Three Lakes Association

DEVELOPMENT OF A PREDICTIVE NUTRIENT-BASED WATER QUALITY MODEL FOR TORCH LAKE

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EXECUTIVE SUMMARY

Great Lakes Environmental Center (GLEC) and Three Lakes Association (TLA) have cooperated in the development of a predictive nutrient-based water quality model for Torch Lake, located in Michigan's Antrim and Kalkaska Counties. This project was funded by a water quality monitoring grant from the Michigan Department of Environmental Quality (MDEQ). The primary goals of this project included (1) the collection of data necessary to develop a mathematical model of water quality in Torch Lake, (2) calibration and confirmation of this model, and (3) application of the model to address water quality concerns and forecast future changes in water quality due to increased nutrient loadings associated with changing land uses and development. Results from the proposed project will provide the Three Lakes Association with an objective tool for relating changes in nutrient loadings to expected short- and long-term changes in water quality in Torch Lake. The results of this project address the following questions:

$ What is the current (baseline) water quality in Torch Lake, and how does it vary with season and location in the lake?

$ What are the current loadings of phosphorus (the nutrient limiting algal growth) to Torch Lake from all sources, including non-point sources (including the atmosphere and groundwater), tributaries, and in-place (sediment) sources?

$ How will water quality in Torch Lake be affected by changes in nutrient loadings?

The water quality model for Torch Lake is intended to support the decision-making process related to maintaining and preserving water quality in Torch Lake. We expect that these results will be used by local units of government, lake associations, property owners, developers and the general public interested in more effective management of water quality resources.

Field data collection was an important aspect of this project. Water quality sampling was conducted from July of 2004 through October of 2005. During that time, TLA sampled lake water, tributaries, precipitation, groundwater and lake sediment. More than 200 samples were analyzed by GLEC for total phosphorus concentrations, and a significant number of these samples were analyzed for other water quality parameters as well. The resulting data confirm the pristine nature of water quality in Torch Lake. The volume-weighted average (i.e., lake-wide) total phosphorus concentration in 2005 was determined to be 2.6 parts per billion (ppb), which is consistent with measurements made in the previous four years. Phytoplankton chlorophyll concentrations were also very low, ranging from 0.5 to 0.7 ppb. Dissolved oxygen (DO) concentrations were high throughout the year; DO concentrations exceeded 11 parts per million (ppm) in the deep hypolimnion throughout the critical winter period. Water transparency was also excellent, with Secchi disk depths ranging from 10 meters in early July to 5 meters in August. This summer decline in water transparency is observed in Torch Lake every year, and appears to be the result of calcium carbonate precipitation, a naturally-occurring phenomenon in many lakes. Comparisons to recent monitoring data show little change in water quality over the past 5 - 10 years.

The field data were used to construct a hydrologic (water) budget for Torch Lake. Components of the hydrologic budget for 2005 are shown in Table 1. Since the water level of the lake remains essentially constant, the sources (Clam River, Spencer Creek and minor tributaries; precipitation; and groundwater seepage) and sinks (Torch River; evaporation) of water balance one another. Based on this rate of outflow, the hydraulic residence time of Torch Lake is calculated to be 10 years.

Table 1. Hydrologic Budget for Torch Lake (November 2004 - October 2005)

Flow Component (inflows and outflows)	Annual flow (cubic foot[1] per second, cfs)	% of water source	% of water loss
Clam River	289	72	
Spencer Creek	11	3	
Other minor tributaries	3	1	
Precipitation	47	12	
Groundwater seepage	52	13	
Torch River outflow	354		88
Evaporation	48		12

(1) Note: 1 cubic foot = 7.5 gallons

The data were also used to calculate a mass balance for phosphorus in Torch Lake. Phosphorus is a water quality parameter of particular concern, because this nutrient controls the growth of phytoplankton (algae) in lakes. High inputs of phosphorus can lead to increased phytoplankton growth, which is in turn associated with a variety of water quality impairments (e.g., loss of water clarity, nuisance algae blooms, depletion of dissolved oxygen). Calculating the mass balance for phosphorus is the first step towards understanding how to manage this nutrient. In Torch Lake, phosphorus inputs include tributary loading from the Clam River, Spencer Creek and the minor tributaries, as well as inputs from precipitation and groundwater. Release of phosphorus from the lake sediments was negligible. Phosphorus losses include sedimentation (i.e., settling with particles and eventual burial in the lake sediments) and outflow through the Torch River. The phosphorus mass balance for 2005 is shown in Table 2. Tributary loading, groundwater and precipitation each contributed roughly equal inputs of phosphorus. On a lake-area basis, the phosphorus loading to Torch Lake (4840 kg/$7.4 \times 10^7 m^2$ = $0.065 gP/m^2/yr$) falls within the 0.01-0.1 $gP/m^2/yr$ range reported for lakes in non-populated regions by Wetzel (1975). Settling was by far the most significant loss. Of the total annual loading of phosphorus to Torch Lake, 85% is removed by settling. The overall mass balance for phosphorus in Torch Lake indicates a net annual loss of 100 kg (or about 1% of the total mass of phosphorus in the lake).

Table 2. Phosphorus mass balance for Torch Lake (November 2004 - October 2005)

Component	Annual loading or loss, kilograms	% of P loading	% of P loss
Tributary loading	1590	33	
Groundwater loading	1480	31	
Atmospheric deposition	1770	37	
Settling loss	4120		83
Torch River outflow	830		17

A phosphorus-based predictive water quality model was developed for Torch Lake using the LAKE2k framework. LAKE2k simulates the seasonal and long-term dynamics for a number of significant water quality parameters (including flow, temperature, light, nutrients, dissolved oxygen and the planktonic food chain) in a seasonally-stratified lake. The model was calibrated and confirmed using data from the project and other data collected in 2003 and 2004. No significant changes were made to the model program, and model parameters were adjusted within the ranges recommended by Chapra (1997), Bowie et al. (1985), and Manhattan College (1996). Settling rates for all particulate nutrients were specified according to fluxes measured in sediment traps, and inorganic suspended solids concentrations were calibrated on the basis of Secchi disk depth measurements. The model predictions of temperature, dissolved oxygen, total phosphorus, and chlorophyll were judged to be acceptable in comparison to data for 2003-2005. The model was also used to perform a hindcast (1996-2005) simulation, to explore longer-term trends in Torch Lake water quality.

Finally, a number of forecasts were performed to simulate the expected water quality response to changes in phosphorus loadings. The forecast results illustrate both the capabilities and limitations of the water quality model:

- $ Three of the four primary water quality parameters modeled in Torch Lake (phosphorus, chlorophyll, and dissolved oxygen) are not expected to change if phosphorus loadings remain at current levels. The fourth parameter, Secchi disk depth, is believed to primarily change in response to factors other than phosphorus.
- $ Water quality would be expected to change rapidly (1-2 years) in response to significant changes in phosphorus loadings.
- $ The water quality responses, in terms of phosphorus and chlorophyll, are about proportional to the change in the total phosphorus loading from all sources (including tributaries, atmosphere and groundwater); dissolved oxygen and Secchi disk depth are less sensitive to changes in loading.

$ The model is capable of forecasting water quality changes to evaluate the impacts of cumulative changes in loading at the watershed/drainage basin scale.

$ There are a number of caveats and limitations that should be kept in mind when considering the accuracy of model results. These include:

  * None of the scenarios is particularly realistic, but each is intended to be readily understandable in terms of how phosphorus loadings are being manipulated;
  * These forecast results do not convey the uncertainty in the predictions due to errors in either the model structure or the calibrated parameters;
  * The forecasts assume that future forcing functions (e.g., meteorology, tributary flows, settling fluxes) can be reasonably extrapolated from prior data.
  * The model simulates water quality as whole-lake average concentrations. Any horizontal gradients in water quality will not be resolved in LAKE2k.

  Despite these shortcomings, we believe that the Torch Lake model is a useful tool to address water quality management questions.

$ To remain useful, the water quality model needs to be updated periodically; TLA should conduct additional model confirmation as data become available from surveillance monitoring.

$ Because the model simulates lake-wide average water quality, no discernable changes in water quality are predicted for phosphorus loading changes smaller than about 100 kg/y. Therefore, it is not appropriate to use the model to forecast water quality for scenarios involving smaller changes in loading, even though localized water quality impacts are possible.

$ The forecast simulations presented in this report were based upon simplifying assumptions about how total phosphorus loadings are related to real-world concerns (e.g., population growth, wastewater management). In the future, TLA and others interested in relating water quality predictions directly to land use change, should consider linking the water quality model to a watershed model, which extends the mass balance into the watershed and predicts loading change in response to changes in land use.

Finally, the “take-home” message of the forecast scenario predictions for land use and water quality managers, is that efforts to prevent or minimize future increases in phosphorus loadings will maintain the current pristine water quality of Torch Lake.

INTRODUCTION

The Three Lakes (Bellaire, Clam and Torch) are part of the Elk River Chain of Lakes (Figure 1), an outstanding natural resource in northern lower Michigan. Torch Lake is by far the largest of the Three Lakes. Narrow, deep and fjord-like, it is the longest and the second-largest inland lake in Michigan. Lake dimensions are summarized in Table 3. With it's length, a depth exceeding 300 feet, and a long hydraulic residence time, Torch Lake is in many ways more comparable to adjacent Grand Traverse Bay than to other inland lakes. Torch Lake has been described as the "second most beautiful lake in the world" by National Geographic, with water renowned for both its clarity and turquoise color.

Table 3. Dimensions of Torch Lake

Property	Dimension	(metric equivalent)
Surface Area	18,800 acres	7,400 hectares
Length	18 miles	29 km
Width (max)	2.35 miles	3.8 km
Depth (max)	302 feet	92 meters
Depth (ave)	142 feet	43.3 meters
Volume	8.5e+11 gallons (850,000 million gallons)	3.2e+09 $meters^3$

Land use in the Chain of Lakes watershed is shown the Figure 2, and the drainage basin for Torch Lake is delineated in Figure 3. The total area of this basin, excluding that associated with Clam River and the upper Chain of Lakes is about 1.6 times the lake area. Of the 1700 lakeshore parcels more than 85% are developed and consist mainly of single family dwellings. Of these dwellings approximately 90% are occupied only during the summer months. The population of "second tier" residences, that is residences that fall in the layer of properties just outside those on the lakeshore around the lake is small (~20%) but growing. Most of the land outside of the riparian residences is about equally divided between farms and forest land. Many of the farms are not heavily worked and some are fallow. Cluster, medium, or high density developments in the Torch Lake watershed are still rare. In addition, there are no cities or industries on the lake. The largest village, Alden, has approximately 1,000 residents and the four other unincorporated villages, Clam River, Torch River, Eastport, and Torch Lake Village, are considerably smaller. None have centralized water supplies or sewer systems. All residences have individual wells and septic systems.

Maintaining and preserving water quality in these lakes is a long-standing goal of residents and other interest groups. Given trends in regional land use, it appears that the greatest immediate threat to the water quality of Torch Lake is nutrient enrichment due to increased population and associated development, which tends to be concentrated near the lake. Between 1964 and 2004, the population of Antrim County grew by 75%, and is projected to grow by another 33% by 2020. According to the Michigan Society of Planning Officials (MSPO, 1995), the northern lower peninsula of Michigan will continue to experience gains in population with a large portion coming from in-migration.

Information regarding the current status of water quality in Torch Lake is limited. Looking toward the future, it is also not clear how current and anticipated development pressures will impact water quality in each of the lakes. This project was conducted to address this lack of information and understanding, as a basis for more effective management of water quality in Torch Lake. In addition, this project also provides a framework to integrate information gained from other efforts (e.g., surveys of septic system performance; proposals to centralize wastewater treatment; and land use planning).

The proposed technical approach combines a comprehensive water quality monitoring program with a modeling approach designed to address the water quality issues of concern. The monitoring/modeling approach is well-accepted as "state of the art" in terms of assessing and evaluating water quality, and develops a scientifically-defensible tool to predict how changes in nutrient mass loadings will affect water quality.

A water quality model is a mathematical description of a body of water, which shows how water quality responds to factors such as flows and mass loadings. *A model is a simplified version of reality that can be tested* (Chapra, 1997). A water quality model is based on applying principles such as mass, momentum and energy conservation. Examples include the water balance and phosphorus mass balances for the lake:

Water Balance:
Change in water storage = tributary inflow - outflow
+ groundwater seepage + precipitation – evaporation

Phosphorus mass balance:
Change in Total Phosphorus (TP) mass
= Mass loading (tributaries + groundwater + precipitation)
- Settling - Outflow ± Sediment flux

Water quality models can be useful, in a number of ways, to those interested in protecting and managing water quality. They can help assess the current water quality status of a water body, because they provide a framework to integrate different information, including hydrology, pollutant sources and inventories, transport, transformations and losses, and relationships between different water quality parameters. They also provide paradigms for understanding how and why water quality responds to external and internal factors. If properly calibrated and confirmed to site-specific data, they can also be applied to forecast expected changes in water quality; for example, testing alternative population growth, land use, or waste management scenarios. Each of these applications can offer an improved understanding of water quality resources, and help prevent surprises.

The Vollenweider models are commonly used as examples to introduce water quality modeling as a management tool. They are named after the Canadian researcher credited with first relating water quality in lakes to phosphorus loading. His models were simple graphical relationships between phosphorus loading and lake hydrology (Figure 4). This model represents a lake as an individual point on the graph, located according to the lake's overflow rate (the outflow divided by the surface area) on the x-axis and the area-normalized total phosphorus loading on the y-axis. Two curves divide the area of the graph into three regions. In the upper region are lakes the model identifies as *eutrophic* (nutrient-rich and overly productive). In the lower region of the graph are lakes identified as *oligotrophic* (nutrient-poor and minimally productive). The Vollenweider models represented the first tools to manage water quality according to whether a lake required remediation to restore desirable water quality characteristics (eutrophic) or preservation to maintain their high water quality (ologotrophic). Also plotted on Figure 4 are several lakes from northern lower Michigan, as well as the lower Great Lakes (Lakes Erie and Ontario) prior to implementation of phosphorus loading reductions which were established and justified by research and models such as Vollenweider's.

Our goal in this project was to develop a water quality model for Torch Lake to simulate current conditions and forecast future trends. We intended to address a number of water quality concerns expressed by TLA members:

$ Increasing phosphorus loadings and concentrations due to population growth and development, and associated nonpoint sources (from septic systems, lawn fertilization, runoff, etc.)
$ Declining water clarity
$ Maintaining dissolved oxygen and the cold water fishery

FIELD DATA COLLECTION AND ANALYSES

Modeling water quality is a data-intensive endeavor. Therefore, field data collection was an important aspect of this project. This section identifies the information that was needed to build a water quality model for Torch Lake, and describes the data collection that was carried out by TLA and GLEC to meet these needs.

An understanding of water resources begins with hydrology. This includes the annual cycles of tributary inflows and outflows, precipitation and evaporation, and groundwater seepage. This information was collected during 2004 and 2005, and was used to calculate a water balance for Torch Lake. The flow data were also combined with nutrient concentration measurements to estimate the mass fluxes entering and leaving the lake. These were used to calculate a mass balance for phosphorus, the critical nutrient in freshwater lakes. Calculating the phosphorus mass balance is the first step towards understanding how to manage this nutrient. Therefore, two principal objectives of the field sampling and analyses were to construct hydrologic and nutrient mass budgets for Torch Lake.

Our goal was to develop a water quality model that would predict the response of water quality to changes in external loadings. Again, data play essential roles in the model development process. Water quality parameters were measured in order to both calibrate (tune) and confirm (test) the water quality model. These measurements included the significant variations in water quality with season, depth, and location in Torch Lake. Because our objectives included modeling long-term changes in water quality, we included selected monitoring data collected over the past decade by organizations such as the USGS, Tip of the Mitt Watershed Center, as well as TLA's own long-term monitoring, in the confirmation process.

Site Map, Sampling Locations and Bathymetry

A map of the various monitoring and sampling points described in this Section is provided in Figure 5.

Bathymetric data was digitized from depth soundings and contours plotted on charts of Torch Lake (Mapping Unlimited, 2000). These data were interpolated to create a volumetric model, which was then used to determine the depth, area and volume properties presented in Table 3. The volumetric model was also used to develop the elevation-surface area and elevation-volume curves required to describe the lake bathymetry to the LAKE2k model. These are displayed in Figure 6. The curves display a number of the prominent bathymetric features of Torch Lake, including the broad, shallow shelf in less than 2 m of water, the rapid dropoff slightly beyond that point, and the rapid decline in cross-sectional area at depths below 60m.

Meteorology

Observations for a number of meteorological parameters are required for water balance and heat flux calculations: air temperature and dew point, wind speed, solar radiation, and precipitation. Hourly data were obtained from three Michigan Automated Weather Network (MAWN) stations located in Elk Rapids, Kewadin, and Eastport. Nearly continuously observations were available from one or more of these stations, beginning in May of 2003. Data were processed by daily averaging and, when available from more than one station, Thiessen weighting was applied to calculate lake-wide values. Long-term (1950 to present) data for temperature and precipitation were also obtained from the Traverse City airport, to asses how representative the 2004-05 monitoring years were in comparison to a longer-term record of regional climate. Evaporation data were obtained from the Northwest Michigan Horticultural Research Station, which operates a Class A evaporation pan near Northport, Michigan.

Flow Monitoring

Tributary and Inlet/Outlet Flows

Tributaries are the most visible and obvious sources of water to the lake, and were expected to be major components of flow in the hydrologic budget for Torch Lake. Unfortunately, no routine monitoring of flows is conducted in the Chain of Lakes. Flow rates were measured on major tributaries entering Torch Lake (Clam River and A-Ga-Ming, Eastport, Spencer, and Wilkinson Creeks) as well as the Torch River lake outlet. On the two rivers, the USGS method was used to measure flow with a current meter. On the creeks, flows were measured by travel time of a floating object. The flow monitoring locations are identified in Figure 5.

Shallow Groundwater Flow

Groundwater seepage is believed to be an important contributor of flow and possibly nutrients to Torch Lake. Throughout northern lower Michigan, including the TLA region, the surficial aquifer system is hydraulically connected to streams and rivers because of its shallow depth, ease of recharge by precipitation, and short groundwater flow systems. The region's lakes are also generally an extension of the water table in the surrounding surficial aquifer system.

In lakes, groundwater flows are most likely to occur near shore and decrease significantly toward the lake center. This is particularly true in the region around Torch Lake where the surficial aquifer is composed mainly of sand and gravel isolated vertically by various clay layers. Nevertheless, groundwater is expected to vary significantly though the year and be localized by subsurface irregularities and topography. However, since there are no swampy, sediment rich, or plant covered areas around the edges of Torch Lake, in this respect the material through which groundwater flows is relatively homogeneous.

To monitor shallow groundwater flows and nutrient fluxes, a network of 24 shallow (3-10' deep) wells or piezometers were installed around Torch Lake. Each piezometer was hammered into place several feet offshore in shallow (2-3' deep) water, and a _" plastic tube was installed to allow sampling and measure piezometric head. The wells were placed more or less uniformly around the lake, as shown by the locations on Figure 5, but also considered the results of a recently-conducted survey of cladophora around the lake edge (Conkle et al., 2005). Cladophora is used as a visual indicator of localized sources of phosphorus (i.e., from septic, fertilizer, and natural sources). These areas of the lakeshore are likely to be associated with enhanced groundwater nutrient fluxes.

Of the 24 sites identified, piezometers were installed at only 13 locations. At the remaining sites, a significant layer of clay was found at or just beneath the sediment surface. Little or no groundwater can flow through clay layers. The piezometers were monitored in May, July and September of 2005. Hydraulic conductivity, the hydrostatic pressure gradient, and groundwater flow rates were measured using methods described by

Hvorslev (1949), Welsh and Lee (1989), and summarized in Lambe and Whitman (1969). Groundwater samples were collected from each piezometer using a peristaltic pump. Samples of lake water were collected at the same time and location as each piezometer sample. A report describing the groundwater sampling effort in detail, as well as the results and computations of flow and phosphorus loadings for Torch Lake, has been prepared by Bretz et al. (2006) and is included as Appendix A to this report.
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Water Quality Sampling and Analysis

TLA volunteers collected samples and other water quality information from Torch Lake and its tributaries, precipitation, groundwater, and settling solids and sediment. Sampling was conducted from July of 2004 through October of 2005. This section describes the various components of the sampling effort.

Tributary Sampling

Tributaries are another potentially significant source of nutrients to the lake. Water samples were collected from the tributaries, generally at the same time that flow measurements were taken. Samples were collected at mid-channel and mid-depth from tributaries by hand, using a pre-cleaned and rinsed Erlenmeyer flask. Tributary samples were then iced and transported to GLEC's Traverse City laboratory for total phosphorus analysis.

Precipitation Sampling

Atmospheric deposition was also expected to be a major contributor of phosphorus to Torch Lake. Wet deposition of phosphorus was be measured by collecting rain samples from four locations – Alden, Eastport and two locations in Bellaire. Rain samples were collected from individual events using a sampler consisting of a 12" polypropylene funnel atop a precleaned Erlenmeyer flask. Samplers were manually deployed at the start of a precipitation event. Rain samples were removed from the flask within 8 hours, acidified and held at 4 °C until analysis. Rain samples were collected between April and September of 2005.

Dry deposition is also known to be an important atmospheric flux pathway for phosphorus. Unfortunately, the dry deposition flux is very difficult to measure. All of the available, scientifically-defensible methods of monitoring dry deposition were prohibitively expensive for this project and were therefore not pursued.

Lake Sampling

Water samples were collected in Torch Lake at two historical deep-water stations (Figure 5). The North station is located directly east of Sand Point, in approximately 250 feet of water. The South station is east of French Point, in greater than 250 feet of water. The Torch Lake water column was sampled from April through October, with sampling every other week during July, August and September. The sampling schedule was intended to capture the expected seasonal variation in water quality parameters related to thermal stratification, nutrient loading, plankton productivity, and oxygen-demanding processes. Water samples were analyzed to determine concentrations of TP, chlorophyll a, nitrate/nitrite nitrogen, total Kjeldahl nitrogen, alkalinity and hardness (Table 4).

After some initial experimentation, a consistent sampling protocol was developed. During each cruise, the same procedures were followed at each station. A Hydrolab sensor was initially lowered into the lake to obtain vertical profiles of pH, temperature, dissolved oxygen and conductivity (HydroLab data are presented in Appendix B). The Secchi disk depth was also measured. When the lake was stratified, discrete nutrient samples were collected from multiple depths at each station. Three depths were sampled in the euphotic zone, defined as 2 times the Secchi disk depth; a fourth sample was collected in the metalimnion (13-26 m), and the 5^{th}-7^{th} samples were collected from three depths in the hypolimnion. During each cruise, a duplicate sample was collected at one station and depth. A single mid-depth sample was collected at each station when the lake was unstratified.

Sediment Sampling

Samples of surficial (i.e., the top 10 cm) sediment were collected using a Ponar dredge at two sampling locations, and analyzed to measure total phosphorus, organic carbon and bulk density.

Additional sediment cores were collected by Michael Holmes of the Central Michigan University Water Research Center, in order to characterize the sediments in Torch Lake and to determine the magnitude of internal phosphorus-release and sediment oxygen demand (SOD). Sediment characteristics of interest included water content, organic carbon, total phosphorus, grain size (% sand, silt, and clay) and the oxygen demand exerted by microbial activity in the sediment. They also examined the effect of hypolimnetic oxygen concentration on sediment phosphorus release. In the laboratory, kinetic experiments were conducted with these cores to determine the rate of phosphorus release under both oxic and anoxic conditions, as well as the sediment oxygen demand. These data were used to estimating the flux of phosphorus released from the lake sediments if dissolved oxygen concentrations were depleted near the lake bottom. A report documenting the sediment flux research (Holmes and McNaught, 2005) is included as Appendix C to this report.

Sediment Traps

Four-inch diameter cylindrical sediment traps were deployed from October of 2004 through September of 2005, near the south Torch Lake deepwater sampling station. The traps, designed and constructed by the National Atmospheric and Oceanographic

Administration (NOAA) Great Lakes Environmental Research Laboratory (GLERL), capture particulate matter as it settles through the water column and collect this material in a sample bottle. The traps were retrieved seasonally, and the particulate matter they collected was removed and analyzed for dry mass and total phosphorus concentrations. The sediment trap data was used to calculate the settling flux of phosphorus, which was believed to be an important loss mechanism for phosphorus in Torch Lake.

Over the winter of 2004-05, four sediment traps were deployed in the lake at depths of 10, 32, 53 and 74 meters, to observe the vertical variation in settling rates during this period of maximum sediment transport due to wind and wave action. In spring and summer, sediment traps were deployed in duplicate at a depth of 43 meters. This depth corresponds to the base of the thermocline, where the flux of particulate matter settling out of the photic zone can be determined most unambiguously (B.Eadie, personal communication).

Sample Analyses

All water samples were analyzed for total phosphorus. Nitrate/nitrite and total Kjeldahl nitrogen were analyzed in samples collected during the July 2004 cruise. Chlorophyll a was measured in a composite formed from samples collected at the same euphotic zone depths as for nutrients. Calcium and alkalinity were measured in nutrient samples collected at the shallowest depth at each station. Selected samples were also filtered and analyzed for dissolved phosphorus. Table 4 identifies the analytes which were measured in lake water, tributary, precipitation, groundwater and sediment samples. With the exception of sediment samples (which were collected and analyzed by CMU), all analyses were performed by GLEC personnel at the Traverse City, Michigan laboratory. The GLEC laboratory has an outstanding record for analytical data quality, particularly for low-level concentrations of phosphorus.

Due to the special requirements of this project, GLEC successfully lowered its detection and reporting limits for total phosphorus analysis. The concentration range of the calibration standards used in the analysis were modified, and a method detection limit (MDL) study was performed to validate the accuracy of the modified method. The calibration standard concentrations were reduced from a range of 3 to 75 ppb, to a range of 1 to 25 ppb. The MDL study was performed by analyzing seven replicates of a 1 ppb standard. The resulting MDL was calculated to be 0.153 ppb and the average recovery was 107%. GLEC's low-level phosphorus analysis also passed a proficiency test conducted by the Canadian Center for Inland Waters (CCIW).

Table 4. Identification of water quality parameters analyzed in Torch Lake samples

Parameter	Water column profiles	Lake samples	Tributaries, groundwater and precipitation	Sediment
Temperature	x			
pH	x			
Dissolved Oxygen	x			
Conductivity	x			
Secchi disk depth	x			
Total Phosphorus		x	x	x
Nitrate/nitrite N		x [1]		
Total Kjeldahl N		x [1]		
Chlorophyll a		x		
Calcium		x		
Alkalinity		x		
TOC				x

Notes: (1) Nitrogen parameters sampled in July 2000

ANALYSIS OF FIELD DATA

Introduction

This section presents the results of the Torch Lake sampling efforts from the previous section and describes what was done to analyze and interpret this information. The data were used to perform a number of important tasks, including:

$ Estimating flows and phosphorus loadings (the product of flow and concentration) from tributaries, groundwater and precipitation,
$ Calculating the water balance and the phosphorus mass balance,
$ Reducing data for comparability with model input and predictions,
$ Determining spatial and temporal trends in the water quality data, and
$ Comparing project data to longer-term monitoring data.

Hydrology

Climatic Data

The lake-wide, daily average meteorological data derived from the MAWN observations in 2004 and 2005 are plotted in Figure 7a. This figure displays both the seasonal trends and daily variability in solar flux, temperature, wind speed and precipitation. Monthly average summaries of these data are also presented in Table 5. These data were forcing functions of the heat flux, vertical mixing, and gas exchange calculations within the water quality model. They were also used to compute the rate of evaporation from the lake, which was a component of the water balance.

