Water Quality Assessment and Modeling

For the

Lake Mitchell Water Quality Improvement Program

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Prepared for

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Acknowledgement

This analysis benefited greatly from data generously provided by Dr. Bob Tatina of Dakota Wesleyan University. He had the insight to sample from the bridge, at the inflow of Firesteel Creek, what we call in this report Stn. 11. In addition, sampling station 13A was sampled by B.T. in 1996 to 1998, when no other data sources are available. A sincere thank you for sharing the data files so willingly.

Gene Stueven of the South Dakota Department of Environment and Natural Resources provided historic data of the Statewide Lake Assessment and any other available data, and patiently responded to numerous questions and inquiries. We thank him profoundly.

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1. Executive Summary

The overall water quality of Lake Mitchell can be summarized as eutrophic to hyper-eutrophic. While TP concentration are similar throughout the reservoir, indicators of algal biomass (chlorophyll and Secchi transparency) decrease significantly from the upstream to the downstream locations. This trend has been found in the study year 2001 and verified with data from earlier studies within the 1991 to 2000 period.

An extensive data set on Secchi transparencies was available for 11 years and up to six stations along the reservoir. Since chlorophyll was much less frequently sampled, but was significantly correlated with Secchi (R^2= 0.92, for summer averages of 5 years), Secchi was used as indicator of algal biomass in Lake Mitchell.

Algal biomass was variable throughout the summer of 2001 and there was no significant temporal trend from May to October. On the other hand, TP concentration significantly increased from spring to fall in 2001 as well as in many other years, even when inflow from Firesteel Creek was marginal and the outflow over the spillway had stopped. These seasonal TP increases can be explained by sediment release of phosphorus or internal load; because under stagnant conditions, sediment surfaces become reduced or free of oxygen, triggering phosphorus release.

Nutrients and algae appear uncoupled in the main part of the reservoir, as suggested by their different trends. Also, the TP concentrations are much higher than expected from algae biomass. Instead of nutrient limitation, algae may be limited by flushing during high flushing years and by light in the deep section because of increased mixing depth. However at the inflow, where algal concentrations are highest, TP algae relationships are closer to those found in other lakes and reservoirs.

Therefore a relationship was developed that predicts bloom frequencies in the upstream part, based on regression equations relating TP with Secchi (from worldwide relationships, Nürnberg 1996), Secchi with chlorophyll from Lake Mitchell, and chlorophyll with bloom frequencies (Walker 1984). Once frequencies for the upstream part are predicted for different TP concentration, a relationship between the decline of algal biomass with distance from the inflow can be used to also predict bloom frequency at any other part of the reservoir.

Water loads were determined from USGS flow data at a gauging station about nine miles upstream of the reservoir on the main inflow, Firesteel Creek. Daily flow data for 45 years were available and used to predict external loading to Lake Mitchell, using adjustments factors for inputs from additional sources, like groundwater, ungauged parts and precipitation according to the mass balance computed by SD-DNR for the year 1993 (Stueven and Scholtes 1997). External TP load was computed for 45 years from a relationship of flow rate with TP concentration in Firesteel Creek, and adjustment factors based on the SD-DNR study, similar to those used for the hydrologic budget. Internal load was determined from TP mass increases throughout the summer for 1991 -2001.

Budget calculations revealed that the climatic conditions are extremely variable: while long-term average water load (q_s) is 18 m/yr, it was only 1.6 m/yr in 2000 and 59 m/yr in 1995. The prediction of lake phosphorus at these extreme conditions is not possible. However, the nine years of remaining data could be used to calibrate the retention factor in the TP model so that summer TP could be predicted from external and internal TP loading, and water load. The mean deviation of predicted from observed TP averages is 4%, under exclusion of the two climatically extreme years.

The TP mass balance model supports the importance of internal load, especially in dry years. In dry years, external load is much lower relative to internal load, and the low water level usually accompanying droughts promotes stagnant conditions within the reservoir. This leads to high water temperature, reduced sediment surfaces, and decreased light limitation in the downstream parts because of a decreased overall depth.

In addition, a relationship between summer average Secchi transparency and water load was found, so that transparency improves with more flow. These results mean that control mechanisms are particularly needed and effective in dry years. This result supports the application of alum as a restoration method, which is most effective at low flow conditions.

2. Introduction

2.1. Purpose of this Report

Algal growth in lakes and reservoirs is usually limited by the supply of phosphorus so that blooms increase with increasing phosphorus concentrations in the water (e.g. Nürnberg 1996). Changes in the mass of phosphorus entering a lake or reservoir from the watershed (external loading) or lake sediments (internal loading), will change the average concentration of phosphorus and consequently of algae. The Firesteel Creek watershed agricultural nonpoint source pollution Model (AGNPS, Stueven and Schulte 1997) addresses the importance of decreasing external phosphorus load from the watershed of Lake Mitchell. However, observed total phosphorus (TP) concentrations in the lake suggest that internal loading from the sediment of the lake may play a major role in its TP budget.

Furthermore, the actual summer algal biomass may be limited by light because of increased turbidity or increased mixing depth in certain reservoir sections, and algal cells may be flushed out faster than they can reproduce under certain climatic conditions. Quantifying internal load and exploring the connections between TP and algal blooms in Lake Mitchell is the main intent of this report. Only when present and historical water quality can be explained, future conditions involving various restoration techniques can be predicted. Therefore, Lake Mitchell's past and present water quality was evaluated, so that meaningful predictions based on restoration measures can be made.

2.2. General Characteristics of Lake Mitchell

Lake Mitchell is situated in South Dakota, Davison County, at the approximate location of 43°46' West and 98°03' North. It is a run-of-the-river reservoir of Firesteel Creek, which represents the main inflow and outlet with a dam and spillway, water also leaves the lake at its downstream end being pumped at depth for the City of Mitchell's water supply.

The watershed/Lake area ratio is large, as is typical for river driven reservoirs. The morphometric characteristics (Table 2-1, especially the morphometric index, Osgood 1988) are typical of a polymictic reservoir, i.e. the water mixes from time to time; it is probably always mixed at the shallower upstream part (Figure 2-2) but may occasionally stratify at the deeper downstream section, especially in the summer under drought conditions.

All morphometric data are based on hypsographic information provided by SD-DNR and the Town of Mitchell and are listed in Appendix A. Volumetric variables are based on the years 1979 to 2001 and therefore are slightly different form those used in previous studies (Stueven and Scholtes 1997). Furthermore, it may be useful to re-measure the bathymetry of Lake Mitchell again, since sedimentation and adjustments of the outflow weir may have altered this information.

Table 2-1. Morphometry

Metric	
Altitude at maximum pool (m above sea level)	19.2
Altitude at average pool[1] (m above sea level)	18.2
Watershed area, A_d (km^2):	930.4
Surface area[1], A_o (km^2):	3.1
Area-Ratio, A_d/A_o,	300
Maximum depth (m):	8.8
Mean depth[1], z (m):	4.0
Morphometric ratio, $z/A_o^{0.5}$:	2.26
Volume[1] (10^6 m^3):	12.42
Outflow volume[1] (10^6 m^3 per yr):	56.55
Water residence time[1], τ (yr):	0.21
Annual flushing rate[1], $\rho = 1/\tau$ (per yr):	4.81
Annual water load[1], $q_s = z/\tau$ (m/yr):	17.8
Shoreline perimeter (km):	16
Non-metric	
Altitude at maximum pool (ft above sea level)	63
Altitude at average pool[1] (ft above sea level)	60
Watershed area (acres):	230,000
Surface area[1] (acres):	790
Maximum depth[1] (feet):	29
Mean depth[1] (feet):	13.3
Volume[1] (acre-feet):	10,068
Outflow volume[1] (acre-feet):	45,843
Shoreline perimeter (miles):	10

Note: [1]Longterm average 1979-2001

To investigate fluctuation in area and volume of Lake Mitchell lake level readings were consulted. There are only sporadic readings available form 1979 to 2001 so that only a very cursory assessment was possible. It is apparent that the morphometric variables are very variable (Figure 2-1), obviously depending on climatic conditions and flows, as described later. The analysis is presented in Appendix B.

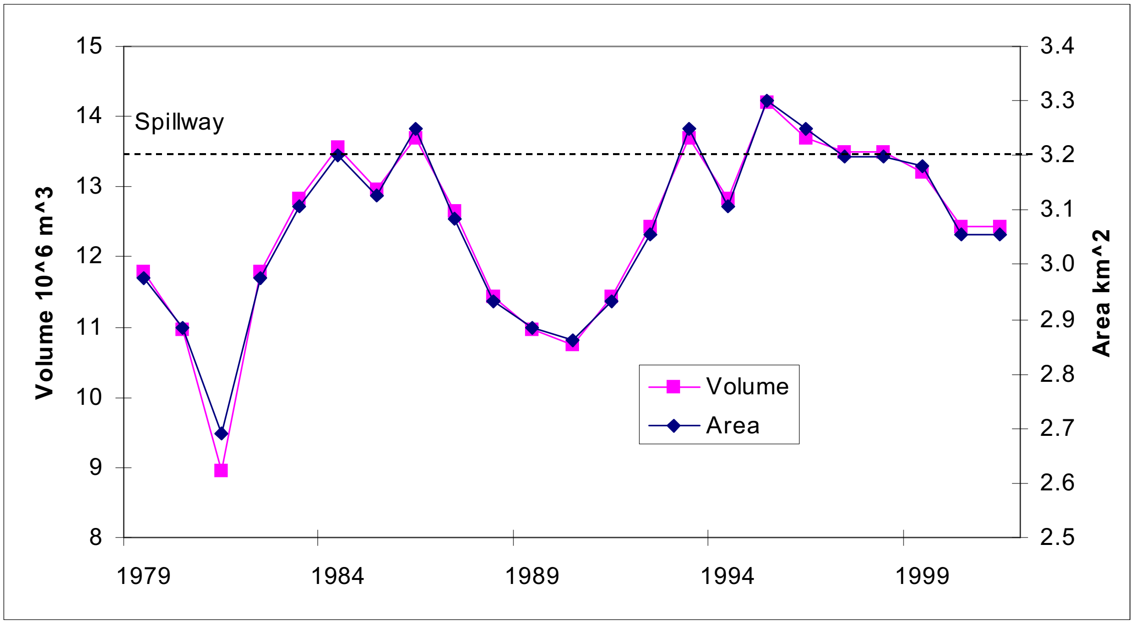

Figure 2-1. Lake area and volume fluctuations between 1979 and 2001.

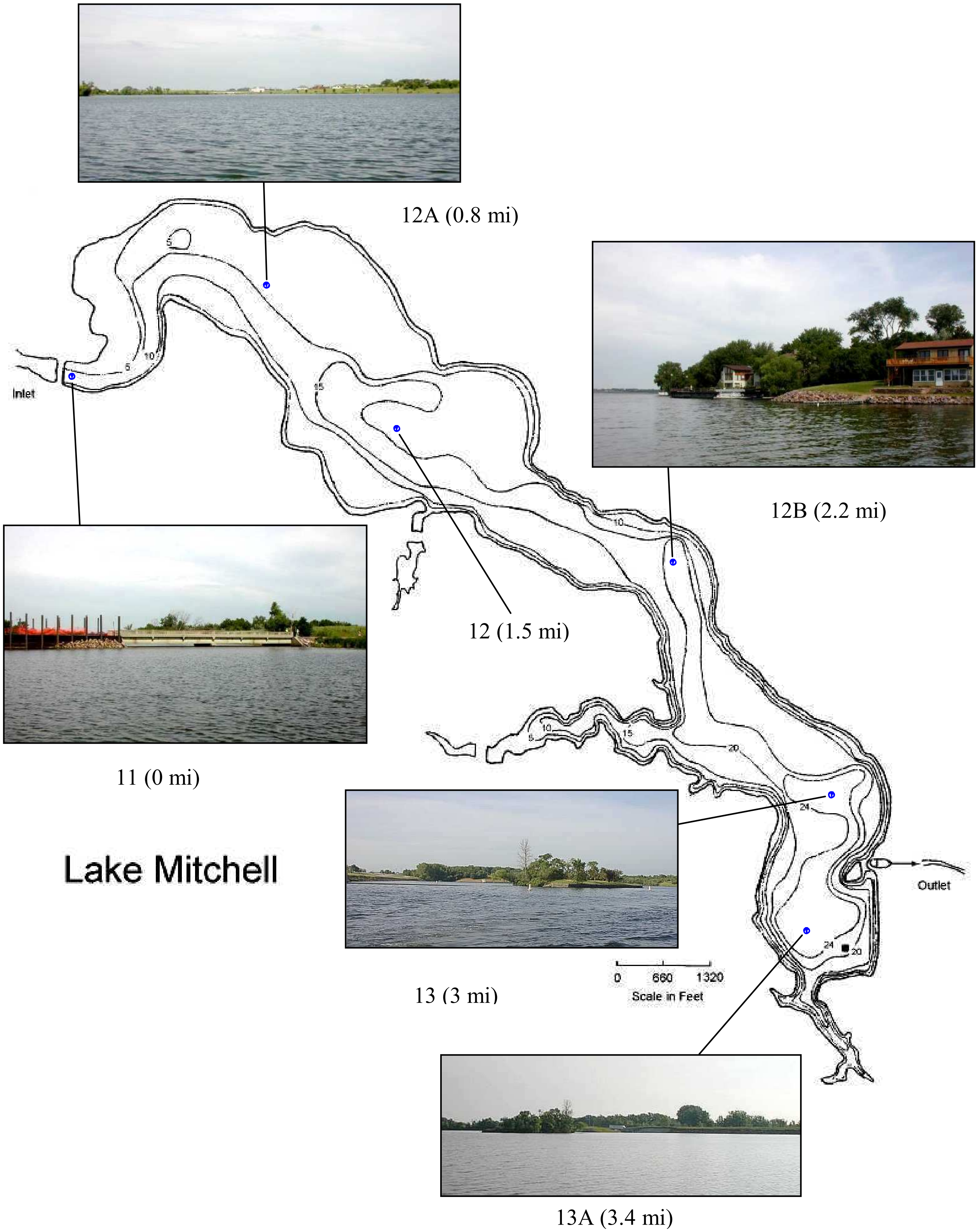

Figure 2-2. Lake Mitchell sampling sites and miles from inflow

3. Water Quality

It is important to evaluate Lake Mitchell's past and present water quality, so that the need for restoration measures can be determined and a baseline set against which they can be evaluated.

3.1. Data Sources, Sampling and Methods

3.1.1. 2001 Monitoring

Weekly samples and analyses from up to five lake stations were collected from late-May through mid-September in 2001.

Once anchored at the respective sampling sites, Secchi disk transparency was measured using an 8-inch, white disk. Dissolved oxygen and temperature profiles were measured using a YSI model 50B meter that was air-calibrated.

A surface water sample was collected for chlorophyll analysis by placing an inverted 500 ml amber bottle to elbow-depth (approximately 0.5 m), then filling by slowly turning the bottle upright. Within one hour, a mixed sample of measured volume was filtered onto a 1.0 µm glass fiber filter, then placed on aluminum foil and folded. The filter was immediately frozen. The frozen filter was sent to the state lab in Pierre for chlorophyll *a* analysis

Another surface water sample was collected for total phosphorus analysis by placing an inverted liter bottle to elbow-depth (approximately 0.5 m), then filling by slowly turning the bottle upright. Four ml sulfuric acid was added to the sample as a preservative. Either the same day or the next day, the sample was placed on ice and shipped to the state lab in Pierre for total phosphorus analysis.

Water samples from the total phosphorus sample bottle were also analyzed for Co-Pt color.

Data are listed in Appendix A.

3.1.2. Historical Data

For the last ten years, several different types of water quality data are available. All data and their sources are summarized in Appendix D.

3.2. Phosphorus

Total phosphorus is one of the water quality variables controlling water quality and the trophic state of a lake. Concentrations of above 0.1 mg/L are considered hyper-eutrophic (Table 3-1). All TP values in Lake Mitchell were above this value.

Table 3-1. Trophic state categories based on summer water quality (Nürnberg 1996)

	Oligotrophic	Mesotrophic	Eutrophic	Hyper-eutrophic
Total Phosphorus (mg/L)	< 0.010	0.010 - 0.030	0.031 - 0.100	> 0.100
Chlorophyll (µg/L)	< 3.5	3.5 - 9	9.1 - 25	> 25
Secchi Disk transparency (m)	> 4	2 - 4	1 - 2.1	< 1

Since there was no apparent TP trend between stations sampled in 2001 (see data in Appendix A and Table 3-3) averages of all stations (i.e. 12, 12A and 13 or 13A) are presented. In summer 2001, Lake Mitchell TP first decreased from May 31 (the first sampling occasion) to June 13, but then increased steadily to the last sampling on September 17 (Figure 3-1). A similar trend of a high initial TP concentration, a drop and subsequent increase over the summer was detected in most of the previous monitored years, although this pattern is less obvious because of lower sampling frequency (Figure 3-2).

The increase in TP concentration in the summers often occurred without any increase in flow of the major tributary, Firesteel Creek. In fact, in 2001 flow rate decreased to below 10 cfs (25,000 m^3/day) in July and remained that low throughout the remainder of the year (Figure 3-1). A similar pattern was observed in several years before (1991, 1994, 1995 - 97, Figure 3-3). Because of this hydrological pattern, external loading must be of minor importance in creating the drastic seasonal increase in TP. Instead, it is likely that internal phosphorus load, i.e. sediment-released phosphorus, increases TP concentration in late summer and fall in Lake Mitchell. Phosphorus is released as ortho-phosphate from iron hydroxides in the sediments, when the sediment surfaces become anoxic (i.e. oxygen concentration is close to zero). This phosphorus fraction is highly biologically available and can directly be used by algae to grow. In comparison, often only one third of the phosphorus from external loads is biologically available and enhances algae blooms. Therefore, it can be concluded, that sediment derived phosphorus is the most important driver of summer and fall algal blooms in Lake Mitchell. Its effect on the overall phosphorus budget will be quantified in Section 4.2.

