TENMILE LAKE NUTRIENT STUDY

Phase I Progress Report

Submitted by

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to the

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EXECUTIVE SUMMARY

A study of Tenmile Lake and its watershed was initiated to better understand the role of the watershed and the lake in generating and processing sediment, phosphorus, and nitrogen. Field work was initiated in November 1998 and extended to August 1999. Three primary tributary sites were selected (Big, Benson, and Murphy Creeks) for sampling during base flow and storm events. Additional sites were sampled throughout the watershed at a less frequent basis. Four sites were sampled in the lake (two each in North and South Tenmile Lakes) and at the outlet on Tenmile Creek. In addition to sampling for sediment and nutrients, the lake sites were also sampled for phytoplankton and profile conditions (dissolved oxygen, temperature, specific conductance). A sediment core was collected from the south basin and analyzed for rates of sediment accumulation, nitrogen, nitrogen isotope (^{15}N), and fossil diatoms. The stream discharge and chemistry data were used to calibrate a watershed model (SWAT) to estimate annual loads of sediment, nitrogen, and phosphorus to the lake.

The results of the stream monitoring showed that two sites, Big and Benson Creeks, generated nearly tenfold more sediment and about threefold more nutrients than were measured at Murphy Creek. Murphy Creek is distinguished from the other two sites by the presence of a major restored wetland at the stream mouth extending up the channel for about 2.5 km. Maximum concentrations of total suspended sediments at Murphy Creek never exceeded 12 mg/L, whereas values of 580 mg/L and 423 mg/L were measured at Benson and Big Creeks, respectively. Concentrations of both total suspended solids and total phosphorus in the streams were strongly related to stream discharge, whereas stream nitrate concentrations were related to season. Nitrate concentrations were greatest in the fall and declined linearly through the winter and into spring.

Water quality in Tenmile Lake varied considerably in time and space. Water quality was generally the most favorable in winter, although the lake was visibly impacted by high inputs of suspended solids and nitrate. In spring, the lake experienced a major diatom bloom and produced chlorophyll *a* concentrations exceeding 60 ug/L. A second major bloom occurred in late summer; in this case the phytoplankton was dominated by Cyanobacteria (blue-green algae). Despite its relatively shallow depth, periods of quiescence were sufficient to allow significant oxygen depletion below depths of 4m. In some cases, the bottom waters were anoxic. Secchi disk transparency varied from a high of 4.9 m in November to a low of 0.6 m following a storm.

Total phosphorus averaged 25 ug/L in Tenmile Lake. Nearly all measures of water quality were indicative of eutrophic conditions. Water quality in the center of the lakes was generally better than that observed near the mouths of major tributaries. The "up-lake" sites were characterized by high concentrations of total phosphorus, higher chlorophyll, and lower transparency. This was particularly the case at site NTB located at the intersection of the Big Creek and Carlson Arms.

The analysis of the lake sediments showed that the sediment accumulation rate has increased substantially over pre-development conditions. The sediment shows both an increase in nitrogen and in the $^{15}N/^{14}N$ ratio suggesting that there has been a qualitative change in the source of nitrogen to the lake. A small number of sediment intervals analyzed for akinetes (cell structures found on nitrogen-fixing Cyanobacteria) showed a twofold increase in their numbers in the surface sediments. This is consistent with an increase in the biomass of Cyanobacteria in the lake. The diatom remains in the lake sediments show an increase in taxa (*Asterionella formosa*) often associated with nutrient-rich waters. Benthic (bottom-dwelling) diatoms have essentially disappeared in the lake, which is consistent with a reduction in lake transparency.

The watershed modeling indicated those loads of sediment and nutrients to the lake have increased through the watershed. Factors most strongly associated with increased loads include land use disturbances that are persistent and close to the lake or streams. In particular, livestock grazing near the base of the tributaries appear to provide the necessary elements for greatly increasing the sediment and nutrient loads to the lake. Despite the high concentrations of sediment and nutrients measured at Big and Benson Creeks, the model indicates that other tributaries may contribute more sediment and nutrients on a weighted-area basis.

The Phase I study consistently showed that sediment and nutrient loads to the lake are substantially elevated above pre-development conditions and that the water quality in the lake has declined accordingly. Measures of water quality in the lake point to eutrophic or near-eutrophic conditions and the trends indicated in the sediments show that the level of deterioration is continuing. Efforts in Phase II will be placed on continued monitoring of stream and lake water quality and collection of additional sediment samples. Modeling will be expanded to include a component for shoreline development and phytoplankton sampling will be redirected to focus more heavily on near-shore aggregations of nuisance algae.

A. INTRODUCTION

The Tenmile Lakes[*], consisting of North Tenmile and Tenmile Lakes, are highly productive lakes located on the southcentral Oregon Coast. The lakes have been the subject of fisheries investigations, related to a large to degree to declining salmonid fisheries and possible interaction with introduced exotic species (Griffiths and Yeoman 1941, Schwartz 1977, Abrams et al. 1991, Dambacher et al. 1999). In addition to its importance as a noted recreational fisheries, Tenmile Lake serves as a drinking water supply for a number of lakeshore residents and has been investigated as a potential drinking water supply for the city of Coos Bay. However, the quality of the drinking water supply was jeopardized with high populations of the cyanobacteria, *Microcystis aeroginosa*, in 1997 when the lake was temporarily closed to use for potable water (Kann 1999). Lastly, Tenmile Lake has reported water quality problems that have caused it to be listed on the Oregon 303(d) list of impaired surface waters and were noted earlier in a statewide assessment of lakes (Johnson et al. 1985). In summary, a list of the recognized problems in Tenmile lake includes:

(1) a major reduction of the historical anadromous fisheries (Abrams et al. 1991)
(2) presence of exotic fish species (Abrams et al. 1991)
(3) presence of exotic macrophytes (Systma 1995)
(4) toxic and nuisance algal blooms (Kann 1999)
(5) exceedences of water quality standards and guidelines (DEQ 305 bReport).

The water quality and fisheries problems in the lake have prompted management agencies and the City of Lakeside to take action to address the issues. Among the activities currently being taken include: (1) stream restoration activities by the Tenmile Lake Watershed Council in conjunction with ODFW to improve habitat for spawning salmon and their progeny, (2) fisheries investigations by ODFW, and (3) surveys of septic systems along the lakeshore by DEQ. In addition, there have been a variety of citizen efforts including the Citizen Lakewatch Program and volunteer efforts to assist in lake and watershed improvement. These actions illustrate the

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[*] Tenmile Lake is actually two lakes, Tenmile and North Tenmile, which are connected by a channel. They are treated jointly as Tenmile Lake by the Tenmile Lake Watershed Council and we follow that convention in this report. Distinctions between the two systems are made here using “north” and “south”, whereas references to both systems are treated as “Tenmile Lake”.

diverse nature of the problems associated with Tenmile Lake and the need to address the problems from multiple avenues. In recognition of the broad-based nature of the problems, the Tenmile Lake Watershed Council sought to develop a more comprehensive understanding of the lake and its watershed. One element of this attempt to better understand this resource involves the nutrient study.

By better understanding important watershed processes affecting the lake, it was hoped that management decisions regarding lake and watershed restoration could be guided by quantitative information. To this end, we developed a study plan designed to provide the following:

(1) measure inputs of nutrients and sediment from selected tributaries to the lake during baseflow and storm runoff,

(2) monitor nutrient concentrations and water quality in the lake,

(3) assess algal community composition in the lake,

(4) measure sediment accumulation in the lake, and

(5) model watershed nutrient and sediment inputs to the lake under current landuse, pre-development conditions, and possible future scenarios.

The scope of the study was further influenced by a need to provide the Oregon Department of Environmental Quality (DEQ) information to support an analysis of Total Maximum Daily Loads (TMDLs) for Tenmile Lake. TMDLs are required under the Clean Water Act which stipulates that surface waters listed on a states' 303(d) list of impaired water bodies need to have an analysis completed leading to an improvement in water quality. Although this study does not constitute the formal TMDL analysis, it was intended to provide useful information in completing such an activity which is scheduled for the area in the year 2005.

B. STUDY AREA

Tenmile Lake watershed is located on the southcentral Oregon Coast between Coos Bay and Reedsport (Figure 1). The municipality of Lakeside is located on the western shore of the lake at the outlet to Tenmile Creek. The study area is bounded by the Pacific Ocean 4 km to the west and the watershed divide occurs at an elevation of 550 m in the Coast Range. The lake was formed by dunal encroachment on Tenmile Creek approximately 8,000 years ago. The resulting lake is highly dendritic and superficially resembles a reservoir (Figure 2). Average depth is

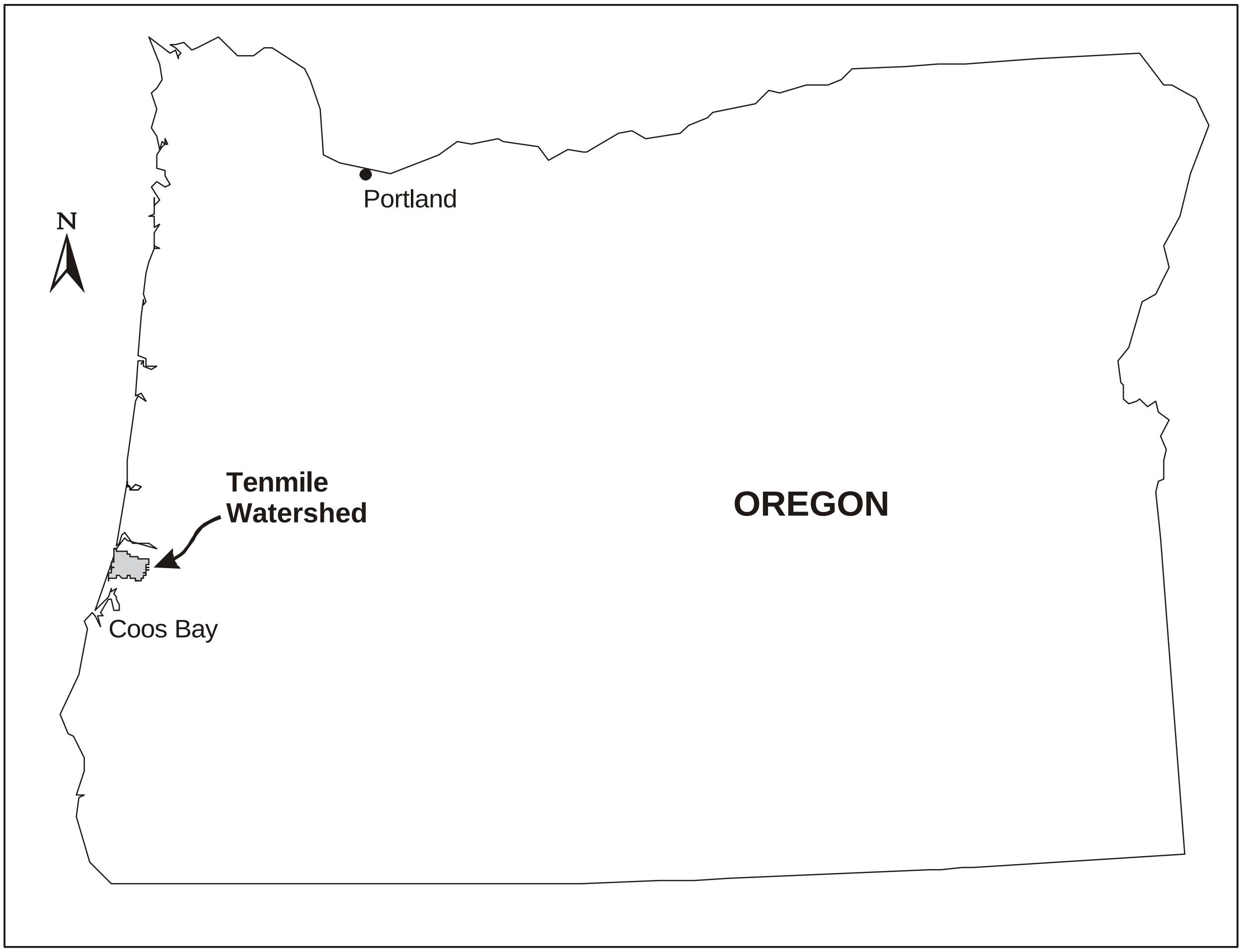

Figure 1. Location of Tenmile Lake.

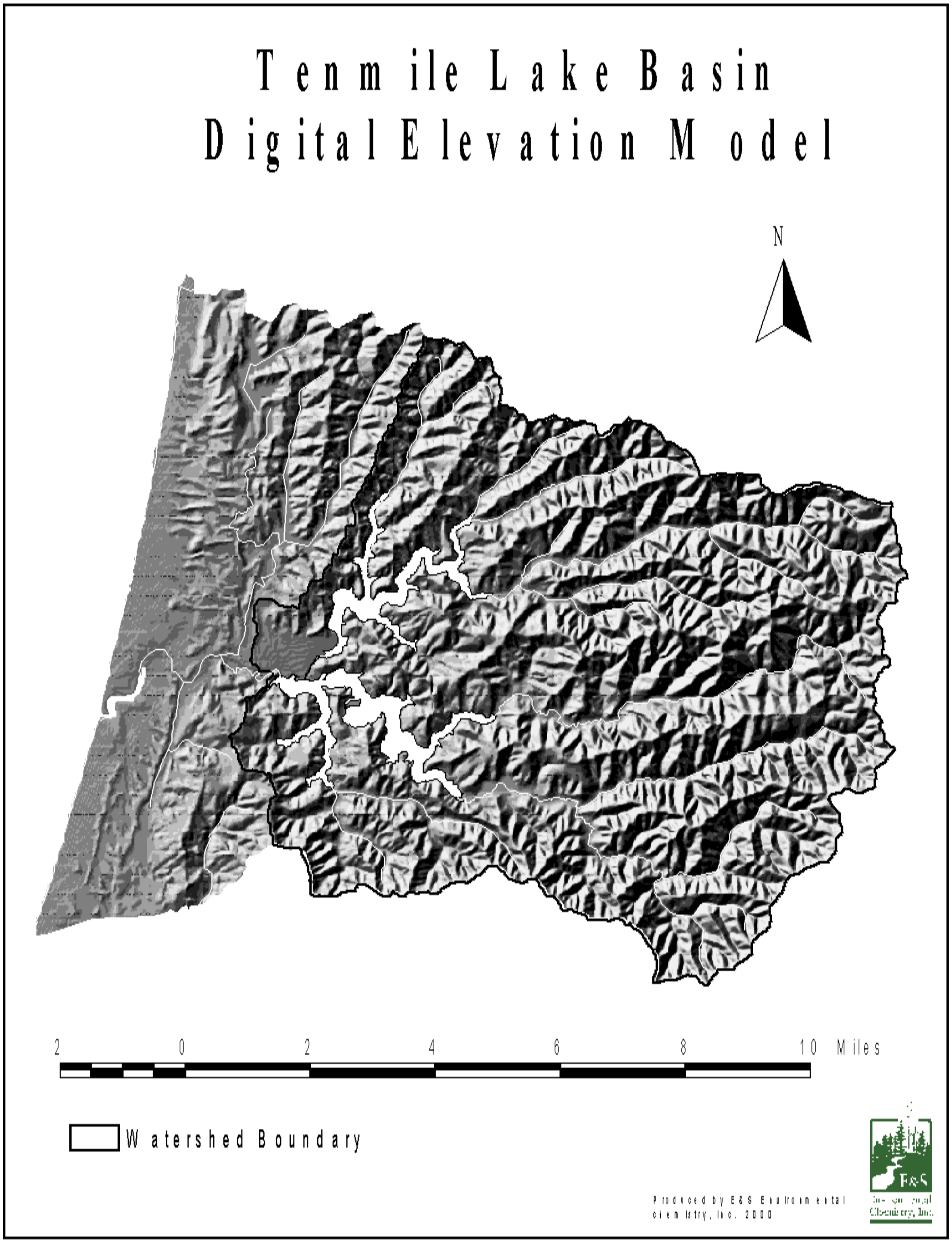

Figure 2. Tenmile Lake Basin digital elevation model (DEM) showing lake outline and general topographic features.

4.5 m in the north lake and 5.0 m in the south lake. Morphometric properties of the lake and watershed are presented in Table 1.

Table 1. Lake morphometry statistics for North Tenmile and Tenmile Lakes based on the May 1995 GPS/SONAR survey. (Source: Eilers et al. 1996)

	North Tenmile	Tenmile	Combined
Area[a] (ha)	335.6	457.3	792.9
(acres)	(829.3)	(1,129.9)	(1,958.2)
Perimeter[b] (km)	31.83	37.28	69.11
(mi)	(19.78)	(23.17)	(42.95)
Depth,[c] maximum (m)	8.17	8.23	-
(ft)	(26.8)	(27.0)	
Depth,[c] mean (m)	4.50	4.98	-
(ft)	(14.75)	(16.33)	

[a] Excluding an area for Willow Island. Two previous digitized versions of the lake area are within 1% of these values (J. Kelsey, pers. comm.).

[b] Includes Willow Island and the channel connecting the two lakes. Digitized from 1:24,000-scale USGS topographic map. Even considering variation associated with scales used on the source maps, actual miles of shoreline are probably within 2% of these measurements.

[c] Normalized to a lake elevation of 9.0 ft MSL

The climate in the area is characterized by cool, wet winters and mild, dry summers. Annual average precipitation ranges from 200 cm in Lakeside to 245 cm in the eastern uplands of the Coastal Range. The higher elevations occasionally receive snow, although accumulations are brief. Nearly all precipitation in the watershed occurs as rain.

The watershed is characterized by flat, narrow valley floors that extend up to 10 km into the watershed leading to abrupt changes in slope to the surrounding hillsides. Soils in the uplands are derived from uplifted marine sediments and are highly erodible when exposed. The dominant pre-settlement vegetative types are Douglas fir in the uplands and wetland communities in the flat lowlands.

The present landuse in the watershed is comprised of timber management in the uplands and agriculture in the valleys. The eastern portion of the watershed is within the Elliott State Forest and is actively managed for timber harvest. Private land holdings to the west of the state forest are also subject to timber harvest. Agricultural land is principally used for livestock grazing. The livestock used to consist primarily of dairy cattle. That has transitioned to beef cattle, although there are small numbers of sheep and horses. High density urban development is restricted largely to the City of Lakeside on the eastern shore. Lakeshore development is widespread on much of the accessible, upland portions of the shoreline. Approximately 500 dwellings are present on the lakes, divided nearly equally between the north and south basins.

The lake is used extensively for recreation, primarily fishing. The watershed historically was a major producer of coho with runs of over 75,000 fish. The lake also had substantial runs of steelhead and sea-run cutthroat. Following the introduction of the largemouth bass, coho escapement into Tenmile Lake has remained below 10,000 adults and jacks (Abrams et al. 1991). Tenmile Lake is currently an important site for bass fishing tournaments in Oregon. The fisheries history is summarized in Table 2.

C. METHODS

1. Sampling Design

The Tenmile Lake watershed is highly dendritic and the task of sampling all tributaries would be prohibitively expensive. We elected to use a model-based approach in which selected watersheds would be monitored and the results from these systems would be used to calibrate a watershed model for computing annual loads of sediment and nutrient to the lake. In addition, we monitored the lake to assess the fate of the watershed inputs and used the information from the sediment diatoms to infer changes in water quality in the 20th century. The sediment data are also used to constrain the model for historical inputs to the lake.

The sampling design focused on two classes of water quality constituents, sediments and nutrients. These are not necessarily mutually exclusive since the sediments transport particulate forms of nutrients, especially total phosphorus and organic nitrogen. The decision to focus the sampling on these sets of constituents was based on observations of erosion and mass failures in the watershed, extensive streambank erosion, siltation at the mouths of some of the tributaries, the presence of algal blooms which are often associated with excessive nutrient inputs, and previously collected data documenting water quality problems in the lake related to macrophytes, algal blooms, and high nutrient concentrations (Johnson et al. 1985; Systma 1995; Eilers et al. 1996; DEQ, unpublished data).

Table 2. Fisheries history of the Tenmile Lakes (derived from Griffiths and Yeoman [1941] and Abrams et al. [1991]).

Species	Native or Introduced	Year Introduced	Management
Coho Salmon	Native	-	Population declined from >75,000 adults/yr to about 4,000. Smolts and pre-smolts stocked.
Winter Steelhead	Native	-	Current population estimated at 20% of 19th century levels; currently stocked
Cutthroat Trout	Native	-	Historically abundant population; currently managed for wild stock
Rainbow Trout	Introduced [a]	1930's	Currently managed as a "put-and-take" fishery.
Brown Bullhead	Introduced[b]	1930's	High population was not impacted by a commercial fishery in 1952-53; not eradicated by rotenone; continued abundant population
Yellow Perch	Introduced[b]	1930's	Large populations developed
Bluegill	Introduced[b]	1960's	Currently most abundant fish in the lakes; attempt to eradicate the species in 1968 with rotenone was unsuccessful
Largemouth Bass	Introduced[a]	1971	Highly successful fisheries
Hybrid Bass[c]	Introduced[a]	1982	Successful fisheries discontinued after 1988 because of concerns for hybrids straying into other river systems
Miscellaneous Native Species eulachron (*Thaleichthys pacificus*) staghorn sculpin (*Eptocottus armatus*) threespine stickle (*Gusterosteus aculeatus*) green sturgeon (*Acipenser medirostris*) Pacific lamprey (*Lampetra tridentata*) western brook lamprey (*Lampetra richardsoni*) prickly sculpin (*Cottus asper*) shiner perch (*Cymatogaster aggregata*)			Populations unknown

[a] managed introduction
[b] illegal introduction
[c] Striped bass x white bass

2. Site Selection

The approach was to select stream monitoring sites that drained major portions of the watershed, were representative of the land cover types in the watershed, and were accessible. Two sites were initially selected that met these criteria, Benson Creek and Big Creek. The Benson Creek site is located at a bridge crossing on Benson Creek Road approximately 1.6 km from the south lake basin on Coleman Arm. The Big Creek site is located at the bridge crossing of North Lake Road about 1.8 km above the entrance to the north lake on Big Creek Arm. These two sites collectively represent 32 percent of the drainage to Tenmile Lake and appear to be representative of the combination of timber management found throughout the uplands and livestock grazing typical of the lowland valleys. A third site was selected that also included timber management, but lacked the influence of domestic livestock. This site was located on Murphy Creek about 200m from the north lake on the Carlson Arm. There are no road crossings on Murphy Creek and access was by boat. This site is located on private land; permission was obtained from the landowner, Ms Sally Thomas. Tenmile Creek, located at the outlet of Tenmile Lake also was sampled on a regular basis to evaluate changes occurring in the lake.

The above four sites formed the core sites for the stream monitoring effort, but additional sites were sampled on one or more occasions to gather some basis for assessing the representativeness of these core sites and to attempt to characterize variability in water quality throughout the watershed. Water samples were collected from public roads at the sites shown in Figure 3. Unlike the core sites which were instrumented, no stream discharge or other real-time data were collected at the supplemental sites.

From the standpoint of morphometry and zonation, Tenmile lake bears some resemblance to a reservoir. Because of this, we sought to measure not only differences between the two main basins, but also to evaluate changes that occur between the major arms and the mid-basin areas. Four lake sites were selected to represent conditions in both basins and to compare mid-lake and transitional zones (Figure 3).

3. Field Instrumentation

Most of the inputs of sediment and nutrients to lakes in western Oregon occur during storms. In some cases, 90 percent of the annual discharge of sediment from a watershed can occur within a several day period. The rapidity of response time in these watersheds required us

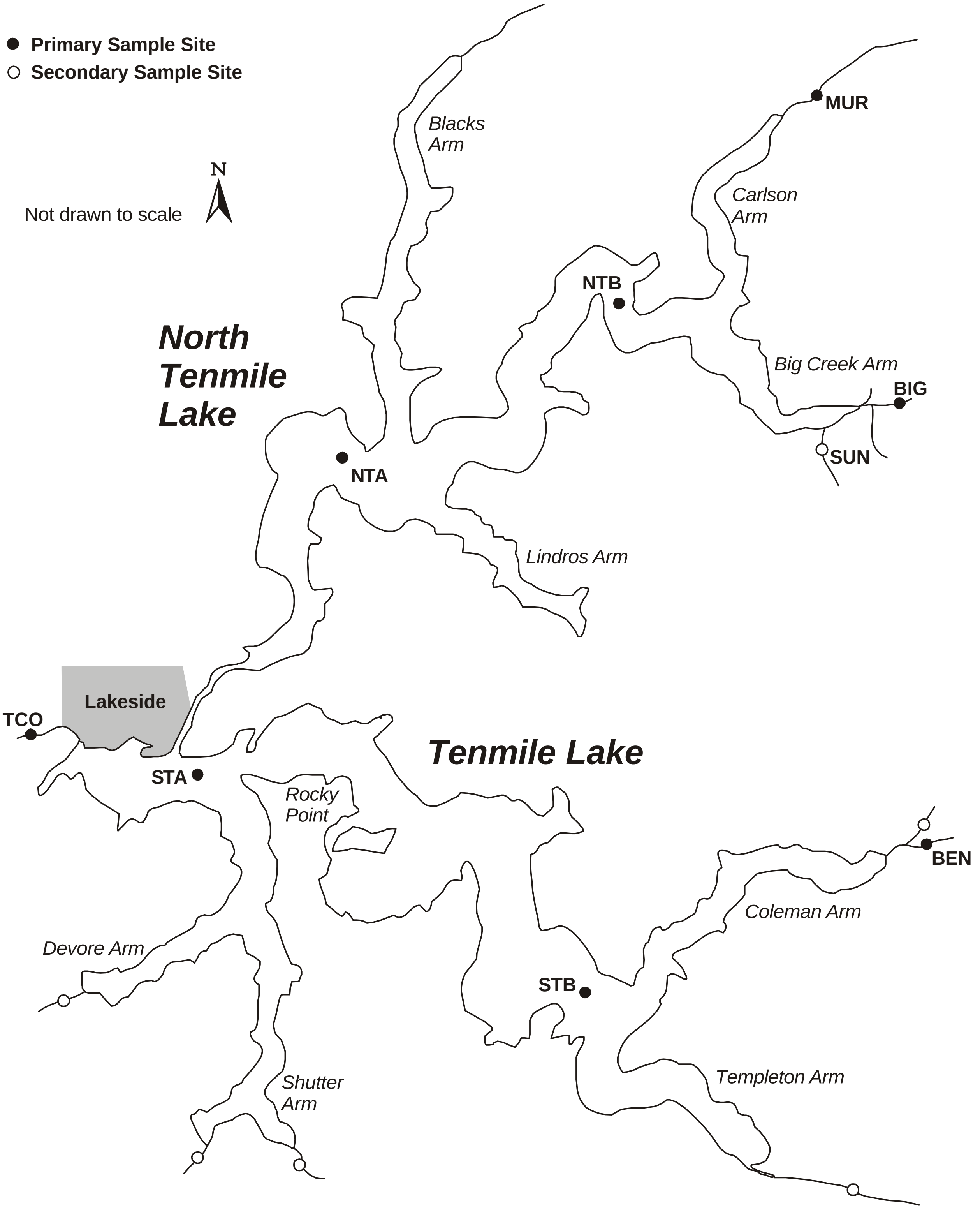

Figure 3. Phase I water quality monitoring sites, Tenmile Lake watershed.

to sample changing water quality conditions intervals of several hours during storm events lasting several days or longer. This frequency of sampling at multiple locations could only be accomplished with instruments designed to collect water samples at prescribed times and through use of continuously recording devices for temperature, precipitation, and streamflow.

Water sampling instruments, ISCO (Model 6700), were installed at Big, Benson, and Murphy Creeks and powered with deep cycle 12 volt batteries. The units were housed in plywood shelters located several feet above expected maximum stream elevation. Intake tubes extended into mid-channel and were secured using lead weights to insure that samples were always drawn from roughly the same positions in the channel and with respect to the stream bottom. After observing the general response times of the creeks, sampling intervals were programmed for every four hours. The units contained 24 1-L bottles which allowed us to sample continuously for up to four days prior to either processing the collected samples or retrieving the samples and resetting the ISCO for further operation.

Stream stage recorders were installed at Big, Benson, Murphy, and Tenmile Creeks. The Solinst pressure transducers were installed at Big and Benson Creeks. A Stevens Level Recorder was installed at Murphy Creek and a Global Water pressure transducer was installed at Tenmile Creek. Hobo Temps, temperature recording devices, were installed in Big and Benson Creeks. Precipitation gages were installed at Benson and Murphy Creeks (elevation ~ 6m) and off Benson Ridge Road at an elevation of about 300 m.

4. Field Methods

ISCO samplers were prepared for use by thoroughly rinsing the sample bottles with stream water followed by either deionized or distilled water. Water samples from the ISCOs were transferred to 1 L Nalgene bottles that were either new, or if used previously, had been acid-washed. Water samples were placed in coolers for transport back to Corvallis, usually on the same day of collection.

Stream discharge was measured at the primary sites using a Marsh-McBirney (Model 2000; Flo-Mate) flowmeter with measurements of stream velocity at 0.2 and 0.8 of the depth at a given site at multiple sites across the channel. Discharge measurements within the cells were summed across the channel.

Electronic data stored on the temperature, precipitation, and pressure transducer gages were periodically downloaded in the field to a laptop computer.

The lake was sampled at the four sites shown previously in Figure 3. Although Tenmile Lake has the capability to stratify under periods of prolonged calm and high temperatures, this did not occur during our sampling. Consequently, all lake samples were near-surface samples (0.5m). Samples were typically collected using a trace-metal grade Plexiglas Van Dorn sampler and distributed to several aliquots. Samples collected for major ions, nutrients, and total suspended solids were placed in 1 L Nalgene bottles. Samples of phytoplankton were placed in 250 mL bottles and preserved with Lugol's solution and samples of chlorophyll a were placed in 50 mL Nalgene bottles and preserved with magnesium bicarbonate. Zooplankton samples were collected from each lake site in July and August 1999 using a plankton net (80 µ mesh size) equipped with a modified Wisconsin bucket and a 10 cm opening. Secchi disk measurements were made using a standard 20 cm disk. Vertical profiles were made of temperature, dissolved oxygen, and specific conductance using YSI field meters (Model 85) after calibrating according to manufacturers recommendations.

All field activities were described in a written sampling plan that was provided to field personnel.

5. Analytical Methods

Water samples were analyzed according to the need to quantify key inputs to Tenmile Lake. High priority analytes were total suspended solids, total phosphorus, and nitrate-nitrogen. These analytes were generally run on most samples. Other analytes that were measured on a less-frequent basis include ammonia, total Kjeldahl nitrogen, major ions, pH, specific conductance, and silica (Table 3). Duplicate and blank samples were included among the routine samples as checks on the quality of the analytical results. Quality assurance protocols and analytical methods were detailed in a QA/QC plan submitted to the TMLBP during the early phases of the project (ref).

6. Watershed Modeling

A variety of models are available for estimating watershed loads of nonpoint source pollution ranging from simple unit-based loading coefficients to detailed simulation models that

Table 3. Chemical methods and detection limits proposed for analysis of samples.

Parameter[a]	Method[b]	Detection Limit[c]	Reporting Unit
pH, lab	Electrode	-	s.u.
Alkalinity, tot. as $CaCO_3$	Titration, double end-point	2	mg/L
Conductivity, lab	Platinum electrode	1.0	µS/cm
Calcium, as Ca^{2+}	AA flame	0.05	mg/L
Magnesium, as Mg^{2+}	AA flame	0.05	mg/L
Sodium, as Na^{+}	Flame emission	1.0	mg/L
Potassium, as K^{+}	Flame emission	0.5	mg/L
Sulfate, as SO_4^{2-}	Ion chromatography	1	mg/L
Chloride, as Cl^{-}	Ion chromatography	0.2	mg/L
Nitrogen, $NO_2 + NO_3$ **as N**	Ion chromatography	0.05	mg/L
Nitrogen, NH_4 **as N**	Perstorp (SM4500)	0.01	mg/L
Nitrogen, Kjeldahl as N	BD-40 auto. phenate	0.05	mg/L
Phosphorus, dis. react as P	Ascorbic acid	0.002	mg/L
Phosphorus, tot. as P	Digest./ascorbic acid	0.002	mg/L
Silica, as Si	AA flame	1	mg/L
Solids, tot. susp. (TSS)	Gravimetric 103C	2	mg/L

[a] Bolded parameters indicate proposed core analytes; italicized parameters indicate supplement analytes that may or may not be measured.
[b] Alternate methods may be necessary due to the composition or matrix of some samples.
[c] Actual detection limit may be higher or lower due to sample matrix.

attempt to represent transport processes as realistically as possible. As the level of model s sophistication increases, so do the requirements for increasingly detailed spatial and temporal data on the watershed. The object of using more complex models is to gain greater insight into the watershed processes and therefore more accurately assess the nature of the problems. However, if the level of data acquisition is not matched to the model, increasing the level of model sophistication can actually be counterproductive.

