Twin Lake Phosphorus Internal Loading Investigation

Prepared by
Bassett Creek Watershed Management Commission

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Executive Summary

During 2008 and 2009, water quality at Twin Lake failed to meet both Minnesota standards and the water quality goals established by the Bassett Creek Watershed Management Commission (BCWMC). The lake was "eutrophic"—characterized by an abundant accumulation of nutrients, such as phosphorous. These nutrients supported the dense algae growth seen in the lake.

Figure ES-1 (below) shows the degradation of water quality in Twin Lake as measured by an increase in total phosphorous and chlorophyll *a* (indicative of algae growth), and a decrease in "Secchi" depth (a measure of transparency). Declining water quality was also suggested by increases in phytoplankton, including increases in *Cylindrospermopsis raciborski*. This blue-green, toxin-producing species comprised 25 percent of the algal community on August 12, 2009, and more than half the algal community on August 26, 2009.

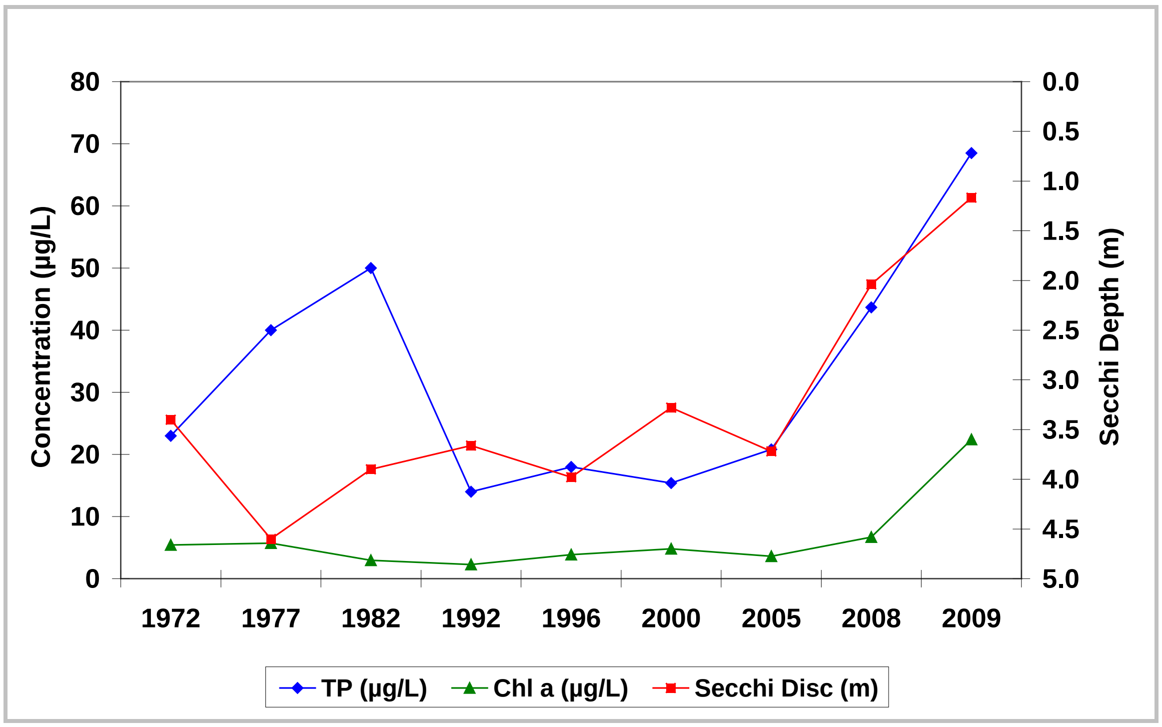

Figure ES-1. Historical Water Quality of Twin Lake

Because 2008 and 2009 were drought years, it was unlikely that stormwater runoff was contributing to increased phosphorous levels. A more likely cause was internal sediment phosphorous loading, which occurs when phosphorus and other nutrients that have settled in a lake's sediments, are reintroduced to the lake water. Among the many variables affecting this complex process are oxygen, temperature, pH, wind mixing, and the displacement of sediment particles by organisms such as carp. To develop a better understanding of internal sediment phosphorous loading at Twin Lake, the Bassett Creek Watershed Management Commission initiated a study which involved:

- Monitoring of Twin Lake during February and March of 2009 and 2010 to evaluate internal loading during winter months;
- Collection of sediment cores from Twin Lake to evaluate the types of mobile and organic phosphorus contributing to the lake's internal loading, and to estimate the internal loading rate (Figure 1);
- A review of historical data to determine why the effects of internal phosphorus loading appear to be increasing in Twin Lake.

2009 and 2010 winter monitoring results revealed one symptom of internal sediment phosphorous loading: low concentrations of oxygen at the sediment-water interface (the boundary between the bed sediment and the overlying water column). When oxygen concentrations at this interface are greater than 2 mg/L, phosphorous is tightly bound to the sediment. However, when dissolved oxygen concentrations are less than 2 mg/L, changes in water chemistry allow mobile phosphorous to break free from the sediment and move into the water column.

During the 2009 and 2010 sampling events, oxygen concentrations in the water column were less than 2 mg/L from a depth of 4 meters to the lake bottom (Figure 2). Historical data suggest that rising water temperatures at Twin Lake are contributing to these decreased oxygen concentrations—and subsequent higher phosphorous levels. Higher water temperatures not only increase oxygen-depleting microbial activity, but increase the rate at which phosphorous is released from the sediment.

The results from sediment analysis, along with previously collected water-quality data, show that Twin Lake has a high level of internal phosphorus loading from the sediment, particularly when compared to other area lakes. Because of the adverse impact on water-quality, management of internal loading is recommended. A number of management options to improve Twin Lake water quality are presented and discussed in this report.

Sediment Phosphorus-Internal Loading Investigation of Twin Lake

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1.0 Background and Study Description

1.1 Introduction

During 2008 and 2009, water quality at Twin Lake failed to meet both Minnesota standards and the water quality goals established by the Bassett Creek Watershed Management Commission (BCWMC). The lake was “eutrophic”—characterized by an abundant accumulation of nutrients, such as phosphorous. These nutrients supported the dense algae growth seen in the lake.

Figure ES-1 in the Executive Summary shows the degradation of water quality in Twin Lake as measured by an increase in total phosphorous and chlorophyll *a* (indicative of algae growth), and a decrease in “Secchi” depth (a measure of transparency). Declining water quality was also suggested by increases in phytoplankton, including increases in *Cylindrospermopsis raciborski.* This blue-green, toxin-producing species comprised 25 percent of the algal community on August 12, 2009, and more than half the algal community on August 26, 2009. This species was previously observed on only one occasion (September 6, 2000) and then at a very low density (105 per milliliter). Large numbers of this species are indicative of degraded water quality.

Because 2008 and 2009 were drought years, it was unlikely that stormwater runoff was contributing to increased phosphorous levels. A more likely cause was internal sediment phosphorous loading, which occurs when phosphorus and other nutrients that have settled in a lake’s sediments, are reintroduced to the lake water. Among the many variables affecting this complex process are oxygen, temperature, pH, wind mixing, and the displacement of sediment particles by organisms such as carp. To develop a better understanding of internal sediment phosphorous loading at Twin Lake, the Bassett Creek Watershed Management Commission initiated a study which involved:

- Winter monitoring of Twin Lake during February and March of 2009 and 2010 to evaluate internal loading occurring during the winter months;

- Collection of sediment cores from Twin Lake during May of 2010 to evaluate the types of phosphorus in Twin Lake sediment that contribute to internal loading and to estimate the lake’s internal loading rate. Some forms of phosphorus in sediment are able to move to the overlying water and contribute to internal loading (mobile and organic phosphorus) while others remain in the sediment (refractory or non-labile phosphorus) and, hence, do not contribute to internal loading. This study evaluated mobile and organic phosphorus in Twin Lake sediment.

- A review of historical lake data to determine why the effects of internal phosphorus loading appear to be increasing in Twin Lake.

1.1.1 Internal Loading in Lakes

Internal loading is a natural process in lakes resulting from the release of phosphorus from lake sediments to the overlying water when oxygen is absent or very low (anoxia) at the sediment water interface. During the ice-free portion of the year, temperature changes in the water column cause stratification, which plays a major role in the process. When the ice melts in the spring, the lake water mixes and the water column has the same temperature from surface to bottom. As air temperatures warm, lakes generally progress from being completely mixed to stratified with an upper layer of warm, well-mixed water (epilimnion) and colder temperatures in a bottom layer (hypolimnion). Separating these two layers is a layer of varying depth that has a sharp temperature gradient (thermocline). Because of the density differences between the lighter warm water and the heavier cold water, lake water becomes resistant to mixing and stratifies. Twin Lake mixes at spring ice-out, becomes stratified, and then remains stratified until the lake cools and mixes in the fall prior to ice-in.

When stratification occurs, oxygen from the air cannot reach the bottom lake water and, if the lake sediments have sufficient organic matter, degradation of the organic matter by biological activity can deplete the remaining oxygen in the hypolimnion. The epilimnion can remain well-oxygenated, while dissolved oxygen supplies can be reduced to low levels in the hypolimnion (anoxic conditions). Loss of oxygen changes the chemical conditions in the water and sediment, allowing phosphorus that would normally remain bound to the sediment to re-enter the water column. Although only a portion of this phosphorus reaches the surface water in summer due to diffusion or partial mixing events (storms and/or high wind), fall mixing distributes this phosphorus throughout the water column.