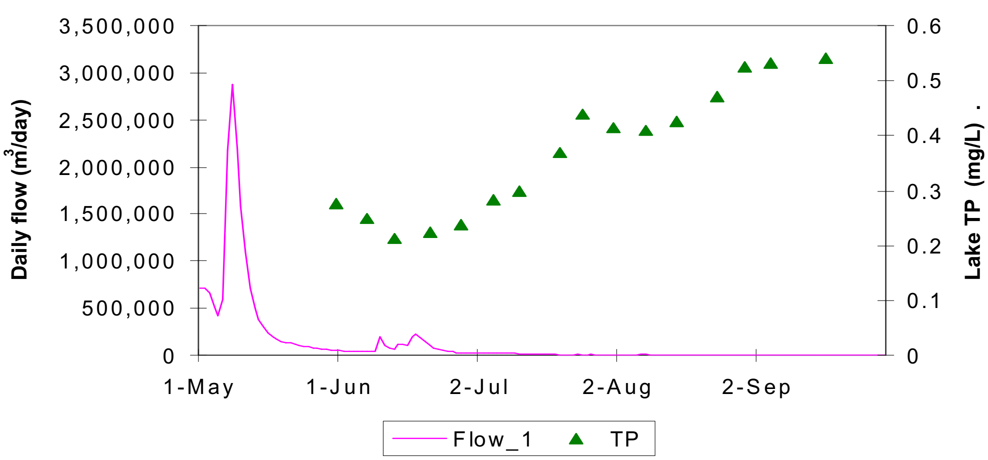

Figure 3-1. Daily inflow volume (Stn. 1 of Firesteel Creek) and lake average TP in summer 2001.

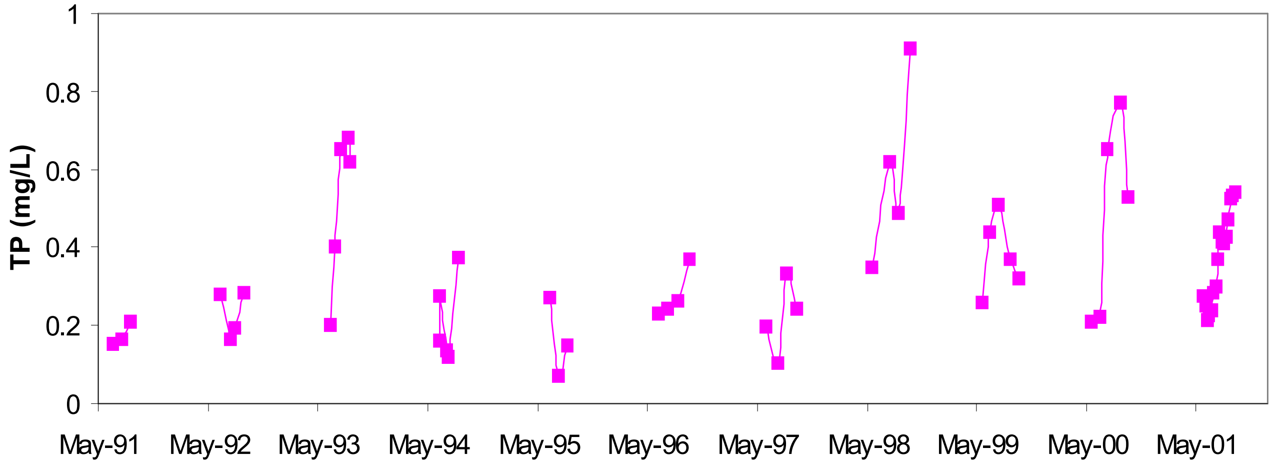

Figure 3-2. Lake average TP during summers of 1991 to 2001

Note : For years 1996, 1997, 1998 Stations 11 and 13A; years 1999, 2000 Station 11 only.

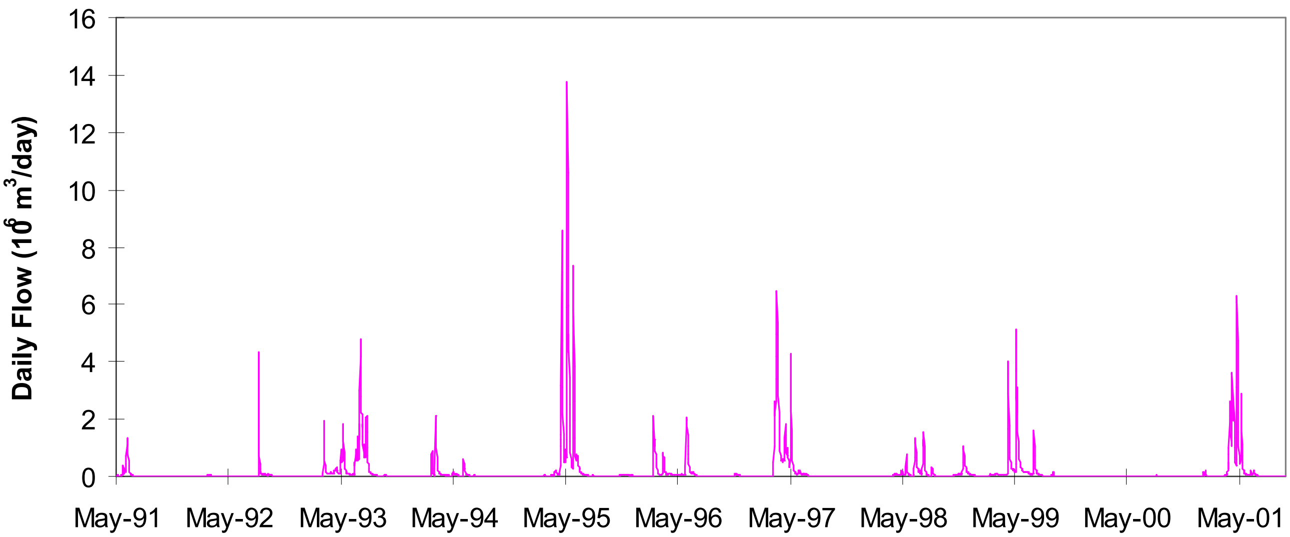

Figure 3-3. Average daily flow of the inflow (Stn. 1 of Firesteel Creek)

Summer averages of water quality variables are often used to characterize annual trends in lakes and reservoirs. Usually, summer is also the season that is most important to lake users. A comparison of average TP concentration for the period from May 1 to September 30 of eleven years is presented in Figure 3-4 (based on data from Table 3-2). With the exception of a very high summer average in the wet year 1993, there is a significant trend for TP increasing from a low of 0.18 mg/L in 1991 to a high of 0.35 mg/L in 2001 with an average rate of 0.028 mg/L TP /year (R^2= 0.60, n=10, p<0.01, TP= -55.7 (16.1) + 0.028 (0.008) Year). This trend cannot be explained by climatic changes (no significant relationship with flow nor external load were found). Future monitoring should be conducted to see whether this trend continues.

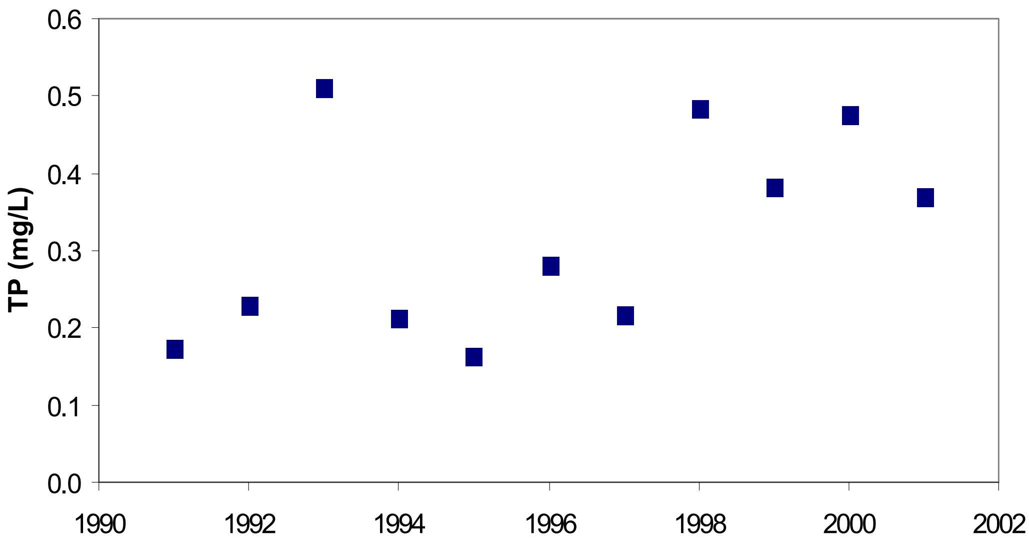

Figure 3-4. Whole lake average summer TP from 1991 to 2001.

Note: 1993 TP concentration was unusually high, perhaps because of a wet summer with higher TP load from the watershed. 1993 data appear real, since they are based on two different monitoring projects by the DENR (the Statewide monitoring and the Lake Mitchell Monitoring).

Note: For years 1996, 1997, 1998 Stations 11 and 13A; years 1999, 2000 Station 11 only.

Table 3-2. Summer average lake quality from 1991 to 2001 and annual water load.

	TP (mg/L)	Chl (μg/L)	Secchi (m)	Water Load q_s (m/yr)
1991	0.174	23.6	0.98	6.0
1992	0.230	30.2	0.90	6.9
1993	0.510	19.2	1.21	37.4
1994	0.213	7.8	1.41	9.1
1995	0.163		1.48	59.4
1996	0.281		1.00	17.0
1997	0.218		1.20	43.3
1998	0.484		1.00	15.8
1999	0.383		1.27	30.3
2000	0.476		1.36	1.6
2001	0.369	14.6	1.37	38.8
Average	0.318	19.1	1.20	24.2
Trophic state	hyper-eutrophic	eutrophic	eutrophic	

3.3. Algae

Most of the algae in Lake Mitchell are bluegreen algae or cyanobacteria of the species *Aphanizomenon flos-aquae* (Stueven and Scholtes 1997). The sickle cells of this alga were seen on June 30, 2001 from the boat throughout the lake. They were much more dense and closer to the surface at the stations closer to the inflow of Firesteel Creek. An intermediate density was observed at the mid-lake station 12B (Figure 3-5). This gradient along Lake Mitchell is reflected by chlorophyll concentration and Secchi disk transparency as presented in Sections 3.3.1 and 3.3.2 below.

Figure 3-5. *Aphanizomenon* in the open water at the mid-lake station 12B.

Note: Secchi disk transparency was 1.3 m. Photo taken by G.N. at 9:30 AM, June 30, 2001 from a boat.

A discussion of the management relevance of Aphanizomenon is found in Osgood and Nürnberg (2002).

3.3.1. Chlorophyll

Algae or phytoplankton biomass is often quantified by the concentration of the green pigment, chlorophyll *a*, in lake water. The determination of chlorophyll includes measuring the absorbency of the pigment after extraction. The precision and accuracy of this method are not always good, due to the fragile nature of the pigment; exposure to light or heat can denature the pigment. The standard analytical technique involves a correction to separate pigment from possibly dead algae (pheophytin) from that of living algae by denaturizing the pigment and using the difference as that belonging to living algae ("normal" or "corrected" chlorophyll). However, because of artificially induced denaturization this method may underestimate the chlorophyll concentration and many monitoring programs choose to report results of both methods. Data for the 2001-monitoring season were reported both ways, as "normal" chlorophyll (denominated here just as "chlorophyll"), that is corrected, and as uncorrected or total chlorophyll. These data were highly significantly correlated and the uncorrected were about twice as high as the corrected values (Appendix E). Data from previous years are considered "corrected".

Chlorophyll concentrations are indicative of the trophic state of lakes and reservoirs. At 3.5 µg/L (same as 3.5 mg/m^3) less, oligotrophic conditions exist, from 3.5 to 9 µg/L mesotrophic, between 9 and 25 µg/L eutrophic and greater than 25 µg/L hyper-eutrophic conditions (Table 3-1).

Chlorophyll average of the stations 12, 12A, and 13 or 13A varied from almost 0 in May 2001 to almost 40 µg/L in the fall, but there was no significant seasonal trend within the summer (after mid-June), since concentrations were variable throughout the summer (Figure 3-6). However, a spatial trend was detectable and chlorophyll concentration was highest close to the inflow and decreased throughout the reservoir towards the outflow (Figure 3-7), so that the conditions are often hyper-eutrophic at the inflow and mesotrophic at the outflow (Table 3-1). Of course, the trophic state is worse if uncorrected values are used. This trend will be further discussed in Section 3.3.2.

There are five years of summer chlorophyll data available (Table 3-2). Summer averages are variable but usually indicate eutrophic conditions.

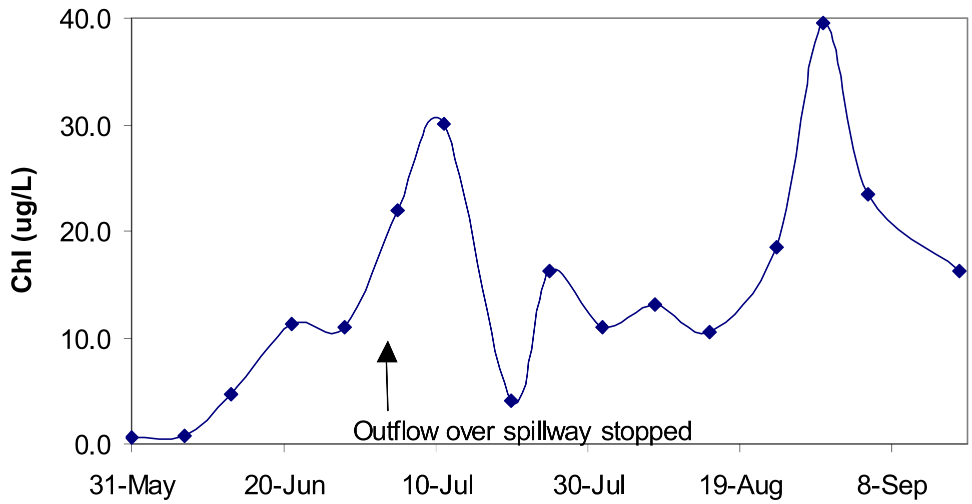

Figure 3-6. Lake average chlorophyll in summer 2001

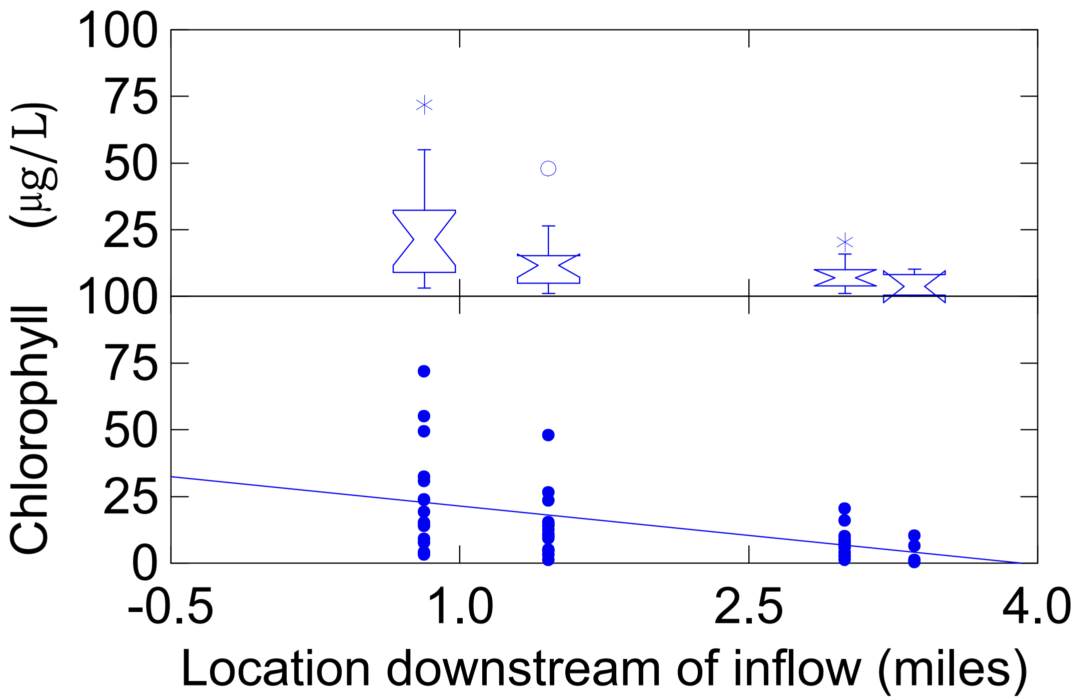

Figure 3-7. Chlorophyll along sampling stations in 2001

Lower panel: Individual data points and regression line for all stations. Upper panel: Medians and non-parametric confidence bands. The horizontal lines are upper hinges or 75th percentile, and lower hinges or 25th percentile, respectively. The narrow "waist" represents the median, the vertical line the range, except that star and circle represent outliers. The slanted lines off the median represent 95% non-parametric confidence bands.

3.3.2. Secchi Disk Transparency

The depth of Secchi disk transparency measures algae biomass in lakes with known color values (for biomass conversion corrections) or unstained by organic acids, and with no turbidity other than that created by algae. In Lake Mitchell, color is 35-50 platinum units and not variable during summer (Appendix C). Secchi disk transparency may indicate high turbidity due to silts and erosion in addition to enhanced algae growth at sites close to the inflow (Station 11), but may more closely represent algae biomass at the deeper sites of 12A and downstream. In fact, measures of total suspended solids (TSS) that are available for stations 12 and 13 for the summers 1993 and 1994 show only slightly elevated values at the upstream station 12. Values are usually below 10 mg/L (Appendix A), indicating only a very small amount of particles. Similarly, the statewide monitoring program 1991 to 1995 revealed TSS summer surface averages of below 11 mg/L of composites from three stations along Lake Mitchell.

Secchi transparency average of the stations 12, 12A, 12B, 13, and 13A varied throughout the summer from slightly below 1 m to almost 3 m (Figure 3-8), indicating eutrophic to mesotrophic conditions (Table 3-1).

