LAKE MITCHELL ALUM TREATMENT SYSTEM

FINAL REPORT & RECOMMENDATIONS

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INTRODUCTION

Lake Mitchell serves as the City of Mitchell's water supply and is a much-valued recreational resource. Lake Mitchell experiences summer-long algae blooms that taint the water supply and make recreation unpleasant. These algae blooms are a serious concern.

The City of Mitchell, along with the state and other partners, has initiated a comprehensive watershed clean up program aimed at reducing the nutrients that run off into the lake and feed the algae. This project is long-term in scope, and will take at least 15 years to complete.

Because the watershed clean up is a long-term effort and also because Lake Mitchell will be slow to respond, it is anticipated that decades will pass before significant water quality improvements will be observed. While this long-term program is needed to address the underlying cause of the algae problems, a supplementary remedy will also be needed in the short-term, if quicker improvements are desired.

Recognizing this dual need, the City of Mitchell retained ECOSYSTEM STRATEGIES and FRESHWATER RESEARCH to:

- Evaluate the lake and watershed conditions
- Develop appropriate water quality goals
- Conduct field studies
- Develop a water quality model, and
- Design an alum treatment system implementation plan

This report, along with an assessment and modeling study (Nürnberg and Osgood 2002), documents the work of ECOSYSTEM STRATEGIES and FRESHWATER RESEARCH and presents their analyses and modeling, summarizes the results of the field studies, and recommends an alum treatment system and implementation plan.

THE PROBLEM

Excessive algae growth causes unpleasant tastes and an odor in the City's drinking water and detracts from the lake's aesthetic qualities. The lake's poor water quality poses minimal public health concerns, because the raw water is treated at the water utility before it is distributed for drinking water. Algae problems in Lake Mitchell are longstanding, and there is evidence that lake phosphorus, which could make algae blooms worse, is increasing over the past decade (Nürnberg and Osgood 2002).

Causes of Eutrophication

Excessive and obnoxious algae blooms are common in lakes with elevated nutrient levels. Lakes enriched with nutrients are referred to as 'eutrophic' or 'hyper-eutrophic' and the process of lake enrichment is referred to as 'eutrophication.' Normally phosphorus is the nutrient that causes algae growth, as it is in shortest supply relative to the growth needs of the algae. Thus, as phosphorus in lakes increases, so does

- The amount of algae
- The likelihood of algae blooms
- The intensity and frequency of algae blooms
- The prevalence of blue-green algae
- The likelihood of toxic-producing algae
- And complaints and concerns with water quality

Lake Mitchell has probably been eutrophic since it was created, because Firesteel Creek, its main tributary, is fed by a large fertile watershed. In other words, Lake Mitchell has not become eutrophic, but rather has always been eutrophic. So the algae problems in Lake Mitchell may be intensifying, but they are not new.

The City will soon be supplementing its municipal water by using the Missouri River pipeline (known as the 'B-Y Water Project Expansion'), which will deliver treated drinking water. The Missouri River water will offset lake water quality concerns only to a small extent. Because this source will supply only the basic needs, like drinking water, and not seasonal demands, like lawn watering, Lake Mitchell water will still be used during the summer. Thus, the taste and odor episodes in the public drinking water will continue.

Present Condition of Lake Mitchell

Lake Mitchell has persistent summertime blooms of the blue-green algae called *Aphanizomenon flos-aquae* which form dense accumulations in the surface waters and along the lake shore. Other blue-green algae, which also create nuisance conditions, also occur at other times throughout the year. The intensity of the algae blooms tends to decrease downstream from the mouth of Firesteel Creek to the spillway. In fact, the amount of algae and water clarity near the spillway are often found at acceptable limits.

Lake Mitchell water quality is highly variable due to climatic and flow conditions. In addition, it is common for conditions to be variable in the lake as algae blooms are typically more intense near the inlet compared to near the dam. However, even its best condition has been deemed unacceptable by the City's Lake Development Committee.

Annual phosphorus inputs and water flows to Lake Mitchell are highly variable. The following table indicates the median (50th percentile[1]) and extreme (10th and 90th percentile) values for annual phosphorus and water inputs based on 1979 – 2001 data (from Nürnberg and Osgood 2002):

Percentile	Outflow (acre-feet/year)	Phosphorus Input (pounds/year)
10th	17,000	1,570
50th (median)	92,600	40,800
90th	434,000	223,000

Similarly, the amount of phosphorus added to the lake water during the summer through internal recycling ranges from 0 to 15,300 pounds per year (from Nürnberg and Osgood 2002).

There is a strong seasonal aspect to the inputs of phosphorus as well. In many years, the inflow from Firesteel Creek stops altogether by the end of June. On average, less than 10% of the annual phosphorus inputs from Firesteel Creek enter Lake Mitchell during July, August and September, while over 70% enter during March, April and May.

[1] Percentiles are used throughout this report to refer to a normal range of conditions. Percentiles are based on long-term observations of rainfall, water flows, etc. The 50th percentile, also known as the median, represents the midpoint in a sequence of observations. Other values indicate the frequency of occurrence. For example, lake outflow of 17,000 acre-feet per year (from above) represents the 10th percentile, outflows are less than this in 10% of the years between 1979 and 2001 and more than this in 90% of the years.

Nürnberg and Osgood (2002) developed a model to predict lake phosphorus concentration based on annual inputs of phosphorus and water flows. By taking the variable inputs into account, we get a picture of the range of conditions expected in Lake Mitchell during wet, dry and normal years. The table below presents predicted summer average lake phosphorus concentrations in a range of scenarios based on water flow:

Percentile	Lake Phosphorus Concentration (parts per billion, ppb)
10th	328
25th	217
50th (median)	241
75th	416
90th	475

For reference, eutrophic conditions occur when lake phosphorus concentrations exceed 30 ppb. Hyper-eutrophic conditions, the most extreme, occur when lake phosphorus exceeds 100 ppb. Internally supplied phosphorus has a much larger impact on lake phosphorus during low flow years. For example, internal phosphorus loading accounts for about three quarters of the lake phosphorus loading during the summer of dry years (25th percentile), but only about 5% during wet years (75th percentile).