After evaluating a number of watershed models we selected a USDA model called SWAT (Soil and Water Assessment Tool). SWAT is a model of intermediate complexity designed to be used in estimating sediment and nutrient loads in large watersheds. SWAT also has the capability to simulate pesticides, bacteria, and organic loads. This is the product of model evolution associated with a long-term effort by the USDA to predict nonpoint sources of pollution. Some of the related models that preceded SWAT and whose code is incorporated to some degree in the current model include CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems; Kinsel 1980), GLEAMS (Groundwater Loading Effects on Agricultural Management Systems; Leonard 1987), EPIC (Erosion-Productivity Impact Calculator; Williams et al. 1985), AGNPS (Agricultural Nonpoint Source; Young et al. 1987), SWRRB (Simulator for Water Resources in Rural Basins; Williams et al. 1985, Arnold et al. 1990) , and ROTO (Routing Outputs to Outlet; Arnold et al. 1995).

SWAT has eight major components: hydrology, climate, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management practices. Surface runoff is generated using a modification of the SCS curve number method (USDA Soil Conservation Service 1972) which incorporates non-linear watershed response to varying antecedent moisture conditions. Peak runoff is predicted based on a modified Rational Formula using Manning's Formula to predict time of concentration. The model accounts for routing of water through percolation into multiple soil layers and a shallow aquifer compartment. Processes reflected in the hydrology include lateral subsurface flow, groundwater flow, evapotranspiration snowmelt and temporary storage in ponds.

Sediment yield is estimated for each subbasin using the Modified Universal Soil Loss Equation (MUSLE; Williams 1975). Cropping factors and other factors affecting erosion follow the procedures described by Wishmeier and Smith (1978). Details of the SWAT model are described further in Arnold et al. (1997).

The model was calibrated by sequentially and iteratively fitting observed versus simulated climate, hydrology, sediment transport, and nutrient transport. Data were withheld from the calibration to verify the robustness of the model output. Model inputs include data related to land use, topography, soils, and climate. Sources of these data sets are described below.

<u>Soils</u>: Natural Resources Conservation Service (NRCS) SSURGO data (1:24000) were used as the basic soils data. Data from Coos and Douglas counties were gathered and clipped to the Tenmile Lake basin. Currently, data from Coos county is still considered provisional by NRCS. A series of spot checks of the digital data against the hardcopy Soils Survey of the county was used as verification of the provisional data.

Landuse: The composite landuse data was developed from two separate data sources. Where available, detailed information from the Oregon Department of Forestry (ODF) was utilized. The dataset, called <SUSAN WILL KNOW THIS>?? is available from the Oregon State Service Center for Geographic Information Systems (SSCGIS). In areas where this coverage was unavailable, landuse values were photointerpreted from air photos.

Elevation: A 30 meter digital elevation model was developed as input for the SWAT model. The data originated at the SSCGIS as 18 United States Geologic Survey (USGS) Quadrangle coverages. These datasets were mosaiced to generate a complete coverage for the watershed.

Climate: Model calibration was performed using daily rainfall and air temperature data collected near the Big and Benson Creek monitoring stations. Precipitation was collected using a tipping bucket attached to a digital data logger. Air temperature was collected at approximately hourly intervals using HoboTemp data recorders.

D. RESULTS

1. Climate and Hydrology

Precipitation in the region is characterized by large frontal systems that often last for three to five days. Precipitation events that were particular noteworthy during the study period included storms of December 27-28, 1998 (70 mm); January 14-23, 1999 (175 mm); February 2-9, 1999 (123 mm); February 21-28 (101 mm); and March 24-30, 1999 (78 mm). These storms were often accompanied by high winds, which in some cases caused temporary damage to collection devices and/or limited the access to the sampling sites. We sampled three of the five major storms during the study period (January and both February storms).

These storms generated high discharge in Big and Benson Creeks which would sometimes increase in flow by an order of magnitude within eight to twelve hours following initial precipitation (Figures 4 and 5). The rapid increase in stream discharge at these sites would be accompanied by large loads of woody debris which also posed some problems for the sampling equipment. Stream flows would increase to bank-full discharge with concomitant increases in stream velocity. The streams would become visibly muddy from both runoff entering the streams and bank erosion, which was evident from measured stream velocity following high flow events. Mass failures were evident in a number of areas around the watershed, particularly along existing roadways and former logging roads. Other ungaged tributaries in the watershed

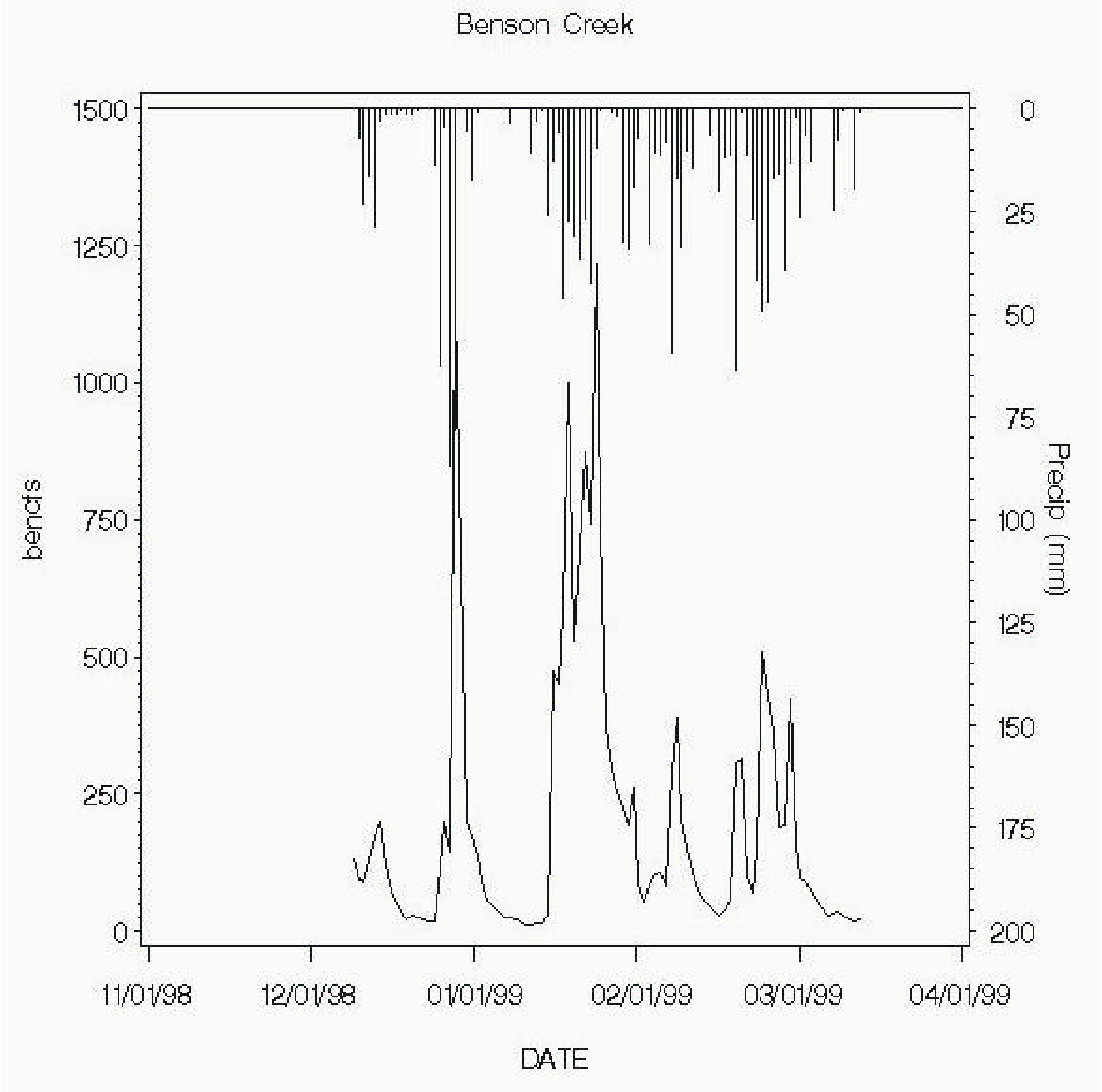

Figure 4. Stream discharge in Benson Creek (cfs).

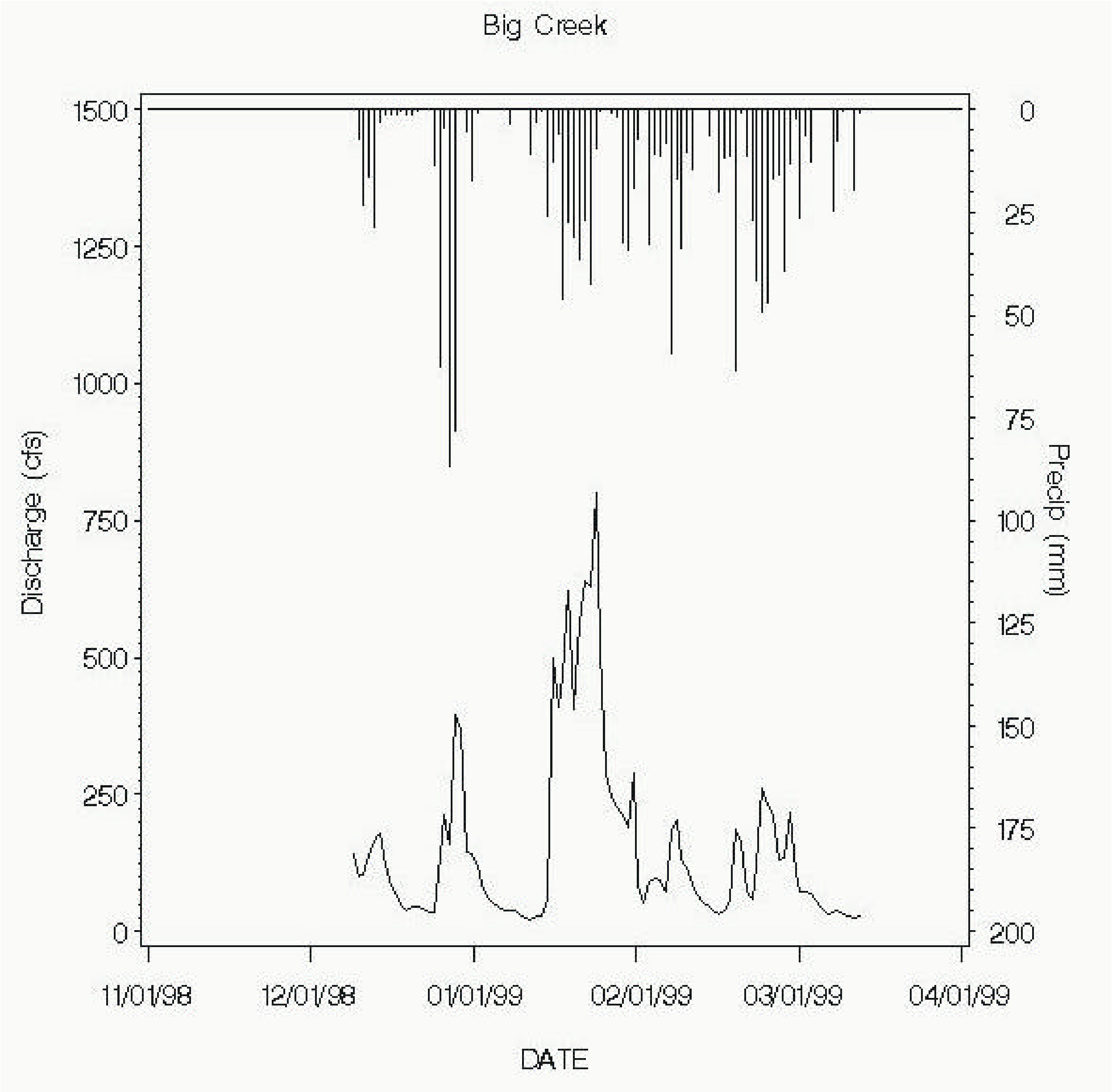

Figure 5. Stream discharge in Big Creek (cfs).

appeared to respond similar to that observed in Big and Benson Creeks. Interim stream-rating curves are shown in Appendix 1.

The discharge response in Murphy Creek was in sharp contrast to that observed in Big and Benson Creeks. The stream channel for Murphy Creek adjacent to the sampling site was narrow (2m wide) and relatively deep (1m) and highly vegetated. Its capacity to carry discharge was very limited and consequently stream discharge would often exceed the stream channel resulting in sheet flow extending across the broad marsh. Because of the channel geometry, maximum stream velocity in Murphy Creek was about 0.6 m/s, compared to values up to 1.2 m/s in Big and Benson Creeks.

Lake stage in Tenmile Lake fluctuated considerably in response to seasonal precipitation and possibly from backwater effects associated with high winter tides. The large seasonal fluctuation in lake stage corresponds with considerable variation in the hydraulic residence time in the lake. High discharge from the tributaries in the winter reduce the hydraulic residence time in Tenmile Lake to approximately 15 days, compared to a residence time of 30 days in the spring and 300 days in the summer.[*] These fluctuations result in important seasonal variations in lake chemistry that are described later.

2. Stream Water Quality

Stream water quality varied as a function of stream discharge in Big and Benson Creeks. Increased stream discharge resulted in increases in total suspended solids (TSS) and total phosphorus (TP; Figures 6 and 7). The largest increases in TSS and TP were associated with the greatest increases in flow. Pollutant concentrations varied not only as a function of stream discharge, but also varied in response to precipitation intensity, antecedent moisture conditions, position of the hydrograph (rising vs falling stage), and duration of the storm. Pollutant concentrations were generally greatest in high-intensity storms with rapidly rising hydrographs. As storms progressed, the pollutant concentrations generally declined, other factors being equal.

Whereas the concentration of pollutants varied by two orders of magnitude in Big and Benson Creeks during storm events, the water quality in Murphy Creek was comparatively constant. Concentrations of TSS never exceeded 12 mg/L in Murphy Creek compared to a

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[*] $J_w = V/Q = 37.9 \times 10^6 m^3 / 2.44 \times 10^6 m^3/d$ at $28.3\ m^3/s$ (1000 cfs)

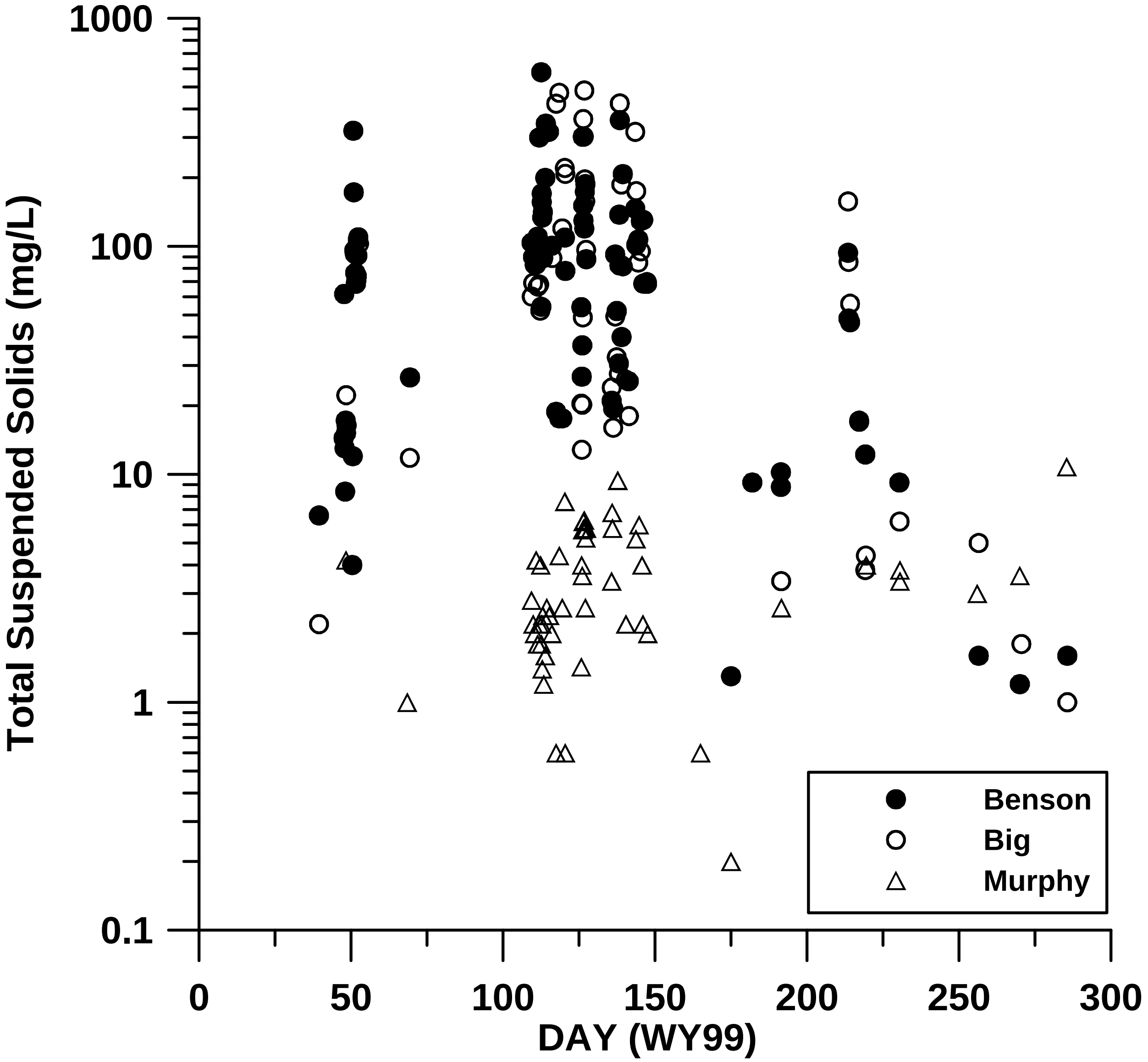

Figure 6. Total suspended solids (TSS, mg/L) for Big, Benson, and Murphy Creeks, WY1999. Note that the data are presented on a $\log_{10}$ scale.

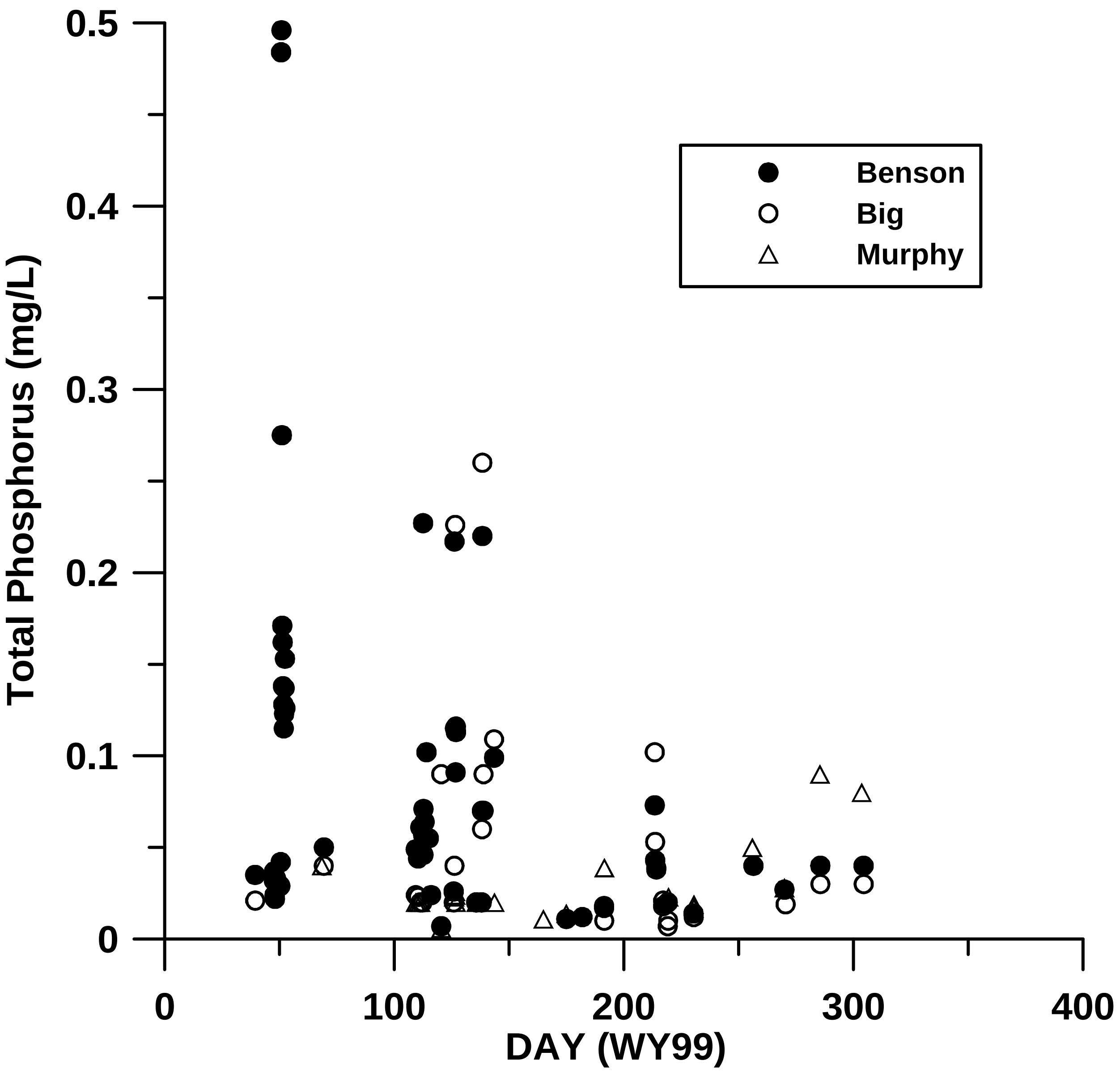

Figure 7. Total phosphorus (TP, mg/L) for Big, Benson, and Murphy Creeks.

maximum of 580 mg/L in Benson Creek and 423 mg/L in Big Creek. Concentrations of TP and nitrate (NO_3) were also much lower for most of the time in Murphy Creek.

Most of the phosphorus was attached to soil particles and was represented by TP. Ortho phosphorus (OP) represented a small proportion of the phosphorus delivered to the lake as indicated in the ratio of OP/TP (Figure 8). Concentrations of ortho phosphorus in Murphy Creek were greater than measured at the other stream sites, presumably because of release of P from wetland soils.

The dominant form of nitrogen in the streams was nitrate. Nitrate concentrations started out high at all sites in the fall and decreased to near zero in the summer (Figure 9). Ammonia was generally below detection limit (0.02 mg/L) in most samples. Total Kjeldahl nitrogen (TKN, reduced nitrogen) was generally well above detection limit (0.2 mg/L) in Big and Benson Creek, but was often below detection limit in Murphy Creek. Many of the streams measured in the synoptic sampling also had measurable TKN.

Specific conductance values for the three tributaries show a decline through winter and gradual increases through spring and summer (Figure 10). These effects show the dilution of groundwater inputs caused by high surface runoff in winter and the return to a higher percentage of groundwater-dominated flow pattern in late spring. pH values in the streams were generally circumneutral and increased by about 0.4 pH units from fall to spring (Figure 11).

Concentrations of TSS, TP, and NO_3 were evaluated by collecting water samples from another twelve sites during the course of the study. These sites were generally sampled during storm events, although there was no effort to synchronize the sampling or sample at maximum discharge. Therefore, the results offer only a qualitative assessment of water quality at other sites in the watershed. The results suggest that the water quality observed at the other sites is most similar to that observed in Big and Benson Creeks, based on measures of central tendency (Table 4). The ranges of values measured at the synoptic sites do not approach the values measured at Big and Benson Creeks, which is to be expected given the transient nature of the nonpoint source loads and the need to sample intensively during storm events. The one synoptic site with a modest number of samples (REX, an unnamed tributary to Benson Creek) exhibited high TSS and NO_3 concentrations. Again, this is consistent with a greater number of samples at this site (thus increasing the probability of measuring higher concentrations), but is also may reflect the recent clearcut in the catchment. In summary, the synoptic stream sampling

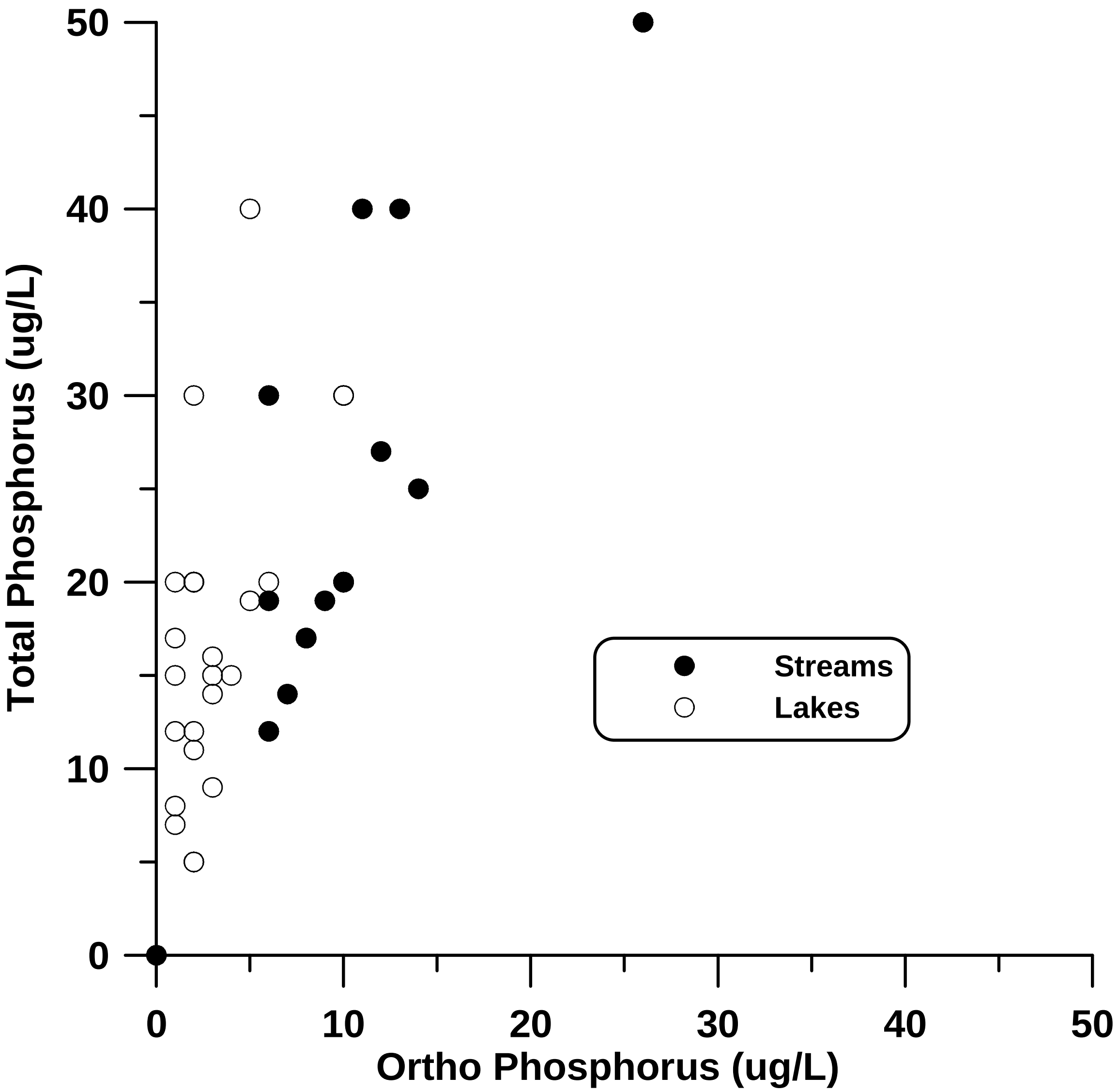

Figure 8. Sediment accumulation rate (SAR, g/m^2/yr) versus depth in lake sediment as measured from sediment core collected in the south basin 200 m east of STA.

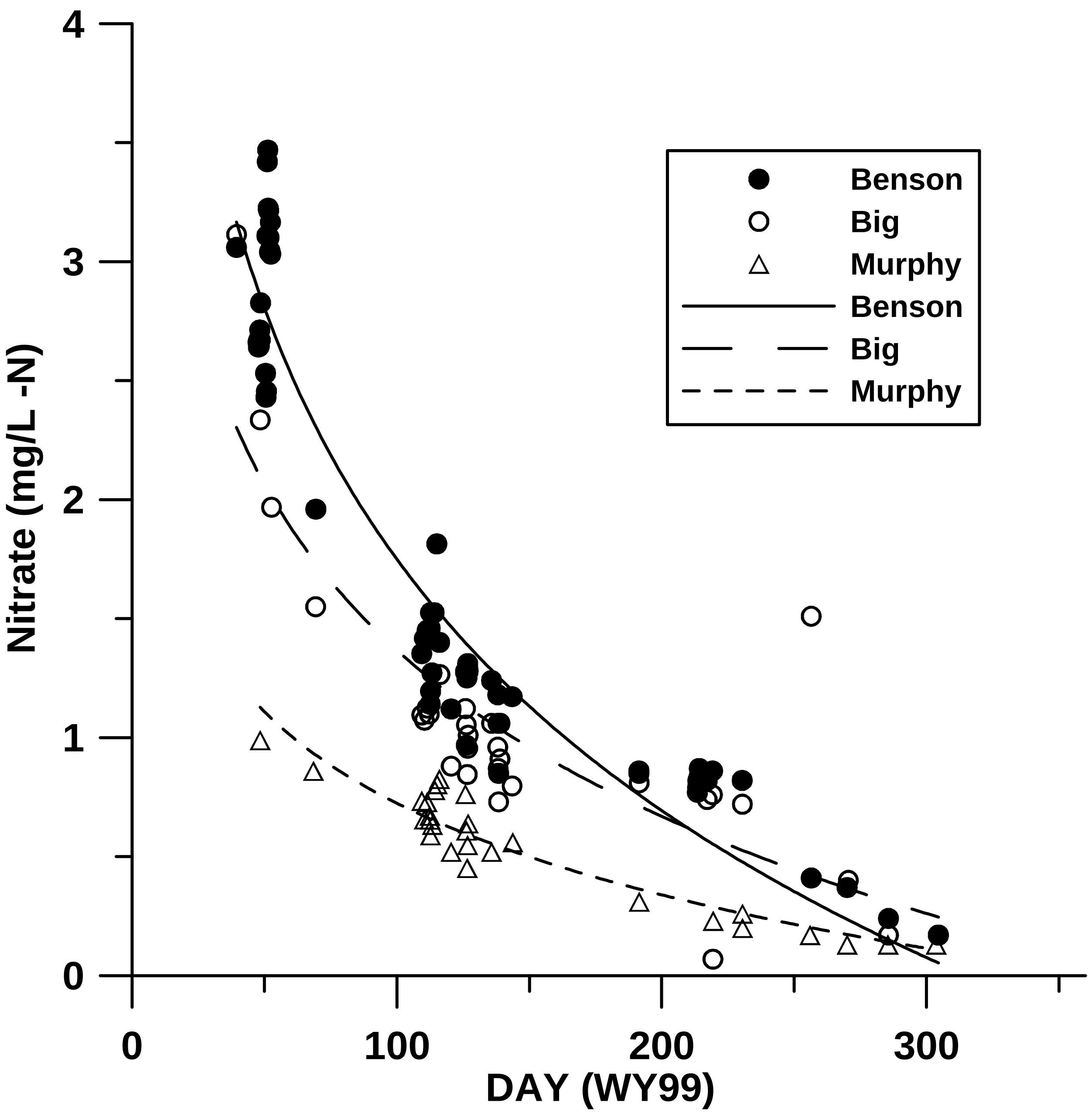

Figure 9. Nitrate (NO_3-N; mg/L) for Big, Benson, and Murphy Creeks.

