MINNEHAHA CREEK
WATERSHED DISTRICT
QUALITY OF WATER, QUALITY OF LIFE

**Meeting:** Operations and Programs Committee
**Meeting date:** 11/6/2025
**Agenda Item #: 4.2**
**Item type: Discussion**

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**Title:** Six Mile Marsh & Halsted Bay Watershed Load Management Exploration

**Prepared by:** Name: Rachel Baker
Phone: 952-641-4522
rbaker@minnehahacreek.org

**Purpose:**
Halsted Bay is impaired for nutrients and requires the largest phosphorus load reduction of any waterbody in the MCWD, requiring a 2,000 lbs/yr nutrient load reduction. Preliminary feasibility assessments identified that 50% of the nutrient load to Halsted Bay is from the Six Mile Marsh wetland, with most of the nutrient input to Halsted Bay being delivered as dissolved phosphorus.

At the November 6, 2025 Operations and Programs Committee (OPC) meeting, staff will provide an overview of past work related to Halsted Bay watershed load management, including the purchase of property along Six Mile Marsh, and will guide discussion and present recommendations for next steps in evaluating solutions to phosphorus loading in Six Mile Marsh. This project is in MCWD's 2025-2029 multi-year capital improvement program (MYCIP).

**Background:**
In 2013, prior to naming Six Mile Creek-Halsted Bay (SMCHB) a focal geography, MCWD staff and consultants conducted a diagnostic study to develop a holistic and comprehensive analysis of the subwatershed that would help refine a strategic implementation approach. The study's monitoring data and modeling of the Six Mile Creek system suggested a large internal load in the lower portion of Six Mile Creek, particularly Mud Lake and Six Mile Marsh.

That same year, a comprehensive feasibility study was ordered to develop a nutrient budget and lake response model for Halsted Bay, and to identify and conceptually define project(s) that would a) reduce in-stream concentrations of nutrients in Six Mile Creek before entering Halsted Bay, and b) reduce internal cycling of nutrients from Halsted Bay. Led by Wenck, the study evaluated project alternatives, considering cost, technical, and regulatory hurdles to implementation. Important findings include:

- Approximately 50% of the nutrient loading to Halsted Bay comes through Six Mile Marsh, primarily as dissolved phosphorus
- About 40%+ is internal loading, and the remaining is dispersed watershed load
- In order to meet TMDL goals, both watershed and internal loading need to be addressed
- The feasibility study investigated three external load alternatives: off-line alum injection, in-line alum injection, and iron filtration
- An off-line alum facility was recommended as the best alternative to address watershed load

A subtask of the feasibility study, led by WSB, analyzed four different site locations for a potential off-line phosphorus removal facility. They found that there is substantial benefit to placing the facility towards the end of Six Mile Marsh as opposed to closer to Mud Lake, as a significant phosphorus transformation, from particulate to dissolved, occurs through the marsh. The Engineer's opinion of probable cost (OPC) estimated the capital cost of the project to be about $7.7 million, with the total project cost (with a 20-year Present Value) to be $13.9 million.

In 2017, MCWD was approached by Three Rivers Park District (TRPD) staff who were working on land acquisitions to complete the Carver Park to Baker Park regional trail connection project, including a trail crossing of Six Mile Creek. They were evaluating a property off Farmhill Circle to site a portion of the trail and did not need the entirety of the property for trail use, thus suggesting a shared acquisition for our project purposes. The site location corresponds with the desirable outtake point for the potential off-line phosphorus removal treatment facility identified in the 2013 feasibility study.

Prior to acquiring the property at 3910 Farmhill Circle, MCWD:

- Conducted a Phase I ESA at the property.
- Contracted Wenck to perform a massing study to verify that a facility would fit on the property, given the constraints of the TRPD trail and the lowland wetland.
    - The study found that the facility would fit, but it would be tight.
- Held an open house for nearby residents to gauge public sentiment around a potential facility.
    - There was concern surrounding aesthetics, noise and smell, and operations, but no strong outright opposition.
- Presented to Minnetrista City Council and staff to confirm that anticipated land use was conceptually acceptable.

The property was subsequently subdivided, with MCWD acquiring 5.3 acres. Since the acquisition of 3910 Farmhill Circle, no additional action has taken place as MCWD's focus was directed toward water quality projects further upstream in the SMCHB subwatershed.

**Summary:**
The past 10 years of significant resource investment into the SMCHB focal geography has brought about successful landscape load reduction projects in the upper portion of the subwatershed. While upstream work will continue, staff feel it is the right time to re-engage on the loading issues in the lower portion of SMCHB subwatershed and re-evaluate the viability of an off-line alum facility in Six Mile Marsh.

