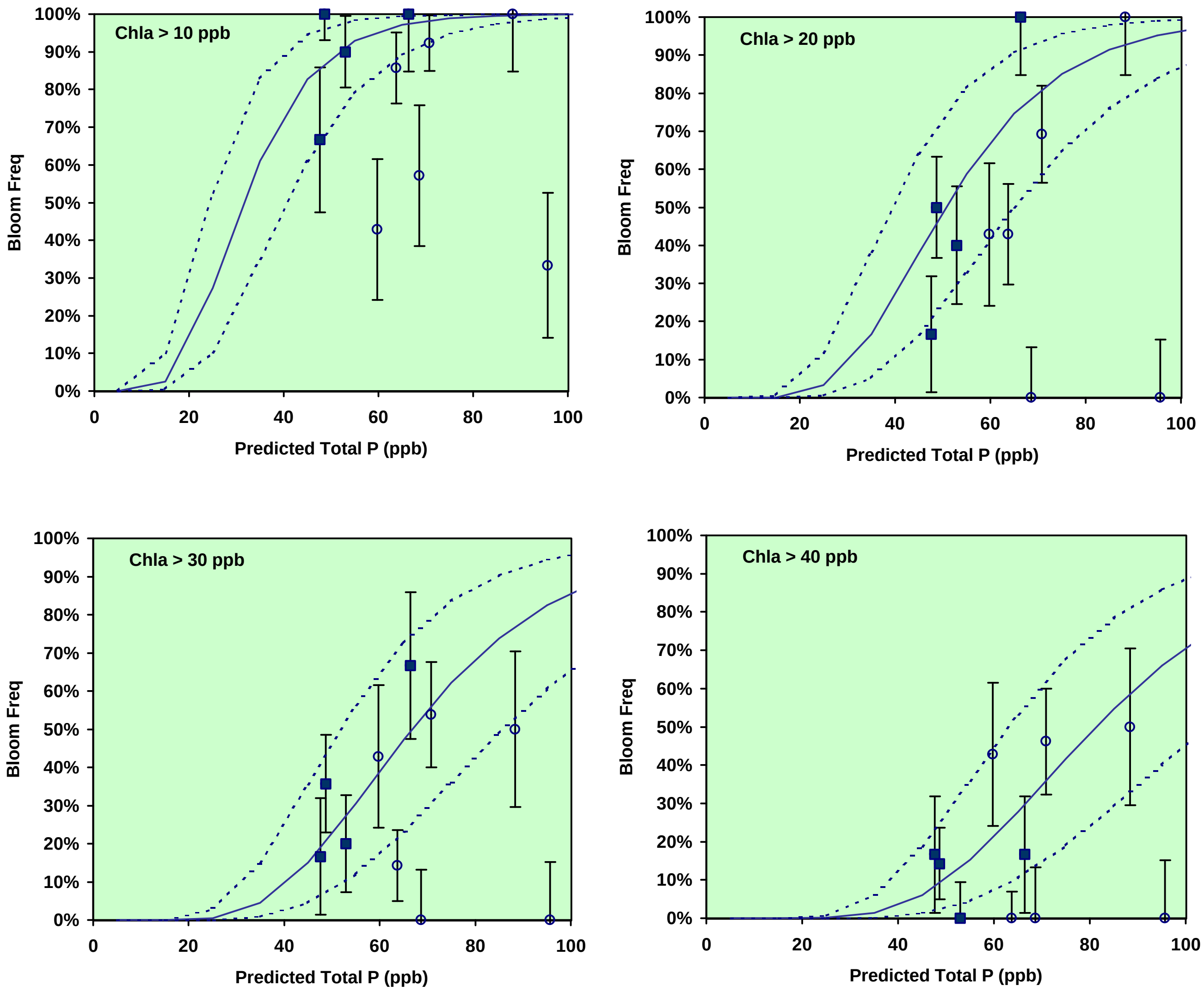


Figure 12-14
Algal Bloom Frequencies vs. Year