Long-term (1950 to present) data for temperature and precipitation was obtained from the Traverse City airport, to asses how representative the 2004-05 monitoring years were in comparison to a longer-term record of regional climate. Figure 7b displays the trends of annual temperature and precipitation since 1950 (data were missing for 1998 and 1999) at Traverse City. While 2004 was near-average in terms of annual mean temperature and precipitation, 2005 was warmer than average and very dry. According to the National Weather Service, 2005 was the 2nd driest year in the last 50 years. This was confirmed by staff at the Northwest Michigan Horticultural Research Station, whose evaporation pan data collected from May to October indicated that 2005 was the driest year since 1988.

Evaporation and Precipitation

Torch Lake evaporation rates were calculated from the lake-wide meteorological data, using a standard engineering estimate of the conduction/convection flux and Dalton’s law (Chapra, 2003). The resulting evaporation rates, averaged on a monthly basis, show a strong seasonal variability as shown in Figure 8. The calculated evaporation rates are low in spring, increase rapidly through the summer months, decline slowly in fall and then drop rapidly as winter begins. Two independent sources of information were used to confirm these rates, and have also been plotted in Figure 8. The first was the pan evaporation data from NWMHRS, adjusted to reflect annual differences in pan vs. lake evaporation depths. We also obtained evaporation rates computed for Lake Michigan by NOAA/GLERL[1] to compare with the evaporation rates for Torch Lake. On an annual basis, these three estimates agree within 13% of one another. On a time-series basis (Figure 8) they differ, due mostly to differences in the heat capacity of the water. The evaporation pan has a much smaller volume and heat capacity than a lake, so its evaporation measurements more directly follow the atmospheric heating and cooling. On the other hand, Lake Michigan has an enormous heat capacity, and so the evaporation rates for that lake lag far behind the other estimates. As expected, the cycle of evaporation rates for Torch Lake falls somewhere in between the others.

1 http://www.glerl.noaa.gov/wr/ahps/curfcst/plots/MIC_PRECP.GIF

Precipitation and evaporation rates are compared in Figure 9. Over the 12 month project period, precipitation (22.2 inches) and evaporation (23.1 inches) almost balance, although significant differences between the rates are seen in some months. The annual balance between precipitation and evaporation is expected, as this is a unique characteristic of the region and is responsible for the abundance of inland lakes as well as the Great Lakes themselves.

<u>Tributary and Inlet/Outlet Flows</u>

The tributary flow rates measured by TLA are presented in Table 6. Based upon these flow measurements, the average flow rates shown in Table 7 were calculated:

Table 6. Flow Data for Torch Lake Tributaries

date	Clam River	Torch River	Spencer Creek	A-Ga-Ming Creek	Wilkinson Creek	Other minor creeks	comments
29-Jul-04	205	280					
23-Sep-04	198	233					
23-Jun-05	179						
30-Jun-05		129					probe failed
29-Jul-05	205	165					weed adjusted
4-Aug-05		170					
11-Aug-05	219						
15-Sep-05	168	229					weed adjusted
14-Oct-05	161	199					weed adjusted
22-Jul-04			12				high flow
29-Jul-04			6.7				
5-May-05			11				high flow
8-May-05			8.9				" "
13-May-05			10				" "
19-May-05			11				" "
23-May-05			12				" "
3-Jun-05			10				" "
25-Jun-05			10				" "
21-Jul-05			10				" "
24-Jul-05			12				" "
8-Aug-05			11				" "
24-Aug-05			12				" "
29-Aug-05			16				" "
22-Jul-04				2.7	0.66	1.23	
25-Aug-05				0.06	0.003	0.06	

Clearly, the inlet (Clam River) and outlet (Torch River) flows are much higher and generally more stable than flows in the creeks. The Clam River flow comprises greater than 90% of the total tributary inflow. Flows in Spencer Creek are higher than the other creeks, and a concerted effort was made to monitor wet weather events in this tributary.

Table 7. Average Tributary Flow Rates

Tributary	Average flow (cfs)
Clam River	188
Spencer Creek	11
A-Ga-Ming Creek	1.3
Wilkinson Creek	0.33
Other minor tributaries	0.64
Torch River	188

Flow monitoring using the USGS method is logistically complex and, as noted in Table 6, difficulties such as equipment failure and weed growth were encountered. It was not always possible to measure flows on the Clam and Torch Rivers on the same day, as would be desired for the lake flow balance; river flows were measured on the same day on only five occasions. Because of the limited data, it was difficult to evaluate the variability of flows in the Clam and Torch Rivers, as well as the difference in flows between the two rivers. The accuracy of these measurements was also a concern, since the river flows are influenced by changes in lake levels, which were not routinely monitored. As a consequence, we were concerned that the river flow data might not be representative of flows over the duration of the project, which are required for the water balance and for estimating tributary loadings.

To address these concerns with the tributary flow data, comparisons were made to the only other known Clam and Torch River flow measurements, which were made by the USGS on a monthly basis in 1990 and 1991. These data are plotted in Figure 10. Comparison of the 1990-91 flows to those measured in 2004-05 reveals a number of differences:

- The flows measured in 1990-91 are considerable higher than the 2004-05 data. The average flows measured by the USGS were 316 for the Clam River and 409 cfs for the Torch River.
- The 1990-91 data indicate a seasonal flow variability not seen in the 2004-05 data; and
- The 1990-91 flows indicate a substantial increase in flow between the Clam and Torch Rivers (i.e., 93 cfs), mostly in the spring and summer of 1990, whereas the 2004-05 data suggest the river flows are practically equal.

These differences suggest that flows monitored on the Clam and Torch Rivers in 2004-05 may be unrepresentative in comparison to the average flow rates expected based on the 1990-91 data.

Of course, one previously-discussed factor that may help to explain these differences is the variation in climate. To judge whether the tributary flows should be comparable between these different periods in time, we reviewed long-term daily monitoring data published by USGS for a number of major rivers in northern lower Michigan, including the Boardman, Jordan and Sturgeon Rivers. Comparisons of hydrologic data between large watersheds is a common practice, and flow rates in each of these tributaries are expected to be influenced by climatic factors in similar ways. To do this, we calculated the ratios of average flow rates for the dates on which the Clam River flows were measured. The flow ratio between the Clam and Sturgeon Rivers was 1.36, and the flow ratio between the Clam Jordan Rivers was 1.69. These ratios were then applied to the average flows measured on the Sturgeon and Jordan Rivers from November 2004 through September 2005 (i.e., the Torch Lake project field year), and extrapolated Clam River flows of 290 and 311 cfs were obtained. Clearly, these estimates suggest that the average of the flows measured on the Clam River in 2004 and 2005, 188 cfs, is probably too low to be explained by the “dry” climate conditions in 2005.

In the course of this review, we found that flows in the Clam and Sturgeon Rivers correlate well based on the 1990-91 data. This relationship is plotted in Figure 11; linear regression of the flows produced a correlation coefficient (r) of 0.72. This regression model was used to extrapolate daily Sturgeon River flows to the Clam River for the project period, resulting in an average flow of 289 cfs for the12 month project period. The extrapolated flows are plotted in Figure 12 along with the Clam River flow measurements. In general, the extrapolated Clam River flows agree reasonably well with the TLA measurements. These extrapolated daily flows were used in the water balance calculations, as well as the tributary load calculations.

The same approach of extrapolating Sturgeon River flows based on flow regressions was applied to Spencer Creek flows, but not to flows in the Torch River (where flows did not correlate with the Sturgeon River or other monitored tributaries).

<u>Shallow Groundwater Flow</u>

The flow of shallow groundwater into Torch Lake was measured at 24 piezometer/shallow well locations around the lake perimeter. The well data are summarized in Table 8. Clay was encountered near the sediment surface at 11 well locations; at these locations, the groundwater flow rate was assumed to be insignificant. At the remaining locations, the hydrostatic pressure gradient (i.e., the difference in pressure between the shallow groundwater and the lake) and the hydraulic conductivity (the resistance to groundwater flow) were determined, based upon 3 monthly measurements at each well. The hydraulic conductivity measurements are consistent with values expected for clean to silty sands, the soil types most representative of the subsurface sediments where these measurements were made. The variation between measurements of the hydrostatic pressure gradient and hydraulic conductivity at a particular well site was significantly less than the variation between sites.

The well data were also used to estimate the total groundwater flow to Torch Lake, by applying Darcy’s law and assuming the shallow lake area associated with the groundwater flow rate measured at each well. These estimates are also presented (as “average flow”) in Table 8. The sum of flows from the individual well areas, produces a total groundwater flow rate of 95.7 cfs. Bretz et al. (2006, Appendix A) discuss the errors and uncertainties associated with these flow estimates. They concluded that the major unknown was how far offshore the shallow groundwater flow persists. The flows in Table 8 are calculated assuming that, at each well location, shallow groundwater enters the lake from a 100-foot wide area along the shoreline. In fact, this width is unknown and is also likely to vary between locations. However, the summed groundwater flow compares favorably to an independent estimate of 75 cfs, based on the rainfall over the Torch Lake watershed in the project period.

Table 8. Groundwater Flow Data

well #	distance around lake perimeter (mi)	shoreline length[1] (ft)	average hydraulic conductivity, K_h (ft/s)	hydrostatic pressure gradient (ft/ft)	average flow (cfs)	standard deviation
1	0	10,300	3.77e-5	0.0113	0.45	0.35
1a	0	10,300	3.58e-5	0.0278	1.0	NA
2	1.9	8,700	1.05e-4	0.0521	4.4	2.3
3	3.3	clay[2]			0	
4	4.6	8,700	1.36e-4	0.1746	21	3.2
5	6.6	clay			0	
6	8.7	clay			0	
7	10.9	15,300	2.34e-5	0.2083	5.8	3.7
8	14.5	18,700	1.17e-4	0.0463	7.1	4.6
9.5	18.1	10,800	1.36e-4	0.1845	27	1.2
10	18.6	6,600	8.03e-5	0.1458	7.6	1.7
11	20.6	10,600	6.78e-5	0.0556	4.0	1.7
12	22.6	8,200	1.13e-4	0.0389	4.1	3.2
13	23.7	5,016	1.36e-4	0.0333	2.3	1.4
14	24.5	clay			0	
15	26.4	clay			0	
16	28	clay			0	
17	29.2	clay			0	
18	31.2	clay			0	
19	33.8	clay			0	
19.5	34.2	400	6.78e-5	0.0347	0.094	0.019
19.5a	34.3	400	4.82e-5	0.0293	0.057	0.020
20	35	clay			0	
21	36.5	clay			0	
22	37.5	7,900	1.08e-4	0.0521	3.5	2.6
23	39.5	10,600	7.08e-5	0.1056	6.92	4.6

Notes: 1. Shoreline length represented by corresponding well # in flow calculation;
2. No groundwater flow assumed due to clay encountered at well location.

The distribution of groundwater flows at the individual well sites is displayed in Figure 13. There was significantly more variation in groundwater flow measurements between well sites than there was in the measurements made at a particular site. For example, more than half (52%) of the total groundwater flow comes from two of the well sites, #1 and #9. Since the well measurements were made during the summer months, the groundwater flows during other seasons are unknown, but we assumed constant values throughout the year.

Water Balance

The water balance for Torch Lake was based upon the following equation, which is simply a volumetric (i.e., mass) balance for water entering and leaving the lake:

Change in water storage = tributary inflow - outflow
+ groundwater seepage + precipitation – evaporation

The water balance was calculated for the 12 month project period, November of 2004 through October 2005. Over this period, we assumed that there was a negligible change in lake storage, which corresponds to a stable lake level. The level of Torch Lake, like the others in the Chain of Lakes, is managed by controlling flows at the dams on the Intermediate River and Elk River, and lake riparians usually observe no changes in lake level. Although we lack data to confirm the constant level assumption, a 1" change in lake level is equivalent to an annual flow of only 2 cfs.

Several of the flow components of the water balance were relatively uncertain based on the 2004-05 data. In addition, the Torch River outflow was essentially unconstrained This uncertainty complicated the determination of the water balance for the lake, and led us to use a Monte Carlo procedure to compute the most likely annual values of each flow component, based upon the precision associated with each measurement. Each flow component was described in terms of probability distributions, as shown in Table 9. Normal distributions were used for all flows, except groundwater flow where a lognormal probability distribution was used, because it better fit the skewed well flow data.

Table 9. Probability Distributions Used for Flow Components in Monte Carlo Water Balance Computation (all flows in cfs units)

Flow Component	Method of calculating probability distribution	Distribution[2]	Mean/ Logmean	SD
Clam River Flow	data & regression error	N	289	45.5
Spencer Creek Flow	data & regression error	N	11.5	2.26
minor tributary flow	data	N	2.26	0
Precipitation	data & between-station variability	N	47.0	1.29
Evaporation	Residuals between LAKE2k predictions & alternative estimates	N	48.3	1.1
Torch River Outflow[1]	Calculated by flow balance			
Groundwater	data for 13 flowing wells	LN	84.2	14.4

Notes: (1) Outflow was constrained (< 409 cfs) by censoring the Monte Carlo output realizations; (2) N=normal, LN=lognormal

For each Monte Carlo realization, the Torch River outflow was calculated to balance the net flows to the lake. After running the Monte Carlo simulations, we censored (discarded or "threw out") the realizations which produced Torch River flows higher than 409 cfs, because this was the 1990-91 average flow that, in our judgement, probably exceeded the 2004-05 outflow. Out of 1,000 Monte Carlo realizations, an average of 142 (14%) were discarded because the Torch River outflow exceeded the 409 cfs criteria. Of the remaining 858 (1,000-142) realizations, the average groundwater flow was found to be 52 cfs. Although this value was only about half of the 95.7 cfs estimated by Bretz et al. (2006), it is still consistent with that value due to variability between wells and the uncertainty regarding the calculation of lake-wide groundwater flow. Using the 52 cfs groundwater flow in the water balance results in a Torch River outflow of 354 cfs:

Outflow = tributary inflow + groundwater seepage + precipitation - evaporation - change in water storage

= 303 cfs + 52 cfs + 47 cfs – 48 cfs – 0 = <u>354 cfs</u>

This rate of outflow agrees fairly well with the annual outflow of 409 cfs measured by the USGS in 1990-91, especially considering the dry weather conditions in 2005.

The hydraulic residence time (HRT), the average time that water remains in the lake, is obtained by dividing the volume of the lake by the rate of outflow. The HRT for Torch Lake is 10.2 years. Although the HRT is sometimes related to the expected rate of change in water quality, we will see that this is not particularly useful in the case of the phosphorus concentration in Torch Lake.

The water balance for Torch Lake in the project field year is also presented on a monthly basis in Table 10, again using the average groundwater flow rate of 52 cfs. Tributary flow rates were highest in April, while the most precipitation occurred in August, and evaporation peaked in September.

Table 10. Monthly Flow Balance (flow in cfs)

month-yr	precipitation	evaporation	tributary inflow	Ground-water	trinbutary outflow
November-04	53	65	350	52	391
December-04	64	73	345	52	387
January-05	23	15	302	52	361
February-05	18	14	284	52	340
March-05	13	13	280	52	332
April-05	38	29	388	52	448
May-05	37	18	281	52	352
June-05	34	18	272	52	339
July-05	72	79	241	52	286
August-05	122	90	334	52	418
September-05	63	95	255	52	275
October-05	27	70	305	52	315
Nov-Oct. average	47	48	303	52	354

Water Quality Data

Introduction

This section describes the water quality data that where collected during this project. Phosphorus was a parameter of particular importance, because it is the controlling nutrient for phytoplankton productivity and is related to the other water quality parameters of concern. Phosphorus data were used to calculate mass loadings and initial conditions for the lake; data for phosphorus and other parameters (T, DO, chlorophyll, Secchi depth) were also to confirm model predictions of water quality.

Total Phosphorus Concentrations in Lake Water

A total of 137 lake water samples were analyzed for total phosphorus during the Torch Lake project. Summary statistics for total phosphorus concentrations are provided in Table 10. In this table, the lake water samples are categorized according to epilimnion (depths from 0 to 13m), metalimnion (13 to 26m) and hypolimnion (greater than 26m) layers at the deep water stations, and shallow water samples which were collected at the time and place of the well sampling. Table 11 presents the total phosphorus statistics two different ways: (1) using all of the concentration data and (2) censoring concentrations greater than 5 ppb. The statistics for all data indicate that epilimnion phosphorus concentrations are both higher and more variable than concentrations in the other sample types, which are all in the 2 to 3 ppb range. If the data are censored to remove concentrations greater than 5 ppb, this difference disappears. The total phosphorus data are also plotted as a time series in Figure 14, showing that the majority of total phosphorus measurements fall below 5 ppb, with concentrations in a few of the epilimnion samples reaching up to 23 ppb.

Table 11. Summary Statistics for Total Phosphorus in Torch Lake Water (concentrations in ppb)

	all data				censored > 5ppm			
sample type	**n**	**average**	**median**	**SD**	**n**	**average**	**median**	**SD**
all lake water	137	3.40	2.40	3.88	121	2.26	2.30	0.98
shallow	19	2.24	2.03	1.08	19	2.24	2.03	1.08
epilimnion	58	4.65	2.70	5.57	43	2.02	2.00	0.92
metalimnion	16	2.45	1.97	1.97	15	2.03	2.20	1.05
hypolimnion	44	2.59	2.50	2.50	44	2.59	2.50	0.89

The sporadic occurrence of elevated total phosphorus concentrations in Torch Lake was puzzling, since it could not be explained in terms of expected water quality variation. We concluded that this was an artifact of either the sampling or analytical procedures. Probit analysis (Figure 15) confirms that the phosphorus data exceeding 5 ppb are unlike the other data in terms of expected sample distributions (the variances, which are proportional to the slopes of each dataset on this plot, increase rapidly above 5 ppb) and are identifiable as “outliers”. TLA and GLEC evaluated many factors which could be responsible for sample contamination, since this is a common problem when working in water bodies with very low nutrient concentrations. The water sampler and sample bottles were found to be clean. On one occasion (June 16, 2005) the samples were apparently contaminated by a bucket used for compositing. Although this was corrected, sporadic elevated total phosphorus concentrations continued. Ultimately, we came to suspect laboratory error, although this could not be confirmed. Operationally, we chose to censor all total phosphorus concentrations that exceeded 5 ppb, due to our suspicions regarding this data.

Of course, whether the difficulties encountered in measuring very low total phosphorus concentrations is a problem, depends upon ones perspective. There is nothing particularly unusual about difficulties with data when working at phosphorus concentrations below 5 ppb. On the other hand, the fact that phosphorus concentrations are this low is good news in terms of water quality. The average total phosphorus concentration in Torch Lake, determined by applying a volume-weighted procedure to the deep water station data from the five cruises between August and October 2005, was 2.6 ppb, with a standard deviation of 0.40. This is a very low phosphorus concentration, as indicated by comparison to other regional water bodies in Table 12:

Table 12. Total Phosphorus Concentrations in Northern Lower Michigan Water Bodies

Water Body	Data Source	Total Phosphorus Concentration (ppb)
Northern Lake Michigan	EPA/GLNPO, 1994-95	2.2
Torch Lake	This report	2.6
Grand Traverse Bay	MDEQ, 2001	4.5
Platte Lake	PLIA, 2003	8.1

Total phosphorus concentrations were neither significantly different between north and south deep lake stations, nor between nearshore and deep water. Figure 16 plots the 2005 total phosphorus data, which has been averaged by cruise, station and vertical lake layer. Presented in this way, the data suggest some seasonal variability in total phosphorus concentrations, with the highest values in late August and early September. However, the 95% confidence limits (calculated as ±3 standard errors) generally overlap between cruises, so based on these data the differences in phosphorus concentrations do not appear to be significant.

In other regards, the quality of the total phosphorus data is good. The analytical method was sensitive, with total phosphorus concentrations quantified in 85% of the lake water samples. Analytical precision was also good, based on comparison between field and laboratory replicates. Analysis of blanks indicated no sample contamination, except as noted above.

We also compared the total phosphorus data for the lake to concentration data from previous years, collected by the Tip of the Mitt (TOM) Watershed Center. TOM's monitoring consisted of collecting surface and bottom water samples at one or both deep

Torch Lake stations, 3 or 4 times a year. The data are plotted together in Figure 17. The range of phosphorus concentrations measured each year between 2001 and 2005 suggests that the data sets appear to be generally comparable, and that no significant changes in total phosphorus concentrations have occurred over the past 5 years.

Tributary Total Phosphorus Concentrations and Loading Estimates

Total phosphorus concentrations were measured in six Torch Lake tributaries. Summary statistics for these data are presented in Table 13. Phosphorus concentrations were highest and most variable in Spencer Creek, although concentrations were elevated in all creeks compared to the Clam River.

Table 13. Summary Statistics for Total Phosphorus in Tributaries (concentrations in ppb)

Tributary	n	average	median	SD	Min	Max
Clam River	4	4.9	4.8	1.63	3.3	6.9
Spencer Creek	13	57	64	43.0	5.3	132
A-Ga-Ming Creek	3	34	37	15.4	17	48
Wilkinson Creek	2	7.9	7.9	2.97	5.8	10
Other minor tributaries	4	22	20	8.38	15	34

Annual tributary loads for the Clam River and Spencer Creek were calculated using AutoBeale, a computer implementation of the stratified Beale Ratio Estimator (Richards, 1998). Total phosphorus loads for the other (minor) tributaries were estimated as the product of measured flows and concentrations, and then summed and averaged to calculate annual values (Table 14). The tributary loading estimates for the Clam River and Spencer Creek were fairly imprecise (as indicated by the wide confidence intervals) because not enough samples were collected for phosphorus analysis. In addition, the accuracy of these estimates was affected by errors in the extrapolated flow rates.

Table 14. Tributary Loading Estimates for Total Phosphorus (units of kg/yr)

Tributary	TP load	95% confidence interval
Clam River	1230	815 - 1640
Spencer Creek	310	110 - 510
Minor tributaries	62	

Precipitation Total Phosphorus Concentrations and Atmospheric Deposition Loading

Total phosphorus concentrations were measured in precipitation samples collected between June and September 2005, at four locations distributed throughout the Torch Lake watershed. These data are summarized in Table 15. The distributions of phosphorus concentrations in rain were positively skewed and approximately lognormal. Phosphorus concentrations were not correlated with either season or amount of rainfall. The phosphorus concentrations were generally comparable in rain collected at the Alden and Eastport locations, both of which are adjacent to the lake. Concentrations were considerably higher at the Bellaire locations, which are about 6 km east of Torch Lake and may reflect sources originating "downwind" of the lake. Because of this difference, we estimated the atmospheric deposition loading for phosphorus using only the Alden and Eastport concentration data. The data were pooled, and the unbiased logmean phosphorus concentration (28 ppb) was multiplied by the total precipitation to Torch Lake over the November-October project period (22.2 inches) to obtain an atmospheric loading of 1,165 kg/yr.

Table 15. Summary Statistics for Total Phosphorus in Precipitation (concentrations in ppb)

Location	n	average	median	SD	Min	Max
Alden	6	31	16	42.8	3	116
Eastport	7	24	15	25.8	3	80
Bellaire (north)	7	57	23	72.1	10	214
Bellaire (south)	6	47	44	45.5	4	130

The phosphorus loading from atmospheric dry deposition was estimated as a proportion of the wet deposition loading, an approach recommended by the Environmental Protection Agency (EPA, 2001). For example, Twaroski and Reding (2003) determined that dry deposition accounted for 19-53% of the total atmospheric deposition of phosphorus across the 10 major watersheds in Minnesota. Based on the land use characteristics of these watersheds, we determined that the Torch Lake watershed was most similar to Minnesota's Lake Superior watershed. Twaroski and Reding (2003) determined that dry deposition loading was 52% of the phosphorus loading from wet deposition in that watershed. Extrapolating this ratio to Torch Lake, the dry deposition loading is $0.52 \cdot 1{,}165 = 606$ kg/yr and the total atmospheric loading of phosphorus to Torch Lake is then $1{,}165 + 606 = 1{,}770$ kg/yr (24 $kg/km^2/yr$).

Independent estimates of atmospheric deposition of phosphorus were also obtained from the literature and from the monitoring and modeling results of the EPA Lake Michigan Mass Balance Study[2]. The atmospheric deposition fluxes determined for phosphorus in this project fell within the range of values reported for remote northern Wisconsin lakes (5 $kg/km^2/yr$), Lake Michigan (5-22 $kg/km^2/yr$) and Lake Simcoe, Ontario (56±24 $kg/km^2/yr$).

2 http://www.epa.gov/glnpo/lmmb/results/loadings.html

Groundwater Total Phosphorus Concentrations and Loading

Groundwater was sampled from the shallow wells at the same time the flow rates were measured, and analyzed for total phosphorus. Summary statistics for these data are presented in Table 16. A considerable range of phosphorus concentrations were measured in shallow groundwater; however, the average phosphorus concentration (21.7 ppb) was about ten times higher than the concentrations in the lake. Bretz et al. (2006) calculated a total phosphorus loading from shallow groundwater of 1,730 kg/yr, based on the product of average flow and concentration at each well site, and assuming a 100-foot wide area of flow along the lake shoreline. The spatial distribution of phosphorus loading estimates from the individual well sites is shown in Figure 18; 36% of the groundwater phosphorus loading comes from two of the sites, #1 and #9.

Table 16. Summary Statistics for Total Phosphorus in Groundwater (concentrations in ppb)

Well	n	average	median	SD
1	4	17	18	3.2
2	4	36	30	13.0
4	3	27	30	5.3
7	3	66	71	8.9
8	3	28	28	2.5
9.5	2	5	5	1.7
10	3	8	9	3.0
11	3	27	12	28.7
12	3	20	23	8.5
13	3	2	2	1.0
19.5	3	22	25	9.5
19.5a	3	12	12	3.7
22	3	6	6	0.7
23	3	34	28	11.9

For mass balance and modeling purposes, we recalculated the total phosphorus groundwater loading, using the unbiased logmean concentration of 31.9 ppb and the shallow groundwater flow rate of 52 cfs from the flow balance calculations. The revised estimate for total phosphorus groundwater loading was 1,480 kg/yr, 14% smaller than the original groundwater loading value.

In general, elevated groundwater phosphorus concentrations were not correlated with shoreline locations where *Cladophora* was found (see Figure 11, Appendix A), or with locations near higher population densities (such as the village of Alden). The site that produced the largest groundwater phosphorus loading to the lake also corresponds to a relatively undeveloped region of the lake shoreline, a two mile stretch that is used as a boy's camp only in the summer. At this site there are no known septic problems, no development for several miles behind the camp, and relatively little human activity compared to other regions of the lake.

Essentially all of the 1,400 single family homes and cottages occupying the Torch Lake shoreline use individual septic systems to treat wastewater. Although a properly designed and maintained septic system can effectively remove pathogens from wastewater, their efficiency in treating phosphorus largely depends upon the sorption capacity of the soil. Surface soils around most of Torch Lake consist of calcerous sands, which have been associated with low phosphorus sorption capacity and removal efficiency in studies of septic systems (Ptacek, 1998). The low phosphorus removal efficiency of these soils, combined with the high water table and permeable soils characteristic of the region, suggests that much of the phosphorus in wastewater being treated in septic systems around Torch Lake may enter the lake via shallow groundwater flow. Other activities, such as lawn fertilization and agriculture, may also elevate phosphorus concentrations in shallow groundwater near the lake.

What fraction of the phosphorus found in shallow groundwater comes from anthropomorphic activities? In this project it was not possible to determine the contribution and proportions of septic, fertilizer, or natural sources to the phosphorus concentrations that were measured in shallow ground water. However, some insight may be gained from a study on nearby Long Lake (Canale and McCool, 2001) in which total phosphorus concentrations were measured in domestic wells used as water supplies, which are expected to withdraw groundwater that is unimpacted by human activity. The Long Lake region shares similar subsoil properties with the Torch Lake region. The average total phosphorus concentrations measured in samples from these wells was 9.7 ppb, with a range of 1.5 to 25.0 ppb. Five of the Torch Lake well sites had average total phosphorus concentrations below 9.7 ppb, while ten were above this concentration, the highest having an average of 66 ppb. At one shallow well location on Torch Lake (19/19a), groundwater was sampled at two different depths. The average phosphorus concentration at the shallower depth (6ft) was 22 ppb, while the concentration at the deeper depth (9ft) was 12 ppb. Phosphorus concentrations in shallow groundwater higher than background concentrations, and higher concentrations at shallower depths both generally indicate that a significant fraction of the phosphorus in shallow groundwater around Torch Lake is probably from human activity.