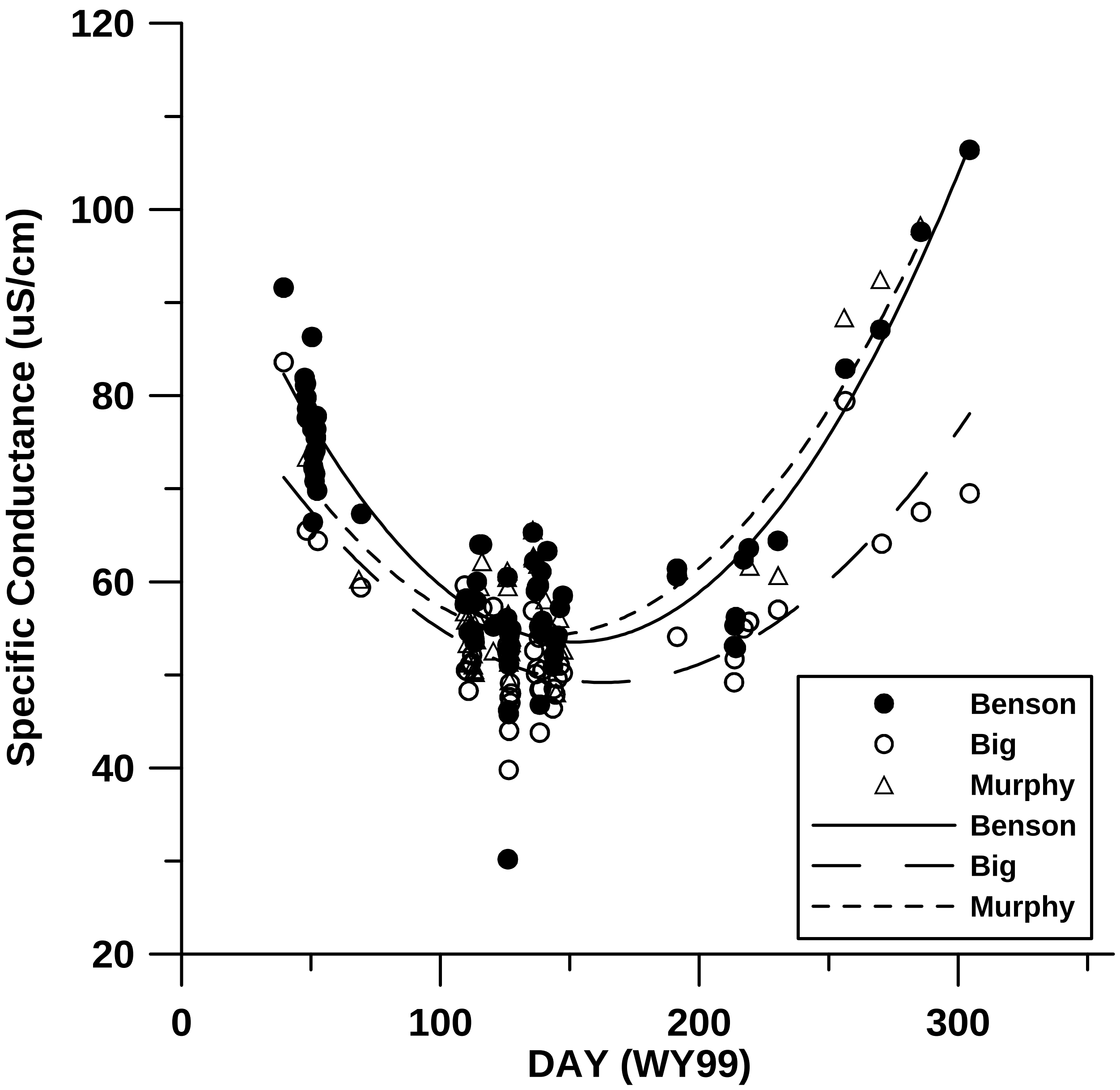

Figure 10. Specific conductance (µS/cm) for Big, Benson, and Murphy Creeks.

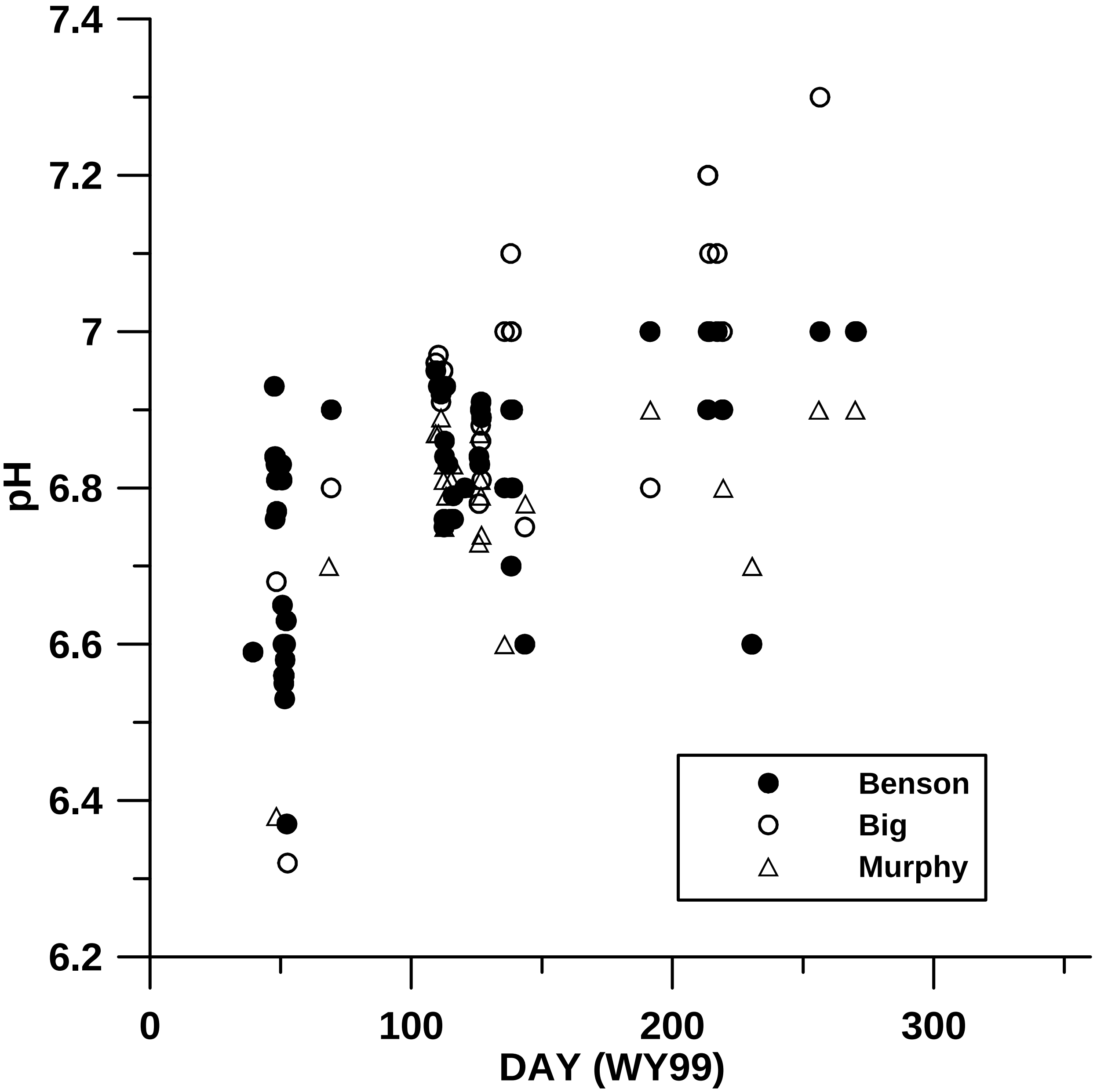

Figure 11. pH (standard units) for Big, Benson, and Murphy Creeks.

Table 4. Concentrations of TSS, TP, NO_3 (all in mg/L) for synoptic sites.

Site ID	Site Name	N	TSS	TP	NO_3
ADA	Adams Creek (A)	2	62	0.102	1.21
ADB	Adams Creek (B)	1	1	0.034	2.03
BGD	Big Creek (Ditch)	2	177	0.167	0.87
BND	Benson Creek (Ditch)	1	21	0.085	0.10
JNA	Johnson Creek (A)	1	142	0.155	0.59
MIL	Johnson Creek (B)	1	100	0.124	0.47
MMR	Murphy Tributary	1	29	0.034	0.73
MUM	Murphy Marsh	2	4	0.030	0.76
NOB	Noble Creek	5	5	0.040	3.79
RAN	Rain	5	1	0.020	0.15
REX	Benson Tributary	12	252	0.066	2.93
SHB	Shutters Creek (B)	1	52	0.092	0.96
SHU	Shutters Creek	1	103	0.158	1.36
SUN	Ditch N. Sunriver M.	1	26	0.055	1.36

suggested that the water quality in Big and Benson Creeks was typical of much of the Tenmile Lake watershed.

3. Lake Water Quality

a. Field Results

Field measurements at the lake sites included temperature, specific conductance, dissolved oxygen, pH, and Secchi disk transparency. In most cases, the lake waters were thermally uniform resulting in relatively little vertical variation in dissolved oxygen and specific conductance. However, during summer some temperature stratification would occur when reduced wind conditions permitted establishment of a temperature differential of several degrees. The greatest temperature difference between the top and bottom waters occurred on June 30, 1999 at site NTA with a temperature difference of 4.9° C (21.6 to 16.7° C). Oxygen depletion in the bottom waters was rapid with DO approaching 0 mg/L at the bottom (Figure 12). A similar depletion of DO was observed at the same site on August 26, 1999 even though the temperature difference between the top and bottom of the lake was only 3° C (Figure 13). Oxygen depletion was equally intense at the shallower NTB site located at the confluence of Big Creek Arm and

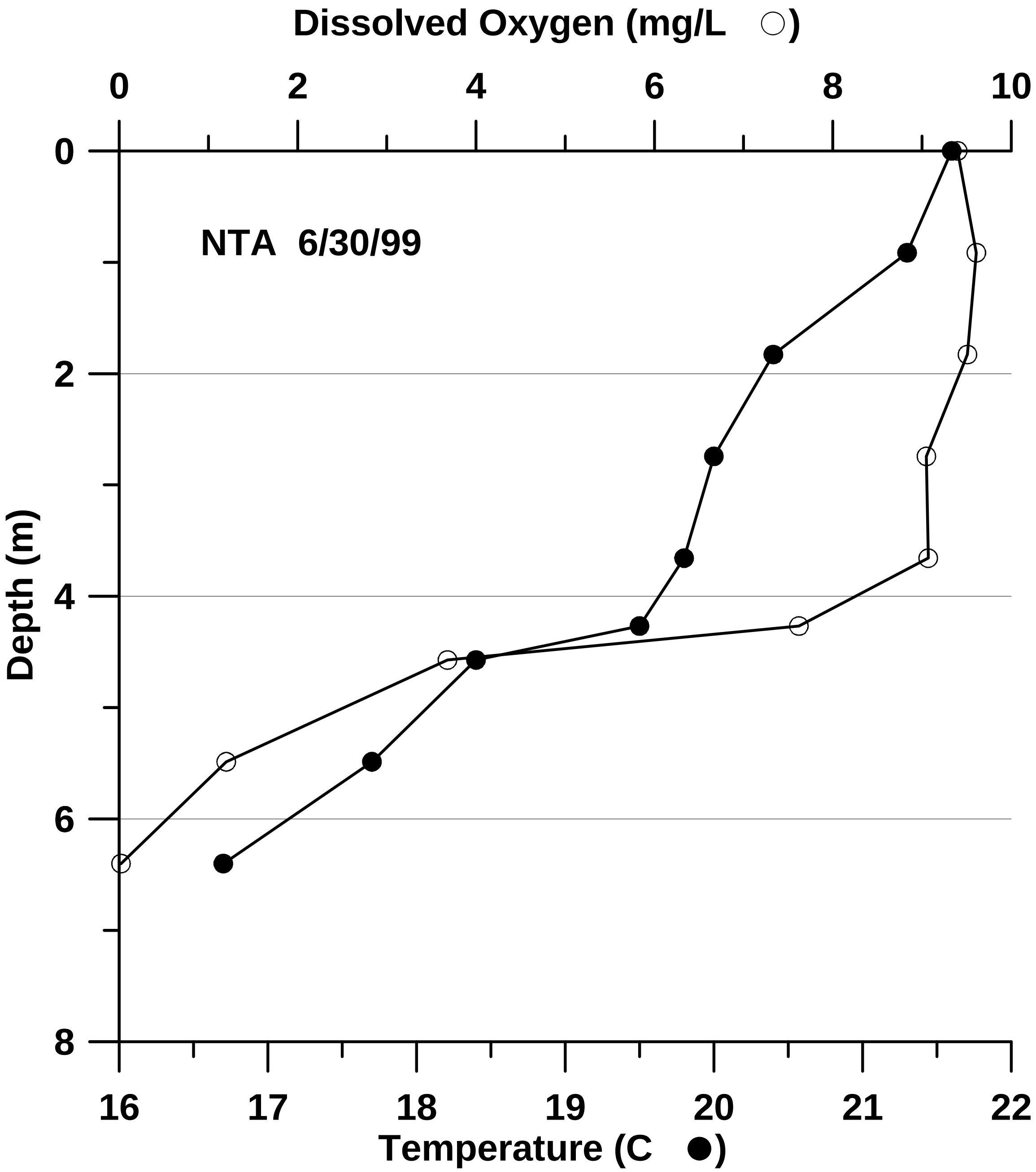

Figure 12. Temperature (°C) and dissolved oxygen (mg/L) at NTA (North Tenmile-Site A) versus depth (m) on June 30, 1999.

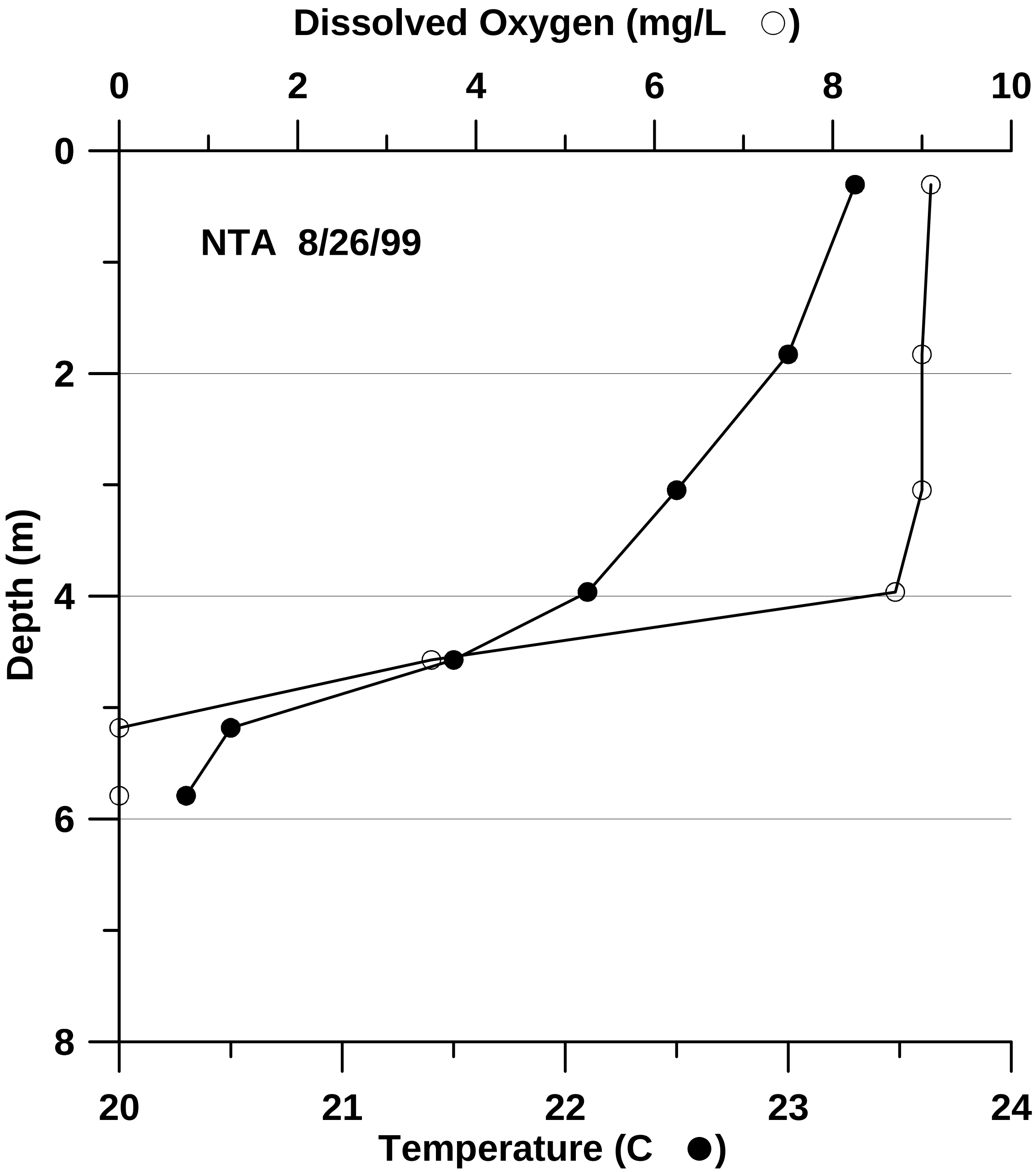

Figure 13. Temperature (°C) and dissolved oxygen (mg/L) at NTA (North Tenmile - Site A) versus depth (m) on August 26, 1999.

Carlson Arm during this August sample (Figure 14). Oxygen depletion rates at the south lake sites (STA and STB) were generally less than that observed in the north lake sites, although there was still evidence of low DO (Figure 15).

Secchi disk transparency varied considerably between the deep and shallow sites (Figure 16). The sites closest to inflowing tributaries (NTB and STB) experienced lower transparency caused by suspended solids from watershed runoff during the winter and by intense algal blooms in the summer. This was particularly evident at site NTB which was proximate to the Big Creek inlet. Turbidity plumes from Big Creek were visible for over 1 km downstream of Big Creek during major runoff events. The transparency in the Big Creek Arm was 0.8m on February 20, 1999 compared to 1.3m in the Carlson Arm which drains Murphy and Wilkins Creeks. This difference of nearly 40 percent was typical of the transparency difference that existed in the winter between the two sites. In the summer, reduced transparency was associated with algal blooms. For example, on August 26, 1999 transparency ranged from 2.4 m at site NTA to 1.2 m at site NTB and down to 0.7 m at Sun Lake Marina located about 100 m from the mouth of Big Creek.

b. Analytical Chemistry

Concentrations of TSS in the lake were generally less than 5 mg/L (Figure 17). The highest TSS value of 28 mg/L was measured at NTB on November 18, 1998 following a storm event. On any given date, TSS values were usually greater at the distal sites (NTB and STB) compared to the open water sites (NTA and STA). A comparison of TSS at the Benson Creek site compared to the outlet of Tenmile Lake illustrates the extent to which the lake serves as a settling basin for erosional inputs from the watershed (Figure 18).

Total phosphorus concentrations in Tenmile Lake generally ranged from 0.10 mg/L to 0.04 mg/L (Figure 19). The extreme value of 0.140 mg/L again was observed at site NTB on November 18, 1998. Concentrations of TP were highest during the winter when sediment loads would remain suspended and again in late summer when high TP was associated with planktonic algae. When we compare the inflowing waters from Benson Creek with the outlet from Tenmile Lake, it is apparent that the lake also serves as sink for phosphorus (Figure 20). However, concentrations of TP in the lake are comparable to those in the stream during the summer.

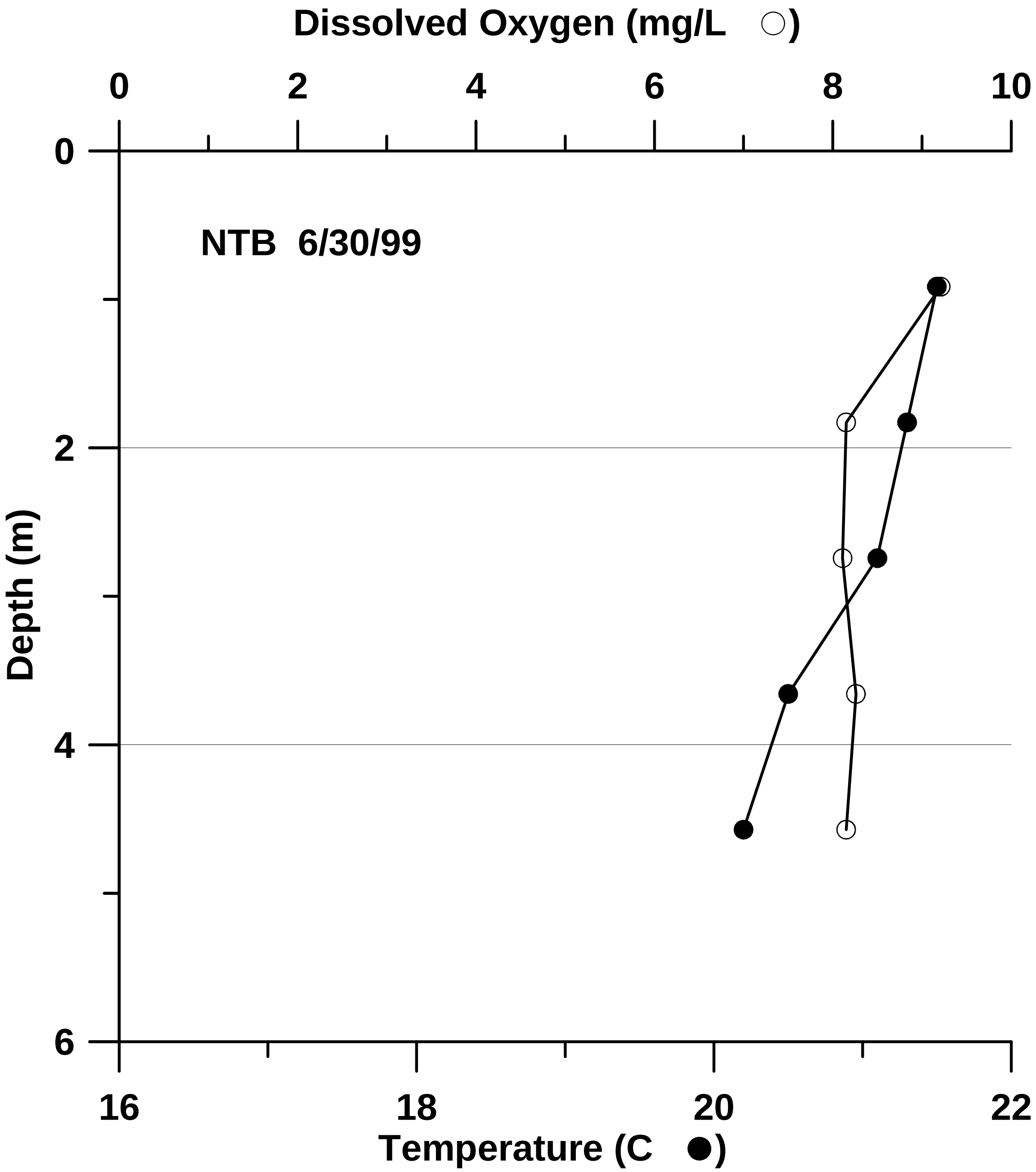

Figure 14. Temperature (°C) and dissolved oxygen (mg/L) at NTB (North Tenmile - Site B) versus depth (m) on June 30, 1999.

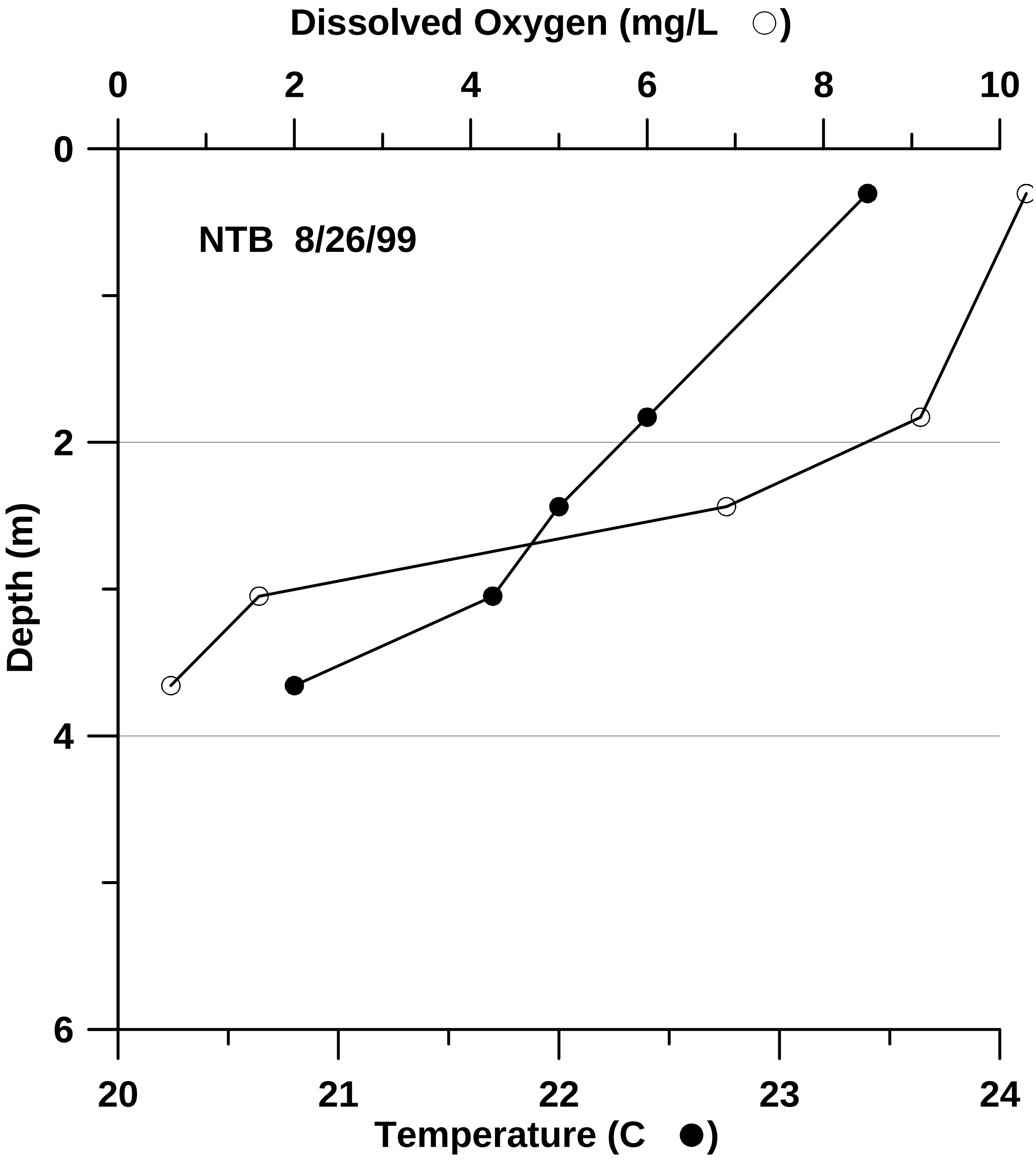

Figure 15. Temperature (°C) and dissolved oxygen (mg/L) at NTB (North Tenmile - Site B) versus depth (m) on August 26, 1999.

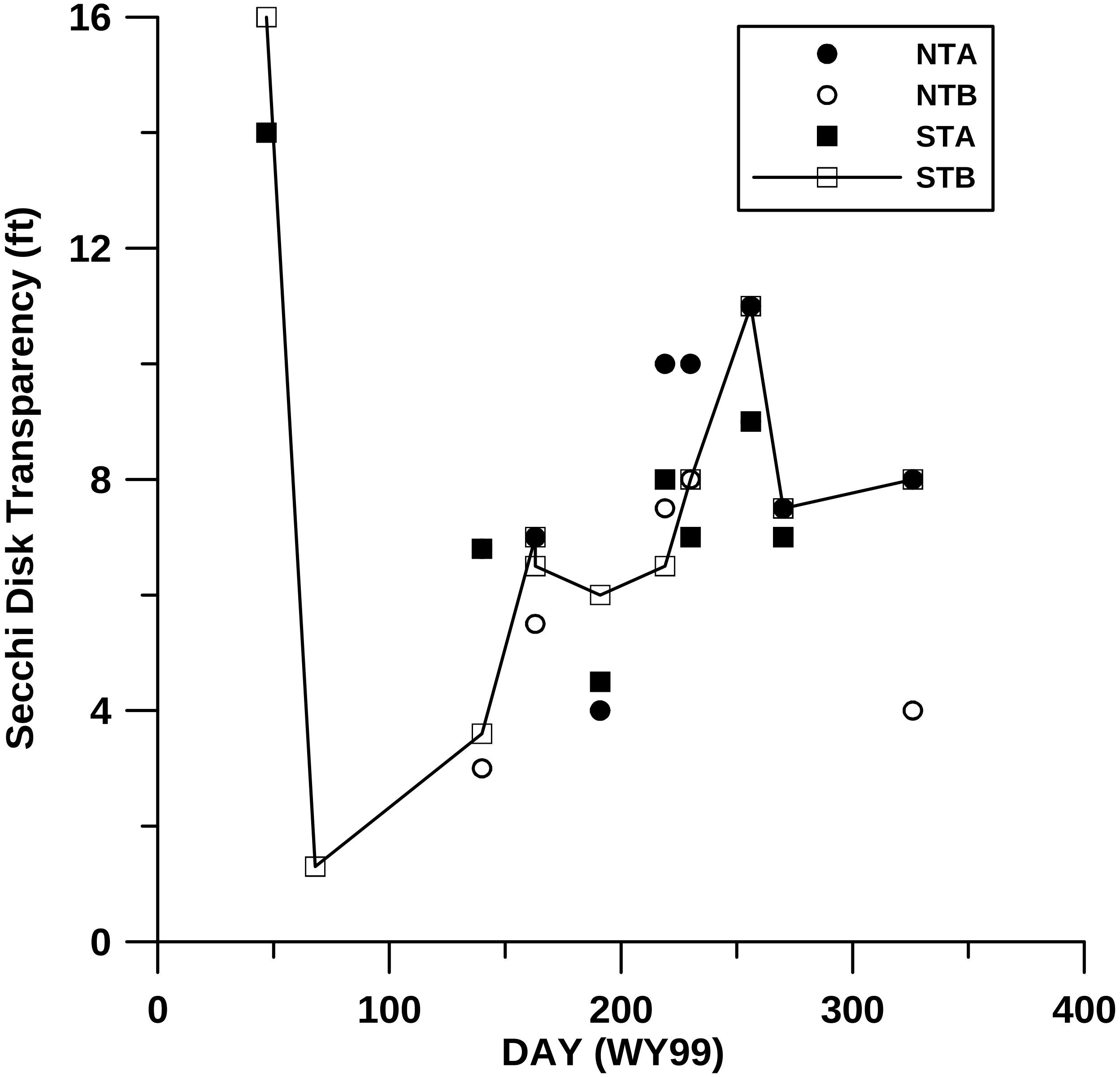

Figure 16. Secchi disk transparency (ft) for the four sites on Tenmile Lake.