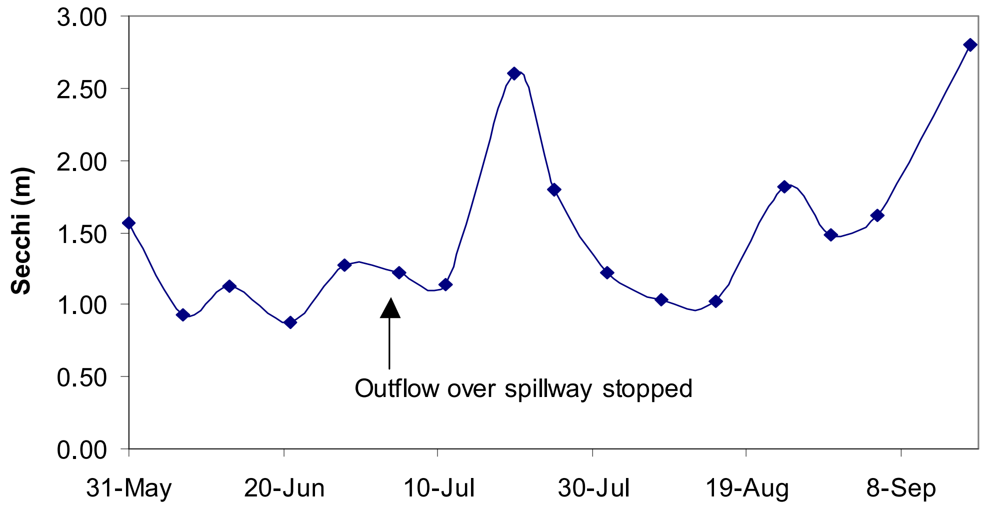

Figure 3-8. Lake average Secchi transparency in summer 2001

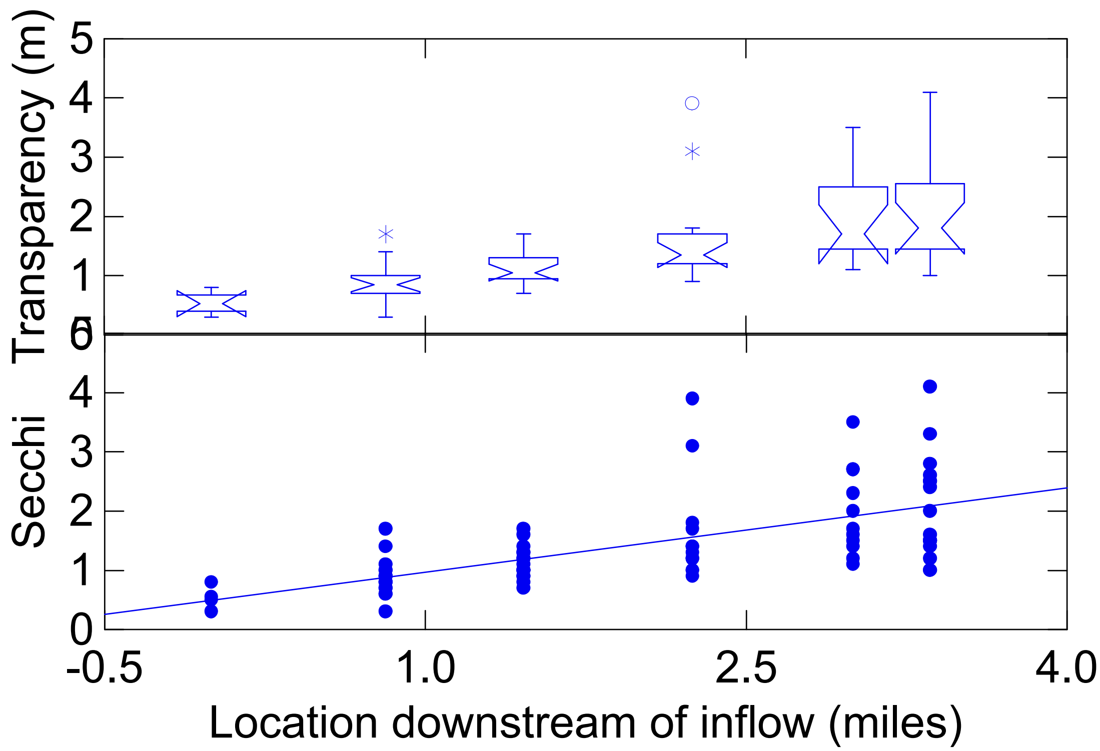

Figure 3-9. Secchi disk transparency along sampling stations in 2001

Note: Location "0" coincides with station 11, under the inflow bridge and represents the first cluster of points.

Lower panel: Individual data points and regression line for all stations. Upper panel: Medians and non-parametric confidence bands. The horizontal lines are upper hinges or 75th percentile, and lower hinges or 25th percentile, respectively. The narrow "waist" represents the median, the vertical line the range, except that star and circle represent outliers. The slanted lines off the median represent 95% non-parametric confidence bands.

Table 3-3. Secchi transparency (and TP) along the length axis of Lake Mitchell.

Stn	Mile	Secchi (m)	TP (mg/L)
11	0	0.54	0.433
12A	0.815	0.90	0.376
12	1.460	1.10	0.367
12B	2.249	1.60	n.d.
13	2.999	2.00	0.366
13A	3.360	2.10	n.d.

n.d., not determined

It is apparent from Figure 3-9 and Table 3-3 that 2001 summer Secchi disk transparency consistently and significantly increased along the length axis of the lake (n= 77, R^2= 0.39, Secchi = 0.49 (0.16) + 0.475 (0.068) miles, with standard errors in parentheses). The same trend was apparent in other years. (For the years 1991 - 1998, n= 42, R^2= 0.47.) This means that the perceptible water quality in Lake Mitchell improves with distance away from the inflow.

As mentioned before, just a visual inspection of the lake water from a boat on June 30, 2001 supports this pattern, as it revealed a dramatic decrease of *Aphanizomenon* flakes with distance from the inflow. A medium density was observed at the mid-lake station 12B (Figure 3-5. At that station Secchi disk transparency was 1.4 m (June 28).

It can be speculated that these spatial trends in Secchi and chlorophyll are produced by increasing depth going downstream. (1) Aphanizomenon biomass is diluted and algal density decreases at deeper depths. In addition (2), light limitation may occur occasionally, as the depth of the downstream locations exceeds the depth of the photic zone (2-3 times the Secchi depth). Hence, the algae may spend some time in the low light zone where reproduction is limited (Reynolds 1997). Because there is no significant change in TP, nutrient availability is likely of minor importance in explaining this trend.

3.3.3. Secchi - Chlorophyll Relationships: Measures of Algae

The assumption that much of Secchi transparency is due to algae is supported by the significant correlations of chlorophyll with Secchi data. For the 2001 log-transformed data, both corrected and uncorrected chlorophyll are significantly correlated with Secchi transparency (chlorophyll: n=42, $p<0.0001$, R^2= 0.282, uncorrected chlorophyll: n=45, $p<0.0001$, R^2= 0.43, Figure 3-10).

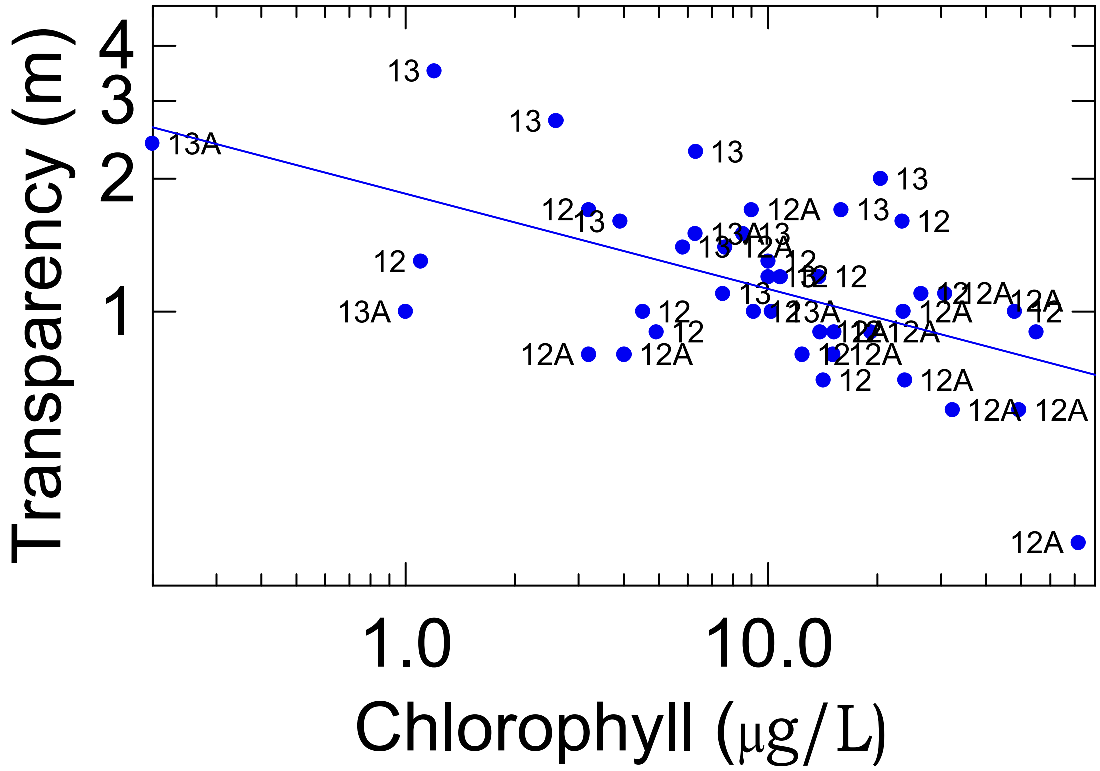

Figure 3-10. Comparison of Secchi transparency with uncorrected chlorophyll data in 2001.

Labels are locations of sampling stations as indicated in Figure 2-1.

As with the individual 2001 data, the correlation between summer averages of Secchi transparency and chlorophyll concentration is highly significant for five years of available data (Figure 3-11). The regression equation can be used to predict chlorophyll averages for those years for which only Secchi averages are available (R^2=0.92, n=5, p <0.01).

Chlorophyll = 61.16 (7.39) - 35.84 Secchi **Equation 1**

These relationships are supported by those found in word-wide lakes, where Secchi disk depth is highly dependent on chlorophyll and color. To examine whether Lake Mitchell's biomass relationships are similar to other lakes, a model, based on 91 worldwide lakes (Equation 3, R^2=0.79, p<0.0001, Nürnberg 1996) was used to predict Secchi transparency (m) from summer average chlorophyll and color.

Secchi Disk Transparency = 1.03 + 0.378 log (Chl_{summer}) - 0.315 log (color) **Equation 2**

This model predicts a Secchi of 1.15 m from an observed chlorophyll concentration of 19 μg/L long-term average and a color value of 35 units, while observed Secchi for this time was 1.18 m. This means that Lake Mitchell's chlorophyll Secchi relationships are typical for lakes and reservoirs.

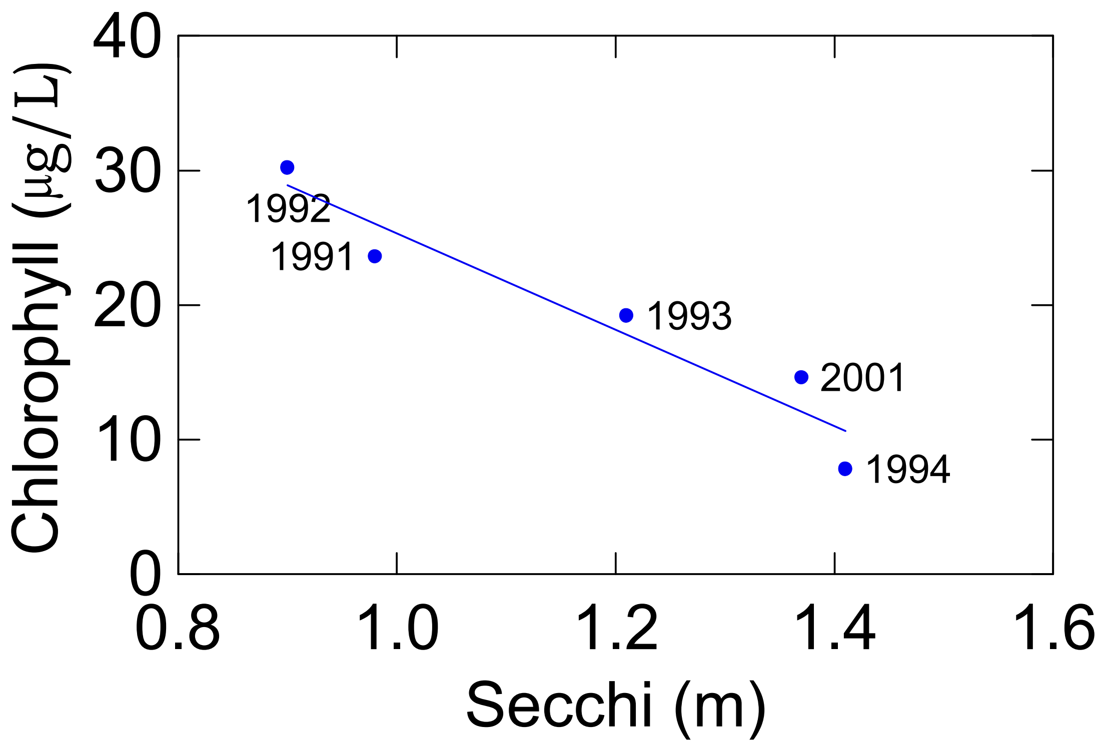

Figure 3-11. Summer average chlorophyll versus Secchi transparency for several years

For these reasons, Secchi disk transparency will be used here to reflect the appearance of Lake Mitchell water, in particular the amount of algae, which mostly are *Aphanizomenon*. This measure is much simpler than chlorophyll *a* extraction, and there are many more long-term data available for Lake Mitchell (Table 3-2). It appears effective to use Secchi transparency for goal setting and predictions in this lake.

3.4. Long-term Relationships

The variation of summer average Secchi transparency, TP, chlorophyll, and annual water load was high in the last 10 years, for which data are available (Figure 3-12, Table 3-2). Chlorophyll and Secchi transparency for 2001 were slightly better than in many preceding years, TP was slightly elevated. In three out of 5 years, summer average chlorophyll was well above the nuisance level of 10 µg/L (see Section 5.2.3). These concentrations would have been much higher at the upper part of the reservoir, because of the observed spatial variability of algal biomass.

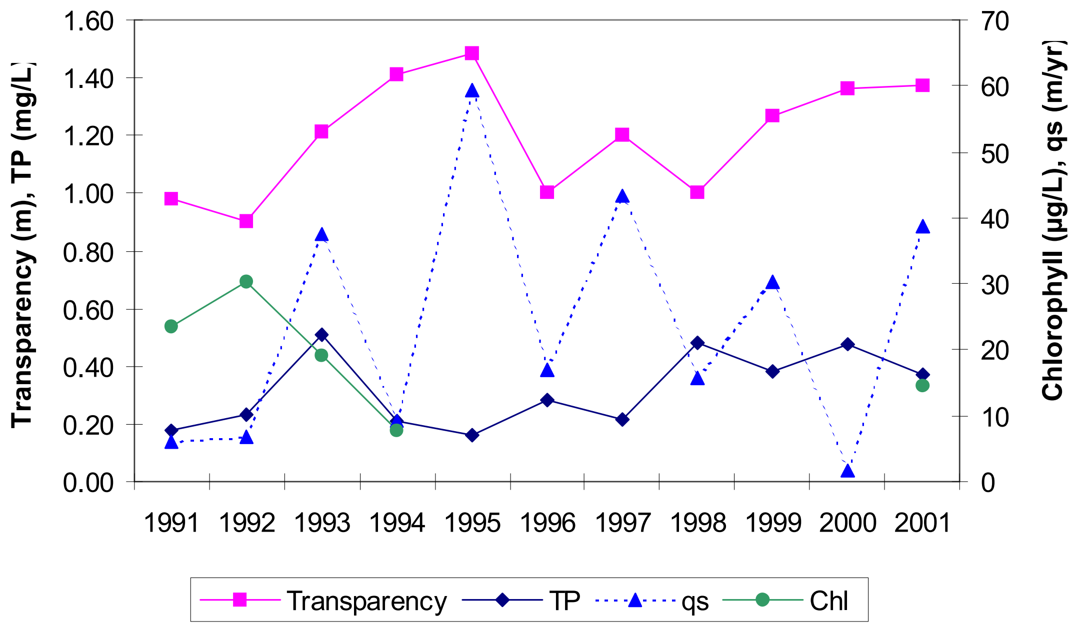

Figure 3-12. Summer average Secchi transparency, TP, chlorophyll, and annual water load q_s.

Note : TP and Secchi for 1996, 97, 98 average of Station 11 and 13A. For 1999, 2000, TP for Stn. 11 only; Secchi adjusted from Stn. 11 data.

It has repeatedly been observed that algae biomass is controlled by TP, as reflected by inverse significant correlations between summer averages of TP and Secchi for worldwide, individual lakes (Nürnberg 1996). However, the empirical models that link biomass to in-lake TP in many lakes (Nürnberg 1996) do not apply to Lake Mitchell. Here, average summer chlorophyll concentration is only poorly correlated with average summer phosphorus concentration as found in this study and before by Stueven and Scholtes (1997, a significant relationship was only obtained by selecting data for 3 years out of 5).

Furthermore, the amount of chlorophyll units per TP (or the slope) is smaller for Lake Mitchell average concentrations, which is common in lakes with *Aphanizomenon* (see Osgood 1982; Osgood and Nürnberg 2002). The worldwide model (Nürnberg 1996) would predict 63 µg/L chlorophyll from the observed TP average of 0.370 mg/L. The average chlorophyll in 2001 was much lower, only 15 µg/L. However, it resembles worldwide relationships more closely at the central sampling stations (#12A, at 0.8 miles) where the 2001 chlorophyll average was about twice as large as the whole lake average concentration at 25 µg/L. This relationship may be even closer at the inflow, although the two chlorophyll values available are still only 35 and 39 µg/L (Station # 11).