SOLUTIONS

Water Quality Management Objective

Excessive blue-green algae growth is the identified problem in Lake Mitchell. Elevated phosphorus concentrations, especially during the summer, are the cause of this problem. We know from studies conducted on other lakes, lake regions and lakes world-wide there is a simple relationship between the amount of phosphorus in lakes and the amount of algae. These relationships are remarkably consistent, and are therefore a reliable tool for setting water quality goals.

For example, Heiskary (1997) presents relationships for Minnesota lakes as:

$$\log CLA = 1.16 \log TP - 0.76$$

where CLA is average summer chlorophyll a (ppb) and TP is average summer total phosphorus (ppb). Similar relationships are found in other regions and on various geographic scales (Nürnberg 1996). Simply, as phosphorus in lakes increases, there are more algae.

While the general relationships are valid, they do not provide adequate guidance for Lake Mitchell. Specifically, lakes dominated by *Aphanizomenon* have less algal abundance (as measured by chlorophyll) than expected from phosphorus concentration (Osgood 1982 and 1988). Furthermore, decreases in lake phosphorus, the presumed management goal, may lead to changes in the dominant alga, which in some circumstances could result in increased algal abundance (Osgood 1988). Therefore, Nürnberg and Osgood (2002) have developed models that are applicable to Lake Mitchell.

Because Lake Mitchell's phosphorus concentration is so high, it is reasonable to conclude that meaningful changes in algal dominance and reductions in algal abundance will only occur when lake phosphorus concentration is drastically lowered below a critical level.

No studies have been published for this area in South Dakota, but a report from Minnesota may be transferable to Lake Mitchell (Heiskary 1997). This study compares lakes in different ecoregions[2] in Minnesota. The 'Northern Glaciated Plains' ecoregion in the southwestern corner of Minnesota should be applicable to the adjacent areas in South Dakota, including the Lake Mitchell watershed.

[2] An ecoregion refers to geographical areas of similar physical and chemical features. Lakes within the same ecoregion are similar to other lakes in the ecoregion, so they can be compared for setting realistic water quality goals.

Lakes in the Northern Glaciated Plains ecoregion are enriched with phosphorus compared to lakes from most other ecoregions in Minnesota. Their phosphorus concentration has the following distribution:

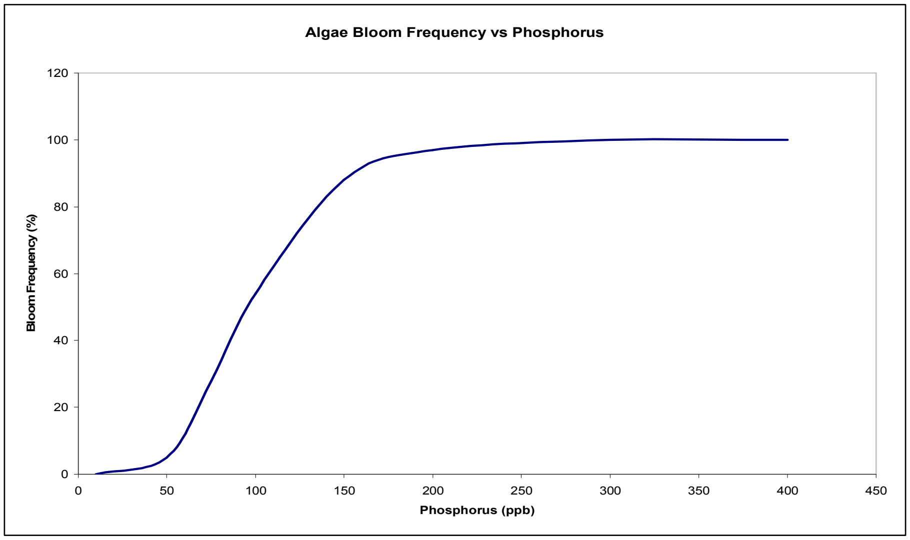
Percentile	Phosphorus Concentration
10 %	116 parts per billion (ppb)
25 %	140 ppb
50 %	179 ppb
75 %	404 ppb
90 %	487 ppb

This means only 10% of the lakes have phosphorus concentrations below 116 ppb, 25% have phosphorus concentrations below 140 ppb, and so on. Lacking studies, we do not know if lakes in the area of Lake Mitchell have a similar distribution of phosphorus concentrations. Also, Lake Mitchell is an impoundment, which is uncommon in the Northern Glaciated Plains ecoregion of Minnesota. Nonetheless, we believe the ecoregion analysis can provide reasonable targets or guidelines for Lake Mitchell.

A common way to assign a water quality goal is to use the 25^{th} percentile, which in this case is 140 ppb. In this context, a phosphorus concentration of 140 ppb may be considered a 'reasonably attainable' goal for a watershed clean-up program. In other words, it is unlikely that Lake Mitchell's phosphorus concentration could realistically be reduced below 140 ppb by watershed management efforts alone.

Lake Mitchell's phosphorus concentration (summer average) typically ranges from 217 ppb to 475 ppb (see Nürnberg and Osgood 2002).

In the context of the ecoregion analysis there is a relationship between the lake's summer average phosphorus concentration and the frequency of algae blooms (see figure below). Here, an algae bloom is considered to occur when the chlorophyll concentration exceeds 30 ppb. At phosphorus concentrations above 160 ppb, we see algae blooms for 90% of the summer; and at phosphorus concentrations above 200 ppb, algae blooms all summer long. As summer phosphorus concentrations are reduced below about 160 ppb, the frequency of algae blooms is also reduced.



This graph can be used to select a desired water quality condition (with respect to algae blooms) and convert that to a water quality goal. For example, if a desired condition is 'algae blooms 50% of the summer,' a management goal, the management objective would be to attain a summer phosphorus average of about 90 ppb. The graph illustrates another critical point: there will be little perceivable water quality improvements (reductions in algae blooms) until the lake phosphorus concentration is reduced to less than about 140 ppb.

Here are some benchmarks that were used for goal-setting by Mitchell's Lake Development Committee:

Management Goal	Management Objective (Phosphorus Concentration)
Blooms 90% (of summer)	160 ppb
Blooms 75%	120 ppb
Blooms 50%	90 ppb
Blooms 25%	70 ppb
Blooms 10%	50 ppb

Figure 5-3 in Nürnberg and Osgood (2002) estimates algae bloom frequencies based on data from Lake Mitchell. These results indicate a lower algal bloom frequency and more linear decrease in algae bloom frequency as phosphorus decreases from 400 ppb. Still, similar conclusions are drawn from both perspectives. The likelihood for noticeable improvements will occur at lake phosphorus concentrations below 100 pp.