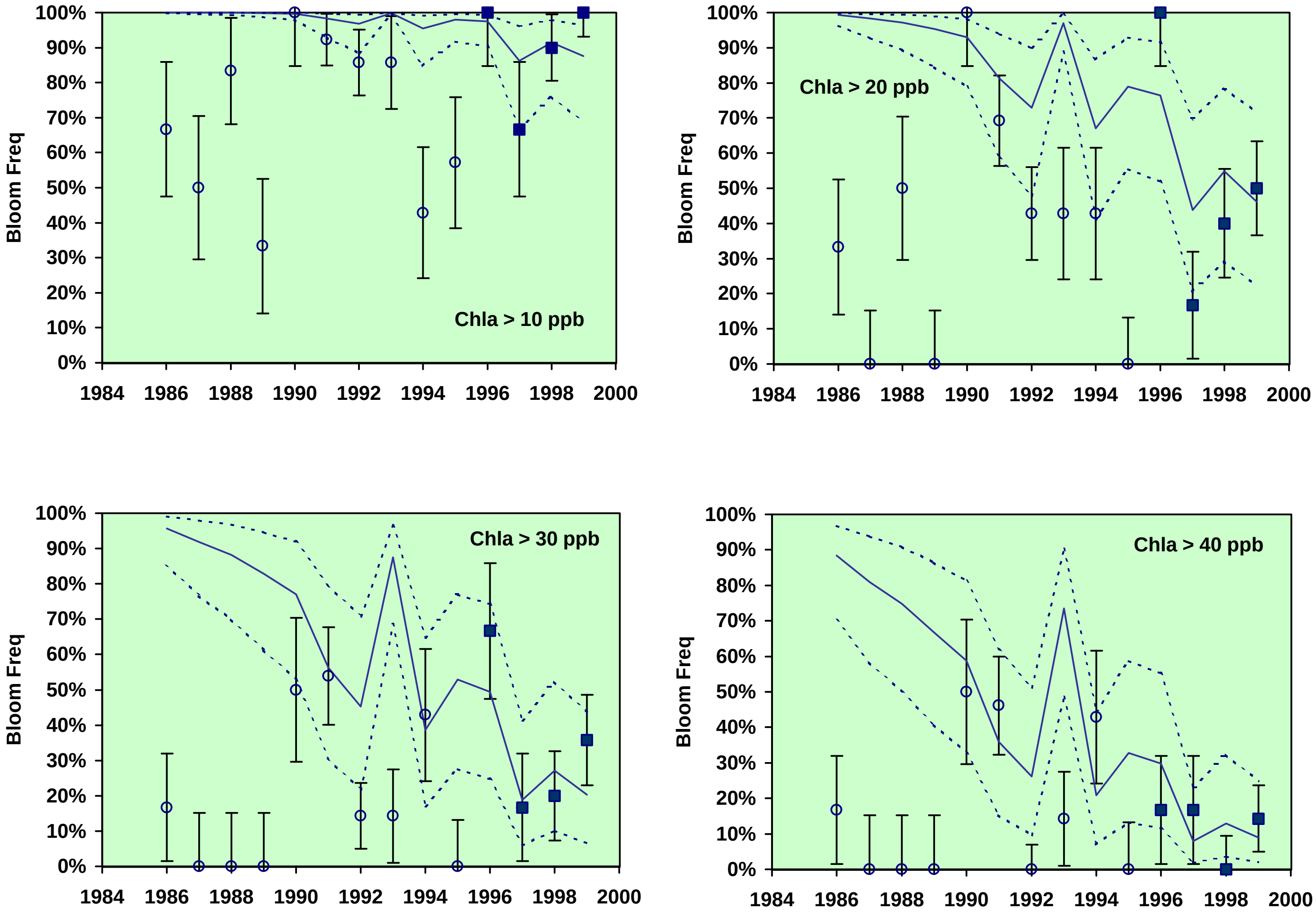
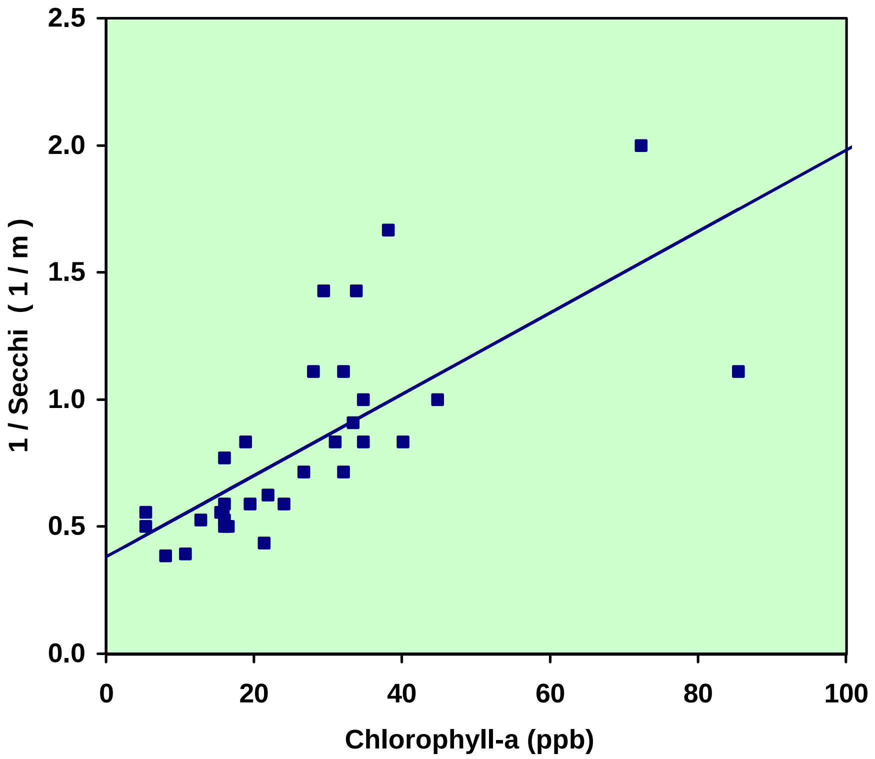