Similarly, there is no simple significant relationship between TP and Secchi transparency detectable in Lake Mitchell whole lake averages (Figure 3-13). It appears that at high flows or high annual water load, transparency is high; it is low at low flows (Figure 3-14). In fact, without the data of the years 1994 and 2000, the regression is highly significant (R^2= 0.87, n=9, p<0.0001). No explanation for the outliers can be offered. Since high water load also means high external TP loading, such a relationship appears counterintuitive. In many lakes, the higher input of water and TP results in higher TP and algal biomass. However, in the run-of-the-river section of reservoirs inverse relationships between algal biomass and water load and external TP loading have been observed before (Brownlee Reservoir, Freshwater Research *and* Brown and Caldwell 2001). Several possibilities can explain such relationships. (1) When flushing is limited and the residence time becomes large, the loss rate of algae due to flushing out of the reservoir is diminished or halted and algae can develop. Often, the water temperature increases as well, increasing algae growth rates. (2) Anoxic conditions may develop in the stagnant water, leading to increased internal loading which again stimulates algal growth because of its highly bioavailable phosphorus (Nürnberg and Peters, 1984).

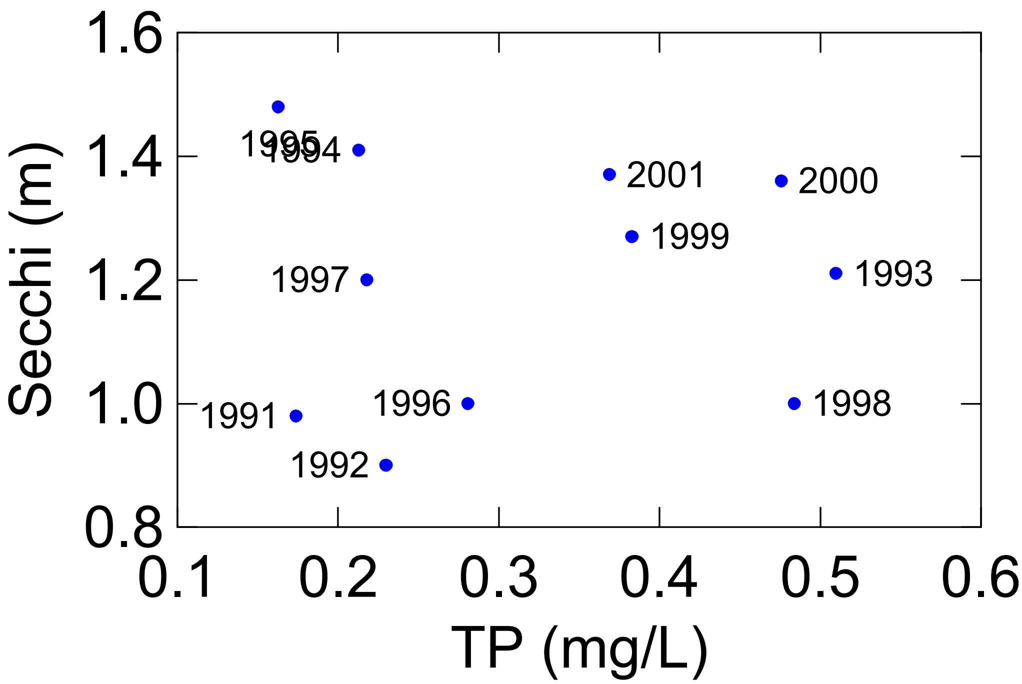

Figure 3-13. Summer averages Secchi transparency versus TP averages.

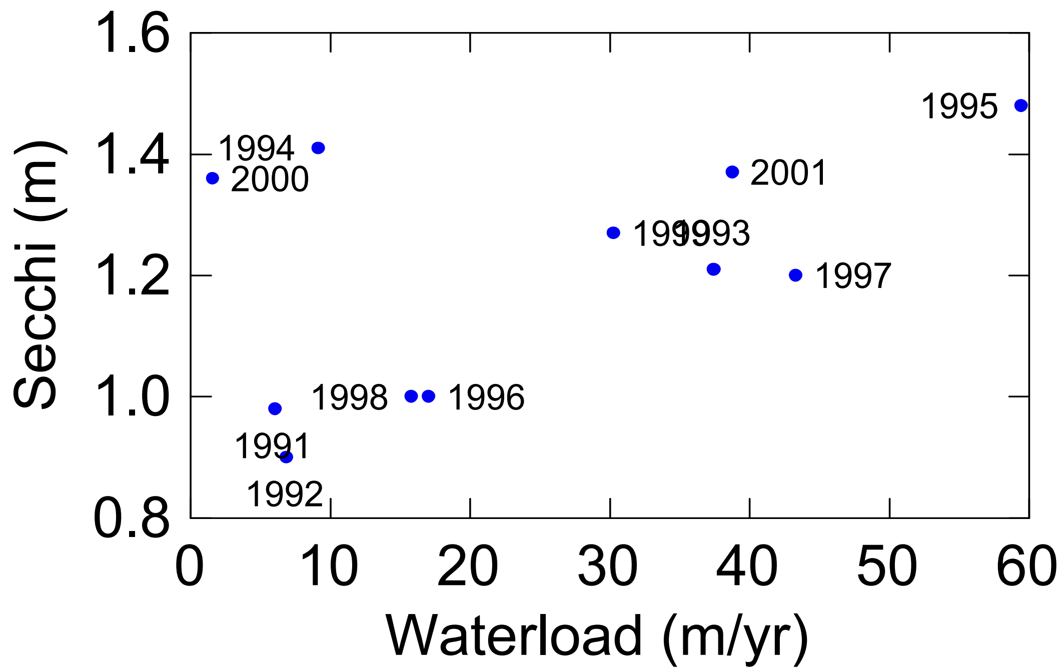

Figure 3-14. Summer average Secchi Transparency versus annual water load.

Even though Secchi and TP whole lake averages do not seem to be correlated on a whole lake basis, they are more closely related at the upstream station, where biomass per unit of TP is more similar to those in other lakes. These global relationships then can be used to model upstream Secchi transparency as explored in the modeling section (Section 5.2.1).

The overall water quality of Lake Mitchell can be summarized as eutrophic to hyper-eutrophic. It appears that in general nutrients and algae are not coupled, as the TP concentrations are much higher than expected from algae biomass. However, algal biomass is larger at the inflow stations and resembles more the worldwide relationships. In the deeper sections, algae may be limited by flushing during high flushing years and by light instead of nutrient limitation. Such changes in biomass control are typical for rivers and run-of-the-river reservoirs (Soballe 1987). It means that control mechanisms should be particularly needed and effective in years that have stagnant periods as during drought conditions.

4. Water and Phosphorus Mass Balance

The current and long-term water and phosphorus mass balances were determined, so that the effect of potential alum additions can be evaluated. In particular is it necessary to assess the natural variability due to climatic conditions, which directly affects the hydrologic (water) budget.

4.1. External Inputs

As is typical for a run-of-the-river reservoir like Lake Mitchell, most of the water input originates in one main inflow, Firesteel Creek. According to Stueven and Scholtes (1997), only 11% originates in other surface and atmospheric sources, and up to 18% in groundwater in 1993. These proportions were used as a guideline in conjunction with historic USGS gage data, to construct long-term water budgets. (Details are presented in Appendix G.)

Year to year variability is great and inflows vary between 0 and 200 x 10^6 m^3/yr (Figure 4-1). The last ten years appear to have a higher frequency of wet years. Most of the flow occurs from March to the beginning of July, while flows are an order of magnitude smaller in the remainder of the year (Table 4-1, Figure 4-2, Figure 3-3). (In 2001, most of the flow occurred in spring and just about stopped completely from June/July to October, Figure 3-1). At that time, usually the outlet disappears as well, and water leaves the lake only via evaporation and pumping by the water plant.

Table 4-1. Monthly flows and loads from Firesteel Creek (#1), average of 1956-2001.

Month	Flow m3	TP kg
Jan	114,807	56
Feb	685,519	490
Mar	7,350,038	6,155
Apr	7,982,962	6,741
May	7,231,597	6,148
Jun	5,774,384	4,819
Jul	2,131,297	1,635
Aug	619,720	421
Sep	85,254	36
Oct	150,402	77
Nov	296,101	181
Dec	90,680	37
Monthly average	2,709,397	2,233

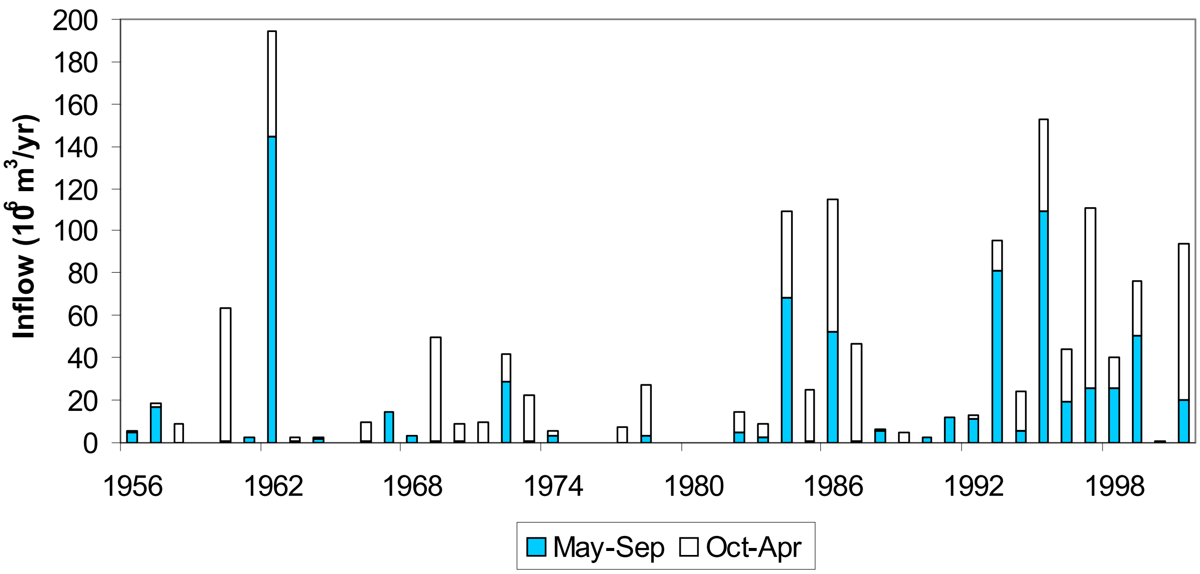

Figure 4-1. Annual inflow (Firesteel Creek, Site#1)

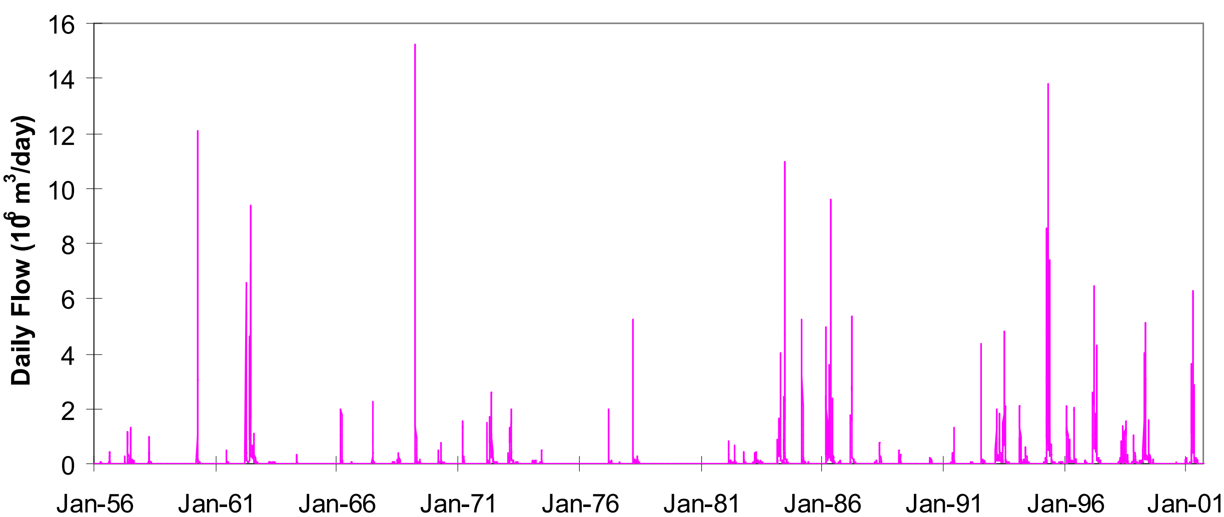

Figure 4-2. Long-term daily flow at the inflow since 1956 (Firesteel Creek, Site#1)

It was found that flow rate and TP concentration of the inflow were correlated for several years of data (Appendix E). This correlation was used to compute TP loading. Therefore, TP loading follows the same pattern as the flow, only it increases a bit more than flow (Figure 4-3). External loading is about 30,000 kg/yr on average or 18,500 kg/yr as a median of the last 45 years, but varies greatly between years as seen by the percentile calculations (Table 4-2 and Appendix G).

In comparison, the agricultural nonpoint source model predicted a TP load of 60.4 non-metric tons (54,794 kg) for a 25-year event (Stueven and Scholtes 1997). This amount compares to the 70th percentile of the last 22 years 1979-2001 (Table 4-2, 51,604 kg) or the average of the last 9 years (Table 4-2, 53,447 kg). It would be interesting to know, what exact hydrological conditions the 25-year hydrological event of the 1997 study represents.

Table 4-2. TP loading from various sources and for different seasons (kg)

	Firesteel Creek inflow #1			Total Surface	Groundwater	**Total**
	May-Sep	Oct-Apr	Annual	Annual	Annual	Annual
			Longterm averages			
1956-2001	13,060	13,736	26,796	28,403	900	**29,303**
1979-2001	17,977	17,428	35,404	37,528	1,032	**38,560**
1991-2001	26,998	22,270	49,268	52,224	1,223	**53,447**
			Percentiles for 1979-2001			
10^{th}	10	11	106	113	600	**713**
25^{th}	365	283	3,650	3,869	600	**4,469**
50^{th}	3,645	9,200	16,916	17,931	600	**18,531**
70^{th}	16,548	19,983	47,692	50,553	1,051	**51,604**
75^{th}	19,466	26,388	68,287	72,384	1,537	**73,934**
90^{th}	57,980	48,591	93,814	99,442	1,986	**101,416**
			Proportion of total for 1979-2001			
	0.47	0.45	0.92	0.97	0.03	**1.00**

Percentiles: for example at the 25^{th} percentile, a quarter of all years fall below the given value.

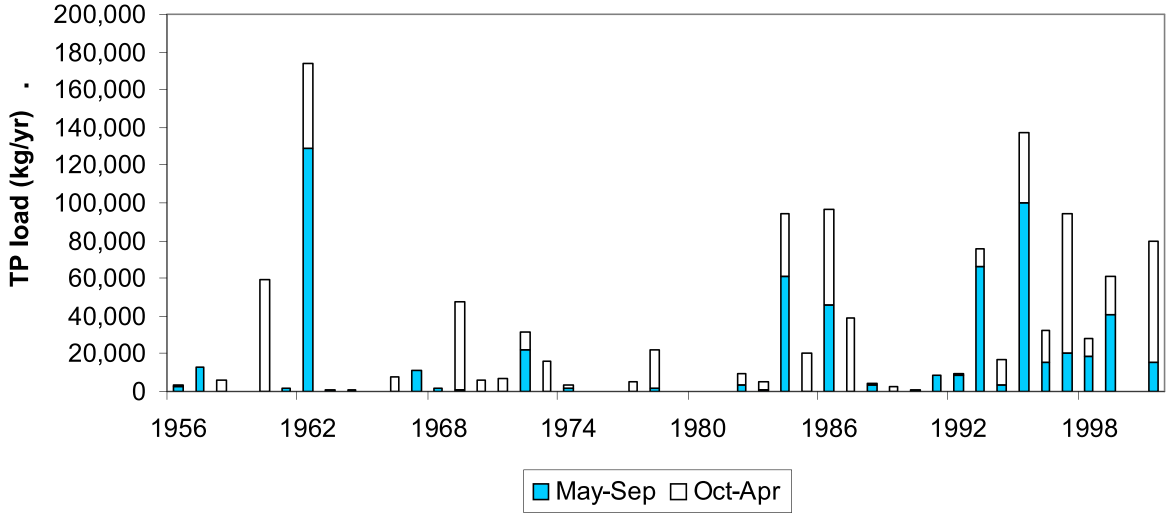

Figure 4-3. Long-term annual TP loading from Firesteel Creek (Site#1)

4.2. Internal Phosphorus Inputs from Sediments

Despite a drop in Firesteel Creek flow and consequently loading to below 10 kg/d by the end of June, 2001, the TP concentration in Lake Mitchell increased significantly throughout the dry summer season as described in Section 3.2. The lake became stagnant, also the outflow over the spillway stopped completely. At such times, the water is warm and the sediment water interface becomes anoxic, resulting in the chemical release of phosphate (from reduced iron hydroxide compounds) into the overlying water. Although this internal load originally stems from external sources, it represents an additional source at the present time and has to be considered separately in an annual mass balance. Apparent internal loading can be computed from the TP increases in the water column and is shown in Figure 4-4. By the end of summer 2001, internal load had accumulated to about 4,000 kg.

In all but one of 10 previous years summer average TP concentration increased as well. Computation of internal loading from these increases yield internal load estimates between 0 (in 1995) and 7,000 kg/summer (Table 4-3). The importance of internal load for the TP budget in this lake becomes apparent when it is compared to summer average TP concentrations. Internal load estimates are significantly correlated with summer average TP (Figure 4-5), while summer external load values are not (Figure 4-6).

There are indications that anoxic conditions may develop occasionally in the winter under ice, so internal loading may also happen during winter and early spring. Hence, the presented internal load values are likely minimum estimates.

The estimates average to a release of 33.5 kg (36.8 kg w/o 1995 data) phosphorus per day or an average areal release rate of 10.7 mg/m^2/day (11.8 w/o 1995 data) from the sediments of the whole lake. Such a release rate is supported by the sediment TP content. The analysis of 5 cores from several stations (12B, 13 and 13A, Appendix H) revealed a concentration of 2.2 mg/g/dry weight for the surface sub-samples (0-5cm), and of 2.05 mg/g/dry weight for the deeper (5-10 cm) samples. A regression model developed for world-wide lakes and reservoirs (Nürnberg 1988) predicts on average an anoxic release rate of 11.5 mg/m^2/day from such sediment TP content. This value is not significantly different from 10.7 or 11.8 mg/m^2/day, based on water TP increases during summer.

Release rates of 11 mg/m^2/day are within the range for eutrophic lakes and reservoirs (Nürnberg 1994, Figure 4-7).

