Red Cedar River/Tainter Lake Phosphorus Assessment

June 1992

Prepared by

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Dear Interested Citizen:

Since this report was first distributed in 1992, several revisions have been made of the lake model used to predict water quality conditions in Tainter Lake. The model used in this study (known as BATHTUB), was revised and re-calibrated for Tainter Lake in 1995 by the models' author William W. Walker.

The earlier modelling effort estimated that a relatively high level of phosphorus (P) control (70-80%) would be needed to measurably improve water quality conditions in Tainter Lake. The recent revision and calibration of the BATHTUB model (Walker, 1995) suggests the lake would be more responsive to P load reductions than earlier predicted (see following page). For example, the revised model predicts that a 50% reduction in the annual P load would result in an approximately 50% reduction in lake mean chlorophyll a concentrations. A significant decrease in mean chlorophyll a concentrations would also result in a significant decrease in the duration and intensity of algae blooms, and improved water clarity.

An ongoing DNR-UWEX study is examining the feasibility of controlling pollutant loads throughout the Red Cedar River basin. One of the study objectives is to determine the level of P control needed from individual watersheds to significantly improve water quality in the Red Cedar River basin impoundments.

The graphs that follow this page should replace Figure 10 in the original report.

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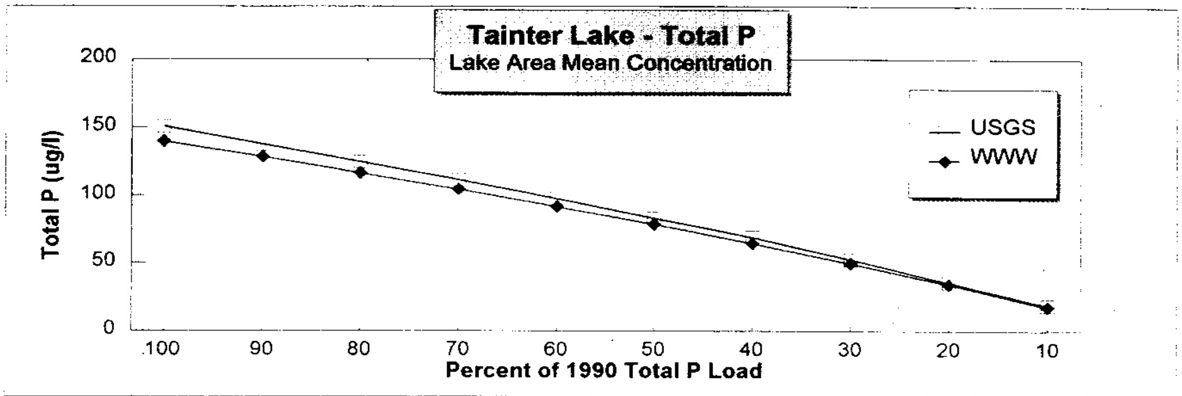
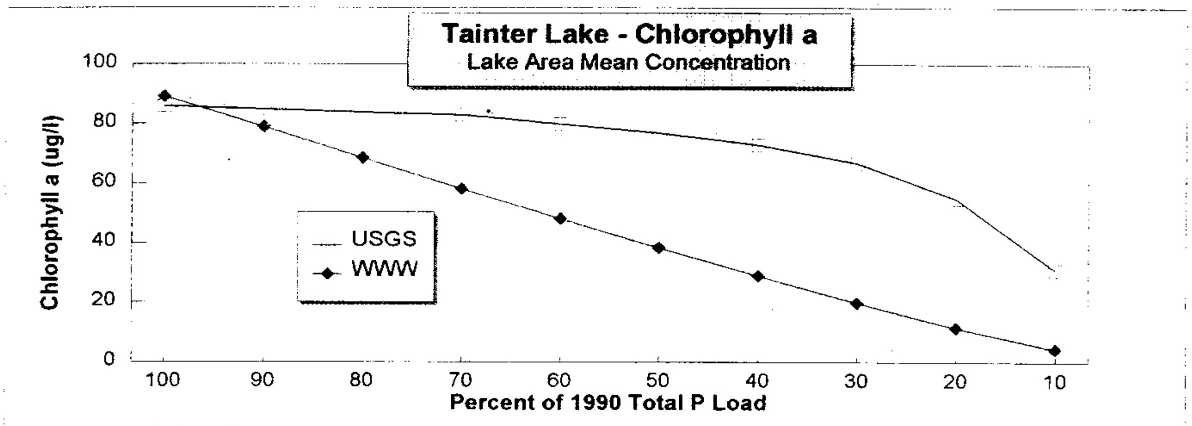
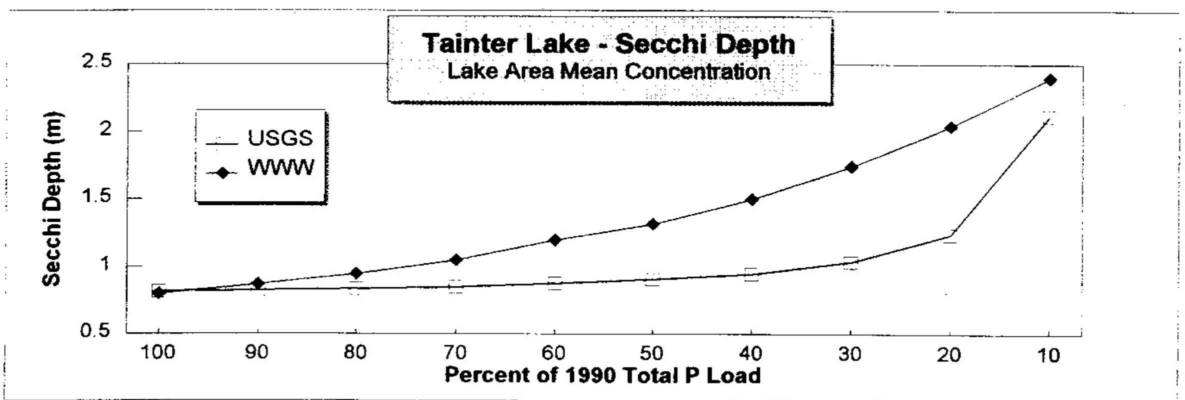
BATHTUB modelling results for Tainter Lake showing 1992 predictions and 1995 William W. Walker (WWW) revisions.







USGS - U. S. Geological Survey (1992) BATHTUB Model Predictions
WWW - William W. Walker (1995) BATHTUB Model Predictions

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Front cover: Aerial photo of Tainter Lake facing northeast.

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Introduction

This report is a portion of a two-part study of the effects of phosphorus on the Red Cedar River and Tainter Lake. One aspect of the study examines macrophyte growth in the Red Cedar River near Barron, and the other portion of the study, included in this report, examines the impact of phosphorus loading to Tainter Lake in Dunn County, Wisconsin. The river macrophyte study was conducted during summer 1989, and the Tainter Lake study occurred from February 1989 to October 1990.

The trophic condition of Tainter Lake was assessed in 1972 as part of the National Eutrophication Survey conducted by the U.S. Environmental Protection Agency (EPA). The study determined Tainter Lake to be highly eutrophic with phosphorus loading nine times that necessary to maintain eutrophic conditions. The survey indicated that less than one percent of the phosphorus load was from point sources and concluded that control of point sources would have little effect on the trophic condition of Tainter Lake (EPA, 1974).

The purpose of this study is to update phosphorus load estimates to Tainter Lake and determine the relative contribution of phosphorus from point and nonpoint sources. The study included data collection from the Red Cedar and Hay rivers, Tainter Lake, and point source discharges in the watershed. A lake eutrophication model was also used to predict how changes in phosphorus loading would effect trophic conditions in Tainter Lake.

Physical Setting

The Red Cedar River/Tainter Lake watershed is 1,680 square miles and drains portions of eight counties in northwestern Wisconsin (Fig. 1). Tainter Lake is highly eutrophic and experiences severe summer algae blooms and poor water clarity. The Hay and Red Cedar Rivers are the primary sources of inflow to Tainter Lake (Table 1). The Red Cedar River enters the northeast end of Tainter Lake, and the Hay River enters on the northwest side of the lake above the CTH D bridge (Fig. 2).

The Red Cedar River basin is located in the North Central Hardwood Forest Ecoregion (Omernik and Gallant, 1988). This EPA ecoregion is characterized by nearly level to rolling glacial till plains and significant agricultural land use. Lakes in the ecoregion are typically eutrophic and have summer total phosphorus concentrations greater than 50 ug/L.

Acknowledgements

The author would like to thank the following individuals for their contributions to this project; Art Bernhardt, Buzz Sorge, John Sullivan, Duane Schuettpelz and Jeff Thornton, Wisconsin Department of Natural Resources, and Steve Field, U.S. Geological Survey for review of this document; Leo House of the U.S. Geological Survey for calibration and initial runs of the BATHTUB model; and Bob Gaugush, U.S. Fish and Wildlife Service who provided additional modeling expertise. Finally, the Department would like to thank members of the Tainter Lake Sportsman Club and Dunn County Fish and Game Association who provided financial contributions to the project.

Methods

The overall monitoring strategy for the phosphorus assessment was aimed at providing adequate water quality data to calculate an annual phosphorus load and utilize a lake eutrophication model. The lake model was used to evaluate the effect of changes in the phosphorus load on water quality in Tainter study period. The study included stream monitoring at two USGS gauging stations, point source monitoring and in-lake sampling. Lake modeling required collection of considerable inflow and in-lake monitoring data during the monitoring and lake sampling.

Figure 1. Red Cedar River and Tainter Lake drainage basin.

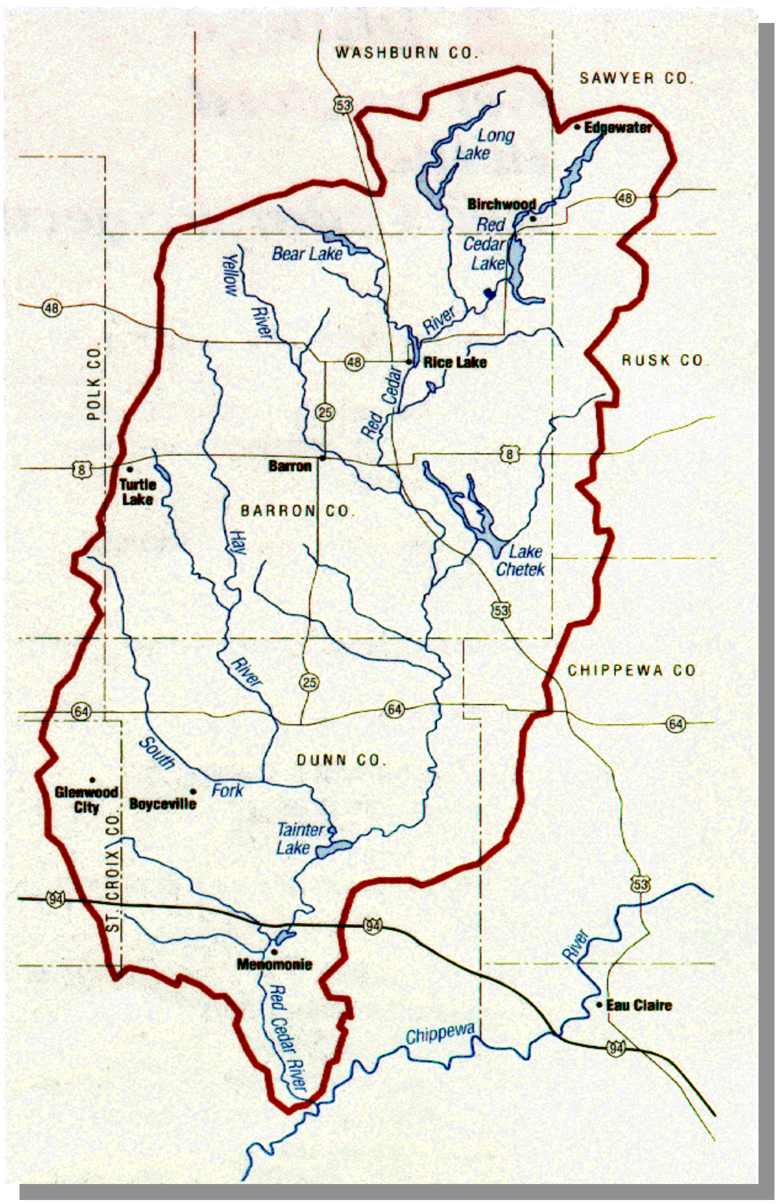


Table 1. Tainter Lake and Red Cedar River drainage basin characteristics.