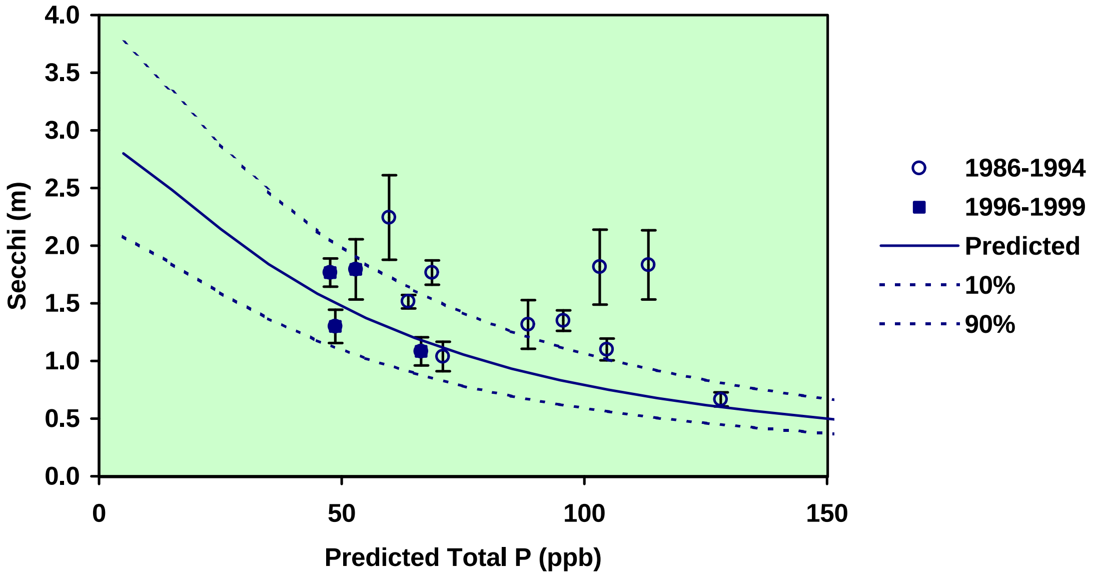
Figure 12-15
Calibration of Secchi Depth Model



Lake South Epilimnion Samples, 0-3 m, July-September, 1996-1999
Regression:

Y =	0.381	+	0.016	X
R^2 =	0.53	SE =	0.27	

Figure 12-16
Observed & Predicted Secchi Depth



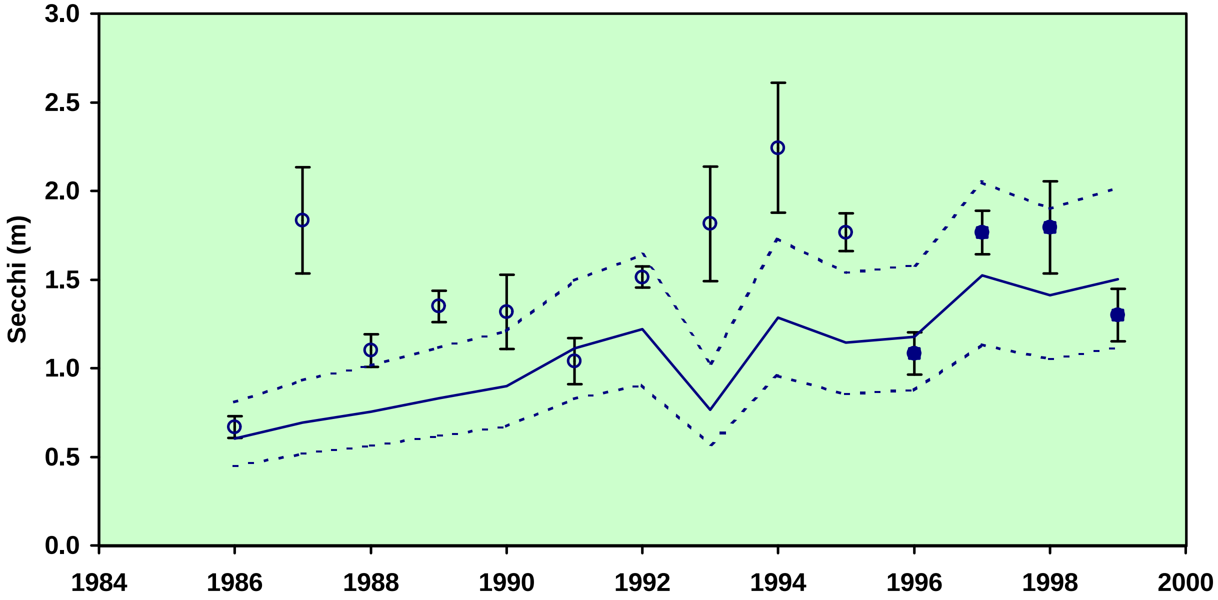
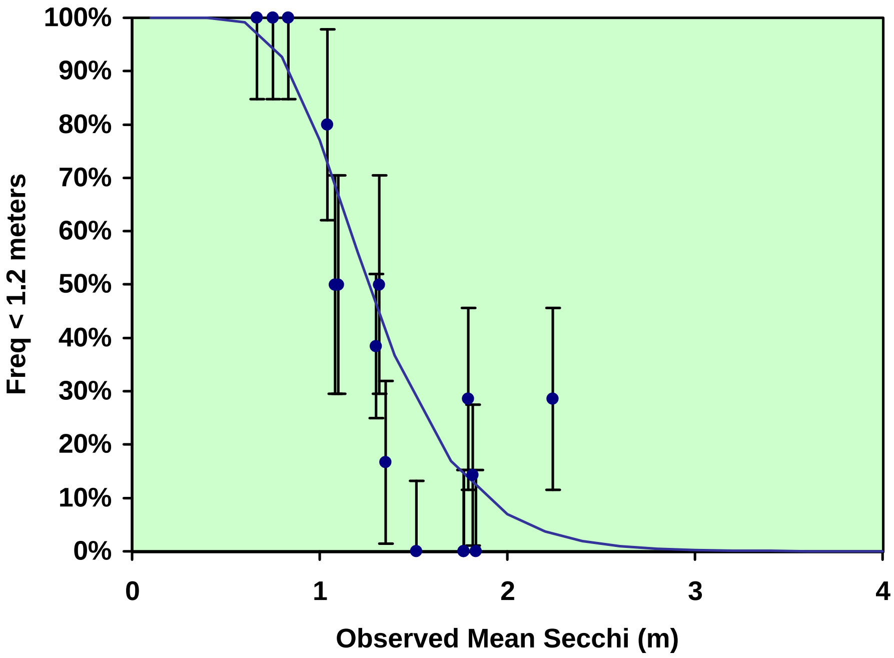