In winter, ice cover on the lake prevents oxygenation and degradation of organic matter by biological activity depletes the oxygen in the lake’s hypolimnion. Similar to summer time stratification, loss of oxygen changes the chemical conditions in the water and sediment, allowing phosphorus that would normally remain bound to the sediments to re-enter the water column. Spring mixing then distributes this phosphorus throughout the water column.

Phosphorus released from the sediment through internal loading processes is considered immediately available because it is in a dissolved form that algae and plants can use directly. Watershed phosphorus loading is generally 35-45% dissolved (on average in MN) while the remaining portion is in the form of particles (either soil or organic matter) that become part of the lake sediment. The particulate form of phosphorus cannot be directly used by algae or plants until it is released from the particles or organic matter.

Phosphorus taken up by organisms in lakes (including algae and plants) is returned to the sediment when the organisms die. Once in the sediment, much of this phosphorus can then be released again after the organic matter breaks down, continuing the internal loading process. While this is a natural process in all lakes, additional inputs of phosphorus due to human activity have caused increases in both the total amount and the rate of internal phosphorus loading in lakes.

1.1.2 Benthic Mixing Effects

Benthic mixing of lake sediments can increase the rate (or speed) of internal loading in lakes. In addition, species like carp can actually increase the depth of sediment mixing in lakes. This means that a greater amount of phosphorus can be transported from the sediment to the water. Because there is little to no oxygen in lake sediments just below the sediment water interface, the pool of phosphorus that might not be available under 'normal' conditions without carp or other mixing drivers is physically pushed out of the sediment due to carp mixing.

1.1.3 Climate Effects

Climate can affect water temperature and mixing in lakes and may be an important driver of increased internal phosphorus loading and changes in water column stability leading to increased mixing of phosphorus from deeper waters to the surface of lakes. Climate is variable and thus, the impacts it may have on lake water quality are variable as well. Research has shown that when lakes become warmer earlier in the season, the mechanisms causing internal loading (bacterial growth and uptake of oxygen) begin earlier as well. This increases the duration of internal phosphorus loading in lakes. In addition, higher temperatures during the year will increase microbial activity, causing increased rates of sediment organic matter breakdown and oxygen uptake. This may increase both the rate of internal phosphorus loading and the area of the lake sediment susceptible to phosphorus release.

When water temperatures increase in lakes during the summer, the potential for mixing of water between the surface and hypolimnion can increase as well. Initially, stratification in the spring occurs more quickly and is stronger than what would normally be expected. However, as temperatures continue to increase during the summer, the added heat (increased energy) can destabilize the water column and mixing can occur more easily in the later part of the season. The sum of the effects from warmer water temperatures can lead to higher surface concentrations of phosphorus because there is more phosphorus released into the hypolimnion and this phosphorus is transported more easily to the surface where it can be used by algae for growth.

1.2 Study Description

A study of Twin Lake was initiated by the Bassett Creek Watershed Management Commission to determine the potential for internal sediment phosphorus loading in Twin Lake. The study involved:

- Winter monitoring of Twin Lake during February and March of 2009 and 2010 to evaluate internal loading occurring during the winter months;
- Collection of sediment cores from Twin Lake during May of 2010 to evaluate the types of phosphorus in Twin Lake sediment that contribute to internal loading and to estimate the lake's internal loading rate.
- A review of historical lake data to determine why the effects of internal phosphorus loading appear to be increasing in Twin Lake.

1.2.1 2009-2010 Winter Monitoring of Twin Lake

Twin Lake was monitored during February and March of 2009 and 2010 to assess internal loading during the winter months. Samples were collected from the deepest location in the lake basin. Table 1 lists the water quality parameters and specifies at what depths the samples or measurements were collected. Dissolved oxygen, temperature, specific conductance, pH, and Oxidation Reduction Potential (ORP) were measured in the field. Water samples were analyzed in the laboratory for total phosphorus.

Twin Lake, pictured above, was monitored during February and March of 2009 and 2010

Table 1 Lake Water Quality Parameters

Parameters	Depth (Meters)	Sampled or Measured During February and March Sample Events
Dissolved Oxygen	Surface to bottom profile at one meter intervals	X
Temperature	Surface to bottom profile at one meter intervals	X
Specific Conductance	Surface to bottom profile at one meter intervals	X
Oxidation Reduction Potential (ORP)	Surface to bottom profile at one meter intervals	X
pH	Surface to bottom profile at one meter intervals	X
Total Phosphorus	0-2 Meter Composite Sample.	X
Total Phosphorus	Profile at one meter intervals from 3 meters to near the bottom (i.e., 0.5 meters off bottom).	X

1.2.2 2010 Twin Lake Sediment Study

Sediment cores were collected in May 2010 from Twin Lake to determine the buildup and distribution of sediment phosphorus as well as the potential for internal phosphorus loading in the lake. The sediment cores were collected from three locations (Figure 1) in the lake to determine spatial differences in phosphorus levels due to external inputs from outside the lake and internal variations due to water depth and sediment accumulation zones. Sediment from Twin Lake was analyzed for mobile and organic bound phosphorus. Mobile phosphorus is the pool of phosphorus that can be released from the sediment under low oxygen conditions and is the main contributor of internal phosphorus loading. Organic phosphorus can also be released from the sediment after the organic material is broken down through microbial activity and converted into mobile phosphorus. This process usually takes more time.

In May of 2010, sediment cores were collected from 3 locations in Twin Lake.

The collected sediment cores were approximately 1 foot (30-40 cm) in depth and were sliced into five or six sections to determine the variation of mobile and organic phosphorus by sediment depth. Sediment sample depths that were analyzed for mobile and organic phosphorus are shown in Table 2.

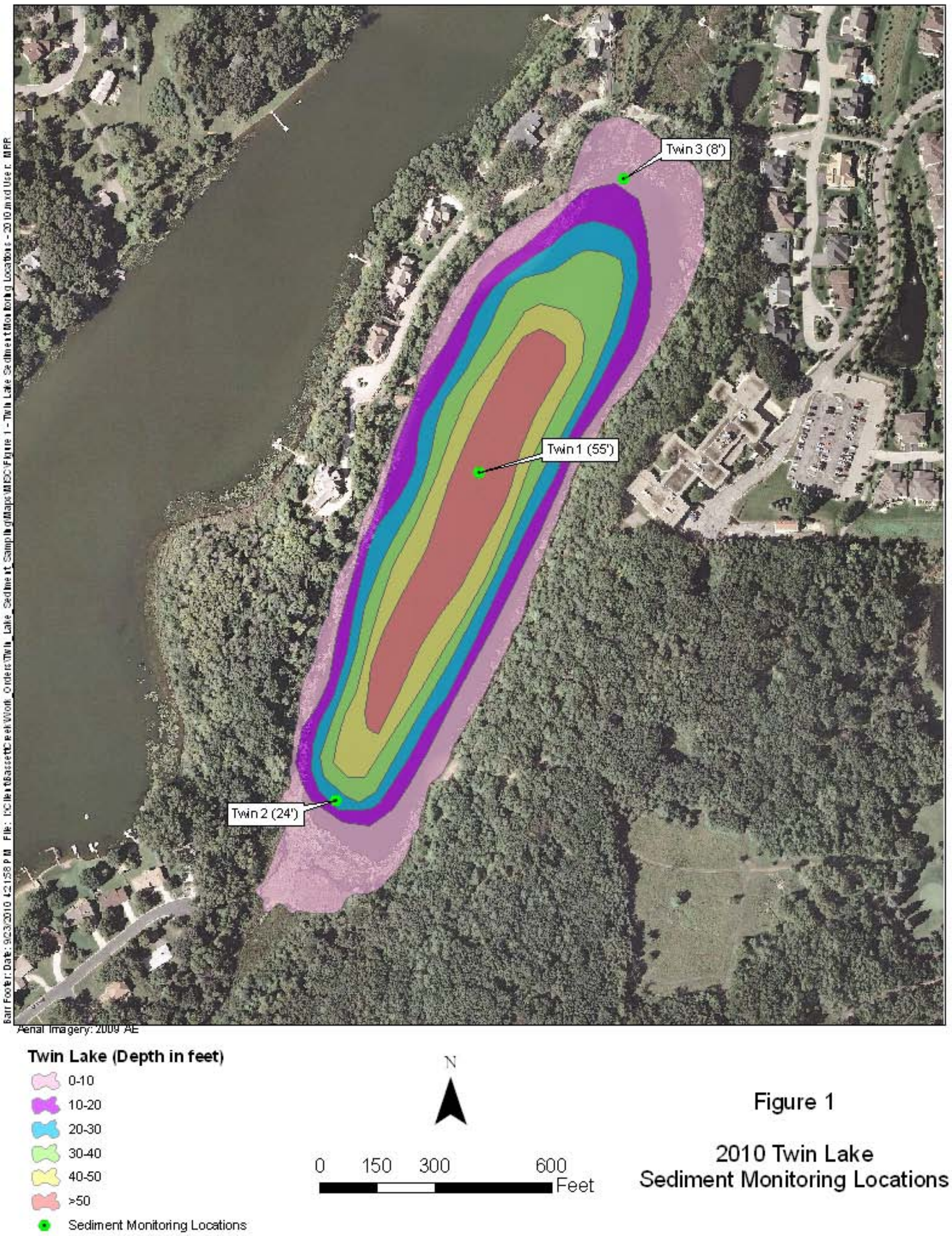

Figure 1 2010 Twin Lake Sediment Monitoring Locations

Table 2 2010 Twin Lake Sediment Core Sample Depths

Twin Lake Site 1	Twin Lake Sites 2 and 3
0-2 cm	0-2 cm
2-4 cm	2-4 cm
4-8 cm	4-8 cm
8-12 cm	8-12 cm
15-20 cm	15-20 cm
25-30 cm	

Analyzing sediment by depth allows for the determination of approximate sediment mixing depths and background phosphorus concentrations. Background concentrations (found deeper in the sediment) can be used to evaluate the effectiveness and cost of different internal loading management methods.