<u>Sediment Trap Fluxes</u>

The sediment trap data revealed that particle settling fluxes in Torch Lake vary both with season and depth in the water column. The trap data for each of the three deployment periods (winter, spring and summer) are presented in Table 17. The phosphorus and solids fluxes are also plotted in Figure 19. The four traps deployed from November through May (top portion of Table 17; left-hand graph in Figure 19) measured increasing solids and phosphorus fluxes with depth in the lake. This is a typical pattern of particle fluxes for deep lakes during unstratified periods, and indicates an increasing supply of resuspended solids near the bottom of the lake. In the case of Torch Lake, the winter supply of solids is probably resuspension of sediment from relatively shallow nearshore water, which is subsequently transported down the drop-offs to the depths of the lake. Visually, the solids collected in the 74 meter-deep trap were predominantly sand. The phosphorus concentrations measured on the winter trap solids (220 to 470 ppm) are somewhat higher than phosphorus concentrations measured in deep lake sediments (120 to 240 ppm).

Table 17. Torch Lake Sediment Trap Data

trap depth (m)	total dry mass (grams)	mass flux (gm/m2/d)	Total phosphorus concentration (mg/kg)	Total phosphorus flux (mg/m2/d)	TSS settling velocity (m/d) assuming 1 mg/L concentration	TP settling velocity (m/d) assuming 0.76 ug/L concentration
Fall-Winter Deployment (deployment date = October 27, 2004; retrieval date = May 25, 2005; duration in lake = 210 days)						
10	0.283	0.166	467	0.078	0.17	0.10
32	0.514	0.302	216	0.065	0.30	0.086
53	1.034	0.607	431	0.262	0.61	0.34
74	1.651	0.970	301	0.292	0.97	0.38
Spring Deployment (deployment date = May 25, 2005; retrieval date = July 26, 2005; duration in lake = 64 days)						
46	0.022	0.043	188*	0.0080	0.043	0.011
46	0.016	0.031	188*	0.0058	0.031	0.0077
Summer Deployment (deployment date = July 26, 2005; retrieval date = October 10, 2005; duration in lake = 74 days)						
46	0.605	1.17	190	0.222	1.2	0.29
46	0.589	1.13	186	0.211	1.1	0.28

Note: * Insufficient mass collected to analyze; TP concentrations estimated from average of summer deployment samples

Two (duplicate) traps were deployed at a depth of 46 meters during June and July. These traps collected a surprisingly small particle mass (middle portion of Table 17; center graph in Figure 19); in fact, the mass collected in the sediment traps during spring was too small to handle for phosphorus analysis. We had expected a significant flux of solids, primarily phytoplankton, to settle out of the photic zone during this period. Obviously, this was not observed. Despite the very small masses, good agreement was obtained between the duplicate traps.

In the summer (August through October), duplicate traps were again deployed at a depth of 46 meters. The fluxes of phosphorus and solids measured in the traps deployed in summer (bottom portion of Table 17; right-hand graph in Figure 19) were quite large, in contrast to the spring deployment. The fluxes measured in the summer deployment were actually fairly similar to the winter fluxes. The phosphorus concentrations measured on the summer trap solids were also similar to the values for the winter trap solids. Visually, however, the appearance of the summer trap solids was quite different. These solids were very flocculent, with particle sizes ranging from almost colloidal to the size of large snowflakes. When dried, we found a few macrozooplankton in the samples; however, the majority of the dried solids had the appearance of a fine, white powder, like ground chalk. We presume that these solids are calcite (solid calcium carbonate).

The sediment trap fluxes were used to measure the rate of phosphorus settling in the lake. This information was used in both the phosphorus mass balance (as a lakewide phosphorus loss) and the water quality model (as a settling velocity for particulate nutrients). Using the phosphorus fluxes from all traps, an annualized flux of 55.6 $mg/m^2/y$ was calculated. Multiplied by the surface area of the lake, this corresponds to a phosphorus settling loss of 4,120 kg/yr. Solids and phosphorus settling velocities were calculated from the trap fluxes, based upon concentrations measured in the lake, and are presented in Table 17. The settling velocities vary seasonally, according to:

Summer > Winter >> Spring

Sediment-Water Fluxes

The rates of dissolved phosphorus release from Torch Lake sediment were found to be negligibly small, for both oxygenated and oxygen-deficient overlying water conditions (Holmes and McNaught, 2005). Based on the experimental results, there is likely to be little or no exchange of dissolved phosphorus compounds between the sediment and the overlying water in Torch Lake, when compared to more eutrophic lakes. Rates of sediment oxygen demand were also quite low, 0.27 g O_2/ m^2/day.

Total Phosphorus Mass Balance

Phosphorus is the rate-limiting nutrient for phytoplankton growth in Torch Lake, based on the observed Redfield (N:P) ratio of 480. Since the eutrophication process is driven by the concentrations of this nutrient, it follows that managing and protecting water quality in Torch Lake depends upon understanding the sources and sinks of phosphorus. Calculating a mass balance is a first step towards such understanding. At this point, we have all the information necessary to calculate the mass balance for phosphorus, which is worked out below for the project period.

The mass balance for phosphorus in Torch Lake can be written as:

Accumulation = Loadings – Outflow – Settling

Phosphorus loadings include contributions from tributaries, atmospheric deposition, and shallow groundwater (there are no point sources to Torch Lake, and other nonpoint sources were neglected). Phosphorus is lost from the lake by outflow and settling with particles, which are ultimately incorporated into the sediment bed. The phosphorus loading and settling loss terms have already been calculated:

Total Phosphorus Loading = Tributary Loading + Atmospheric Deposition
+ Groundwater Loading
= 1,590 kg/y + 1,770 kg/y + 1,480 kg/ = 4,840 kg/y

Phosphorus Settling = 4,110 kg

The loss due to outflow is simply the product of the rate of outflow and the average lake concentration:

Outflow = (0.893) · 354 cfs · 2.6 ppb = 830 kg/yr

For the annual project period, the phosphorus mass balance is:

Accumulation	=	**Loadings – Outflow – Settling**
	=	**4,840 kg/y – 830 kg/y -4,120 kg/y**
	=	**-100 kg/y**

The phosphorus mass balance is also shown graphically in Figure 20. Atmospheric deposition, tributary loading, and groundwater each contribute roughly equal inputs of phosphorus to the lake. Settling was by far the most significant phosphorus loss process. Of the total annual loading of phosphorus to Torch Lake, 85% is removed by settling. The overall mass balance for phosphorus in Torch Lake indicates a net annual loss of 100 kg (or about 1% of the total mass of phosphorus in the lake). Thus, the sources and sinks of phosphorus were found to nearly balance in Torch Lake.

The phosphorus mass balance calculation was also repeated in the Monte Carlo simulations, which provides an estimate of the precision of the phosphorus accumulation computed by the mass balance. The standard deviation of the phosphorus accumulation was 511 kg/y so, assuming a normal distribution, the 95% confidence interval would be ±1,000 kg/y. Clearly, this confidence interval includes 0 and leads us to conclude that phosphorus accumulation in Torch Lake is probably negligible. This means that phosphorus loadings and losses balance, and at an annual time scale the phosphorus concentrations in Torch Lake should be nearly constant. In fact, this is consistent with monitoring data from the last 5 years.

The total phosphorus loading, when normalized by the surface area of Torch Lake (4840 kg/7.4x$10^7$$m^2$ = 0.065gP/m^2/yr) falls within the 0.01-0.1 gP/m^2/yr range reported for lakes in non-populated regions by Wetzel (1975). This areal phosphorus loading rate is fairly typical for oligotrophic ("preservation zone") lakes.

Phytoplankton

Phytoplankton were measured as chlorophyll-a concentrations in the photic zone of the lake, which varied from 8 to 17 meters in depth. Summary statistics for chlorophyll concentrations are provided in Table 18, indicating consistency between the two deep lake sampling stations. The highest chlorophyll concentrations were measured in June and July, with a possible second peak occurring in September.

Table 18. Summary Statistics for Chlorophyll Concentrations (concentrations in ppb)

Deep Lake Station	n	average	median	SD
North	9	0.54	0.53	0.0730
South	9	0.55	0.55	0.0778

Secchi Disk Depth and Water Clarity

Secchi disk depths have been measured in Torch Lake each summer since at least 1990 to monitor water clarity. This data, plotted as a time series in Figure 21, shows a regularly-repeating annual pattern of Secchi disk depths that is more obvious if each year's data are plotted as a function of the Julian date (Figure 22, for the north Torch Lake station; Secchi disk data have been removed for years in which fewer than normal measurements were made, since these tend to skew the results). The highest Secchi depths (10-12 m) are measured in early June, and then steadily decline until early to late August, when Secchi depths reach their minimum (4.5 to 5 m). The maximum and minimum Secchi depths at each deep lake station are plotted in Figure 23. If a few values are ignored (e.g., the maximum Secchi depth at the north station in 1994, and the 2005 data to be discussed subsequently), there appears to be no significant trend in minimum or maximum annual Secchi disk depths, at either station.

In addition to the regular trend of declining Secchi disk depths during summer, numerous observers have noted fairly abrupt declines in water transparency following heavy rainfalls. According to field notes taken by the TLA sampling crews, this may have influenced Secchi disk depths measured on one or more cruises during 2005. Consequently, the seasonal trend of the Secchi depths measured during the project year appears somewhat anomalous in comparison to the long-term data. This will be illustrated in the Model Calibration section of this report.

Light extinction, a more precise measure of water clarity, was determined on a single cruise (August 18, 2005). On that date, staff from the Platte Lake Fish Hatchery assisted TLA in measuring light extinction using a Licor light intensity meter. Based on these measurements, a light extinction coefficient of 0.03/m was determined (R. Canale, personal communication). In comparison, the extinction coefficient of pure water is also 0.03/m, while a value of 0.05/m has been reported for Lake Tahoe. It is somewhat surprising that the light extinction coefficient measured in Torch Lake is this small, since the Secchi depths measured in Lake Tahoe are significantly greater (e.g., 70 ft) than those in Torch Lake.

We will return to the issue of water clarity; however, we must first consider another important factor that appears to be related to the seasonal trends in Secchi depths discussed above.

Calcium Carbonate

One of the most striking visual characteristics of Torch Lake is its turquoise hue. This color is also a clue regarding a natural process which influences water clarity as well as other water quality parameters in the lake. According to Wetzel (1975):

> "Hard-water lakes with high suspensions of $CaCO_3$ characteristically backscatter light that is predominantly blue-green" (p.49),

and:

> "Colloidal $CaCO_3$, common to very hardwater lakes, scatters light in the greens and blues and gives these waters a very characteristic color appearance" (p.61).

Torch Lake is a hardwater lake (average hardness = 150 ppm $CaCO_3$), due to the predominantly calcerous soils in the drainage basin. Because of its appearance, we can safely assume that Torch Lake is saturated or supersaturated with $CaCO_3$ at least seasonally. Furthermore, colloidal $CaCO_3$ is probably suspended in the water column throughout the year.

The equilibrium chemistry of $CaCO_3$ is well understood. If the solubility limit of calcium carbonate is exceeded, solid $CaCO_3$ (calcite) will precipitate. We used the Visual MINTEQ model[3] to calculate $CaCO_3$ equilibria, based on measurements of the relevant water quality parameters: temperature, pH and calcium and alkalinity concentrations. These are plotted for the south Torch Lake station in Figure 24 (similar parameter values were observed at the north station), along with the Visual MINTEQ predictions of the corresponding equilibrium calcite concentrations. The equilibrium calcite concentrations are highest in spring, remain elevated through the beginning of August, and then decline fairly continuously through the rest of the summer. The decline in equilibrium calcite is due to (1) the reduction in calcium concentrations in August and September and (2) declining water temperature in October. Regarding the reduction in calcium concentrations, Wetzel (1975) again provides the likely explanation:

> "The calcium concentrations in headwater lakes, however, undergo marked seasonal dynamics…Both the calcium levels and total alkalinity decreased markedly as a result of the precipitation of $CaCO_3$ during the summer months from May through September" (p.155)

Thus, the decline in calcium concentrations in Torch Lake during August and September is probably due to precipitation of calcium carbonate, which is then lost from the surface water of the lake by settling. If this is true, then we would expect to see transparency decline while calcium carbonate is precipitating, and then increase as the particulate calcite settles.

The same equilibrium calcite concentrations are plotted together with chlorophyll concentrations and Secchi disk depths in Figure 25. Conventionally, declines in lake transparency during summer are attributed to the bloom of phytoplankton, measured as increasing chlorophyll concentrations. However, inspection of the Torch Lake data (Figure 25) reveals that the trend in chlorophyll concentrations does not adequately explain the decline in Secchi disk depths (in fact, the Torch Lake data show that transparency *increases* as chlorophyll concentrations rise). Instead, it appears that the Secchi disk depths (and water clarity) are increasing at the same time that equilibrium calcite concentrations are decreasing in August and September. This suggests that calcium carbonate precipitation may be an important factor related to changes in water clarity.

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3 Visual MINTEQ: An equilibrium speciation model, which calculates chemical equilibria in aqueous systems at low ionic strength. (http://www.lwr.kth.se/English/OurSoftware/vminteq/)

Unfortunately, attempts to correlate equilibrium calcite concentrations with Secchi disk depths were not successful. This may be due to the fact that calcium carbonate precipitation in lakes is often controlled by kinetic (not equilibrium) factors, as many researchers have noted (e.g., Snoeyink and Jenkins, 1980). Unlike equilibria, the kinetics of calcium carbonate precipitation is less well-understood, and models to predict this phenomenon are not generally available.

Light Model

The standard light/transparency model used in LAKE2k and other water quality models calculates water transparency as a function of the concentrations of chlorophyll, particulate organic carbon (POC), and inorganic suspended solids (ISS). In the development of the water quality model for Torch Lake, chlorophyll concentrations were monitored, and POC was estimated from the chlorophyll concentrations; however, ISS was not measured and could not be directly inferred from other measured parameters. Instead, we calibrated ISS by fitting the light model to the observed Secchi disk depths. The resulting ISS timeseries are plotted in Figure 26. Similar results were obtained using data from the north and south lake stations, even though each was independently calibrated.

Our conjecture from the previous section, was that the ISS responsible for the summertime decline in light transparency was predominantly calcite. To test this idea, we compared the calibrated ISS to particulate calcium carbonate concentrations, determined from limited measurements of total and dissolved (filtered) calcium (Figure 26). The calibrated ISS concentrations, which vary from 1 to 3 ppm, appear comparable with several of the lower particulate $CaCO_3$ measurements. However, much higher (up to 17 ppm) particulate $CaCO_3$ concentrations were also observed. We cannot explain the large variability in the particulate $CaCO_3$ values, nor why most of these measurements are much higher than the calibrated ISS concentrations. It is possible that our filtration and sample handling (i.e., icing of samples during transport) procedures may have interfered with the determination of particulate $CaCO_3$.

LAKE2K CALIBRATION AND CONFIRMATION

A major goal of the Torch Lake project was the development and application of a predictive water quality model, to simulate and forecast changes in water quality due to changes in phosphorus loadings. The field data presented in the previous sections were used to develop a water quality model for the lake, using the LAKE2k modeling framework (Chapra, 2003). LAKE2k is a model designed to compute seasonal trends in water quality in stratified lakes, based on numerical integration of mass balance equations similar to the water and phosphorus mass balances presented in the previous section. The model simulates lake-wide water quality in three vertical layers, as depicted in Figure 27, to represent the seasonal stratification of the water column. The LAKE2k framework includes a water balance, vertical mixing, thermal balance, and ice, light and sediment flux submodels. One attractive feature of LAKE2k is that it is implemented using spreadsheet software found on virtually every personal computer (Microsoft Excel). The model predicts the most important water quality parameters in freshwater lakes: water temperature, DO, organic and inorganic nutrients, phytoplankton and zooplankton concentrations. The beta test version (0105) of the LAKE2k model was provided to TLA and GLEC by Dr. Stephen Chapra of Tufts University.

Several modifications were made to the LAKE2k program for this application. These included:

$ Settling rates for all particulate nutrients were converted from constants to time functions, a requirement based upon the use of seasonal sediment trap fluxes to specify settling; and

$ Inorganic suspended solids concentrations were specified as a forcing function instead of a state variable. This modification was necessary because ISS, which is a variable used in the light submodel to compute light absorption and scattering in the water column, was believed to originate from calcium carbonate precipitation, as previously discussed. The kinetic factors involved in calcium carbonate (calcite) precipitation in the lake are not well understood, and this process is not included in the LAKE2k framework.

Neither of these modifications significantly alter the overall function of the model, and each was tested by comparisons to hand calculations and by reproducing simulations with different versions of the model program. Although not a modification to the LAKE2k program, it was necessary to preprocess and convert total phosphorus loadings into equivalent tributary concentrations, because only tributary loadings can be input to the model.

Initial conditions and loadings for the calibration runs were calculated from field data. It was necessary to divide total phosphorus loadings into organic and inorganic fractions, because LAKE2k uses these two forms of phosphorus as state variables. To do so, we assumed that the inorganic fraction of total phosphorus was 10% in tributary loads (Wetzel, 1975), 50% in atmospheric deposition (naïve assumption), and 80% in groundwater loading (MPCA, 1999).

The model was calibrated using project data as well as other data collected in 2003 and 2004. A three year calibration period was chosen because (1) MAWN data was available to describe meteorological forcing functions for this period and (2) multi-year model runs prevent initial conditions from excessively influencing the simulations. Calibration involved adjusting model parameters within the ranges recommended by Chapra (1997), Bowie et al. (1985), and Manhattan College (1996), in order to obtain the best fit of the data. Settling rates for all particulate nutrients were specified according to fluxes measured in sediment traps, as discussed previously. Inorganic suspended solids concentrations were calibrated so that the light submodel reproduced Secchi disk depth measurements; this was also discussed previously. We used the Munk-Anderson vertical mixing model, O'Connor reaeration formula, the Arrhenius temperature model for phytoplankton growth, and the Steele light model. We modeled a single phytoplankton class and, although it had no impact on phytoplankton concentrations, herbivorous zooplankton as well. The optimal values of the model parameters, based upon calibration, are presented in Table 19. Although there are many parameters, the model for Torch Lake is fairly insensitive to the values of the majority of them. In fact, the calibration effort focused on only seven parameters:

- $ Phosphorus half-saturation concentration,
- $ Organic phosphorus hydrolysis rate,
- $ Phytoplankton respiration rate and temperature coefficient,
- $ Phytoplankton growth rate,
- $ Chlorophyll:Carbon stoichiometric ratio, and
- $ Phytoplankton settling velocity.

The calibration results for each water quality parameter are presented and discussed below.

The calibration of the model to temperature data in the three vertical layers of the lake is shown in Figure 27. The model does a good job of simulating water temperatures in each layer, as well as differences in temperature which develop between layers during summer. The seasonal progression of temperatures in the epilimnion and metalimnion can be seen to differ between the 3 years, indicating the extent to which climatic variability influences the lake. Two parameters (the Munk-Anderson vertical mixing coefficients) were adjusted to calibrate temperature.

The calibration of the model to phosphorus concentration data in the epilimnion of the lake is shown in Figure 28. Predictions for both total and inorganic phosphorus (TP and IP) are plotted. Total phosphorus concentrations are predicted to be fairly stable, within the range of 2-3 ppb, while the data are more variable. The model predictions do fall within the 95% confidence limits of most of the data collected in August-October of 2005, when sampling was being conducted consistently throughout the water column. The lack of fit in total phosphorus concentrations at other times may be related to data quality and quantity.

In contrast to total phosphorus concentrations, inorganic phosphorus concentrations are predicted to vary dramatically between summer and the other seasons (Figure 28). This is because inorganic phosphorus is bioavailable, and is rapidly taken up by phytoplankton in summer. We have plotted dissolved phosphorus data for comparison to the inorganic phosphorus predictions, although these forms of phosphorus are not exactly comparable (i.e., dissolved phosphorus includes some organic phosphorus which is not bioavailable). The dissolved phosphorus data generally suggest that inorganic phosphorus is depleted from the epilimnion in summer, in agreement with the model.

The calibration of the model to total phosphorus concentration data in the metalimnion and hypolimnion of the lake is shown in Figure 29. Total phosphorus concentrations are again predicted to be fairly stable, although slightly higher than epilimnetic concentrations during the latter half of stratification (August through December) of each year. The model predictions fall within the 95% confidence limits of most of the data for both the metalimnion and hypolimnion. The model predicted only very low rates of sediment phosphorus release (< 0.01 mg/m^2/d), in agreement with the results of the sediment flux experiments.

Table 19. Calibrated Parameter Values for LAKE2k Torch Lake Model

Parameter	Symbol	Units	Torch Lake calibration value	suggested[1]		
				low	moderate	high
Stoichiometry:						
Dry weight	**gD**	gD	100		100	
Carbon	**gC**	gC	40		40	
Nitrogen	**gN**	gN	7.2		7.2	
Phosphorus	**gP**	gP	1		1	
Chlorophyll	**gA**	gA	0.5	0.5		1
Chlorophyll:Carbon		ugA/mgC	12.5	10		20
Settling Rates (Organic Carbon, Nitrogen and Phosphorus):						
winter [JD<145 or JD>283]	v_s	m/d	0.678			
spring [145<JD<209]		m/d	1.6×10^{-6}			
summer [209<JD<283]		m/d	0.106			
Particulate organic carbon:						
Hydrolysis rate	k_{hc}	/d	0.03	0.02		0.05
Temperature parameter	q_{hc}		1.047	1.02		1.047
Dissolved organic carbon:						
Oxidation rate	k_{dc}	/d	0.01			
Temperature parameter	q_{dc}		1.047			
Organic phosphorus:						
Hydrolysis rate	k_{hp}	/d	0.005	0.03		0.14
Temperature parameter for organic P hydrolysis	q_{hp}		1.045	1.02		1.08
Dissolved oxygen:						
Temperature parameter for reaeration	q_{ox}		1.024			
Oxygen per C oxidized	r_{oc}	gO2/gC	2.69			
Oxygen per N nitrified	r_{on}	gO2/gN	4.57			
Total Phytoplankton:						
Maximum growth rate	k_{gp}	/d	1.0	1.3	1.8	2.5
Theta	q_{gp}		1.04		1.066	
Respiration rate	k_{rp}	/d	0.10	0.05		0.2
T parameter for resp. and death	q_{rp}		1.08		1.08	
Death rate	k_{dp}	/d	0.02	0.01	0.02	0.1
Nitrogen half saturation	K_{sn}	mgN/L	25	5		25
Phosphorus half saturation	K_{sp}	mgP/L	0.5	0.5	2.5	30
Steele (optimal) light parameter	k_{si}	langleys/d	300	100	350	400
settling rate	v_s	m/d	0.1	0.05		0.2

note: (1) Various sources, including Chapra (1997), Manhattan College (1996) and Bowie et al., 1985)

The calibration of the model to chlorophyll data is shown in Figure 30. The predictions show that phytoplankton growth begins in May (in response to increasing temperature and light intensity) and reaches a peak each year in mid to late June. Some phytoplankton is also predicted to grow in the metalimnion, because in high-clarity Torch Lake, the photic zone extends well into this lake layer. Phytoplankton/chlorophyll concentrations then gradually decline through the remainder of the year, due to the depletion of available phosphorus from the photic zone and increasing phytoplankton losses, primarily via respiration, settling and death. At such low chlorophyll concentrations, we found that zooplankton were unable to grow and reach abundances where their grazing would affect phytoplankton. The model predicts the magnitude and duration of the phytoplankton bloom fairly well, as indicated by comparison to the chlorophyll data, although the elevated chlorophyll concentrations which persist through October of 2005 are underpredicted.

The calibration of the model to dissolved oxygen data in the three vertical layers of the lake is shown in Figure 31. In each layer, the model predictions and data agree well. No parameters were adjusted to calibrate dissolved oxygen. The saturation concentration of dissolved oxygen in the epilimnion is also plotted in this figure. Dissolved oxygen concentrations in the epilimnion and metalimnion vary seasonally, with the highest values in winter/spring and the lowest concentrations in summer, which follows the trend of the DO saturation concentrations. Hypolimnetic dissolved oxygen concentrations are consistently within the range of 12 to13 ppm, indicating no tendency for hypolimnetic oxygen depletion to occur in winter, even under ice cover. The model predicted very low rates of sediment oxygen demand ($< 0.01 g/m^2/d$), which again agrees with the results of the sediment flux experiments.

The final state variable used to calibrate the Torch Lake model was Secchi depth (Figure 32). The model does a good job of reproducing light extinction by this measure, although it should be remembered that this agreement is due, in part, to calibration of ISS concentrations in the light submodel. The model also captured the somewhat unusual Secchi depths observed in 2005, as well as the data from 2003 and 2004, which were similar to the long-term data.

The model calibration of each of the state variables shown above was judged to be acceptable in comparison to data for 2003-2005. The fit of the chlorophyll data could be improved by modeling a second, slower-growing phytoplankton class, although this would be curve fitting exercise since we have no data regarding the abundance of plankton functional groups (i.e., diatoms vs. green algae) in Torch Lake. As mentioned above, the calibration also suffers because of the variability in the total phosphorus data, which could only be improved by collecting additional data with an improved sampling design. Additional measurements of inorganic (i.e., dissolved) phosphorus would be helpful as well.

The model was also used to perform a hindcast of water quality over the past ten years (1996-2005), to confirm the model's predictions of longer-term trends in Torch Lake water quality. Model parameters and mass loadings used in the hindcast were unchanged from the calibration simulation. Tributary flows were again extrapolated from USGS daily flows for the Jordan River, which were available for this period. Meteorological data prior to 2003 was based on observations from the Traverse City airport. The Torch River outflow rates were adjusted to maintain a constant lake level on an annual basis. And, based on limited data, we chose a higher (6 ppb) initial condition for total phosphorus in the hindcast.

The results are displayed in Figures 33 through 36. Figure 33 is a plot of the temperature simulation for 1996 through 2005. Surface temperatures were available in the summers of 1996, 1997 and 2000 for comparison to the epilimnion temperature simulation, in addition to the calibration data. The data suggest that the hindcast temperatures are reasonable, although the measurement of water temperatures exceeding 25° were somewhat surprising and not reproduced by the model.

Figure 34 is a plot of the total phosphorus hindcast in the epilimnion and hypolimnion layers. Total phosphorus concentrations predicted in the hindcast simulation decline from 6 ppb to around 3 ppb in 5 to 6 years. Here it is more difficult to judge the hindcast, in part because the monitoring data are too few to compute confidence intervals, and the 2000 data exhibit a very large range of phosphorus concentrations, from 1.2 to 5.7 ppb. Furthermore, we can have no real confidence in either the initial conditions or the first five years of the hindcast simulation, since no phosphorus data was available for this period.

The hindcast for phytoplankton is plotted in Figure 35. In this case, there was a good quantity of chlorophyll data to compare with the simulation. As was the case during the calibration, the model does a reasonable job predicting the overall magnitude and duration of the phytoplankton bloom, although there is a tendency to overpredict the chlorophyll peak, sometimes by as much as a factor of 2 to 3. Since the hindcast predicts a lower chlorophyll peak each year, while the data show no such decline, we must question whether it was correct to assume that the initial total phosphorus concentrations were as high as 6 ppb in 1996. A lower total phosphorus initial condition would improve the fit of the hindcast prediction for chlorophyll.

As an additional test of the model, we calculated the ratio between the annual average predictions of epilimnetic total phosphorus and chlorophyll concentrations, and compared these ratios to the regression model of Bartsch and Gakstatter (1978), which predicts chlorophyll concentrations in lakes using a regression to total phosphorus concentrations. The comparison is shown in Figure 36. Although the ratios predicted by the Torch Lake model are smaller than the regression model, by an average of 40%, this difference is well within the range of residuals from Bartsch and Gakstatter's data. It is reassuring that the model predictions are consistent with this regression, since it was derived from data for many lakes and reservoirs.