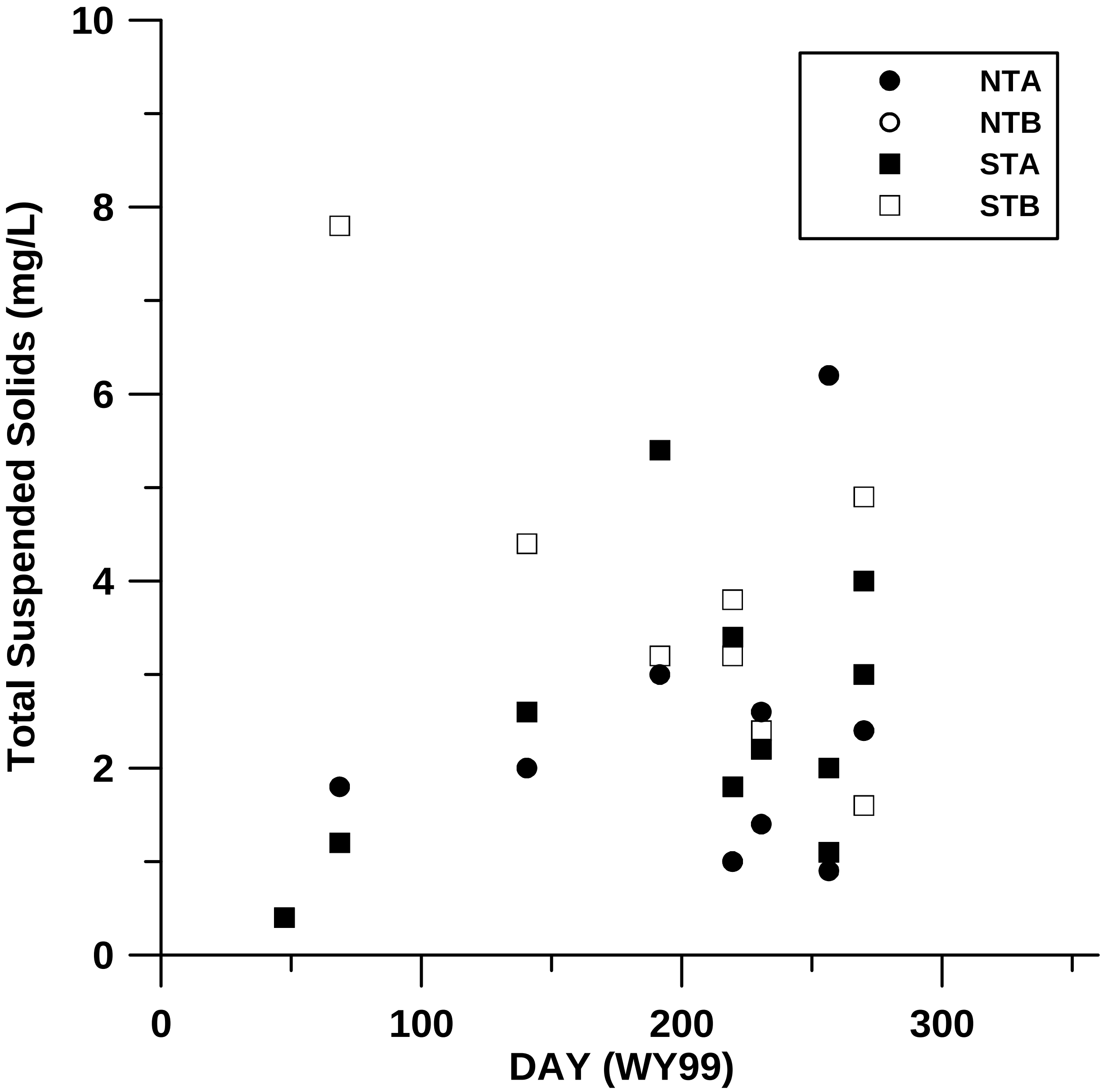

Figure 17. Total suspended solids (mg/L) for the four sites on Tenmile Lake. One observation from site NTB on November 18, 1998 exceeded the plot scale (26 mg/L).

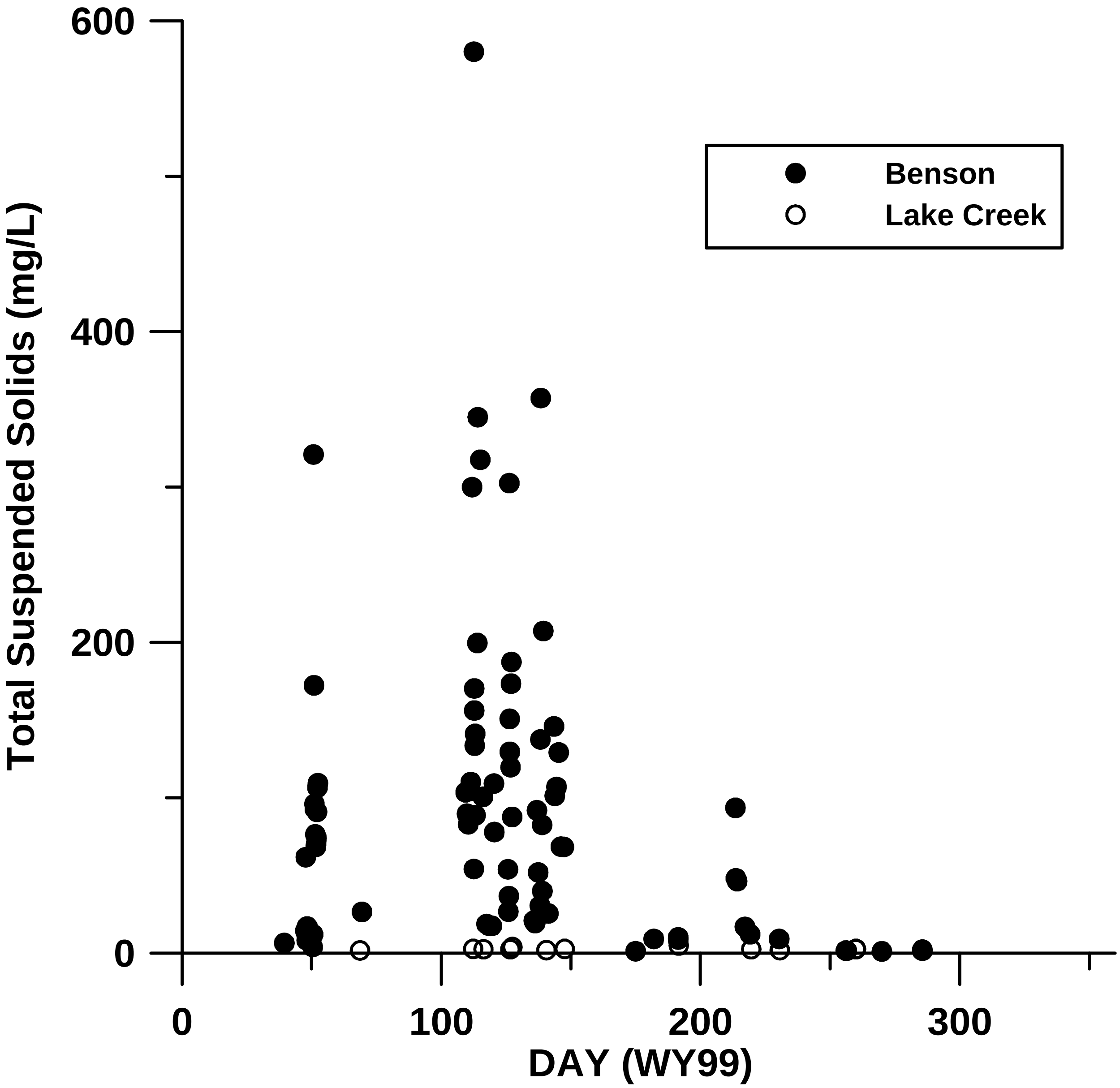

Figure 18. Total suspended solids (mg/L) at Benson Creek (**!**) and the outlet of Tenmile Lake (**"**).

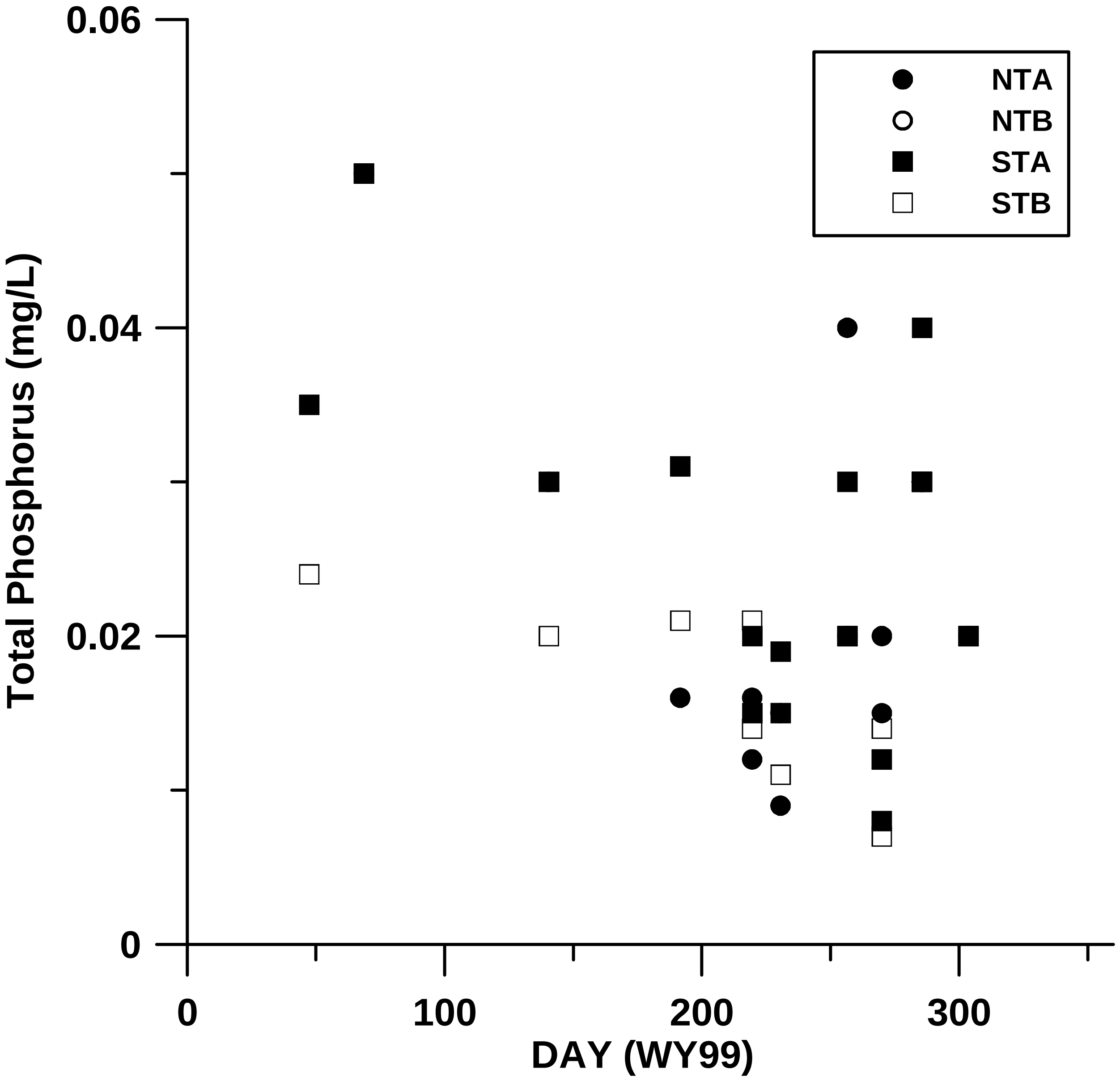

Figure 19. Total phosphorus (mg/L) at the four sites on Tenmile Lake. One observation from site NB on November 11, 1998 exceeded the plot scale (0.14 mg/L).

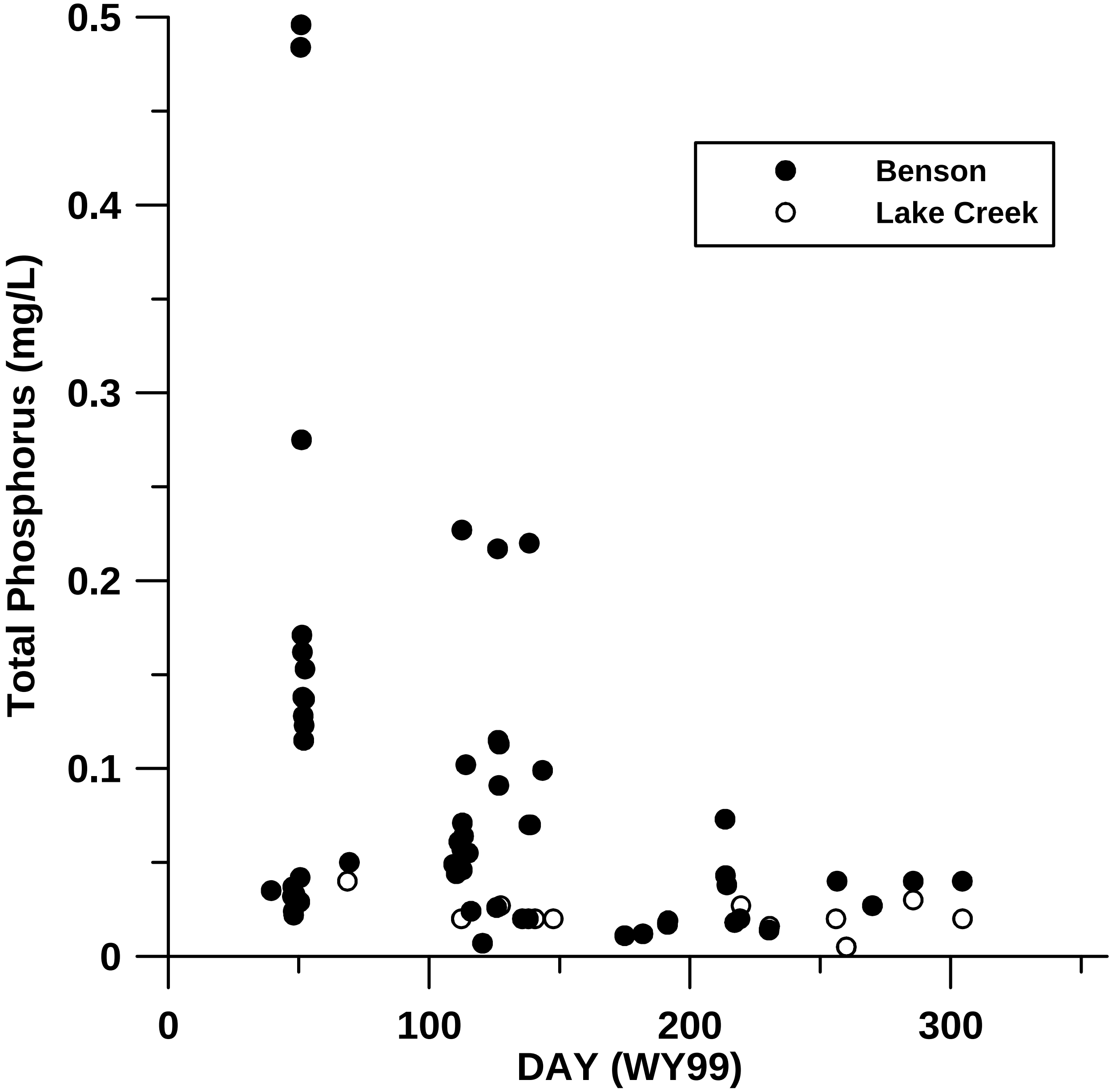

Figure 20. Total phosphorus (TP; mg/L) in Benson Creek (!) compared to the outlet of Tenmile Lake (").

Concentrations of ortho phosphorus were generally only 20 to 30 percent of the TP values for a given lake sample.

Inorganic nitrogen was present in the lake almost exclusively as nitrate; ammonia was seldom detected. Nitrate concentrations in the lake exhibit a striking seasonal effect with low concentrations in the fall followed by a sharp rise with input from winter runoff and a linear decline to the summer (Figure 21). Concentrations of nitrate in the lake were below detection limit in summer. The pattern of nitrate decline in the lake matches the changes in tributary concentrations during the winter. However, during the spring, nitrate losses in the lake occur at a rate greater than the declines from the tributary inputs (Figure 22).

pH values (lab) in Tenmile Lake were typically from 6.8 to 7.6 (Figure 23). These values measured in the laboratory may have equilibrated with CO_2 in the atmosphere and may not reflect actual field conditions. However, the maximum field pH measured during Phase I did not exceed 8.0. As expected, there is a noticeable seasonality in the pH data where pH in the summer is higher than that measured in the winter. This reflects the increase in photosynthetic activity in the warmer months.

Specific conductance is proportionally related to the concentrations of major ions in the water. The values in Tenmile Lake closely reflect the pattern observed in the tributaries in which higher concentrations in the fall are diluted by winter runoff. As groundwater becomes a greater proportion of streamflow and evapotranspiration increases, specific conductance increases (Figure 24). The variation in specific conductance has no particular consequence with respect to water quality within the observed ranges, but does illustrate the importance of runoff versus groundwater on the lake chemistry. The increase in the relative importance of groundwater in the spring and summer, however, does have significance with respect to transport of dissolved nutrients that enter the lake.

c. Chlorophyll a and Phytoplankton

The aquatic plants in a lake reflect the trophic nature of the system and in turn affects the lake fisheries and water quality. Tenmile Lake has an abundant macrophyte population which is evident in most areas of the lake less than a depth of 5m. However, no analysis of the macrophyte population was included in the scope of this study. The assessment of primary production for this report was based solely on the phytoplankton composition and abundance.

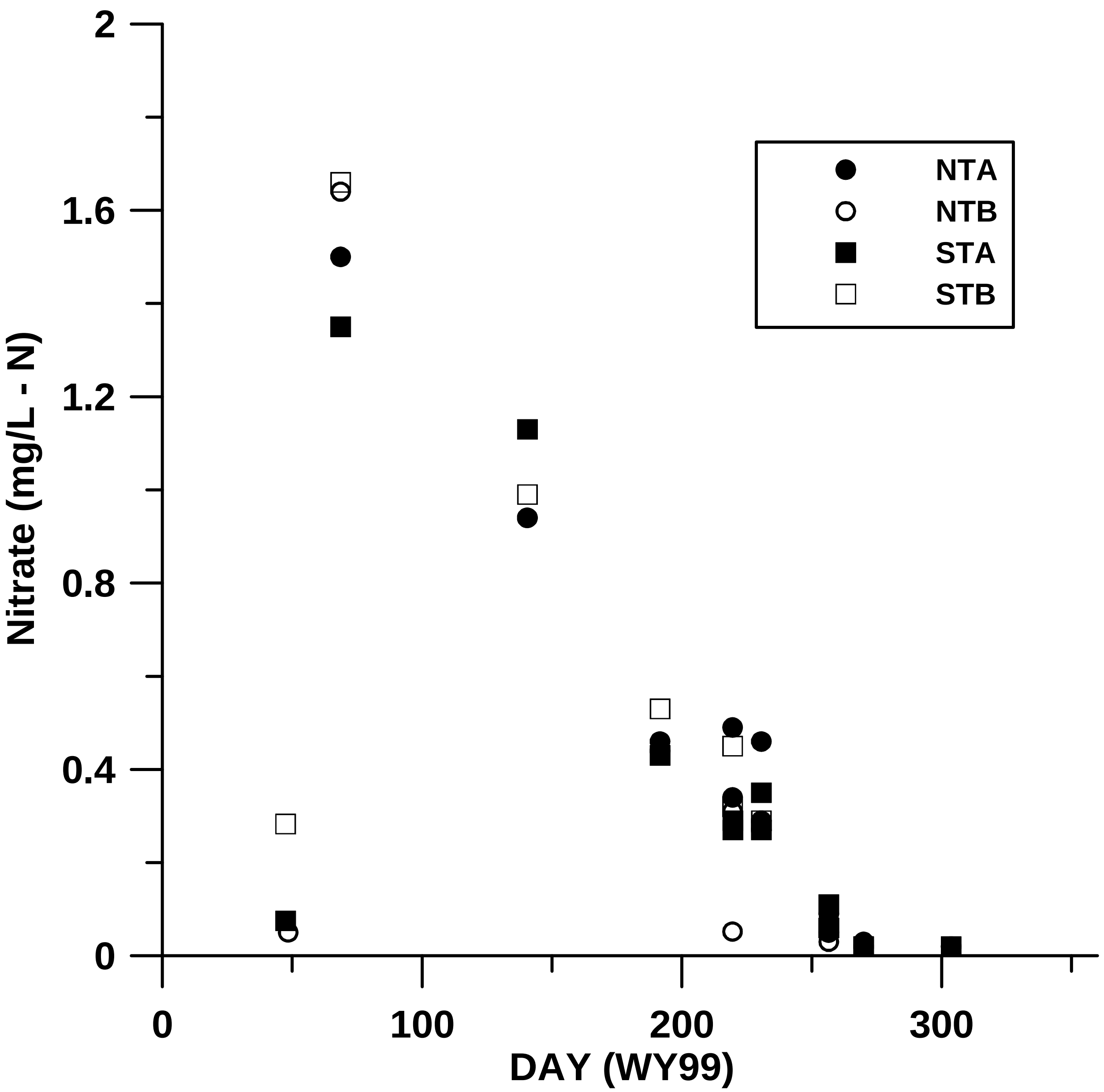

Figure 21. Nitrate (NO_3-N, mg/L) for the four sites on Tenmile Lake.

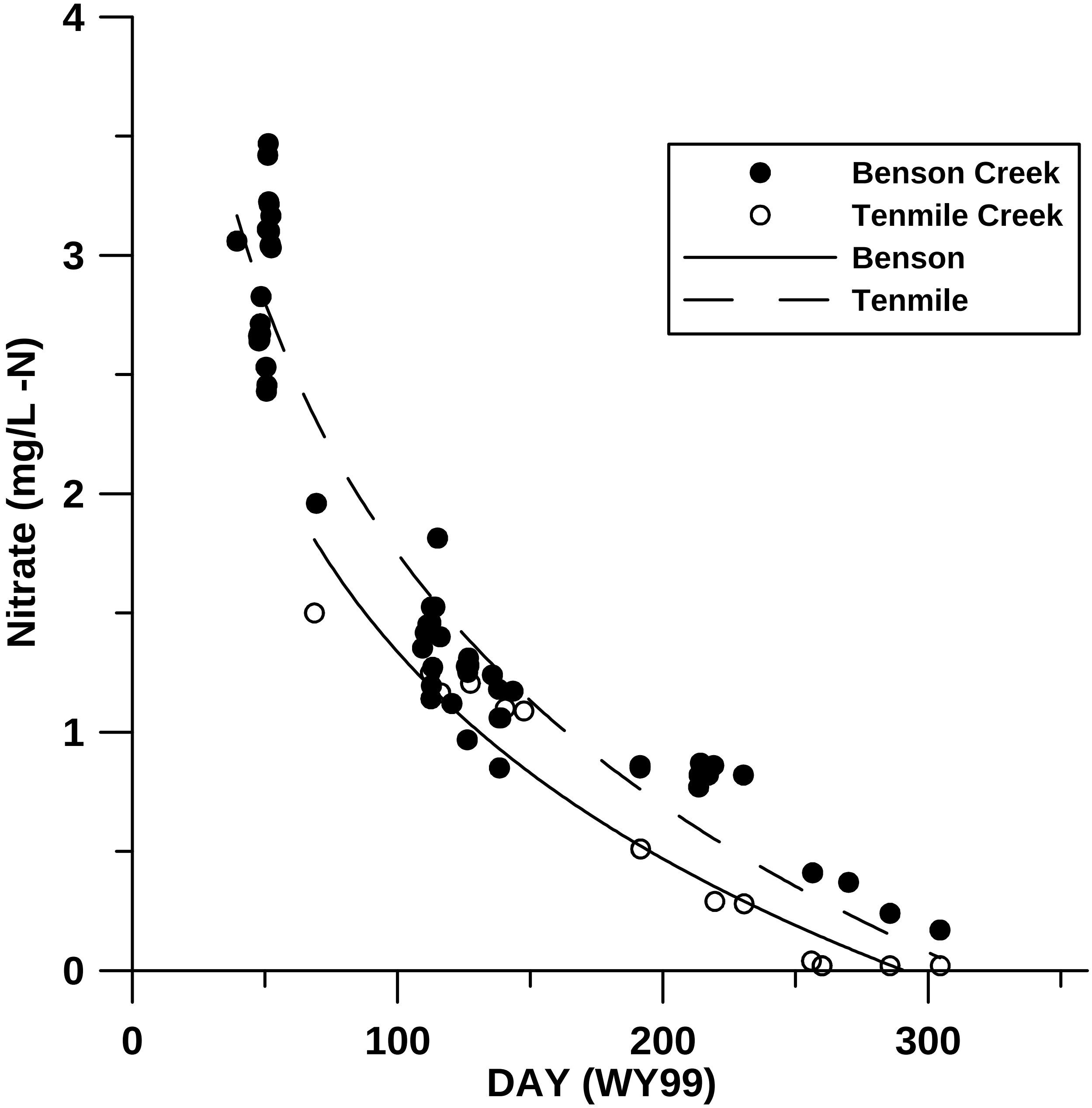

Figure 22. Nitrate (NO_3-N, mg/L) in Benson Creek (!) compared to the outlet of Tenmile Lake (").

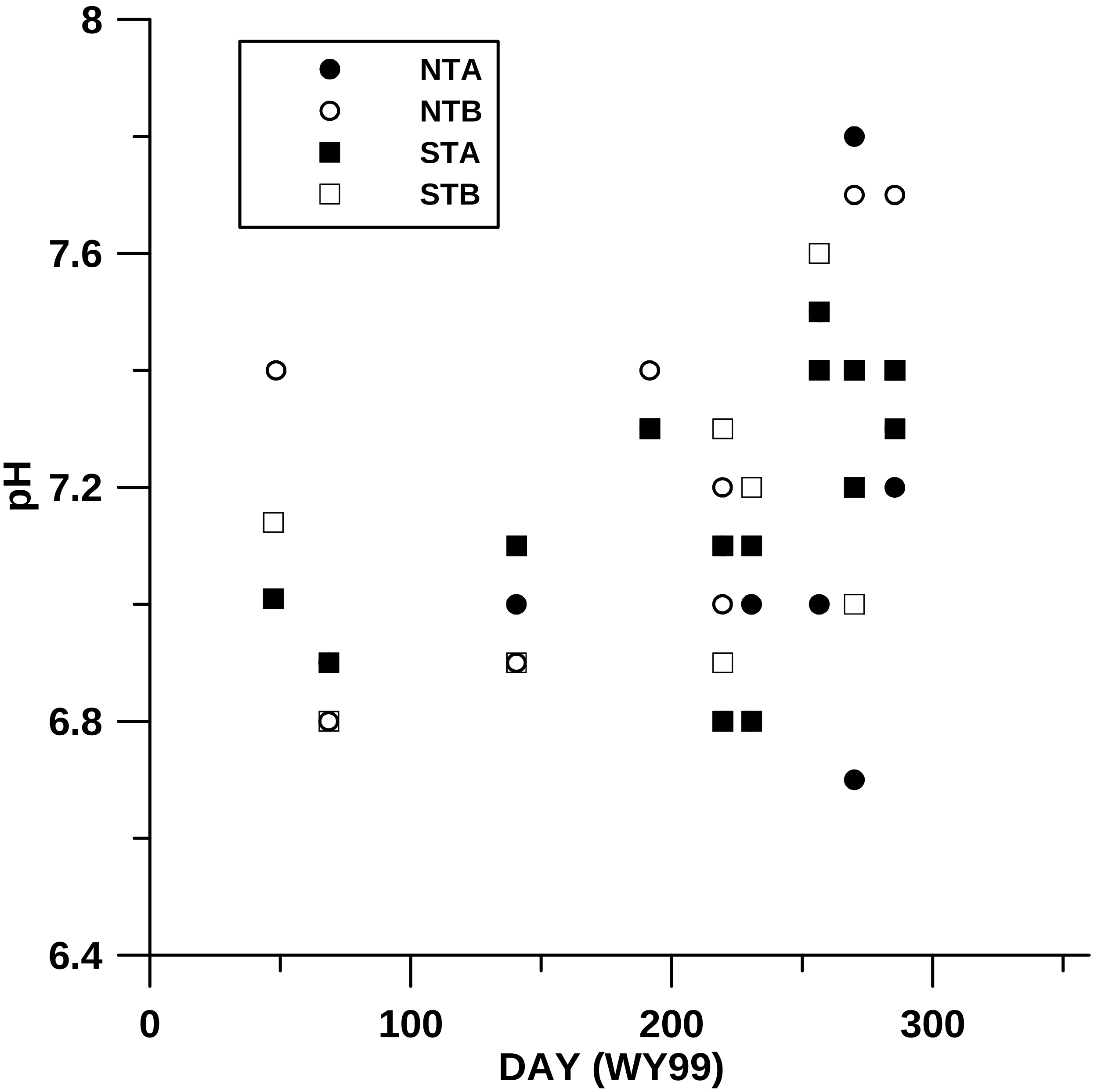

Figure 23. Laboratory pH values in Tenmile Lake.

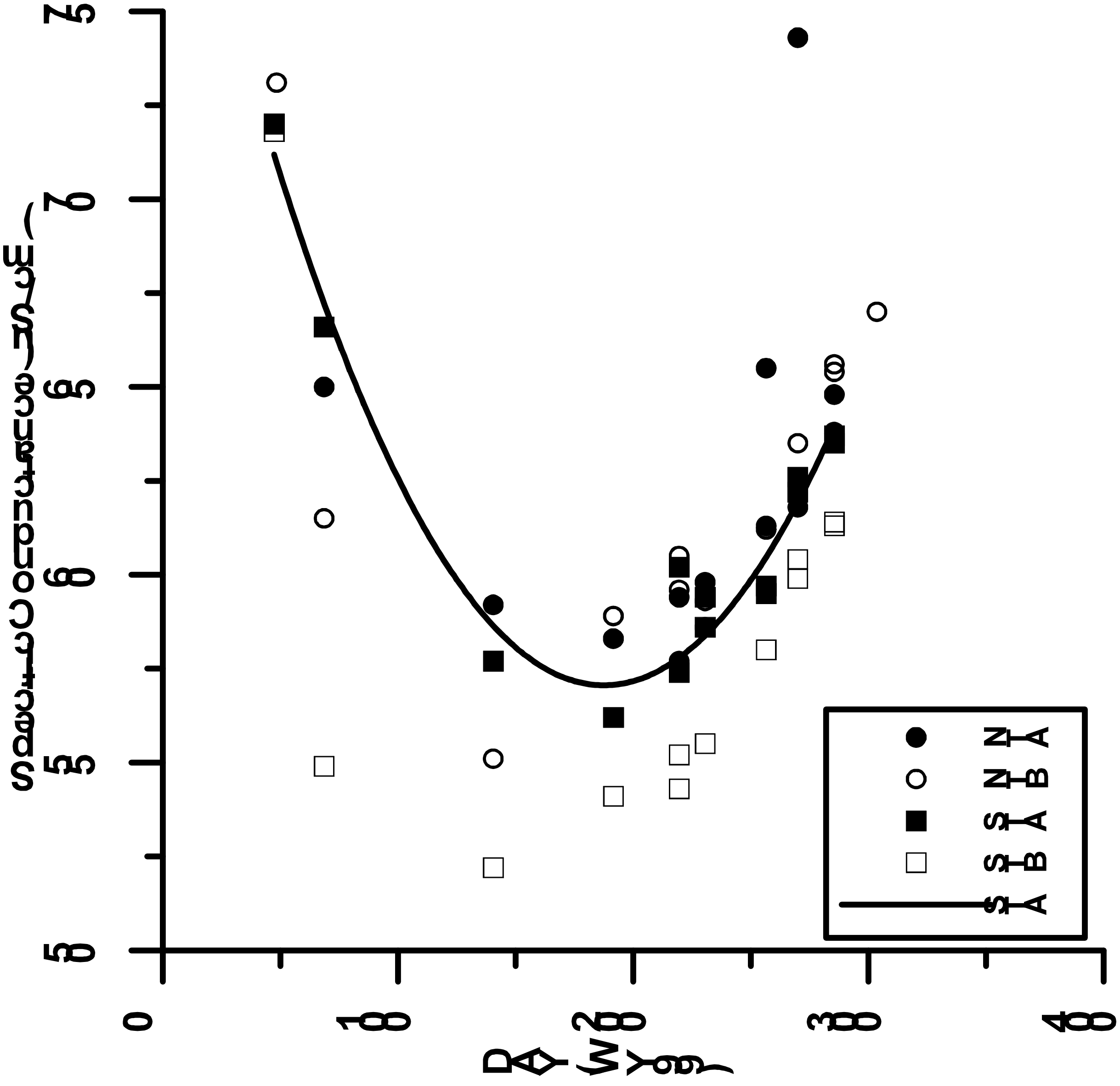

Figure 24. Specific conductance (µS/cm) in Tenmile Lake.