At the November 6, 2025 Operations and Programs Committee Meeting, staff will brief the Board on the lower subwatershed's history and 2025 due diligence efforts, and guide the board in discussion around the approach in Six Mile Marsh, including engaging with outside consulting firms to advance a feasibility study.

**Supporting documents (list attachments):**

- Halsted Bay Watershed Load Management CIP 1-pager
- Halsted Bay Load Management Feasibility Study, Wenck, 2013
- Halsted Bay Load Management Siting Study, WSB, 2013

# MINNEHAHA CREEK WATERSHED DISTRICT

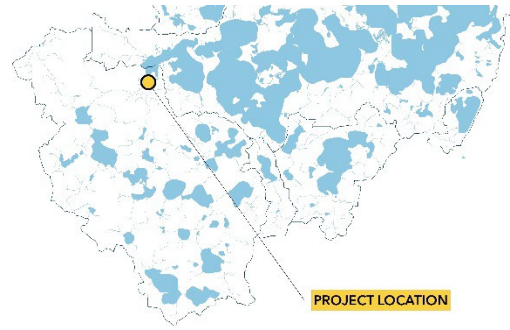
## MULTI-YEAR CAPITAL IMPROVEMENT PLAN 2025-2029

## OVERVIEW

**PROJECT NAME**
Lake Minnetonka-Halsted Bay Watershed Load Management

**LOCATION**
Minnetrista (Six Mile Creek Halsted Bay)

**TARGET WATERBODY**
Halsted Bay, Lake Minnetonka




## DESCRIPTION

**SCOPE**
Evaluate the construction of a phosphorus removal facility which would pump water from Six Mile Creek, treat it using aluminum sulfate (alum), and discharge treated water into the Creek before entering Halsted Bay. Alum treatment to address internal loading in Halsted Bay may also be cosidered as a complementary component of this project.

**GOALS**
This project would reduce nutrient loading to Halsted Bay by an estimated 1,620 lbs/yr. If paired with an in-lake alum treatment, an additional 1,900 lbs/yr reduction could be achieved. Secondary benefits include increased water clarity, reemergence of aquatic habitat, and improved recreational value.

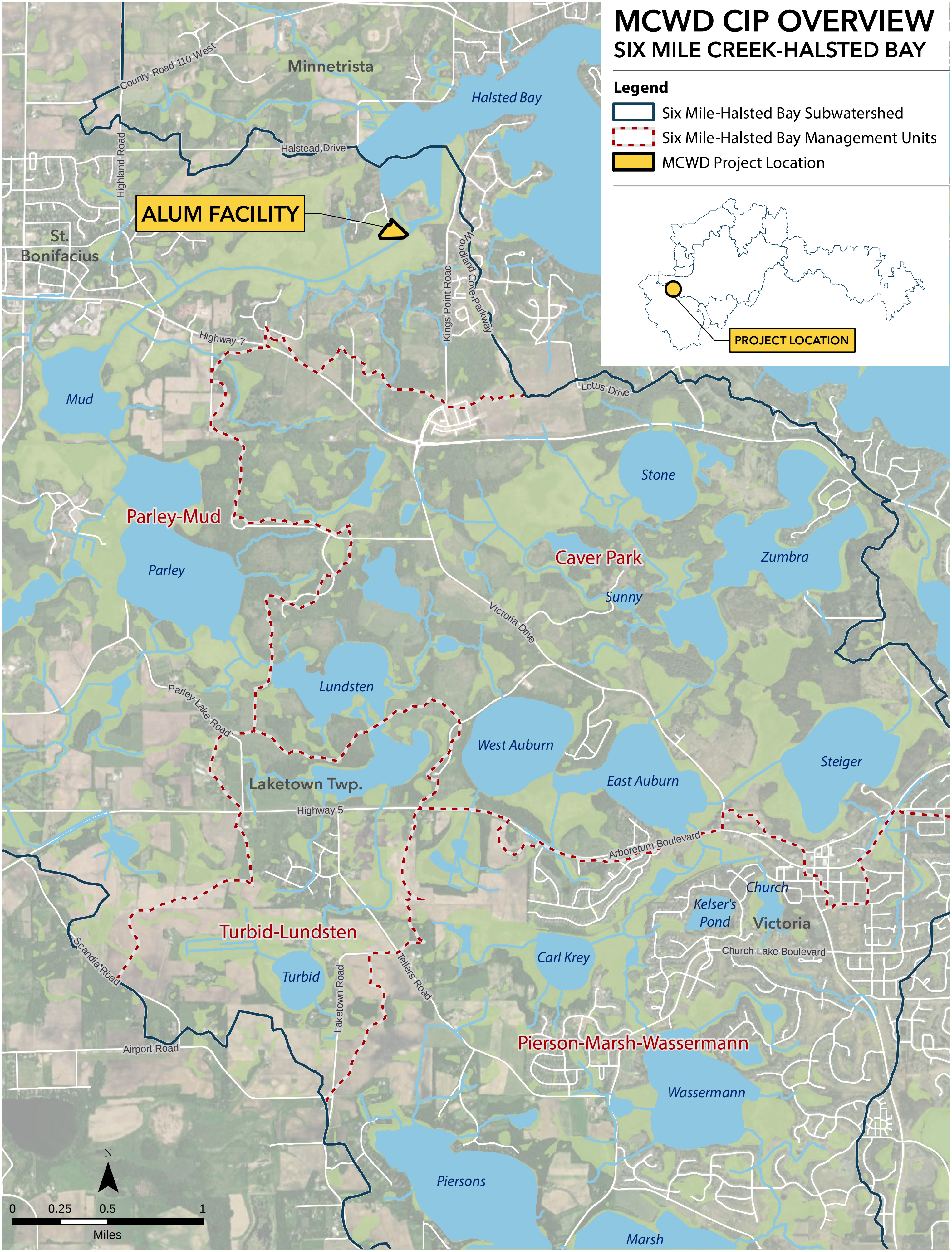
**JUSTIFICATION**
Halsted Bay is impaired for nutrients and requires the largest phosphorus load reduction of any waterbody in the MCWD. Preliminary feasibility assessments identified that 50% of the nutrient load to Halsted Bay is from the Six Mile Marsh wetland (40% internal load, 10% other watershed load), requiring a 2,000 lbs/yr nutrient load reduction. The vast majority of nutrient input to Halsted Bay is dissolved phosphorus, which requires chemical treatment for removal. Meeting state water quality standards in Halsted Bay will require addressing both watershed and internal loading.