Phosphorus in the sediment cores is quantified in two different ways, by concentrations and phosphorus mass. Phosphorus concentration is used to show the relative difference of how much phosphorus is contained in different types of soil particles. For example, sediment at the top of a sediment core usually contains more phosphorus for each unit of dry matter because mobile phosphorus migrates from deeper layers to the sediment surface in lakes. However, there is more water at the sediment surface so even though there might be more phosphorus in each particle of sediment, there are less particles and more water at the sediment surface. Therefore, the total mass of phosphorus may be lower in the surface sediment simply due to the fact that there is more water and less sediment near the surface. This is just an example, however, and many times phosphorus concentration and mass will be highest at the sediment surface.

2.0 Results

2.1 Winter Monitoring Results

2009 and 2010 winter monitoring results revealed one symptom of internal sediment phosphorus loading: low concentrations of oxygen at the sediment-water interface (the boundary between the bed sediment and the overlying water column). When oxygen concentrations at this interface are greater than 2 mg/L, phosphorus is tightly bound to the sediment. However, when dissolved oxygen concentrations are less than 2 mg/L, changes in water chemistry allow mobile phosphorus to break free from the sediment and move into the water column.

Twin Lake winter monitoring results indicate oxygen was very low (anoxia) at the sediment water interface and phosphorus was released from lake sediments to the overlying water. In order to understand the relationship between low oxygen concentrations in Twin Lake and internal loading, it is helpful to understand some basic limnology. As long as oxygen concentrations are greater than 2 mg/L at the sediment water interface, phosphorus is tightly bound to sediment and is unable to break free and enter the overlying water. However, when dissolved oxygen concentrations at the sediment water interface drop below 2 mg/L, the chemistry of the sediment water interface changes from "oxidized conditions" to "reducing conditions." When "reducing conditions" occur, the mobile phosphorus is able to break free from the sediment and be released into the overlying waters. The 2010 winter oxygen data, as well as winter data collected during 2009, indicate Twin Lake consistently had "reducing conditions" at the sediment water interface. All 2009 and 2010 winter oxygen concentrations at the sediment water interface were 0.2 mg/L (Figure 2). Oxygen concentrations in the water column were less than 2 mg/L (anoxia threshold) from the 4 meter depth to the bottom during all 2009 and 2010 winter sample events (Figure 2). This is a very high level of oxygen depletion.

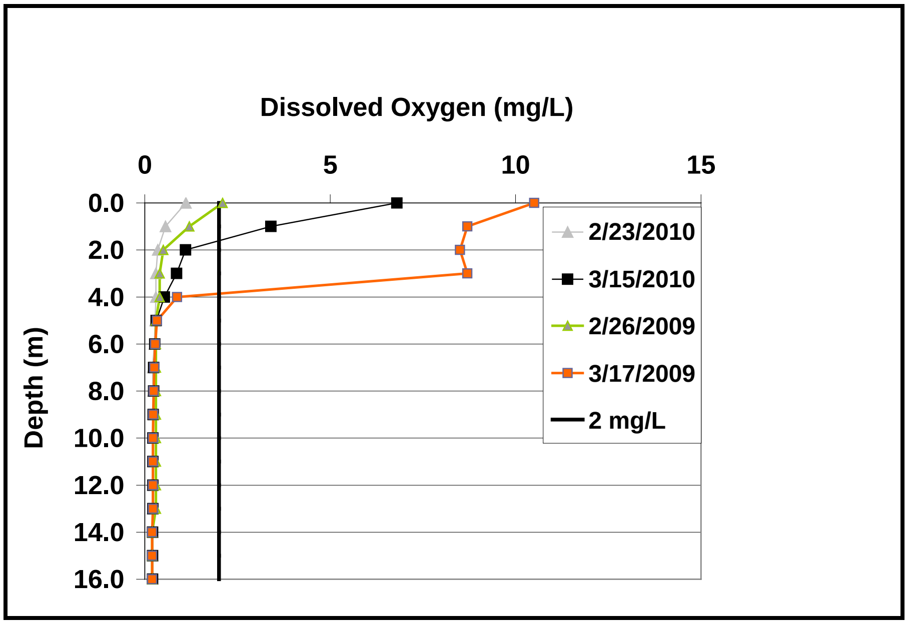

Figure 2 2009-2010 Twin Lake Winter Dissolved Oxygen Data

"Reducing conditions" can be confirmed by measuring oxidation reduction potential (ORP). A high positive ORP value indicates "oxidative conditions" while a low negative ORP value indicates "reducing conditions." Twin Lake ORP winter monitoring results confirm that "reducing conditions" consistently occurred at the sediment water interface (Figure 3). An oxidation reduction potential of -200 millivolts was consistently measured in Twin Lake from 8 meters to the bottom (Figure 3). The smell of hydrogen sulfide or rotten egg smell in waters collected from 8 meters to the bottom further confirmed that "reducing conditions" were present. Under "reducing conditions", sulfate is reduced to hydrogen sulfide which has a distinctive odor similar to rotten eggs. This smell confirms that reducing conditions are present and that phosphorus can break free from sediment to enter the overlying water. A comparison of Figures 2 and 3 indicates that decreases in oxygen levels consistently corresponded with decreases in oxidation reduction potential. The data indicate that as oxygen concentrations decreased to less than 2 mg/L, oxidation reduction potential decreased to less than -200 millivolts.

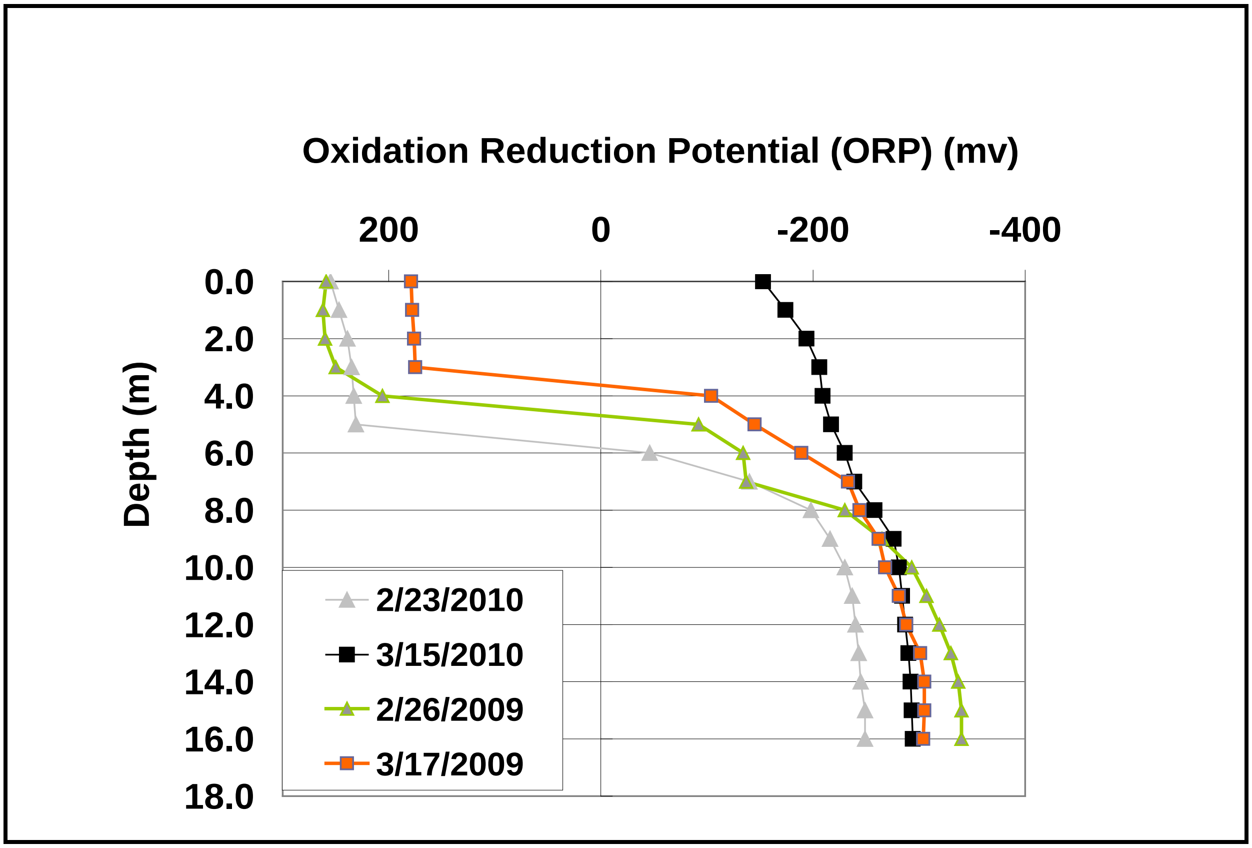

Figure 3 **2009-2010 Twin Lake Winter Oxidation Reduction Potential Data**

Increases in phosphorus concentration in Twin Lake bottom waters confirm that internal loading of phosphorus from the sediment occurred during the winter periods of 2009 and 2010. A comparison of Figures 2, 3, and 4 indicates that a decrease in dissolved oxygen concentrations to less than 2 mg/L corresponded with a decrease in oxidation-reduction potential to less than -200 millivolts and an increase in total phosphorus concentrations. In 2009 and 2010, winter surface water total phosphorus concentrations ranged from 31 to 140 µg/L while bottom water total phosphorus concentrations, on average, ranged from 397 to 667 µg/L (Figure 4). The difference in concentration between the surface and bottom waters is attributed to the release of phosphorus from bottom sediments due to low oxygen and resultant "reducing conditions" that allowed phosphorus to break free and move from the sediment into the water column.