The final hindcast plot, Figure 37, is for the Secchi disk depth. Here, the model does a good job of fitting the data, which tend to repeat themselves in a predictable manner.

Overall, the hindcast simulated with the Torch Lake model revealed no major surprises, and suggested that the model behaves about as well as we understand the variation in water quality over the past ten years. This exercise also illustrates the importance of ongoing surveillance of water quality: without such data, there is no foundation for understanding long-term changes in water quality. A model cannot be substituted for such information.

TORCH LAKE MODEL FORECAST SIMULATIONS

The Torch Lake model was applied to forecast water quality for a number of scenarios, intended to address the following issues of concern to Three Lakes Association:

$ Under present conditions (i.e., loadings), will water quality in Torch Lake remain the same, improve, or degrade?
$ If loadings were to change, how would water quality change? (i.e., in proportion to the change in loading, or some other relationship?)
$ If loadings were to change, how rapidly would this change be reflected by water quality in Torch Lake?
$ More generally, how can this model be used in the planning process to manage and protect water quality in Torch Lake?

The model forecasts presented here were based upon a number of common assumptions. Each was based on meteorology and tributary flows for the 1997 – 2005 period, using methods that have been described previously. Total phosphorus concentrations in tributaries, groundwater and precipitation were held at values determined in the project year, unless noted otherwise. The following five specific scenarios were forecast using the Torch Lake model:

1. No Change
2. Phosphorus Loading Cutoff
3. Projected Annual Population Growth of 1.5%
4. Projected Annual Population Growth of 5%
5. Alden Centralized Sewage Treatment Options

Details regarding each of these scenarios are provided below. We consider these forecasts to be more *illustrations* than *expectations*, due to a number of caveats and limitations that impact their accuracy. These include:

$ None of the scenarios is particularly realistic, but each is intended to be readily understandable in terms of how phosphorus loadings are being manipulated;
$ These forecast results do not convey the uncertainty in the predictions due to errors in either the model structure or the calibrated parameters;
$ The forecasts assume that future forcing functions (e.g., meteorology, tributary flows, settling fluxes) can be reasonably extrapolated from prior data. Such extrapolation cannot anticipate factors such as global warming impacts, exotic species introduction, etc.
$ The model simulates water quality as whole-lake average concentrations. Any horizontal gradients in water quality will not be resolved in LAKE2k. Although analysis of total phosphorus data did not reveal any statistically-significant differences between north and south deep-water stations, or between deep-water and shallow water samples, the sampling design was not intended to detect horizontal spatial gradients.

Despite these shortcomings, we believe that the Torch Lake model is a useful tool to address the questions posed above.

Description of Forecast Scenarios

No Change

This scenario was intended to represent a future in which factors related to nonpoint phosphorus loadings such as land use, population, etc. do not change in the drainage basin. The phosphorus concentrations specified for tributary inflow are not varied from the values based on 2005 data in this scenario. Because the tributary flow rates and rainfall vary according to the 1997-2005 data, the tributary loading and atmospheric deposition of phosphorus to the lake tends to vary somewhat (±10%) from year to year in this scenario. This is probably realistic, as higher nonpoint source loadings of phosphorus would be expected in wetter years.

Phosphorus Loading Cutoff

In this scenario, phosphorus loads are cut off at end of the first year, 2005. This scenario illustrates how rapidly water quality in Torch Lake changes in response to a change in loadings.

Projected Annual Population Growth of 1.5%

This scenario uses the 1.5% annual population growth rate, projected by the NWMCOG (1998), to calculate future increases in phosphorus loading. We base this estimate on growth within the riparian zone around Torch Lake, and ignore growth occurring elsewhere in the drainage basin. TLA estimates that the current seasonally-adjusted population in the riparian zone is 2,000 people. Using the standard 2.25 gP/d per capita waste loading, this is equivalent to 1,640 kg/yr of phosphorus originating from the riparian population. We will assume that all of this phosphorus eventually enters the lake. If the1.5% annual growth rate is applied to this population, we calculate an additional 30 people residing in the riparian zone each year, as well as the generation of an additional 25 kg of phosphorus. Since we have ignored the impact of population growth elsewhere in the drainage basin, this is a conservative estimate of phosphorus loading increase.

Projected Annual Population Growth of 5%

This scenario repeats the previous one, however a higher annual population growth rate of 5% is assumed. This growth rate corresponds to an additional 100 people residing in the riparian zone each year, as well as the generation of an additional 82 kg of phosphorus.

Alden Centralized Sewage Treatment Options

This scenario deals with a more specific example of how an actual development proposal could be evaluated in terms of a water quality changes forecast by the Torch Lake model. The proposal is the implementation of centralized sewage treatment in the village of Alden. TLA has estimated the seasonally-adjusted population of the village to be 290. Using the same per capita waste loading, this population generates 240 kg of phosphorus. The question we wish to address with the model, is whether there would be any water quality benefits in Torch Lake, if the proposed sewage treatment plant included treatment to remove phosphorus as opposed to conventional secondary treatment. Secondary treatment generally removes about 20% of phosphorus from domestic wastewater; for this alternative, the effluent phosphorus load estimate is 0.8 * 240 = 190 kg/y. On the other hand, phosphorus treatment (e.g., alum-FeCl addition) removes about 85% of phosphorus, resulting in an effluent phosphorus loading of 0.15 * 240 = 35 kg/y. Based on this source evaluation, the net impact of phosphorus treatment at of centralized sewage treatment plant in the village of Alden is a 190 - 35 = 155 kg/y reduction in phosphorus loading. We can judge the water quality benefit of phosphorus treatment by comparing forecast predictions between (for example) the no change scenario, and the same scenario repeated with a 155 kg/y reduction in phosphorus loading.

Forecast Scenario Predictions

The model was run to forecast water quality for each of the five scenarios. The results are displayed in Figures 38 through 42. Each figure plots the predictions of a single water quality parameter, for each of the five scenarios, to facilitate comparisons of the results. Figure 38 plots total phosphorus concentrations in the epilimnion layer of the lake, while Figure 39 plots total phosphorus concentrations in the hypolimnion. Figure 40 plots the forecasts of chlorophyll concentrations; Figure 41 plots hypolimnetic dissolved oxygen concentrations; and, Figure 42 plots the forecasts of Secchi disk depths

No Change

The no change scenario forecast predictions show that, for each of the water quality parameters in Figures 38-42, future concentrations/values are essentially the same as present conditions. This means that water quality in Torch Lake is expected to remain the same under present loading conditions. This also implies that the appropriate role of land use and water quality managers is to maintain the current water quality of Torch Lake, by preventing or minimizing future increases in phosphorus loadings.

The no change predictions also serve as a baseline for comparison to the other scenario forecasts.

Phosphorus Loading Cutoff

Phosphorus (Figures 38 and 39) and phytoplankton (Figure 40) concentrations decline quite rapidly following the cut-off of phosphorus loadings. In the epilimnion, total phosphorus concentrations drop by half within 1_ years; in the hypolimnion, the response is slightly slower, taking a little more than 2 years for total phosphorus concentrations drop by half. Clearly, the response of phosphorus concentrations to loading reduction is much faster than the 10-year hydraulic residence time. Similarly, peak chlorophyll concentrations drop by half in the second year following the loading cut-off. Although these response times were based on a loading reduction scenario, the water quality responses are similar in the case of a loading increase.

The rapid response of water quality parameters to changes in phosphorus loading predicted by the model, is consistent with the results of paleolimnological studies conducted elsewhere in the Chain of Lakes (Fritz et al., 1993). Based upon variations in diatom assemblages from dated sediment cores, Fritz et al. determined that phosphorus concentrations increased in Lakes Bellaire and Elk coincident with local land clearing for settlement and logging, and have returned to presettlement levels in recent decades. Thus, both mass balance and paleolimnological approaches predict that lake phosphorus concentrations respond quite rapidly to changes in loading.

Dissolved oxygen concentrations were completely insensitive to the phosphorus loading cutoff, as shown in Figure 41. In fact, all five scenarios produced essentially the same forecast predictions for hypolimnetic dissolved oxygen.

Forecast predictions of Secchi disk depth (Figure 42) show a small increase in transparency (up to 1m) in June and early July, following the phosphorus loading cutoff. This is the period of each year when chlorophyll concentrations reach high enough concentrations to influence light extinction in the water column.

Projected Annual Population Growth of 1.5%

The 1.5% growth scenario forecast predicts only a marginal increase (0.08 ppb or 3%) in total phosphorus concentrations at the end of 8 years, compared to the no change scenario. This increase is slightly smaller than the increase in total phosphorus loading over the same period (4.5%). Only marginal changes in the other water quality parameters (chlorophyll, DO and Secchi depth) were predicted for this scenario.

Projected Annual Population Growth of 5%

The 5% growth scenario forecast predicted a more significant increase in total phosphorus and chlorophyll concentrations, compared to the no change scenario. Total phosphorus concentrations had increased by 0.27 ppb (10%) at the end of 8 years. Peak chlorophyll concentrations are also forecast to increase by 10% (0.1 ppb) in the last year of this scenario. As in the previous scenario, only marginal changes in the other water quality parameters (DO and Secchi depth) were forecast.

Alden Centralized Sewage Treatment Options

The Alden centralized treatment scenario forecast predicts a small but discernable reduction in total phosphorus concentrations (0.07 ppb or 3%) compared to the no change scenario forecast. Peak chlorophyll concentrations are also forecast to decline by 3%. These percent reductions are the same as the reduction in total phosphorus loading attributable to phosphorus removal at the proposed Alden sewage treatment plant. Again, only marginal changes in the other water quality parameters (DO and Secchi depth) were forecast.

As this scenario demonstrates, the phosphorus loading impact of an individual development needs to be quite large (on the order of 100 kg/yr or more) to impact water quality at the scale of Torch Lake. On the other hand, water quality is affected *cumulatively* by the sum of loadings to the lake, based on decisions made at many potential development sites, so the model may be more valuable in terms of forecasting changes occurring at the scale of the watershed or the drainage basin.

CONCLUSIONS AND RECOMMENDATIONS

1. The water quality of Torch Lake is pristine in comparison to the normal measures of lake trophic status, as demonstrated by the data collected in this project:

Variable	Torch Lake	Oligotrophic	Mesotrophic	Eutrophic
Total Phosphorus (ppb)	***2.6***	<10	10-20	>20
Chlorophyll (ppb)	***0.55***	<4	4-10	>10
Secchi Disk Depth (m)	***5-10***	>4	2-4	<2
Hypolimnetic Oxygen (% saturation)	***100***	>80	10-80	<10

2. Comparisons to recent monitoring data indicate little change in water quality over the past 5 - 10 years.
3. Management should emphasize protection of existing Torch Lake water quality.
4. Water and phosphorus mass balances demonstrate that flow, loading and loss estimates appear reasonable in comparison to independent estimates and data for other water bodies; however, accuracy of some of these components were less than desired due to lack of data.
5. Tributaries, groundwater and precipitation all contribute significant phosphorus loadings to Torch Lake.
6. The groundwater monitoring work is unique in this region and results are provocative, indicating that seepage of shallow groundwater is comparable to tributary loading and atmospheric deposition as a source of phosphorus to Torch Lake.
7. Settling removed 90% of the phosphorus entering the lake in 2005.
8. The LAKE2k Model is a useful tool for illustrating the expected water quality responses to changes in phosphorus loadings occurring at the watershed/drainage basin scale.
9. The analysis of project data demonstrated a number of shortcomings and missed opportunities, which suggest improvements that can be made to either the water quality project in Clam and Bellaire Lakes being conducted in 2006, or follow-up efforts in Torch Lake:

   $ A consistent program to monitor major tributary flows (employing stage-discharge relationships) and lake levels must be in place during water quality modeling projects. Flows and levels should be monitored weekly, or more frequently during periods of wet weather.

   $ Additional phosphorus analyses should be allocated to load component sampling; all tributary samples should be accompanied by flow measurements.

   $ TLA should consider extending the highly-successful shallow groundwater sampling program to other lakes in the region, and pursue the factors responsible for elevated phosphorus concentrations in shallow groundwater.

$ Water column sampling must be conducted consistently from May through October; it may be appropriate to sample every 3 weeks (instead of every 2), to allow for data review between sampling cruises.

$ All total phosphorus samples should be split into two sample bottles, to allow reanalysis of samples if questionable laboratory results are obtained.

$ Dissolved (field-filtered) as well as total phosphorus should be analyzed in all epilimnetic lake samples.

$ Phytoplankton functional groups as well as chlorophyll should be analyzed in selected lake samples. Phytoplankton should be sampled at consistent depths, defined by the water quality model's vertical segmentation.

$ Cooperative efforts with the Platte Lake Fishery should continue, to measure light extinction together with Secchi disk depth.

$ TLA and GLEC should investigate experimental methods to better understand the kinetics of calcium carbonate precipitation and possible relationships between declining light transparency and rainfall.

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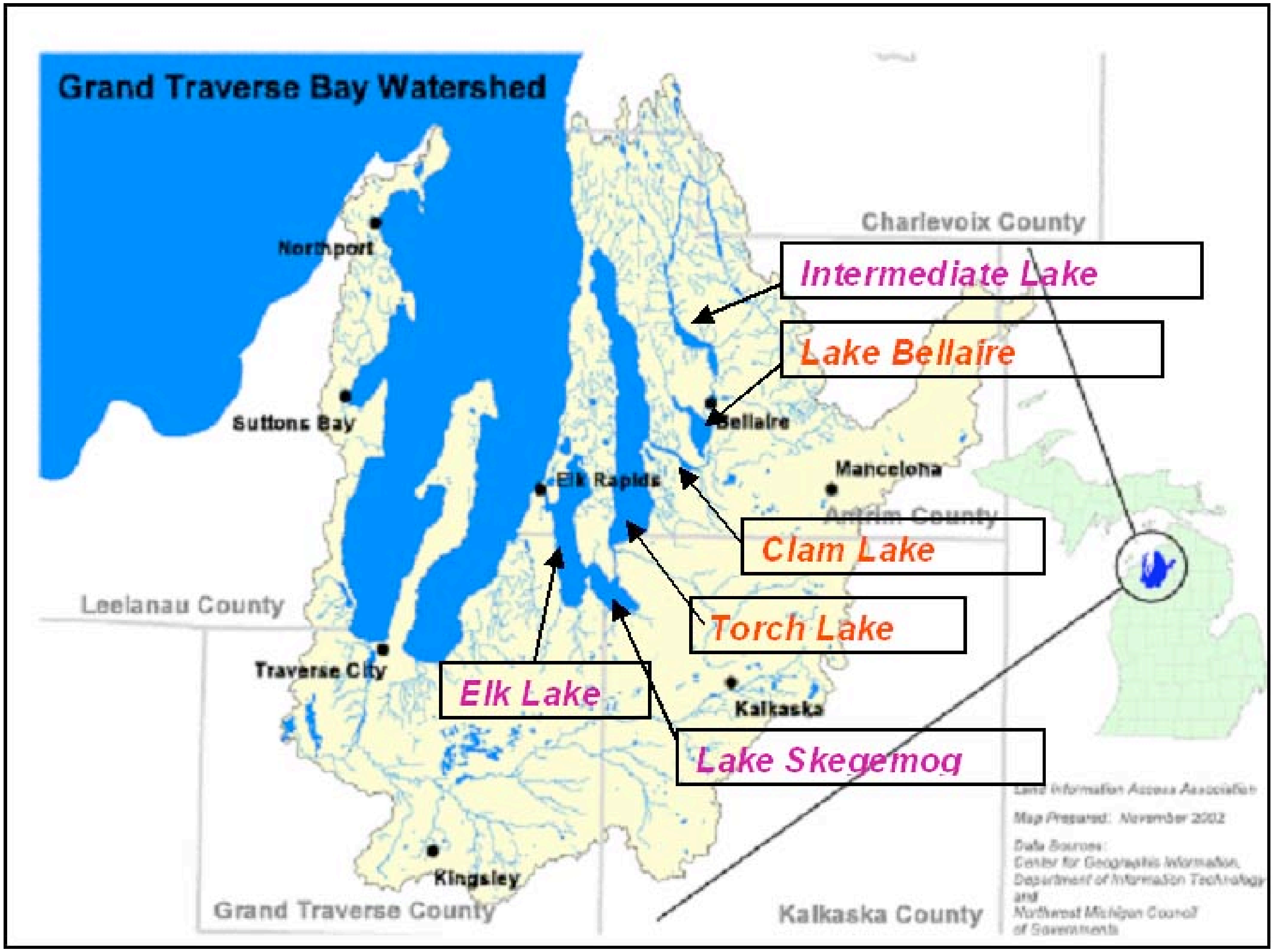


Figure 1. Watershed of Grand Traverse Bay; Elk River Chain of Lakes are Identified

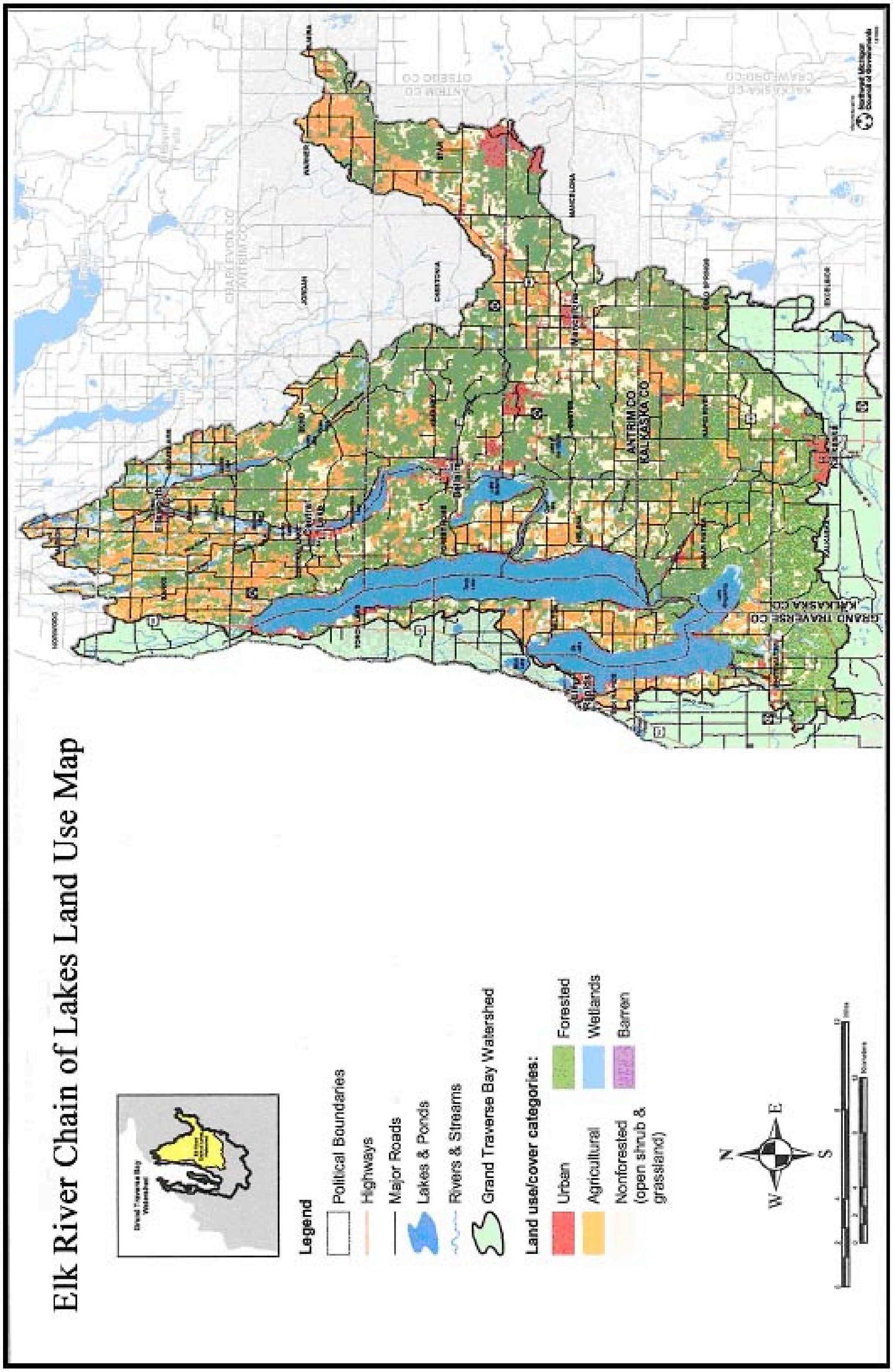


Figure 2. Map of Land Use in the Elk River Chain of Lakes Watershed

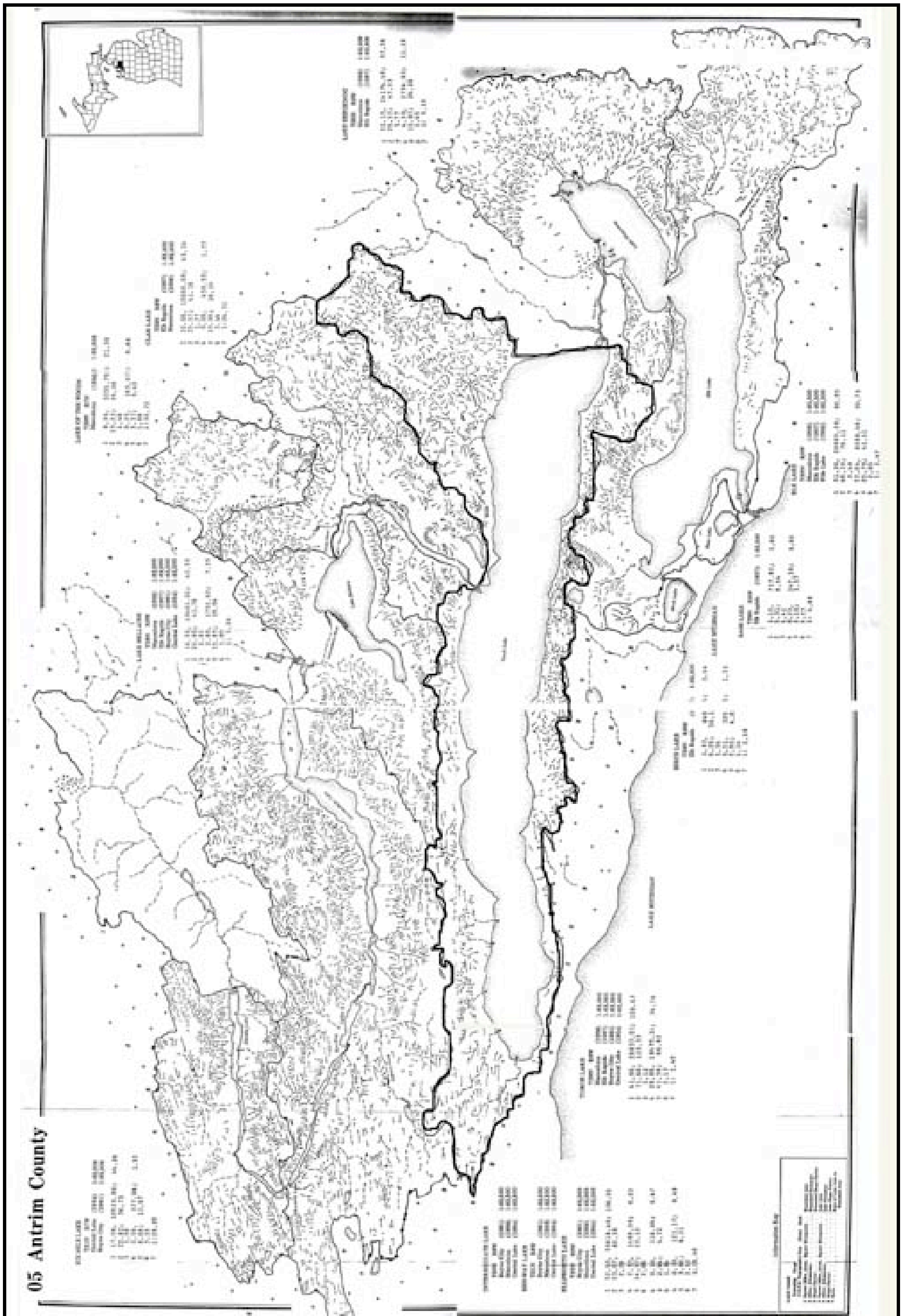


Figure 3. Torch Lake Watershed Boundary

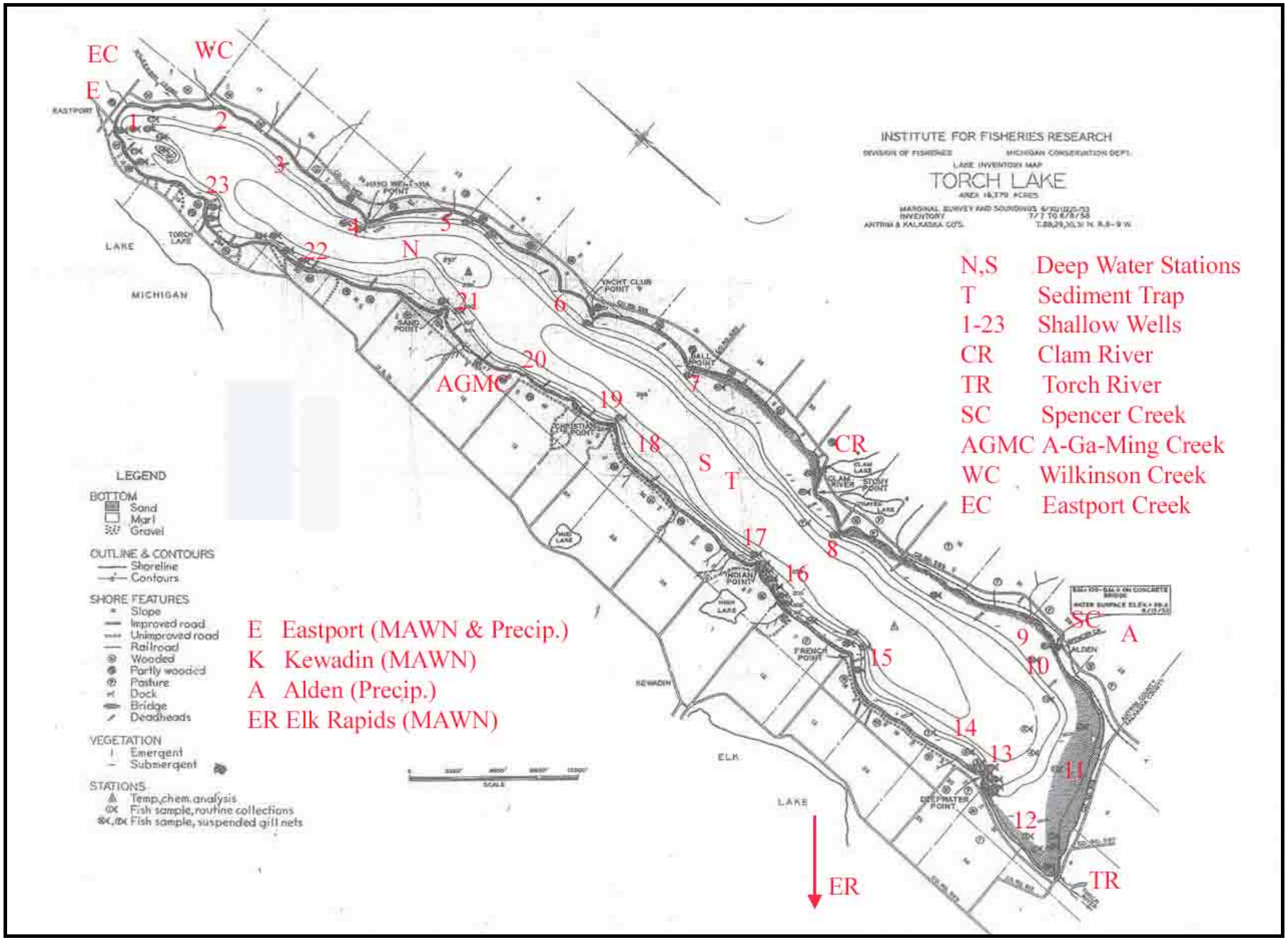
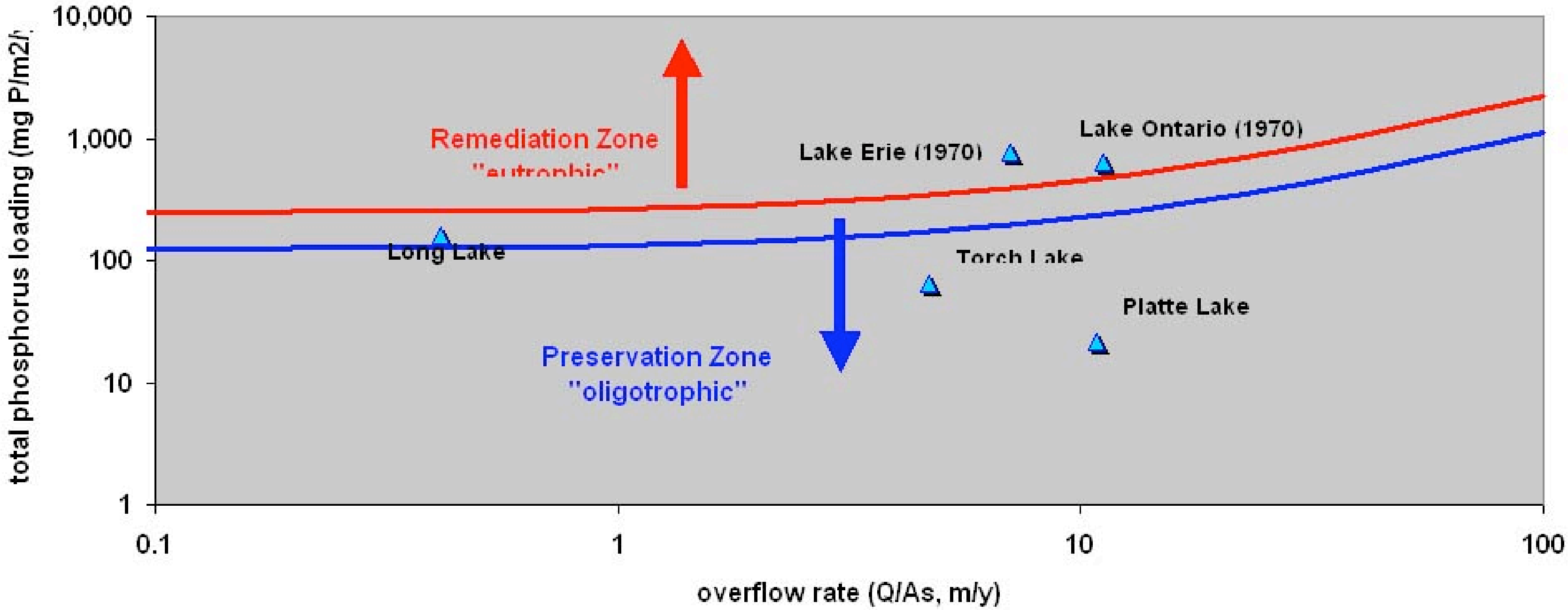