Measures of phytoplankton abundance include chlorophyll, phytoplankton density, and phytoplankton biovolume. Chlorophyll *a* concentrations exceeded 20 µg/L on two occasions in the spring and the late summer (Figure 25). This bimodal distribution of chlorophyll is common in temperate lakes. Typically, the spring bloom is associated with diatoms, whereas the summer bloom is caused by cyanobacteria (bluegreen algae). In general, the south lake sites had higher concentrations of chlorophyll. The trophic state index (TSI) computed based on the chlorophyll measurements shows that the lake typically has a TSI value between 50 and 60 (Figure 26).

Phytoplankton density, another metric of algal abundance, shows a similar pattern to that of chlorophyll with the exception that the density does not exhibit a late summer peak (Figure 27). This is consistent with a higher proportion of larger algal cells and colonies which cause a decrease in the cell density relative to the biovolume. This effect is consistent with a diatom (generally individual cells) bloom in the spring and a cyanobacteria (filamentous and clumped cells) bloom in the summer.

Phytoplankton biovolume appears to integrate the information provided in the chlorophyll and plankton density data. Biovolume is high in the spring at all four sites, corresponding to a lakewide diatom bloom (Figure 28). However, in the late summer it is primarily site NTB (Big Creek Arm) which exhibits a high biovolume. Again, this is consistent with a higher proportion of cyanobacteria at NTB (high biovolume, high chlorophyll, low density).

The phytoplankton taxa vary widely in the lake depending on the season. In the winter when biovolume is low, the dominant taxa are cryptomonids (*Cryptomonas erosa* and *Rhodomonas minuta*) followed by diatoms (Appendix 2). No cyanobacteria were observed in February. In the spring, biovolume increases dramatically and diatoms represented at least 94 percent of the biovolume at each of the four lake sites. The dominant diatom was *Asterionella formosa*, a species often abundant in productive lakes. Again, cyanobacteria were virtually absent. In late August, cyanobacteria are the dominant planktonic group representing over 40 percent of the biovolume in the south lake and over 85 percent of the biovolume in the north lake. The dominant cyanobacteria species was *Anabaena planctonica*. The cyanobacteria are considered a poor quality food for zooplankton, whereas the cryptomonids and, to a lesser extent, diatoms are high quality food sources.

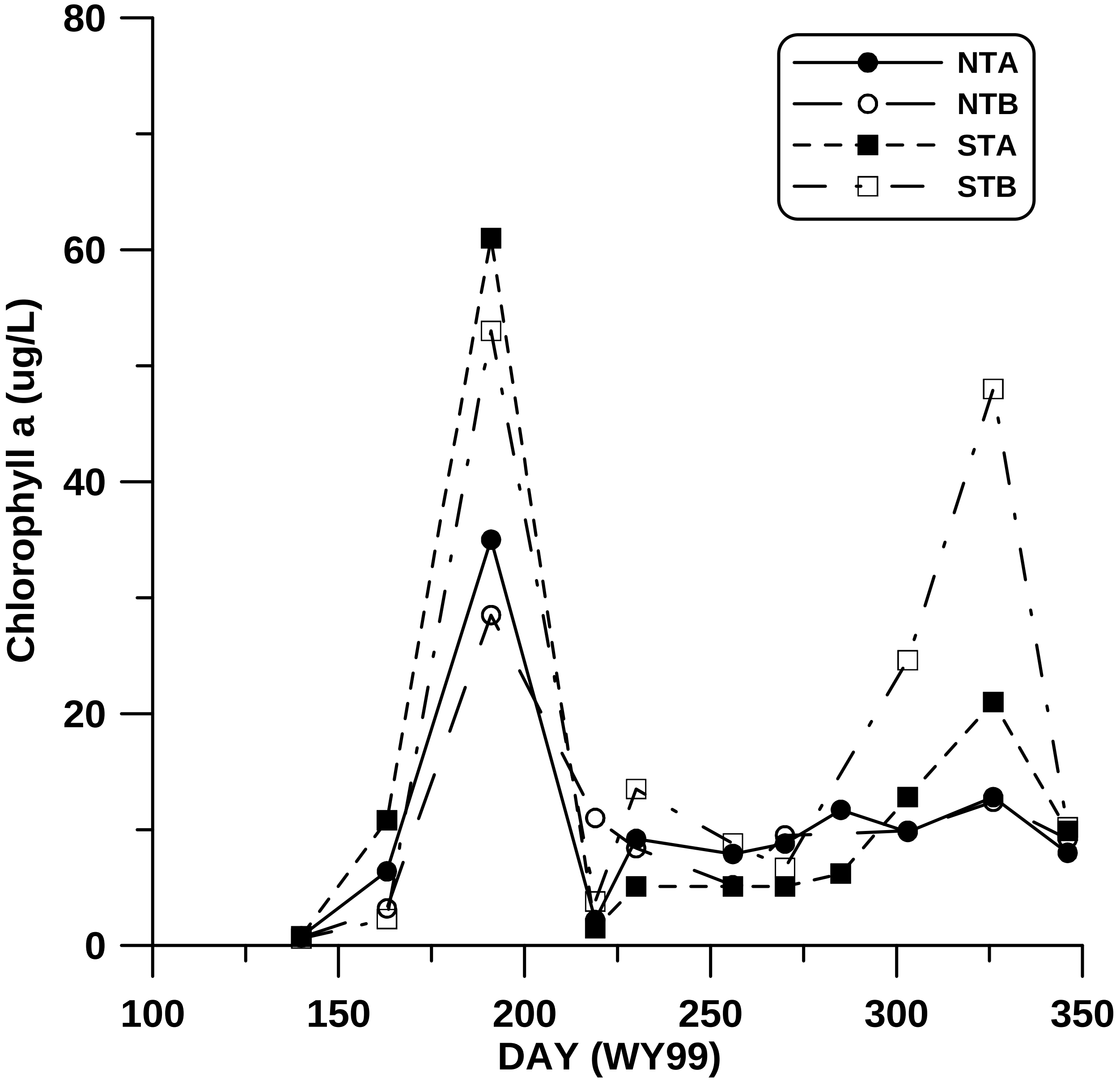

Figure 25. Chlorophyll *a* (µg/L) in Tenmile Lake.

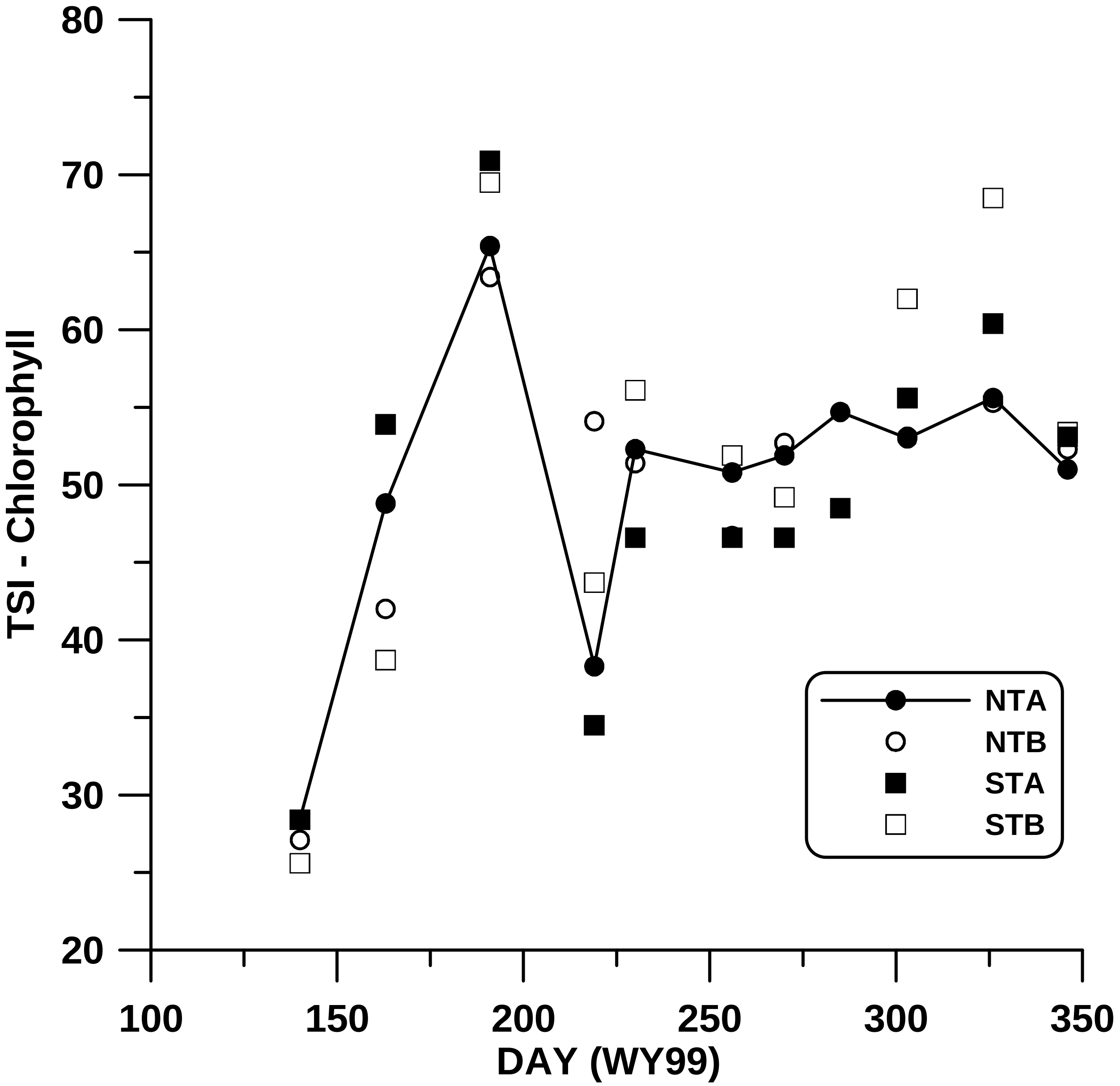

Figure 26. Trophic state index (TSI, after Carlson [1977]) in Tenmile Lake based on chlorophyll *a*.

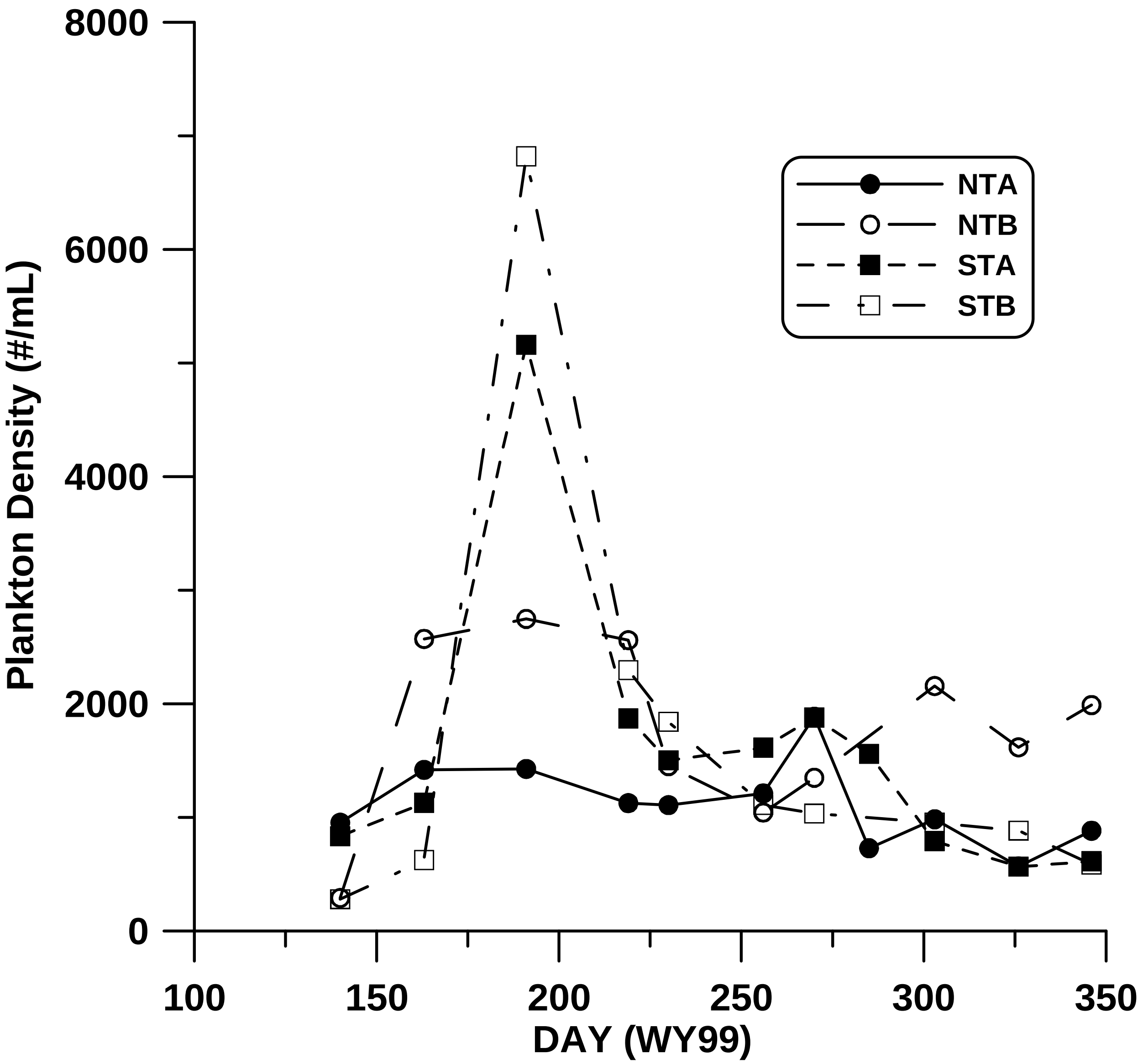

Figure 27. Phytoplankton density (#/ml) in Tenmile Lake.

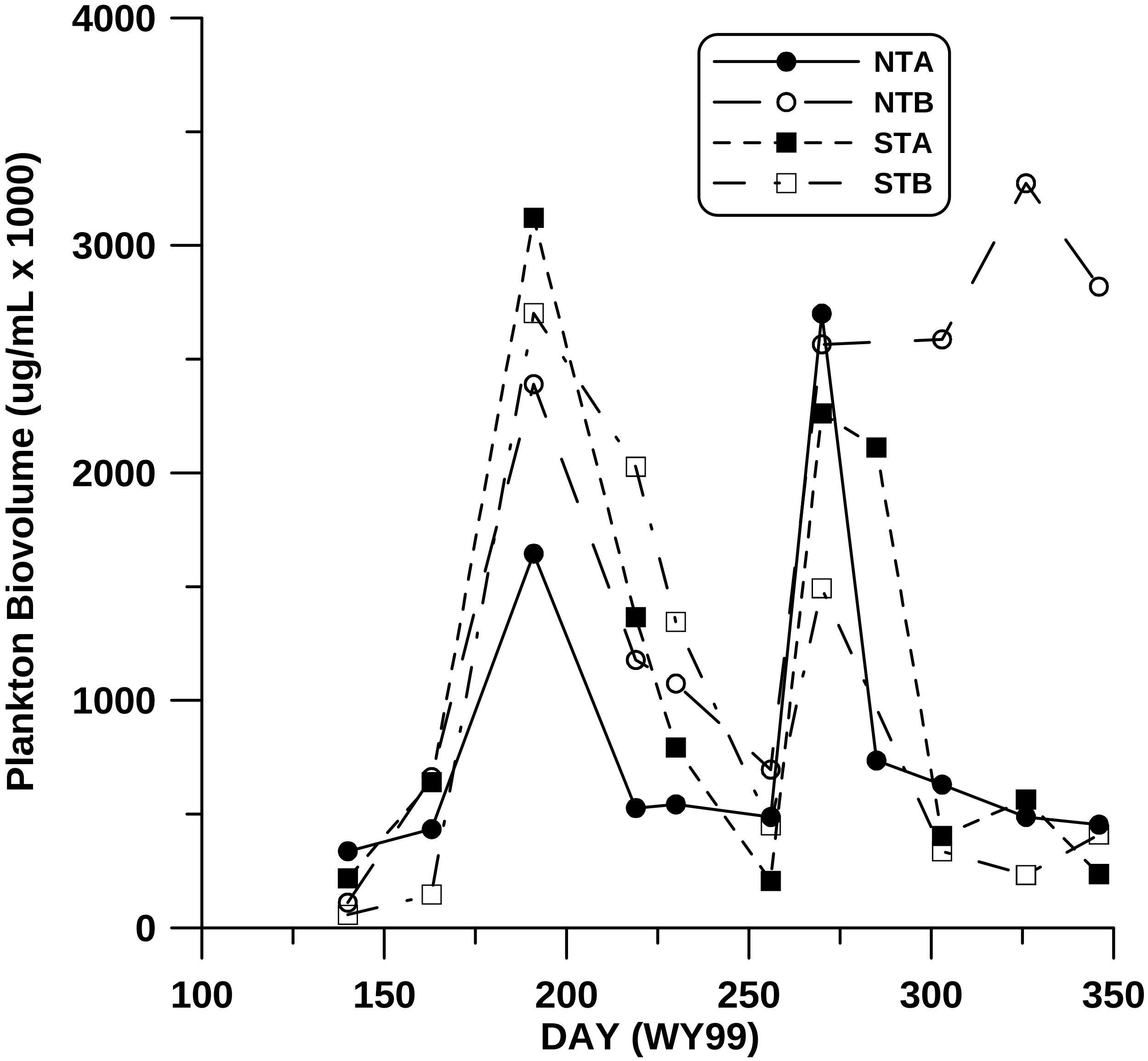

Figure 28. Phytoplankton biovolume (m^3/ml x 1000) in Tenmile Lake.

4. Lake Sediment

The sediment core from the south lake was dated using ^{210}Pb and analyzed for fossil diatoms, ^{15}N, and cyanobacteria akinetes. The ^{210}Pb provides estimates of the age of the sediments and therefore allows one to compute the sediment accumulation rate (SAR). Diatom taxa preserve well in lake sediments because the cell wall is composed of silica. Diatoms have specific environmental requirements and the type of species in the sediments provide considerable information about the historical water quality in the lake. Nitrogen-15 is a natural isotope of nitrogen (atomic weight 14). A shift in the $^{15}N/^{14}N$ ratio can provide insight into shifts in major sources of nitrogen to the lake. In particular, an elevated ratio can be associated with high inputs of marine-derived N from anadromous fish. It also can be caused by a shift in the proportion of N-fixing phytoplankton that might occur if the relative amount of cyanobacteria had increased. Akinetes are structures found on N-fixing cyanobacteria that can be preserved in the sediments. An increase in akinetes might signal an increase in cyanobacteria.

The age of the sediments from site STA shows that there has been a substantial increase in SAR during the last century (Figure 29). Although the sediment dating is not without uncertainty, the data indicate that SAR has increased about four-fold over pre-development levels (Figure 29). The lake appears to have experienced three significant increases in SAR. The first increase occurred near 1890, corresponding to some of the early settlement which involved timber harvest and agriculture. The second increase occurred in the period from about 1900-1920. This coincided with a major increase also observed in Devils Lake, OR on the central coast (Eilers et al. 1996). As was observed in Devils Lake, Tenmile Lake appeared to recover during the 1920s and 1930s. However, by the 1950s the SAR was once again elevated. This trend of increasing SAR continues to the present. The age of the sediments can be distorted by mixing of the sediments caused by either bioturbation (e.g. mixing caused by organisms living in the sediments such as chironomid larvae) or physical disturbance from currents or side-slumping. However, had either of these occurred to any significant extent we would have expected to observe discontinuities in the diatom stratigraphy. The diatoms exhibit monotonic increases and decreases which suggests that the sediments are reasonably undisturbed. Without further evidence to the contrary, we conclude that the sediment dating is a reasonable approximation of the actual chronology.

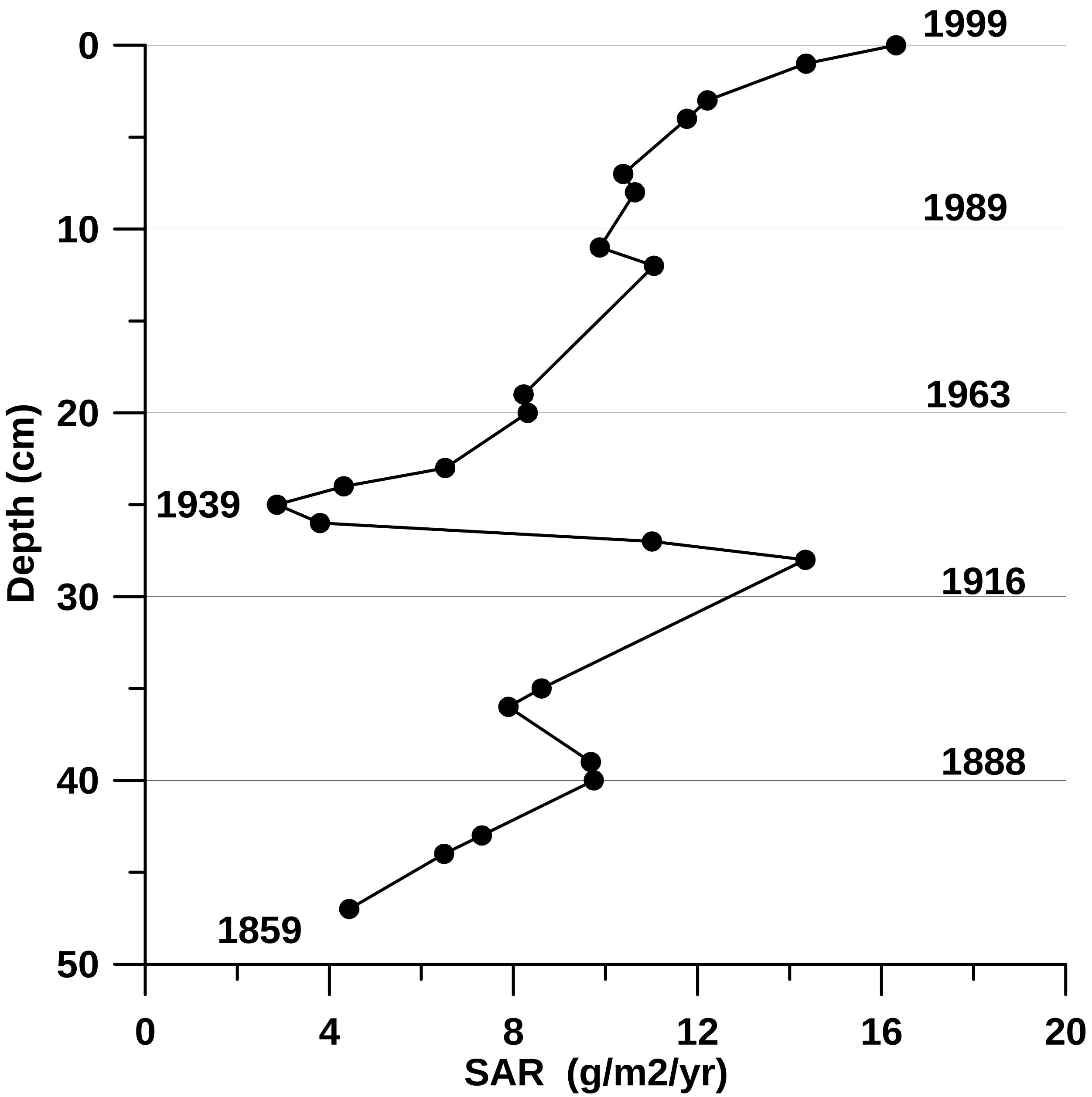

Figure 29. Sediment accumulation rate (SAR, g/m^2/yr) near site STA in Tenmile Lake.

The dominant diatom taxa in the lake sediments are illustrated in Figure 30. One hundred and ten diatom taxa were identified in the sediment core. The entire core is dominated by planktonic diatoms (78-98%). Three zones have been identified and are described below.

Zone I (76 cm-26 cm [<1000-1931 (± 14 yrs)])

Zone I is dominated by centric diatoms (86-96%), including *Aulacoseira*, *Melosira*, *Cyclotella*, *Stephanodiscus*, and *Thalassosira*. *Aulacoseira* cf. *ambigua* and *A. granulata* (59-77%) occur in the greatest abundances. *Cyclotella stelligera*, is also important (10-26%). *Stephanodiscus* (4-9%), mainly *S. medius*, *S. minutulus* and *S. Oregonicus*, and small benthic *Fragilaria* species (<1-4%) are present in small numbers. Araphideae diatoms occur in some samples, but only in trace numbers. For example, *Asterionella formosa* occurs in five out of seven level (<1-2%), *F. crotonensis* occurs in three levels (<1-3%), *F. capucina* occurs in four levels (<1-2%) and *Tabellaria* occurs in four levels (<1%).

Zone II (26 cm-10 cm [1931 (± 14 yrs) - 1984 (± 1 yr)])

Zone 2 is marked by an increase in Araphideae diatoms (15-28%) and a coincident decrease in centric diatoms (60-76%). Specifically, *Asterionella formosa* (9-18%), *F. crotonensis* (3-6%), *F. capucina* (1-5%), and *Tabellaria* (<1-2%) increase, whereas *Aulacoseira ambigua* and *A. granulata* (41-48%), *Cyclotella stelligera* (4-9%) and *Stephanodiscus* (2-3%) decrease. Notably, *Aulacoseira sp.* TM1 (5-7%) and *C. pseudostelligera* (6-8%) appear for the first time in significant numbers. Small benthic *Fragilaria* species (<1%) all but disappear, whereas two Monoraphideae diatoms, *Achnanthes* (2-4%) and *Cocconeis*, increase from <1.5% and <1%, respectively.

Zone III (10 cm-0 cm [1984 (± 1 yr) - 1999])

Zone III is delineated by a further increase in Araphideae diatoms (42%) and a further decrease in centric diatoms (49-50%). Specifically, *A. formosa* (24-28%), *F. crotonensis* (9-12%) and *F. capucina* (4%) increase, whereas *A. ambigua* and *A. granulata* (29-32%), *C. stelligera* (4-5%), and *Stephanodiscus* (2%) decrease. Several taxa, including *Tabellaria* (<1-1.5%), *Aulacoseira* sp TM1 and *C. pseudostelligera* (4-7%) decrease slightly and small benthic *Fragilaria* taxa almost disappear.

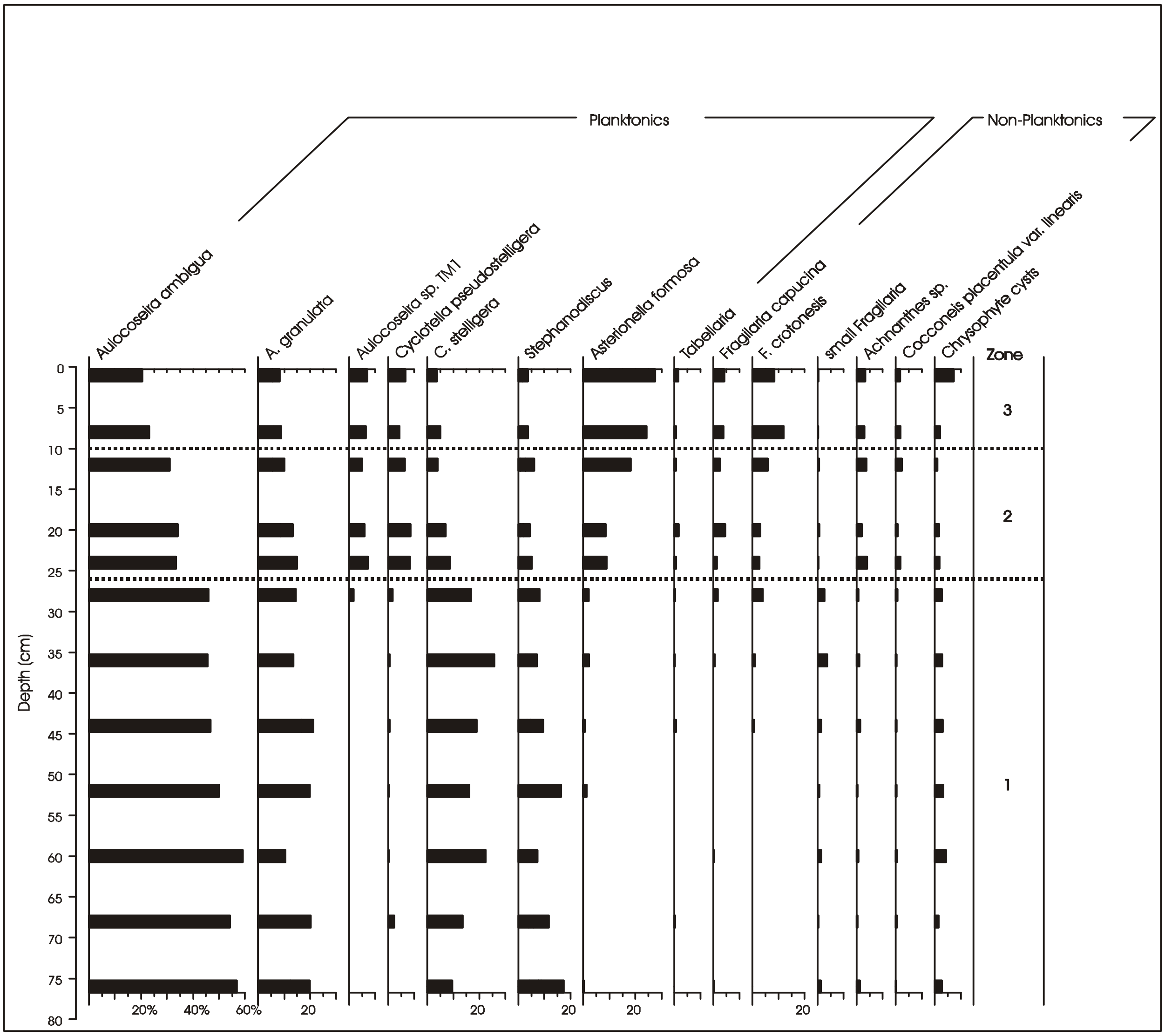

Figure 30. Dominant diatom taxa in the sediments of Tenmile Lake.

In summary, the diatom community composition in Tenmile Lake, as reflected in the sediments, has changed significantly. The direction of the change is towards taxa that are usually found in highly productive lakes.

The sediment was analyzed for nitrogen, both to determine ambient concentrations and to examine the ratio of naturally occurring isotopes. The results show that the upper sediments have nearly twice as much nitrogen as the bottom sediments (Figure 31). In addition, the proportion of ^{15}N is increasing in the upper sediments. One of the concerns in evaluating nutrients in sediment is the extent to which they are labile and subject to processes that would alter the concentrations independent of the deposition history. Thus, it is possible that the sediment nitrogen profile is simply an artifact of in-lake processes. However, it is more difficult to attribute the increasing ratio of ^{15}N to diagenesis. The possibility exists that the ^{15}N/^{14}N ratio is also changing as benthic organisms differentially accumulated the heavier isotope (cf., Adams and Sterner 2000). However, taken in conjunction with results of the diatoms and the akinetes (discussed below), it is difficult to attribute both sets of sediment nitrogen results to sediment processes. If the nitrogen results do reflect their depositional history, it would indicate an increase in the productivity of the lake and a qualitative change in the organisms associated with that change. Specifically, the increase in ^{15}N would be expected if the population of N-fixing cyanobacteria (bluegreen algae) had increased. Furthermore, the increase in ^{15}N would have had to be large to overcome the expected loss of marine-derived ^{15}N associated with the decline in the salmon runs into Tenmile Lake.