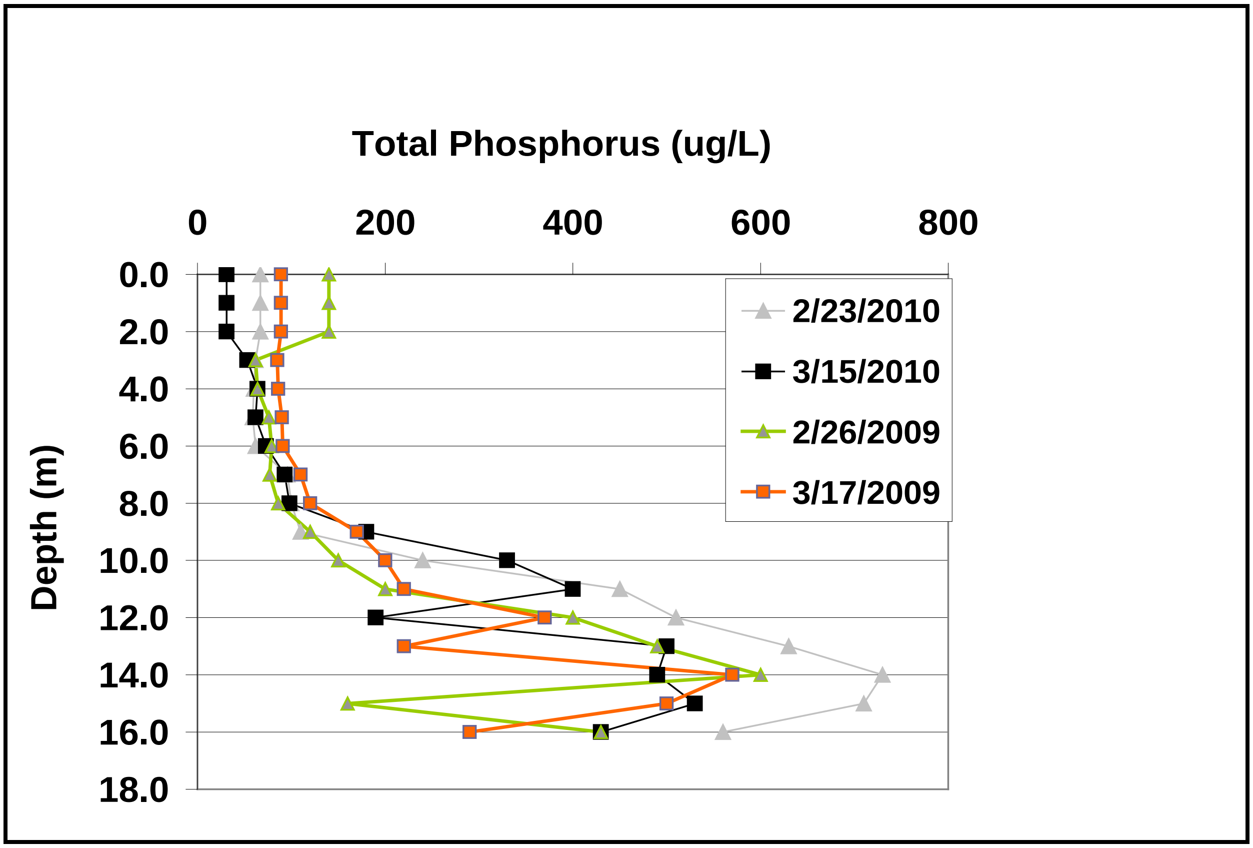

Figure 4 2009-2010 Twin Lake Winter Total Phosphorus Data

In summary, the winter monitoring results from 2009 and 2010 confirm that internal loading of phosphorus from the sediment consistently occurred due to low oxygen levels and “reducing conditions” at the sediment water interface.

2.2 Sediment Study Results

Phosphorus concentrations in Twin Lake sediments were generally higher at the surface and decreased in the deeper sediment (Figures 5 and 6). The decreasing trend was more evident for the sediment organic phosphorus than the mobile phosphorus, as can be seen in Figures 5 and 6. Organic phosphorus was substantially higher than mobile phosphorus in each of the cores. While this is typical in shallow areas of lakes, mobile phosphorus is generally higher than organic phosphorus in deeper areas of dimictic lakes. The core collected from the deep hole (Twin 1) contained the highest amount of phosphorus (both mobile and organic) while lower amounts were found in the cores from the shallower areas (Twin 2 and Twin 3).

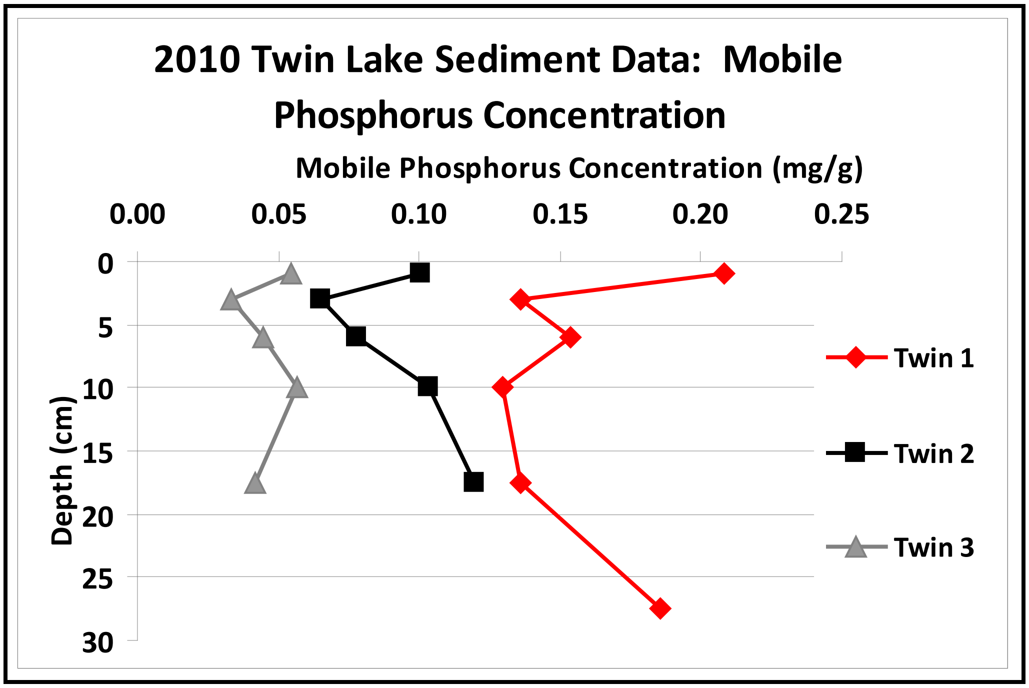

Figure 5 **2010 Twin Lake Sediment Data: Mobile Phosphorus Concentration**

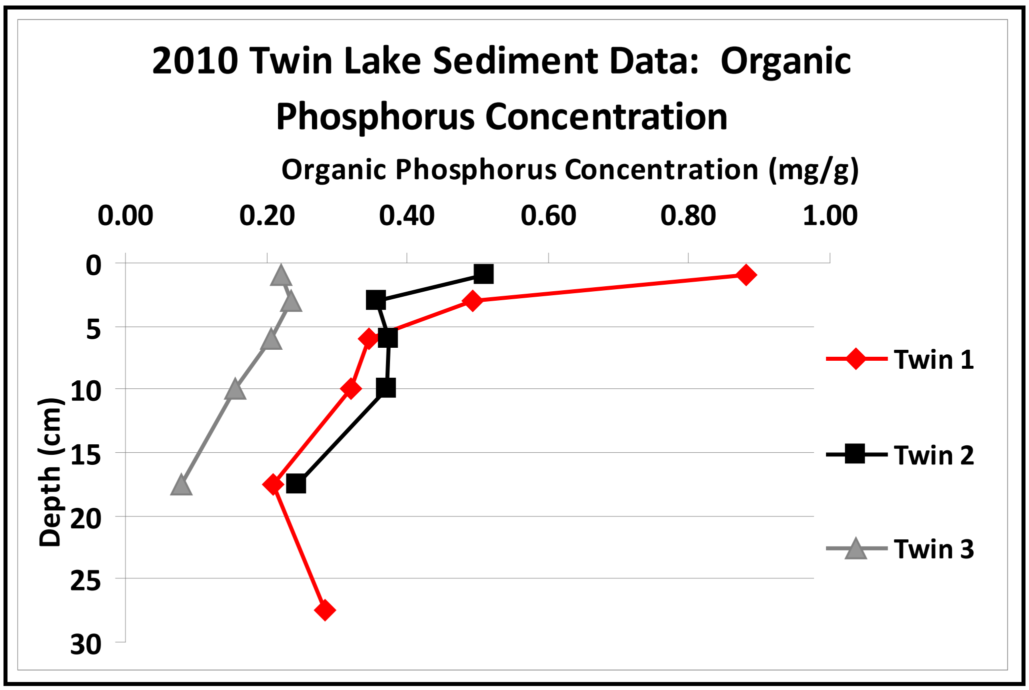

Figure 6 **2010 Twin Lake Sediment Data: Organic Phosphorus Concentration**

Table 3 shows the potential internal phosphorus loading rates based on both mobile and organic phosphorus content of the sediment in Twin Lake. The lowest potential for internal loading was found in the shallower areas of the lake and the highest was found in the deep hole.