Figure 4. Monitoring and Sampling Locations for Torch Lake



Figuure 5. Vollenweider Phosphorus Budget Model for Lakes

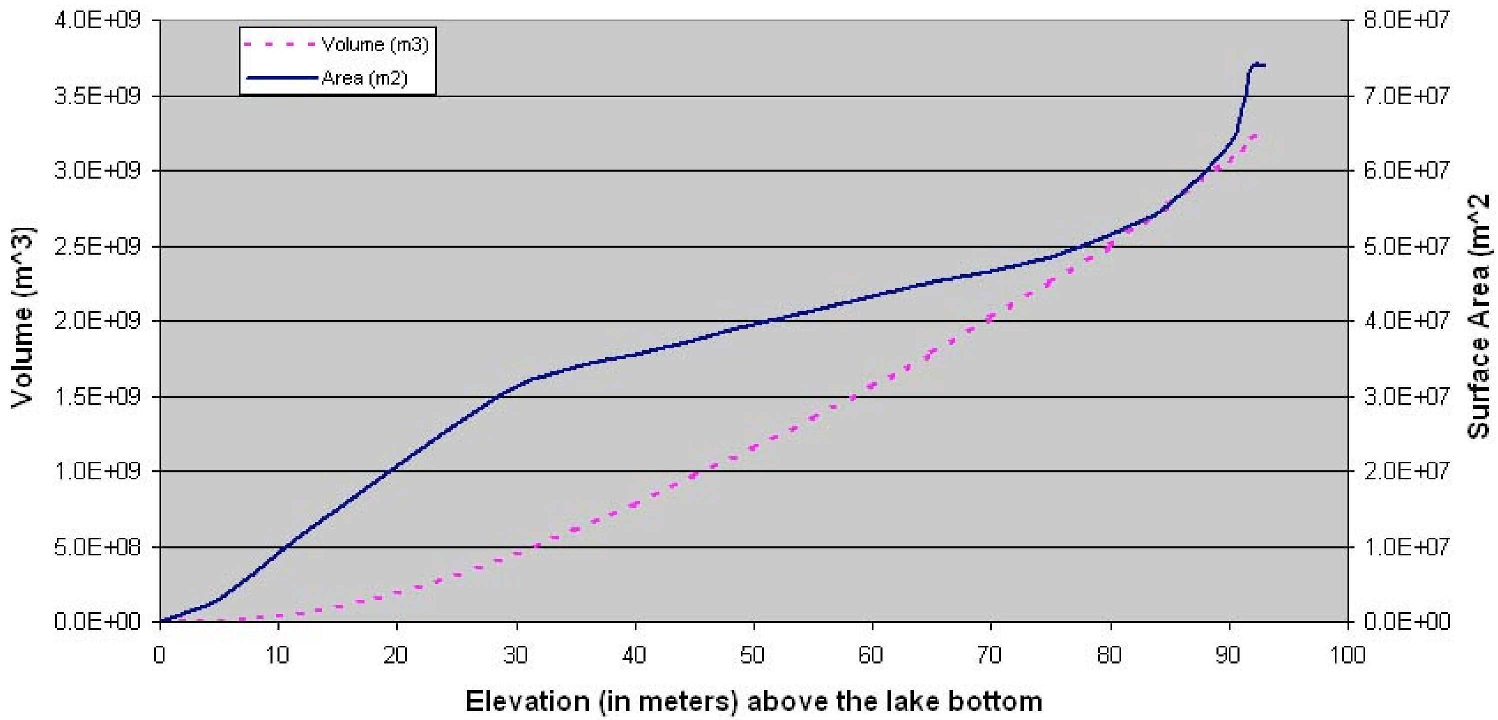


Figure 6. Elevation-Area and Elevation-Volume Curves for Torch Lake

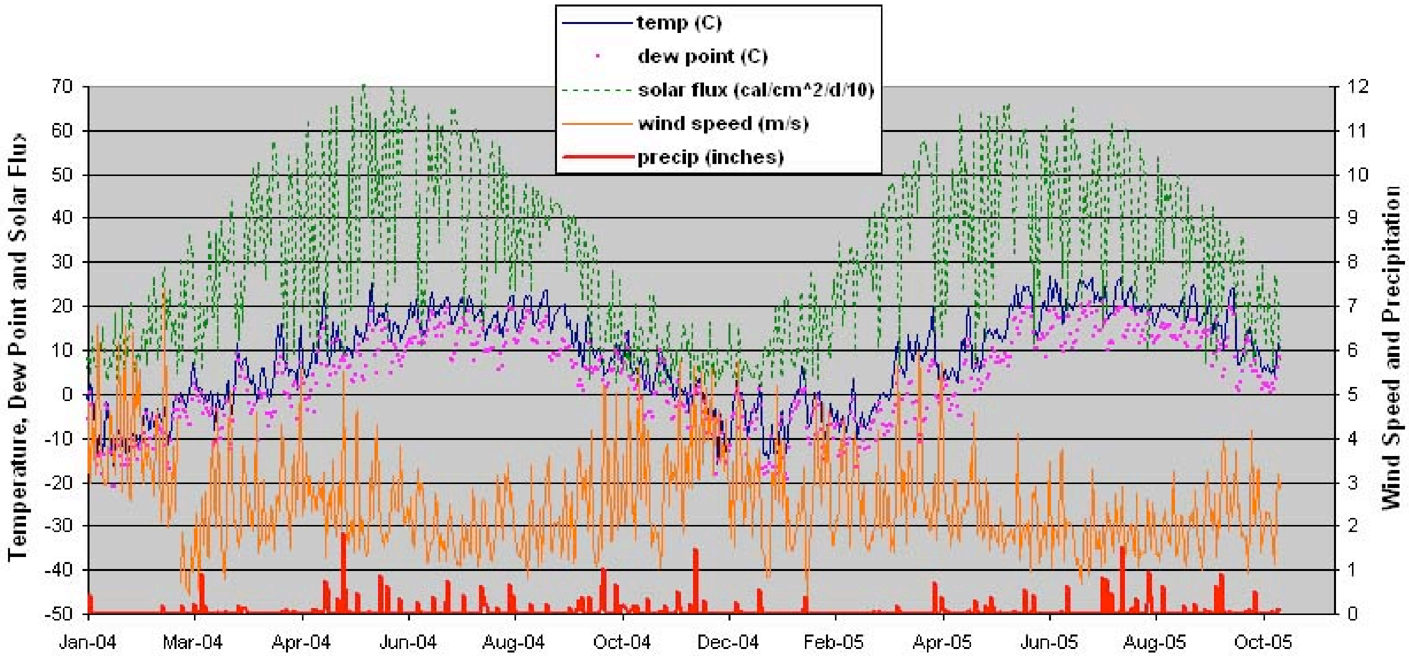
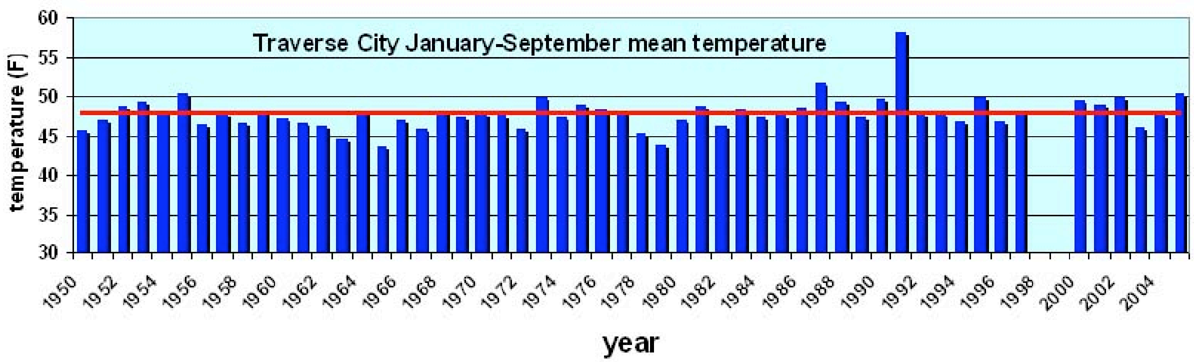


Figure 7a. Average Daily Torch Lake Meteorologic Data for 2004 and 2005



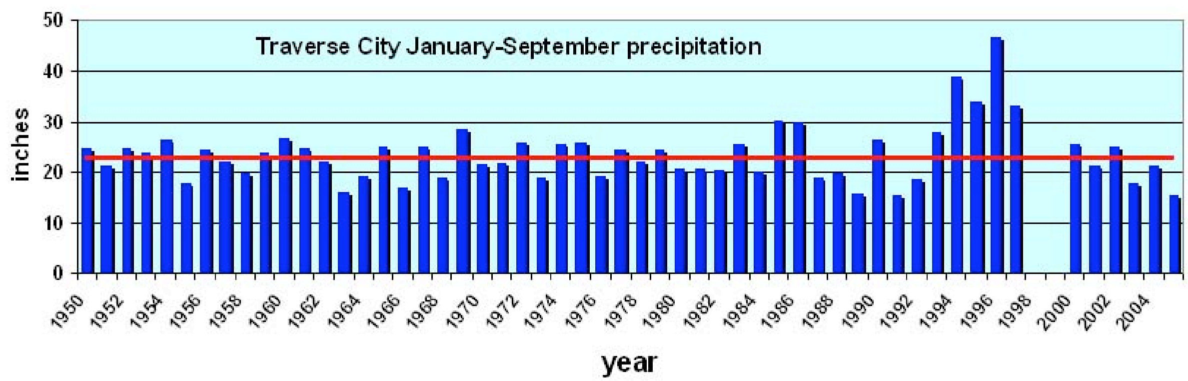


Figure 7b. Long Term Annual Trends in Temperature (top panel) and Precipitation (bottom panel) Measured at Traverse City Airport (dashed line is long-term average; data missing for years 1998 and 1999)

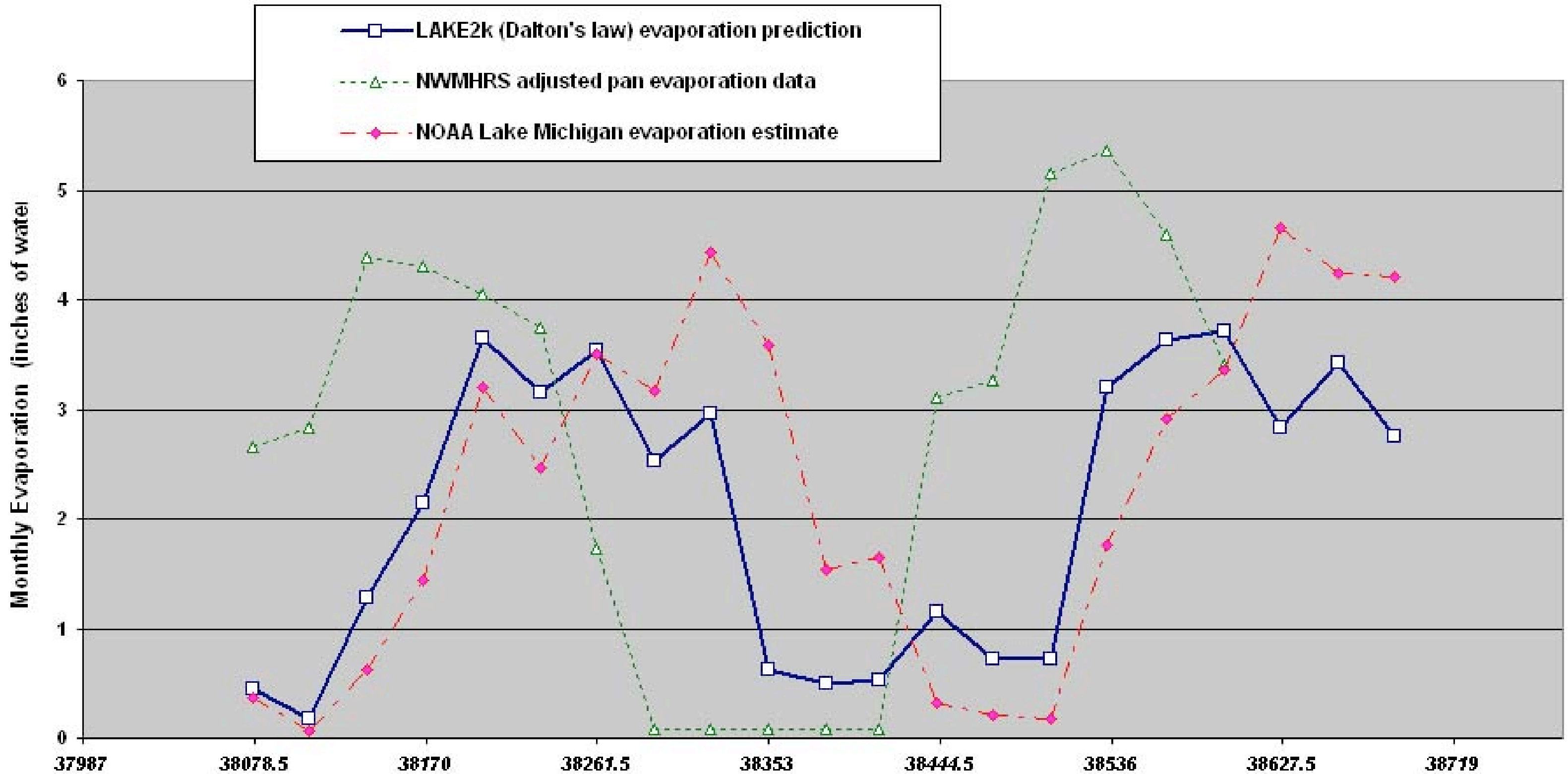


Figure 8. Comparison of Evaporation Estimates for Torch Lake

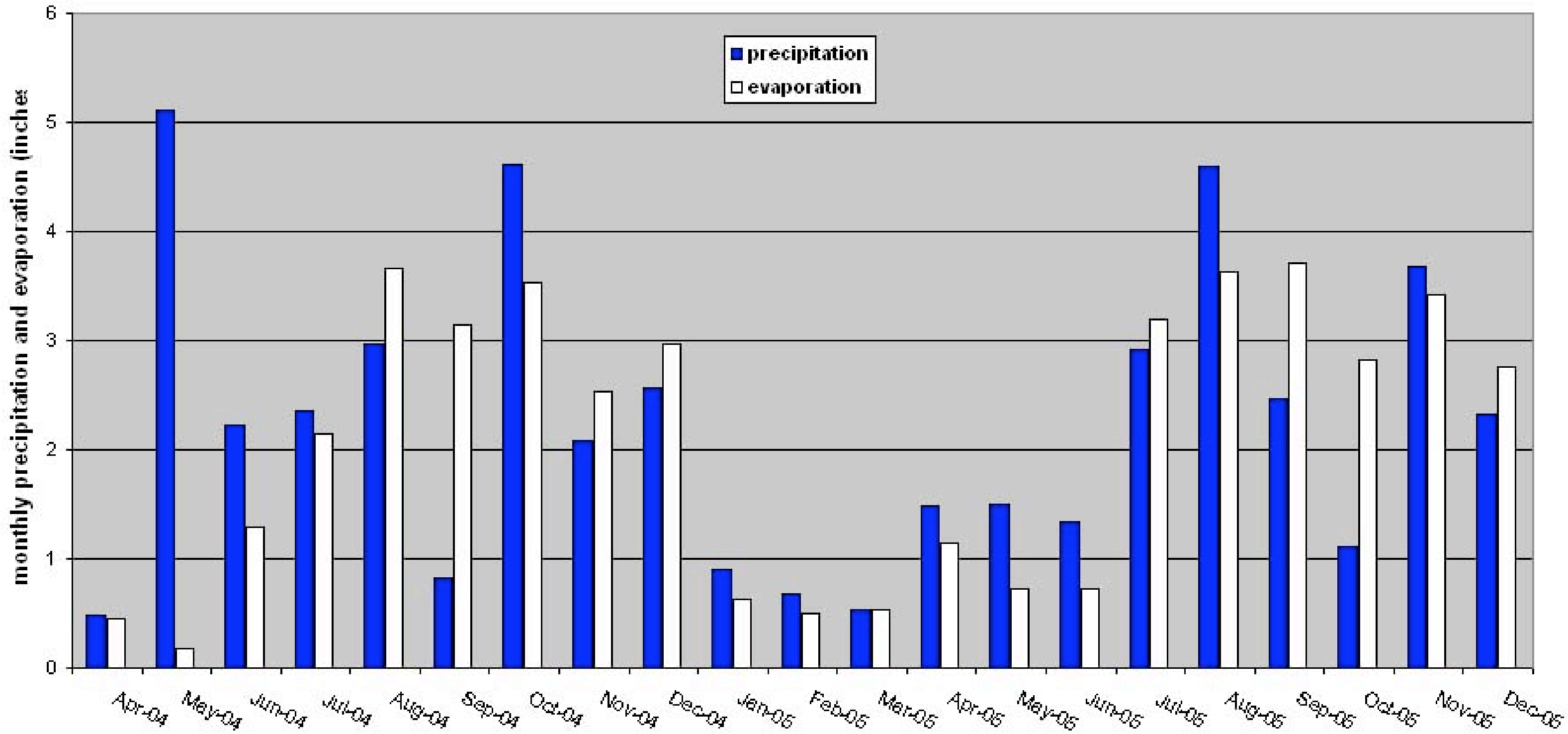


Figure 9. Comparison of Precipitation and Evaporation Rates for Torch Lake

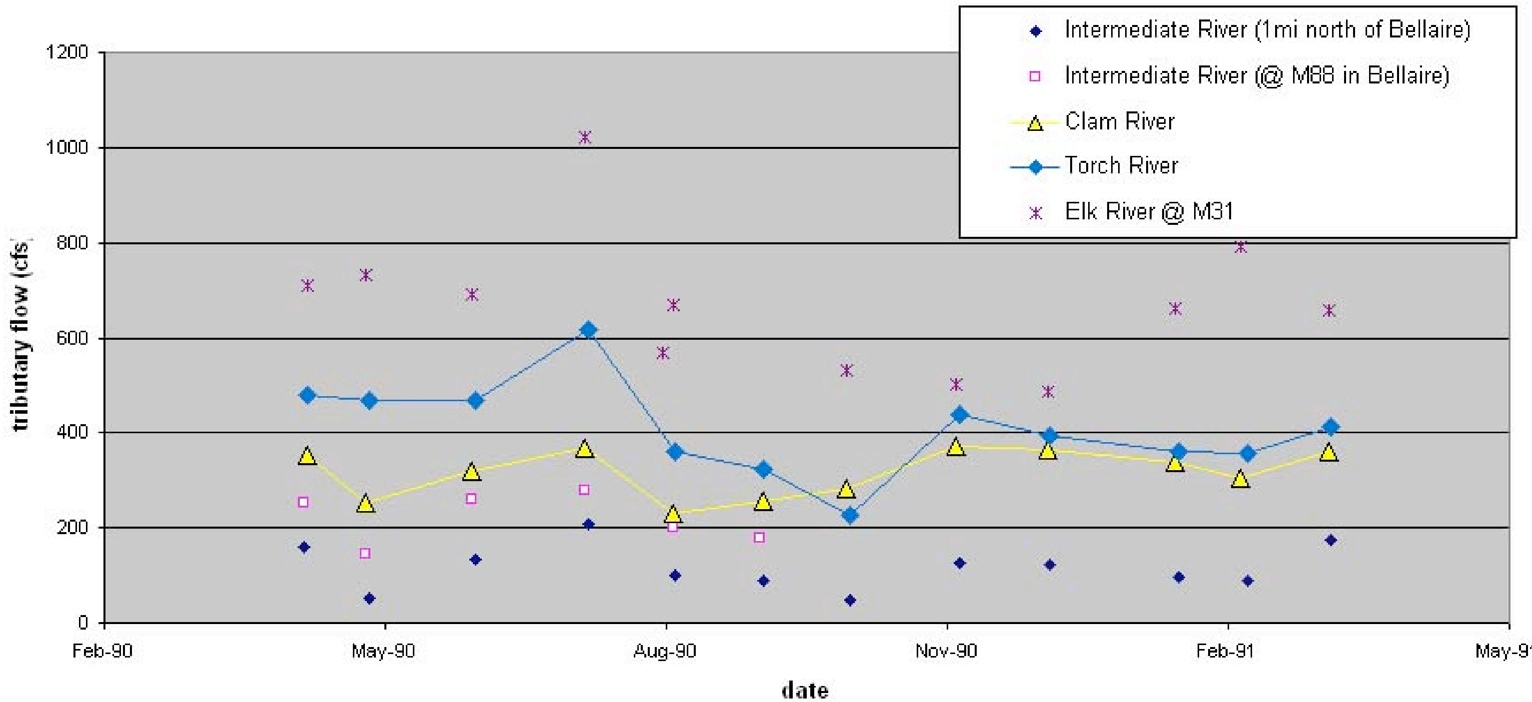


Figure 10. USGS Flow Data for the Elk River Chain of Lakes, Including Clam and Torch Rivers

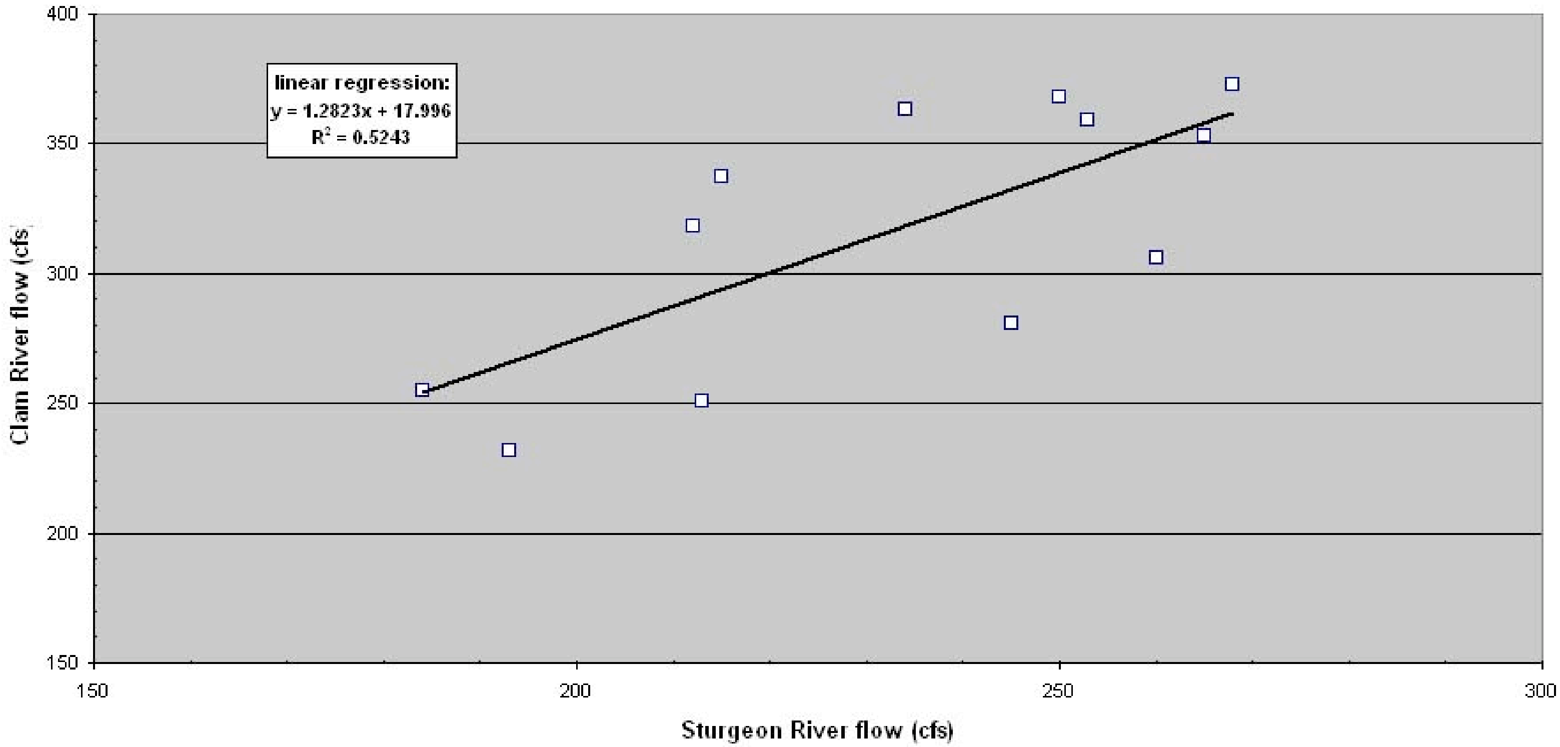


Figure 11. Correlation Between Sturgeon and Clam River Flows (1990-91 USGS data)