A brief examination was made of akinetes present in the sediments to determine if more detailed analyses would be warranted. The results of the five sediment samples analyzed to date show that the surface sediments contain considerably more akinetes than the bottom sediments (Figure 32). The greater concentration of akinetes is indicative of an increase in cyanobacteria, particularly those taxa that fix nitrogen. These results are consistent with the results on the sediment nitrogen (Figure 31) and the diatom stratigraphy which show an increase in lake productivity. One of the issues to be resolved with the deposition of akinetes in the sediment is the shape of the curve. If the pattern of akinete deposition is similar to that in Figure 32, it suggests that conditions in the lake are currently improving following a peak in lake productivity near 20 cm. However, if the akinete deposition follows pattern associated with a log-fit of the

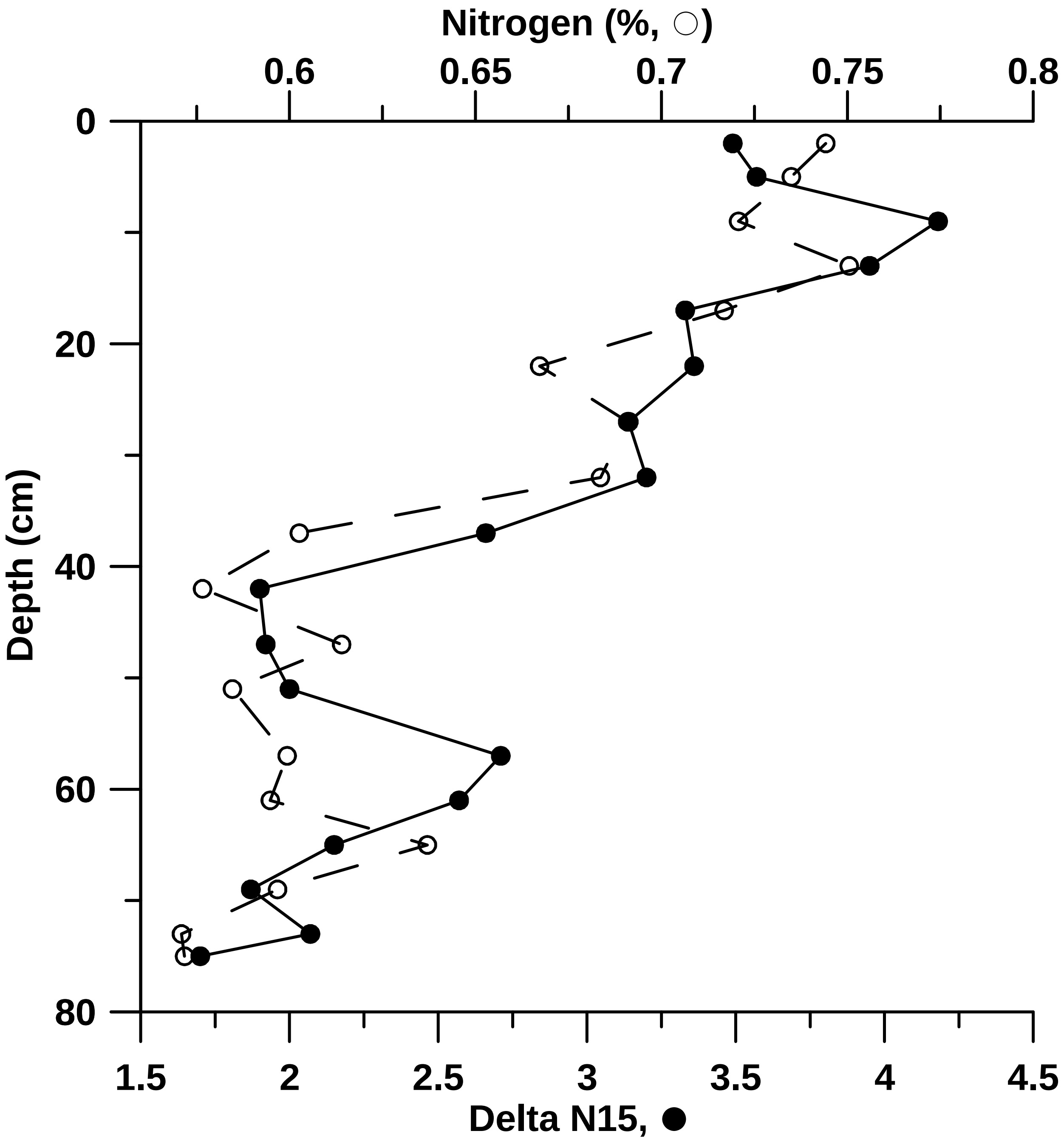

Figure 31. Nitrogen (N, % N by dry weight) and ^{15}N (as delta $^{15}N/^{14}N$) versus depth in sediments, Tenmile Lake.

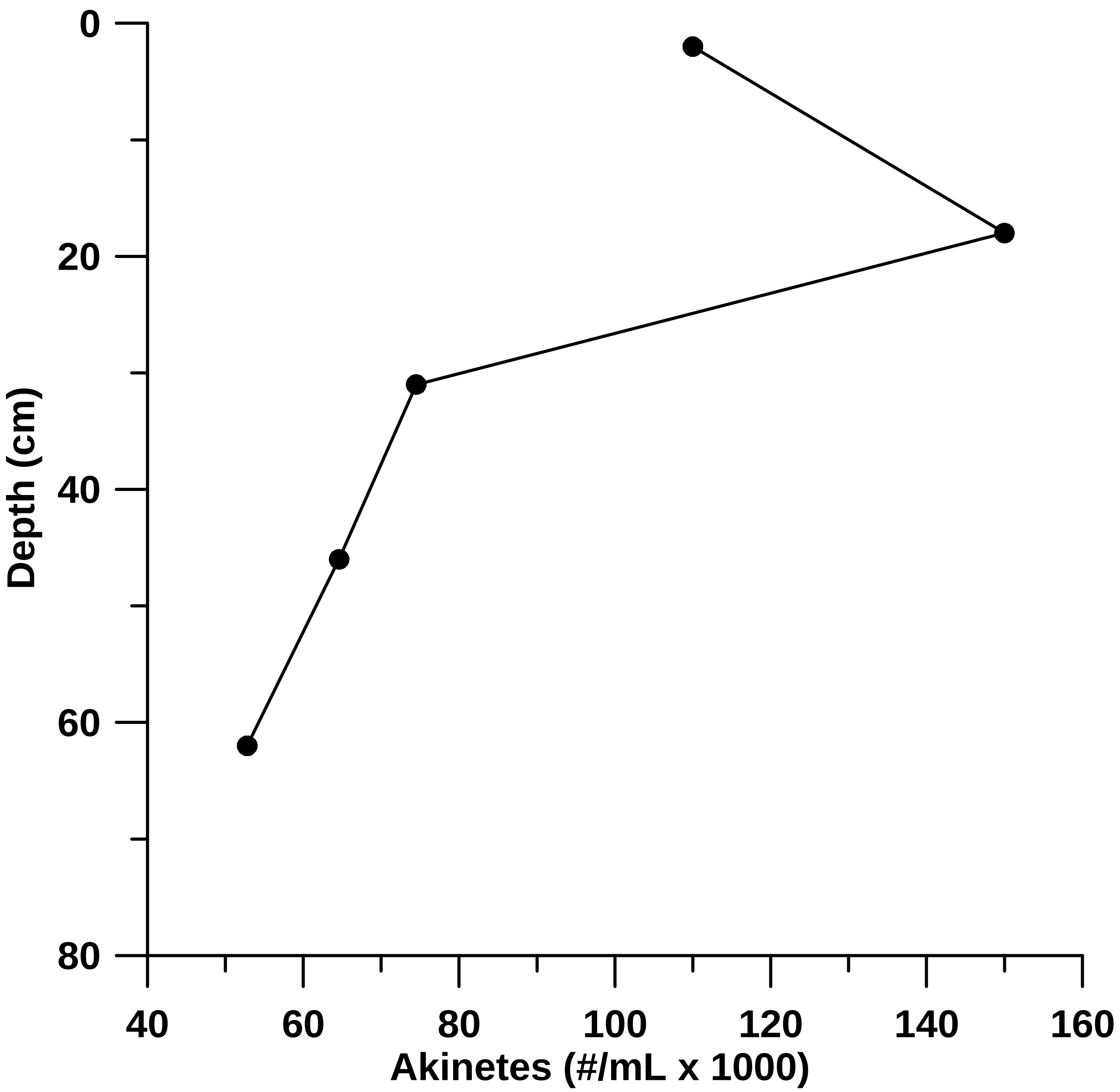

Figure 32. Akinetes (# mL x 1000) versus depth (fitted with a cubic spline function) in sediments of Tenmile Lake.

data (Figure 33), then the interpretation is that the lake is continuing to deteriorate with respect to water quality.

E. WATERSHED MODELING

1. Model Calibration

The SWAT model was calibrated using data primarily from the three principal tributary monitoring sites, Big, Benson, and Murphy Creeks. Supplemental information was derived from the unnamed tributary to Benson Creek, particularly with respect to nitrate loading from recent clearcuts. As noted earlier, the model was calibrated first for hydrology before proceeding with calibration of sediment, phosphorus, and nitrogen. The simulated versus measured discharge at the three primary stations is shown in Figure 34. The model was able to simulate discharge at Big and Benson reasonably well. The hydrologic simulation for Murphy Creek was not as precise as the other two sites. We attribute this to the large proportion of unmeasured discharge which occurred at the Murphy Creek site during high flow events. Traditional gaging techniques (stage-discharge rating curves) are problematic in these wetland-stream systems. Nevertheless, the difficulty in the hydrologic calibration for Murphy Creek, as we shall see in the following section, is minimized because of the low concentrations of the parameters of interest. Water quality simulations proceeded following the hydrology calibration. Results from calibration of TSS, TP, and NO_3 for Murphy, Big, and Benson Creeks are presented in Figures 35-37. Results are presented as mean monthly loads for the period January 1999 to April 1999.

Using the interim calibrations, we generated the following model estimates of water, sediment, nitrogen, and phosphorus yields for each of the 20 catchments (Figure 38) within the Tenmile Lake watershed (Table 5). Model estimates for annual loads are presented on a unit-area basis in Figures 39-42. Model estimates for individual catchments and individual storms are summarized by month in Figures 43-46. The results illustrate a number of factors with respect to differential loading of nonpoint source pollutants to the lake. First, the model predicts that water yield (the amount of total discharge from a catchment) varies by nearly a factor two among catchments (Figure 39). Catchments such as Murphy Creek exhibit a low yield of water runoff. Other sites such as West Shutters and Devore also had similarly low runoff values. These three sites all have wetlands in the lower part of their respective watersheds which either causes an underestimation of the actual amount of measured runoff or the presence of the

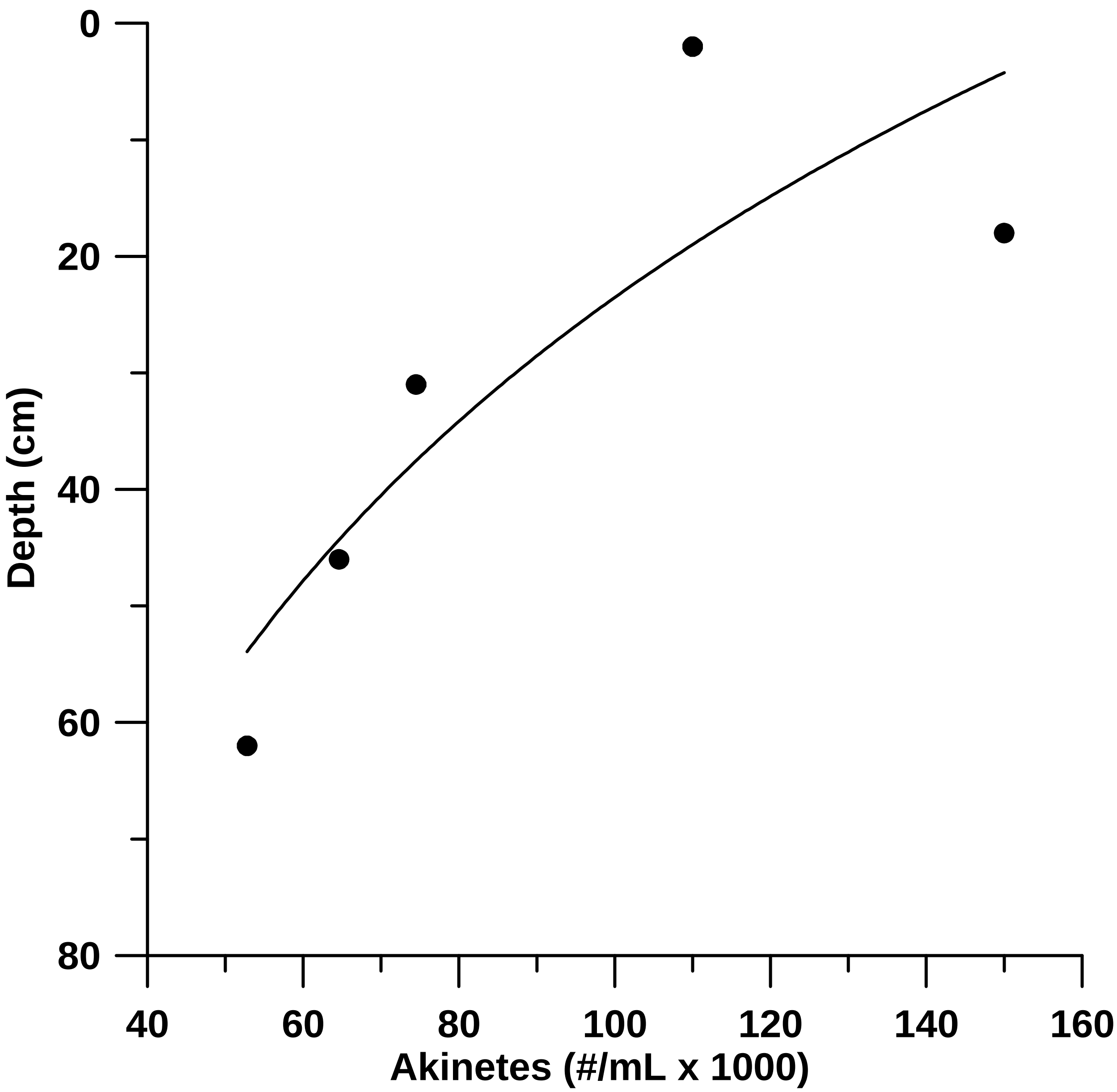

Figure 33. Akinetes (# mL x 1000) versus depth (fitted with a $\log_{10}$ function) in sediments of Tenmile Lake.

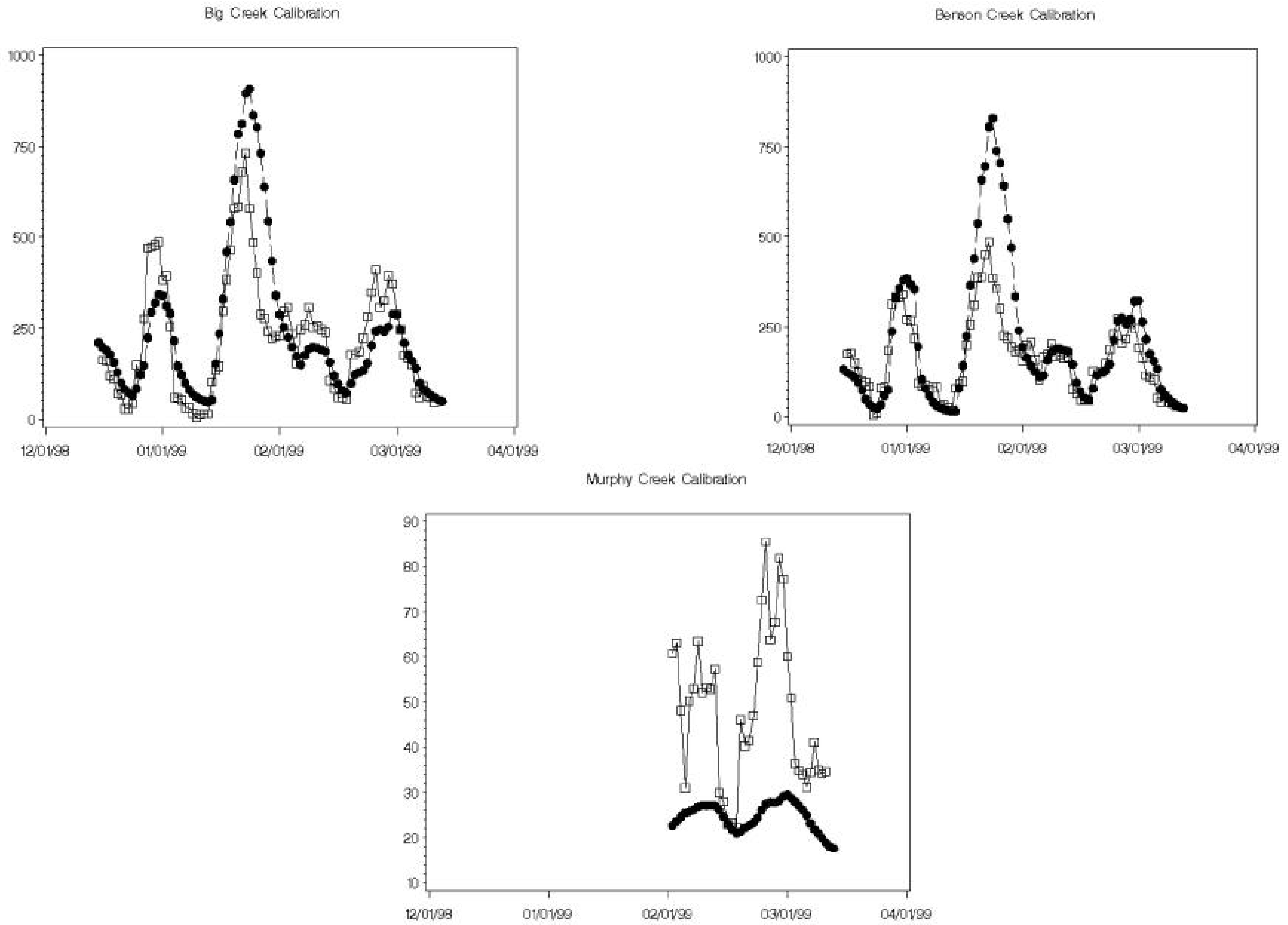

Figure 34. Simulated (**Q**—**Q**—**Q**) versus measured (**!** — **!** — **!**) stream discharge (cfs) at Big, Benson, and Murphy Creeks.

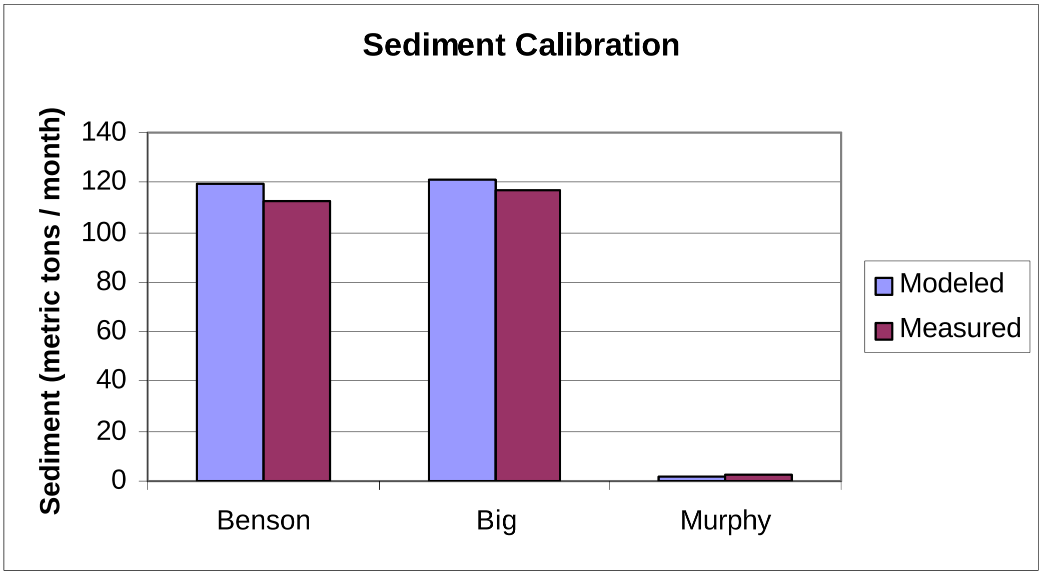

Figure 35. Simulated versus measured concentrations of TSS (mg/L) for Big, Benson, and Murphy Creeks.

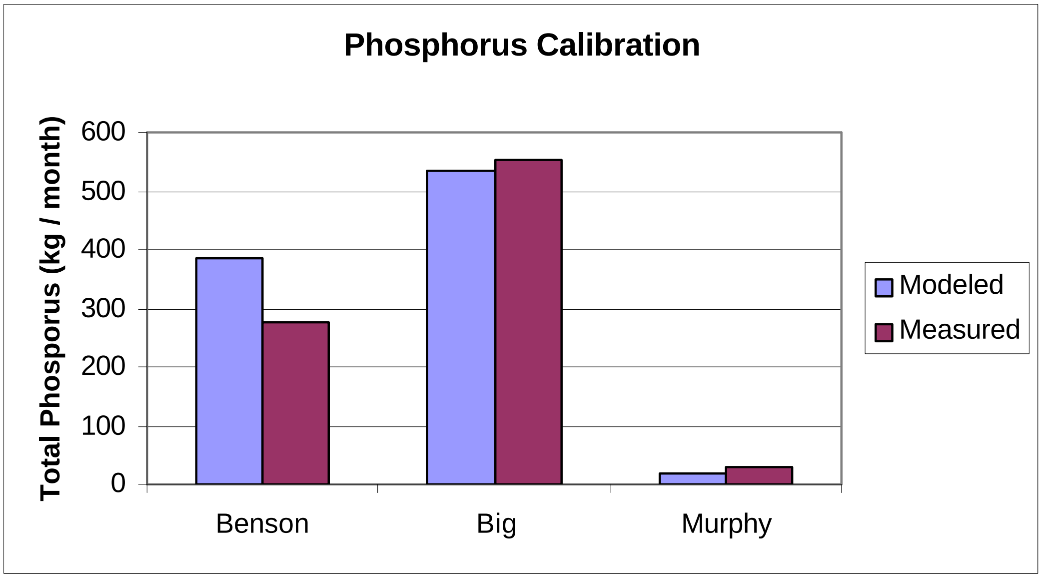

Figure 36. Simulated versus measured concentrations of TP (mg/L) for Big, Benson, and Murphy Creeks.

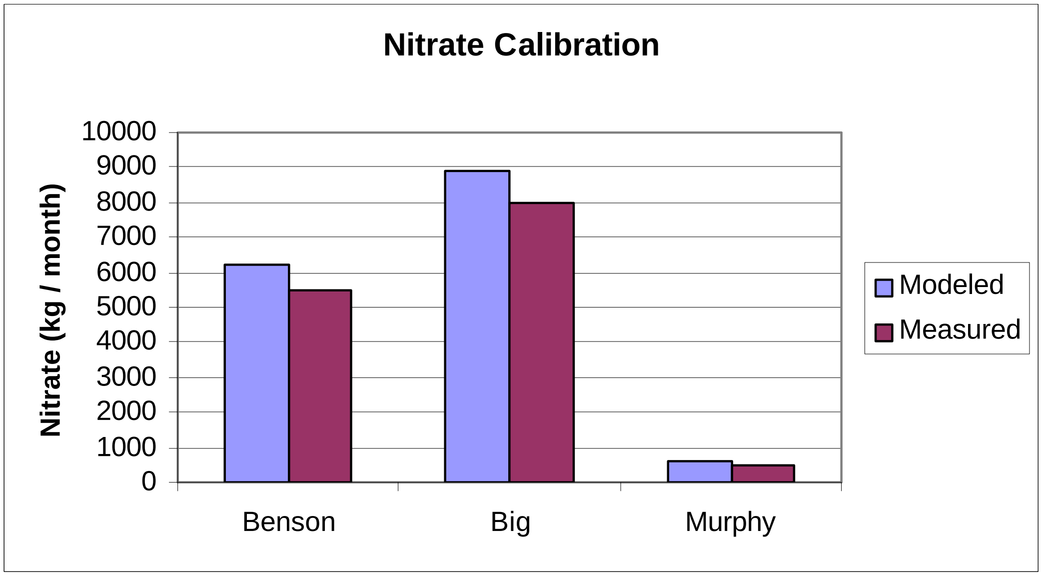

Figure 37. Simulated versus measured concentrations of nitrogen (mg/L) for Big, Benson, and Murphy Creeks.

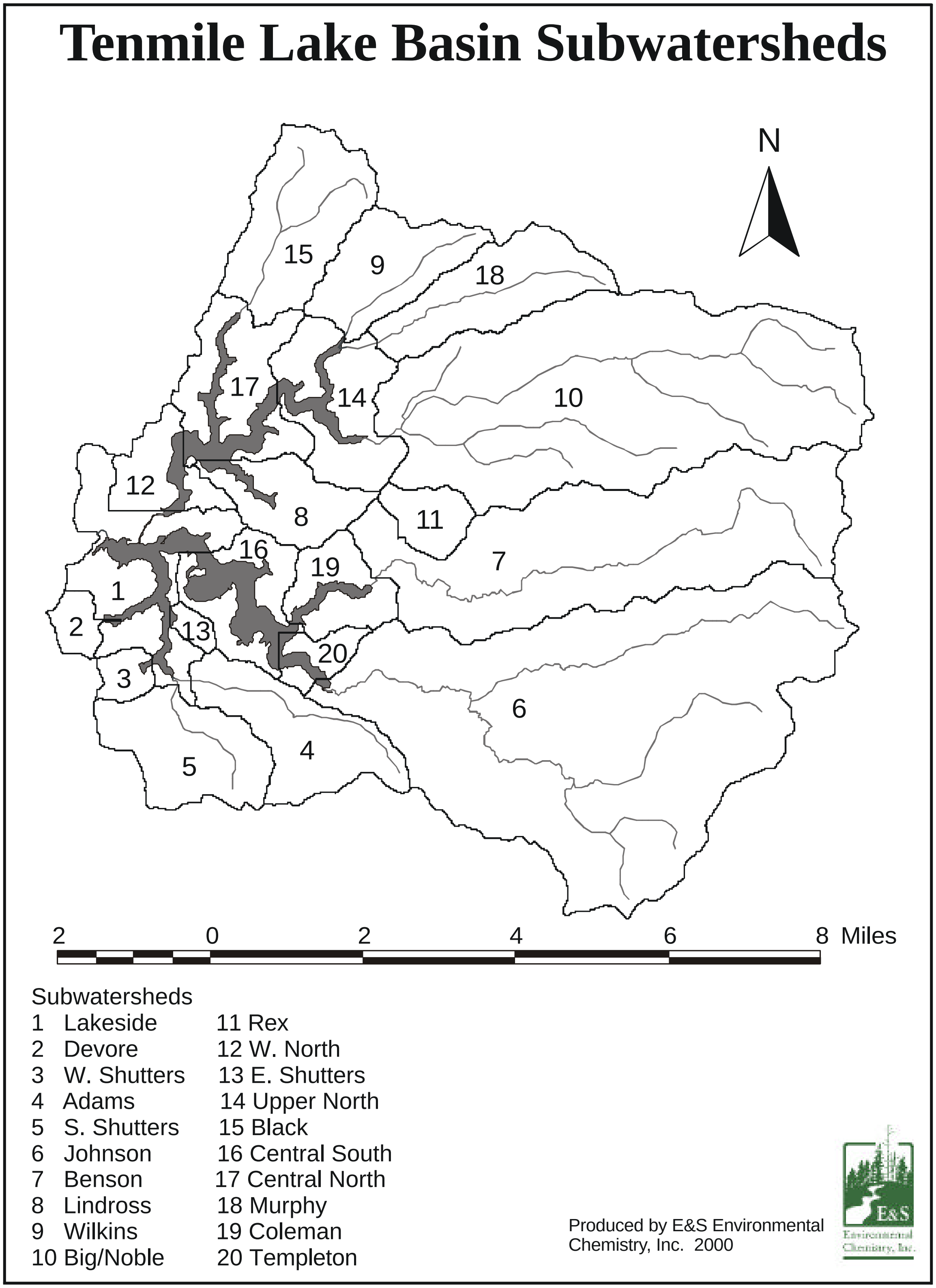

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Figure 38. Partitioning of catchments in the Tenmile Lake watershed for purposes of SWAT model application.

Table 5. SWAT model estimates of suspended solids, phosphorus, and nitrogen for 20 catchments in the Tenmile Lake watershed using 1994 landuse. Also included are the percent of each watershed representing water yield and the percent landuse category for each catchment. Units for the estimates are: water - mm/yr; sediment - tonnes/ha/yr; and nitrogen and phosphorus - kg/ha/yr.

Basin	Name	Area (%)	Water	Sediment	Nitrogen	Phosphorus	Urban	Water	Clearcut	Forest-O	Forest-Y	Wetland	Graze-W	Graze-U
1	Lakeside	4.67	832	43	45	0.31	18.46	19.95	10.28	46.36	4.95	0	0	0
2	Devore	0.64	591	36	5.4	0.02	0	0	47.73	41.02	9.95	1.31	0	0
3	W. Shutters	0.62	529	4	1.8	0.01	0	4.06	2.47	88.92	0	4.54	0	0
4	Adams	3.77	878	21	3.5	0.07	0	0	8.54	61.81	22.19	0	7.45	0
5	S. Shutters	3.53	914	152	44	0.22	0	0	24.24	36.77	6.72	0	7.75	24.52
6	Johnson	24.86	975	44	3.9	0.05	0	0	2.59	88.18	5.57	0	3.65	0
7	**Benson**	**13.18**	**823**	**56**	**2.3**	**0.03**	**0**	**0**	**3.12**	**73.62**	**18.56**	**0**	**4.7**	**0**
8	Lindross	2.35	810	188	16	0.12	0	8.42	33.48	47.01	7.02	0	4.07	0
9	Wilkins	3.07	782	133	9.9	0.09	0	0	11.72	78.32	4.23	0	5.73	0
10	**Big/Noble**	**18.65**	**730**	**41**	**2.9**	**0.03**	**0**	**0**	**5.24**	**88.46**	**3.51**	**0**	**2.78**	**0**
11	**Rex**	**1.17**	**856**	**81**	**5.3**	**0.05**	**0**	**0**	**9.73**	**51.28**	**37.44**	**1.55**	**0**	**0**
12	W. North	1.82	857	124	24	0.13	8.14	13.94	17.42	25.46	35.04	0	0	0
13	E. Shutters	0.35	875	50	7.6	0.09	0	5.67	15.58	78.75	0	0	0	0
14	Upper North	3.7	751	61	6.3	0.07	0	13.54	19.45	32.7	29.07	2.47	2.79	0
15	Black	4.45	759	220	12.8	0.09	0	0	30.29	55.81	11.44	0	2.46	0
16	Central South	2.79	818	22	3.9	0.05	0	39.84	6.49	50.47	3.2	0	0	0
17	Central North	3.75	850	146	11.3	0.1	0	23.63	30.02	28.4	17.95	0	0	0
18	**Murphy**	**3.72**	**569**	**4**	**0.7**	**0.01**	**0**	**0**	**7.43**	**83.89**	**5.68**	**3**	**0**	**0**
19	Coleman	1.99	837	103	9.4	0.09	0	11.76	20.66	39.49	26.77	0	1.31	0
20	Templeton	0.89	841	0.5	3.5	0.06	0	21.19	58	20.81	0	0	0	0
	Sum	99.97	15877	1529.5	219.5	1.69	26.6	162	364.48	1117.53	249.29	12.87	42.69	24.52
	Average	**5.00**	**793.85**	**76.48**	**10.98**	**0.08**	**1.33**	**8.10**	**18.22**	**55.88**	**12.46**	**0.64**	**2.13**	**1.23**

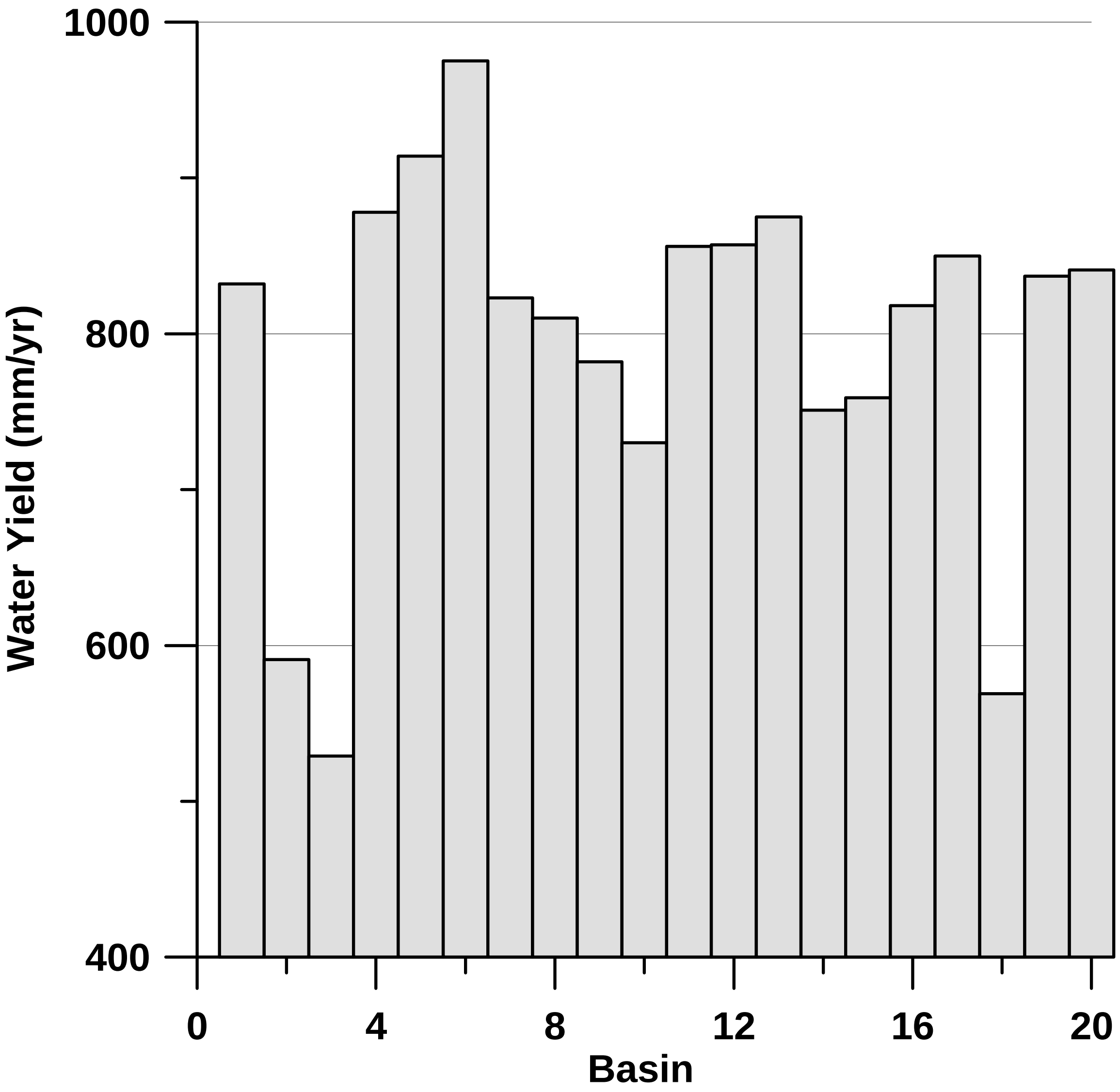

Figure 39. SWAT model estimates of annual water yield (mm/yr) for the 20 catchments in the Tenmile Lake watershed.