**WORKPLAN SUMMARY**
MCWD plans to commence the project planning phase in fall 2024 and will continue through 2025. Preliminary work will focus on reviewing the 2012 feasibility report and validating the conceptual design; meeting with project partners to initiate discussions around facility operations, regulatory frameworks, and funding; and developing a project outreach plan. Consideration of advancing the project into design will be carefully considered by MCWD’s Board in collaboration with project partners.

## SCHEDULE + BUDGET

| PLANNING | DESIGN | CONSTRUCTION |
|---|---|---|
| 2024 – 2026 | 2027-2028 | 2028 – 2030 |
| $125,000 | $2,600,000 | $10.4 million |

# MCWD CIP OVERVIEW
## SIX MILE CREEK-HALSTED BAY



Wenck
Engineers • Scientists
Business Professionals

Wenck File #0185-5076

**NOVEMBER 2013**

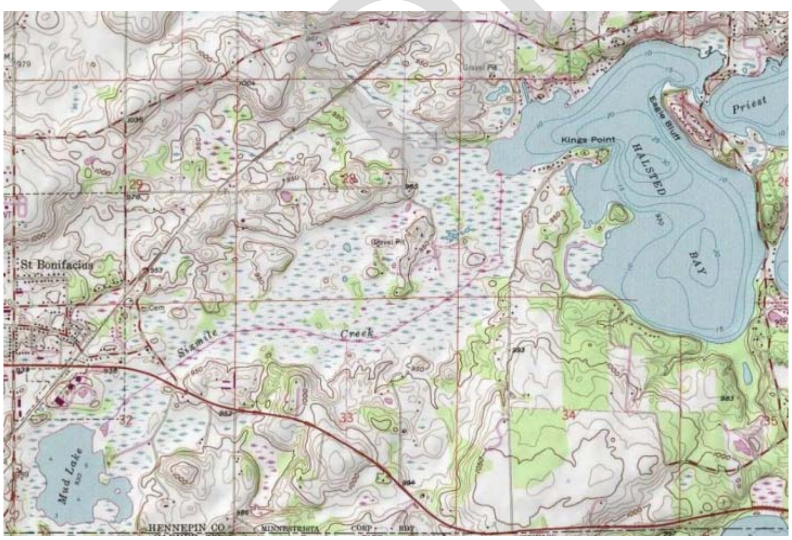

# Halsted Bay Load Management Feasibility Project



MINNEHAHA CREEK
WATERSHED DISTRICT

Prepared for:

**MINNEHAHA CREEK WATERSHED DISTRICT**
15320 Minnetonka Blvd.
Minnetonka, MN, 55345




Prepared by:

**WENCK ASSOCIATES, INC.**
1800 Pioneer Creek Center
P.O. Box 249
Maple Plain, Minnesota 55359-0249
(763) 479-4200

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## APPENDICES

# 1.0 Executive Summary

This report presents the results of the Halsted Bay load management feasibility study. The focus of the study is to identify alternatives to improve Halsted Bay water quality by managing its phosphorus load, both internal and external. The current average summer in-lake concentration of phosphorus is 88 µg/l. The goal is to reach the State of Minnesota's in-lake concentration of 40 µg/l. The study was completed by Minnehaha Creek Watershed District with the involvement of the City of Minnetrista. The study team consists of designated MCWD staff, Wenck, and WSB.