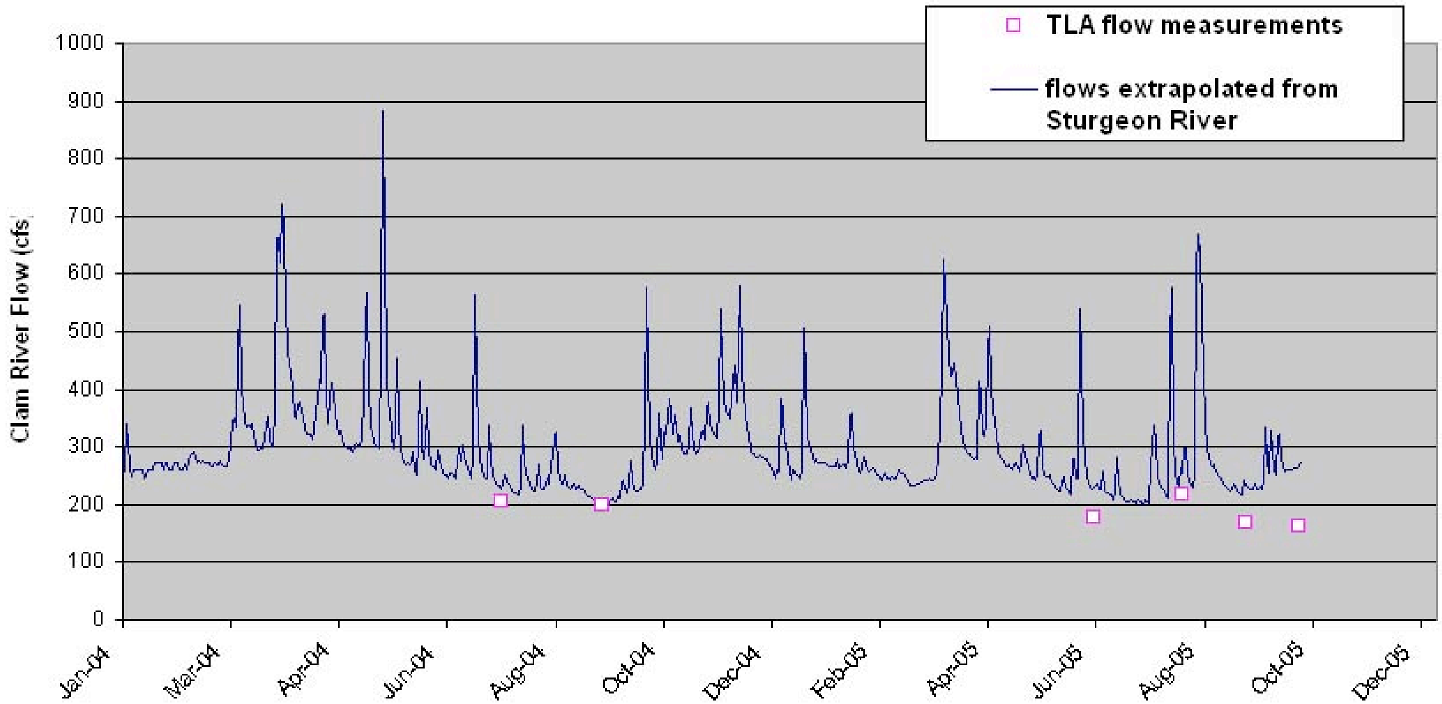


Figure 12. Comparison of Measured and Extrapolated Flows for the Clam River in 2004-05

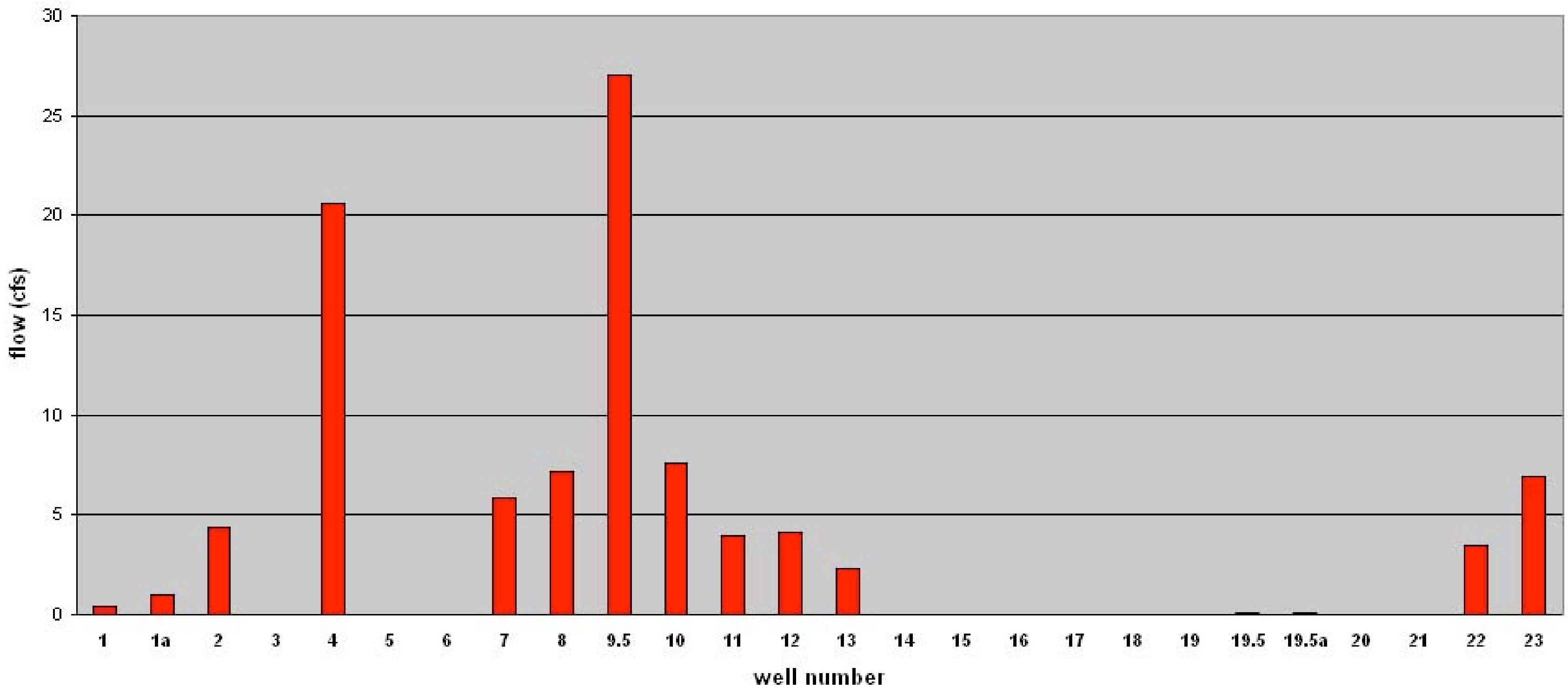


Figure 13. Average groundwater flows measured at shallow well (piezometer) locations

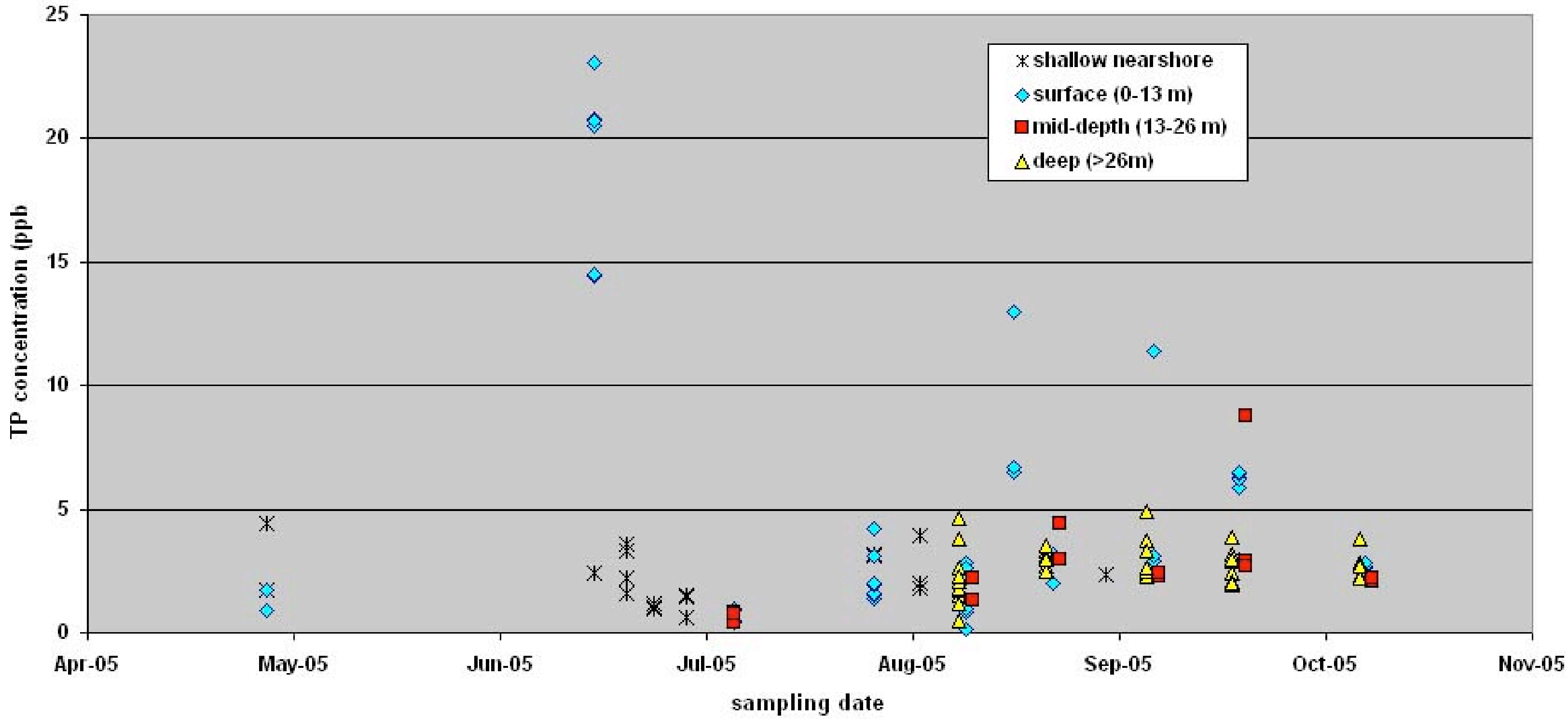


Figure 14. Time Series: All Total Phosphorus Concentrations Measured in Torch Lake During 2005

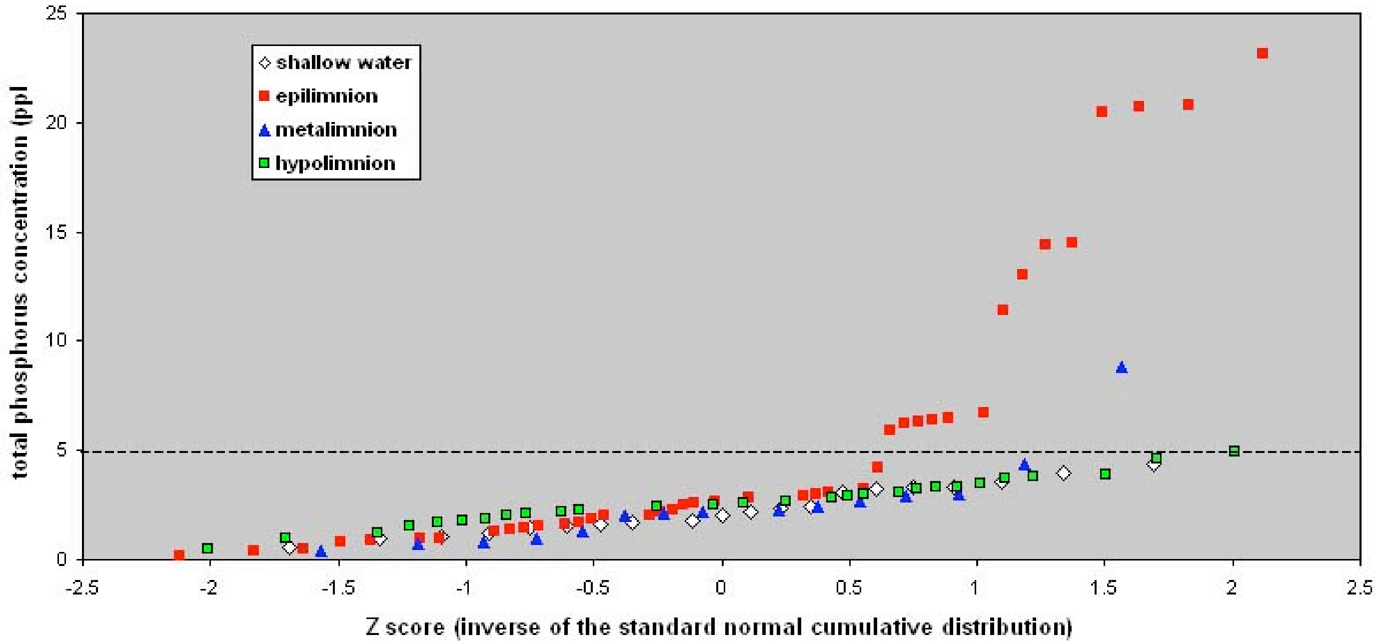


Figure 15. Cumulative Frequency Distributions for Phosphorus in Torch Lake Water

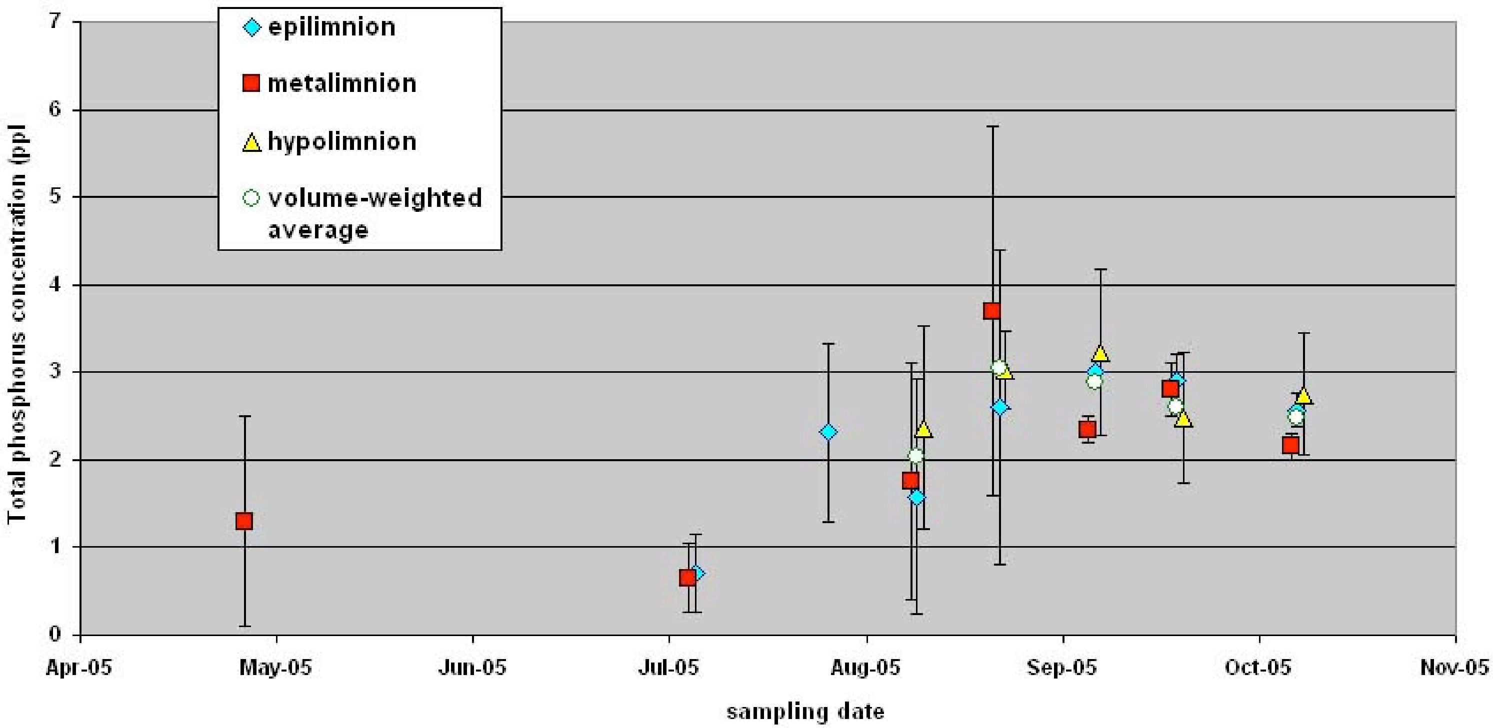


Figure 16. Cruise and Station-averaged Total Phosphorus Concentrations (error bars indicate approximate 95% confidence limits)

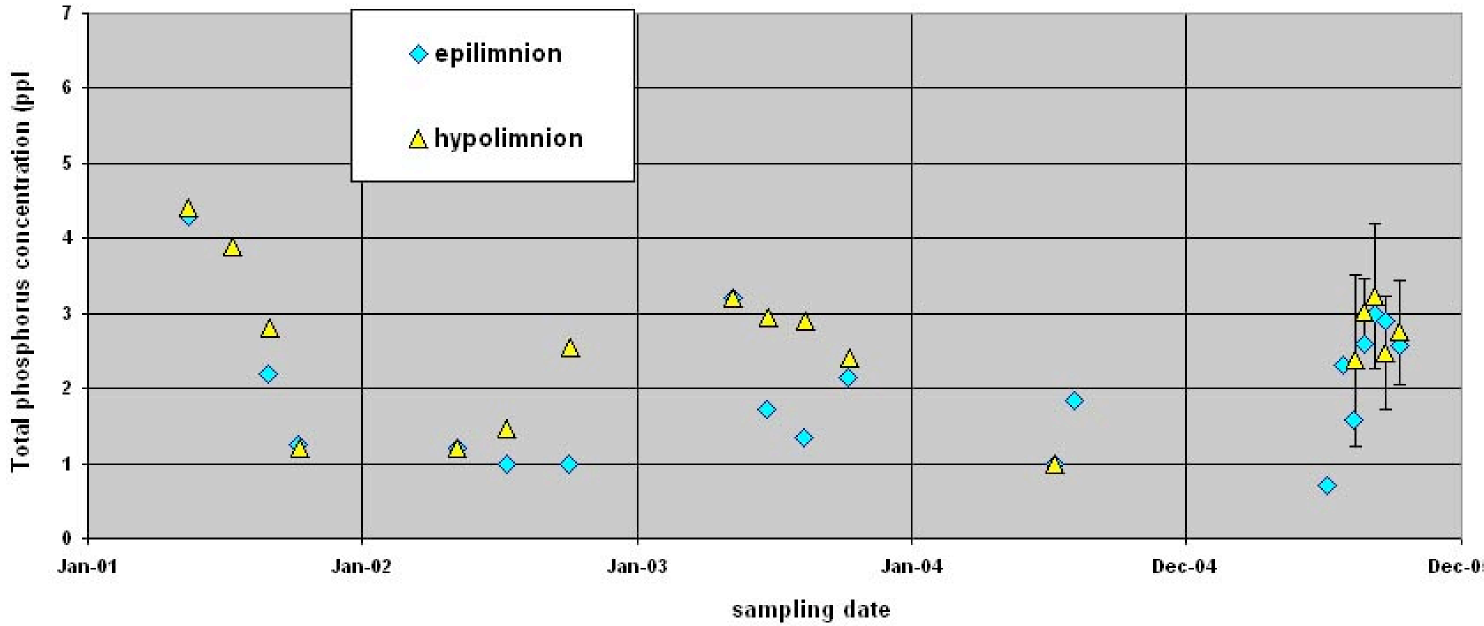


Figure 17. 5-Year Record of Total Phosphorus Concentrations in Torch Lake (TLA/GLEC and TOM data)

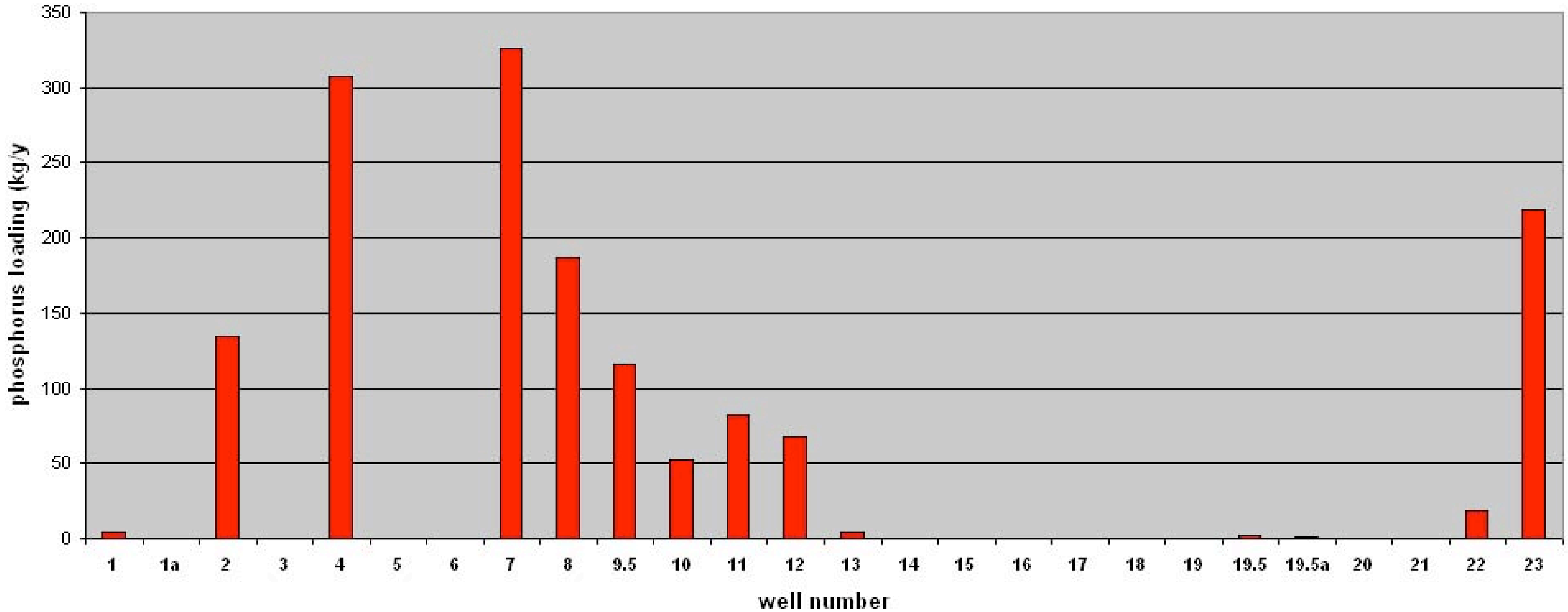


Figure 18. Groundwater Phosphorus Loading Estimates at Shallow Well Locations

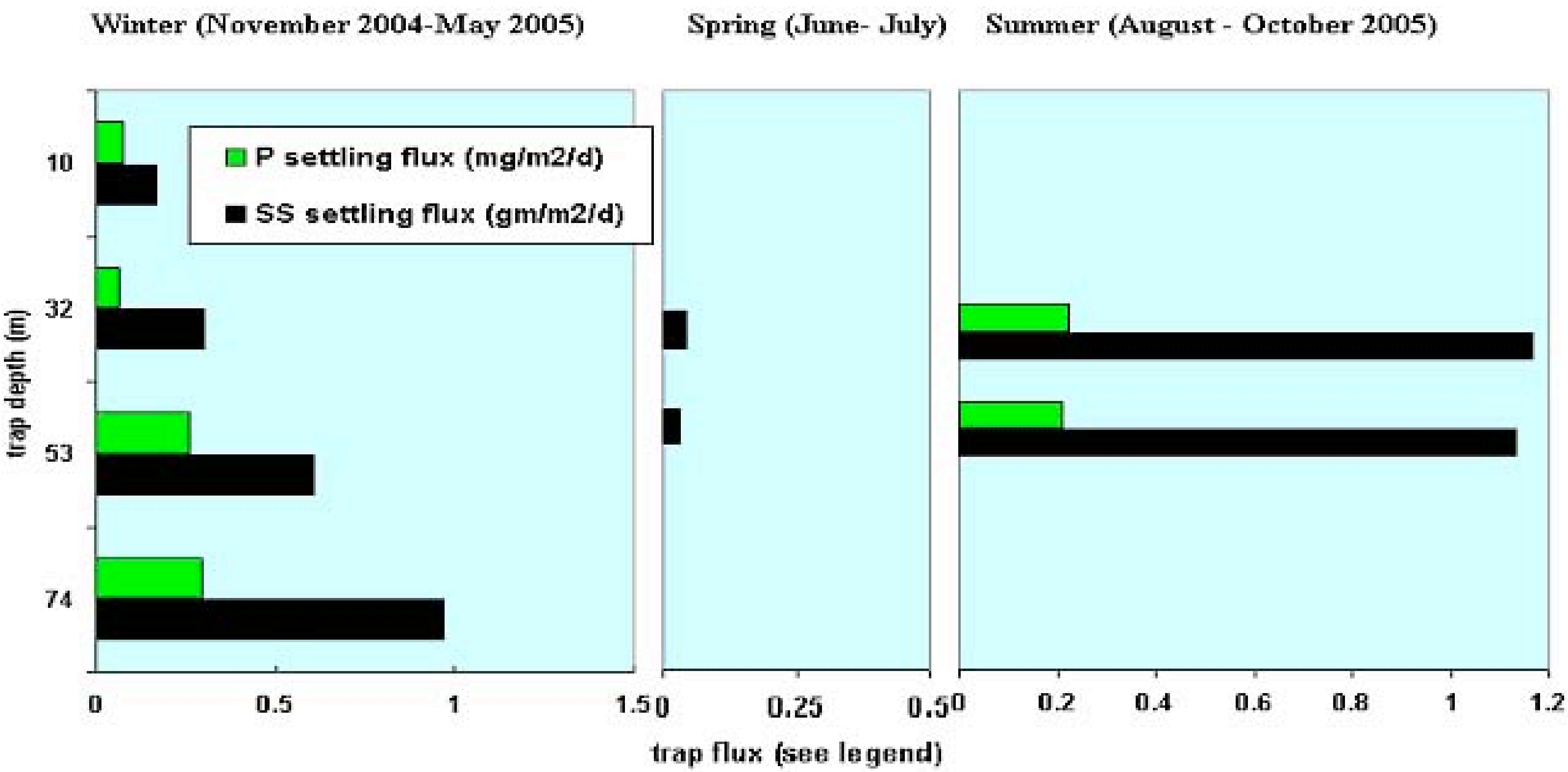


Figure 19. Phosphorus (P) and Suspended Solids (SS) Settling Fluxes Measured Each Season in Torch Lake Using Sediment Traps (Duplicate Traps were Deployed at 46 meter depth in Spring and Summer)