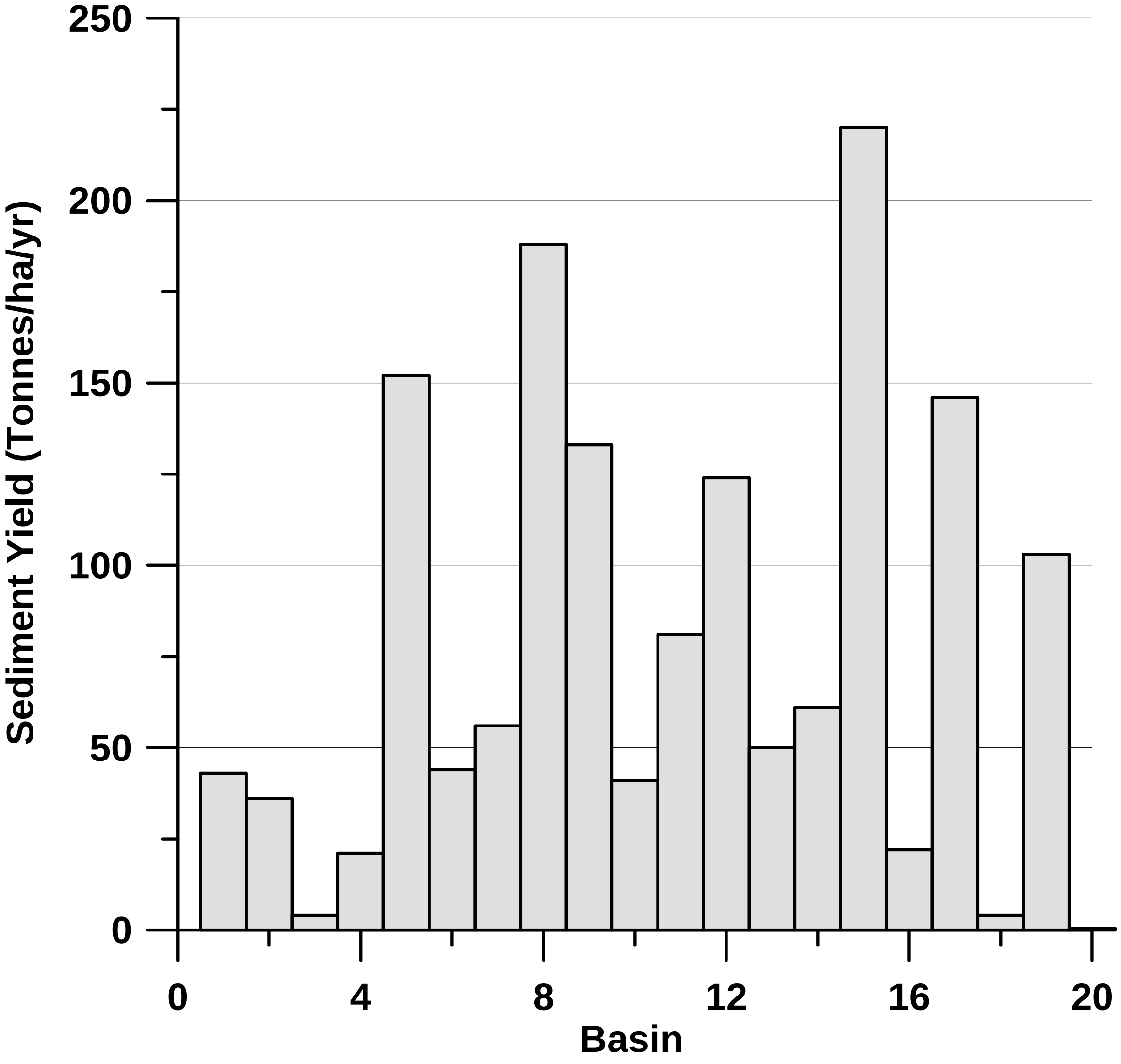

Figure 40. SWAT model estimates of annual sediment yield (tonnes/ha/yr) for the 20 catchments in the Tenmile Lake watershed.

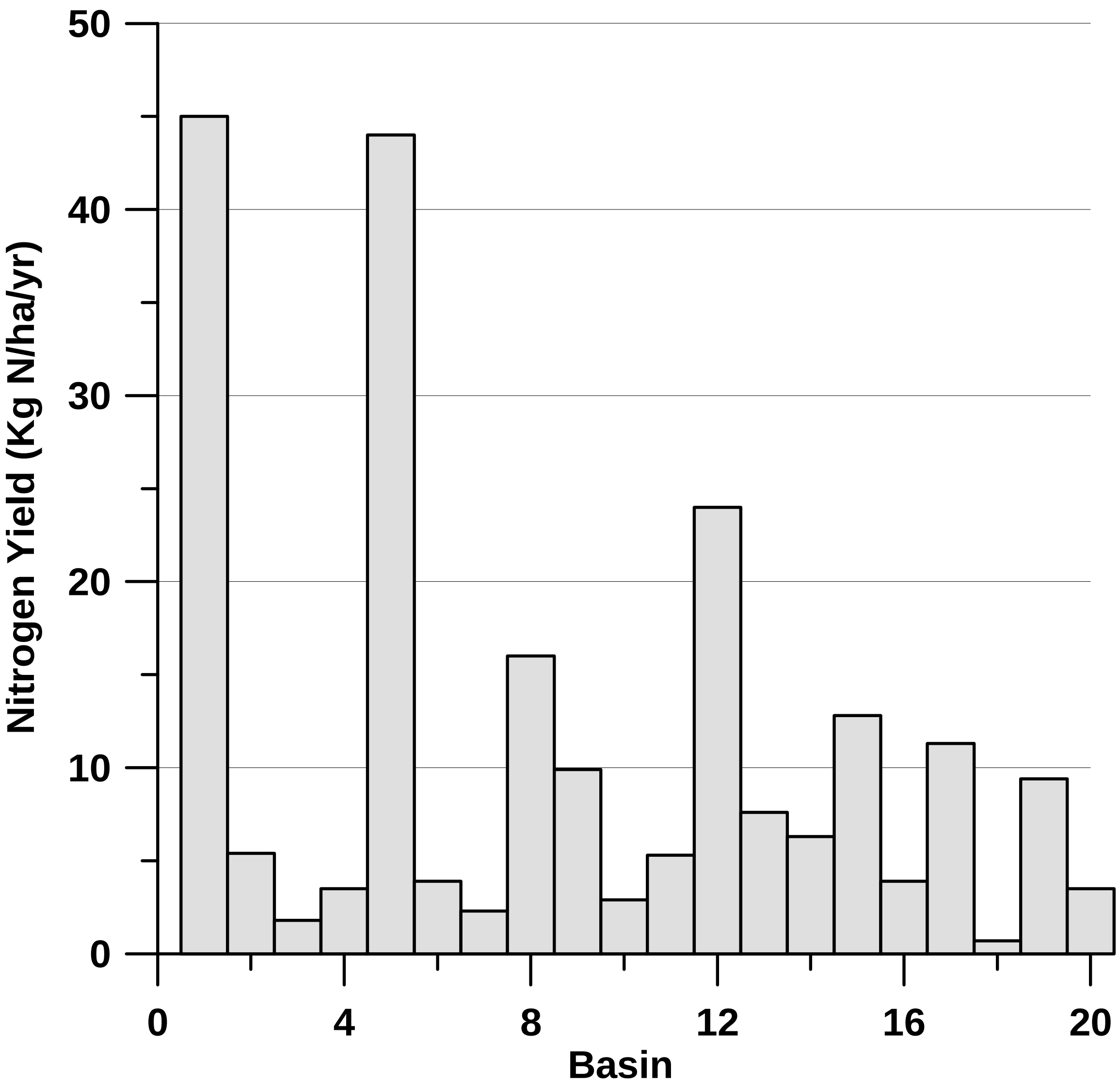

Figure 41. SWAT model estimates of nitrogen yield (kg/ha/yr) for the 20 catchments in the Tenmile Lake watershed.

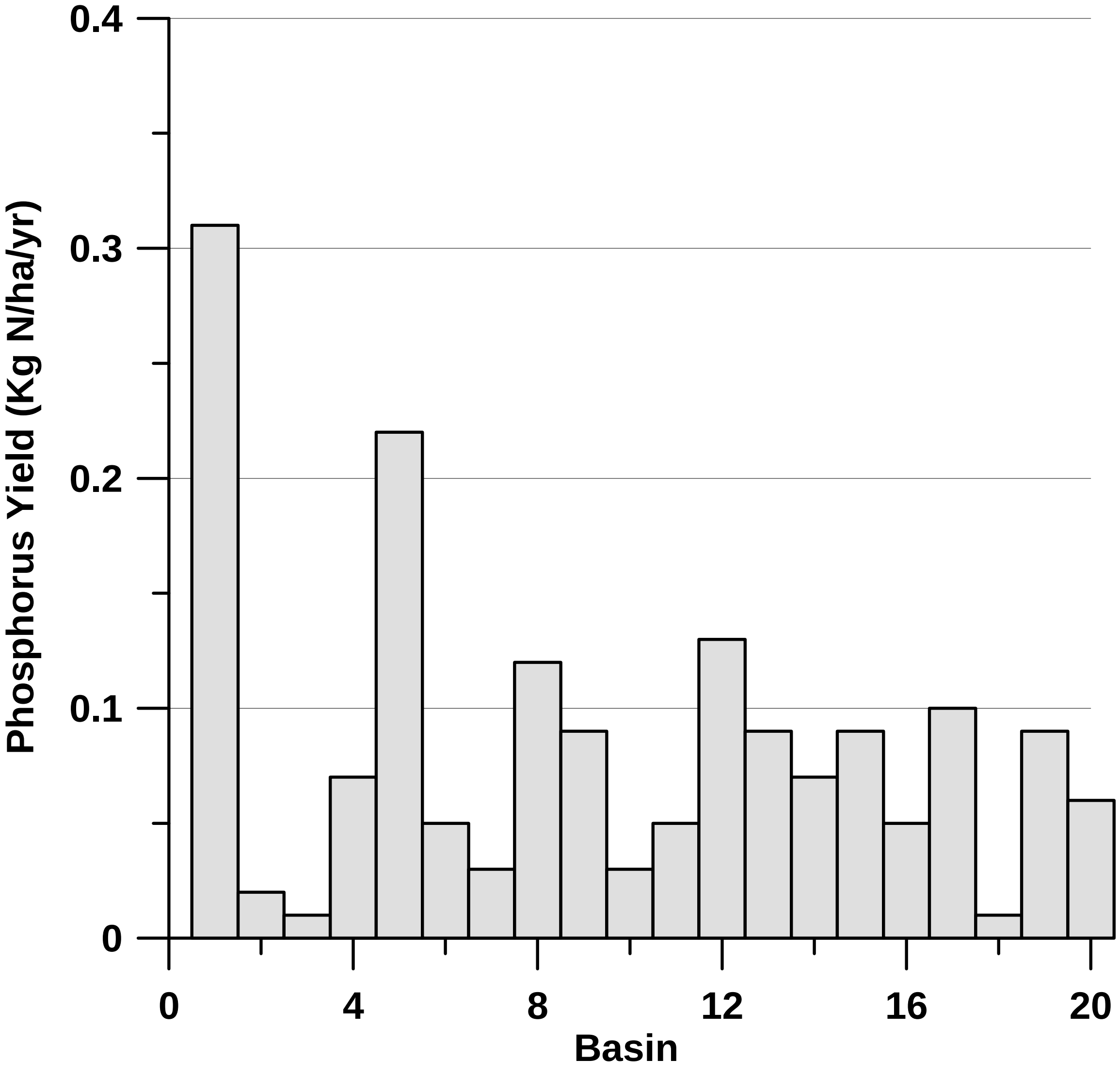

Figure 42. SWAT model estimates of annual phosphorus yield (kg/ha/yr) for the 20 catchments in the Tenmile Lake watershed.

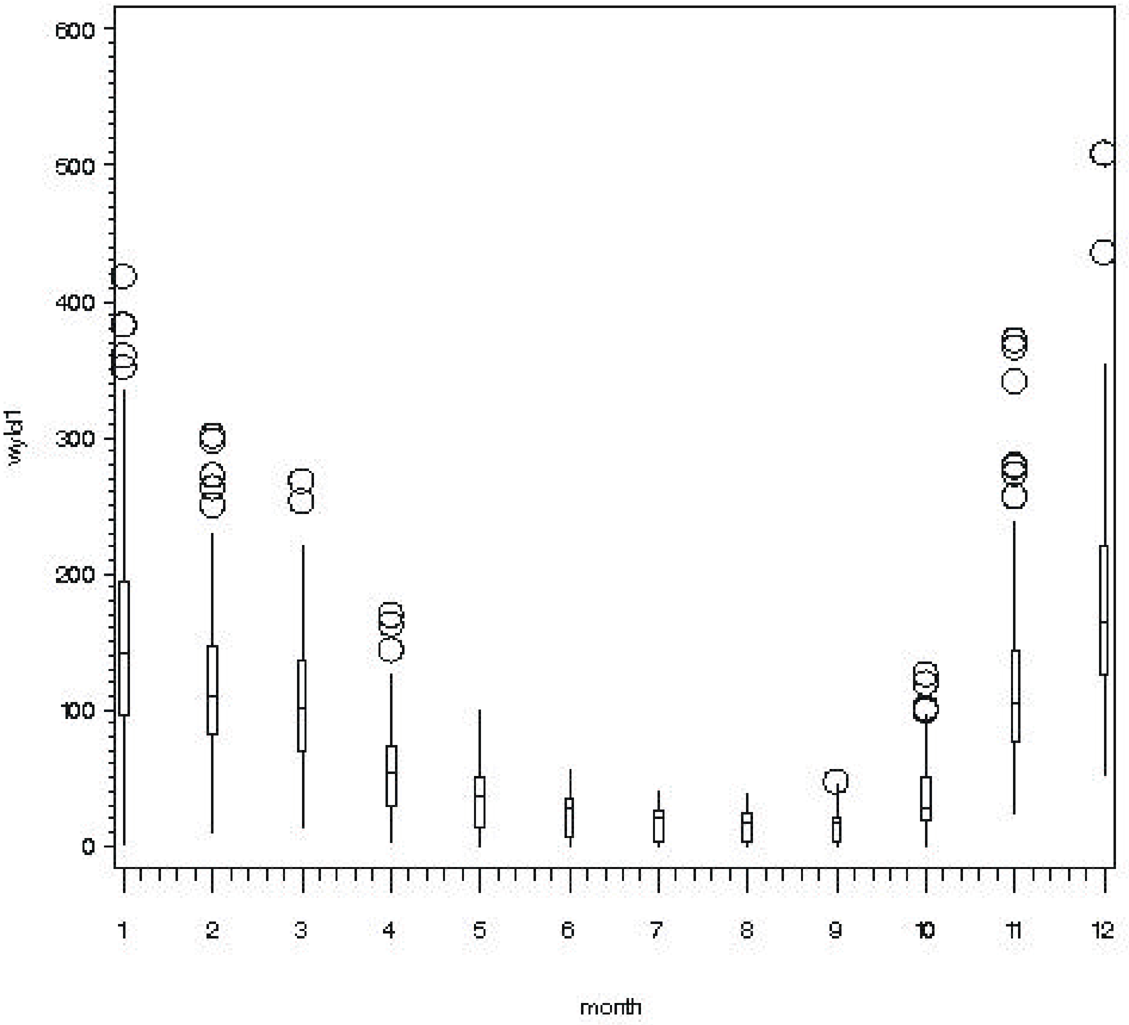

Figure 43. Distributions of water yield (mm/event) for each of the 20 catchments for the Tenmile Lake watershed. The results show results for a 10-year climatic record applied to the study area.

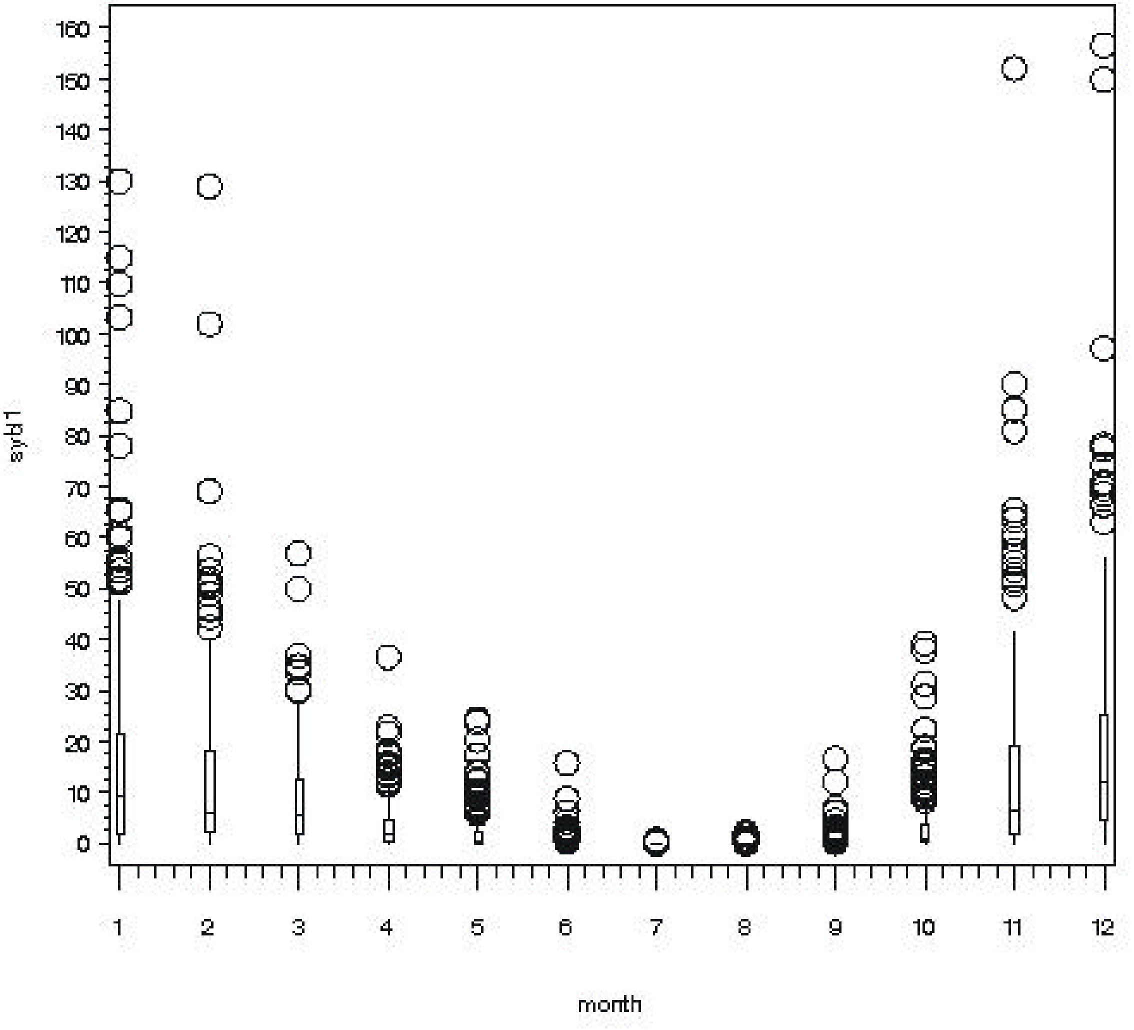

Figure 44. Distributions of sediment yield (tonnes/ha/event) for each of the 20 catchments for the Tenmile Lake watershed. The results show results for a 10-year climatic record applied to the study area.

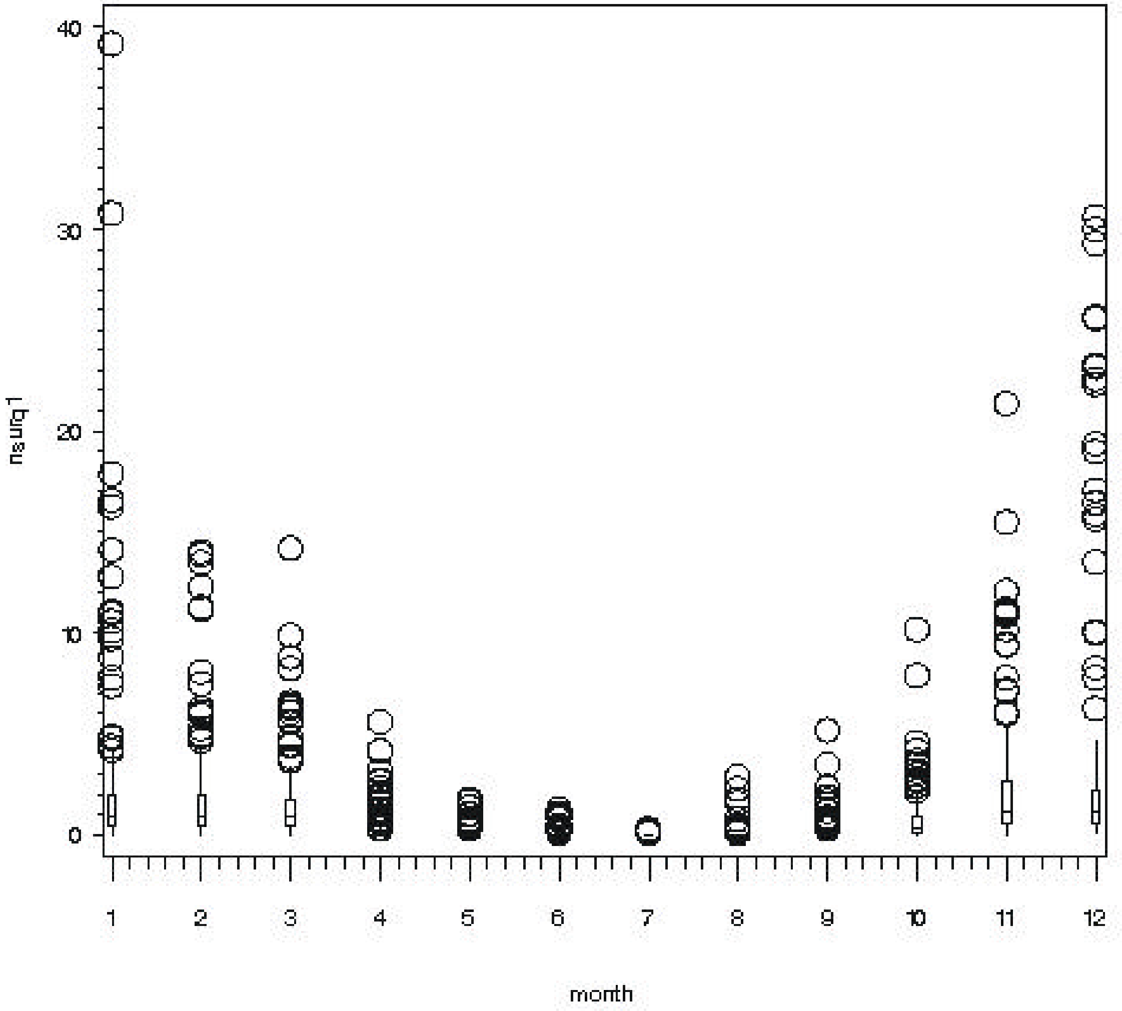

Figure 45. Distributions of nitrogen yield (kg/ha/event) for each of the 20 catchments for the Tenmile Lake watershed. The results show results for a 10-year climatic record applied to the study area.

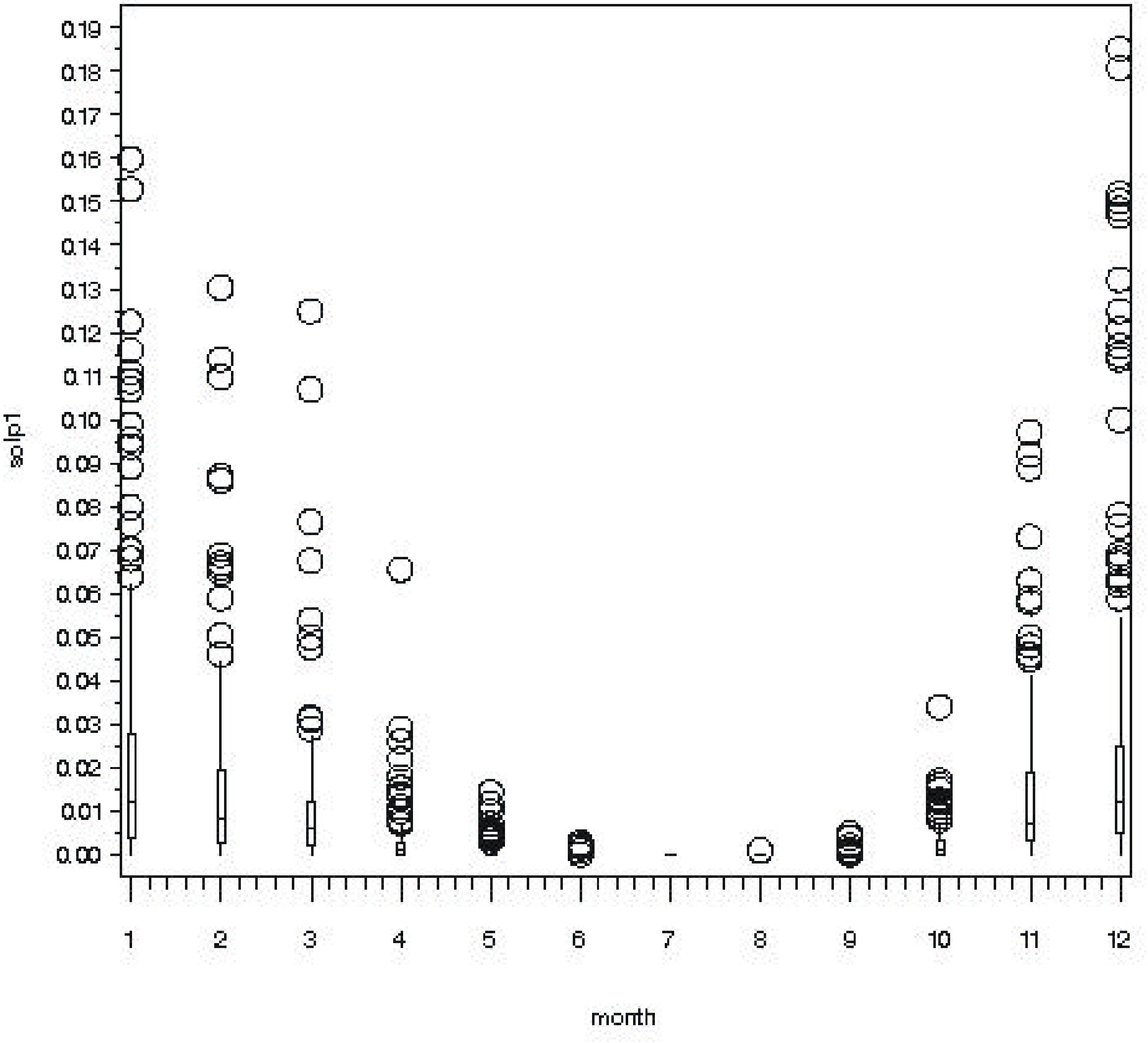

Figure 46. Distributions of phosphorus yield (kg/ha/event) for each of the 20 catchments for the Tenmile Lake watershed. The results show results for a 10-year climatic record applied to the study area.

wetlands at the base of the watersheds actually alters the amount of runoff. Regardless of whether the amount of watershed discharge is altered or whether the flow becomes rerouted to the extent that it can't be easily measured, the effects appear to be the same. Watersheds with high water yields include Johnson Creek, South Shutters, and Adams Creek. Some of the elevated runoff for Johnson Creek may reflect the orographic influence from high precipitation in the upper (eastern) portion of the watershed. However, Johnson Creek also exhibits a high rate of timber harvest and grazed wetlands that contribute to the modeled response. South Shutters catchment is notable for the high percentage of grazed uplands which, combined with grazed wetlands, promote a high degree of runoff.

Simulated sediment yield varied by three orders of magnitude ranging from less than 5 T/ha/yr in catchments such as Templeton, Murphy, and West Shutters to values over 150 T/ha/yr in catchments such as Black Creek, Lindross Arm, and South Shutters (Figure 40). Murphy Creek and West Shutters both have wetlands at the base of the catchments which serve to filter upland sediment production. The low simulated sediment load in Templeton is, in part, an artifact of having to include part of the lake surface in partitioning the catchment (22 percent is listed as water surface). On the high end of sediment production are Black Creek, Lindross Arm, and South Shutters. All three of these catchments have a comparatively high percentage of clearcut land, but other factors are involved as well. The catchment with the greatest percentage of clearcut is Devore Arm (48 percent), yet the model simulation shows that sediment production is only a small fraction of that found in the high-sediment production catchments. The primary difference is the location of the land use disturbance with respect to the receiving water. The clearcutting in the Devore catchment is mostly upland with a buffer of established forest, whereas the timber harvest in the other catchments occurred on steep slopes closer to the lake. Additionally, the high sediment production catchments all have grazed wetlands, whereas the Devore catchment contains intact wetlands. One factor specifically influencing the sediment production in South Shutters is the high percentage of grazed uplands.

Nitrogen export ranged by nearly two orders of magnitude from 0.7 Kg N/ha/yr in Murphy Creek to 44 Kg N/ha/yr in South Shutters and 45 Kg N/ha/yr in Lakeside (Figure 41). The other catchment with a large component of urban land use, West North Lake, also had a high yield of nitrogen (24 Kg N/ha/yr). The general ranking of phosphorus loads from the catchments was similar to that of nitrogen, whereby high loads were associated with urban and grazing activities and low loads were associated with catchments with a high percentage of mature forest and intact wetlands at the base of the watershed (Figure 42).