Lake Morphometry

Surface Area	1,692 acres
Maximum Depth	37 feet
Mean Depth	13.3 feet
Volume	22,543 acre-feet
Mean Hydraulic Residence Time*	7.3 days (summer, 1990)
Watershed/Surface Area Ratio	635:1

Basin Characteristics**

Tributaries	*Drainage Area (mi^2)*
Red Cedar River	1,140
Hay River	466
Lamb Creek	18
Minor Tributaries & Direct Drainage	53

*Hydraulic residence time is the time required for a volume equal to the full lake volume to be replaced by inflowing waters.

**Source: USEPA, 1974.

USGS Monitoring Stations

Phosphorus and sediment loading to Tainter Lake was measured from October 1989 through September 1990 at two U.S. Geological Survey (USGS) gauging stations located on the Hay and Red Cedar rivers. The Hay River station was located in Wheeler, and the Red Cedar River station was located about 2.5 miles upstream of Colfax. The stations represented approximately 90% of the drainage area to Tainter Lake and were used to measure total phosphorus, suspended solids, and continuous streamflow. The USGS conducted monthly baseline water quality monitoring and stream gauging, and Wisconsin Department of Natural Resources (WDNR) staff collected weekly and event-related water chemistry samples.

Weekly and event-related water samples were collected with a depth-integrated (D-49) sampler, and sent on ice to the State Laboratory of Hygiene (SLOH) in Madison, and analyzed for total phosphorus and suspended solids. Total phosphorus samples were analyzed according to methods outlined in Bowman and Delfino (1982). Monthly water quality samples were collected by USGS staff using the equal-width increment method described by Guy and Norman (1970). Field measurements during each sampling event included water temperature and dissolved oxygen.

The USGS used data from these stations to determine annual nutrient and sediment loads to Tainter Lake. The lake and stream monitoring data were then used by USGS and WDNR staff to apply a lake eutrophication model to predict changes in Tainter Lake under different phosphorus loading scenarios.

Point Source Monitoring

All point sources discharging directly into surface waters of the Tainter Lake watershed were monitored during the study. Wastewater treatment plant (WWTP) operators collected bi-weekly effluent samples from October 1989 through September 1990. Samples were also collected bi-weekly from seasonal discharges, when they occurred. The samples were refrigerated and sent to the SLOH for total phosphorus analysis.

The following point source discharges were sampled during the Tainter Lake study:

Rice Lake WWTP	Chetek WWTP
Colfax WWTP	Cumberland WWTP
Almena WWTP	Comstock WWTP
Prairie Farm WWTP	Turtle Lake WWTP
Jerome Foods, Inc. (Barron)	Ridgeland WWTP
Glenwood City WWTP	Twin Town Cheese, Inc.

Point source monitoring data were used with USGS continuous monitoring data to estimate the relative proportion of phosphorus loading to Tainter Lake from point and nonpoint sources.

Lake Sampling

Three ambient lake water quality monitoring sites were established on Tainter Lake in February 1989 (Fig. 2). Site TL1 was located in the northwest basin of Tainter Lake, which receives flow from the Red Cedar River watershed. Site TL2 was located in the middle portion of Tainter Lake, which receives flow from both the Hay and Red Cedar river watersheds. The furthest downstream site (TL3) was located in the lower pool near the Cedar Falls dam.

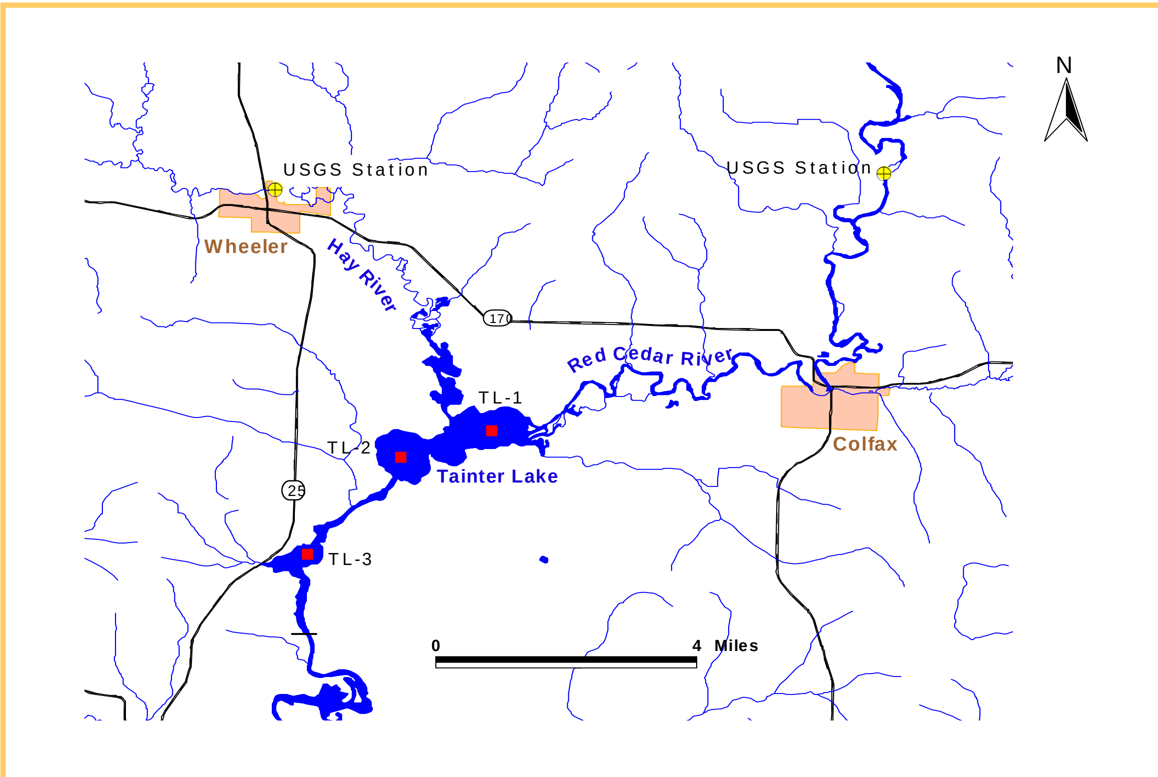
Monitoring in Tainter Lake was conducted from February 1989 to October 1990, including two summer and winter sampling seasons. Sampling parameters and frequency were comparable to those conducted on WDNR trend monitoring lakes (Appendix 1). Lake water samples were collected with a Kemmerer sampler 0.5 meters from the surface and 0.5 meters above the bottom. Depth profiles of water temperature and dissolved oxygen (D.O.) were determined at one meter intervals at each site using a YSI Model 57 temperature/D.O. meter.

Data collected from Tainter Lake were used to establish existing water quality conditions and to calibrate and verify the lake eutrophication model. Primary water quality inputs to the model included total phosphorus, chlorophyll-a, and Secchi disc transparency (Secchi depth).

Phosphorus Loading Estimates

Phosphorus (P) loading to Tainter Lake was calculated by the USGS using the total integration method described by Porterfield (1972) in the monitored watersheds, and estimated in the unmonitored watersheds by applying unit area loading values from the monitored watersheds. Hay River unit area loading values were applied to the unmonitored Otter and Lamb Creek watersheds; and Red Cedar River

Figure 2. Water quality monitoring sites in Tainter Lake during 1989-1990 study.



values were used to estimate loading from the Sinking and 18-Mile Creek watersheds. Hay River unit area loading values were used to estimate loads from direct runoff (overland flow) from the west side of Tainter Lake, and Red Cedar River values were used to estimate loading from the east side of the lake.

Phosphorus loading from point sources was determined from mean daily flow and bi-weekly phosphorus concentration data collected by the WWTP operators. Atmospheric P loading (including dry fallout and precipitation) was estimated using unit area load values from Walker (1988).

Seasonal P loading was also estimated for May-September 1988 low-flow conditions. During summer 1988, streamflow conditions in the Red Cedar and Hay rivers were the lowest in ten years. The total P load was expected to be less, and the relative contribution of phosphorus from point sources was expected to be greater, during a dry year, assuming loading from point sources remained constant.

For modeling purposes, the Hay River low-flow discharge was assumed equal to the mean July 1988 flow at the Wheeler USGS station for the May-September period. The Red Cedar River discharge was estimated using unit area flow based on 1988 monitoring data from a USGS station at Menomonie, located about 2 miles downstream of Tainter Lake. May-September 1990 mean total phosphorus concentrations were used to estimate 1988 P loading. Assumptions used in the low-flow analysis probably overestimate phosphorus concentrations and underestimate streamflow during a drought year. Because the P load determinations for low-flow conditions are based entirely upon estimates, the loads should only be considered rough approximations.

Modeling Tainter Lake

A U.S. Army Corps of Engineers reservoir model named BATHTUB was used with in-lake and inflow water quality data to simulate changes in nutrient loading to Tainter Lake. This eutrophication model consists of three parts:

1. FLUX - estimates tributary nutrient loads from concentration data and continuous flow records.

2. PROFILE - assists in the compilation and analysis of lake water quality measurements.

3. BATHTUB - applies empirical eutrophication models to waterbodies. The program performs water and nutrient balance calculations in a steady-state, spatially segmented hydraulic network. Eutrophication-related water quality conditions (expressed as total phosphorus, chlorophyll-a and transparency) are predicted using empirical relationships previously developed and tested for reservoir applications (Walker, 1987).

Hydraulic and water quality data were entered into the PROFILE utility and the FLUX program was used to estimate phosphorus loading to Tainter Lake. The BATHTUB program was then used to simulate existing conditions in Tainter Lake, and to predict lake conditions under different P loading scenarios. Water quality data collected during the study were used to calibrate the model for Tainter Lake.

The PROFILE program computed volume-weighted total phosphorus concentrations for each pool area and in-lake total P concentrations that represented mixed-layer (epilimnion) averages. The lake was conceptually divided into three pools for modeling purposes, two upstream pools (represented by Sites TL1 and TL2) and a downstream pool (Site TL3) near the dam.

A storage-elevation relationship was determined for each pool area by use of a digital planimeter and bathymetric maps. The PROFILE program requires a storage-elevation relation for each pool area to compute volume-weighted concentrations (House, 1991).

The BATHTUB model was used to simulate average conditions in each pool for the May-September period, according to application guidelines (Walker, 1987). Annual averaging was not used in applying the model because of the relatively short hydraulic residence time in Tainter Lake. The BATHTUB model was calibrated with minimal adjustment of default coefficients, suggesting that the model is appropriate for Tainter Lake. However, additional years of monitoring data would be necessary to fully verify the model for predictive purposes (House, 1991).

Results and Discussion

Tainter Lake

Physical

Most of Tainter Lake remains thermally mixed during summer months due to its generally shallow depth and long fetch relative to its surface area (Fig. 3). The upper pool (TL1) is relatively shallow and wide, and remains mixed throughout the growing season. The middle pool (TL2) is slightly deeper and is weakly stratified for a short period in summer. The lower pool (TL3) is deeper and narrower than the upper pools and becomes more strongly stratified than the other pools. The only evidence of summer hypolimnetic oxygen depletion occurred for short periods in the two lower pools. Anoxic conditions in bottom waters can cause phosphorus to be released from sediments at a higher rate than under aerobic conditions, thereby increasing overlying water concentrations.