Figure 12-17
Secchi Interval Frequencies vs. Mean Secchi



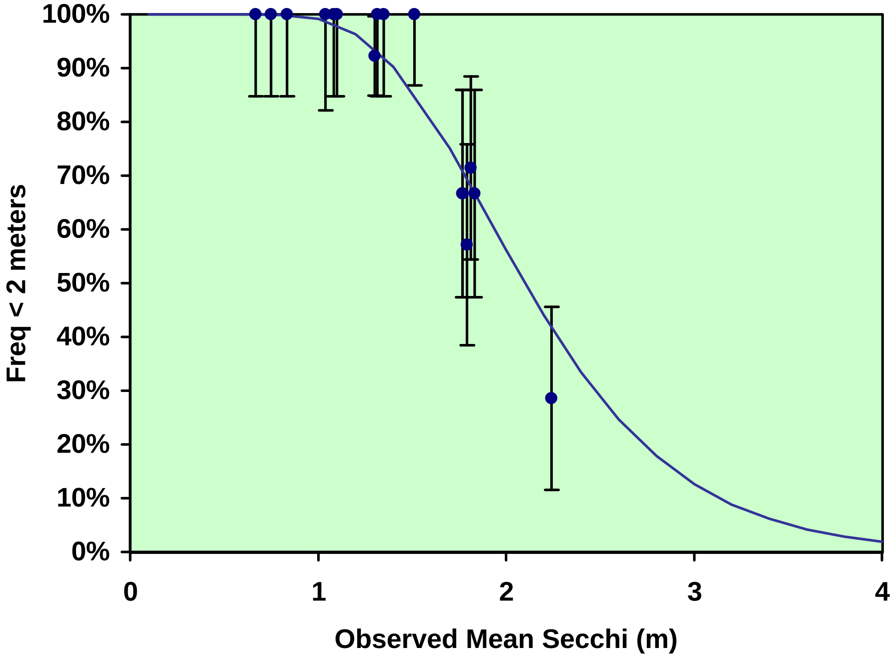


Figure 12-18