F. DISCUSSION

1. Current Conditions

Water quality in Tenmile Lake can be assessed from direct measurement of nutrients, Secchi disk transparency, dissolved oxygen depletion, and phytoplankton community composition, chlorophyll *a* and phytoplankton abundance. Mean annual values for typical parameters used to assess conditions in lakes indicate that Tenmile Lake is mesotrophic to eutrophic, with most indicators present in the "eutrophic" ranges (Table 6). This assessment of water quality varies depending the parameter used to assess the conditions and the site in the lake. The site most consistently exhibiting the lowest water quality is NTB, at the intersection of Big Creek Arm and Carlson Arm. Secchi disk transparency is low, and total phosphorus, phytoplankton density, and phytoplankton biovolume are greatest at this site which is consistent with visual observations of turbid inputs from Big Creek (low transparency, high TP) and significant algal blooms in the

Table 6. OECD boundary values for fixed trophic classification system (modified from OECD 1982). Classified values for Tenmile Lake are highlighted.

Trophic Category	Mean TP[1]	Mean Chlorophyll *a* [2]	Maximum Chlorophyll *a* [3]	Mean Secchi[4]	Minimum Secchi[5]
Ultra-oligotrophic	<4.0	<1.0	<2.5	>12.0	>6.0
Oligotrophic	<10.0	<2.5	<8.0	>6.0	>3.0
Mesotrophic	**10-35**	2.5-8	8-25	6-3	3-1.5
Eutrophic	35-100	**8-25**	**25-75**	**3-1.5**	**1.5-0.7**
Hypertrophic	>100	>25	>75	<1.5	<0.7

[1] mean annual in-lake total phosphorus concentration (µg/l)
[2] mean annual chlorophyll *a* concentration in surface waters (µg/l)
[3] peak annual chlorophyll *a* concentration in surface waters (µg/l)
[4] mean annual Secchi depth transparency (m)
[5] minimum annual Secchi depth transparency (m)

summer. However, the peak chlorophyll *a* concentrations were measured in the south lake. Other metrics of lake trophic status such as ^{14}C primary production rates and macrophyte biomass were not available in this study, however reconnaissance of the lake showed high abundance of macrophytes throughout the lake at depths less than 5m. Previous examination of the macrophyte community showed that the dominant species was *Egeria densa* (Systma 1995), an exotic species morphologically similar to the native genera, *Elodea*. Despite its relatively shallow morphometry and polymictic nature, Tenmile Lake also exhibits rapid uptake oxygen in the bottom waters during brief periods of stratification. These all suggest that Tenmile Lake is mesoeutrophic to eutrophic. An assessment of water quality in Tenmile Lake conducted in July and August, 1994 showed similar results for TP, chlorophyll *a*, transparency, and dissolved oxygen depletion (Systma 1995). Earlier investigations by Phinney and McLachlan (1956), McHugh (1972), and Johnson et al. (1985) all cite the presence of algae or cyanobacteria taxa indicative of eutrophic lakes. The following sections discuss whether the current conditions represent a change from historical conditions and if so, the nature of the change.

An additional space-for-time substitution available is to compare water quality in neighboring Eel Lake with Tenmile Lake. The comparison of total phosphorus, chlorophyll *a*, and Secchi disk transparency shows that Eel Lake exhibits much better water quality than Tenmile Lake (Figure 47). Although Eel Lake is considerably deeper than Tenmile Lake, both lakes are highly dendritic and share the same physiographic features. The striking differences in water quality between the two lakes indicates that it is reasonable to assume water quality in Tenmile Lake could be improved by dealing with some of the watershed and in-lake sources of nutrients.

2. Historical Conditions Based on Space-for-Time Substitutions

Three tributaries to Tenmile Lake were monitored on an intensive basis from November 1998 through May 1999. Streamflow declined after May and tributary inputs became relatively insignificant (on a lake-wide basis). During this period, Big and Benson Creeks, which appear to be representative of most tributaries to the lake, delivered sediment and nutrients at a rate far greater than occurred in Murphy Creek. Loads, expressed on a per-hectare basis, show that sediment from Big and Benson Creeks is at least ten times greater than the yield from Murphy Creek. The loads of nitrogen and phosphorus from Big and Benson Creeks are at least three

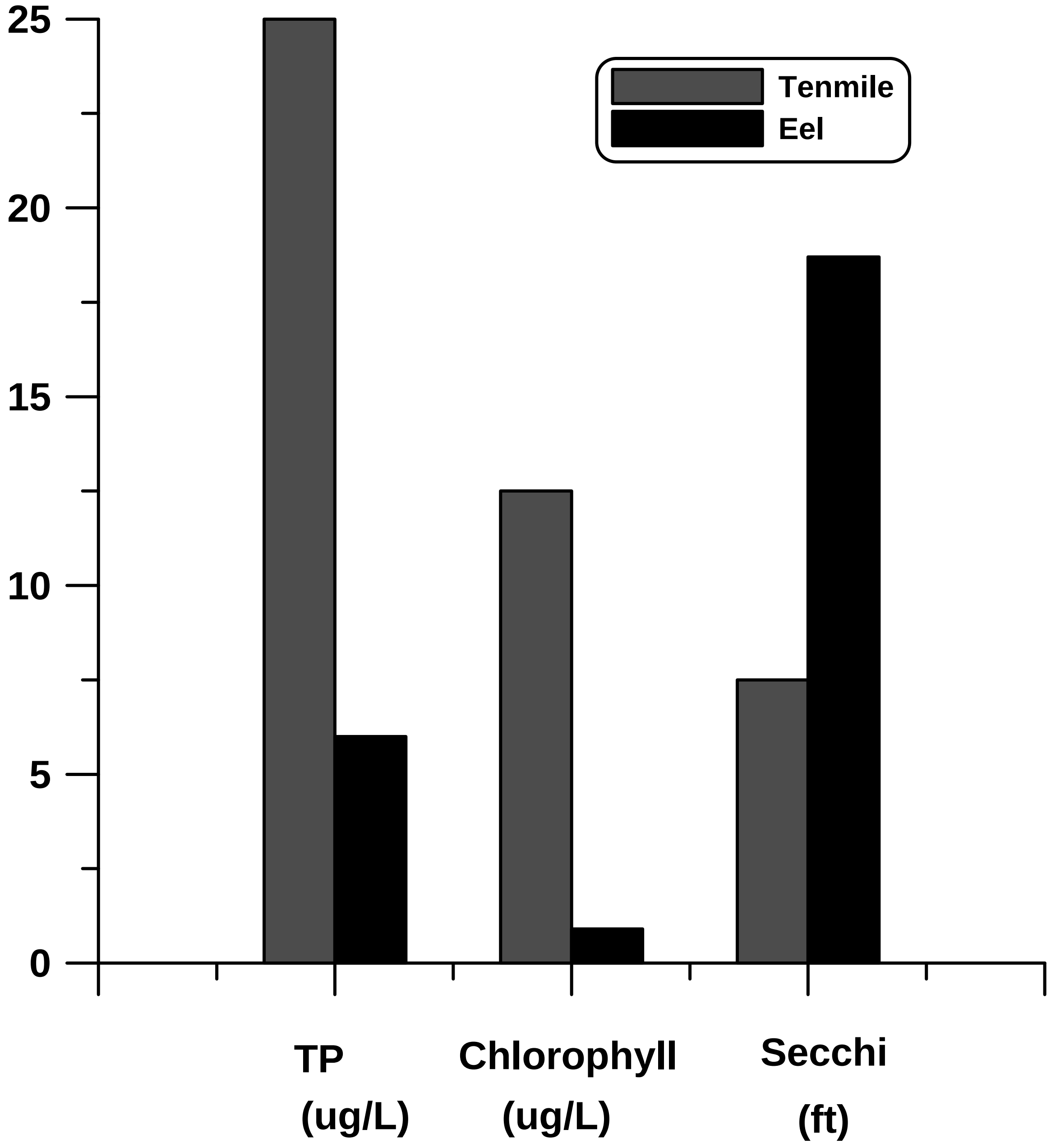

Figure 47. Comparison of total phosphorus, chlorophyll *a*, and Secchi disk transparency in Eel Lake and Tenmile Lake.

times those from Murphy Creek. Although Big and Benson Creeks are degraded relative to Murphy Creek, these two catchments may not represent worse-case conditions in the watershed.

The modeling results indicate that nearly one-half of the remaining catchments may have higher yields (on a per-hectare basis) than Big and Benson Creeks. The modeling results are based on aerial photography collected in 1994. Consequently, the actual spatial information on land use does not correspond precisely with current distributions of nonpoint source loads. One of the most variable factors in the watershed land use is timber harvest. Areas which were harvested in the early 1990's have since experienced appreciable timber regrowth, causing the sediment and nutrient loads to decline. Conversely, some areas which were mature timber in 1994 have since been harvested, causing loads to increase in those areas. The location of wetlands and recent clearcuts affects all phases of the modeling. Not only are sediment and total phosphorus production increased during logging, but nitrogen export is also affected. For example, a comparison of nitrate concentrations in Murphy Creek and a tributary to Benson Creek show a dramatic change in nitrogen yield (Figure 48). About 80% of the Benson Creek tributary catchment had been logged the previous year. The second phase of this project will attempt to address these rapid changes in land use activity.

The comparatively high water quality delivered from Murphy Creek is attributed largely to the restored wetland on the lower 2.5 km of the stream which provides a high degree of protection from timber harvest in the uplands. Using Murphy Creek as an indication of historical stream water quality shows that current water quality in most of the tributaries has been severely degraded. A modeling analysis of sediment and nutrient loads under pre-development conditions (i.e., native mature forest in the uplands and intact, unchanneled wetlands in the lowlands) indicates that historical water quality in Tenmile Lake would have been much greater relative to current conditions (Table 7). This analysis does not account for the loss of marine-derived nutrients to the watershed that has occurred with the decline in the anadromous fisheries. Schmidt et al. (1998), Kline et al. (1993), and Bilby et al. (1996) have shown that marine-derived nutrients from anadromous fish can be important components of nutrient cycling in Alaska and Washington. The run of sockeye salmon in Karluk Lake, AK provides an estimated 40 percent of the total phosphorus in the lake (Schmidt et al. 1998). In a small Washington stream, spawning coho salmon provided more than 30 percent of the nitrogen found in juvenile coho salmon (Bilby et al. 1996). However, even a 50 percent increase in the

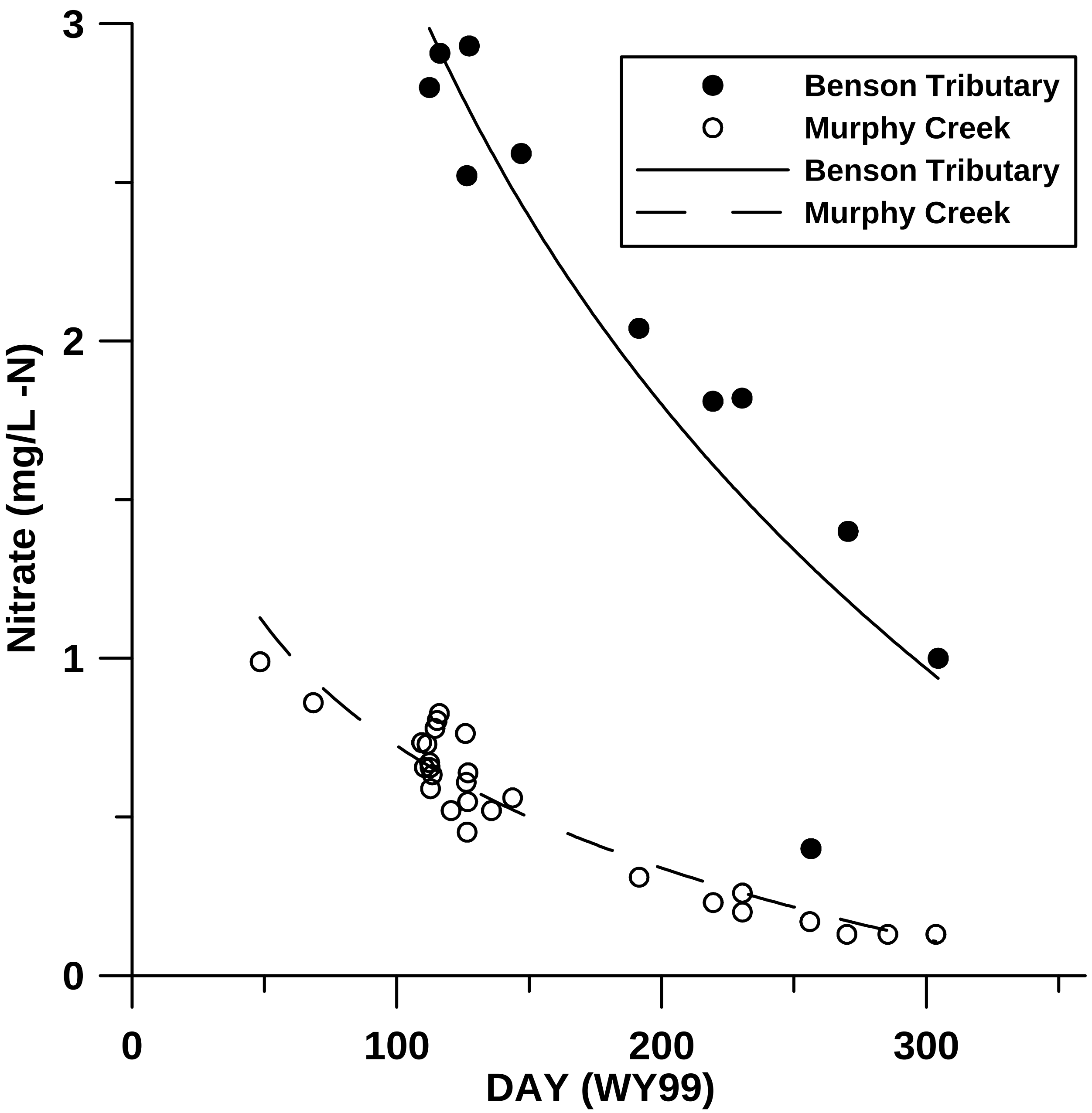

Figure 48. Nitrate (NO_3-N, mg/L) concentrations in Murphy Creek and an unnamed tributary to Benson Creek.

estimated historical nutrient load from Murphy Creek results in the undeveloped nutrient load being at least double its present rate from Big and Benson Creeks. Recall that the model estimates show most of the tributaries having considerably greater loads than Big and Benson Creeks. Furthermore, consideration of the effect of historical anadromous runs would not alter the estimates for sediment production from the watershed. In summary, the tributary monitoring and the modeling derived from the monitoring show that the watershed loads of sediment and nutrients are substantially greater than historical values.

3. Historical Conditions Inferred from Analysis of the Sediments

The sediments were analyzed for sediment accumulation rate (SAR), nitrogen, ^{15}N, akinetes, and diatoms. The SAR has increased four-fold over pre-development conditions. An initial increase was noted in the late 19th century, corresponding with the early land clearing and settlement in the area. A major increase in SAR occurred in the period 1910-1930, at a time when commercial logging activity was high. The SAR declined in the Depression when economic activity and population decreased. SAR increased somewhat in the 1950s and continued to increase, reaching a maximum in 1999. The general shape of the SAR record is similar to that observed in Devils Lake, located on the Oregon central coast (Eilers et al. 1996). The increased SAR is consistent with both the monitoring and watershed modeling results which point to high rates of sediment yield from much of the watershed.

Nitrogen and the ratio of $^{15}N/^{14}N$ show increases in the upper sediments. As noted earlier, the nitrogen results are subject to a moderate degree of uncertainty because of diagenesis within the sediments, but the findings are consistent with an increase in lake productivity and an increase in the biomass of nitrogen-fixing cyanobacteria. The small number of sediment akinete samples also suggest that there has been a two to three fold increase in the biomass of cyanobacteria in Tenmile Lake in recent years.

The diatom results show a significant increase in the relative abundance of taxa that favor eutrophic waters. There has been a major increase in *Asterionella formosa* and a smaller increase in *Fragilaria crotonensis*. The diatom bloom observed in April, 1999 was comprised largely of *A. formosa*. Benthic (bottom-dwelling) diatoms have almost disappeared from the lake and the diatom community is now entirely planktonic. These changes are consistent with a decrease in transparency in the lake, most likely caused by an increase in planktonic algae and cyanobacteria.

4. Watershed Versus In-Lake and Near-Shore Factors

The data consistently show that water quality in the lake is impaired, that the tributary water quality is in most cases degraded, and that the lake water quality has declined during the last century. Because the focus of this study has been largely on watershed processes and stream monitoring, it is tempting to infer that the degradation of the lake has been caused by practices within the watershed such as timber harvest, livestock grazing, and stream channelization. Indeed, it is clear that watershed activities have altered the loads of sediment and nutrients to the lake. However, it does not necessarily follow that a lake improvement program based solely on improving land use practices in the watershed will yield proportional improvements in lake water quality. Although decreasing the sediment and nutrient loads from the watershed is a necessary element of improving Tenmile Lake, there are at least three other factors that have not been addressed in this study that may have a major influence on the lake.

One factor is the issue of land use development along the lakeshore. The SWAT model in its present formulation has limited capability for including nutrient input associated with housing development. Housing development increases sediment production during construction and continues to supply the lake with increased loading of nitrogen and phosphorus for the duration of occupancy and beyond. A recent survey of septic systems around Tenmile Lake found a number of them had no records of permits or were deficient in a number of respects (M. Mader, pers. comm.). Even a well-functioning septic system in a coastal environment remains problematic for a lake, because the sandy soils in the area provide minimal reduction to groundwater transport of nutrients. In many cases, the development associated with shorelines resembles development elsewhere, including installation of extensive lawns and landscaping that require fertilizer input. This is often accompanied by removal of natural vegetation. One improvement to the model that we hope to make would be creation of a land use category that represented lakeshore development. In this way, it would be possible to provide some basis for estimating the nearshore contribution of nutrients relative to tributary inputs.

A second factor not addressed in this study is the presence and abundance of aquatic macrophytes. The current information indicates that Tenmile Lake is heavily infested with the exotic *Egeria densa*. It is unknown if the *E. densa* has simply replaced the native *Elodea*, or whether the current spatial distribution and density of the plant exceeds the historical condition. Macrophytes have the capacity to alter internal processes in the lake through increased primary production (macrophytes have a greater primary production rate per unit than algae [cf., Chapra 1997]) and can extract nutrients from the sediments. Upon senecsing in the fall these accumulated nutrients are made available through mineralization and the decaying macrophytes exert a biochemical oxygen demand. If the macrophyte biomass has increased, it would be expected to have a negative effect on the lake.

Lastly, we have not evaluated the effect of the fisheries on water quality in Tenmile Lake. It is now understood that lake productivity is affected not only by inputs from the watershed, but also by the biological activity within the lake. Altering the fisheries can promote major changes in the zooplankton community which in turn can alter the grazing rate of phytoplankton. Tenmile Lake historically was dominated by anadromous fisheries of coho, steelhead, and sea run cutthroat trout. The coho spawning used to be so intense in the tributaries that redds were systematically destroyed by incoming fish intent on locating suitable sites. The lake served as a nursery for rearing smolts to a size that would guaranty a successful return of adults salmonids.

The current fisheries is vastly different than the historical condition. The dominant fish are now exotic species, centrarchids endemic to the Midwest. Largemouth bass is the primary game fish and there are abundant populations of bluegill, yellow perch, and crappie (Abrams 1991). The fisheries is currently dominated by highly planktivorous fish. According to our present understanding of biomanipulation effects, these taxa (e.g. bluegill, yellow perch) are very efficient at consuming the larger zooplankton species. The reduction of large zooplankton, in turn, reduces grazing pressure on the phytoplankton which allows phytoplankton biomass to increase. Phytoplankton biomass is able to take advantage of the reduced grazing pressure because more nutrients are available from watershed inputs. If the biomanipulation theory is correct, as it applies to Tenmile Lake, it suggests that water quality problems in the lake are the product of changes in both the watershed and fisheries. Therefore, a water quality improvement program for Tenmile Lake may need to incorporate both watershed restoration and some modification of the fish community composition.

5. Proposed Activities Under Phase II of the Study

Phase I of the Tenmile Lake Nutrient Study identified a number of factors in Tenmile Lake and its watershed that should be beneficial in developing a remedial plan of action. The stream monitoring showed conclusively that sediment and nutrient loads are greatly elevated in Big and Benson Creeks. These sites appear to be representative of a number of other tributaries in the watershed. Murphy Creek, which contains a large wetland at the base of the watershed , exhibits water quality that is probably similar to pre-development conditions. Long-term efforts to reduce sediment and nutrient loads to the lake should focus on the beneficial effects associated with intact wetlands at the stream mouths. Land use restoration in these areas will probably provide large water quality benefits relative to the percentage of the watershed that would need to be treated. Phase II will sample additional stream sites to verify the representative nature of Big and Benson Creeks and to establish with greater certainty the value of lowland wetlands in reducing nonpoint source pollutant loads. Phase II sampling will also begin at the initiation of the water year (October 1) which will provide information on the nutrient inputs in the fall.

The phytoplankton sampling under Phase I was conducted at the four established lake stations also used to sample the water quality. These sites were probably representative of mid-lake conditions. However, concern over *Microcystis* populations and their impact on drinking water quality requires a different sampling strategy for the phytoplankton. Under Phase II, *Microcystis* sampling will be targeted for nearshore areas because *Microcystis* often accumulates in these areas and the nearshore areas also serve as the intake sites for drinking water. Because of the high cost of analyzing samples for *Microcystis* and the toxin produced by the cyanobacteria (microcystin), a sampling design will be implemented that relies on local participation to identify periods when *Microcystis* would be a concern.

The sediment sampling under Phase I was based on one sediment core collected from the south lake. Under Phase II, we plan to collect additional sediment cores to substantiate the patterns observed in the first sample and to explore spatial variation in sediment inputs to the lake. In this way, the sediment sampling can be used to examine long-term sediment production adjacent to selected tributaries.

The additional information will be used to refine the SWAT watershed modeling and increase the level of confidence in the output. The monitoring and modeling results will be used by the Oregon Department of Environmental Quality to establish Total Maximum Daily Loads (TMDLs) of sediment and nutrients for the Tenmile Lake watershed.

G. LITERATURE CITED

To be completed for final draft

APPENDIX 1

INTERIM STREAM-RATING CURVES

APPENDIX 2

TENMILE LAKE PHYTOPLANKTON AND CHLOROPHYLL DATA, 1999

APPENDIX 3

TENMILE LAKE PROBLEM ASSESSMENT - A LAKE REPORT CARD

Tenmile Lake Problem Assessment - A Lake Report Card

The assessment of status and trends in a lake involves analysis of water quality, lake biota, and the activities in the lake and watershed that may contribute to the observed problems. In addition, any problem analysis requires some assessment of whether conditions are changing and, if so, in which direction. Problems in aquatic systems are seldom associated with a single cause: the causes are often multiple and the effects are usually interrelated. Nevertheless, we have attempted to summarize our current understanding of the lake and watershed in a qualitative format.

This lake and watershed "report card" provides a range of condition assessments from "none" (i.e., no problem) to "serious". These assessments are based on impairment of beneficial uses and perceived or measured change from pre-development conditions. The perceptions of problems are intended to provide a lake-wide perspective.

The development of the **Lake Report Card** involved assigning points to each of several lake and watershed categories based on the perceived and measured problems and trends. A maximum of six points could be assigned to each category with six representing a situation with demonstrated public concern, evidence of current lake impairment, and evidence of a trend toward increasing degradation. Quantitative information was given greater weighting in the ranking of the problems. Further explanation of the assigned values is described in the accompanying tables.

Tenmile Lake: Problem Status & Trends

The problems in Tenmile Lake are considered from the viewpoint of both lake biota and water quality metrics. The three elements most evident to the public are aquatic macrophytes, algae, and the fisheries. All three of these components are moderately to seriously impaired. The aquatic weed community is currently dominated by an exotic species: no information is available to determine if the macrophyte density or extent has been altered. The phytoplankton community experiences significant blooms in spring and late summer. Although the Cyanobacteria sampled mid-lake in 1999 did not include *Microcystis*, previous outbreaks of *Microcystis* in 1997 have impaired us of the lake as a drinking water supply. The fisheries community has been radically altered by introduction of exotic species, particularly from largemouth bass, bluegill, yellow perch, and bullheads. The introductions have not only contributed to a decline of the native coho populations, but have probably contributed to water quality changes by increased predation on zooplankton and increased sediment disturbance from benthivorous fish.

The water quality in the lake appears to be degraded compared to pre-development conditions. Monitoring of tributary streams, watershed modeling, paleolimnological results, and comparisons with nearby lakes all indicate that water quality in Tenmile Lake has declined. Most indicators of water quality place Tenmile Lake in the eutrophic class. Nutrient concentrations in the lake are moderately high, chlorophyll *a* levels are very high in spring and later summer, and dissolved oxygen becomes depleted in the bottom waters despite the shallow depths and frequent mixing. Transparency in the lake is often impaired by suspended sediment in the winter and phytoplankton populations in spring through summer. Use of the lake for domestic water supplies have been impaired in recent years by outbreaks of toxic Cyanobacteria.

Most of the indicators of lake water quality in Tenmile Lake show evidence of deteriorating conditions. Virtually all trends represented in the sediments show increased perturbations in the lake. Sediment accumulation rates have increased dramatically. Some evidence exists that Cyanobacteria populations are increasing base on the $^{15}N/^{14}N$ ratio and the increasing akinete counts. The diatom remains show an elimination of benthic diatoms and increase in species commonly found in nutrient-rich waters.

Watershed Issues

The status of watershed and lake management issues illustrate a number of potential causes for the water quality problems in Tenmile Lake. Shoreline development is extensive and its obvious proximity to the lake makes it a prime concern with respect to nutrient loading. Nutrient input from shoreline development occurs as an initial pulse during clearing and construction and continues indefinitely through septic inputs, elimination of riparian and shoreline vegetation, and landscaping practices. Urbanization from the City of Lakeside contributes storm runoff to Tenmile Lake. However, the urbanization is located on the far western shore, much of which is near the lake outlet.

Timber harvest is the most widespread land use activity in the watershed. Recent high rates of timber harvest may be decreasing as mature timber becomes less available. Timber harvest cycles are projected to increase for the Elliott State Forest which represents about one-half the watershed. Thus, the impacts from timber harvest are expected to decrease in the next several decades without any further intervention.

Agricultural activity in the watershed is largely limited to livestock-related businesses. The land currently used for livestock occupies a relatively small portion of the watershed, but the position of the grazing land at the base of the major tributaries makes this a critical activity with respect to affecting nutrient export from the watershed. The comparison of water quality from Murphy Creek (No grazing) versus Big and Benson Creeks (grazing) illustrates the dramatic impact associated with grazing in these former wetland areas. This problem is interrelated with hydrologic modifications because the channelization that allows the grazing to occur also aids in the transport of the sediment and nutrients generated by not only the livestock activities, but also from the timber harvest located further upstream. Thus, grazing in upland areas is not as significant to nutrient loading as the grazing that occurs in the lowlands with the channelized streams.

The presence of exotic species in the lake presents a challenge to managing the watershed, because the potential benefits of a reduction of nutrient loading from the watershed will yield uncertain benefits in the lake. The introduced fish species may be altering the expression of lake productivity and water quality through manipulation of the food web. No quantitative analysis on the consequences of the introduced fish or macrophytes on the lake water quality has been conducted.

Lake Comparison

The last feature of the lake “report card” is a comparison of measures of trophic status with lakes in the immediate area and lakes in the same ecoregion. The bar chart at the bottom shows the trophic state index (TSI) based on Secchi disk transparency, total phosphorus, and chlorophyll *a*.

TSI values above 50 are often associated with eutrophic lakes. The symbols associated with the bars show the same results for lakes in the Oregon Coastal Ecoregion and for Eel Lake individually. Many of the lakes in the ecoregion have been impacted in a similar fashion to Tenmile Lake and comparison with these lakes simply reinforces the extent of these impacts. The comparison with Eel Lake, which is relatively undeveloped, illustrates what Tenmile Lake may have been like prior to development. The TSI values for Eel Lake are generally in the oligotrophic range.

LAKE STATUS AND TRENDS - SCORING SHEET

	(2) Public Concern/ Intervention	(1)	(2)	(1)	(2)	TOTAL
		STATUS Supporting Information		TRENDS Supporting Information		
		Qual	Quan	Qual	Quan	
BIOLOGY						
Algae/Cyanobacteria	T		T		T	6
Aquatic Macrophytes	T	T		T		4
Fisheries	T		T		T	6
WATER QUALITY						
Nutrients	T		T		T	6
Dissolved Oxygen			T	T		3
Transparency	T		T	T		5
Sediment/Siltation	T		T		T	6
Water Contact	T					2
Water Supply	T		T	T		5

1-2	Slight or Unknown
3-4	Moderate
5-6	Severe

LAKE STATUS AND TRENDS - SCORING EXPLANATIONS

	Current Status	Supporting Data?	Trends	Supporting Data?
LAKE BIOLOGY				
1. Aquatic Macrophyte	Heavy lakeside (< 5m) infestation of exotic *Egeria densa*	Systma (1995)	Unknown, possibly stable	None
2. Algae (including cyanobacteria)	Large blooms of diatoms (*Asterionella formosa*) in spring and cyanobacteria in late summer (*Anabaena* and *Microcystis*); some toxic	This study Kann (1998)	Likely increases in algal bloom	This study. Paleo. Increasingly eutrophic diatoms; increase in cyanobacteria akinete
3. Fisheries	Major decline in salmonids, esp. coho	Abrams et. al (1991)	Possible short-term minor increases in coho	M. Mader (pers. comm.)
WATER QUALITY				
1. Nutrients	Moderate [P], moderate to high [N]	DEQ (unpublished) This study Supported by modeling	Likely increases in N	This study, paleo Increasing N in sediments, increasing akinetes, and increasing eutrophic diatoms
2. Chlorophyll *a*	High concentrations in spring and late summer	This study; max chlorophyll *a* as	Likely increases in chlorophyll *a*	This study, paleo. Increasing diatoms in sediments
3. Dissolved oxygen	DO depletion in bottom waters during summer periods	Johnson et al. (1985) Systma (1995) This study	Unknown, although suspected trend towards increasing rates of DO depletion	None

	Current Status	Supporting Data?	Trends	Supporting Data?
4. Transparency	Low transparency from siltation in winter, algae in spring and summer	This study	Likely decrease in transparency	Diatom suggests a decrease in transparency (this study)
5. Sediment/siltation	Rates of sediment production high	This study (stream monitoring)	Major increase in sediment accumulation rate	Sediment SAR (this study)
6. Water contact	Some anecdotal information suggesting incidences of contact dermatitis	-	Unknown	None
7. Water supply	Current drinking water impaired by algae (*Microcystis*)	Kann (1998)	Unknown	Increase in sediment akinete suggests increase in cyanobacteria

SCORING SHEET
WATERSHED/LAKE MANAGEMENT ISSUES

	STATUS			TRENDS			
	Extent	Position	Intensity	Extent	Position	Intensity	
Urbanization			**T**		**T**	**T**	3
Shoreline Development	**T**	**T**		**T**	**T**	**T**	5
Timber Harvest	**T**	**T**	**T**	**T**			4
Livestock		**T**	**T**		**T**	**T**	4
Hydrologic Modifications		**T**	**T**		**T**	**T**	4
Exotics	**T**	**T**	**T**	**T**	**T**	**T**	6

WATERSHED/LAKE MANAGEMENT ISSUES - SCORING EXPLANATIONS

	STATUS			TRENDS		
	Extent	Position	Intensity	Extent	Position	Intensity
Urbanization	Low, only on west shore	Near lake outlet	Moderate in localized areas	Development expanding slightly	Into more sensitive areas	More lowland fill
Shoreline Development	High	Near lakeshore	Moderate	Continued development	Lakeshore	Increasing
Timber Harvest	High	Variable	High	Decreasing (extended harvest cycles)	Decreasing (most shoreline areas harvested)	Stable
Livestock	Low	High (in wetlands)	Moderate	Decreasing livestock	Stable	Stable
Hydrologic Modifications	High	High (in wetlands)	High	Stable	Stable	Stable
Exotics	High	High (in-lake)	High (multiple species)	Unknown	Unknown	Unknown