Table 4-3. Internal load estimation from in-situ concentration changes

			TP (mg/L)		Lake Volume	Internal TP Load		
	End-Date	Days	TP at Date	Change	10^6 m^3	(kg)	(kg/d)	(mg/m^2/d)
1991	19-Aug	60	0.208	0.058	11.43	662	11.0	3.8
1992	26-Aug	42	0.282	0.117	12.43	1,455	34.6	11.3
1993	18-Aug	67	0.620	0.421	13.70	5,768	86.1	26.5
1994	13-Aug	63	0.372	0.212	12.83	2,719	43.2	13.9
1995	11-Aug	59	0.149	-0.121	14.20	0	0.0	0.0
1996	21-Sep	76	0.320	0.055	13.70	1,507*	19.8	6.1
1997	14-Aug	70	0.340	0.165	13.49	2,227	31.8	9.9
1998	20-Aug	126	0.488	0.140	13.49	2,675	21.2	6.6
1999	25-Sep	121	0.320	0.060	13.20	792	6.5	2.1
2000	27-Aug	97	0.770	0.560	12.43	6,963	71.8	23.5
2001	17-Sep	96	0.540	0.327	12.43	4,066	42.4	13.9
Average		**80**	**0.401**	**0.181**	**13.03**	**2,621**	**33.5**	**10.7**
w/o 1995		**82**	**0.426**	**0.211**	**12.91**	**2,883**	**36.8**	**11.8**

Note: The days of release are days between sampling efforts; when the available efforts were not spread to the beginning (May 1996) adjustments of internal load (kg) were made based on the daily rates (*). In some years, TP concentration dropped in September, therefore estimates that were recorded until August only, were not adjusted. However, they may underestimate internal load of the whole summer.

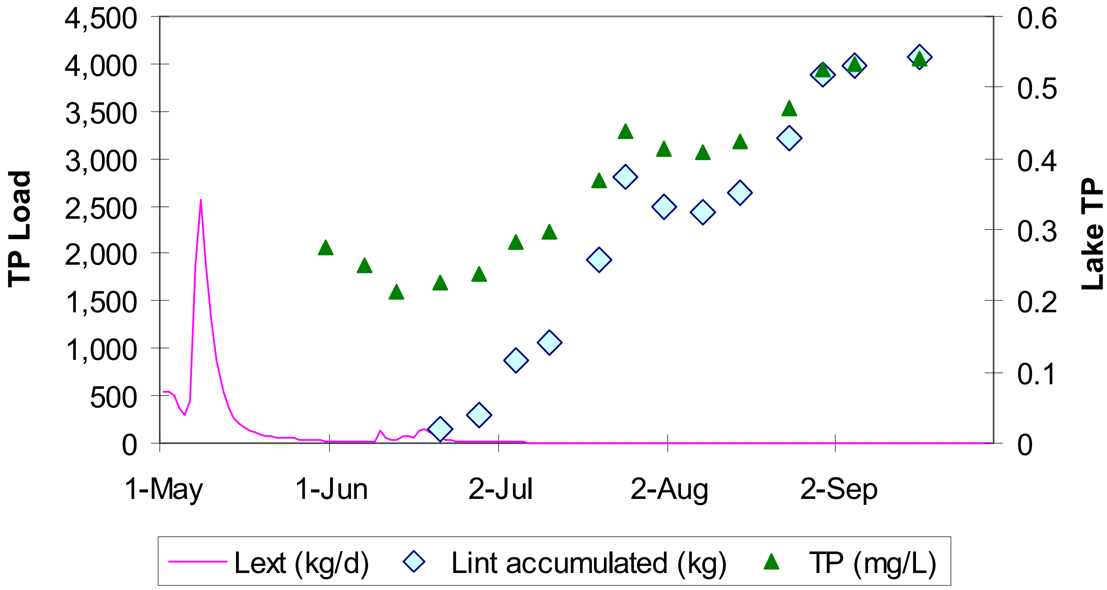

Figure 4-4. TP Load from Firesteel Creek #1 (ext. load) compared to internal accumulated load and lake TP concentration in summer 2001.

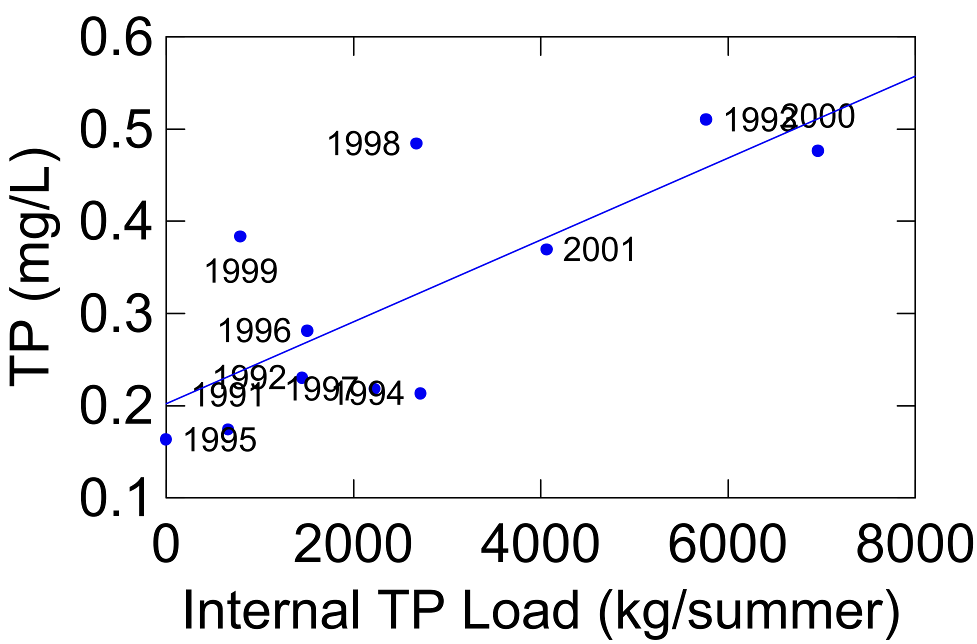

Figure 4-5. Internal load versus summer average TP.

R^2= 0.55, n=11, p< 0.01. If a high value of 0.9 mg./L TP of Sept. 26 1998 at Stn. 11 is included, internal load for 1998 would increase to 7,590 kg and the significance level would increase: R^2= 0.72, p<0.001

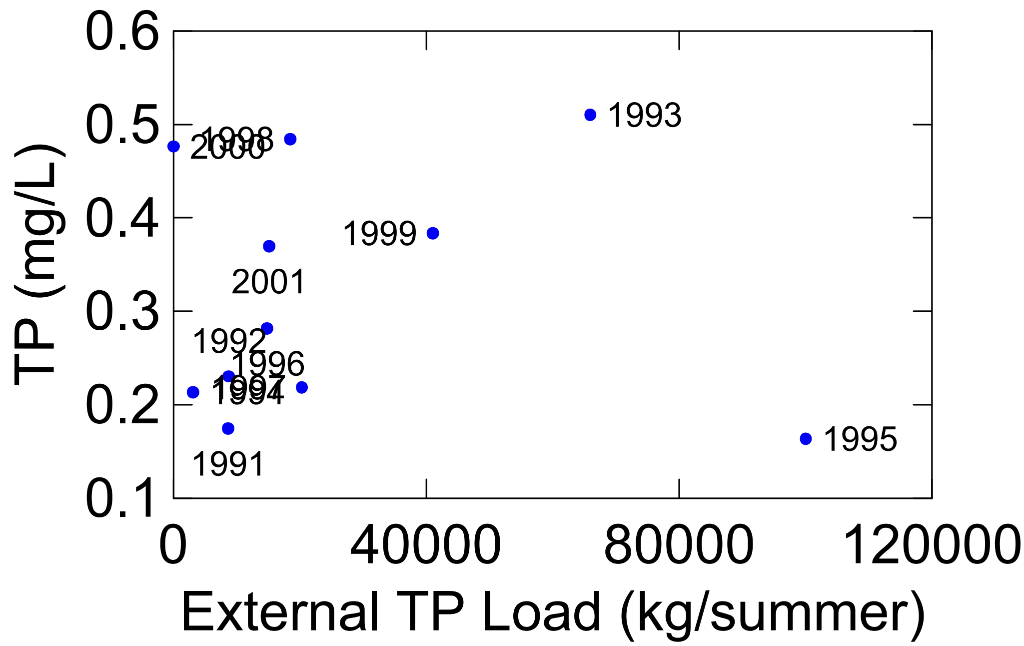

Figure 4-6. External load (May - September) versus summer average TP.

Note: Even without the 1995 value, the relationship is not significant.

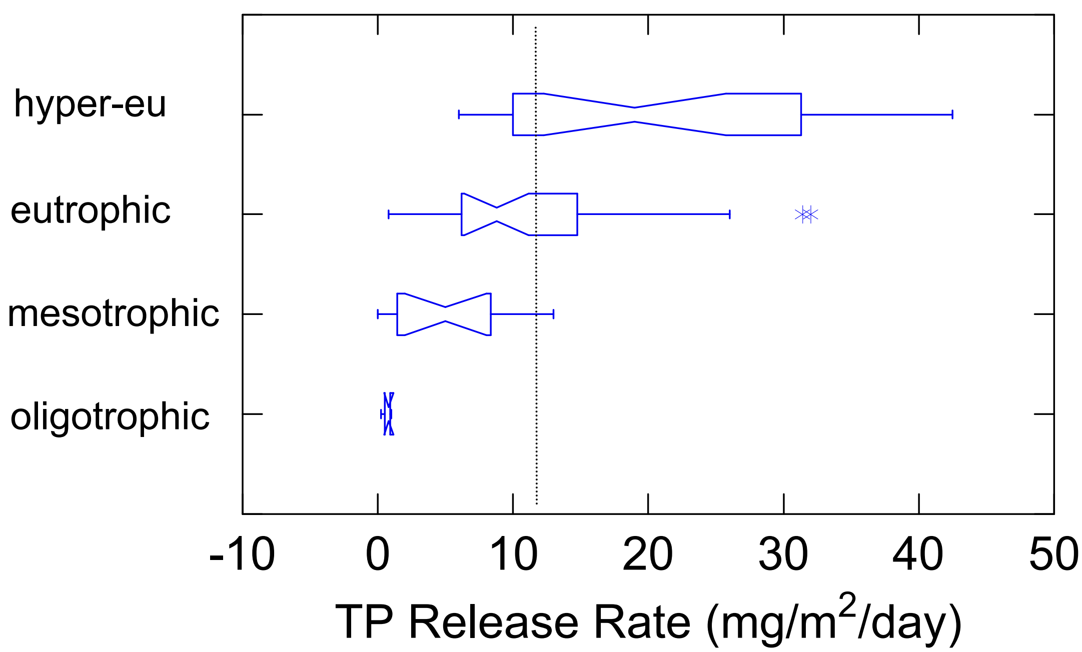

Figure 4-7. TP release rate as related to lake trophic state for 72 lakes and reservoirs

Note: Dashed line indicates calculated release rate for Lake Mitchell. Sample size is for oligotrophic 3, mesotrophic 12, eutrophic 32, and hyper-eutrophic 25.

5. Water Quality Model

A water quality model is required to predict the effects of any reductions in TP loading on TP and algal biomass concentration due to remediation efforts in Lake Mitchell.

5.1. Prediction of Summer Average TP

Using the approach of Nürnberg and LaZerte (2001) and Nürnberg (1998), a TP model was developed to predict summer average TP concentration from external and internal TP loading. Since summer TP is the most important season with respect to water quality, and since there were many data available in the May to September season, but virtually none for the rest of the year, no attempt was made to model annual average whole lake TP. Instead, the models for polymictic lakes were used and the retention or sedimentation term calibrated to best reflect the observed data.

A settling velocity (v) of 25 m/yr in the retention model of $R=v/(v+q_s)$, yielded the best predictions (Table 5-1). The comparison of predictions based solely on external load with those that include internal load revealed that internal load is especially important in dry years, when external loads are low. The model does not predict well at extreme climatic conditions and exclusion of the wettest year 1995 and the driest year 2000 of the 11-year period, improves predictions. Using summer external loading instead of annual and re-calibration of v does not improve predictability.

Table 5-1. Modeling results to predict summer average TP

				Predicted			Observed	
	Ext Load	Int. Load	Water Load	Retention	TP[1]	TP[2]	TP	Residual[3]
Year	kg/yr	kg/summer	q_s, m/yr	R	Ext only, mg/L	Ext & Int, mg/L	mg/L	
1991	9,874	662	6.0	0.81	0.108	0.131	0.174	-25%
1992	10,406	1,455	6.9	0.78	0.107	0.149	0.230	-35%
1993	81,804	5,768	37.4	0.40	0.403	0.441	0.510	-14%
1994	18,531	2,719	9.1	0.73	0.175	0.235	0.213	11%
1995	148,034	0	59.4	0.30	0.531	0.531	0.163	227%
1996	34,810	1,507	17.0	0.59	0.255	0.274	0.281	-3%
1997	101,264	2,227	43.3	0.37	0.464	0.477	0.218	119%
1998	30,142	2,675	15.8	0.61	0.231	0.268	0.484	-45%
1999	66,065	792	30.3	0.45	0.376	0.382	0.383	0%
2000	806	6,963	1.6	0.94	0.010	0.775	0.476	63%
2001	86,179	4,066	38.8	0.39	0.442	0.470	0.369	27%
1991-2001	53,447	2,621	24.2	0.58	0.282	0.376	0.318	30%*

See Note next page

Note: According to Nürnberg and LaZerte 2001:

[1] TP= Ext. Load/q_s x (1-R)

[2] TP= *average of* {(Ext. Load + Int. Load)/q_s x (1-R)} *and* {Ext. Load /q_s x (1-R) + int. Load/q_s}

[3]Residual is (predicted-observed)/predicted, where the predicted value is the TP value based on the inclusion of external and internal load. If the extreme wet and dry years are excluded (1995 and 2000), the average deviation is only 4%.

5.2. Prediction of Algal Abundance

To predict algal bloom frequency as a consequence of lake TP concentration a series of predictive equations have to be employed, since no model is known that combines TP and bloom frequency directly (Figure 5-1).

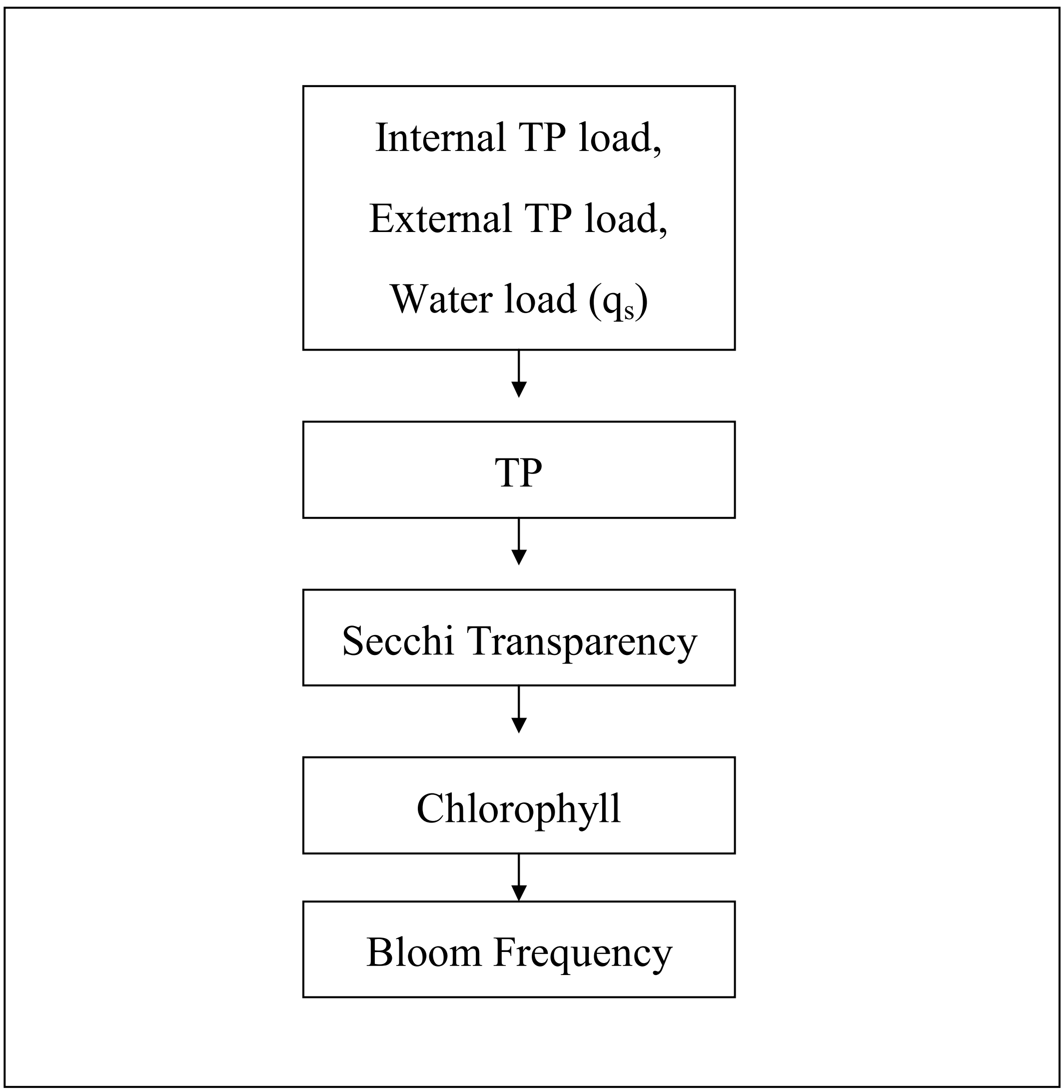

Figure 5-1. Schematic of the prediction sequence

5.2.1. Prediction of Secchi Disk Transparency from TP

The algal biomass indicator that is available for the most years and locations in Lake Mitchell is Secchi transparency. Section 3.3 demonstrates that Secchi disk transparency is a simple indicator of algal biomass, as well as lake water transparency and clarity.