Observed & Predicted Frequency of Secchi < 1.2 meters

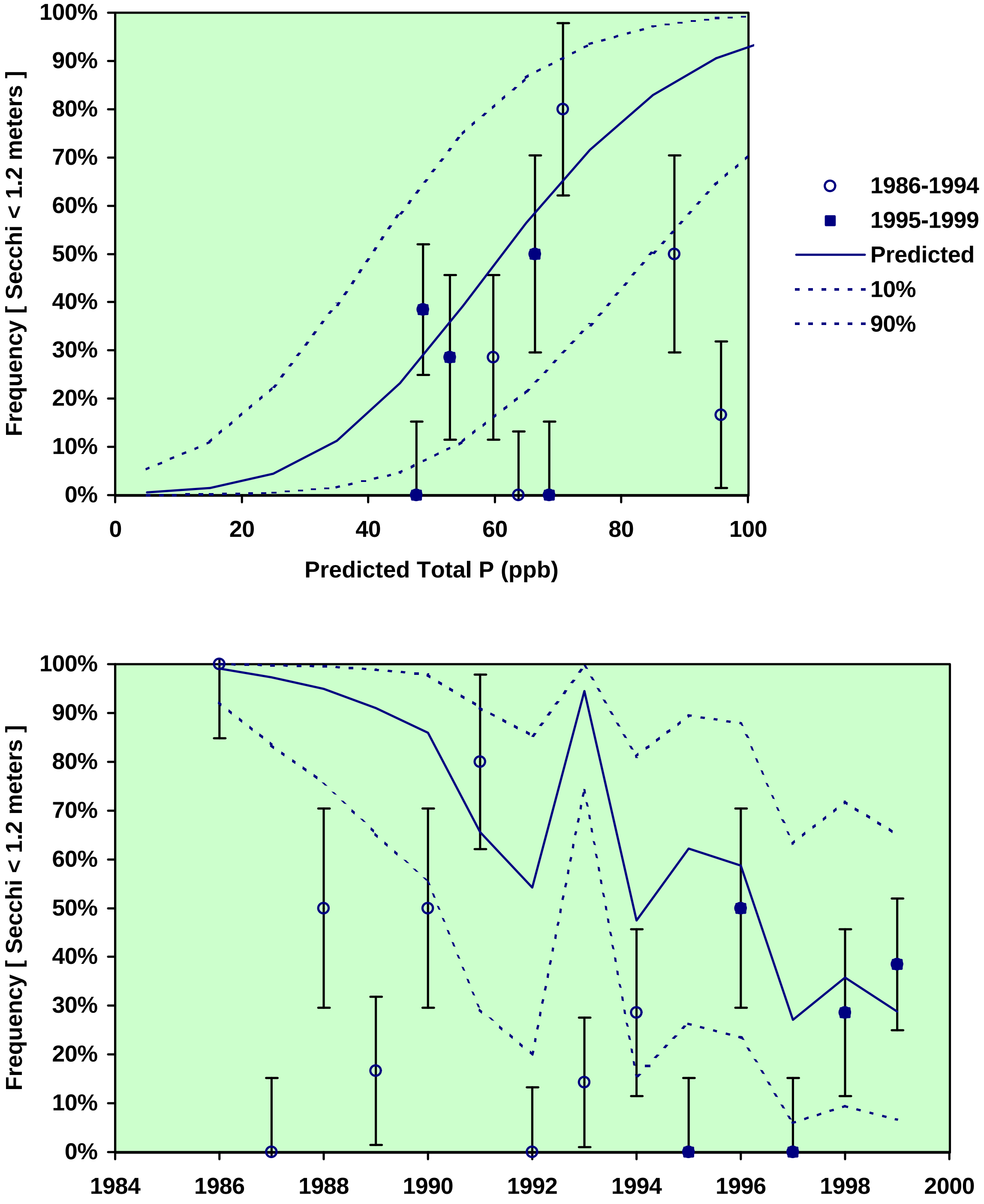
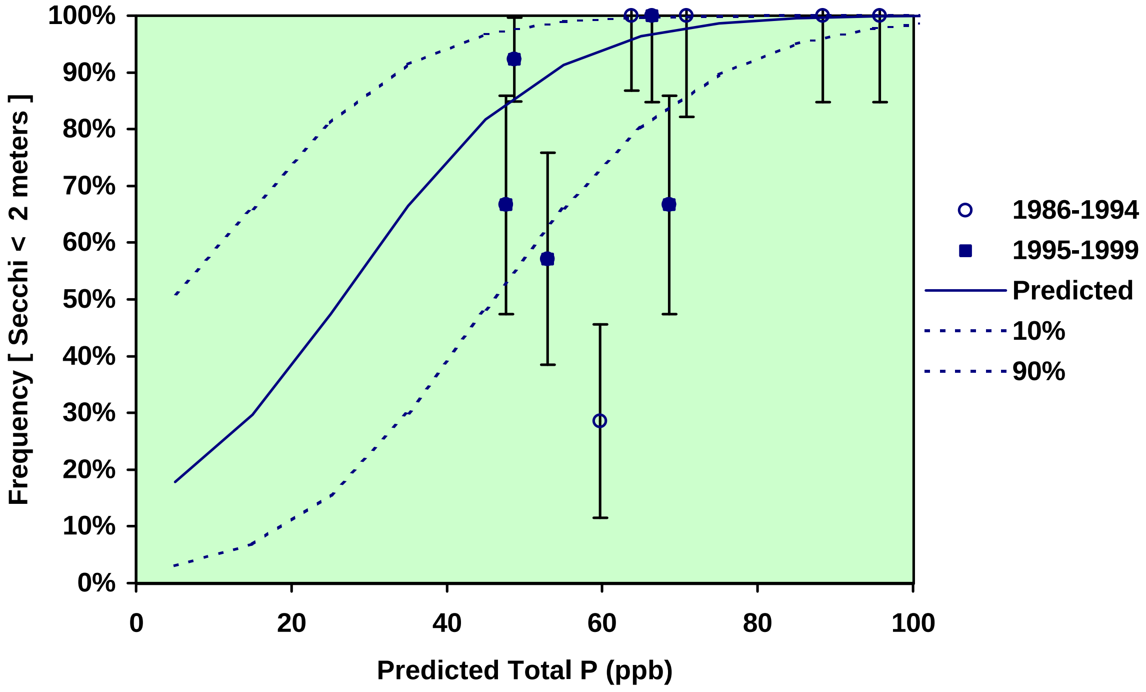