Based on these analyses, the Lake Development Committee agreed that a phosphorus concentration of 90 ppb should be a provisional management objective for Lake Mitchell. It is 'provisional' because a) at this level visible water quality improvements will occur, but b) once attained, it may be discovered there remain water quality concerns (see discussion below).

Lakes with *Aphanizomenon*

Aphanizomenon is a filamentous (hair-like) blue-green alga that can form dense accumulations in lakes. *Aphanizomenon*, when it blooms, causes unpleasant tastes and odors in public water supplies (typically a 'dead fish' smell), turns the water murky, accumulates on lake shores where they stink upon decompositions, and may even form substances that are toxic to livestock and pets. *Aphanizomenon* filaments may form colonies that look like grass clippings. This is the form observed in Lake Mitchell.

The colonial form of *Aphanizomenon* is a result of an association with a large zooplankton, called *Daphnia*, which 'helps' *Aphanizomenon* by eating competing algae and clearing the water (Lynch 1980). In turn, *Aphanizomenon* 'helps' *Daphnia* by providing visual shields, which allows *Daphnia* to avoid predators.

Lakes with colony-forming Aphanizomenon have significantly less chlorophyll (a measure of algae) compared to other lakes with similar phosphorus content (Osgood 1988). Even though these lakes have less overall algae, the *Aphanizomenon* still forms nuisance blooms. Interestingly, when the colony-forming *Aphanizomenon* are replaced by other algae, the overall amount of algae may increase, even when the amount of phosphorus decreases (Osgood 1988).

Aphanizomenon is formed from resting cells on the lake bottom. As these cells 'germinate,' they rise into the water and bring phosphorus from the lake sediments (Osgood 1988; Barbiero and Welch 1992; Barbiero and Kahn 1994). The *Aphanizomenon*-mediated phosphorus transfer from lake sediments probably occurs in shallow as well as deep waters.

Expected Results of the Firesteel Creek Watershed Project

The stated goal of the Firesteel Creek Watershed Project is to 'reduce phosphorus delivery to Lake Mitchell to reduce in-lake phosphorus by 50% by 2015.' The diagnostic-feasibility study (Stueven and Scholtes 1997) indicates a 50% reduction in phosphorus delivery to Lake Mitchell can be achieved by eliminating the soluble phosphorus export from 116 identified animal feeding areas. Further, the study indicated that a 50% reduction in phosphorus inputs would reduce Lake Mitchell chlorophyll concentrations to a mesotrophic level.

The Firesteel Creek Watershed Project began in 1998 and is funded through March 2007. As of this time, six feedlot systems have been installed and about six more are in various stages of planning and design. In addition, other conservation practices, such as clean water diversions, are being considered for smaller, upstream feedlots. It appears the goal of reducing phosphorus inputs to Lake Mitchell by 50% may be optimistic. Ultimately, watershed monitoring, which is included in the Project, ought to quantify the results.

The phosphorus concentration in Lake Mitchell can be predicted following a 50% reduction in the total external phosphorus inputs using the model in Nürnberg and Osgood (2002). The following table provides predicted lake phosphorus concentrations during a range of flow conditions and internal inputs. Lake phosphorus concentrations are compared to the present condition (no decrease in external input) with average internal phosphorus input rates (+/- 2x):

Flow Percentile	Lake P Concentration (ppb) Present Condition	Lake P Concentration (ppb) 50% Reduction in External Load
10^{th}	328	325 (167 – 642)*
25^{th}	217	194 (112 – 358)*
50^{th} (median)	241	156 (123 – 220)*
75^{th}	416	223 (212 – 244)*
90^{th}	475	250 (242 – 267)*

* Predicted lake P concentration using ½ the average internal load and twice the average internal load in parenthesis. See also Table 5-4 in Nürnberg and Osgood (2002).

In every scenario, the management objective of 90 ppb is exceeded. Therefore, even if the external phosphorus inputs to Lake Mitchell are reduced by 50%, the water quality of Lake Mitchell is not anticipated to improve to an acceptable condition.

Management Alternatives

Controlling nuisance blue-green algae in Lake Mitchell will be a large challenge due to the extreme phosphorus concentrations. Given that Lake Mitchell was impounded along Firesteel Creek at the base of a large, fertile watershed, it is likely Lake Mitchell has always been eutrophic.

Given that a) the Lake Mitchell watershed contributes over 90% of the total phosphorus inputs to Lake Mitchell, b) a thorough watershed evaluation has been completed (Stueven and Scholtes 1997), and c) the fact that the Firesteel Creek Watershed Project is already being implemented, additional watershed management strategies and techniques, such as those in Thornton and Creager (2001), do not require further evaluation.

Instead, here we evaluate in-lake management alternatives for their feasibility in addressing concerns with nuisance blue-green algae. Below is an inventory of accepted lake management options for controlling algae in lakes. In particular, Wagner (2001) lists 17 categories of management in-lake techniques that can be applied in lakes and reservoirs. The aptness of those techniques are summarized in the table below:

Technique	Description	Comments referring to Lake Mitchell
Hypolimnetic aeration or oxygenation	Adds oxygen below the lake's thermocline retard the release of internal phosphorus.	Lake Mitchell has a poorly developed thermocline.
Circulation and destratification	Induces an artificial circulation to mix algae into dark waters and reduce their productivity.	Lake Mitchell already circulates through wind action.
Dilution and flushing	Adds high volumes of water to either dilute the high nutrients in a lake or flush algae out of the lake.	There is no high volume, low P water source nearby.
Drawdown	A lake is drawn down to expose near shore sediments, where they may oxidize and be compacted. This reduces sediment capacity to re-circulate nutrients.	It may be feasible to draw down Lake Mitchell, but the potential improvement is small.
Dredging	Removes nutrient-rich sediments to remove an internal P source and deepens a lake.	Very costly.
Light-limiting dyes and surface covers	Reduces or blocks sunlight availability to algae	Neither feasible nor appropriate for Lake Mitchell.
Mechanical removal (of algae)	Filters or skims algae from the lake water.	Too large a scale for Lake Mitchell.
Selective withdrawal	Removes nutrient-rich or low oxygen water from a lower strata, thus reducing internal P supplies.	Lake Mitchell is only weakly stratified and City's water already taken from deep water.
Algicides	Chemicals that kill algae.	Inefficient. There is evidence that blue-green algae will adapt, so increasing doses are required.
Phosphorus inactivation	Removing P from lake water by precipitating with alum or other chemicals.	An alum application system is described in detail below.
Sediment oxidation	An oxidizing agent is added to deep lake sediments to bind P and reduce internal supplies.	The alum system described below includes a sediment element to control internal P.
Settling agents	Lime, alum or polymers added to settle P and algae.	The alum system described below includes a sediment element to control internal P.
Selective nutrient addition	The addition of non-limiting nutrients to change the composition of algae to a more desirable form.	Not appropriate at the extreme P levels in Lake Mitchell.
Enhanced grazing	Manipulating fish communities to alter food chain to favor algae consumption.	Not effective in hypereutrophic lakes.
Bottom-feeding fish removal	Removes fish that feed on the lake bottom thereby reducing an internal P source.	Bottom-feeding fish have not been shown to be problematic.
Fungal/bacterial/viral pathogens	Biological agents that attack and kill algae.	Highly experimental with uncertain results.
Competition and allelopathy	Encouraging the growth of competing plants or adding plant exudates that inhibit algae growth.	Too large a scale for Lake Mitchell.

Simply put, the algae problems in Lake Mitchell are of such a large scale and extreme nature, that most lake management techniques are either not feasible or insufficient. Controlling the nutrient that limits algae growth, phosphorus, is the most direct and appropriate management target. In the long-term, the Firesteel Creek Watershed Project is intended to reduce incoming phosphorus by 50%. Due to the effects of internally recycled phosphorus however, it is not anticipated that Lake Mitchell's management objective will be met (see modeling analysis above). Thus, internal phosphorus supplies will need to be reduced as part of any long-term solution.

In the short-term, until the incoming phosphorus load is reduced substantially, a system to apply alum is recommended to reach the provisional lake management objective.

How Alum Works to Inactivate Phosphorus

Alum is applied to lake water as aluminum sulfate, or $Al_2(SO_4)_3 \cdot 14\ H_2O$. As aluminum sulfate is added to water, it forms aluminum ions, which are hydrated (combined with water):

$$Al^{+3} + 6\ H_2O \rightleftarrows Al\ (H_2O)_6^{3+}$$

In a series of chemical hydrolysis steps, hydrogen ions are liberated, which may lower the water pH, and ultimately forms aluminum hydroxide ($Al(OH)_3$), which is a solid precipitate:

$$Al^{3+} + H_2O \rightleftarrows \text{intermediate reactions} \rightleftarrows Al(OH)_3(s) + H^+$$

The solid precipitate forms a flocculent material, referred to as a floc, that has a high capacity to adsorb phosphates. At the pH of Lake Mitchell, these reactions occur quickly and the floc is stable. Aluminum hydroxide ultimately settles to the lake bottom where it remains stable and poses no toxicity to aquatic life.

If aluminum sulfate is applied as a bulk application, the aluminum hydroxide floc coagulates quickly. Bulk applications are thus intended to form an aluminum hydroxide layer on the lake bottom, which forms an effective barrier to the release of phosphates from the lake bottom sediments. Lake phosphorus concentrations are reduced markedly as an additional benefit of a bulk alum application. The aluminum hydroxide layer may be disrupted by wind and wave action or become inefficient if the incoming phosphorus supplies remain unabated.

Alum can also be applied in lower doses directly to the incoming water or into the lake water. By this technique, aluminum hydroxide is injected into the lake or stream water as colloidal-sized (microscopic) particles that remain suspended for longer periods scavenging phosphates. Essentially, the alum uses (eliminates or inactivates) phosphates. In this way, the aluminum hydroxide particles compete with algae for available phosphates, thereby starving the algae. Eventually, the particles coagulate and settle to the lake bottom.

ALUM TREATMENT SYSTEM

A system to apply aluminum sulfate, or alum, to Lake Mitchell is recommended. The alum system is designed to reduce phosphorus concentrations in Lake Mitchell to levels where algae blooms are no longer problematic. The alum treatment system is a short-term remedy, intended to be operational until watershed treatments are fully implemented and beneficial effects to the lake quality become apparent.

The conditions in Lake Mitchell are extreme; so much so, that ordinary lake management techniques are cost-prohibitive or not feasible. For example, copper sulfate is commonly used as an herbicide to treat nuisance algae. Copper sulfate, if it were to be used in Lake Mitchell, would require at least three applications per year at an estimated cost of (minimally) $345,000 to $690,000 per season (from Wagner 2001). Due to the numerous concerns with copper sulfate use for nuisance algae control (non-target toxicity, copper accumulation in the lake sediments, etc.), we would not recommend its use in Lake Mitchell, even if the cost were much less.

Alum is recommended as a short-term solution to mitigating nuisance blue-green algae blooms in Lake Mitchell because:

- Alum will directly precipitate phosphorus from the lake water and inactivate phosphorus from the lake sediments, thus addressing the cause of the algae blooms.
- Alum is not toxic when applied under the alkaline conditions observed in Lake Mitchell.
- Alum will result in immediate and controllable improvements.
- Alum is readily available and can be applied using proven methods.

Alum is ordinarily applied to lakes to provide a chemical seal to the lake bottom and control internal phosphorus supplies. In this context, an alum application is considered a one-time treatment following a reduction in external phosphorus inputs. In that way, the improved conditions can last up to 15 years (Welch and Cooke 1999).

According to this typical scenario, alum is not recommended for a) reservoirs, because of their high flushing rates and b) where external phosphorus inputs are high (Wagner 2001). Both conditions are true for Lake Mitchell. This means alum, if it is to be effective, should not be applied to Lake Mitchell in the typical way.

In addition to the typical whole-lake alum application technique, alum has been used in two other ways: 1) Alum has been applied to inflowing streams to remove phosphorus before it enters a lake (Harper et al. 1983; Cooke and Carlson 1986) and 2) alum has been applied directly to lake water in low doses (Sweetwater Technology, unpublished). In the former case, alum is added to an incoming stream through an in-line treatment system to bind phosphorus, thereby keeping it unavailable for algae. In the latter case, alum is injected directly into the lake water where alum particles scavenge phosphorus, thereby keeping it unavailable for algae. Neither method is well documented in the literature.