Chemical and Biological

Phosphorus is generally the plant nutrient that limits algal production in lakes (Wetzel, 1983). However, nitrogen often becomes limiting to primary production when phosphorus concentrations are very high. When P is not limiting to algal growth, increased P loading will not appreciably effect lake water quality. Total nitrogen: total phosphorus (N:P) ratios can be used to determine whether P is limiting; a ratio greater than 10 generally indicates that a lake is P-limited. Growing season N:P ratios indicate Tainter Lake was usually P-limited except during late summer 1989 (Table 2). A rainfall event that occurred on August 19-20, 1989 probably caused reduced N:P ratios in the lake on August 21.

Lake trophic conditions can be evaluated using Carlson's Trophic State Index (TSI) (Carlson, 1977). The TSI is calculated using total P and chlorophyll-a concentrations and Secchi disc transparency readings. Carlson's TSI equations were modified by Ron Martin (WDNR) for Wisconsin lakes. Figure 4 shows Tainter Lake was well within the eutrophic category during the summers of 1989 and 1990.

Table 2. 1989-90 growing season N:P ratios in Tainter Lake.

Date	Upper Pool (TL1)	Middle Pool (TL2)	Lower Pool (TL3)	
5/02/89	14.3	15.6	14.1	
6/21/89	10.7	12.8	12.7	
7/17/89	13.4	16.8	16.0	* N:P ratios <10 indicate
8/21/89	8.8*	9.8*	8.6*	possible nitrogen limitation.
6/25/90	11.9	13.1	13.5	
7/17/90	9.9*	15.2	16.0	
8/14/90	12.0	10.5	13.4	

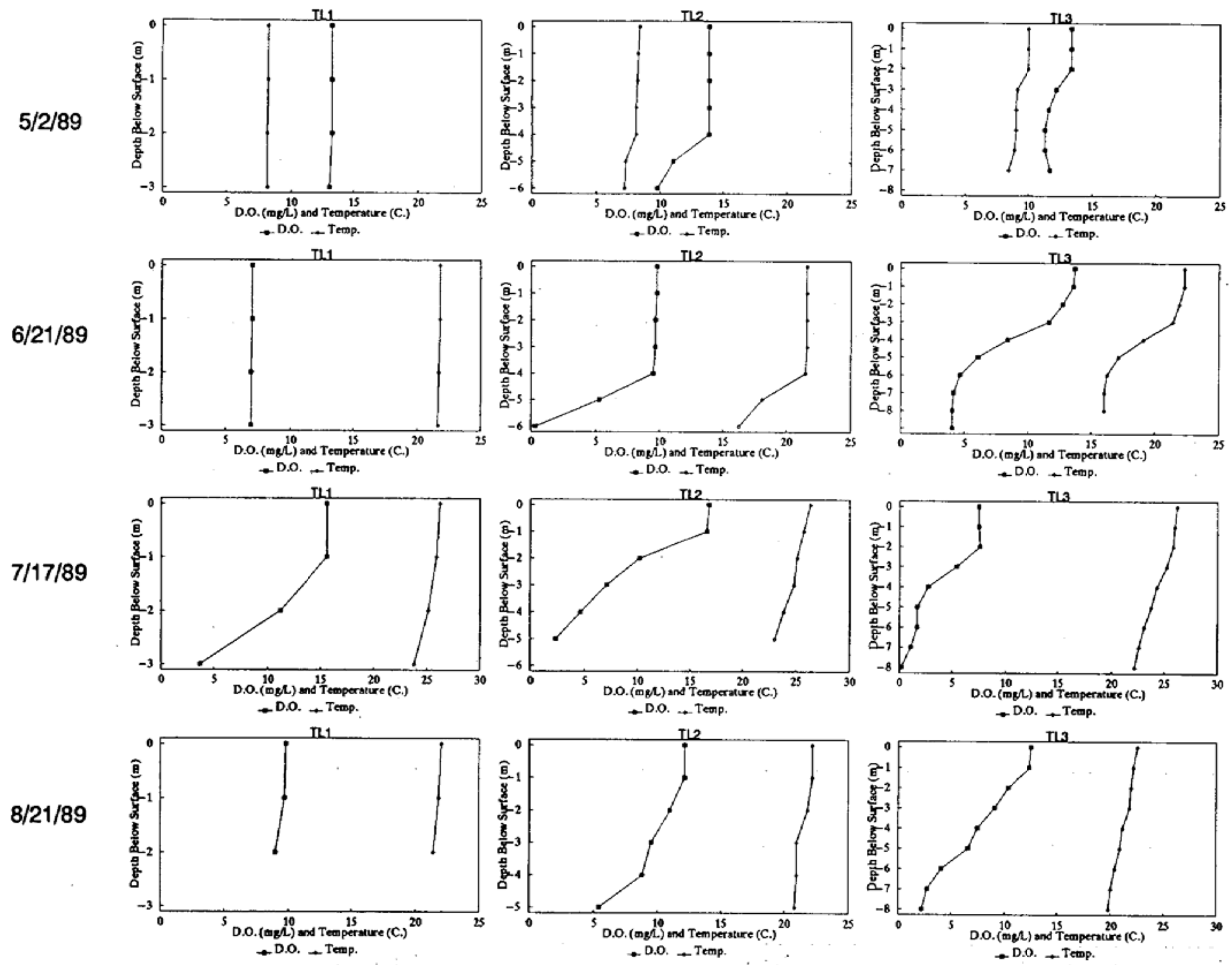


Figure 3. 1989 and 1990 growing season D.O./temperature profiles in Tainter Lake.

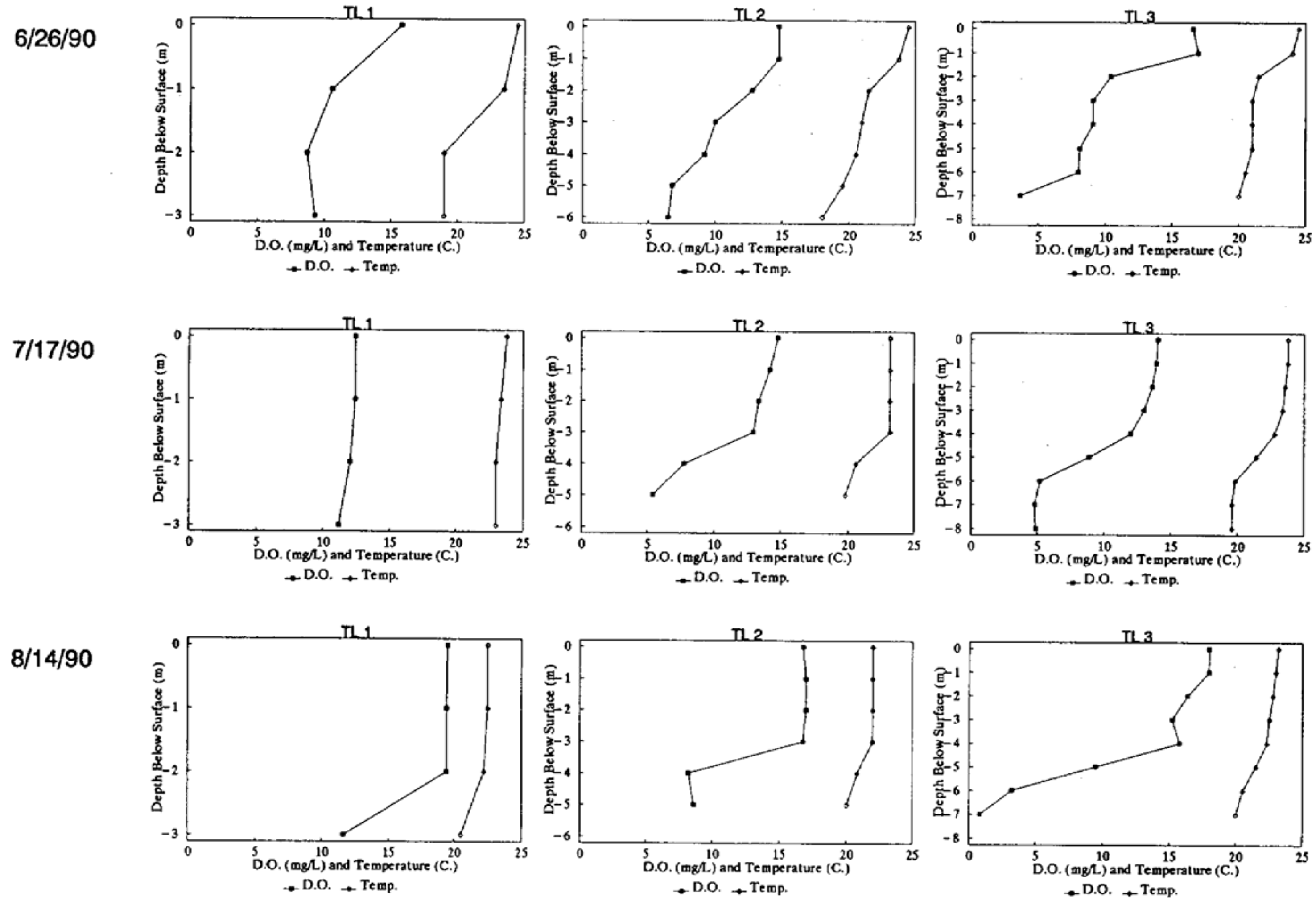


Figure 3 (cont.). 1989 and 1990 growing season D.O./temperature profiles in Tainter Lake.

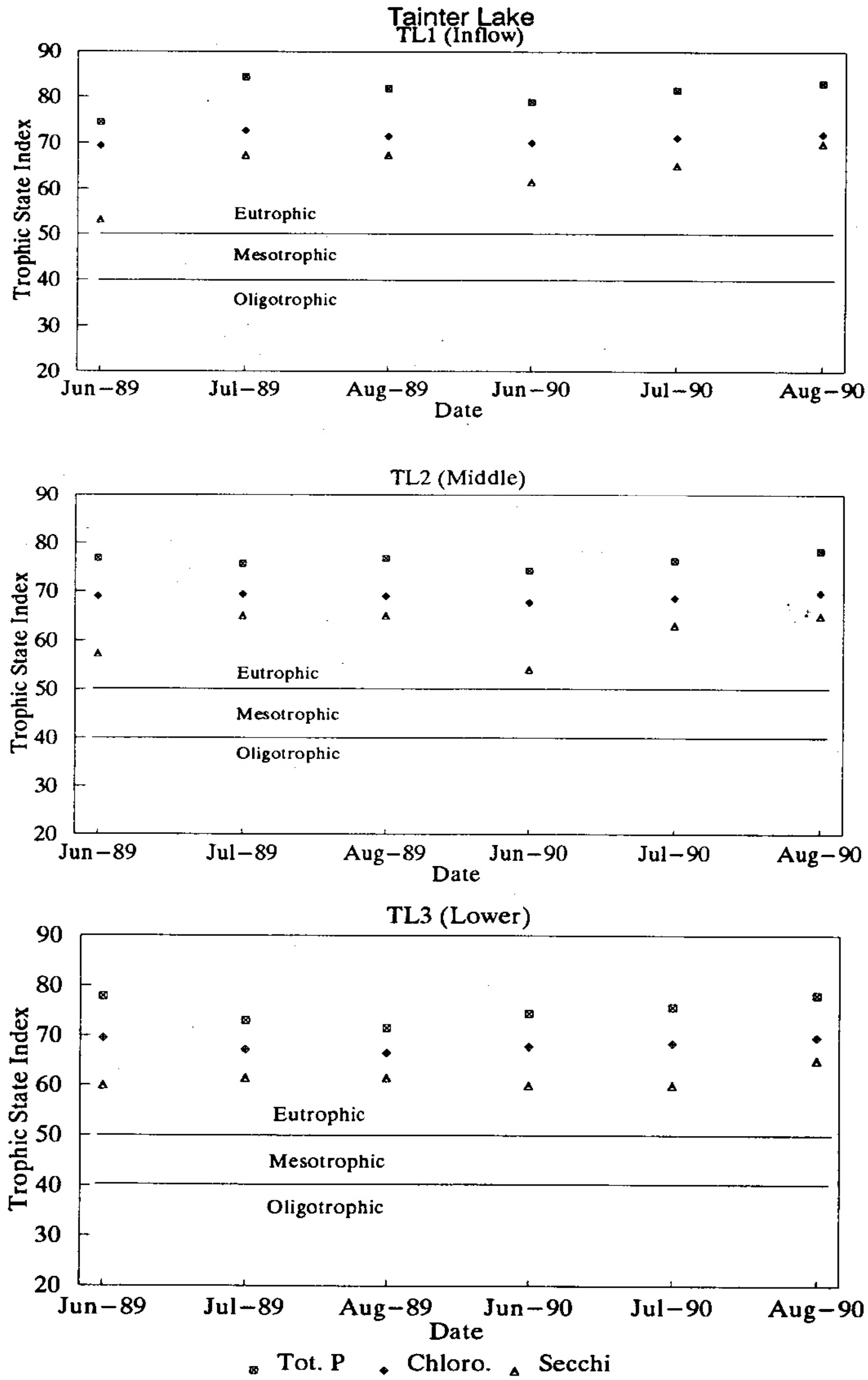


Figure 4. Carlson's Trophic State Index plots of Tainter Lake.