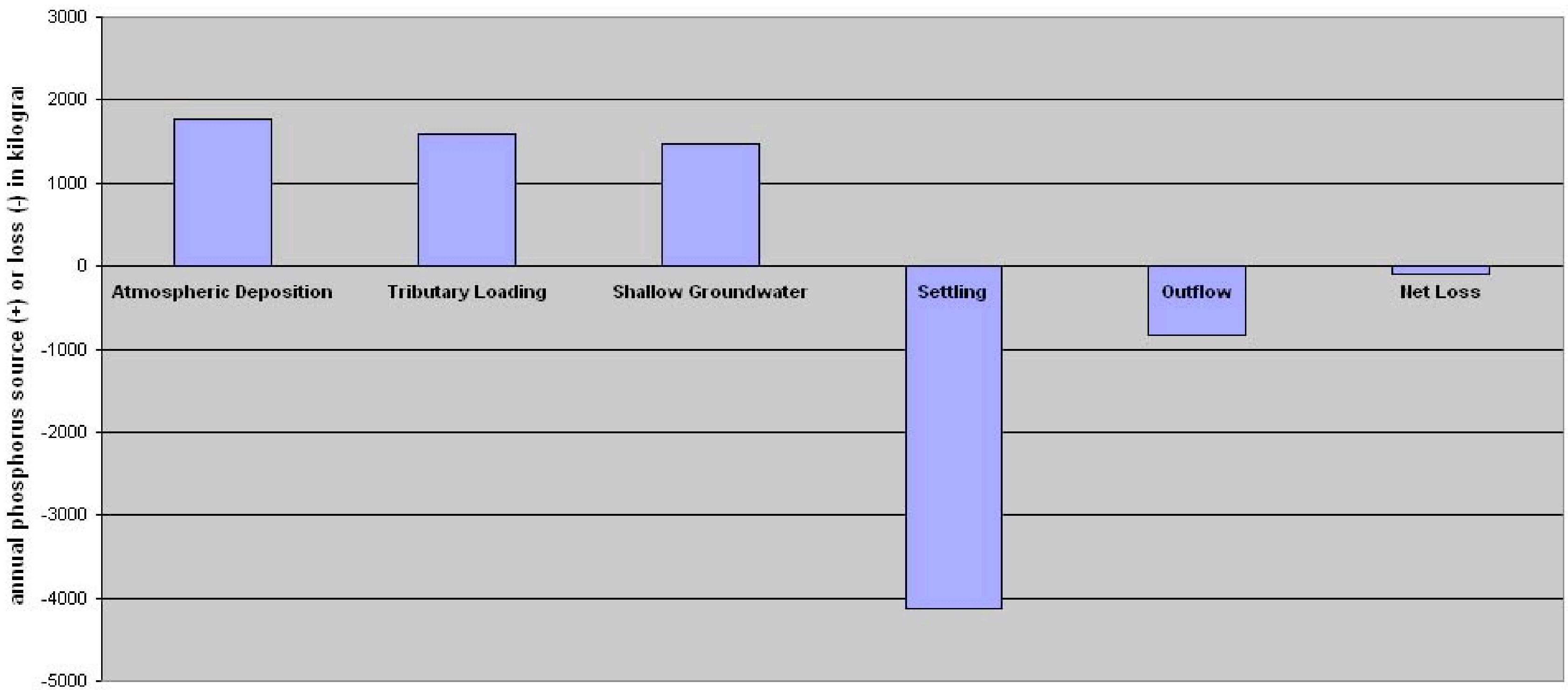


Figure 20. Total Phosphorus Mass Balance for Torch Lake (November 2004 - October 2005)

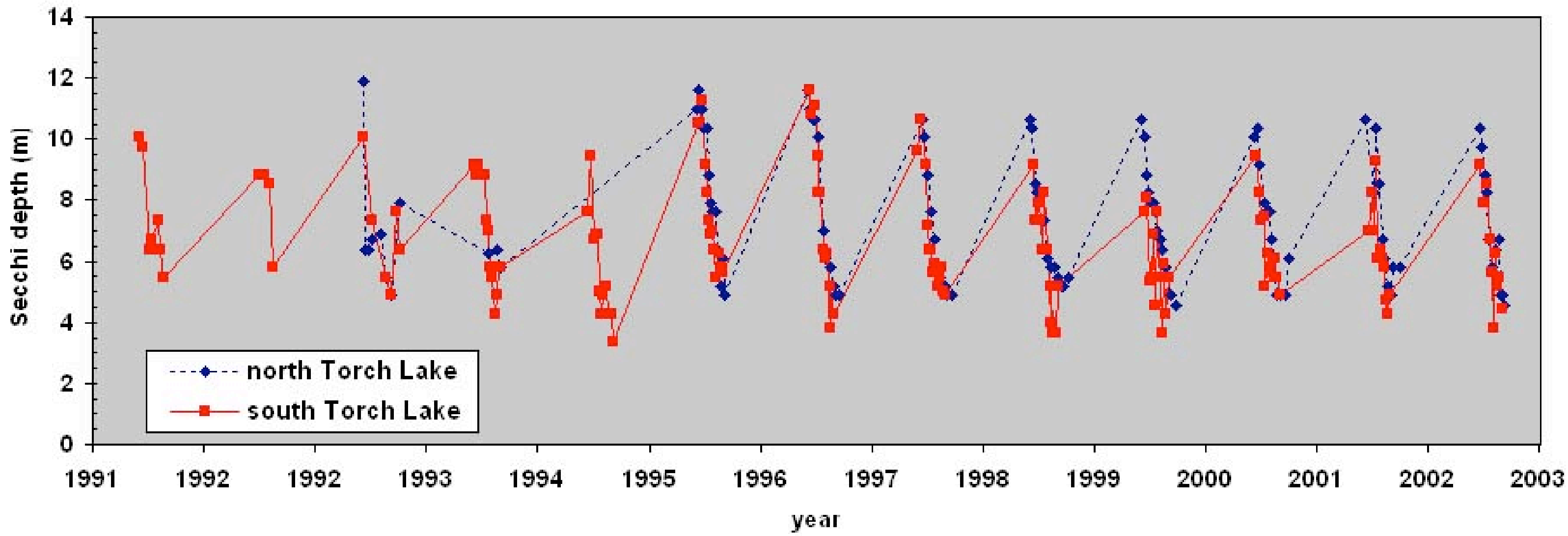


Figure 21. 13 Years of Secchi Disk Depths in Torch Lake (TOM data)

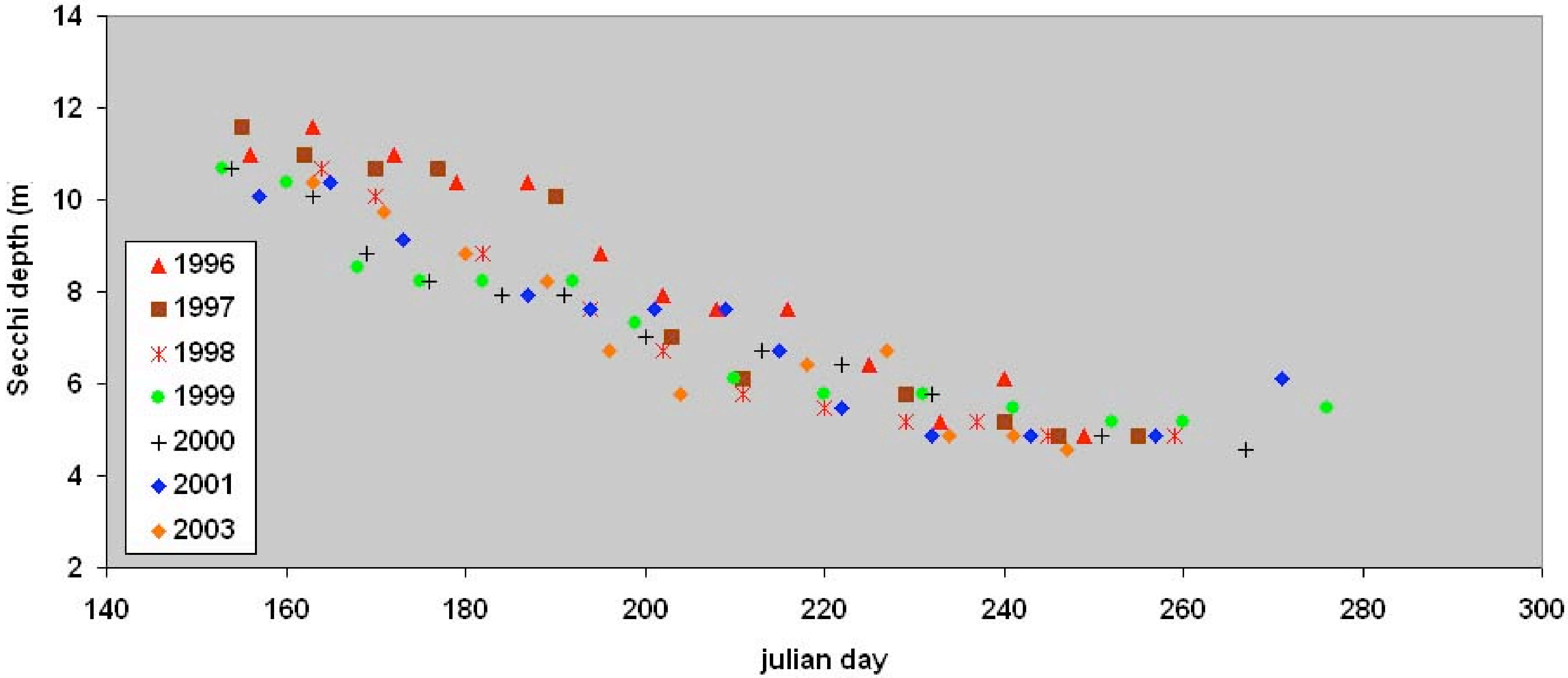


Figure 22. Within-Year Observations of Secchi Disk Depths at North Torch Lake Station (sparse data years removed)

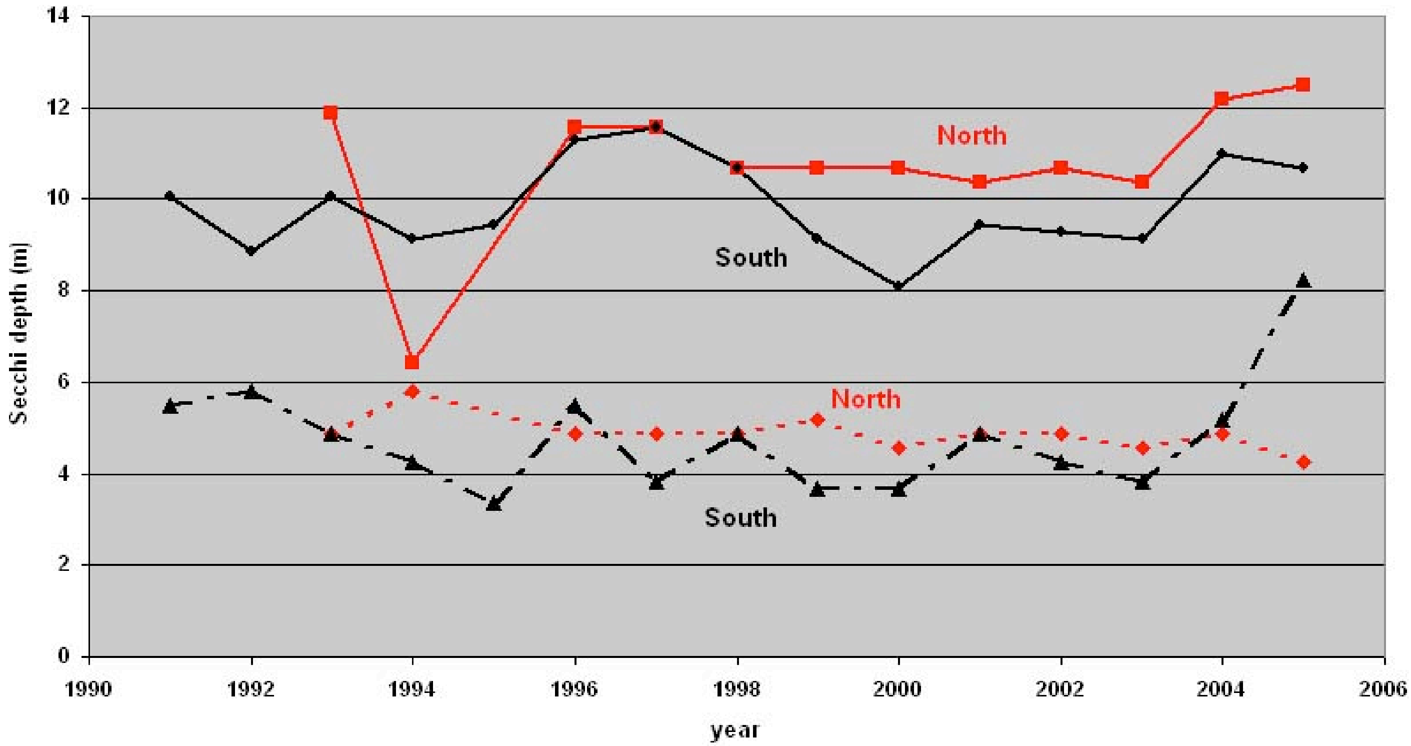


Figure 23. Minimum and Maximum Secchi Disk Depths Observed Each Year in Torch Lake

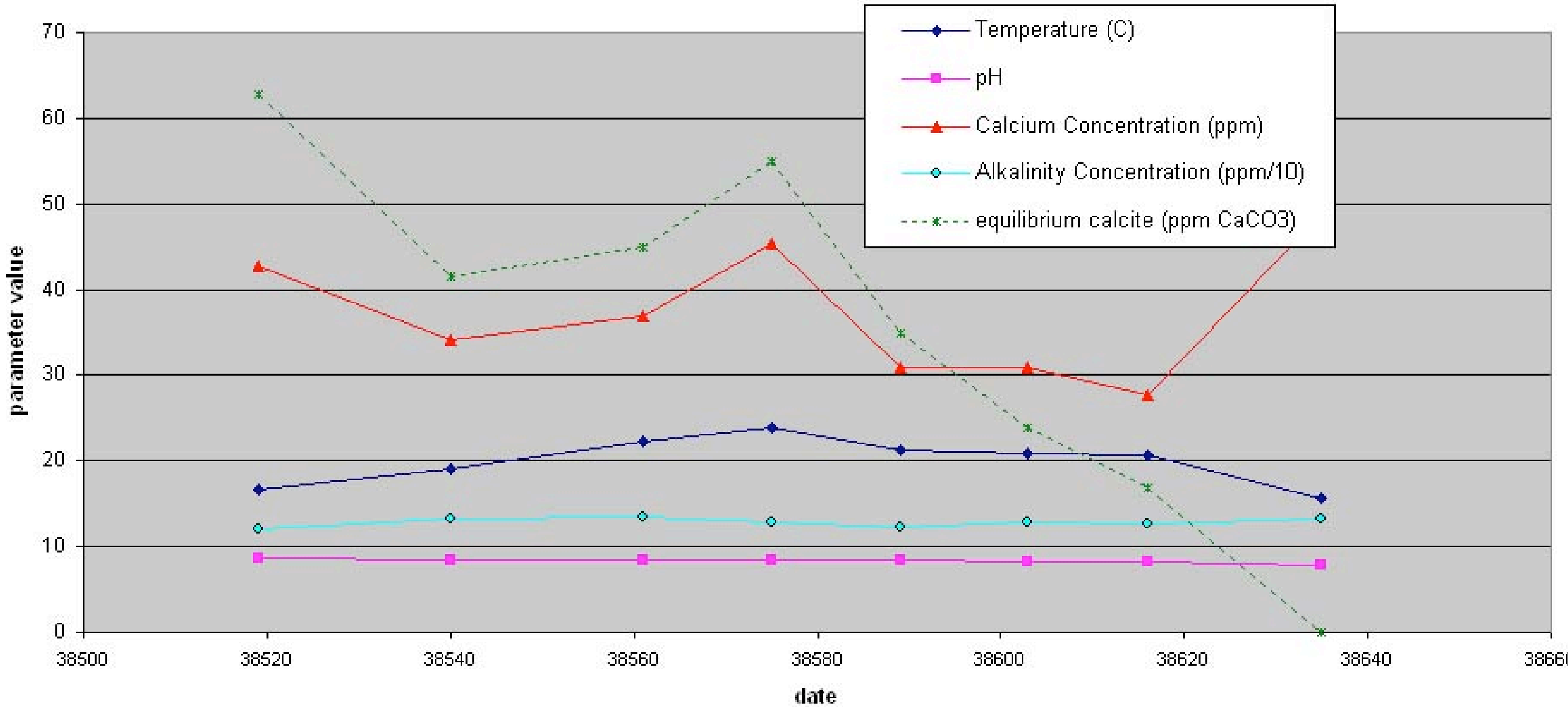


Figure 24. Seasonal Trend of Water Quality Parameters Associated with Calcium Carbonate Equilibria (South Torch Lake Epilimnion data)

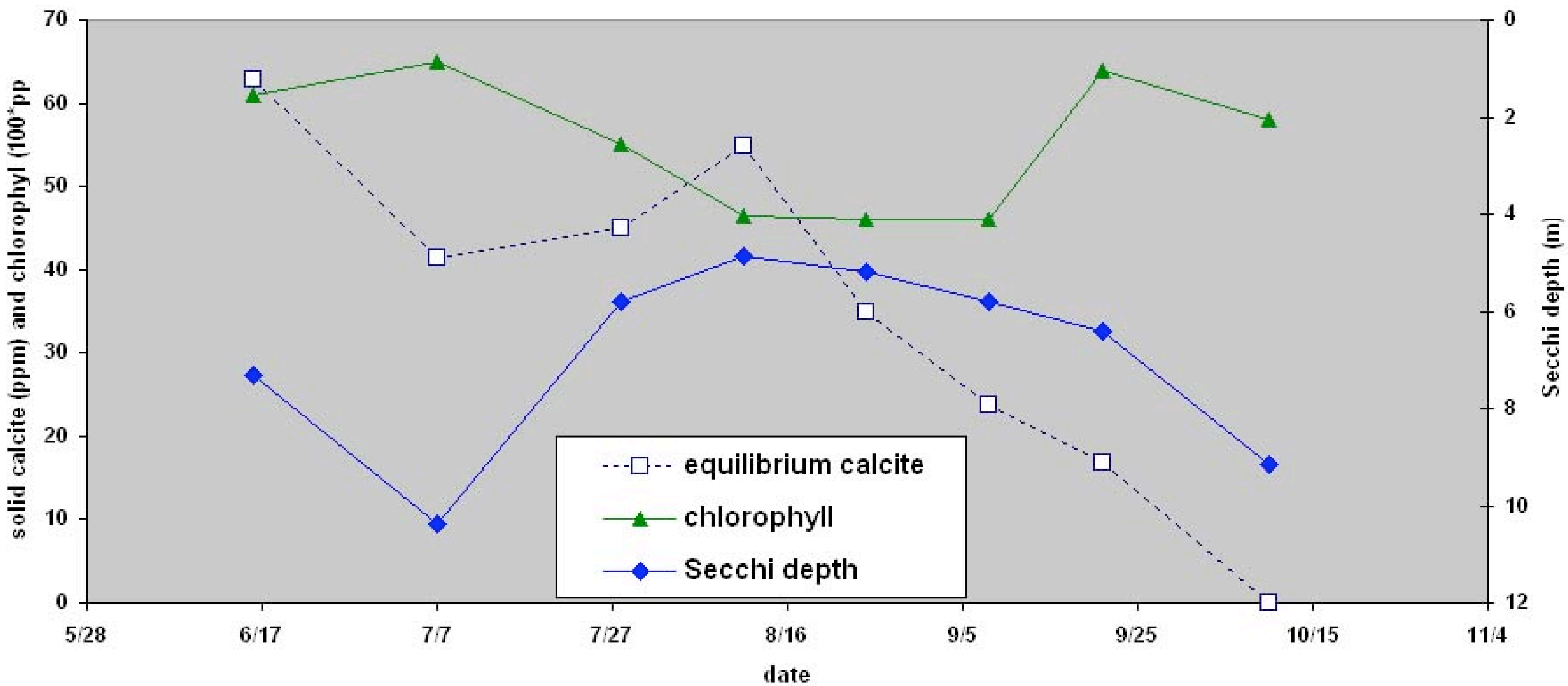


Figure 25. Relationships Between Secchi Disk Depth and Chlorophyll and Equilibrium Calcite Concentrations at South Torch Lake Station

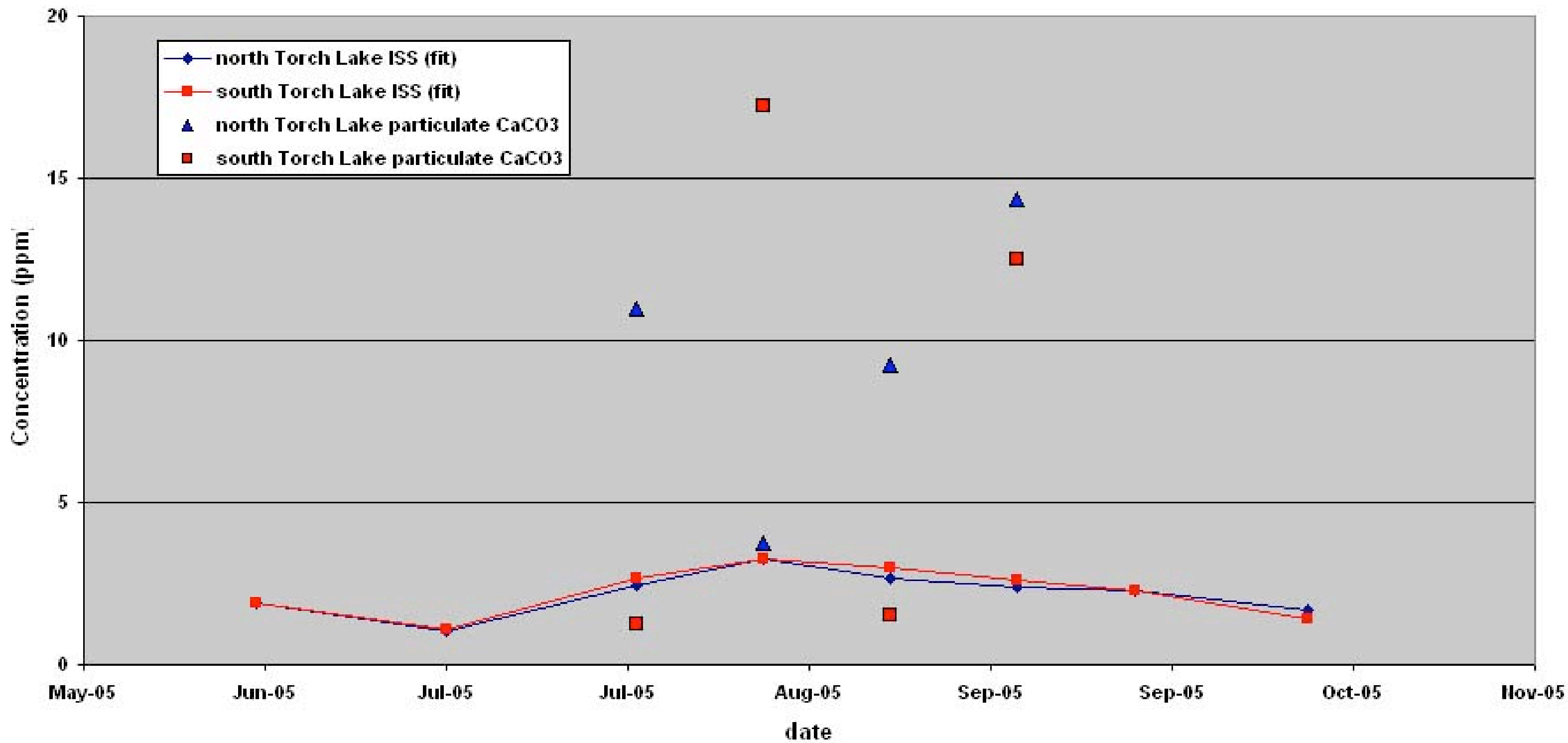


Figure 26. Comparison of ISS Concentrations (Fit to Secchi Depth Data in Light Model) to Particulate Calcium Carbonate Measured at North and South Stations

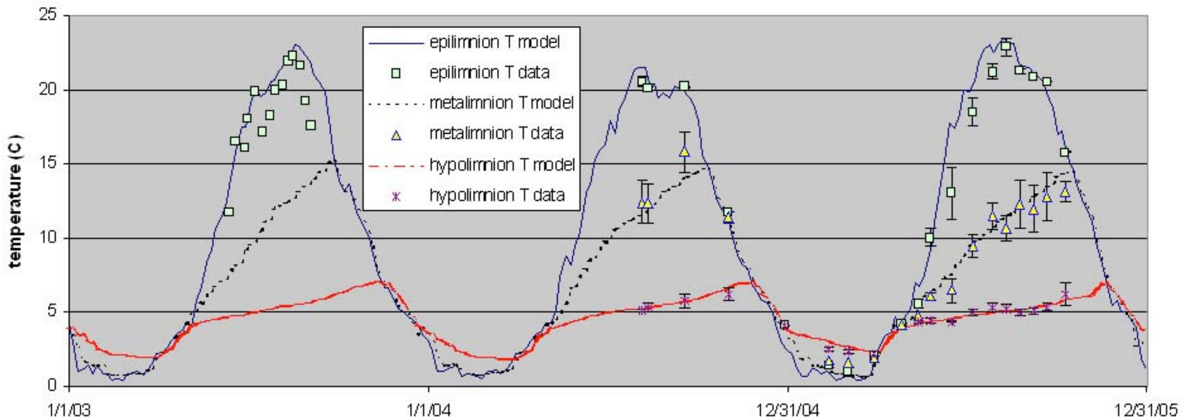


Figure 27. Calibration of Torch Lake Model to Water Temperature Data

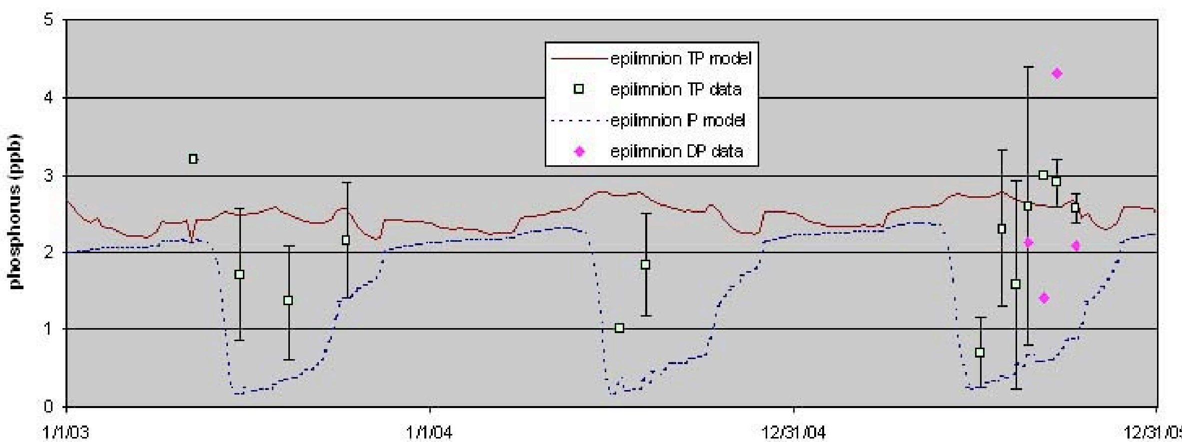


Figure 28. Calibration of Torch Lake Model to Epilimnion Total and Dissolved Phosphorus Data