As discussed in Section 3.4, models exist for world-wide lakes to predict Secchi as a function of summer average TP and Color (Nürnberg 1996, Equation 3). The model is based on 82 worldwide lakes (R^2=0.70, $p<0.0001$, Nürnberg 1996) and was used to predict Secchi transparency (m) from summer average TP (where units are in µg/L) and color.

Secchi Disk Transparency = 1.11 - 0.275 log (TP) - 0.325 log (color) Equation 3

When such a model is applied to whole lake averages in Lake Mitchell, Secchi disk depth is underestimated, which is consistent with the comparably low algae biomass in the deep section. However, summer 2001 Secchi in the upstream station (Stn. 12A, 0.8 mile) was more adequately predicted (predicted Secchi 0.79 m vs. observed 0.91 m for TP of 0.376 mg/L). The correctly predicted value should occur at mile 0.63 downstream of the inflow, based on the relationship of Figure 3-9 (n= 77, R^2= 0.39, Secchi = 0.49 (0.16) + 0.475 (0.068) miles, with standard errors in parentheses). Therefore, this model was used in conjunction with Equation 3 to predict an estimate of Secchi for changing TP values for the upstream location at mile 0.6.

This model is further supported by TP and Secchi data from mile 0 at the inflow (Station 11) of summer 2000. That summer was the driest of the last 11 years and had the lowest external load (Table 5-1). Most of the observed TP concentration must have originated from the sediment as internal load. The regression of log-transformed Secchi on TP was significant (R^2= 0.86, n=5, $p<0.02$, Figure 5-2) and the Secchi values predicted by the above model were close to observed after adjustment for the "0" location (Table 5-2). This result suggests that the model is applicable to dry years, a situation that is the most critical in need of remediation.

Table 5-2. Application of model to summer 2000 observed TP and Secchi data.

	TP (mg/L)	Secchi (m)		
Location (mile)	0.0	0.6	0.0	0.0
Stn.11	obs TP	Predicted	Predicted	Observed
22-May-00	0.210	0.93	0.57	0.65
19-Jun-00	0.220	0.92	0.57	0.90
18-Jul-00	0.650	0.68	0.42	0.30
27-Aug-00	0.770	0.65	0.40	0.30
23-Sep-00	0.530	0.72	0.44	0.50

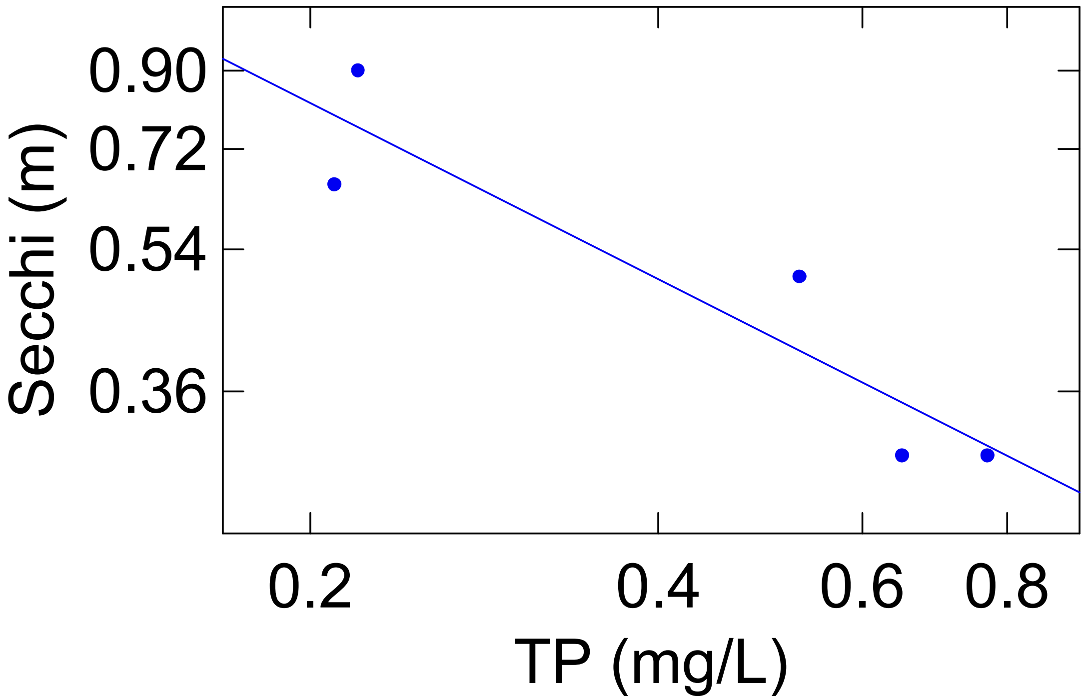

Figure 5-2. Station 11 (Mile 0) individual Secchi versus TP values for summer 2000.

5.2.2. Prediction of Chlorophyll from Secchi Disk Transparency

Because there doesn't exist a good relationship between chlorophyll and TP in Lake Mitchell, chlorophyll was predicted from Secchi disk transparency. To predict chlorophyll from Secchi, the model developed in Section 3.3.3 (Figure 3-11) was used, that predicts chlorophyll averages from Secchi averages in Lake Mitchell (R^2=0.92, n=5, p <0.01).

Chlorophyll = 61.16 (7.39) - 35.84 Secchi **Equation 4**

5.2.3. Predicting Frequency of Algal Blooms

When chlorophyll summer average concentration is above 10 µg/L, nuisance algal blooms of 30 µg/L or more can be expected (Walmsley 1984). Based on U.S. Army Corps of Engineer reservoirs (258 station-years), South African reservoirs (34 station-years), and Vermont Lakes (148 station-years), Walker (1984) developed a model that predicts the frequency (% of summer) of nuisance algal blooms (at chlorophyll concentration above 30 µg/L) from summer average chlorophyll concentration (Chl_{summer}).

Bloom Frequency (%) = 1.83 x (Chl_{summer} - 10) **Equation 5**

This model was used to predict nuisance bloom frequency in Lake Mitchell.

5.3. Results

These models (Equation 2 to 5) were used to predict algae bloom frequency from average summer TP at the upstream location, 0.6 miles downstream of the inflow. The additional influence of water flow (annual water load) on Secchi transparency (Figure 3-14) is not considered here. Climatic conditions cannot be controlled, but it should be kept in mind that dry years will likely result in worse conditions, and wet years may have improved water quality.

Current conditions and predictions with respect to TP are summarized in Table 5-3 and shown in Figure 5-3. Over the long-term and during the study period algal bloom frequency of about 50% is predicted. If average reservoir TP concentrations are decreased due to remediation efforts lower frequencies are predicted.

The model results are not linear with respect to TP reductions, and a 50% decrease in TP from 0.4 to 0.2 mg/L leads only to a 20% decrease in chlorophyll and an absolute decrease of 10% bloom frequency. The response increases the lower the beginning TP concentration is. Such performance is reasonable because it may take substantial TP decreases for phosphorus limitation to occur in such a way that it noticeably affects algal biomass.

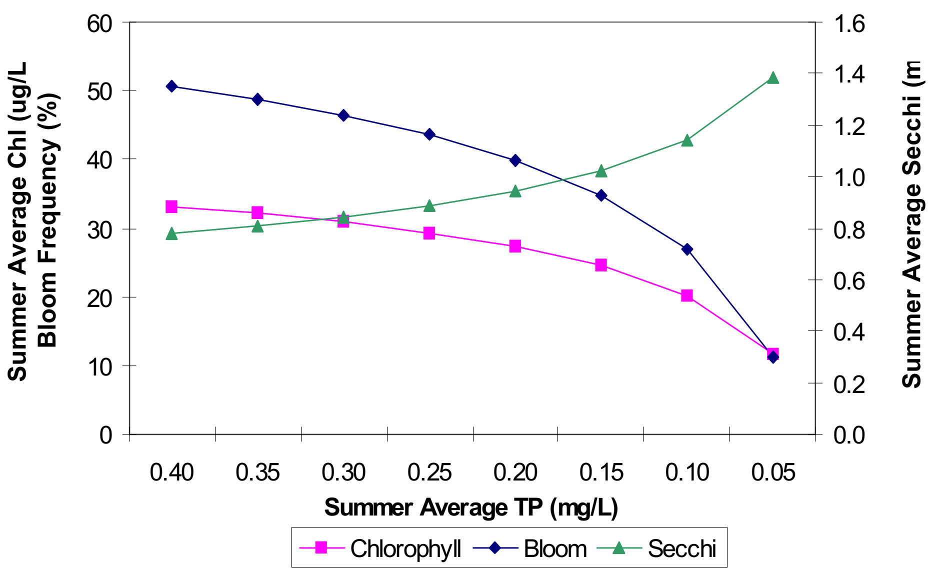

Figure 5-3. Restoration scenarios for algal biomass changes at mile 0.6 in response to TP reduction

Table 5-3. Predictions of summer average algal biomass measures for 0.6 and 1.6 miles (mid-reservoir) downstream of the inflow.

Location:		0.6 miles			1.6 miles		
	TP	Secchi	Chlorophyll	Bloom	Secchi	Chlorophyll	Bloom
	mg/L	m	µg/L	%	m	µg/L	%
2001	0.369	0.80	32.55	49.6	1.29	15.00	17.4
1991-2001	0.318	0.83	31.36	47.4	1.34	13.07	13.9
	0.400	0.78	33.17	50.7	1.26	16.00	19.3
	0.350	0.81	32.12	48.8	1.31	14.31	16.2
	0.300	0.85	30.87	46.5	1.36	12.28	12.5
	0.250	0.89	29.31	43.6	1.43	9.77	7.9
	0.200	0.94	27.29	39.9	1.52	6.52	1.9
	0.150	1.02	24.51	34.8	1.65	2.02	0
	0.100	1.14	20.18	26.9	1.84	Low*	0
	0.050	1.38	11.58	11.2	2.23	Low*	0

Note: All variables are summer (May to September) averages

*At "Low" chlorophyll concentrations negative values are predicted.

According to the relationship of Figure 3-9, Secchi improves downstream and consequently chlorophyll concentration and the bloom frequencies can be expected to decrease as well. Therefore, even though blooms may be high in the upper reservoir, they should be almost non-existent at central and lower parts. Table 5-3 can serve to indicate how much TP should be precipitated by an alum treatment to achieve acceptable conditions. If, for example, a bloom frequency of 40% at the upstream location is deemed acceptable, average summer TP concentration should be reduced by more than a third to 0.200 µg/L.

5.4. Scenarios

Several scenarios were modeled to predict the potential decrease in average summer TP as a result of a reduction of the external surface loading from Firesteel Creek (Table 5-4). The diagnostic-feasibility study (Stueven and Scholtes 1997) indicated that a 50% reduction in phosphorus delivery to Lake Mitchell should be achieved in the year 2015, by eliminating the soluble phosphorus export from 116 identified animal feeding areas. Three different scenarios of internal load are modeled as well, since internal load varies unpredictably from year to year but is expected to decrease in response to external load reductions.

Table 5-4. TP predictions for changes in internal and external load

				Predicted		
Percentile	Ext Load kg/yr	Int Load kg/yr	Water Load m/yr	Retention	TP, mg/L Ext only	TP, mg/L Ext & Int.
Base scenario (1979 - 2001):						
0.1	713	2.900	1.687	0.94	0.009	0.326
0.25	4.469	2.900	3.351	0.88	0.053	0.217
0.5	18.531	2.900	9.203	0.73	0.176	0.241
0.75	73.934	2.900	33.584	0.43	0.395	0.416
0.9	101.416	2.900	43.183	0.37	0.458	0.475
average	38.560	2.900	18.435	0.58	0.289	0.326
Internal Load changed (doubled and halved):						
0.1	713	5.800	1.687	0.94	0.009	0.643
0.25	4.469	5.800	3.351	0.88	0.053	0.381
0.5	18.531	5.800	9.203	0.73	0.176	0.305
0.75	73.934	5.800	33.584	0.43	0.395	0.437
0.9	101.416	5.800	43.183	0.37	0.458	0.491
0.1	713	1.450	1.687	0.94	0.009	0.168
0.25	4.469	1.450	3.351	0.88	0.053	0.135
0.5	18.531	1.450	9.203	0.73	0.176	0.208
0.75	73.934	1.450	33.584	0.43	0.395	0.405
0.9	101.416	1.450	43.183	0.37	0.458	0.466
External surface Load decreased by 50% and three scenarios for internal load:						
0.1	656	2.900	1.687	0.94	0.009	0.325
0.25	2.534	2.900	3.351	0.88	0.030	0.194
0.5	9.566	2.900	9.203	0.73	0.091	0.156
0.75	37.729	2.900	33.584	0.43	0.201	0.223
0.9	51.707	2.900	43.183	0.37	0.233	0.250
0.1	656	5.800	1.687	0.94	0.009	0.642
0.25	2.534	5.800	3.351	0.88	0.030	0.358
0.5	9.566	5.800	9.203	0.73	0.091	0.220
0.75	37.729	5.800	33.584	0.43	0.201	0.244
0.9	51.707	5.800	43.183	0.37	0.233	0.267
0.1	656	1.450	1.687	0.94	0.009	0.167
0.25	2.534	1.450	3.351	0.88	0.030	0.112
0.5	9.566	1.450	9.203	0.73	0.091	0.123
0.75	37.729	1.450	33.584	0.43	0.201	0.212
0.9	51,707	1,450	43.183	0.37	0.233	0.242

Note: Predictions based on model described in Table 5-1.

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Appendix A. Hypsographic information

Provided by City of Mitchell

Gage ft	Elevation ft	Area Acres	Area km^2	Volume 10^6 gallons	Volume $10^6 m^3$
0	63	790	3.197	3,565	13.494
1	62	755	3.055	3,285	12.434
2	61	725	2.934	3,020	11.431
3	60	700	2.833	2,770	10.484
4	59	680	2.752	2,535	9.595
5	58	660	2.671	2,315	8.762
6	57	635	2.570	2,105	7.967
7	56	610	2.469	1,905	7.210
8	55	585	2.367	1,715	6.491
9	54	560	2.266	1,535	5.810
10	53	525	2.125	1,365	5.167
11	52	495	2.003	1,200	4.542
12	51	465	1.882	1,045	3.955
13	50	430	1.740	895	3.388
14	49	400	1.619	765	2.896
15	48	365	1.477	645	2.441
16	47	335	1.356	535	2.025
17	46	300	1.214	435	1.646
18	45	265	1.072	340	1.287
19	44	235	0.951	250	0.946
20	43	205	0.830	165	0.625
21	42	175	0.708	105	0.397
22	41	150	0.607	50	0.189
23	40	130	0.526	0	0.000

Appendix B. Lake Level Variation with Time

Year	Period	Lake level (ft)	Volume $10^6 m^3$	Area $10^6 m^2$
1976	Mar-Dec	-7.65	6.743	2.403
1977	Jan - Aug	-3.24	10.484	2.833
1978	Mar	0.05	13.550	3.200
1979	Mar-Dec	-1.65	11.782	2.977
1980	Jan - Dec	-2.50	10.958	2.883
1981	Jan - Dec	-4.76	8.962	2.690
1982	Jan - Dec	-1.79	11.782	2.977
1983	Jan - Nov	-0.72	12.826	3.108
1984	Jan - Dec	0.08	13.550	3.200
1985	Jan - Dec	-0.50	12.964	3.126
1986	Jan - Sep	0.26	13.700	3.250
1987	Mar - Dec	-0.81	12.646	3.084
1988	Feb - Dec	-2.01	11.431	2.934
1989	Jan - Dec	-2.50	10.958	2.883
1990	Jan - Nov	-2.72	10.749	2.861
1991	Feb - Oct	-2.05	11.431	2.934
1992	Jan - Dec	-1.23	12.434	3.055
1993	Jan - Dec	0.27	13.700	3.250
1994	Jan - Dec	-0.65	12.826	3.108
1995	Feb - Nov	0.59	14.200	3.300
1996	Feb - Dec	0.22	13.700	3.250
1997	Jan - Dec	-0.12	13.494	3.197
1998	Feb - Dec	0.00	13.494	3.197
1999	Jan - Dec	-0.33	13.200	3.179
2000	Jan - Sep	-1.08	12.434	3.055
2001	Apr - Oct	-1.00	12.434	3.055

Appendix C. 2001 Data Collected for the Study

Date	Stn	Secchi m	TP mg/L	Chl µg/L	Chl_un µg/L
31-May-01	12A	1.00	0.250		4.74
31-May-01	12	1.30	0.294	1.10	2.27
31-May-01	13A	2.40	0.283	0.20	0.70
7-Jun-01	12A	0.80	0.230	4.01	20.17
7-Jun-01	12	1.00	0.247	-2.80	6.56
7-Jun-01	13A	1.00	0.272	1.00	6.68
13-Jun-01	12A	0.80	0.213	3.20	15.92
13-Jun-01	12	1.00	0.205	4.51	15.80
13-Jun-01	12B	1.20			
13-Jun-01	13A	1.50	0.222	6.30	15.10
21-Jun-01	12A	0.70	0.229		
21-Jun-01	12	0.80	0.212	12.42	51.93
21-Jun-01	12B	1.00			
21-Jun-01	13A	1.00	0.233	10.22	46.70
28-Jun-01	12A	0.70	0.258	23.83	49.71
28-Jun-01	12	1.00	0.225	9.11	17.53
28-Jun-01	12B	1.40			
28-Jun-01	13A	2.00	0.230	-0.20	2.06
30-Jun-01	12A	0.85			
30-Jun-01	12	1.50			
30-Jun-01	12B	1.30			
30-Jun-01	13	2.70			
30-Jun-01	13A	2.90			
5-Jul-01	12A	0.60	0.320	49.26	109.97
5-Jul-01	12	1.20	0.263	10.81	21.04
5-Jul-01	12B	1.40			
5-Jul-01	13	1.40	0.267	5.81	6.06
5-Jul-01	13A	1.50			
11-Jul-01	12A	0.30	0.364	71.79	153.45
11-Jul-01	12	1.30	0.253	10.01	26.24
11-Jul-01	12B	1.20			
11-Jul-01	13	1.50	0.278	8.51	15.39