Stream flow

Daily discharge data for the Hay and Red Cedar stations were published in the 1990 USGS annual monitoring data publication (Holmstrom et al., 1990). Stream flow data from the USGS stations indicated the 1990 water year had near average stream flow. The annual mean stream flow in the Hay River during the 1990 water year at Wheeler was within 6% of the 40-year average of 309 cubic feet per second.

Phosphorus Loading Estimates

Annual Phosphorus Load

The total annual phosphorus (P) load to Tainter Lake during the October 1989-September 1990 monitoring period was estimated at 696,642 pounds (Appendix 2). The monitored watershed (above the USGS sites) represents about 89% of the annual P load to the lake. Phosphorus loading from groundwater and septic systems around Tainter Lake was not monitored, but was considered negligible. Greater than 50% of the annual P load entered the lake from the Red Cedar River watershed, which constitutes about 65% of the lake drainage area (Fig. 5). The Hay River watershed contributed 30% of the annual P load, from about 25% of the lake drainage area. Table 3 shows the annual mean and range of P concentrations and streamflow, and P loading at the USGS monitoring sites.

Streamflow and P loading measured at the USGS stations were highly variable during the monitoring period. Phosphorus loading was lowest during winter ice-cover and summer open-water, and highest during spring runoff. A single runoff event during March 11-17, 1990 produced 39% and 56% of the annual P load from the Red Cedar and Hay rivers, respectively. Maximum daily P loads reached 48,900 pounds in the Red Cedar River and 33,700 pounds in the Hay River during the event (Fig. 6). Although spring runoff events are a significant proportion of the annual P load, much of the phosphorus probably moves through the lake rapidly due to high flushing rates during these events, and some probably settles to the bottom and is generally unavailable to algae.

Point Source P Load

The annual P load from point sources was approximately 42,921 pounds, which is about 6% of the total annual load (Fig. 5 and Table 4). A greater proportion of the annual P load was from point sources in the Hay River watershed (12%) than in the Red Cedar River watershed (4%). The difference between the total P load and the point source load was assumed to approximate the nonpoint source load. A complete summary of point source loading to Tainter Lake is presented in Appendix 3.

1990 Seasonal P Load

Phosphorus loading during the growing season probably has a greater impact on water quality in Tainter Lake than loading that occurs during the remainder of the year. Much of the phosphorus entering the lake during spring high flow probably moves through rapidly without creating water quality problems due to "washout" of algae and nutrients (Dillon, 1975). However, phosphorus entering the lake during summer results in blue-green algae blooms and poor water clarity. The 1990 seasonal P load was 223,895 pounds, which was about 32% of the annual load to Tainter Lake (Appendix 4). The relative proportion of phosphorus from the Red Cedar River to Tainter Lake increased slightly during the

Table 3. Annual streamflow and phosphorus loading as measured at the Red Cedar and Hay River USGS monitoring sites.

Stream	Drainage Area (mi^2)	Total P Concentration (ug/L) Mean	Range	Annual Streamflow (cfs) Mean	Range	Annual Total P Load (pounds)	Unit Area P Load ($pounds/mi^2$)
Red Cedar River	1,101	271	70-2130	799	330-7440	408,404	370.9
Hay River	418	326	40-1820	326	130-4500	211,172	505.0
					Total:	619,576	

Table 4. Annual and seasonal point source P loading to Tainter Lake watershed.

Receiving Water	Point Source P concentrations (ug/L) Mean	Range	Point Source Total P Load (pounds) Annual	May-Sept.
Red Cedar River	4210	350-5090	16,798	7,063
Hay River	8860	900-43,600	26,123	11,562
		Totals:	42,921	18,625

growing season (Fig. 5). Phosphorus loading from point sources were fairly constant throughout May-September (except for non-continuous discharges), but streamflow and nonpoint source loading were quite variable. Figure 7 shows that several relatively small runoff events occurred between May and September, 1990.

An important factor in managing Tainter Lake is determining the proportion of the summer P load that is theoretically "controllable". A portion of the P load is due to existing background conditions (here referred to as "base load") and is generally uncontrollable, and the remainder, associated with point and nonpoint pollution sources, is potentially controllable. The base load was estimated using a representative summer "dry" period in which little or no precipitation occurred (August 7-16, 1990). Loading from controllable nonpoint sources was assumed to be minimal during this period. The base load was assumed as the difference between the point source load and the mean daily P load. The controllable nonpoint source (event) load was estimated as the difference between the daily P load and base load.

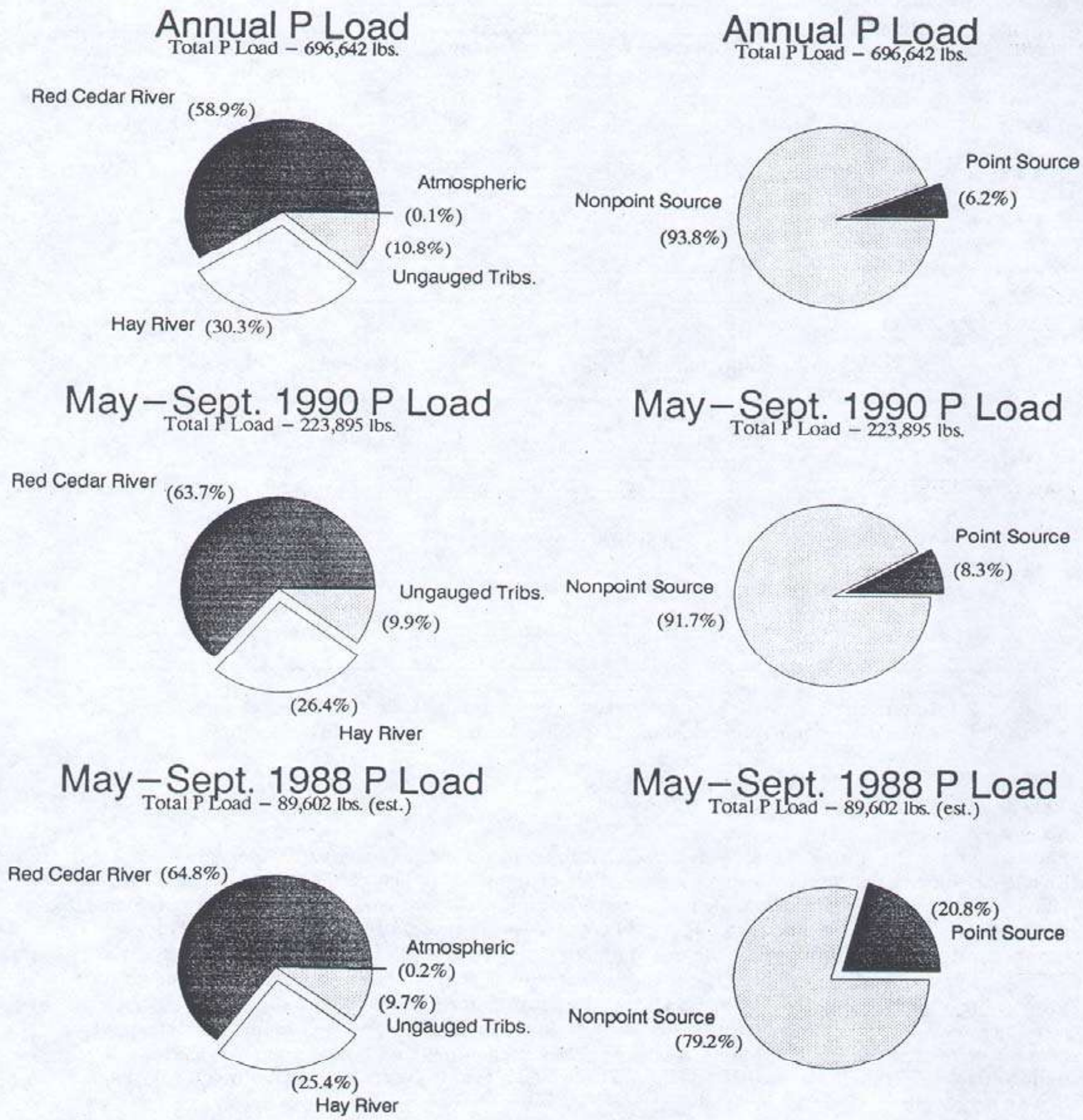
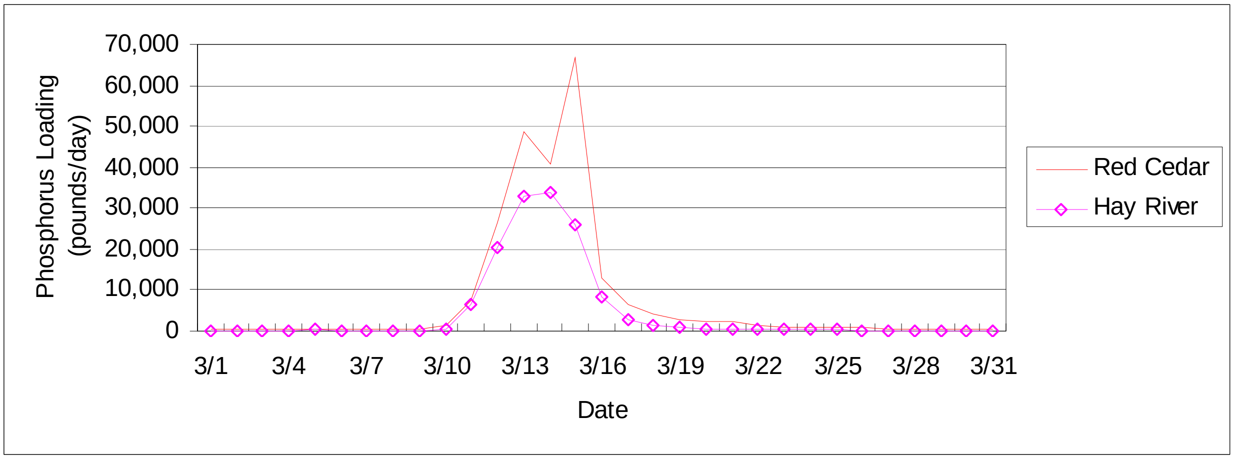


Figure 5. Annual and seasonal P loading to Tainter Lake showing proportion of load from various sources.