Table 3 Potential Internal Phosphorus Loading Ranges and Lake-Wide Averages Based on Mobile and Labile Organic Phosphorus in the Sediment of Twin Lake

	Mobile P	Mobile + Organic P
Sample Location	**Internal Loading Rate Li (mg/m2/day)**	**Internal Loading Rate Li (mg/m2/day)**
Twin 1	0.93	3.1
Twin 2	0.35	2.5
Twin 3	0.33	3.0
Average	**0.53**	**2.9**

When comparing the results above to data from water quality samples collected previously from the lake, it appears the sediment data under represent the true amount of internal loading in Twin Lake. This is an unusual occurrence because results from sediment core analysis generally tend to give the maximum potential for internal loading in lakes. However, in some cases it may be difficult to collect sediment during a period when no internal loading is occurring in a lake. When this happens, internal loading can be under estimated using modern sediment analysis techniques because a portion of the mobile phosphorus in the sediment has been released and is in the lake water. This appears to be the case with Twin Lake and means further analysis is required to determine the true potential for internal phosphorus loading in the lake.

Using the 2009 water quality data, an internal loading estimate was calculated for the year. The lake-wide internal loading rate was approximately 12 mg/m^2/day from late April through late September of 2009 (see Figure 7). As shown in Table 3, the average internal loading rate calculated using the sediment data from the 2010 cores was 2.9 mg/m^2/day. It should be noted that this comparison is made between two different years, so the values are not expected to be the same. However, the difference between the internal loading estimate from sediment samples (2.9 mg/m^2/day) and water quality data (12 mg/m^2/day) is much greater than would be expected.

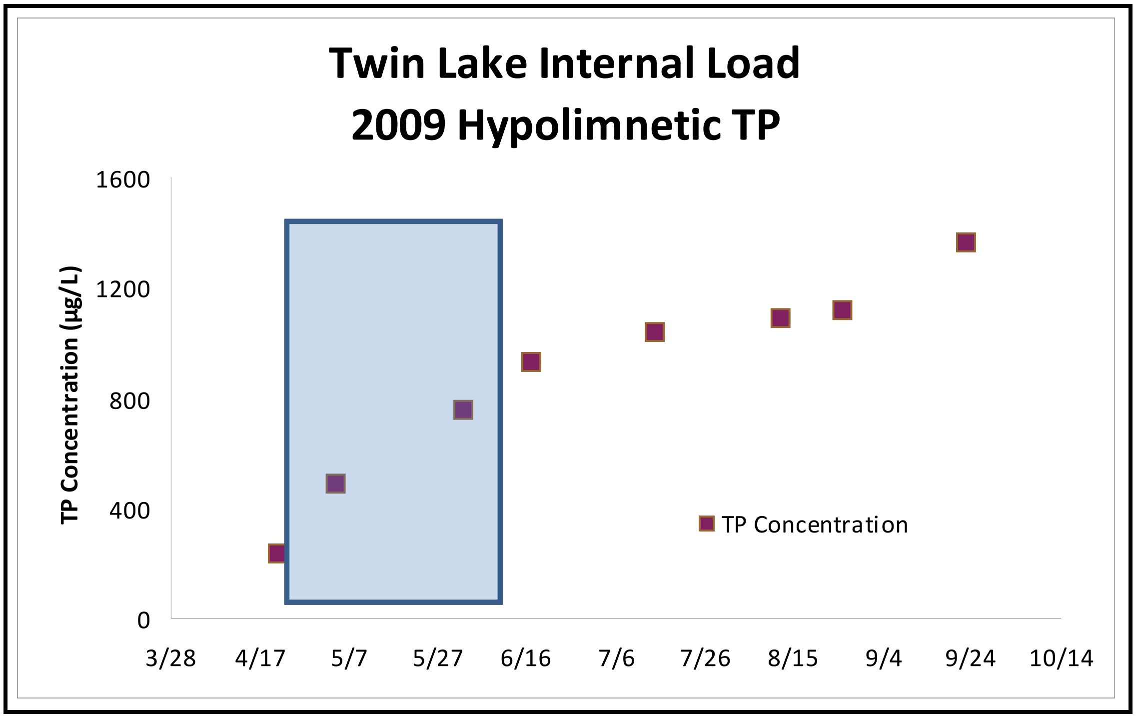

Figure 7 Total Phosphorus (TP) Concentrations in Twin Lake during 2009

Note: The shaded area in Figure 7 represents the estimated time frame and estimated amount of internal loading that may have occurred before sediment coring in 2010.

The likely reasons for the seemingly low prediction of internal phosphorus loading in Twin Lake (based on sediment analysis) are two-fold. First, substantial internal phosphorus loading in the lake during the winter means that a significant portion of mobile P that would normally be found in the sediment is in the water column. Second, after spring turnover, internal loading appears to initiate quickly in the lake. Thus, not only is there a high level of phosphorus in the entire water column after turnover (over 200 µg/L from top to bottom in April 2009), internal loading begins soon after turnover, releasing even more sediment phosphorus to the water column.

Typically, sediment cores are collected in spring, after turn over, to avoid 'missing' any mobile P that might be in the water column instead of the sediment. The results then give the internal phosphorus loading potential in the lake. This is considered more accurate than basing internal phosphorus loading estimates on water quality data alone because water quality data can vary from year to year. In addition, the same phosphorus can be released from the sediment multiple times during a growing season, leading to inaccurate estimates. However, given the two reasons stated in the previous paragraph, it can be difficult to time core collection in Twin Lake to coincide with the short window where all of the mobile phosphorus is in the lake's sediment. In fact, looking at the data from 2009, there may be years where this does not occur at all.

Using the water quality data from 2009, it is possible to estimate how much internal load may have occurred before sediment cores were collected in 2010. To do this, the water column phosphorus data from 2009 (Figure 7) are used with the volume of the lake to estimate the mass of phosphorus already released due to internal loading. This phosphorus can then be added to the mobile phosphorus found in the sediment cores to estimate a potential internal loading rate. This rate was then compared with the lake wide estimate for internal loading in Twin Lake using just the water quality data from 2009.

The shaded area in Figure 7 represents the time frame where internal loading may have occurred before sediment core collection in 2010. The amount of internal load that occurred through this period was approximately 73 kg, which translates to roughly 5.4 $mg/m^2/day$, lake wide, over a period of 155 days which is the same time period used to estimate the season long internal loading rate of 12 mg/m2/day (Bassett Creek Watershed Management Commission, 2010). Adding this to the results gained from the sediment analysis, the internal loading rate is approximately 8.3 $mg/m^2/day$. This is still lower than what the water quality data showed for 2009. However, this initial estimate does not account for the phosphorus present throughout the water column after turnover in 2009 (due to winter internal loading). This phosphorus represents an additional loading rate of 4.8 $mg/m^2/day$, making the total internal loading estimate 13.1 $mg/m^2/day$ in Twin Lake.

Even though the two different internal loading rates of 12 and 13.1 $mg/m^2/day$ were estimated using two different years of data, the results are fairly similar. In addition, loading rates based on sediment phosphorus can be higher than what might be observed in-lake because they represent the maximum possible internal loading rate, under normal conditions (e.g., not a shallow lake infested with a large population carp)

3.0 Comparison to Other Lakes

It can be useful to compare the internal phosphorus loading rate estimate for Twin Lake with loading rates found in other lakes in the area. Table 4 shows that the internal loading rate for Twin Lake is quite high in comparison to loading rates found in other lakes in the area. However, care should be taken when directly comparing internal loading rates, because water quality in a lake is a product of both internal and external phosphorus loading. Nonetheless, the results from this study show that internal phosphorus loading in Twin Lake is elevated and likely has a strong impact on water quality in the lake.

Table 4 Lake wide internal loading rates in some selected MN lakes. *(Huser et al. 2011), **(Pilgrim et al. 2007)

Lake	Internal P **Load ($mg/m^2/d$)**
Isles (pre-alum, deep hole)*	14.1
Fountain-Dane Bay	13.6
Twin Lake (by Sweeney)	**13.1**
Harriet (pre-alum, deep hole)*	11.1
Calhoun (pre-alum, deep hole)*	10.8
Fish E**	10.5
Cedar (pre-alum)*	9.3
Fountain-Edgewater Bay	9.0
Fountain-Bancroft Bay	8.1
Fish W**	8.1
Como**	7.6
Harriet**	6.9
Fountain-Main Bay	6.8
North Twin	6.0
South Twin	9.2
Como-littoral**	5.7
Calhoun (pre-alum, shallow)**	5.6
Pickerel Lake	3.9
White Lake	3.8
Albert Lea Lake	3.6
Parkers**	3.5
Earley Lake	2.9
Phalen**	2.3
McCarrons**	2.0
Bryant**	1.5
Nokomis**	1.0
Minnewashta	0.2
Christmas**	0.0

4.0 Climate Effects on Internal Phosphorus Loading

To determine why it appears that the effects from internal phosphorus loading have increased in recent years, we examined historical data for temperature and dissolved oxygen and compared these to surface and bottom water total phosphorus concentrations. Average surface water temperatures did not seem to explain the recent increase in surface water total phosphorus (June-September) in Twin Lake (Figure 8).