Alum System Elements

The 'alum system' we speak of designing evaluates some combination of the three alum application methods. It is clear from the models developed for Lake Mitchell (Nürnberg and Osgood 2002) the management objective of a lake phosphorus concentration 90 ppb cannot be achieved without addressing both the external and internal phosphorus sources.

a. Whole-Lake Application

A one-time whole-lake alum application would add enough alum to create an aluminum hydroxide floc sufficient to chemically seal the bottom sediments and retard phosphorus recycling. It appears the internal phosphorus originates from shallow and deep water sediments. Thus, a one-time whole-lake application would be of limited effectiveness due to the impracticality of applying alum in very shallow water and the likelihood that the floc would be carried into deep waters by wave action.

Internal phosphorus inputs in Lake Mitchell come from shallow as well as deep areas. Alum blankets applied in shallow lakes tend to have a shorter longevity (Welch et al. 1988; Welch and Schrieve 1994). In addition, alum-treated shallow lakes may not fully eliminate filamentous blue-green algae or the phosphorus the algae may translocated from the lake bottom (Jacoby et al. 1994; Perakis et al. 1994; Sonnichsen et al. 1997); although sediment phosphorus release is reduced and there are cases where blue-green algae is reduced (Welch and Schrieve 1994). Welch and Cooke (1999) found the alum treatments in lakes with extensive macrophytes was largely ineffective, but in other shallow lakes, the alum treatments lasted for at least five years and the lake phosphorus content was reduced by 50 to 80%. In fact, they observed "a complete absence of *Aphanizomenon* for eight years in Campbell and Long Lakes."

Determining the rate of alum application is an evolving science. Most methods or calculations focus on deep-water sediments. Welch and Cooke (1999) report alum application rates ranging from 5.5 to 10.9 gm $Al \cdot m^{-3}$ for polymictic (shallow) lakes. Rydin and Welch (1999) calculated a rate of 150 gm $Al \cdot m^{-2}$ should have been used in Lake Delavan. These rates, if applied to Lake Mitchell's entire volume or surface, would translate to:

Rate*	Amount of Alum
5.5 to 10.9 gm $Al \cdot m^{-3}$	307,000 to 609,000 gallons
150 gm $Al \cdot m^{-2}$	2,100,000 gallons

* Note the different units.

The rates calculated above are applied to the entire surface of Lake Mitchell, whereas, they are meant to be applied only to deep-lake sediments in most other situations.

Rydin et al. (2000) showed that phosphorus will be sufficiently bound and effectively removed from internal recycling if aluminum (as alum) is added at a rate of 11-times (by weight) that of the mobile phosphorus pool in the sediments. Thus, a whole-lake alum application would bind the available phosphorus in the sediments. Accordingly, the appropriate dose for Lake Mitchell is 530,000 gallons alum. Such an application would not account for phosphorus that is in the lake at the time of treatment or that washes into the lake subsequent to the treatment.

Normally, an alum treatment is designed to seal the lake sediments for the longest possible time. Ideally, such a treatment follows a substantial reduction in watershed phosphorus inputs, so the duration of treatment is maximized. To the extent phosphorus is added, a whole-lake treatment should be great enough to retard internal phosphorus release, but small enough so as not to be wasteful. With this balance in mind, a five-year alum dose for Lake Mitchell is calculated to be 656,000 gallons alum (Appendix A). Due to extensive mixing and *Aphanizomenon* translocation of phosphorus, we think the impact of this treatment would be a reduction in internal loading roughly 50%, although we have no objective way to calculate this reduction.

A whole-lake alum application alone, assuming it reduces internal phosphorus loading by 50%, will not achieve the provisional management objective of a lake phosphorus concentration of 90 ppb. Lake summer average phosphorus concentration under various flow regimes is estimated as (from Table 5-4 in Nürnberg and Osgood 2002):

Flow Percentile	Lake P Concentration (ppb) Present Condition	Lake P Concentration (ppb) 50% Reduction in Internal Load
10th	328	168
25th	217	135
50th (median)	241	208
75th	416	405
90th	475	466

Whole-lake alum applications are considered in combination with other alum application methods in the scenarios presented below.

b. Inflow Injection

Because the inflow to Lake Mitchell stops entirely in June in most years (Nürnberg and Osgood 2002), injecting alum into the inflow does not make sense as the benefits of the treatment would not reach the lake during the summer. Therefore, it will not be considered.

c. In-Lake Injection

Alum may be applied to lakes by injecting and circulating liquid alum directly into lake water as a fine floc, or microfloc, for the purpose of stripping phosphorus from the lake water (Sweetwater Technology, unpublished). A shore station is constructed that pumps liquid alum and compressed air in parallel lines to a system of diffusers (multiple lines) placed on the lake bottom. The liquid alum is pumped through a microfloc generator (Sweetwater Technology) into the rising bubble column, which help mix the alum throughout the lake. The daily alum dose can be regulated according to an operational plan or demand.

The shore station must have an electrical supply and the equipment must be housed in a secure structure. In addition, an alum reservoir must be located nearby.

We have evaluated two scenarios, one using in-lake alum injection alone and the second using in-lake alum injection and periodic whole-lake alum applications. Both scenarios will achieve the provisional management objective of 90 ppb lake phosphorus concentration.

Scenario #1 applies alum only by injecting it into the lake and would use these amounts of alum (Appendix A):

Low Range[3]	137,000 gallons alum per year
Mid Range	215,000 gallons alum per year
High Range	445,000 gallons alum per year

Scenario #2 applies alum by injecting into the lake plus a whole-lake alum application every five years and would use these amounts of alum (Appendix A):

Low Range	186,000 gallons alum per year
Mid Range	262,000 gallons alum per year
High Range	438,000 gallons alum per year

* The annual alum rates include 1/5 of the five-year whole-lake dose.

[3] Low-, mid- and high-ranges are calculated based on the median (mid-range) and the interquartiles (see Appendix A)

d. Annual Whole-Lake Alum Application

Here, we evaluate a method to apply alum using a low dose, annual, whole-lake application as a way to a) take advantage of the fact that the inflow to Lake Mitchell decreases in late-Spring and often stops in mid-June and b) use less alum on an annual basis compared to scenario nos. 1 and 2.