Figure 6. Phosphorus loading from March 11-17, 1990 runoff event in the Red Cedar and Hay rivers.



The combined Red Cedar and Hay River May-September P loads measured at the USGS stations were 201,217 pounds (Fig. 7). Approximately 84% of the summer P load is estimated as theoretically "controllable". About 9% of the controllable load is attributable to point sources, and the remaining 75% of the controllable load is assumed from nonpoint sources. It should be noted that a portion of the base load may include additional controllable sources such as milk house and septic wastes that may enter surface waters even during non-event periods.

Approximately 94% of the Hay River seasonal P load was estimated as controllable, with point sources contributing about 20%. A high level of P control in the Hay River watershed may not have a significant impact on the main body of Tainter Lake, but could have a greater impact in the Hay River inlet area above the CTH D bridge. The Hay River inlet area may respond somewhat independently of the main body of Tainter Lake due to the constriction and noticeable flow at the CTH D bridge. The inlet area is relatively shallow and probably has a shorter residence time than the main body of Tainter Lake. Although water quality data were not collected in the inlet area, severe summer algae blooms and poor water clarity have been noted. Additional data would be necessary to evaluate the impact of P load reductions in the Hay River watershed on this portion of Tainter Lake.

Low-flow Seasonal P Load

The 1988 low-flow seasonal P load was estimated from July 1988 mean streamflow data and May-September 1990 mean total P concentrations. The seasonal P load during a low-flow summer was estimated at 89,602 pounds, which is about 60% less than during a "normal" summer (Appendix 5). The relative proportion of phosphorus from point sources increased to 21% of the P load during the growing season (Fig. 5).

Water Quality Modeling

1990 Stream flow conditions

Figure 8 shows May-September 1990 observed (measured) and estimated values of water quality in Tainter Lake using the BATHTUB model. Segments 1, 2 and 3 in Figure 8 correspond to sites TL1, TL2 and TL3, respectively, and model calculated lake area mean values are represented by Segment 4. Observed values represent area-weighted, mixed layer (epilimnion) concentrations, and estimated values were predicted by the model. Statistical analysis was conducted on the input data set (observed) and the model development data set (estimated). The error bars in Figure 8 represent 95% confidence limits (2 standard errors) of the observed and estimated mean values for each segment. The lake area mean estimates generally have the least associated model error and represent the most reliable values. Table 5 is a summary of in-lake means and 95% confidence intervals for the area-weighted means represented by Segment 4 in Figure 8.

The observed and estimated means indicate water quality generally improves downstream along the longitudinal axis of the impoundment. The observed and estimated mean lake values generally agree, indicating the model is appropriate for Tainter Lake. The relative error in predicting chlorophyll-a and Secchi depth is generally greater than in predicting P levels because of error associated with the regressions used to estimate these parameters. The model predicts in-lake P concentrations, then estimates chlorophyll-a concentrations and Secchi depths using regression equations. According to Walker (1987), pool nutrient concentrations can be predicted relatively easily from inflow concentrations in reservoirs with high flushing rates (short residence times), but predictions of biological response (ie. chlorophyll-a) is more difficult because of temporal variability in nutrient levels and/or controlling effects of turbidity and flushing rate.

Low-flow Conditions

The analysis under low-flow conditions found decreased in-lake P concentrations, but increased chlorophyll-a concentrations and decreased Secchi depths (Fig. 9 and Table 5). The cause of apparently poorer water quality under low-flow conditions is related to an increase in lake residence time and is further discussed below. Not surprisingly, estimated mean phosphorus, chlorophyll-a and Secchi depth values were considerably different than the observed 1990 values.

Sensitivity Analysis

Sensitivity analysis of the BATHTUB model was conducted to determine the effect of incremental P load reductions on the water quality of Tainter Lake. The model was calibrated using May-September 1990 P loading data and in-lake water quality data. The impacts of P loading were simulated under 1990 conditions and 10% incremental reductions from the existing 1990 load. The analysis shows that overall water quality in Tainter Lake, as represented by chlorophyll-a concentration and Secchi depth, is relatively insensitive to changes in P loading (Fig. 10 and Appendix 6). A 50% reduction in the 1990 P load resulted in a 45% reduction in-lake mean P concentrations, a 10% reduction in chlorophyll-a concentrations and an 11% increase in Secchi depths. Water clarity (measured as Secchi depth) and chlorophyll-a concentrations did not appreciably improve until P loading was reduced by 70-80% of the 1990 levels. A 70% reduction in P loading resulted in a 65% reduction in-lake P concentrations, a 22% (19 ug/L) reduction in chlorophyll-a concentrations, and a 27% (0.22 meters or 0.72 feet) increase in mean Secchi depths.

The relative insensitivity of in-lake chlorophyll-a concentrations and Secchi depth values to reductions in P concentrations reflects the short hydraulic residence time and excessive P concentrations of Tainter Lake. The reduced P concentrations are still adequate to support high algal populations, resulting in reduced water clarity. Predicted model values only reflect overall lake and seasonal mean values and may not adequately reflect the severity, location and extent of algae blooms in specific locations around the lake. Slight reductions in lake mean values may actually indicate appreciable changes in the severity and length of algae blooms in these specific areas. The longevity and severity of algae blooms are functions of climatic as well as nutrient conditions.

Figure 10 shows that water quality generally improves along the axis of the impoundment, but the lower pool responds more slowly to reductions in P loading. Model results indicate that changes in lower pool (TL3) quality are somewhat buffered by the two upstream pools (TL1 and TL2). Monitoring data and model estimates indicate some of the inflowing P at the upstream pool is quickly taken up by algae, and some probably settles out with sediment in deeper areas and is not readily available for algal growth in the lower pools.

Low-flow Sensitivity Analysis

A sensitivity analysis of the BATHTUB model was run using estimated 1988 low-flow conditions to simulate the lake response to drought conditions. The model predicted that in-lake P concentrations would be considerably reduced under low-flow conditions, but chlorophyll-a levels and water clarity would actually worsen relative to the "normal" year described above (Fig. 11). The model predicts that at 100% of the estimated P load, lake area mean chlorophyll-a concentrations are approximately 52% higher during a dry summer. A 50% reduction in P loading only resulted in a 27% reduction in-lake P concentrations, an 11% decrease in chlorophyll-a concentrations and an 11% increase in Secchi depth. Model results suggest that although phosphorus concentrations are lower, lake water quality (as measured by chlorophyll-a concentration and Secchi depth) is poorer under low-flow conditions. Lake hydraulic residence times during low-flow conditions increase significantly, allowing more time for algal bloom development. Consequently, chlorophyll-a concentrations increase and Secchi depths decrease. Summer mean hydraulic residence times increased from 7.3 days in 1990, to 20.3 days in 1988. Water quality benefits of reductions in P loading appear to be offset by such an increase in hydraulic residence times. A reduction in P loading combined with a reduction in hydraulic residence time would be necessary to significantly improve in-lake water quality.

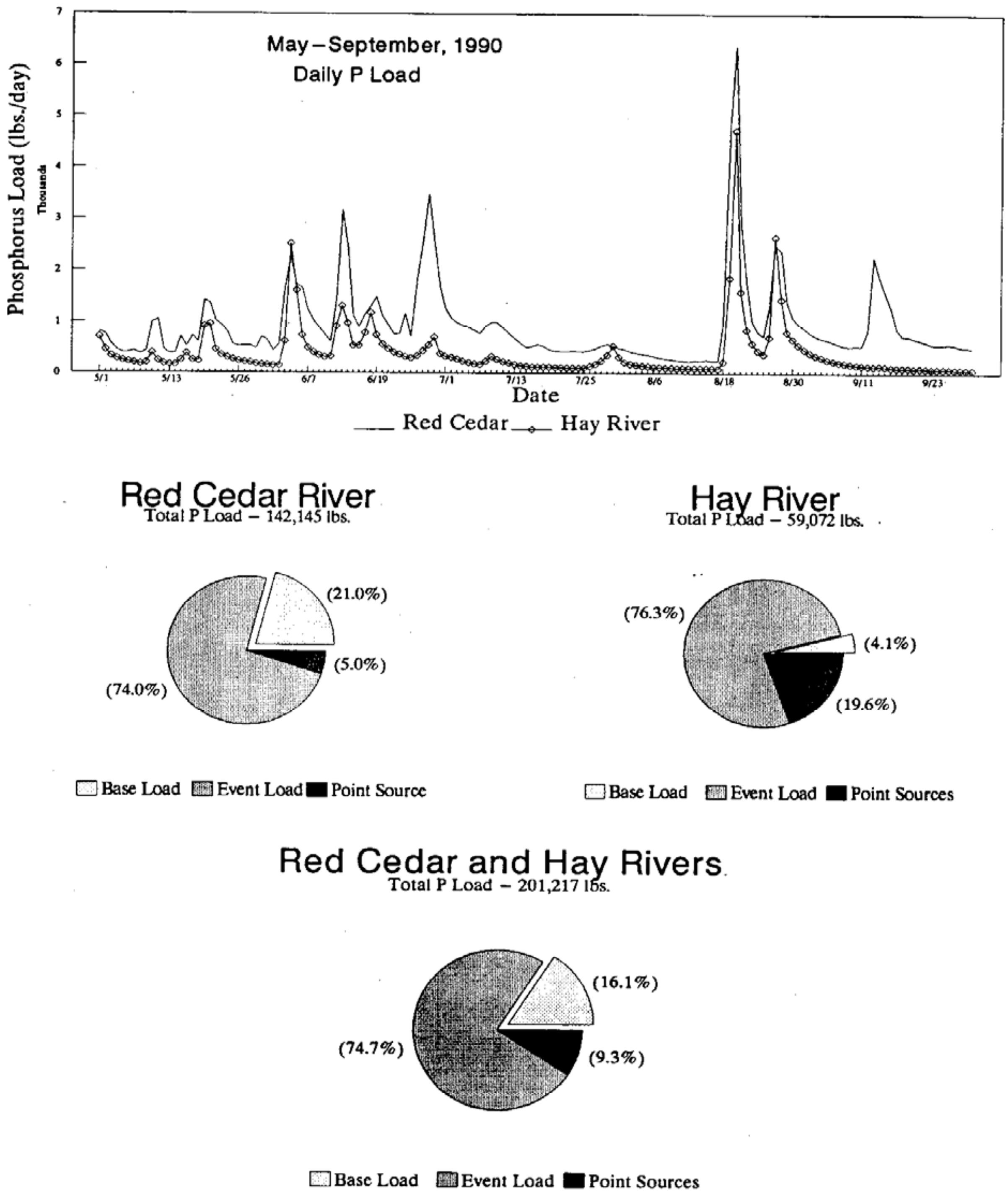


Figure 7. May−September, 1990 daily P load measured at USGS stations on Red Cedar and Hay rivers.

Table 5. In-lake means and 95% confidence intervals ($CI_{0.95}$) for BATHTUB model results under 1990 flow and estimated 1988 low-flow conditions.

		Area-weighted Mean	$CI_{0.95}$
Total Phosphorus (ug/L)			
	Observed	150.5	135-168
	Estimated (1990)	150.5	139-163
	Estimated (Low-flow)	133.9	118-151
Chlorophyll-a (ug/L)			
	Observed	86.6	73-102
	Estimated (1990)	87.2	58-131
	Estimated (Low-flow)	142.5	103-197
Secchi Depth (m)			
	Observed	0.8	0.7-0.9
	Estimated (1990)	0.8	0.6-1.1
	Estimated (Low-flow)	0.5	0.4-0.7

Figure 8. Observed and estimated confidence limits for BATHTUB modelling of Tainter Lake under "normal" flow conditions. Lines represent 95% confidence limits (2 std. errors) for observed and estimated mean values for each segment (pool). Segment 4 represents area-weighted mean value for entire lake.