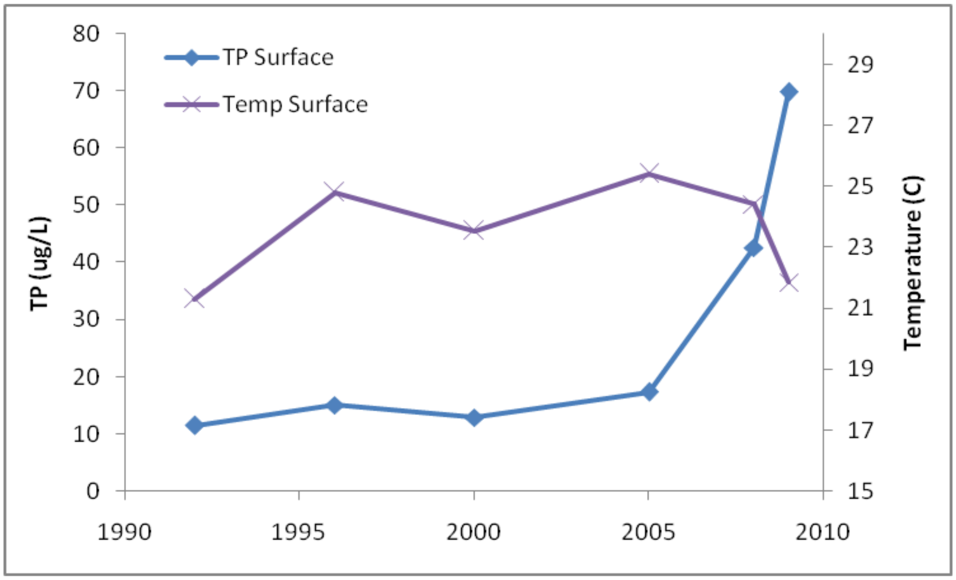

Figure 8 Total Phosphorus (TP) Concentrations and Average Surface Water Temperatures in Twin Lake (1992-2009)

While surface water temperature does appear to increase from 1992 through 2008 (peaking in 2005), the average summer temperature in 2009 was similar to that found in 1992. However, when average bottom water temperatures are compared to surface total phosphorus concentrations, a relationship appears where increasing temperature in the hypolimnion corresponds to greater total phosphorus at the surface of the lake (Figure 9).

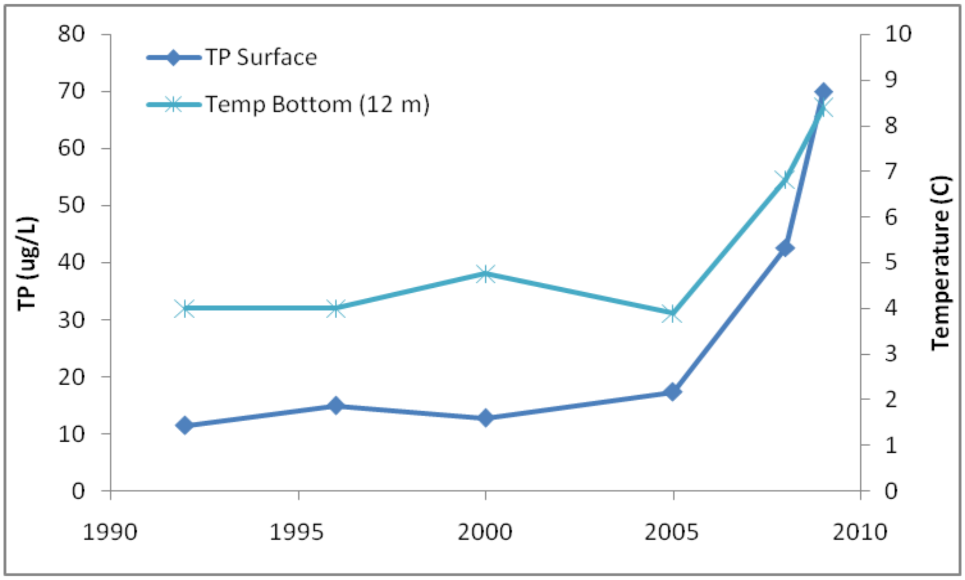

Figure 9 Total Phosphorus (TP) Concentrations and Average Bottom Water Temperatures in Twin Lake (1992-2009)

Average temperature in the hypolimnion is generally stable through 2005 but increased sharply in 2008 and was more than double in 2009 when compared to data from 1992 -2005. It is difficult to determine if the increase in temperature in the hypolimnion is due to increased mixing of the lake or if temperature increased in the lake as a whole, but it is safe to say that overall water temperatures during 2008 and 2009 in Twin Lake were substantially higher than those detected during previous years. Even 2005 had slightly elevated temperatures (on a whole lake basis) compared to previous years.

Dissolved oxygen concentrations in Twin Lake changed during the period from 1992-2009 as well. Figure 10 compares surface water total phosphorus to the water column depth of oxygen depletion in Twin Lake.

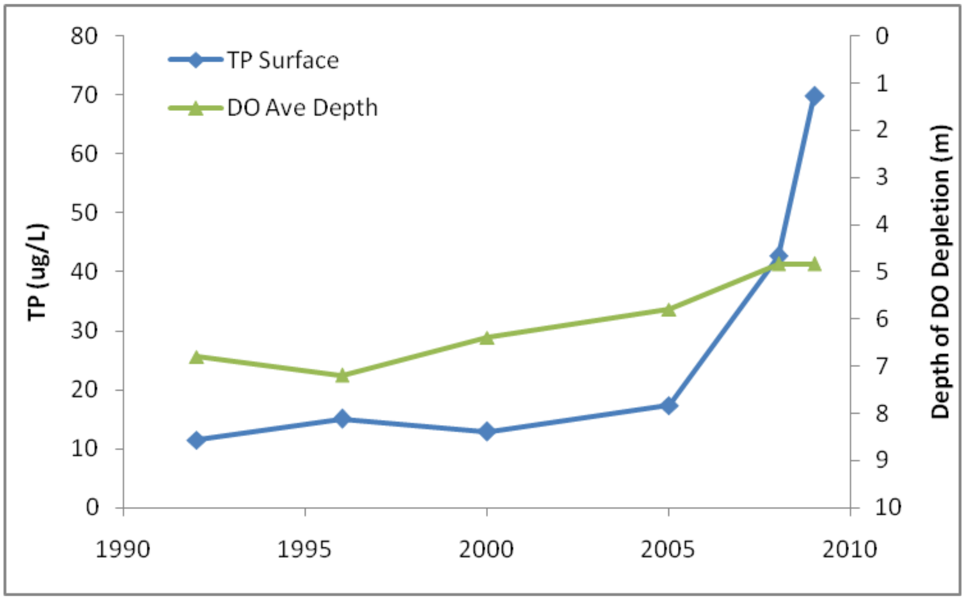

Figure 10 Total Phosphorus (TP) Concentrations and Average Depth of Oxygen Depletion in Twin Lake (1992-2009)

The total water column depth of oxygen depletion increases slightly in 2000 and continues to increase through 2008, stabilizing in 2009. What this means is that the zone of water with low dissolved oxygen has been increasing in size and has gone from an average upper water depth of 7 meters (1995) to approximately 5 meters (2008), an increase of 2 meters. This means the area of lake sediment exposed to low oxygen levels has increased, from approximately 10.4 to 13.4 acres, an increase of nearly 30% between 1995 and 2008.

Changes in temperature and dissolved oxygen correlate well to changes in hypolimnetic phosphorus concentrations. As Figure 11 shows, average summer total phosphorus in the hypolimnion increased from approximately 550 to 650 µg/L (1992-2000) to over 1000 µg/L (2009), nearly a doubling in concentration. Surface water TP also increased in a similar manner.

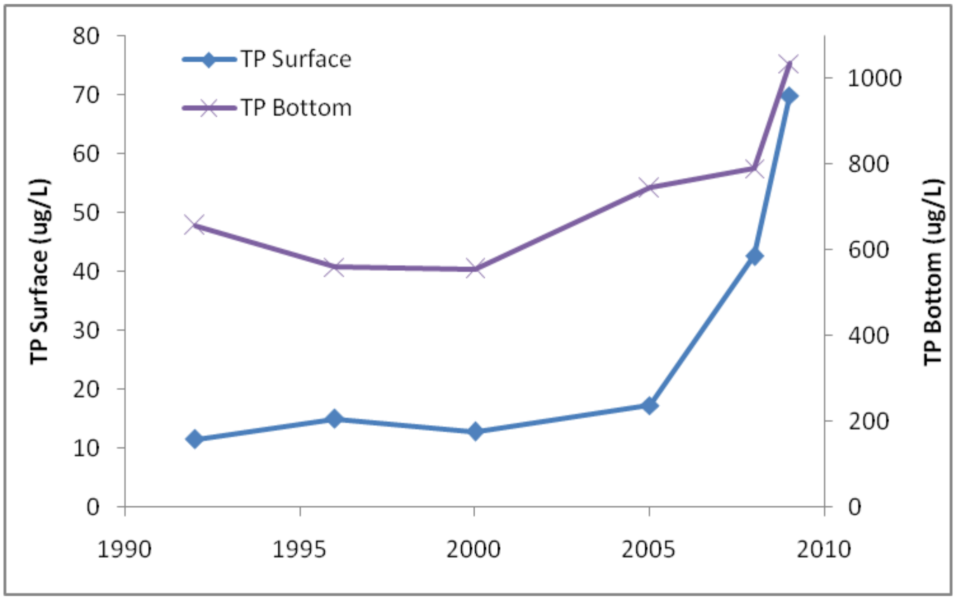

Figure 11 Total Phosphorus (TP) Average Surface and Bottom Concentrations in Twin Lake (1992-2009)

The graphs above show that temperature increased and dissolved oxygen decreased in recent years, leading to both an increase in the amount of sediment exposed to low oxygen conditions and an increase in total phosphorus concentration in the hypolimnion of the lake. These changes, along with the increased mixing potential due to elevated lake water temperature, are the likely reasons for increased internal loading effects and degraded water quality in Twin Lake in recent years.