Figure 12-19
Observed & Predicted Frequency of Secchi < 2 meters



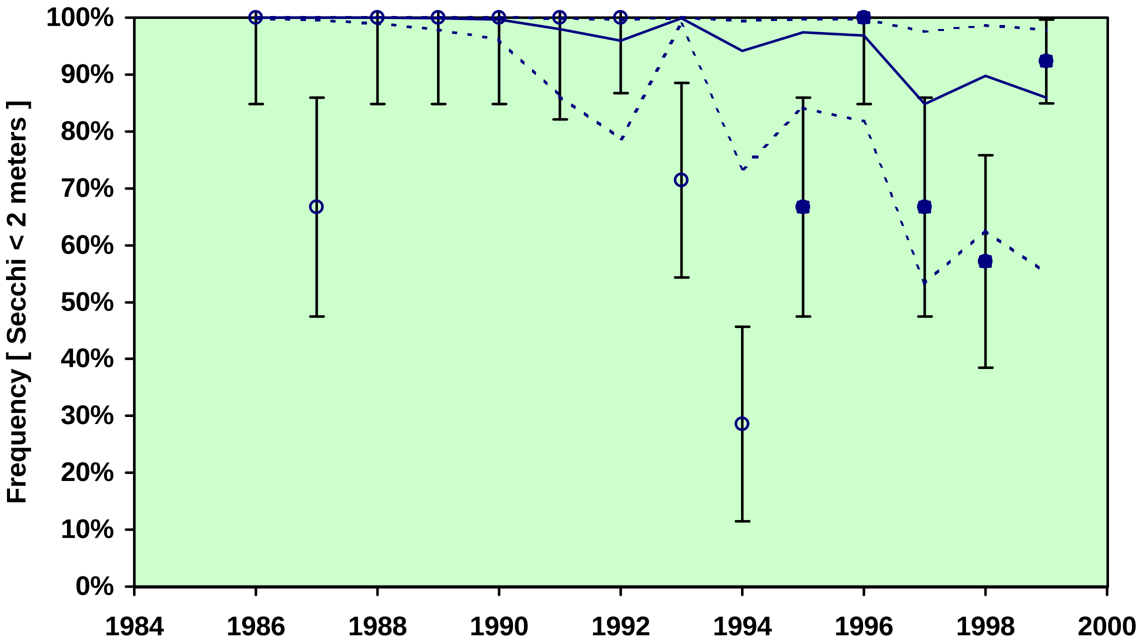
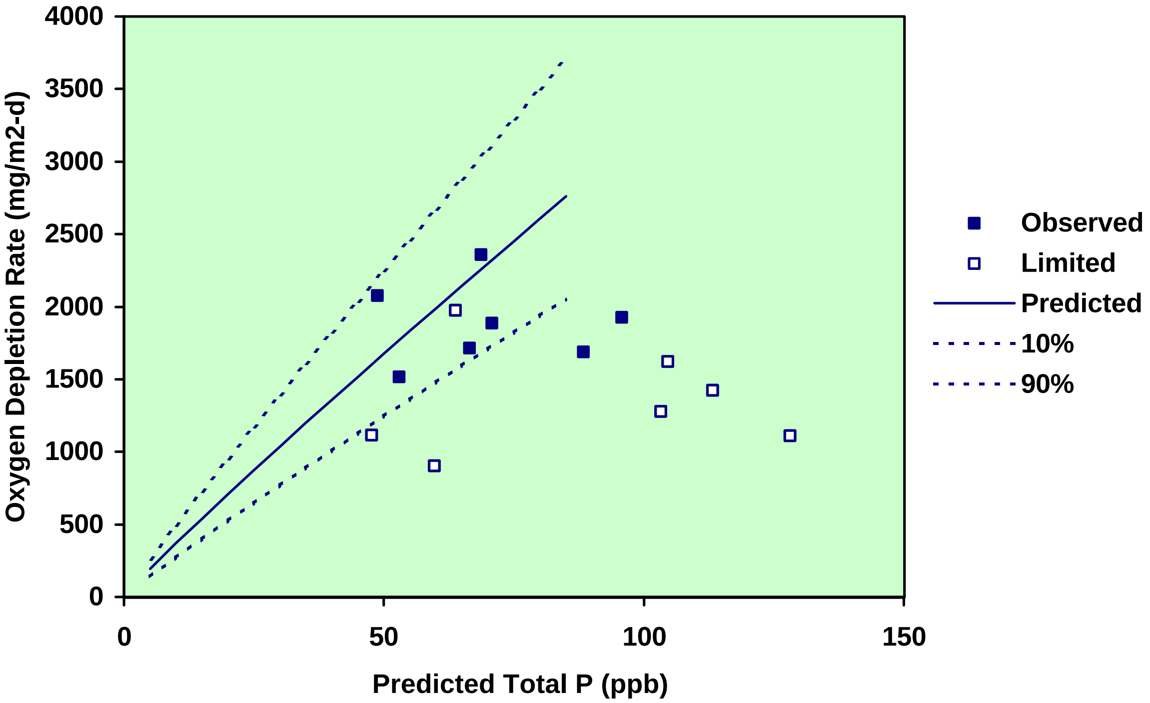
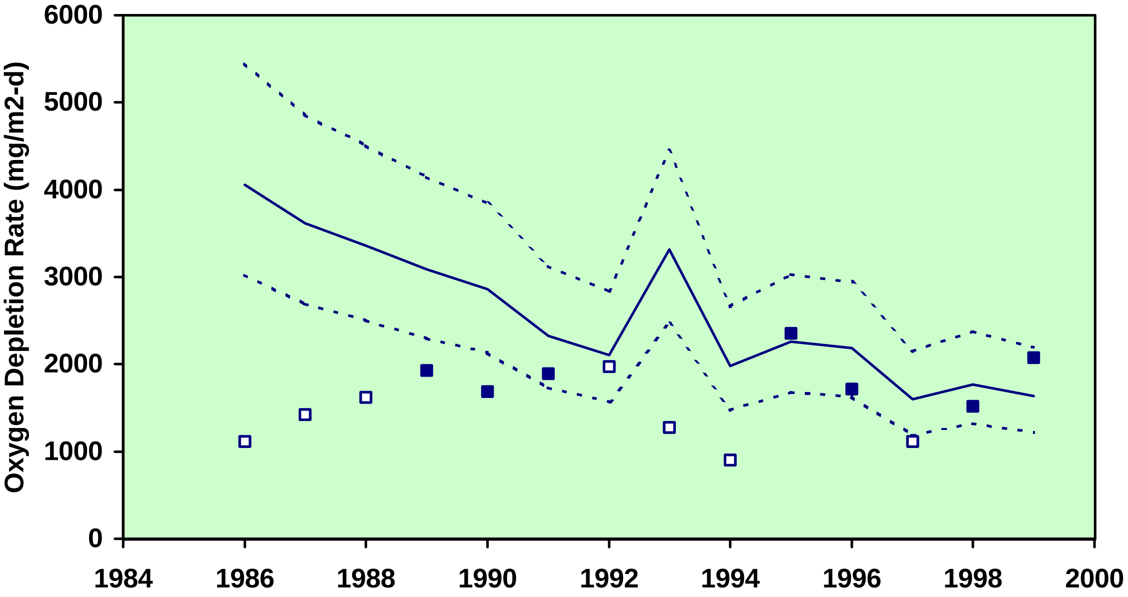