Scenario #3 annually applies alum to the whole lake, timed to occur when the inflow stops or nearly stops, but before algae blooms become problematic – about mid-June. The annual dose is (Appendix A):

First Year	150,000 gallons alum

Under scenario #3, we expect less alum will be needed each year. Further, scenario #3 requires no investment in equipment to distribute the alum. In addition, it is more likely compared to scenario nos. 1 and 2, the phosphorus concentration objective of 90 ppb will be met. Finally, this approach can be easily modified.

Because a single, mid-June treatment is proposed, there is a risk that a large summer runoff event (after mid-June) could pervert the treatment and cause algae blooms. Unusually high flows of twice the average can be expected in 5% of the years (1 year in 20) based on flows of the years between 1979 and 2001.

All three scenarios represent, either singly or in combination, the alum system elements, and are designed to achieve the provisional phosphorus concentration objective of 90 ppb. We recommend and provide further evaluation for scenario #3 as the preferred method for applying alum in Lake Mitchell.

Expected Results

Reducing Lake Mitchell's phosphorus concentration to 90 ppb, as in Scenario nos. 1 and 2, will lower the amount of algae somewhat, especially if the algae remain dominated by *Aphanizomenon*. There is contrary evidence in the literature regarding the effectiveness of alum treatments in eliminating or controlling *Aphanizomenon* and other filamentous algae, however, in most cases improvements have occurred. Because lowering the lake's phosphorus concentration to 90 ppb represents a drastic reduction, the algae will, hopefully, shift to other species. Even if such a shift occurs, the algal abundance, as measured by chlorophyll, may increase.

The best guidance is the frequency of algae blooms, those periods where algae are at extreme concentrations, will be reduced from practically all summer to about half the summer. Whether this improvement is judged to be worth while ought to be left up to the community of people using Lake Mitchell.

Reducing Lake Mitchell's phosphorus concentration below 90 ppb, as in scenario #3, should have an even more marked benefit. Based on the experience of many whole-lake alum treatments, it is common for lake phosphorus concentrations to be reduced to very low levels, often below 50 ppb. At this very low level, all algae should be controlled.

To the extent water clarity increases following an alum treatment, the light environment will be more favorable for rooted aquatic plants and attached algae growth. Based on an inspection conducted in the summer of 2001, there are practically no rooted plants or attached algae in Lake Mitchell. As well, the substrate (bottom type) is mostly sand and gravel in the nearshore areas, which is not conducive to rooted aquatic plant growth. Carp and other bottom-feeding fish will likely keep any rooted plants that may appear in check. Attached algae, sometimes called angle hair, may grow on hard surfaces like docks, pilings, seawalls and boat ramps in clearer water.

Finally, as Lake Mitchell's water clears, the episodes of taste and odor caused by algae blooms will be reduced. Normally, such an improvement translated into savings in treating public water supplies (Walker et al. 1989); although we have not evaluated that benefit for Lake Mitchell's water supply.

Permits

South Dakota Department of Environment and Natural Resources must approve a 'Water Resources Enhancement or Restoration Project' application for the addition of alum to Lake Mitchell (Appendix B). In addition, an alum application to Lake Mitchell could not violate South Dakota Surface Water Quality Standards. The following sections of the state's standards may be applicable to this project:

- 74:51:01:58. Water resource enhancement or restoration projects – Use of toxic pollutants.
- 74:51:01:59. Water resource enhancement or restoration projects – Use of EPA-registered pesticides.
- 74:51:01:60. Water resource enhancement or restoration projects – Department approval required.
- 74:51:01:61. Publication of notice of application for water resource enhancement or restoration projects – Exception for registered pesticides.
- 74:51:01:61. Hearing procedure for water resource enhancement or restoration projects.

Recommendations

A three-phase lake management approach is recommended. The three phases are:

- Phase One – Diagnostic evaluation and design of alum treatment system (present study)
- Phase Two – Initial project implementation and fine tuning
- Phase Three – Ongoing operation

The present study has described an alum treatment system that will improve Lake Mitchell's water quality. The extreme magnitude of the problem as well as the solution, has necessitated a design and recommendation of an alum system tailored to the needs of Lake Mitchell. Because the system is unique, at least as it is recommended for Lake Mitchell, we expect some 'fine tuning' will be needed to adapt our approach to Lake Mitchell.

Here we make recommendations for Phase Two.

Phase Two Implementation

We recommend a three-year Phase Two implementation. During that time, annual alum applications (Scenario #3), lake monitoring and evaluation will occur so that in each subsequent year, the annual alum application will be refined and the outcome will be more predictable. The goal of Phase Two is to turn over the operation of the alum treatment system to local control with minimal, if any, outside consulting needed.

1. Annual Alum Treatments

We recommend a mid-June, whole-lake alum applications at diminishing rates. The alum dose for the first year should be 150,000 gallons. The dose for the second and thirds years will be determined based on the results of the first year, but will not likely be less than 100,000 gallons.

Provisions should be made ahead of time for the possibility that a wetter than normal summer will prematurely re-supply Lake Mitchell with phosphorus from Firesteel Creek and cause an algae bloom. Based on past monitoring, there appears to be a 10 to 15% chance this will occur. If this occurs, the City can either 'live with the result' or provide for a second alum treatment. Should a second treatment be needed, we anticipate a much lower dose will be required; although that determination must be made at that time.

2. Monitoring and Field Services

a. Measure Lake Bathymetry

Lake bathymetry refers to a detailed bottom contour map. Detailed depth soundings and position measurements are required to accurately map Lake Mitchell's bottom contours. More accurate lake bathymetry will improve the utility of the lake models and the calculation of the required alum dose.

b. Lake Monitoring

Lake monitoring activities should include weekly, biweekly and automated monitoring activities. The data and observations from this monitoring are necessary so the efficacy of the alum treatments can be evaluated, the lake models refined and the continuing alum applications fine-tuned.

<u>Weekly</u>

Weekly Secchi disk measurement should be taken from mid-April through September from lake stations 11, 12A, 12B and 13A.