Date	Stn	Secchi	TP	Chl	Chl_un
		m	mg/L	µg/L	µg/L
11-Jul-01	13A	1.40			
20-Jul-01	12A	1.40	0.400	7.61	19.10
20-Jul-01	12	1.70	0.372	3.20	6.48
20-Jul-01	12B	3.10			
20-Jul-01	13	3.50	0.336	1.20	3.42
20-Jul-01	13A	3.30			
25-Jul-01	12A	0.60	0.490	32.24	81.92
25-Jul-01	12	1.20	0.428	13.82	24.09
25-Jul-01	12B	1.70			
25-Jul-01	13	2.70	0.399	2.60	9.57
25-Jul-01	13A	2.80			
1-Aug-01	12A	0.90	0.397	13.92	48.63
1-Aug-01	12	0.90	0.416	15.22	34.53
1-Aug-01	12B	1.20			
1-Aug-01	13	1.60	0.428	3.90	9.12
1-Aug-01	13A	1.50			
8-Aug-01	12A	0.80	0.399	15.12	23.51
8-Aug-01	12	0.70	0.419	14.22	30.40
8-Aug-01	12B	0.90			
8-Aug-01	13	1.20	0.410	10.01	37.83
8-Aug-01	13A	1.60			
15-Aug-01	12A	0.90	0.439	19.22	41.46
15-Aug-01	12	0.90	0.436	4.91	29.00
15-Aug-01	12B	1.00			
15-Aug-01	13	1.10	0.400	7.51	29.78
15-Aug-01	13A	1.20			
24-Aug-01	12A	1.10	0.492	30.74	44.43
24-Aug-01	12	1.40	0.478		
24-Aug-01	12B	1.80			
24-Aug-01	13	2.30	0.445	6.31	8.75
24-Aug-01	13A	2.50			
30-Aug-01	12A	0.90	0.511	54.97	71.73
30-Aug-01	12	1.00	0.539	47.86	56.60

Date	Stn	Secchi m	TP mg/L	Chl µg/L	Chl_un µg/L
30-Aug-01	12B	1.30			
30-Aug-01	13	1.70	0.526	15.92	21.08
30-Aug-01	13A	2.50			
5-Sep-01	12A	1.00	0.506	23.63	36.75
5-Sep-01	12	1.10	0.527	26.43	30.03
5-Sep-01	12B	1.40			
5-Sep-01	13	2.00	0.565	20.43	32.63
5-Sep-01	13A	2.60			
17-Sep-01	12A	1.70	0.513	9.01	15.30
17-Sep-01	12	1.60	0.552	23.43	63.11
17-Sep-01	12B	3.90			
17-Sep-01	13	2.70	0.556		
17-Sep-01	13A	4.10			

Chl, chlorophyll

Chl_un. Uncorrected chlorophyll, i.e., not corrected for pheophytin

In addition, true color was estimated on three occasions (measured in units of platinum cobalt):

1-Aug-01, Station 13: 50

30 Aug-01, Station 12: 35

30 Aug-01, Station 13: 35

Temperature and dissolved oxygen profiles

			Site 13A		Site 12		Site 12A	
Date	**Depth (m)**	**Depth (ft)**	**DO (mg/L)**	**Temp. (°C)**	**DO (mg/L)**	**Temp. (°C)**	**DO (mg/L)**	**Temp. (°C)**
10-May	0	0.0	9.4	16.2	8.7	16.1		
	1	3.3	9.5	16.2	8.4	16.1		
	2	6.6	9.5	16.2	8.3	16.1		
	3	9.9	9.4	16.2	8.1	16.2		
	4	13.2	9.6	16.1	8.4	16.1		
	5	16.4	9.6	16.1				
	6	19.7	7.5	15.1				
	7	23.0	6.5	14.7				
					7.9	19.7	8.2	20.1
31-May	0	0.0	8.0	19.2	7.9	19.3	8.0	19.9
	1	3.3	8.0	18.9	7.5	18.0	6.8	17.8
	2	6.6	7.9	17.4	7.5	17.6	5.4	17.7
	3	9.9	7.4	16.9	7.1	17.3		
	4	13.2	7.5	16.7				
	5	16.4	6.8	16.3				
	6	19.7	6.4	15.9				
7-Jun	0	0.0	7.7	20.2	8.1	19.6	9.8	19.4
	1	3.3	7.6	18.7	7.5	18.2	8.4	18.5
	2	6.6	7.0	18.4	7.5	18.0	7.9	18.1
	3	9.9	7.4	18.3	7.3	17.9	8.3	18.1
	4	13.2	7.0	17.6	7.1	17.8		
	5	16.4	6.9	17.4				
	6	19.7	6.7	17.3				
13-Jun	0	0.0	9.3	21.9	8.6	21.9	8.5	22.2
	1	3.3	8.8	21.6	8.6	21.8	8.3	22.0
	2	6.6	8.6	21.4	8.4	21.7	8.3	22.0
	3	9.9	8.4	21.2	8.6	21.6	8.0	21.8
	4	13.2	8.2	21.0	8.0	21.4		
	5	16.4	6.1	19.7				
	6	19.7	3.9	18.2				
21-Jun	0	0.0	15.8	23.5	14.9	22.8	14.8	23.0
	1	3.3	15.9	23.5	14.7	22.8	13.8	22.9
	2	6.6	15.7	23.5	14.8	22.8	8.3	22.2
	3	9.9	15.8	23.4	14.8	22.8	5.6	22.0
	4	13.2	15.8	23.4	8.6	22.0		
	5	16.4	15.8	23.4				
	6	19.7	7.9	22.0				
28-Jun	0	0.0	6.7	24.2	8.7	25.4	8.4	25.4
	1	3.3	6.7	24.2	7.6	25.3	8.4	25.4
	2	6.6	6.8	24.1	7.5	25.2	8.4	25.4
	3	9.9	6.8	24.0	7.5	25.1	8.1	25.3
	4	13.2	6.7	24.0	7.4	25.0		
	5	16.4	6.8	24.0				
	6	19.7	6.8	23.9				

Temperature and dissolved oxygen profiles, continued

			Site 13A		Site 13		Site 12B		Site 12		Site 12A	
Date	Depth (m)	Depth (ft)	DO (mg/L)	Temp. (°C)	DO (mg/L)	Temp. (°C)	DO (mg/L)	Temp. (°C)	DO (mg/L)	Temp. (°C)	DO (mg/L)	Temp. (°C)
30-Jun	0	0.0	6.0	24.7	6.0	24.8	7.2	25.6	7.4	26.0	6.9	26.4
	1	3.3	5.9	24.7			6.9	25.5	7.2	26.0	6.8	26.4
	2	6.6	5.7	24.6	6.0	24.7	6.2	25.3	6.9	25.9	6.3	25.9
	3	9.9	5.8	24.5			5.9	25.1	6.4	25.6	6.1	25.8
	3.7	12.2							4.9	25.0		
	4	13.2	5.8	24.5	5.7	24.6	5.8	24.9			5.0	25.7
	5	16.4	5.5	24.3	5.4	24.3	4.5	24.2			3.5	25.7
	5.5	18.1					2.7	23.8				
	6	19.7	4.7	24.1	3.5	23.6						
	6.8	22.4	3.1	24.1		23.3						
	7	23.0			2.6							
5-Jul	0	0.0			7.5	25.7			8.4	25.9	11.3	26.2
	1	3.3			7.6	25.6			8.2	25.9	10.8	26.2
	2	6.6			7.5	25.4			8.3	25.8	10.8	26.1
	3	9.9			5.9	24.7			8.4	25.7	10.7	25.9
	4	13.2			3.7	24.0			5.0	24.5		
	5	16.4			3.0	23.7			10.1	26.8	11.1	27.0
11-Jul	0	0.0			8.4	26.1			10.2	26.8	10.3	26.9
	1	3.3			8.1	26.1			9.3	26.6	8.3	26.7
	2	6.6			7.8	26.0			9.3	26.6		
	3	9.9			7.3	25.9			1.4	25.2		
	4	13.2			2.9	24.3						
	5	16.4			1.3	23.9						
20-Jul	0	0.0	6.3	26.8	6.5	27.0	6.0	27.7	5.3	28.2	5.1	28.4
	1	3.3							5.2	28.2	4.8	28.4
	1.5	4.9									4.5	28.4
	2	6.6	6.2	26.7	6.2	27.0	5.9	27.6	5.2	28.1		
	3	9.9					6.1	27.5	5.8	27.8		
	4	13.2	5.0	26.0	6.1	26.8	6.4	27.2	4.8	27.6		
	4.5	14.8							0.2	27.3		
	5	16.4	3.7	25.4	3.4	25.2	2.3	25.1				
	6	19.7	1.4	24.3	1.1	24.2						
	7	23.0	0.1	22.3								
25-Jul	0	0.0			7.8	28.0	8.7	28.2	10.5	28.2		
	1	3.3			7.4	28.0			8.7	28.2	10.2	28.2
	2	6.6			7.5	27.9			8.5	27.9	10.1	28.2
	3	9.9			7.3	27.9			7.2	27.7	7.9	28.1
	4	13.2			7.1	27.5			6.7	27.4		
	4.5	14.8							4.2	27.3		
	5	16.4			4.1	26.7						
	6	19.7			0.2	25.0						
1-Aug	0	0.0			6.8	27.5			7.6	27.9	8.0	28.1
	1	3.3			6.7	27.4			7.4	27.9	7.7	28.1
	2	6.6			6.7	27.3			7.3	27.8	7.5	28.0
	3	9.9			6.5	27.2			7.2	27.7	4.7	27.8
	4	13.2			6.4	27.1			6.0	27.5		
	4.5	14.8							4.0	27.5		
	5	16.4			6.1	26.9						
	6	19.7			3.6	26.3						
	6.5	21.4			2.0	26.3						

Temperature and dissolved oxygen profiles, continued

			Site 13		Site 12		Site 12A	
Date	Depth (m)	Depth (ft)	DO (mg/L)	Temp. (°C)	DO (mg/L)	Temp. (°C)	DO (mg/L)	Temp. (°C)
8-Aug	0	0.0	10.3	28.9	10.3	29.7	10.5	30.0
	1	3.3					9.9	30.0
	2	6.6	8.4	28.5	9.9	29.4	9.6	29.6
	3	9.9			9.8	29.2	5.8	29.4
	4	13.2	6.0	28.0	6.3	29.0		
	4.5	14.8			6.4	29.0		
	5	16.4	3.8	27.7				
	6	19.7	1.1	26.8				
	6.5	21.4	0.1	26.7				
15-Aug	0	0.0	8.1	24.9	8.7	24.4	8.7	24.1
	1	3.3					8.4	24.1
	2	6.6	7.6	24.8	8.2	24.4	8.3	24.0
	2.5	8.2					6.8	23.9
	3	9.9			8.0	24.2		
	4	13.2	7.7	24.8	7.3	24.2		
	4.5	14.8			6.0	24.2		
	5	16.4	7.5	24.7				
	6	19.7	6.1	24.7				
	6.5	21.4	5.1	24.7				
24-Aug	0	0.0	7.9	25.4	8.3	25.9	9.4	26.2
	1	3.3					9.3	26.1
	2	6.6	7.7	25.1	8.1	25.7	9.2	26.1
	3	9.9			7.7	25.5	6.9	26.1
	4	13.2	5.7	24.3	4.7	25.2		
	4.5	14.8			3.7	25.2		
	5	16.4	4.9	24.1				
	6	19.7	0.0	23.9				
30-Aug	0	0.0	7.4	25.4	9.2	25.1	11.1	25.2
	1	3.3					10.3	25.1
	2	6.6	6.1	25.0	7.6	24.5	8.5	24.6
	2.5	8.2					7.7	24.6
	3	9.9			7.7	24.4		
	4	13.2	5.7	24.7	7.1	24.4		
	4.5	14.8						
	5	16.4	6.0	24.7				
	5.5	18.1	5.6	24.6				
17-Sep	0	0.0	5.9	19.5	7.8	18.8	7.1	18.2
	1	3.3			7.6	18.7	7.0	18.0
	2	6.6	5.6	19.3	7.1	18.5	6.3	18.0
	3	9.9			7.2	18.5	5.9	17.9
	4	13.2	5.8	19.2				
	5	16.4	5.5	19.2				
	6	19.7	0.7	19.0				

Appendix D. Lake Data for 1991 to 1999

Data Source	Date	Station	Secchi m	TP mg/L	TDP mg/L	Chl µg/L
Statewide Lake Assessment	20-Jun-91	All*	1.16	0.150	0.110	27.5
Statewide Lake Assessment	20-Jul-91	All*	0.81	0.165	0.100	20.7
Statewide Lake Assessment	19-Aug-91	All*	0.98	0.208	0.145	22.7
Statewide Lake Assessment	11-Jun-92	All*	1.96	0.280	0.042	6.9
Statewide Lake Assessment	15-Jul-92	All*	0.63	0.165	0.080	50.8
Statewide Lake Assessment	28-Jul-92	All*	0.61	0.193		38.9
Statewide Lake Assessment	26-Aug-92	All*	0.41	0.282	0.186	24.1
Statewide Lake Assessment	12-Jun-93	All*	1.57	0.199	0.142	10.6
Statewide Lake Assessment	20-Jul-93	All*	1.13	0.653	0.560	14.0
Statewide Lake Assessment	18-Aug-93	All*	1.49	0.620	0.560	26.9
Statewide Lake Assessment	11-Jun-94	All*	1.44	0.160	0.130	
Statewide Lake Assessment	13-Jul-94	All*	1.51	0.119	0.097	
Statewide Lake Assessment	13-Aug-94	All*	1.20	0.372		
Statewide Lake Assessment	13-Jun-95	All*	0.58	0.270	0.228	
Statewide Lake Assessment	12-Jul-95	All*	1.58	0.069	0.039	
Statewide Lake Assessment	11-Aug-95	All*	2.29	0.149	0.124	
DENR 1997	02-Feb-93	12		0.096	0.096	
DENR 1997	02-Feb-93	13		0.106	0.103	
DENR 1997	28-Jun-93	12	0.61	0.501	0.378	
DENR 1997	28-Jun-93	13	1.22	0.299	0.209	
DENR 1997	10-Aug-93	12	1.01	0.684	0.611	30.8
DENR 1997	10-Aug-93	13	0.91	0.674	0.611	20.1
DENR 1997	08-Nov-93	12	4.57	0.266	0.246	
DENR 1997	08-Nov-93	13	4.57	0.279	0.242	
DENR 1997	13-Jun-94	12	0.91	0.346	0.153	
DENR 1997	13-Jun-94	13	1.68	0.206	0.140	
DENR 1997	06-Jul-94	12	1.37	0.140	0.133	11.4
DENR 1997	06-Jul-94	13	1.83	0.133	0.120	4.2
Bob Tatina	10-Jun-96	13A	2.35			
Bob Tatina	10-Jul-96	13A	0.75			
Bob Tatina	14-Aug-96	13A	1.3	0.265		
Bob Tatina	21-Sep-96	13A	0.9	0.320		

Data Source	Date	Station	Secchi m	TP mg/L	TDP mg/L	Chl µg/L
Bob Tatina	10-Oct-96	13A	1.3	0.165		
Bob Tatina	30-Dec-96	13A	4			
Bob Tatina	1-Feb-97	13A	3.3	0.435		
Bob Tatina	6-Mar-97	13A	4.3	0.420		
Bob Tatina	5-Jun-97	13A	4	0.175		
Bob Tatina	15-Jul-97	13A	1.5	0.085		
Bob Tatina	14-Aug-97	13A	1.3	0.340		
Bob Tatina	13-Sep-97	13A	0.7	0.230		
Bob Tatina	25-Jan-98	13A	5.4	0.430		
Bob Tatina	21-Feb-98	13A	6.2	0.130		
Bob Tatina	23-May-98	13A	1.6	0.105		
Bob Tatina	23-Jul-98	13A	1.3	0.365		
Bob Tatina	20-Aug-98	13A	1.6	0.395		
Bob Tatina	30-Jan-99	13A	3.2			

*Station: All is a composite of three stations, probably located close to Stations 12, 13, and perhaps 12A.