5.0 Management Methods to Reduce Internal Loading

There are a number of management options available for the control of internal phosphorus loading in lakes. These options and their potential effectiveness are discussed below.

5.1 Hypolimnetic Withdrawal

Hypolimnetic withdrawal involves the direct removal of phosphorus laden bottom waters. The water can be removed and sent further downstream or treated and returned to the lake. The benefit of this technique is the removal of high phosphorus content of water which has an indirect benefit of removing water low in oxygen, decreasing the potential for internal loading. However, there are a number of drawbacks to this method. As previous projects have shown, water removed from the hypolimnion has a strong odor (rotten egg smell caused by hydrogen sulfide) and systems often need to be shut down during summer (when internal loading is highest) due to complaints from lake users or neighboring residents. If water is not returned to the lake, lake level may drop, causing shoreline erosion among other problems. If treated and returned to the lake, the increased temperature of the water may destabilize the water column, causing it to mix with the surface water and transport the remaining phosphorus in the hypolimnion to the surface. The chances for lake mixing can be minimized by reducing the withdrawal rate of the water from the lake. The length of time needed to reach an acceptable level of sediment phosphorus release is difficult to predict without closer examination of the sediment and modeling of the system.

Some of the advantages of hypolimnetic withdrawal are the relatively low capital cost and potentially long term effectiveness once the excess sediment phosphorus has finally been depleted. Costs for a hypolimnetic withdrawal system would range between $300,000 and $400,000, with an annual operating cost of $8,000 to $10,000 for treatment and return of the hypolimnetic water.

5.2 Sediment phosphorus inactivation

Sediment inactivation of phosphorus involves the conversion of easily released phosphorus into a form that will remain in the sediment over time. The two main elements used to accomplish this are aluminum and iron. Aeration is generally needed along with iron addition to prevent the reduction of iron and subsequent release of phosphorus during low oxygen conditions. Aluminum does not require aeration because it is not affect by oxygen levels in the lake water. Both of these elements are usually added to the lake water where they form a solid and mix into the sediment, binding available phosphorus. Both have been used for over four decades in lakes to varying degrees of effectiveness. Until recently, dosing methods were crude and many lakes (especially shallow lakes) were under-dosed causing short lived longevity in some cases. Better methods have been developed recently, reducing the chance for under-dosing. Treatment longevity has ranged from 4 to 21 years in stratified lakes and from less than 1 year to 11 years in shallow lakes (Welch and Cooke 1999). An indirect benefit resulting from sediment phosphorus inactivation is the resulting increase of dissolved oxygen in the hypolimnion. This occurs because productivity in the lake (algal growth) is lower after treatment, resulting in less organic matter deposition to the sediment.

Drawbacks can include the public perception that the addition of aluminum and iron are considered unnatural chemical treatments even though both elements are present naturally in both soil and lake sediment. Most aluminum and iron salts are slightly acid when added to water so care must be taken to maintain lake water pH above 6.0 during treatment. Aluminum can be toxic at low pH (5.5 or less) but these pH levels are generally only seen in acidified lakes.

Calcium has also been used in lakes but phosphorus binding is most efficient at higher pH levels (around 8 to 9) and thus it is better suited for use in wetlands or other high pH systems. Longevity of calcium treatments in lakes has been short, usually less than two years.

Costs for treatment with aluminum (e.g. alum) would be approximately $25,000 to $35,000, and the treatment would last 10-to-15 years. Costs for treatment with iron are usually somewhat higher due to the need for aeration to prevent low oxygen conditions that can cause phosphorus release from the added iron.

5.3 Biomanipulation

Biomanipulation usually involves the removal of rough fish and introduction of piscivores (for example, bass and northern pike). In lakes with low populations of piscivores, small planktivorous fish reduce zooplankton populations leaving algae free to reproduce and bloom. When piscivores are added, they reduce the planktivorous fish population, allowing zooplankton to graze algae more effectively. Benefits of this method are comparatively low cost and an improved fishery. Without fixing the underlying problem of internal phosphorus loading, however, the lake is likely to return to a poor condition, as previous studies have shown. This is because the high level of nutrients tends to disrupt the food web and desirable fish species have difficulty reproducing. Additionally, surface water phosphorus concentrations may not meet goals or water quality standards set by the State.

Costs for biomanipulation are usually low but are difficult to estimate without more detailed information.

5.4 Barley Straw

Barley straw is added to small water bodies (usually ponds) to limit the growth of algae. Recent research shows that during the breakdown of barley straw in lake water, chemicals are produced that prevent the growth of some algae during the summer. For barley straw to be effective, it must be added every year otherwise conditions are likely to return to as they were before treatment. Others have proposed that the breakdown of barley straw increases organic carbon in the lake water, promoting the growth of bacteria thereby limiting algal growth. Evidence of this, however, has not been shown to date. In addition, eutrophic lakes are generally high in dissolved organic carbon and research has shown that adding more organic carbon is not likely to stimulate substantial increases in bacterial growth in such lakes.

The use of barley straw has decreased the growth of algae in approximately 50% of the cases studied. Dosing methods are variable, so it is difficult to determine why some cases are successful and others are not. However, the use of barley straw does not reduce internal loading and may actually increase phosphorus release from the sediment in some cases. The breakdown of barley straw in lake water uses oxygen, increasing the chance for phosphorus release from the sediment. The additional organic matter can also interfere with the natural binding of metals (i.e. iron and aluminum) with phosphorus in the sediment of lakes, increasing the potential for internal loading.

5.5 Aeration

Aeration involves the addition of oxygen to the hypolimnion which reduces the release of phosphorus from lake sediment. There are a number of ways to aerate bottom waters in lakes. Oxygen or air can be pumped to the bottom of the lake where oxygen then diffuses into the water. Hypolimnetic water can also be pumped to the surface, run through a baffle system where oxygen can diffuse into the water, and then returned to the hypolimnion. Aeration of the hypolimnion also provides an added benefit to the fishery in a lake because an oxygenated, cold water refuge is provided for larger fish species.

Aeration has been successful at increasing dissolved oxygen and reducing internal loading in a good number of cases. In some of these cases, however, lake water quality did not improve (and in a few cases worsened) because the remaining phosphorus in the hypolimnion was mixed into the surface water more frequently. Thus, design of aeration systems must be precise, both in the amount of aeration needed to keep sediment oxygenated and to prevent mixing of the water column. The sediment must also contain adequate phosphorus binding capacity in order to prevent the release of phosphorus, even under oxygenated conditions. In lakes with high internal loading, sediment binding capacity is often low relative to the amount of mobile phosphorus and either iron or aluminum would need to be added to better control internal phosphorus release from the sediment.

Cost information for aeration systems is limited and highly variable. Rough estimates show that costs can typically range from $500 to $1,500 per acre per year (using oxygen injection) over a 10 year period.

5.6 Dredging

Dredging involves the physical removal of phosphorus rich sediment from the lake. The main benefit is the direct removal of phosphorus from the lake. However, costs for sediment dredge in lakes located in urban areas are generally prohibitively high due mainly to storage and transportation of the dredged material. For example, costs for hydraulic dredging (the most likely option for Twin Lake) would typically range from $3 to $8 per cubic yard of sediment removed but costs could be as high as $50 per cubic yard if specialized methods (due to pollutants or to protect downstream resources) and/or long transportation distances are required. Costs for similar sediment removal projects have ranged up to $25,000 per acre for lakes like Twin Lake that have limited near-shore disposal areas. The total cost for dredging would likely exceed $400,000.

6.0 Summary and Recommendations

Twin Lake is an example of how it can sometimes be quite difficult to determine the true extent of internal phosphorus loading in a lake. Because of the substantial internal loading during the winter and the tendency for internal loading to begin so quickly after lake turnover, collecting sediment cores that can be used to precisely determine the potential for internal phosphorus loading is extremely difficult. However, we used the results from the sediment analysis, along with an estimate for how much phosphorus was released from the sediment previous to coring, to estimate the internal phosphorus loading potential in Twin Lake.

The results from sediment analysis, along with previously collected water quality data, show that Twin Lake has a high level of internal phosphorus loading from the sediment, especially compared to other lakes in the area. Because of this, internal phosphorus loading from the sediment negatively affects water quality in Twin Lake during the growing season.

Additional study may be required to determine the best internal loading management method for Twin Lake. Of the options listed in section 5 above, sediment nutrient inactivation appears to be the most effective option to manage internal phosphorus loading and to improve Twin Lake water quality given the location of the lake, the nearly year round internal release of phosphorus, and the high amount of phosphorus released from the sediment.

7.0 References

Bassett Creek Water Management Commission. 2010. 2009 Water Quality Study: Sweeney Lake, Twin Lake, Northwood Lake, North Rice Pond, and South Rice Pond.