At least weekly stage measurements should be taken from the dam overflow throughout the year. An accurate stage-overflow curve should be verified. More frequent stage measurements should be taken during periods of increasing or decreasing flow. Measurements of stage (lake level) should be taken, even during periods when no water is flowing over the dam.

<u>Bi-Weekly</u>

Bi-weekly sampling from mid-April through September for the following parameters should occur at lake stations 12A, 12B and 13A:

- Dissolved oxygen/temperature (profile)
- Total phosphorus (surface sample)
- Chlorophyll *a* (surface sample)
- pH (surface sample)

<u>Automatic</u>

The U.S.G.S. monitoring station at Firesteel Creek Inflow #1 provides continuous flow data. These data should be evaluated as part of this project.

The daily water usage of the Mitchell Water Utility should be evaluated as part of this project.

Other Monitoring

Aluminum should be monitored as required under the SD Department of Environment and Natural Resources Permit. Monitoring will likely entail lake and water supply samples.

Sediment components that were analyzed in 2001 should be analyzed in a similar manner once before the third treatment. Sediment TP and Al concentrations will give insight about the effect of alum additions on internal phosphorus load.

Finally, surface total alkalinity and water color should be analyzed three times (May, July and September) at the three lake stations (12A, 12B and 13A).

c. Field Services

Field services include collecting water samples, making observations, preparing and submitting water for analysis, assembling data from automatic stations and lab reports, and submitting data and observation reports to the consultants.

3. Consulting

a. Monitoring oversight

General oversight for field monitoring and observations.

b. Data evaluation

Evaluating field data and observations, statistical analyses and reporting. Under consideration of 2002-flow conditions, comparison with long-term water quality conditions to evaluate the treatment's effect.

c. Model refinement

Using field and flow data and analyses to refine and update lake models. Incorporate alum treatment results into the model so that future alum application methods can be optimized.

d. Operational oversight

Assisting the City in preparing RFP's, interviewing and selecting contractors and on-site oversight for the alum applications.

e. Operational plan (year three)

During the third year of Phase Two, preparing an operational plan that will allow the substantial transfer of the alum system operations to local managers.

Estimated Costs

Estimated costs for Phase Two are listed below. Refer to Appendix C for details.

	Alum Treatment	Monitoring	Consulting	ANNUAL TOTAL
Year One	$150,000	$6,679	$30,000	**$ 186,679**
Year Two	$120,000	$6,879	$30,000	**$ 156,879**
Year Three	$120,000	$4,879	$35,000	**$ 159,879**

Phase Three

Phase Three involves the ongoing operation of the alum system. We anticipate the majority of the operations and evaluations can be assumed by local managers. The operational plan we prepare will guide those operations.

At this time, it appears the annual alum application will occur, along with a reduced monitoring and evaluation task. Program costs should be approximately $100,000 per year.

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APPENDIX A

Alum Dose Calculation Worksheet

Alum doses are calculated here for the normal conditions (here estimated as median or 50th percentiles reported in Nürnberg and Osgood 2002) and the normal extremes (here estimated as the 25th and 75th percentiles).

Phosphorus Loads & Lake Phosphorus

External Phosphorus Loads:

25%	9,800 pounds P per year
50%	40,800 pounds P per year
75%	63,000 pounds P per year

Internal Phosphorus Loads:

½ Average	3,200 pounds P per year
Average	6,400 pounds P per year
2x Average	12,800 pounds P per year

Mass of Phosphorus in Lake Water:

Based on estimated lake P concentration multiplied times the lake volume (= 12.4×10^6 m^3).

217 ppb P	5,800 pounds P
241 ppb P	6,600 pounds P
416 ppb P	11,300 pounds P

Dose Calculation - Whole Lake Alum Application

A whole lake alum application to reduce internally supplied P entails:

Assumptions: 1) 5 pounds of Al to remove 1 pound P that occurs from internal sources (Eberhardt, Sweetwater Technology, personal communication).

2) Multiple dose by number of years' of treatment effectiveness. In this case, five year is the most to consider due to the extremely high external P loading.

3) One gallon liquid alum (the form it that is applied) contains 0.488 pounds Al.

4) Treat for the highest internal loading (= 12,800 pounds P per year).

Dose calculation:

12,800 pounds P (to be removed)
x 5 (pounds Al per pound P)
x 5 (years)

= 320,000 pounds Al

or 656,000 gallons alum every five years

Alum Treatment Scenarios

The alum treatment scenarios are designed to achieve the provisional goal to reduce lake phosphorus concentration to 90 ppb.

Scenario #1 – Inject alum into lake water during summer and no whole lake application.

The alum injection system would need to remove all phosphorus supplied from internal sources as well as all the phosphorus in the lake's volume (V). Internal phosphorus has been estimated above for the quartiles. Lake-associated phosphorus is the model phosphorus concentrations (above), less 90 ppb, multiplied by lake volume. The calculations of lake-associated phosphorus are:

25%	(217 – 90 ppb) x V*	3,500 pounds P
50%	(241 – 90 ppb) x V	4,100 pounds P
75%	(416 – 90 ppb) x V	8,900 pounds P

* Lake volume = 12.4×10^6 m^3

Phosphorus to be removed is estimated in low, mid and high ranges, which are the sum of the lake-associated P + internal P at the 25^{th}, 50^{th} and 75^{th} quartiles:

Low Range	3,500 + 3,200	6,700 pounds P
Mid Range	4,100 + 6,400	10,500 pounds P
High Range	8,900 + 12,800	21,700 pounds P

Assumption: 1) 10 pounds of Al to remove 1 pound P (Eberhardt, Sweetwater Technology, personal communication).

2) One gallon liquid alum (the form it that is applied) contains 0.488 pounds Al.

Dose Calculation:

Low Range	(6,700 x 10) / 0.488	137,000 gallons
Mid Range	(10,500 x 10) / 0.488	215,000 gallons
High Range	(21,700 x 20) / 0.488	445,000 gallons

Scenario #2 – Inject alum into lake water during summer and a whole lake application every five years.