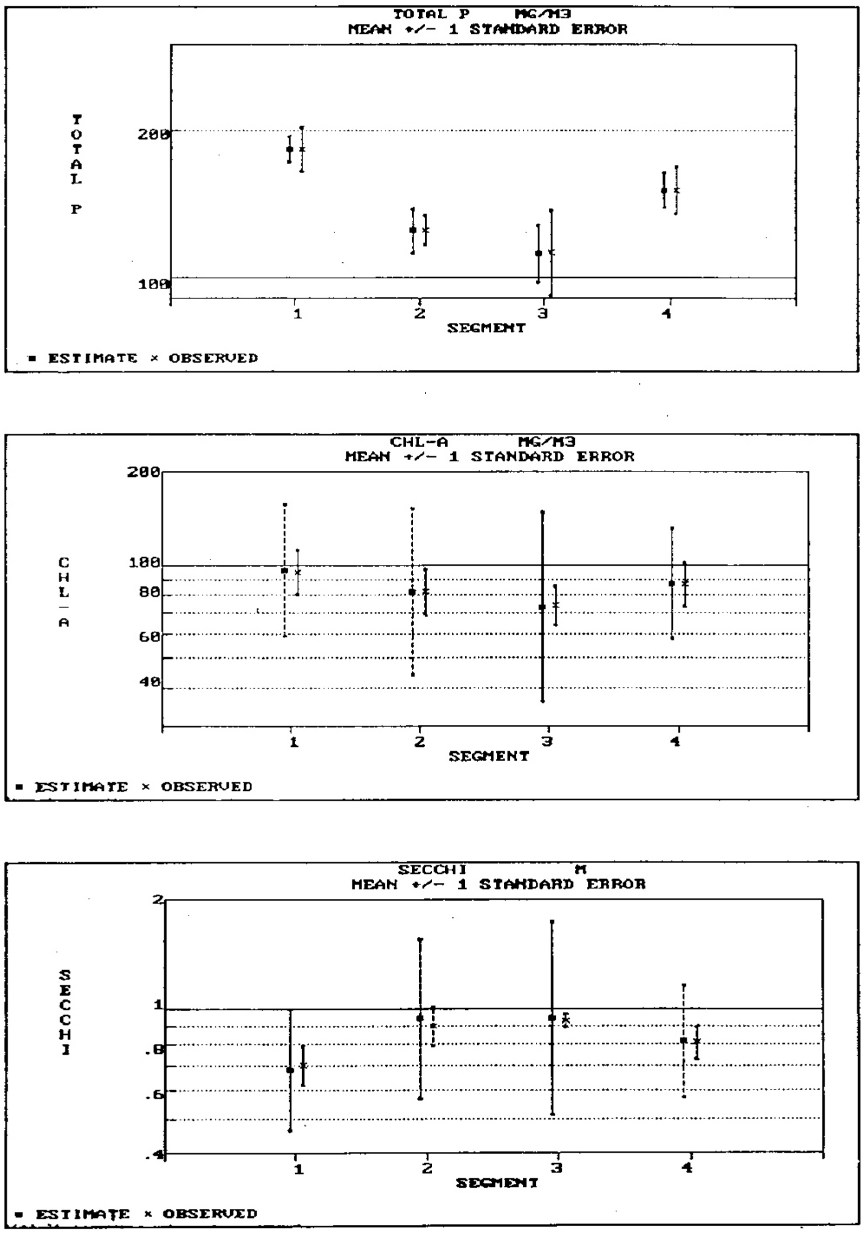
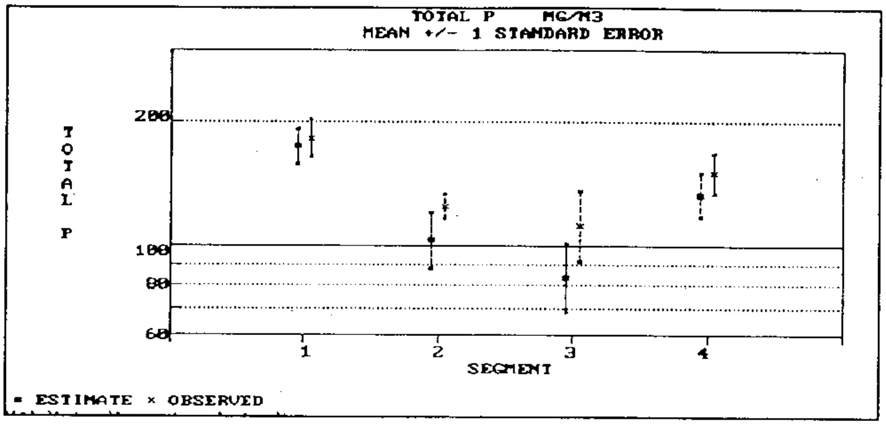
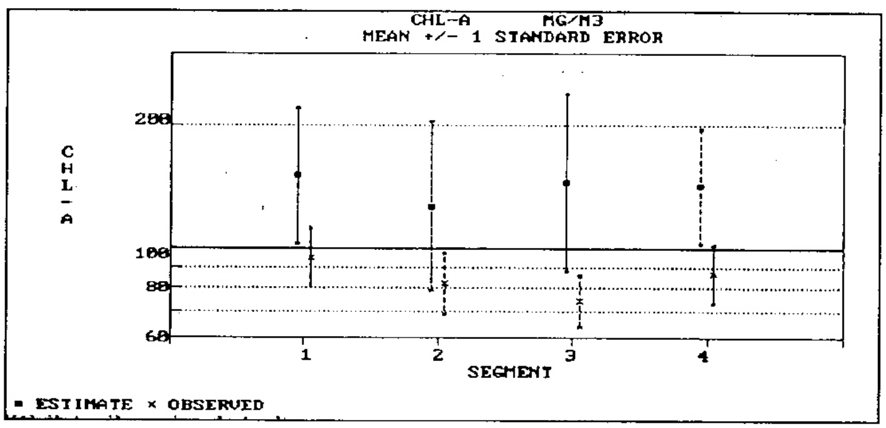
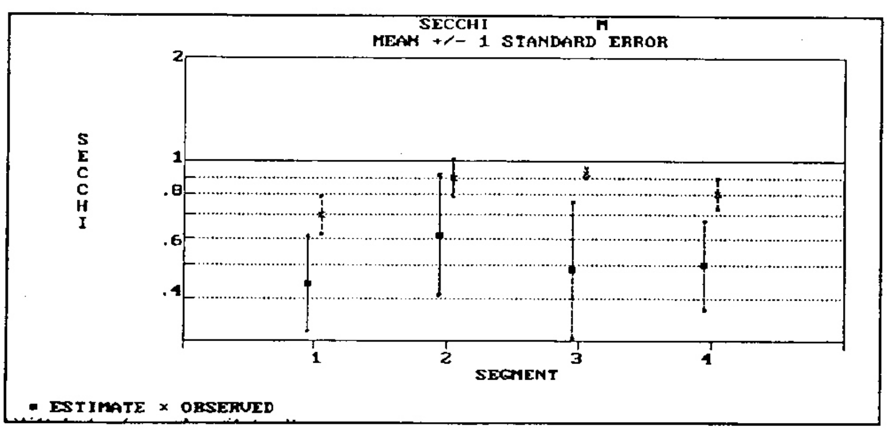


Figure 9. Observed and estimated confidence limits for BATHTUB modelling of Tainter Lake under estimated low-flow conditions. Lines represent 95% confidence limits (2 std. errors) for observed and estimated mean values for each segment (pool). Segment 4 represents area-weighted mean value for entire lake.







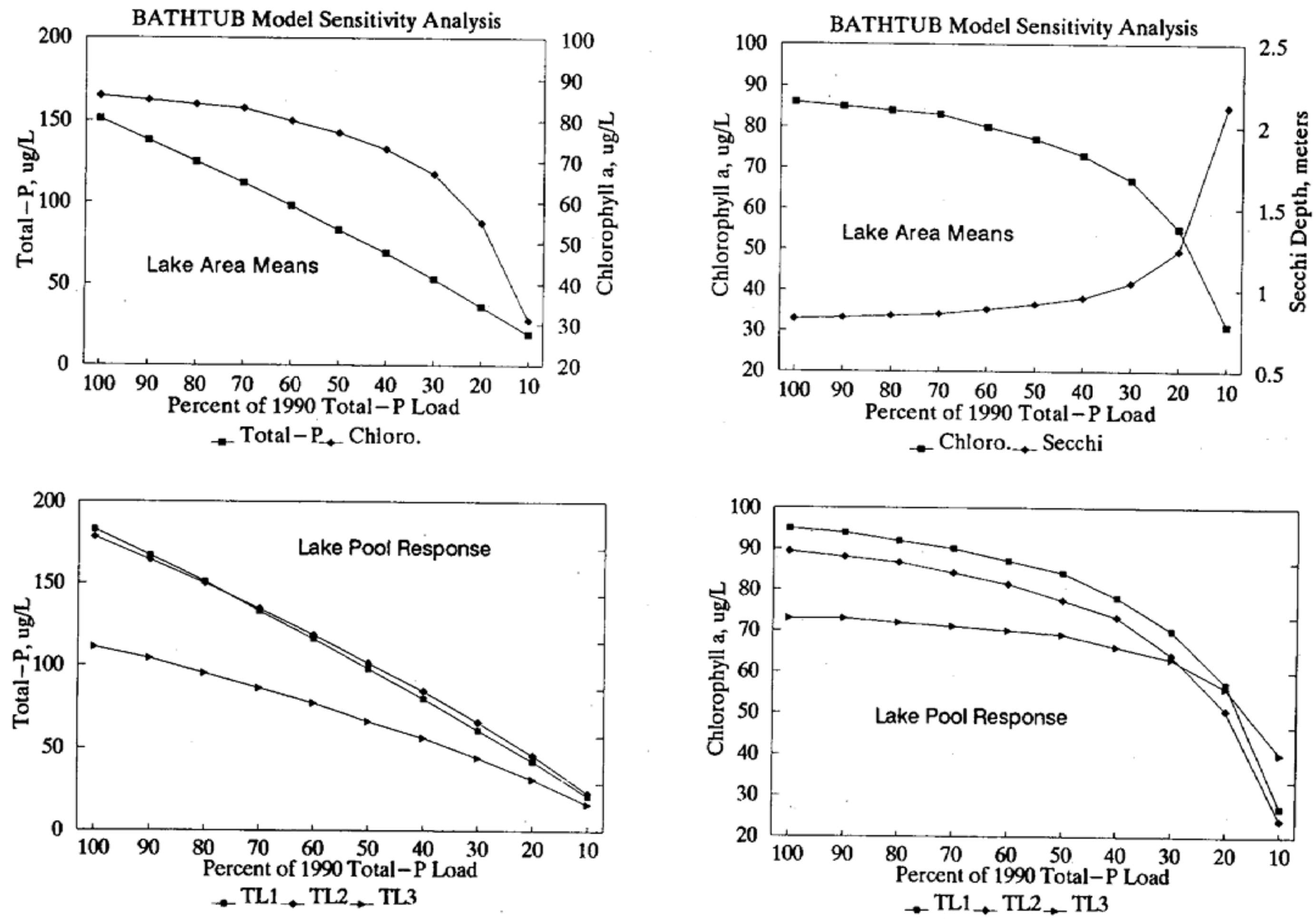
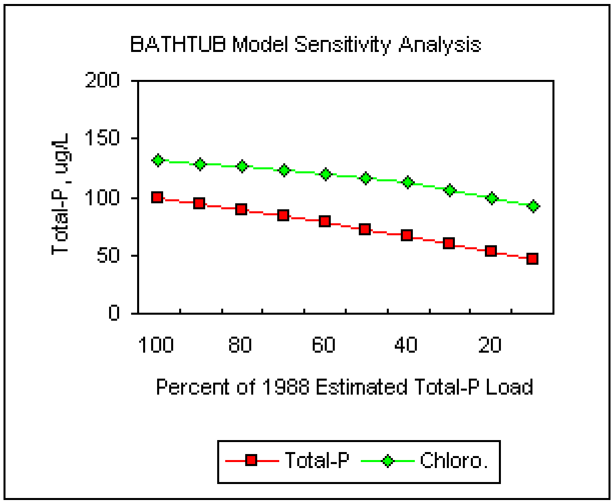


Figure 10. Tainter Lake model sensitivity analysis under May-Sept., 1990 flow conditions.