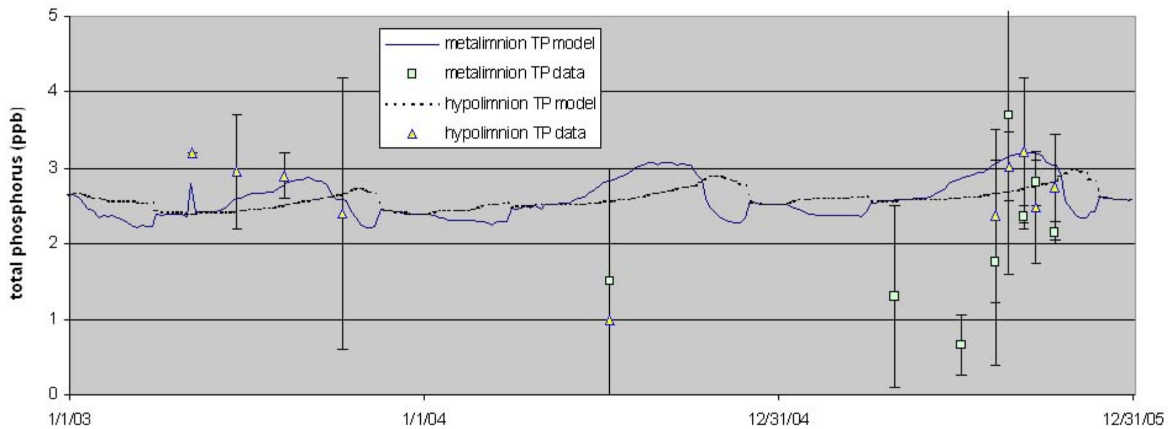


Figure 29. Calibration of Torch Lake Model to Metalimnion and Hypolimnion Total Phosphorus Data

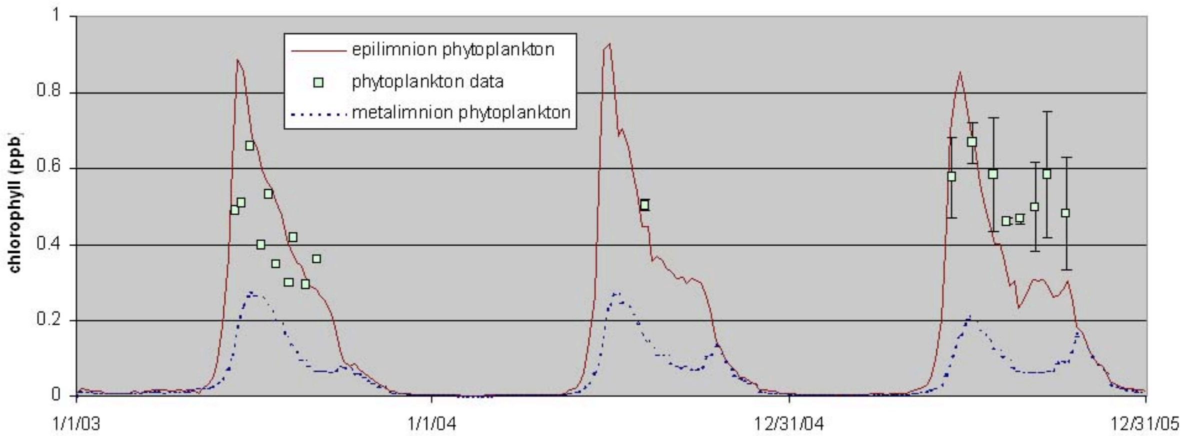


Figure 30. Calibration of Torch Lake Model to Phytoplankton (chlorophyll a) Data

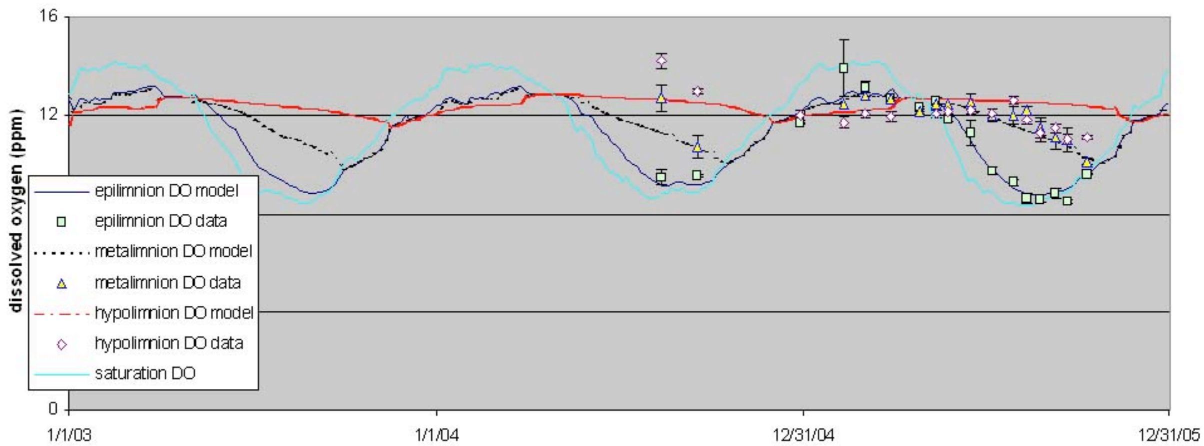


Figure 31. Calibration of Torch Lake Model to Dissolved Oxygen Data

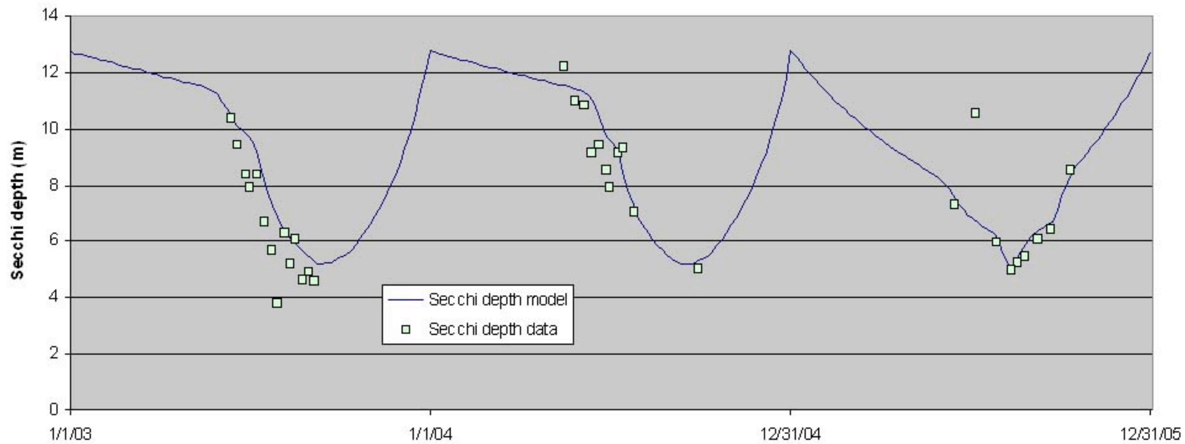


Figure 32. Calibration of Torch Lake Model to Secchi Disk Depth Data

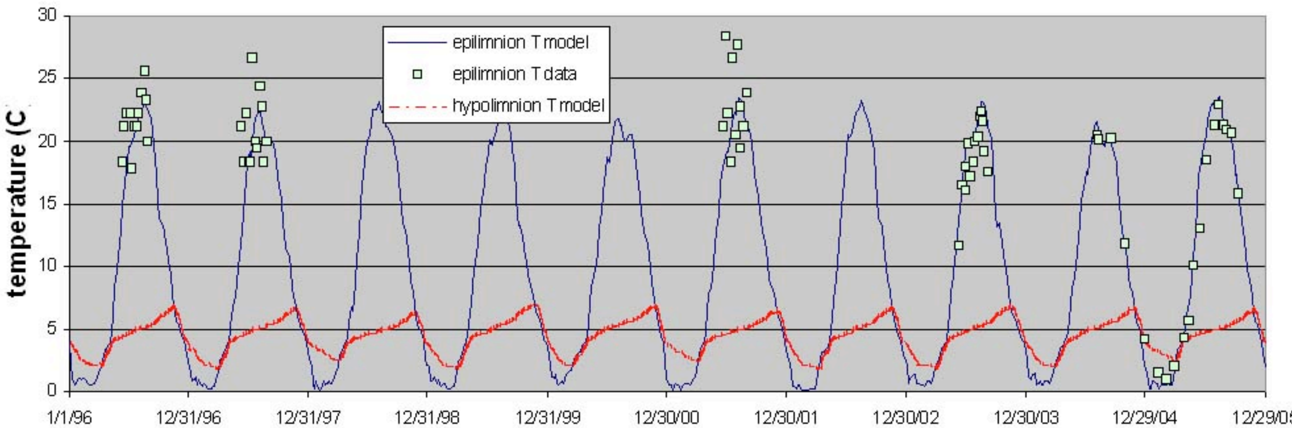


Figure 33. Torch Lake Model Hindcast of Water Temperature Data

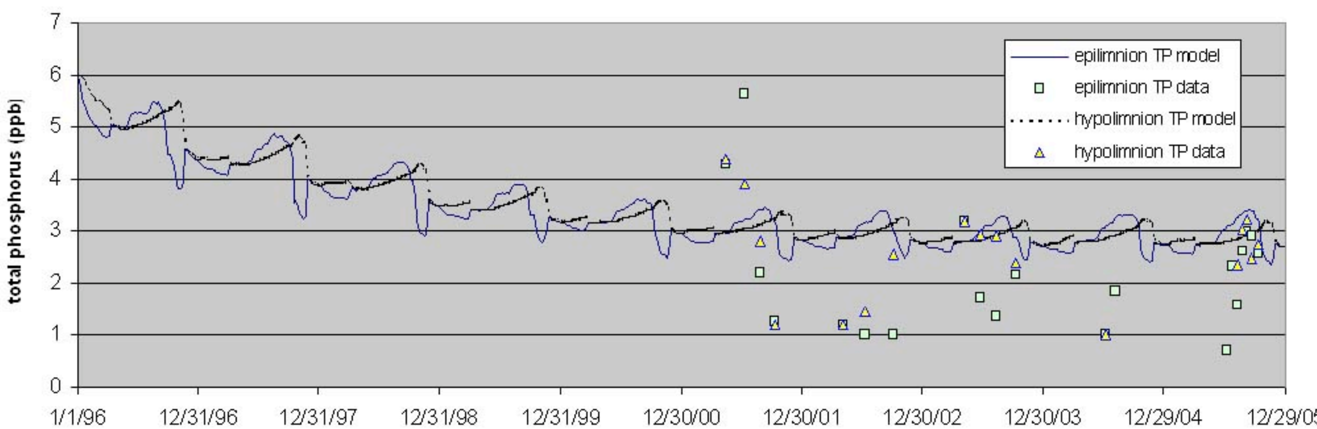


Figure 34. Torch Lake Model Hindcast of Total Phosphorus Data

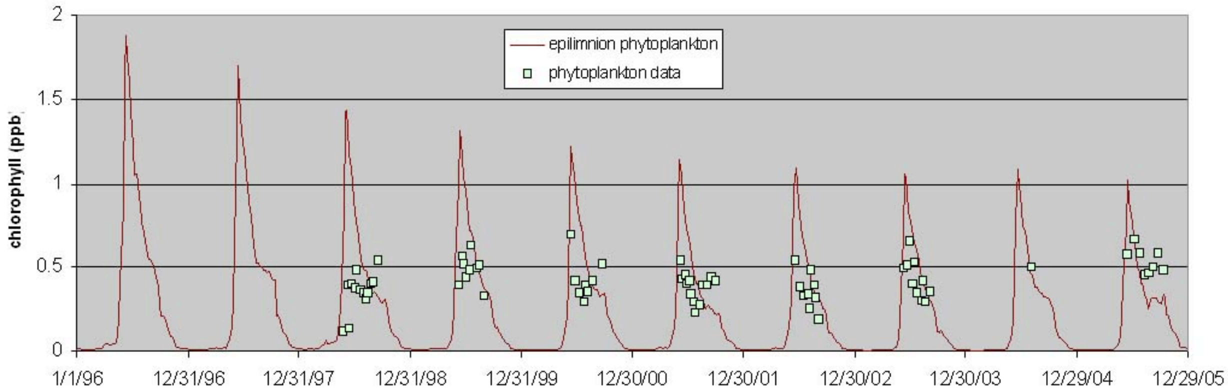


Figure 35. Torch Lake Model Hindcast of Phytoplankton (chlorophyll a) Data

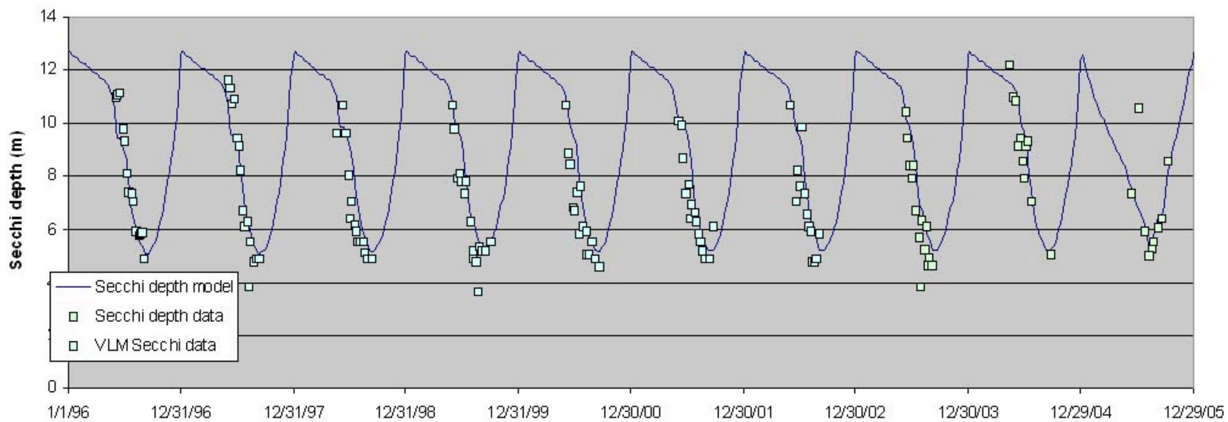


Figure 37. Torch Lake Model Hindcast of Secchi Disk Depth Data

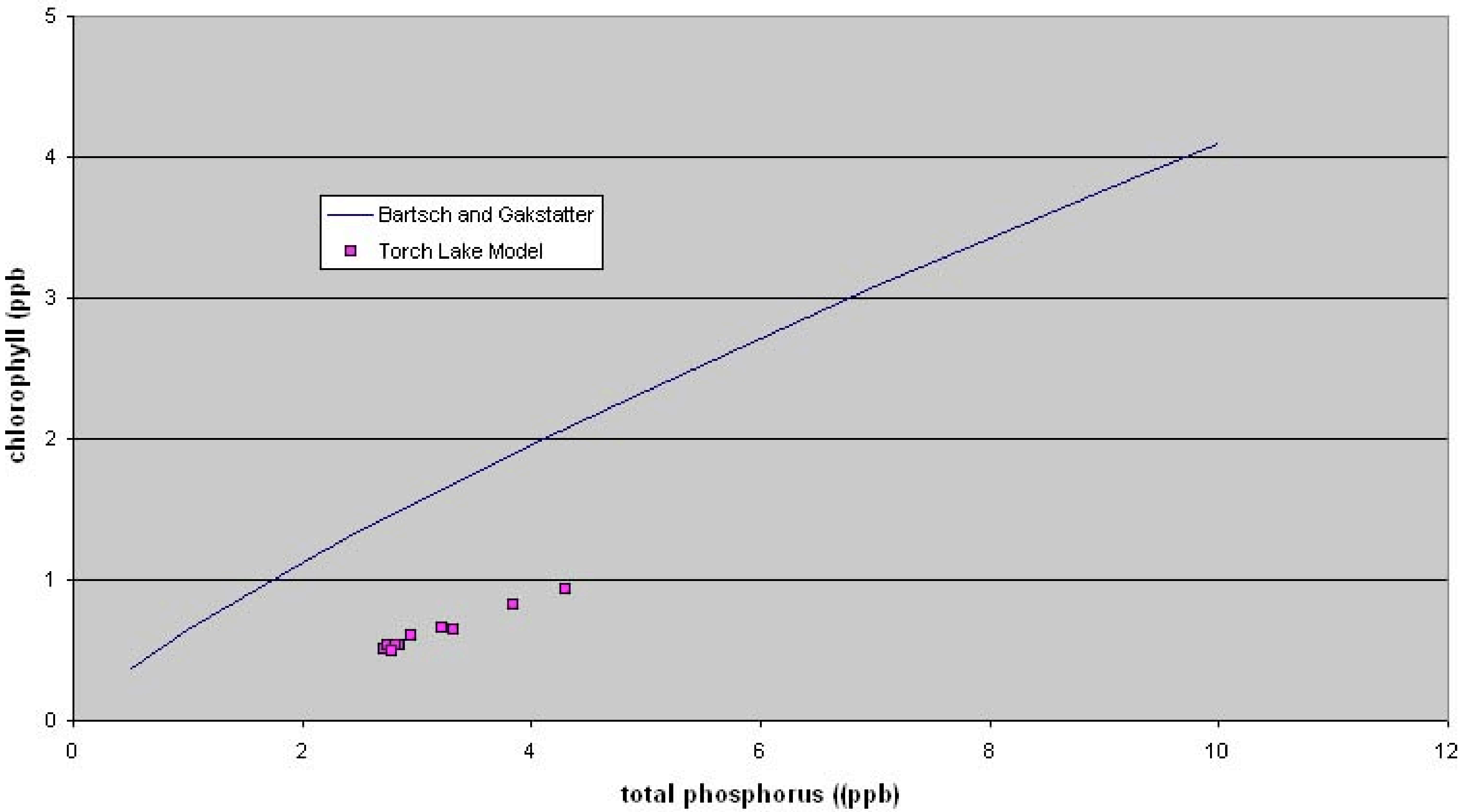


Figure 36. Relationship Between Total Phosphorus and Chlorophyll Concentrations

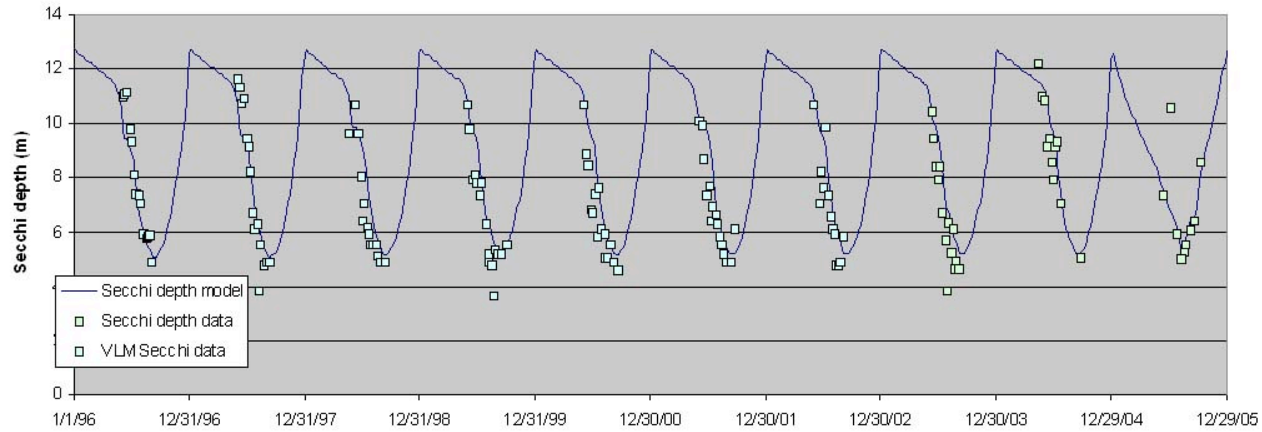


Figure 37. Torch Lake Model Hindcast of Secchi Disk Depth Data

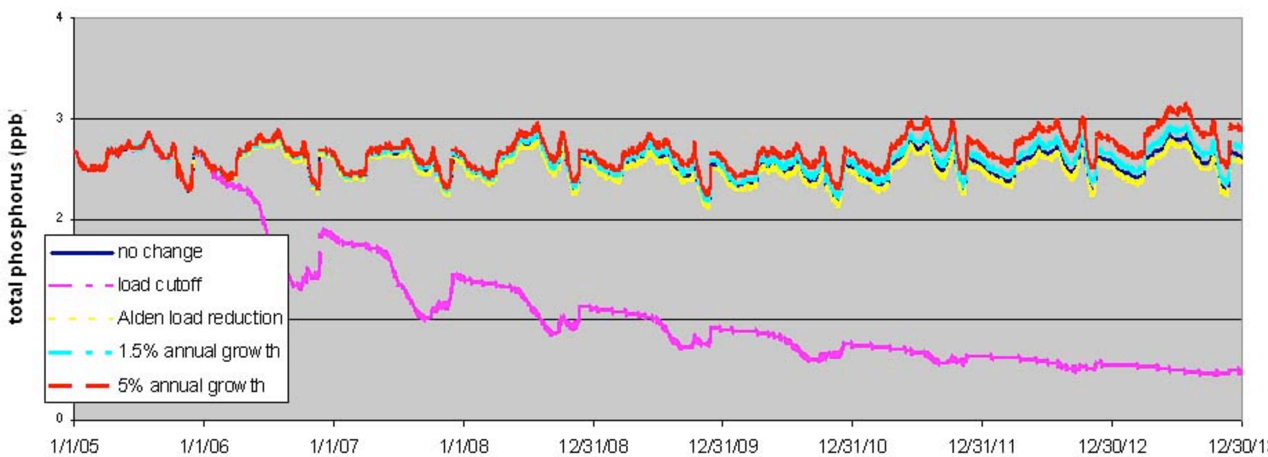


Figure 38. Torch Lake Model Forecasts of Total Phosphorus in Epilimnion

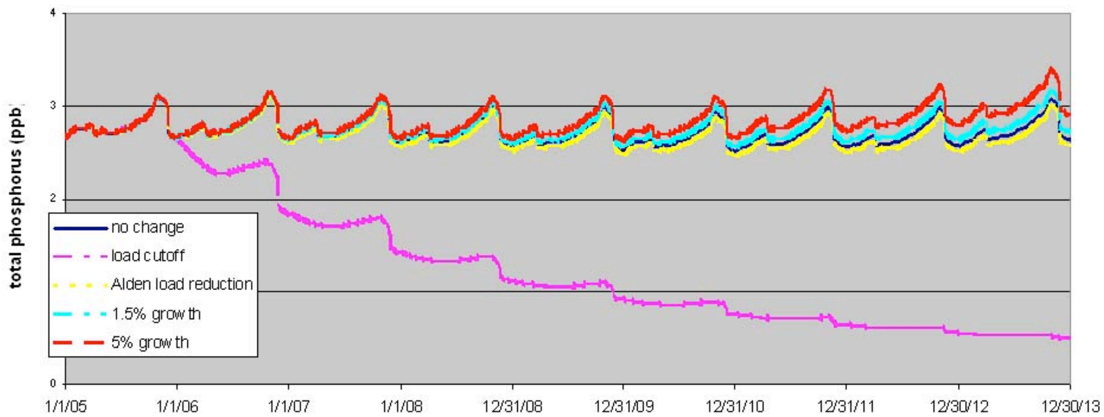


Figure 39. Torch Lake Model Forecasts of Total Phosphorus in Hypolimnion

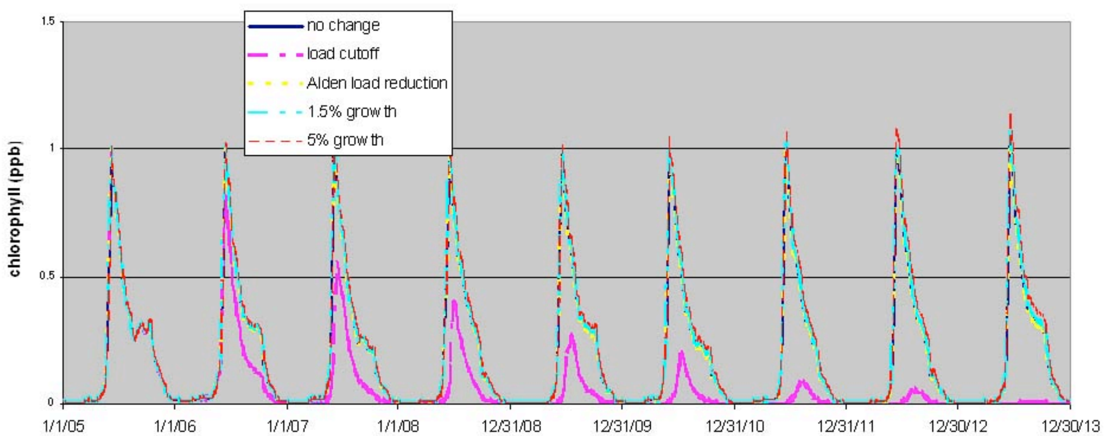


Figure 40. Torch Lake Model Forecasts of Phytoplankton (chlorophyll)

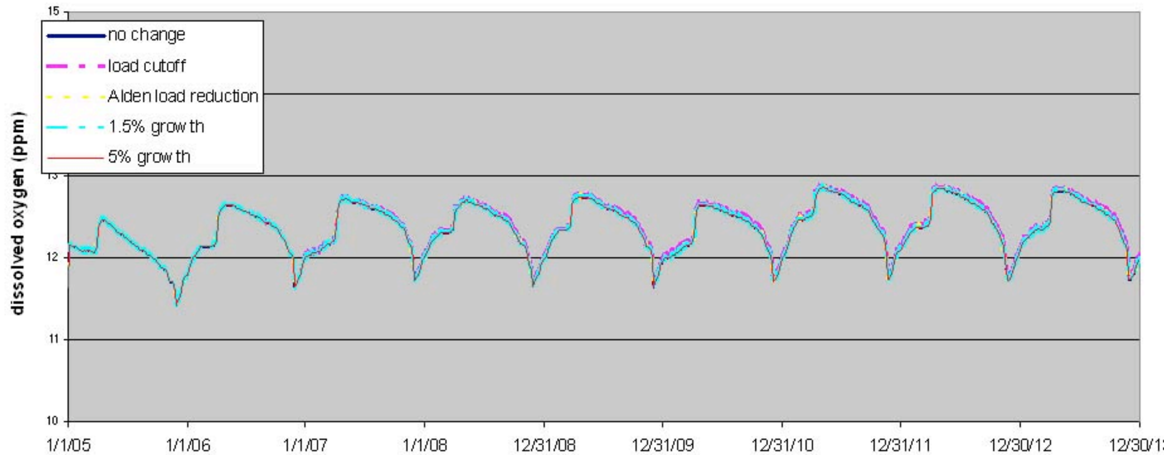


Figure 41. Torch Lake Model Forecasts of Dissolved Oxygen

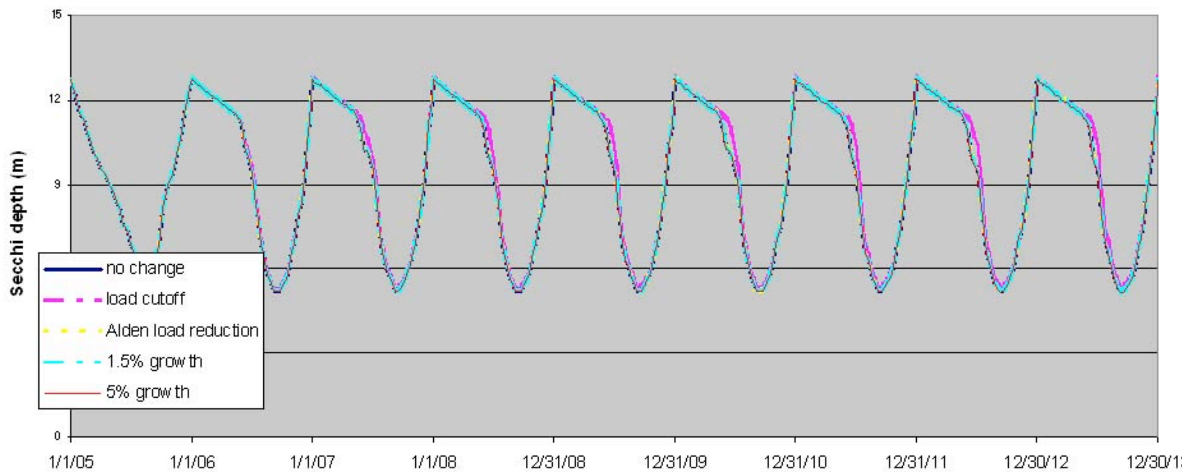


Figure 42. Torch Lake Model Forecasts of Secchi Disk Depth