No entry means data not available

Appendix E. Data for the Inflow - "Under the Bridge", Stn. 11

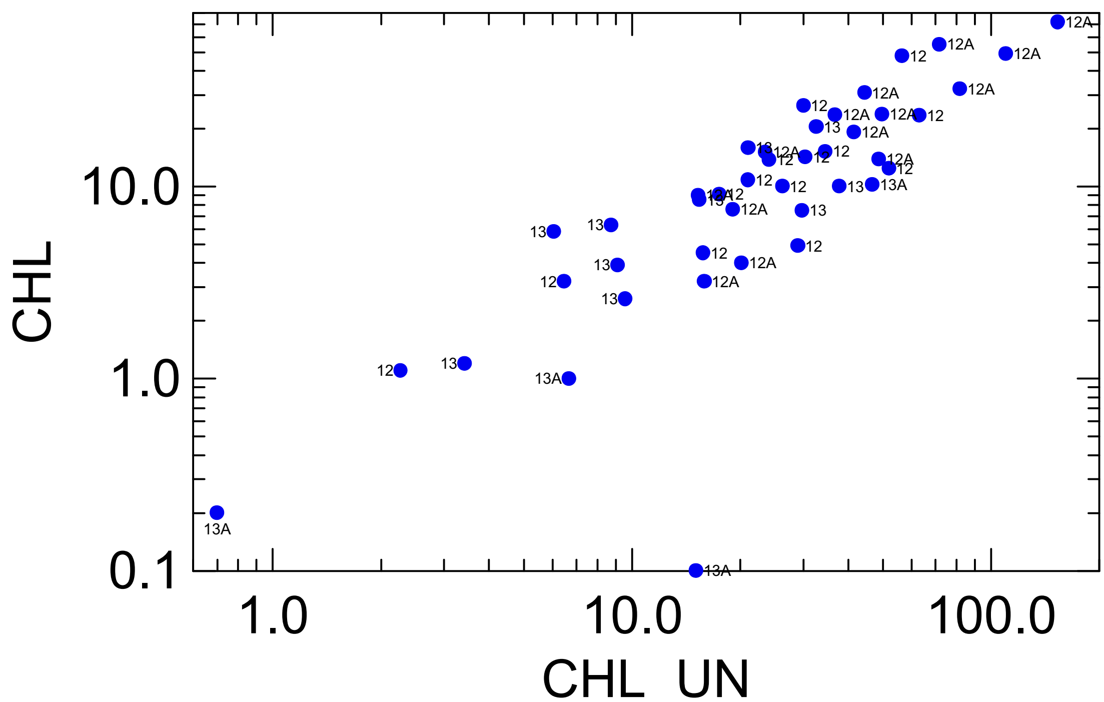
Data provided by Bob Tatina, Dakota Wesleyan University

Date	TP	Secchi	Date	TP	Secchi
	mg/L	m		mg/L	m
21-May-96	0.200	0.45	27-Mar-99	0.290	0.50
10-Jun-96	0.230	0.55	24-Apr-99	0.310	0.30
10-Jul-96	0.240	0.85	27-May-99	0.260	0.30
12-Aug-96	0.260	0.50	21-Jun-99	0.440	0.20
21-Sep-96	0.420	0.60	20-Jul-99	0.510	0.40
12-Oct-96	0.230	0.80	28-Aug-99	0.370	0.80
23-Nov-96	0.280	1.90	25-Sep-99	0.320	0.50
30-Dec-96	0.360	2.50	30-Oct-99	0.420	1.00
1-Feb-97	0.350	3.20	26-Nov-99	0.430	2.00
6-Mar-97	0.360	1.70	27-Dec-99	0.470	3.50
12-Apr-97	0.390	0.40	28-Jan-00	0.430	1.50
5-Jun-97	0.220	0.60	22-Feb-00	0.300	1.30
15-Jul-97	0.120	0.50	23-Mar-00	0.250	0.75
14-Aug-97	0.320	0.60	26-Apr-00	0.310	0.40
13-Sep-97	0.250	0.70	22-May-00	0.210	0.65
25-Oct-97	0.400	0.80	19-Jun-00	0.220	0.90
26-Nov-97	0.290	2.80	18-Jul-00	0.650	0.30
31-Dec-97	0.370	3.40	27-Aug-00	0.770	0.30
25-Jan-98	0.360	3.20	23-Sep-00	0.530	0.50
21-Feb-98	0.250	1.60	28-Oct-00	0.660	0.50
28-Mar-98	0.220	0.60	20-Dec-00	0.660	2.50
29-Apr-98	0.140	1.20	27-Jan-01	0.870	2.00
23-May-98	0.590	0.30	5-Mar-01	0.940	1.00
23-Jul-98	0.870	0.40	14-May-01	0.530	0.30
20-Aug-98	0.580	0.70	18-Jun-01	0.210	0.50
26-Sep-98	0.910*	0.65	21-Jul-01	0.490	0.55
24-Oct-98	0.550	0.70	25-Aug-01	0.500	0.80
21-Nov-98	0.540	0.30	17-Oct-01	0.440	1.55
30-Jan-99	0.330	0.90	17-Nov-01	0.390	1.10
28-Feb-99	0.370	0.70			

*High value is not included in the summer average for 1998.

Appendix F. Chlorophyll Method: Pheophytin Correction

Chlorophyll values were reported as total or uncorrected (higher values) and "normal" or pheophytin corrected. The uncorrected values include non-living algae cells as they effect the water clarity of the lake. "Normal" chlorophyll is used in comparison with other water quality variables.



Regression equation w/o outlier of June 13, 2001, Stn 13A, Lake Mitchell:

n=41, R^2= 0.85, p<0.0001

LogChl= -0.436 + 1.046 Log Chl_uncorrected

In the reported chlorophyll data, the outlier value was computed from the regression equation as 6.3 µg/L chlorophyll instead of 0.1 µg/L, for an uncorrected chlorophyll value of 15.1 µg/L.

Appendix G. Mass Balance Assumptions and Computations

Most assumptions are based on the 1993 hydrological budget by Stueven and Scholtes (1997). It should be noted, that the 1993 year was an extremely wet year with in- and outflows that flowed all summer long.

Hydrology

Firesteel Creek: The daily average flow data for Firesteel Creek of the US-GS gauging station # 06477500 (named Sampling Site #4 in Stueven) are available from the beginning of the reservoir in 1956 to the present. The flow of Firesteel Creek increases from this US-GS to the inflow at Lake Mitchell (named Sampling Site #1 in Stueven) by 7%.

Inflow: Additional surface flow from ungauged runoff and precipitation amounts to 11% of Firesteel Creek Site #1 flow.

Groundwater: Stueven estimated groundwater flow by difference of his 1993 hydrologic budget. It was estimated as 14% of total surface inflow or 18% of the Firesteel Creek Stn 1 flow. In the present study a minimum groundwater flow of 6.0 10^6 m^3/yr was assumed so that there was always some groundwater flow, even under dryer conditions (i.e. below Site #1 flow of 33 10^6 m^3). At wetter conditions Stueven's value of 18% of the Site #1 flow was applied.

Storage change: Difference between the first and last level reading of the present year was used to determine changes in volume according to morphometric information.

Outflow: Firesteel Creek Outlet or "spillway" and "pumping": Since the outflow is not gauged, outflow volume was estimated by difference of total input minus evaporation and pumping by Lake Mitchell's water plant. For evaporation a constant value of 1.8 10^6 m^3/yr was used, based on an average evaporation height of approximately 590 mm. Annual pumping rates were available for several recent years. From the earlier of these data an average rate of 3.5 10^6 m^3/yr was used for the years 1979 to 1992. Total outflow, used to compute annual water load and flushing rates then was the sum of "spillway" outflow and "pumping".

Total Phosphorus

Firesteel Creek: Available TP concentration data for several years (1993 to 2001) suggest a correlation between flow rate and TP concentration for both Sites #1 and #4 in Firesteel Creek ($n= 37$, $R^2= 0.48$, $p< 0.0001$). The regression equation of this relationship was used to compute TP concentration in Firesteel Creek, Site #1 (log TP= 0.196 + 0.227 Flow). (There was no significant effect with respect to the origin of the data, either from Stn. 1 or Stn. 4.)

Inflow: Additional TP input from surface flow from ungauged runoff and precipitation amounts to 6% of Firesteel Creek Site #1 flow, according to Stueven and Scholtes (1997).

Groundwater: Groundwater was assumed to have an average TP concentration of 0.100 mg/L. This is larger than Stueven assumption of 0.02 mg/L as computed from his data on groundwater volume and flow. It is assumed that groundwater may be slightly contaminated with fertilizer and manure, considering that most of the immediate watershed around Lake Mitchell is urbanized or used for cattle grazing.

Outflow: TP concentration data were only sporadic for the outflow of the spillway (22 individual data for three years 1993, 1994, 1995, 1999, 2001 are available; and are not available for the water withdrawal by the water plant. Therefore, insufficient data preclude the determination of "observed" TP export.

External water load for 1956 to 2001

	Water volumes and flows (10^6 m^3)									
	Firecreek inflow #1									
Year	Oct-Apr	May-Sep	Annual	Total Surface	Ground-water	Storage change	Pumping	Evaporation	Spillway out	Total outflow
1956	0.84	4.53	5.37	5.93	6.00			1.80		
1957	1.10	17.27	18.36	20.29	6.00			1.80		
1958	8.90	0.33	9.23	10.20	6.00			1.80		
1959	0.05	0.01	0.06	0.07	6.00			1.80		
1960	62.55	0.56	63.11	69.74	11.36			1.80		
1961	0.08	2.53	2.60	2.88	6.00			1.80		
1962	49.41	144.58	193.98	214.35	34.92			1.80		
1963	1.66	1.12	2.78	3.08	6.00			1.80		
1964	0.23	1.90	2.12	2.34	6.00			1.80		
1965	0.06	0.06	0.11	0.12	6.00			1.80		
1966	9.37	0.52	9.89	10.93	6.00			1.80		
1967	0.27	14.13	14.40	15.91	6.00			1.80		
1968	0.41	3.14	3.55	3.93	6.00			1.80		
1969	48.93	1.10	50.03	55.28	9.00			1.80		
1970	7.88	0.61	8.49	9.39	6.00			1.80		
1971	9.50	0.27	9.77	10.80	6.00			1.80		
1972	12.41	29.23	41.64	46.01	7.49			1.80		
1973	21.52	0.74	22.25	24.59	6.00			1.80		
1974	2.66	3.12	5.78	6.38	6.00			1.80		
1975	0.13	0.01	0.14	0.16	6.00			1.80		
1976	0.05	0.02	0.07	0.07	6.00			1.80		
1977	7.29	0.31	7.61	8.41	6.00			1.80		
1978	24.49	2.83	27.32	30.19	6.00			1.80		
1979	0.24	0.07	0.32	0.35	6.00	0.47	3.50	1.80	1.53	5.03
1980	0.02	0.01	0.03	0.03	6.00	-1.36	3.50	1.80	0.00	3.50
1981	0.07	0.03	0.10	0.11	6.00	-2.38	3.50	1.80	0.00	3.50
1982	9.64	4.79	14.44	15.95	6.00	6.28	3.50	1.80	22.94	26.44
1983	6.45	2.59	9.04	9.99	6.00	-2.54	3.50	1.80	8.15	11.65
1984	41.44	67.99	109.42	120.91	19.70	2.01	3.50	1.80	137.32	140.81
1985	24.02	1.01	25.03	27.66	6.00	-0.53	3.50	1.80	27.83	31.33
1986	62.57	52.57	115.14	127.23	20.73	1.27	3.50	1.80	143.93	147.43
1987	45.42	0.88	46.30	51.17	8.33	-2.74	3.50	1.80	51.46	54.96
1988	1.59	5.23	6.81	7.53	6.00	-0.69	3.50	1.80	7.55	11.04
1989	4.70	0.04	4.74	5.24	6.00	-0.68	3.50	1.80	5.27	8.77
1990	0.03	2.27	2.30	2.54	6.00	0.68	3.50	1.80	3.92	7.42
1991	0.05	12.19	12.24	13.53	6.00	0.00	3.50	1.80	14.23	17.73
1992	1.27	11.28	12.55	13.87	6.00	2.93	3.50	1.80	17.50	21.00
1993	14.39	81.43	95.82	105.88	17.25	0.35	2.86	1.80	118.82	121.68
1994	18.42	5.38	23.80	26.30	6.00	-2.12	3.50	1.80	24.89	28.38
1995	42.69	109.57	152.27	168.25	27.41	2.27	3.50	1.80	192.64	196.13
1996	24.46	19.63	44.09	48.72	7.94	0.50	3.50	1.80	51.87	55.36
1997	84.91	25.62	110.53	122.14	19.90	-1.77	4.11	1.80	134.36	138.47
1998	14.36	26.06	40.43	44.67	7.28	0.39	3.56	1.80	46.98	50.54
1999	25.80	50.66	76.46	84.49	13.76	-0.18	3.51	1.80	92.76	96.27
2000	0.45	0.30	0.76	0.84	6.00	-0.21	4.11	1.80	0.72	4.82
2001	74.05	20.23	94.28	104.18	16.97	-0.88	4.11	1.80	114.37	118.47
1956-2001	**16.67**	**15.84**	**32.51**	**35.93**	**9.00**	**0.05**	**3.55**	**1.80**	**53.00**	**56.55**
1979-2001	**21.61**	**21.73**	**43.34**	**47.90**	**10.32**	**0.05**	**3.55**	**1.80**	**53.00**	**56.55**
1991-2001	**27.35**	**32.94**	**60.29**	**66.63**	**12.23**	**0.12**	**3.61**	**1.80**	**73.56**	**77.17**

External TP load for 1956 to 2001

	TP Load (kg) Firecreek inflow #1					
Year	May-Sep	Oct-Apr	Annual	Total Surface	Ground-water	Total
1956	2,888	355	3,243	3,438	600	4,038
1957	12,569	528	13,097	13,883	600	14,483
1958	101	6,203	6,304	6,682	600	7,282
1959	1	11	12	13	600	613
1960	200	59,256	59,456	63,023	1,136	64,159
1961	1,508	15	1,523	1,615	600	2,215
1962	128,446	44,921	173,367	183,769	3,492	187,260
1963	450	698	1,148	1,217	600	1,817
1964	1,138	57	1,195	1,267	600	1,867
1965	16	11	27	29	600	629
1966	208	7,209	7,416	7,861	600	8,461
1967	10,981	91	11,073	11,737	600	12,337
1968	1,720	189	1,910	2,024	600	2,624
1969	506	47,111	47,617	50,474	900	51,375
1970	246	5,288	5,534	5,866	600	6,466
1971	89	6,965	7,054	7,477	600	8,077
1972	22,387	9,358	31,745	33,650	749	34,399
1973	289	15,629	15,918	16,873	600	17,473
1974	1,899	1,222	3,122	3,309	600	3,909
1975	1	30	31	33	600	633
1976	3	10	13	14	600	614
1977	116	5,312	5,429	5,754	600	6,354
1978	1,511	20,558	22,069	23,393	600	23,993
1979	15	69	85	90	600	690
1980	2	3	5	6	600	606
1981	7	14	21	22	600	622
1982	3,049	5,868	8,916	9,451	600	10,051
1983	1,255	3,898	5,153	5,462	600	6,062
1984	61,120	32,733	93,853	99,484	1,970	101,454
1985	391	20,044	20,435	21,661	600	22,261
1986	45,419	51,124	96,542	102,335	2,073	104,407
1987	339	38,463	38,802	41,130	833	41,963
1988	3,645	700	4,345	4,606	600	5,206
1989	8	2,946	2,954	3,132	600	3,732
1990	1,233	5	1,239	1,313	600	1,913
1991	8,739	10	8,749	9,274	600	9,874
1992	8,791	459	9,251	9,806	600	10,406
1993	66,000	9,546	75,546	80,079	1,725	81,804
1994	3,169	13,747	16,916	17,931	600	18,531
1995	100,104	36,965	137,069	145,293	2,741	148,034
1996	14,861	17,229	32,091	34,016	794	34,810
1997	20,381	73,273	93,655	99,274	1,990	101,264
1998	18,550	9,200	27,749	29,414	728	30,142
1999	41,084	19,943	61,027	64,689	1,376	66,065
2000	88	106	194	206	600	806
2001	15,214	64,487	79,700	84,482	1,697	86,179
1956-2001	**13,060**	**13,736**	**26,796**	**28,403**	**900**	**29,303**
1979-2001	**17,977**	**17,428**	**35,404**	**37,528**	**1,032**	**38,560**
1991-2001	**26,998**	**22,270**	**49,268**	**52,224**	**1,223**	**53,447**

Appendix H. Sediment sampling

Lake Mitchell sediment samples were collected from five locations on October 26 and 27, 2001. Whenever possible, duplicates for each site were taken from an anchored boat, using a Wildco "K-B" Corer. Each core was sectioned into 0-5 cm and 5-10 cm lengths, which were placed into amber glass bottles and stored on ice in the dark. Samples were submitted to a commercial laboratory within 48 hours of collection.

Samples were collected near the five lake stations (Fig. 2-2) with following coordinates:

Station ID	Latitude	Longitude
12A	43º 45.696	98º 03.850
12	43º 45.340	98º 03.128
12B	43º 44.782	98º 02.114
13	43º 44.585	98º 01.722
13A	43º 44.304	98º 01.829

Sediment samples were analyzed for % moisture, % solids, % organic matter, total phosphorus, total aluminum, total calcium, total iron and total manganese on a wet weight basis. Dry weights were computed as:

$$\text{Dry weight} = \text{Wet weight} / (\text{percent solids} / 100)$$

The regression model used to predict an average release rate (RR, $mg/m^2/day$) from the sediment surface (0-5 cm) TP concentration (mg/g dry weight) of Lake Mitchell ($R^2 = 0.21$, $n=63$, $p<0.0001$, Nürnberg 1988) is:

$$\text{Log (RR)} = 0.8 + 0.76 \log (\text{sediment TP})$$

Sediment content

Sample #	Lake Station	Sub-sample	Station Depth (feet)	Sample Depth	% Moisture	Total Solids (%)	% Organic
1	12A	1	approx. 5	grab (< 5cm)	51%	49%	3
2	12A	2	approx. 5	grab (< 5cm)	98%	2%	9
3	12	1	13.7	grab (< 5 cm)	33%	67%	8
4	12	2	13.7	grab (< 5 cm)	41%	59%	3
5	12B	1	19.1	0 - 5 cm	86%	14%	19
6	12B	1	19.1	5 - 10 cm	79%	21%	nd
7	12B	2	19.1	0 - 5 cm	87%	13%	19
8	12B	2	19.1	5 - 10 cm	80%	20%	nd
9	13	1	20.7	0 - 5 cm	65%	35%	9
10	13	1	20.7	5 - 10 cm	48%	52%	nd
11	13A	1	23.8	0 - 5 cm	83%	17%	20
12	13A	1	23.8	5 - 10 cm	80%	20%	nd
13	13A	2	23.8	0 - 5 cm	84%	16%	12
14	13A	2	23.8	5 - 10 cm	80%	20%	nd
Average				**0 - 5 cm**	**81%**	**19%**	**16**
				5 - 10 cm	**73%**	**27%**	

	Dry weight (mg/g)					Wet weight (mg/kg)				
Sample #	**TP**	**TAl**	**TCa**	**TFe**	**TMn**	**TP**	**TAl**	**TCa**	**TFe**	**TMn**
1	2.24	3.47	24.49	12.24	0.61	1,100	1,700	12,000	6,000	300
2						1,300	1,600	8,000	4,100	200
3	2.39	2.54	14.93	5.52	0.25	1,600	1,700	10,000	3,700	170
4	1.54	3.73	27.12	10.51	0.64	910	2,200	16,000	6,200	380
5	2.07	21.43	92.86	37.86	2.43	290	3,000	13,000	5,300	340
6	1.81					380	nd	nd	nd	nd
7	2.00	23.85	107.69	46.15	3.15	260	3,100	14,000	6,000	410
8	1.75					350	nd	nd	nd	nd
9	2.11	10.00	48.57	21.43	1.71	740	3,500	17,000	7,500	600
10	1.79					930	nd	nd	nd	nd
11	2.41	28.82	100.00	44.12	3.12	410	4,900	17,000	7,500	530
12	2.40					480	nd	nd	nd	nd
13	2.38	26.88	93.75	41.88	2.94	380	4,300	15,000	6,700	470
14	2.50					500	nd	nd	nd	nd
0 - 5 cm	**2.19**	**22.2**	**88.6**	**38.3**	**2.7**	**416**	**3,760**	**15,200**	**6,600**	**470**
5 - 10 cm	**2.05**					**528**				

Shaded data are used in the modeling approach.