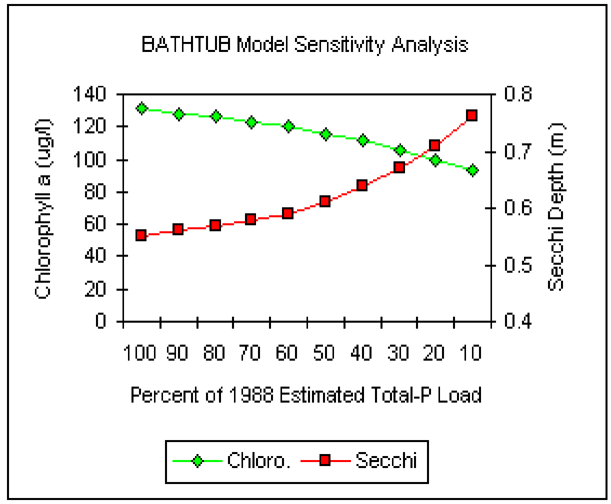


Figure 11. Tainter Lake model sensitivity analysis under estimated 1988 low-flow conditions.

Management Scenarios

Several P load reduction scenarios were simulated with the BATHTUB model to assess the lake water quality response under various point source discharge control levels. Each P load scenario was evaluated under measured 1990 streamflow and estimated 1988 low-flow conditions.

The following P loading scenarios were simulated with the BATHTUB model:

Case 1 - Represents the existing situation in 1990.

Case 2 - Assumes implementation of a 1.0 mg/L P limit on all point source discharges with design flows >0.250 MGD. (Proposed NR 217 standards would apply to all wastewater treatment plants (WWTPs) with a design flow >0.250 MGD). Affected WWTP effluent concentrations would be reduced from a mean P concentration of 7.8 mg/L to 1.0 mg/L under this scenario.

Case 3 - Applies existing 1990 point source P concentrations to design WWTP flows (worst case scenario).

Case 4 - Assumes WWTP design flows and 1.0 mg/L P limit for all point source dischargers with design flows >0.250 MGD (worst case scenario - post NR 217).

Scenarios 2, 3 and 4 include a proposed WWTP discharge at Boyceville (design flow >0.250 MGD).

The management scenarios indicate that point source phosphorus control in the watershed would have little appreciable effect on the quality of Tainter Lake under "normal" or low-flow conditions (Fig. 12). The most significant increase (+14%) occurred in lake area mean P concentrations using design WWTP flows and 1990 P concentrations during low-flow conditions (Fig. 13). The most significant decrease (-12%) occurred in lake area mean P concentrations using design WWTP flows with a 1.0 mg/L P limit, again during low-flow conditions. In-lake chlorophyll-a levels changed only 2-3% and Secchi depths changed less than one percent under the various modeling scenarios.

Conclusions

Tainter Lake is highly eutrophic and receives excessive phosphorus from its relatively large agricultural watershed. The P load to Tainter Lake during the 1990 water year was estimated at 696,642 pounds. A significant portion of the annual P load occurred during a single spring runoff event that probably had little impact on summer lake water quality. Approximately 6% of the annual P load was attributable to point source discharges, with most of the remainder likely from agricultural nonpoint sources in the watershed. Modeling determined overall lake water quality to be relatively insensitive to P load reductions. A model sensitivity analysis predicted that a 70-80% P load reduction would be required to achieve noticeable improvements in lake water quality. The model also predicted that water quality in Tainter Lake is poorer during dry years primarily due to increased hydraulic residence times.

Simulating various phosphorus load reduction scenarios suggested that implementation of a 1.0 mg/L P limit on significant point source discharges in the watershed alone would have a minimal impact on water quality in Tainter Lake. However, a significant reduction in point source loading combined with the implementation of extensive nonpoint source controls could improve water quality in Tainter Lake. For example, with an overall 65-70% reduction of the total P load through nonpoint source controls, an additional 10% reduction in the total load through point source controls could achieve a noticeable improvement in Tainter Lake.

Recommendations

Based on findings of this study, the following actions are recommended:

1. A comprehensive watershed management plan should be developed to determine the feasibility and means of reducing the P load sufficiently to measurably improve water quality in Tainter Lake. Specifically, it would be critical to determine whether adequate nonpoint source control can be achieved considering the agricultural nature of the watershed. Significant improvements in lake water quality are not likely until at least 70-80% of the annual P load is controlled.

2. Long-term phosphorus monitoring stations should be established to measure P-loading and year-to-year water quality variability in large (>1000 square miles) river systems. The current study only monitored water quality for a single water year and lacked data for unusually wet or dry years. Currently, there are no large-river USGS monitoring sites operating in Wisconsin that can provide phosphorus loading information. The Red Cedar and Hay River sites used in this study would be suitable for northwestern Wisconsin.

3. The BATHTUB model should be verified and re-run on Tainter Lake if future monitoring data become available.

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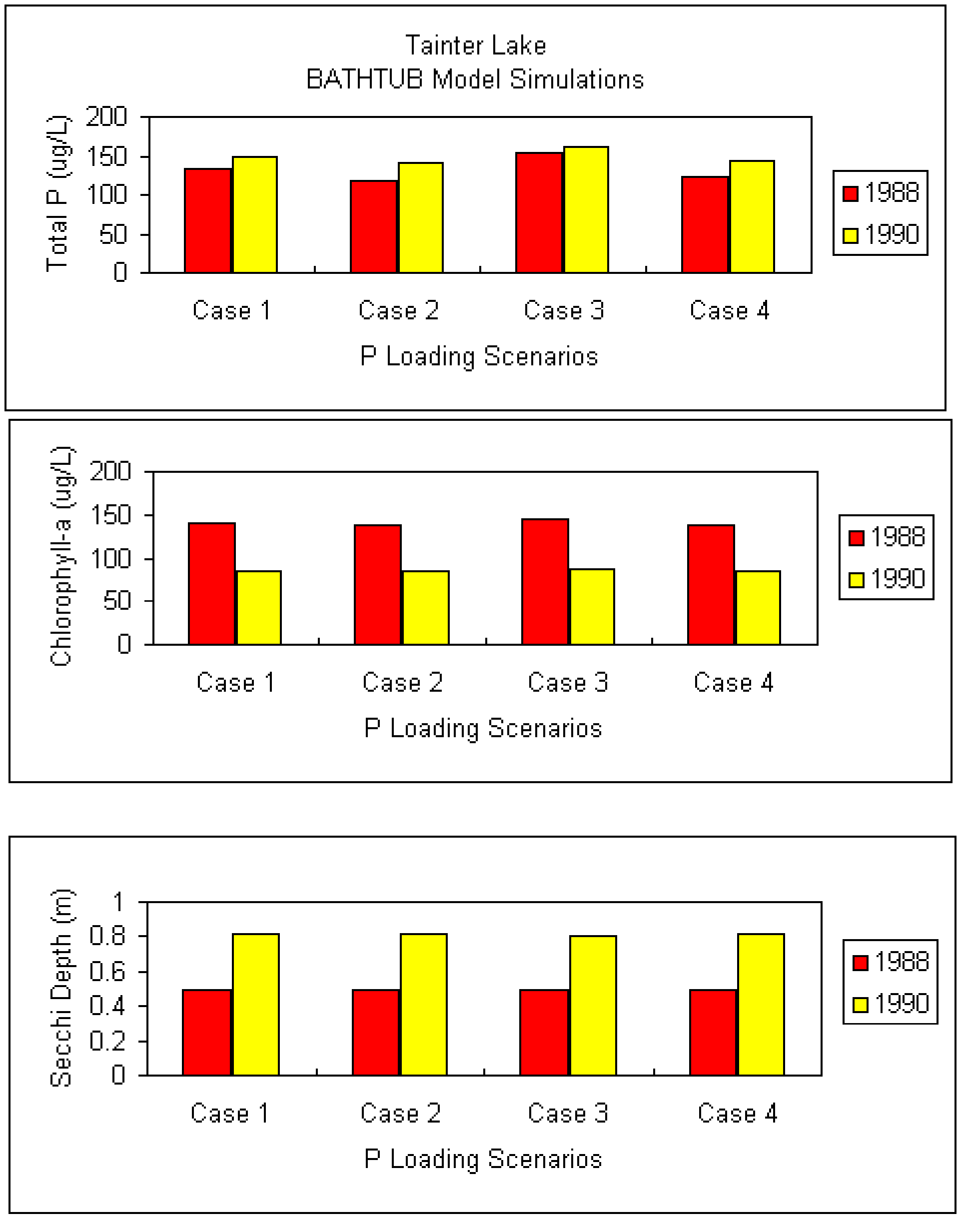

Loading Scenarios:

Case 1 - Existing 1990 streamflow and P load conditions.
Case 2 - Existing 1990 WWTP flows and 1.0 mg/L P limit.
Case 3 - Full design WWTP flows at 1990 P concentrations.
Case 4 - Full design WWTP flows and 1.0 mg/L P limit.

Figure 12. BATHTUB Model simulations of Tainter Lake showing changes in lake area mean phosphorus, chlorophyll-a and Secchi depth values under various P loading scenarios.

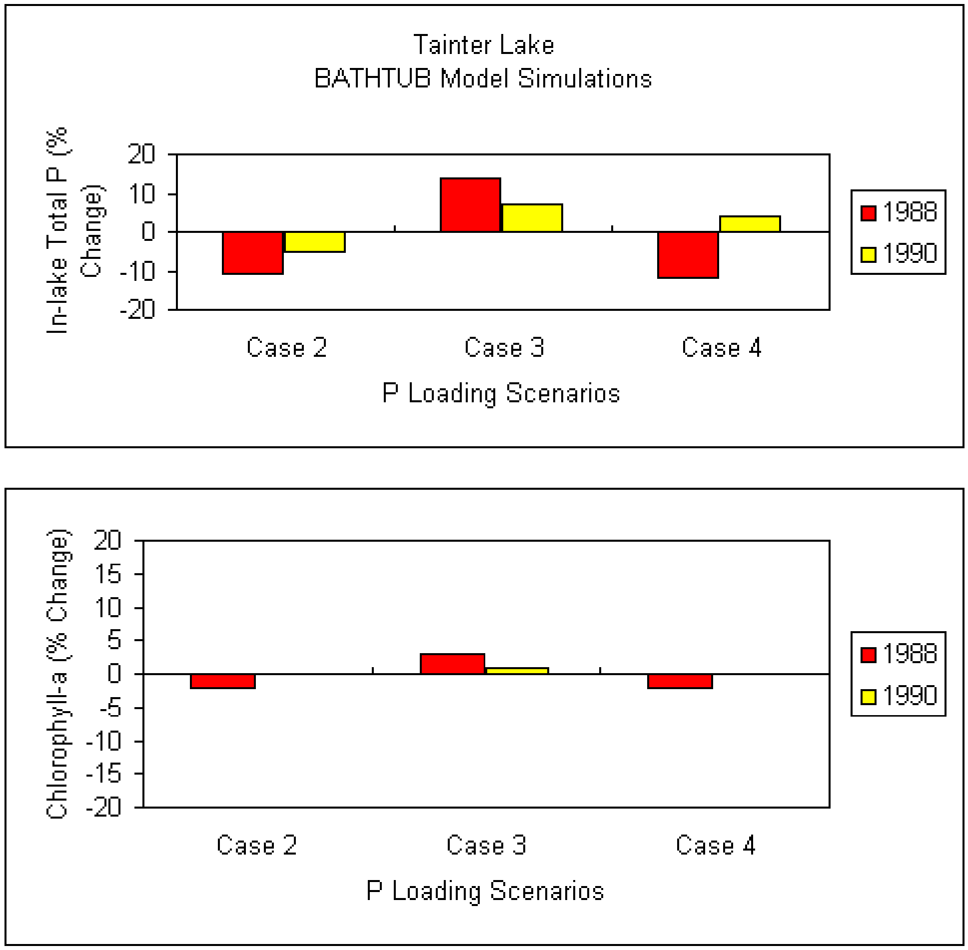

Figure 13. Comparison of various loading scenarios with 1990 existing conditions showing percent change of lake area mean values.