The alum injection system would need to remove all phosphorus from the remaining internal sources as well as all the phosphorus in the lake's volume. Internal phosphorus has been estimated above for the quartiles. Assume a 50% reduction in internal phosphorus following a whole-lake application. Lake-associated phosphorus is the model P concentrations (adjusted to account for reduced internal P), less 90 ppb, multiplied by lake volume. The quartiles for lake-associated P are:

25%	(135 – 90 ppb) x V	1,200 pounds P
50%	(208 – 90 ppb) x V	3,200 pounds P
75%	(405 – 90 ppb) x V	8,600 pounds P

Phosphorus to be removed is estimated in low, mid and high ranges, which are the sum of the lake-associated P + internal P at the 25th, 50th and 75th quartiles:

Low Range	1,200 + 1,600	2,800 pounds P
Mid Range	3,200 + 3,200	6,400 pounds P
High Range	8,600 + 6,400	15,000 pounds P

Assumption: 1) 10 pounds of Al to remove 1 pound P (Eberhardt, Sweetwater Technology, personal communication).

2) One gallon liquid alum (the form it that is applied) contains 0.488 pounds Al.

Dose Calculation:

Low Range	(2,800 x 10) / 0.488	57,400 gallons
Mid Range	(6,400 x 10) / 0.488	131,000 gallons
High Range	(15,000 x 10) / 0.488	307,000 gallons

In addition, one fifth of the five-year whole-lake alum dose should be added to these to compare the annualized dosages:

Low Range	(656,000 / 5) + 54,400	186,000 gallons
Mid Range	(656,000 / 5) + 131,000	262,000 gallons
High Range	(656,000 / 5) + 307,000	438,000 gallons

Scenario #3 – In mid-June, a whole-lake application to a) strip phosphorus from the lake water to levels that will not likely be replenished for the remainder of the summer, and b) provide incremental control of internal P supply. The application dose should be enough to remove phosphorus in the lake water plus enough to provide an incremental benefit in terms of binding phosphorus in the lake sediments.

Assumptions: 1) 10 pounds of Al to remove 1 pound P from the lake water (Eberhardt, Sweetwater Technology, personal communication).

2) Regardless of the summer average phosphorus concentration in the lake water, it is unlikely to exceed 250 ppb in mid-June.

Dose Calculation:

Method a: 250 ppb x V = 6,800 pound P

6,800 pound P x 10 = 68,000 pounds of Al

68,000 / 0.488 = 139,000 gallons of alum

Method b: 1/5th the five-year dose for sediment treatment

From above, the five-year dose is 656,000 gallons of alum

656,000 / 5 = 131,000 gallons alum

Note: This first year's dose may be increased to 150,000 gallons of alum to provide a margin for error. In subsequent years, this dose should diminish.

APPENDIX B

South Dakota Department of Environment and Natural Resources Permit Requirements

South Dakota
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DEPARTMENT of ENVIRONMENT and NATURAL RESOURCES
JOE FOSS BUILDING
523 EAST CAPITOL
PIERRE, SOUTH DAKOTA 57501-3182
www.state.sd.us/denr

September 25, 2001

Don Osgood
Ecosystem Strategies
22035 Stratford Place
Shorewood MN 55331

Re: City of Mitchell/Lake Mitchell

Dear Mr. Osgood:

Thank you for contacting the South Dakota Department of Environment and Natural Resources. I have reviewed the project proposed by the City of Mitchell to have alum applied to Lake Mitchell. As alum may be considered a toxic pollutant it will be necessary for the City of Mitchell to apply for a Restoration and Enhancement approval. I have included a form and the sections of the South Dakota Surface Water Quality Standards (SDSWQS) that pertain to Restoration and Enhancement.

As Lake Mitchell is classified as a domestic water supply it will be necessary to "Public Notice" this project, which will be written by this Department. However, the City of Mitchell will have the responsibility to pay for this public notice which will be placed in the local newspaper for one publication.

If approval of this project is given it must be remembered that the SDSWQS may not be violated.

If you have any questions please feel free to contact me at the number listed below.

Sincerely,

John Miller

John Miller
Environmental Program Scientist
Surface Water Quality Program
Phone: (605) 773-3351

APPENDIX C

Phase Two Cost Estimate Worksheet

Alum Treatments

We have estimated that 150,000 gallons of liquid alum should be applied to Lake Mitchell during the first year. Less alum will likely be required in year nos. 2 and 3, but probably at least 100,000 gallons. In this budget we assume the application of 120,000 gallons per year.

We estimate the applied cost (inclusive of product, product delivery, mobilization, application crew and equipment) for alum will be $1.00 per gallon. The applied alum costs could possibly be as low as $0.75 per gallon, but here we use the higher rate to be conservative.

Year One	$150,000
Year Two	$120,000
Year Three	$120,000

Monitoring and Field Services

Monitoring and field services involve costs for staff time and laboratory analyses.

a. Bathymetry. This project should be completed in year one only. This will require about one day in the field and one day in the office (16 hours at $100). Costs for materials and equipment are estimated to be $200. **Total cost = $1,800 (year one only)**.

b. Lake Monitoring. This project involves making observation and collecting and analyzing water and sediment samples.

   The following observation and measurements can be made routinely by water utility staff or other field staff as they are performing their routine duties: Secchi disk, outlet stage, dissolved oxygen/temperature profiles. We assume there will be no cost for these measurements and observations.

   Water samples collected bi-weekly from mid-April through September (12 occasions) from three lake stations have these estimated costs:

Analysis	# Sample Dates	# Lake Stations	Unit Cost	Total
Total P	12	3	$ 20	$ 720
Chlorophyll	12	3	$ 28	$ 1,008
pH	12	3	$ 6	$ 216
Alkalinity	3	3	$ 15	$ 135
Color	3	3	$ 20	$ 180
Aluminum*	12	3	$ 15	$ 540
Annual Total				**$2,799**

* or the specific requirements of the SD DENR permit.

Repeat the sediment analysis following the second annual alum application and before the third application. This will require about one day in the field plus travel (14 hours at $100). Costs for materials and equipment are estimated to be $600. **Total cost = $2,000 (year two only).**

c. Field Services. This estimate includes the time for a field technician to conduct field monitoring and observations.

Preparation	1 day
Sampling, 12 times, ½ day	6 days
Data assembly, entry and reporting,	6 days
13 days per year @ $160 per day =	**$2,080 per year**

Consulting

Consulting services to provide monitoring oversight, data evaluation, model refinement, operational oversight and to prepare an operational plan (year three) are estimated to cost **$30,000 per year for years one and two and $35,000 for year three.**