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Appendix A

Twin Lake Winter Monitoring Data Summary

Twin Lake February 2009

Site	Date	Max Depth	Sample Depth (m)	DO Concentration, mg/L	Temperature, deg C	Conductivity	TP, mg/L	pH	Oxidation Reduction Potential (ORP) (mv)	DO Anoxia Threshold, mg/L
Twin	2/26/2009	16.4	0-2				140			
Twin	2/26/2009		0	2.1	0.2	819		8.2	259	2
Twin	2/26/2009		1	1.2	2.9	826		7.6	262	2
Twin	2/26/2009		2	0.5	3.1	827		7.6	260	2
Twin	2/26/2009		3	0.4	3.1	826	62	7.6	250	2
Twin	2/26/2009		4	0.4	3.1	826	64	7.6	206	2
Twin	2/26/2009		5	0.3	3.3	832	76	7.6	-92	2
Twin	2/26/2009		6	0.3	3.4	832	79	7.6	-134	2
Twin	2/26/2009		7	0.3	3.5	835	77	7.6	-137	2
Twin	2/26/2009		8	0.3	3.5	841	86	7.5	-230	2
Twin	2/26/2009		9	0.3	3.5	851	120	7.5	-265	2
Twin	2/26/2009		10	0.3	3.5	860	150	7.4	-293	2
Twin	2/26/2009		11	0.3	3.6	876	200	7.4	-307	2
Twin	2/26/2009		12	0.3	3.8	887	400	7.2	-319	2
Twin	2/26/2009		13	0.3	3.7	895	490	7.2	-330	2
Twin	2/26/2009		14	0.2	3.8	904	600	7.2	-337	2
Twin	2/26/2009		15	0.2	3.8	910	160	7.2	-340	2
Twin	2/26/2009		16	0.2	3.8	960	430	7.2	-340	2

Twin Lake March 2009

Site	Date	Max Depth	Sample Depth (m)	DO Concentration, mg/L	Temperature, deg C	Conductivity	TP, mg/L	pH	Oxidation Reduction Potential (ORP) (mv)	DO Anoxia Threshold, mg/L
Twin	3/17/2009	16.4	0-2				89			
Twin	3/17/2009		0	10.5	1.1	421		7.76	179	2
Twin	3/17/2009		1	8.7	3.7	810		7.78	178	2
Twin	3/17/2009		2	8.5	3.7	812		7.8	176	2
Twin	3/17/2009		3	8.7	3.7	812	85	7.82	175	2
Twin	3/17/2009		4	0.87	3.4	817	86	7.55	-104	2
Twin	3/17/2009		5	0.33	3.4	816	90	7.53	-145	2
Twin	3/17/2009		6	0.28	3.4	817	91	7.5	-189	2
Twin	3/17/2009		7	0.26	3.5	824	110	7.42	-233	2
Twin	3/17/2009		8	0.24	3.5	832	120	7.38	-244	2
Twin	3/17/2009		9	0.23	3.5	842	170	7.36	-262	2
Twin	3/17/2009		10	0.22	3.5	852	200	7.31	-268	2
Twin	3/17/2009		11	0.22	3.5	864	220	7.21	-281	2
Twin	3/17/2009		12	0.22	3.6	871	370	7.17	-288	2
Twin	3/17/2009		13	0.22	3.8	882	220	7.12	-301	2
Twin	3/17/2009		14	0.2	3.7	893	570	7.16	-305	2
Twin	3/17/2009		15	0.2	3.5	917	500	7.19	-305	2
Twin	3/17/2009		16	0.2	3.5	956	290	7.2	-304	2

Twin Lake February 2010

Date	Max Depth (m)	Sample Depth (m)	D.O. (mg/L)	Temp (°C)	Sp. Cond. (µmhos/cm @25°C)	Oxidation Reduction Potential (ORP) (mv)	Total P (µg/L)	pH	DO Anoxia Threshold, mg/L
02/23/10	16.4	0-2					67		
		0.0	1.11	0.13	862	255		7.38	2
		1.0	0.56	1.6	864	247		7.31	2
		2.0	0.35	2.5	863	239		7.41	2
		3.0	0.30	2.6	862	235	62	7.46	2
		4.0	0.3	2.7	863	233	60	7.46	2
		5.0	0.28	2.8	862	231	59	7.51	2
		6.0	0.26	3.0	860	-46	62	7.53	2
		7.0	0.21	3.2	861	-140	96	7.56	2
		8.0	0.22	3.2	873	-198	100	7.56	2
		9.0	0.22	3.4	880	-216	110	7.52	2
		10.0	0.22	3.7	891	-230	240	7.4	2
		11.0	0.22	3.8	902	-237	450	7.33	2
		12.0	0.21	3.9	913	-240	510	7.27	2
		13.0	0.21	4.0	923	-243	630	7.21	2
		14.0	0.21	4.0	929	-245	730	7.2	2
		15.0	0.21	4.0	939	-249	710	7.26	2
		16.0	0.21	4.1	965	-249	560	7.21	2
		16.4	Bottom						
		Slight sulfur odor from 8 meters to 16 meters							

Twin Lake March 2010

Date	Max Depth (m)	Sample Depth (m)	D.O. (mg/L)	Temp (°C)	Sp. Cond. (µmhos/cm @25°C)	Oxidation Reduction Potential (ORP) (mv)	Total P (µg/L)	pH	DO Anoxia Threshold, mg/L
03/15/10	16.4	0-2					31		
		0.0	6.8	0.9	824	-153		8.26	2
		1.0	3.4	2.5	835	-174		8.00	2
		2.0	1.10	2.7	834	-194		7.91	2
		3.0	0.86	2.7	834	-206	53	7.86	2
		4.0	0.53	2.8	834	-209	64	7.83	2
		5.0	0.31	2.9	832	-217	62	7.80	2
		6.0	0.27	3.0	834	-230	73	7.75	2
		7.0	0.24	3.0	846	-239	93	7.68	2
		8.0	0.24	3.1	856	-258	98	7.65	2
		9.0	0.23	3.6	857	-276	180	7.54	2
		10.0	0.22	3.6	872	-281	330	7.49	2
		11.0	0.22	3.8	882	-284	400	7.39	2
		12.0	0.22	3.7	889	-287	190	7.37	2
		13.0	0.22	3.8	897	-290	500	7.33	2
		14.0	0.21	3.6	906	-292	490	7.32	2
		15.0	0.21	3.5	928	-293	530	7.33	2
		16.0	0.21	3.5	980	-294	430	7.35	2
		16.4	Bottom						
Slight sulfur odor from 6 meters to 16 meters.									
12 inches of ice.									

Appendix B

Twin Lake Sediment Data Summary

Twin Lake Sediment Data Summary: Water Content, Loss on Ignition (LOI), and Sediment Density

Sample Location	Depth (cm)	Water (%)	LOI (%)	Sediment Density (g/cm^3)
Twin 1	**0-2**	96.49	33.75	1.01
	2-4	93.60	27.36	1.03
	4-8	90.10	24.53	1.05
	8-12	88.81	23.78	1.06
	15-20	82.93	30.50	1.08
	25-30	87.86	20.21	1.06
Twin 2	**0-2**	93.34	28.37	1.03
	2-4	91.47	26.61	1.04
	4-8	89.86	25.04	1.05
	8-12	88.88	25.83	1.05
	15-20	85.49	24.07	1.07
Twin 3	**0-2**	88.23	16.61	1.06
	2-4	87.69	17.93	1.07
	4-8	86.51	17.31	1.07
	8-12	84.66	16.14	1.09
	15-20	77.09	11.58	1.14

Twin Lake Sediment Data Summary: Phosphorus Concentration (mg/g)

Sample Location	Depth (cm)	Mobile P (mg/g)	Organic-P (mg/g)	Total P (mg/g)
Twin 1	0-2	0.21	0.88	1.12
	2-4	0.14	0.49	0.77
	4-8	0.15	0.35	0.67
	8-12	0.13	0.32	0.65
	15-20	0.14	0.21	0.56
	25-30	0.19	0.28	0.63
Twin 2	0-2	0.10	0.51	0.83
	2-4	0.06	0.36	0.64
	4-8	0.08	0.37	0.73
	8-12	0.10	0.37	0.73
	15-20	0.12	0.24	0.58
Twin 3	0-2	0.05	0.22	0.45
	2-4	0.03	0.23	0.43
	4-8	0.04	0.21	0.42
	8-12	0.06	0.16	0.41
	15-20	0.04	0.08	0.25

Twin Lake Sediment Data Summary: Phosphorus Mass ($\mu g/cm^3$)

Sample Location	Depth (cm)	Mobile P ($\mu g/cm^3$)	Organic P ($\mu g/cm^3$)	Total P ($\mu g/cm^3$)
Twin 1	0-2	7.4	31.3	39.8
	2-4	8.9	32.4	50.5
	4-8	16.0	35.9	69.9
	8-12	15.3	37.8	76.3
	15-20	25.0	38.4	102.7
	25-30	24.0	36.6	81.8
Twin 2	0-2	6.9	34.9	56.9
	2-4	5.8	31.6	57.2
	4-8	8.3	39.7	77.9
	8-12	12.1	43.5	85.3
	15-20	18.6	37.8	90.6
Twin 3	0-2	6.8	27.8	55.9
	2-4	4.4	30.8	56.9
	4-8	6.5	29.9	61.5
	8-12	9.4	26.0	68.1
	15-20	11.0	20.7	66.2