Appendix 1. Trend monitoring protocol for Wisconsin lakes.

Parameter	Approximate date of sample collection: Spring Turnover	Mid June	Mid July	Mid August	Late Winter	Remarks
Complete Water Chemistry	X					Two depths: .5 meter from the water surface 1 meter above the lake bottom. Parameters: Cl, Diss.P, Ca, Mg, Na, K, pH, SO4, total alkalinity, Fe, Mn, color, turbidity, volatile and suspended solids.
Total Phosphorus Nitrogen series: (TKN-N, NH_3N, NO_2-N + NO_3-N), pH	X**	X***	X***	X***	X**	** = 2 depths: 1 foot below water surface and 2 feet above lake bottom. *** = third additional depth at the top of the hypolimnion, if lake is stratified.
Water Temperature, Dissolved Oxygen	X	X	X	X	X	Profile - 1 foot below water surface and proceed to lake bottom using 1 meter intervals.
Chlorophyll a (uncorrected)	X	X	X	X	X	One depth - Composite sample from 0-2 meters.
Secchi disk depth	X	X	X	X		Monthly

Appendix 2. Tainter Lake - 1990 Water Year Total P Load

Source	Drainage Area (km2)	Annual P load lbs P/year	Unit Area Load lbs P/km2/year
Red Cedar River	2852	410127	143
Hay River	1083	211172	195
Ungauged Tribs.*			
Otter Creek	91.1	17919	195
Sinking/18 Mile Cr.	108	15444	143
Lambs Creek	46.9	9145	195
Direct Runoff	155	30223	195
	15.5	2216	143
Total (Ungauged):	416.5	74947	
Atmospheric**	5.9	396	66.7
Grand Total:	4357.4	696642	

* Estimated P load using unit area loading values for respective monitored watersheds.

** Estimated atmospheric P load = 0.3 Kg/ha/year (Walker, 1988)

Appendix 3. Phosphorus loading from point sources to Tainter Lake watershed.

(OCTOBER 1, 1989 - SEPT. 30, 1990)

RED CEDAR RIVER:

WWTP	n**	MEAN TOTAL P (MG/L)	AVE. DAILY FLOW MGD (MAY-SEPT.)	TOTAL P LOADING (LBS./YEAR)
COLFAX WWTP	7	5.05	0.056	1722.80
RICE LAKE WWTP	22	3.50	1.127	11384.04
JEROME FOODS, INC.*	2	5.06	0.332	1693.97
CHETEK WWTP	20	3.26	0.285	1997.45
			TOTAL:	16798.26

HAY RIVER:

WWTP	n**	MEAN TOTAL P (MG/L)	AVE. DAILY FLOW MGD (MAY-SEPT.)	TOTAL P LOADING (LBS./YEAR)
GLENWOOD CITY WWTP	20	1.74	0.186	951.55
RIDGELAND WWTP*	2	1.49	0.355	123.52
PRAIRIE FARM	19	2.84	0.105	194.18
CUMBERLAND WWTP	21	14.91	0.279	12591.49
TWIN TOWN CHEESE	4	1.89	0.118	176.20
ALMENA WWTP*	9	4.32	0.175	992.12
TURTLE LAKE WWTP	16	10.81	0.304	8952.97
CRYSTAL LAKE*	2	32.90	0.062	2141.04
			TOTAL:	26123.07
			GRAND TOTAL:	49921.33

* SEASONAL DISCHARGE
** n = NUMBER OF SAMPLES COLLECTED

Appendix 3. (cont.)

1990 FLOWS AND P CONCENTRATIONS
MONTHLY TOTAL P LOAD (LBS.)

RED CEDAR RIVER:	MAY	JUNE	AUG.	SEPT.	TOTAL P (LBS.)
COLFAX WWTP	14.9	84.6	101.9	97.6	299
RICE LAKE WWTP	900.4	1008.8	1037	1064	4010.2
JEROME FOODS, INC.*	0	325.4	0	0	325.4
CHETEK WWTP	230.9	272.4	233.3	200	936.6
TOTALS:	1146.2	1691.2	1372.2	1361.6	5571.2

1990 FLOWS AND P CONCENTRATIONS
MONTHLY TOTAL P LOAD (LBS.)

HAY RIVER:	MAY	JUNE	AUG.	SEPT.	TOTAL P (LBS.)
GLENWOOD CITY WWTP	45.7	45.1	46.9	43	180.7
RIDGELAND WWTP*	61.8	0	0	0	61.8
PRAIRIE FARM	14.6	14.3	20	17.3	66.2
CUMBERLAND WWTP	1210.4	1096.8	1040.8	835.6	4183.6
TWIN TOWN CHEESE	18.3	18.3	11.8	9.6	58
ALMENA WWTP*	220	0	0	190.2	410.2
TURTLE LAKE WWTP	849.6	1095.4	760.2	595	3300.2
CRYSTAL LAKE*	508.4	0	0	534	1042.4
TOTALS:	2928.8	2269.9	1879.7	2224.7	9303.1

* SEASONAL DISCHARGE

Appendix 3. (cont.)

DESIGN FLOWS AND EXISTING P CONCENTRATIONS

MONTHLY TOTAL P LOAD (LBS.)

RED CEDAR RIVER:	MAY	JUNE	AUG.	SEPT.
COLFAX WWTP	133.4	129.1	133.4	129.1
RICE LAKE WWTP	2796.1	2705.9	2796.1	2705.9
CHETEK WWTP	324.5	314	324.5	314
JEROME FOODS, INC.*	798	772.3	798	772.3
TOTALS:	4052	3921.3	4052	3921.3

DESIGN FLOWS AND EXISTING P CONCENTRATIONS

MONTHLY TOTAL P LOADS (LBS.)

HAY RIVER:	MAY	JUNE	AUG.	SEPT.
GLENWOOD CITY WWTP	117.9	114.1	117.9	114.1
PRAIRIE FARM	36.7	35.5	36.7	35.5
CUMBERLAND WWTP	1541.9	1492.2	1541.9	1492.2
RIDGELAND WWTP*	61.8	0	0	0
TWIN TOWN CHEESE	57.7	55.8	57.7	55.8
ALMENA WWTP*	159.7	0	0	154.6
TURTLE LAKE WWTP	1182.2	1144	1182.2	1144
CRYSTAL LAKE*	272.2	0	0	263.4
BOYCEVILLE**	414.2	400.8	414.2	400.8
TOTALS:	3844.3	3242.4	3350.6	3660.4

* SEASONAL DISCHARGE

** ASSUMED CONCENTRATION (5 MG/L TOT.P)

Appendix 4. Tainter Lake - Seasonal P Load (May-Sept. 1990)

Source	Drainage Area (km2)	P load (May-Sept.) lbs P/ period	Unit Area Load lbs P/km2/period
Red Cedar River	2852	142506	49.97
Hay River	1083	59072	54.54
Ungauged Tribs.*			
Otter Creek	91.1	4969	54.54
Sinking/18 Mile Cr.	108	5397	49.97
Lambs Creek	46.9	2558	54.54
Direct Runoff	155	8454	54.54
	15.5	774	49.97
Total (Ungauged):	416.5	22152	
Atmospheric**	5.9	165	
Grand Total:	4357.4	223895	

* Estimated P load using unit area loading values for respective monitored watersheds.

** Estimated atmospheric P load = 0.3 Kg/ha/year (Walker, 1988)

Appendix 5. Tainter Lake - Seasonal P load (Est. May-Sept. 1988)

Source	Drainage Area (km2)	P load (May-Sept.) lbs P/ period	Unit Area Load lbs P/km2/period
Red Cedar River*	2852	58039	22.35
Hay River**	1083	22734	20.99
Ungauged Tribs.***			
Otter Creek	91.1	1929	20.99
Sinking/18 Mile Cr.	108	2198	20.35
Lambs Creek	46.9	984	20.99
Direct Runoff	155	3254	20.99
	15.5	315	20.35
Total (Ungauged):	416.5	8680	
Atmospheric****	5.9	165	
Grand Total:	4357.4	89618	

* Estimated P load using mean July 1988 unit area flow data from Menomonie USGS site and May-Sept. 1990 mean P concentration data from Colfax site.

** Estimated P load using mean July 1988 flow data from Wheeler USGS site, and May-Sept. 1990 mean P concentration data from Wheeler site.

*** Estimated P load using unit area loading values for respective monitored watersheds.

**** Estimated atmospheric P load = 0.3 Kg/ha/year (Walker, 1988)

Appendix 6. Results of Tainter Lake **BATHTUB** Model Sensitivity Analysis

Existing 1990 P Load, Average Total-P Inflow Concentration - 188 ug/L

	Inflow Pool Obs./Model	Middle Pool Obs./Model	Lower Pool Obs./Model	Area Mean Obs./Model
In-lake:				
Total-P, ug/L	183/183	125/125	112/111	151/150
Chlorophyll, ug/L	95/95	82/82	74/73	87/86
Secchi, meters	.88/.92	.90/.94	.93/.94	.81/.82

90% of 1990 Load, Average Inflow Concentration - 169 ug/L

	Inflow Pool	Middle Pool	Lower Pool	Area Mean
Total-P, ug/L	167	115	104	138
Chloro., ug/L	94	81	73	85
Secchi, meters	.70	.95	.95	.83

80% of 1990 Load, Average Inflow Concentration - 150 ug/L

Total-P	151	105	95	125
Chloro.	92	80	72	84
Secchi	.71	.96	.96	.84

70% of 1990 Load, Average Inflow Concentration - 131 ug/L

Total-P	133	94	86	112
Chloro.	90	78	71	83
Secchi	.73	.98	.97	.85

60% of 1990 Load, Average Inflow Concentration - 112 ug/L

Total-P	116	83	77	98
Chloro.	87	76	70	80
Secchi	.75	1.01	.98	.88

50% of 1990 Load, Average Inflow Concentration - 94 ug/L

Total-P	98	71	66	83
Chloro.	84	73	69	77
Secchi	.78	1.04	1.00	.91

40% of 1990 Load, Average Inflow Concentration - 75 ug/L

Total-P	80	59	56	69
Chloro.	78	70	66	73
Secchi	.83	1.10	1.03	.95

30% of 1990 Load, Average Inflow Concentration - 56 ug/L

Total-P	61	46	44	53
Chloro.	70	63	63	67
Secchi	.92	1.20	1.09	1.04

Appendix 6. (cont.)

	Inflow Pool	Middle Pool	Lower Pool	Area Mean
20% of 1990 Load, Average Inflow Concentration = 38 ug/L				
Total-P	42	32	31	36
Chloro.	57	53	56	55
Secchi	1.13	1.43	1.22	1.24
10% of 1990 Load, Average Inflow Concentration = 19 ug/L				
Total-P	21	16	16	19
Chloro.	27	33	40	31
Secchi	2.25	2.23	1.67	2.12