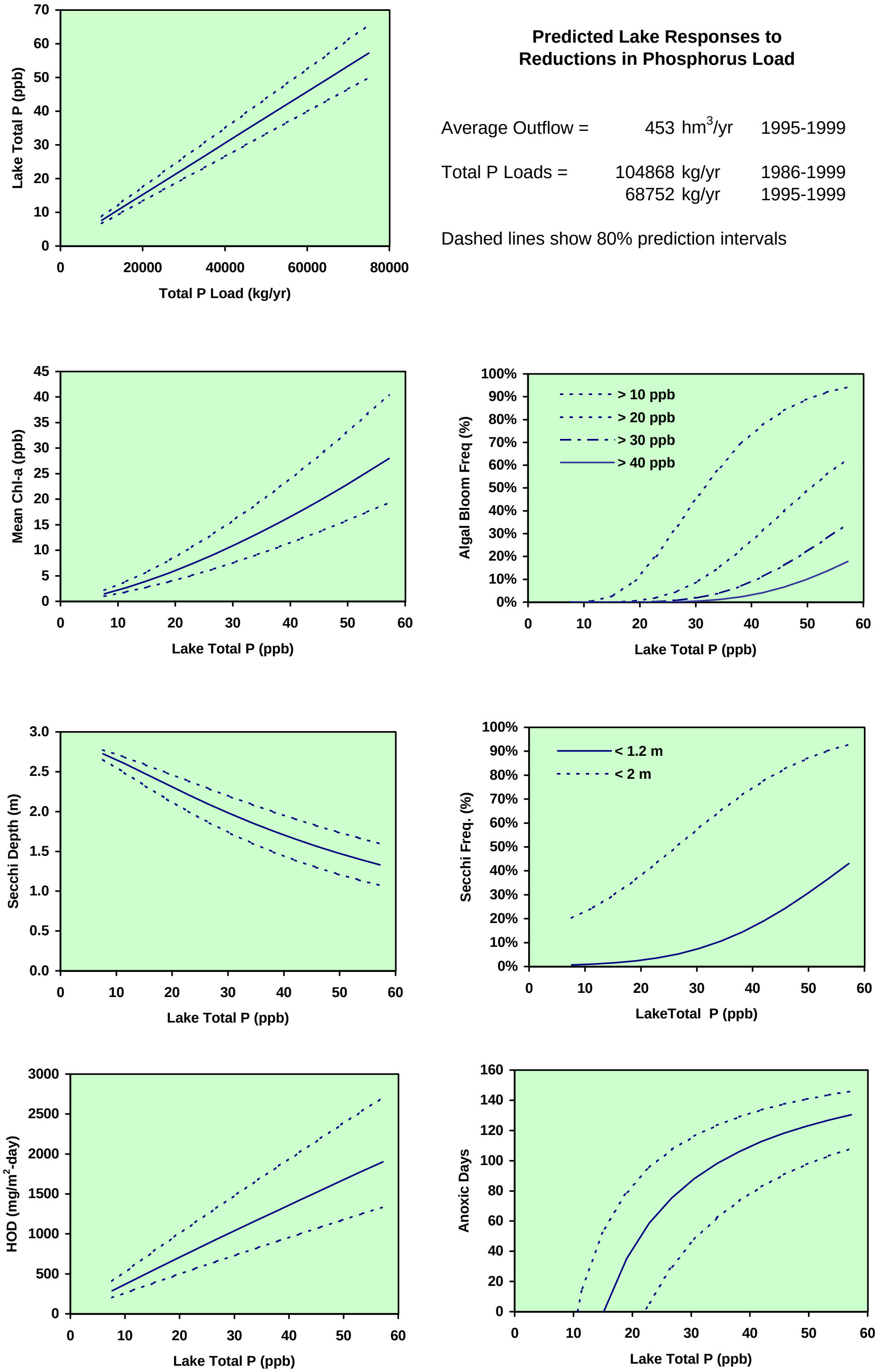
Figure 12-20
Observed & Predicted Hypolimnetic Oxygen Depletion Rates





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

Figure 12-21



Predicted Lake Responses to Reductions in Phosphorus Load

Average Outflow = 453 hm^3/yr 1995-1999

Total P Loads = 104868 kg/yr 1986-1999
68752 kg/yr 1995-1999

Dashed lines show 80% prediction intervals