Halsted Bay is a 560-acre water body located in the western most portion of Lake Minnetonka in the City of Minnetrista. The primary inflow from the 30-square-miles drainage area is from Six Mile Creek located in the northwest corner of the bay.

A large portion of the study investigates the in-lake and external or watershed sources of phosphorus. In-lake loading was documented by results of sediment samples taken as part of the study. Watershed loads are based on the recently completed diagnostic study of Six Mile Creek by MCWD in early 2013. This work was extended by an additional study of Six Mile Marsh located just upstream of the bay and downstream of Mud Lake. Based on the data collected and modeling to date, Six Mile Marsh does appear to be releasing some phosphorus, however more flow and water quality data and analysis is needed to further document this.

Lake response modeling indicates that both watershed loading and internal loading need to be aggressively pursued to reach the goal in Halsted Bay. One key factor is that 90 percent of the water comes through Mud Lake which only has a target of 60 µg/l while Halsted Bay has a target of 40 µg/l. This means additional reductions may need to be found in other parts of the watershed.

Restoration of upstream Mud and Parley Lakes will be critical in restoring Halsted Bay. Both of these lakes are very shallow and carp infested. To reach water quality goals in these lakes, the carp need to be addressed, plants reestablished in the lakes and nutrients reduced. This is an extensive undertaking.

Addressing external sources, accomplishing the goals of the Six Mile Creek Diagnostic Study, is going to be a long process with uncertain outcomes. The process could take 30 years or more and is dependent on numerous landowners. A large engineering project, such as an off-line phosphorus removal plant, provides the water quality benefits immediately however at a significant cost.

# 2.0 Introduction

## 2.1 PURPOSE AND SCOPE

Halsted Bay is a 560-acre water body located in the western most portion of Lake Minnetonka in the City of Minnetrista. The bay is very eutrophic due to high nutrient levels. The purpose of this load management feasibility study is to identify alternatives to improve Halsted Bay water quality by managing its phosphorus load, both internal and external. The current average summer in-lake concentration of phosphorus is 88 µg/l. The goal is to reach the State of Minnesota's in-lake concentration of 40 µg/l.

This study investigates the in-lake and external or watershed sources of phosphorus. In-lake loading is documented by results of sediment samples taken as part of the study. The primary external load is from the 30-square-mile Six Mile Creek drainage area located in the northwest corner of the bay. Watershed loads are based on the recently completed diagnostic study of Six Mile Creek by MCWD in early 2013. This work is extended by an additional study of Six Mile Marsh located just upstream of the bay and downstream of Mud Lake.

# 3.0 Site Description

## 3.1 WATERSHED DESCRIPTION

Halsted Bay (DNR# 27-0133-09) is the western most bay of Lake Minnetonka (DNR# 27-0133-00). The Halsted Bay drainage area covers approximately 19,489 acres in Hennepin and Carver Counties and includes portions of Mound, St. Bonifacius, Minnetrista and Victoria (Figure 3-1). The watershed was divided into four major subwatersheds for the purpose of this report: Six Mile Creek Subwatershed upstream of Mud Lake, Six Mile Creek Subwatershed downstream of Mud Lake (Six Mile Marsh drainage area), North tributary to Halsted Bay, and Hasted Bay direct subwatershed (Figure 3-1).

## 3.2 HALSTED BAY INFORMATION

### 3.2.1 Lake Morphometry

With a maximum depth of 32 feet and a littoral area of 57%, Halsted Bay is considered a deep lake by Minnesota rules and standards (Table 3-1). However the bay has a rather large littoral area suggesting that it may have several functional aspects similar to shallow lakes. Halsted Bay has a residence time of 0.8 years meaning the bay, on average flushes approximately once every 292 days. The bay has a very large watershed with a watershed to lake surface area ratio of 34:1 suggesting that the bay is sensitive to changes in watershed nutrient loading.

**Table 3-1. Physical Features of Halsted Bay.**

| Parameter | Result |
|---|---|
| Surface Area (acres) | 561 |
| Average Depth (ft) | 13.2 |
| Maximum Depth (ft) | 32 |
| Volume (acre-feet) | 7,401 |
| Residence Time (years) | 0.8 |
| Littoral Area (acres) | 318 |
| Littoral Area (%) | 57% |
| Watershed (acres) | 19,321 |
| Mixing Depth (ft) | 8 |

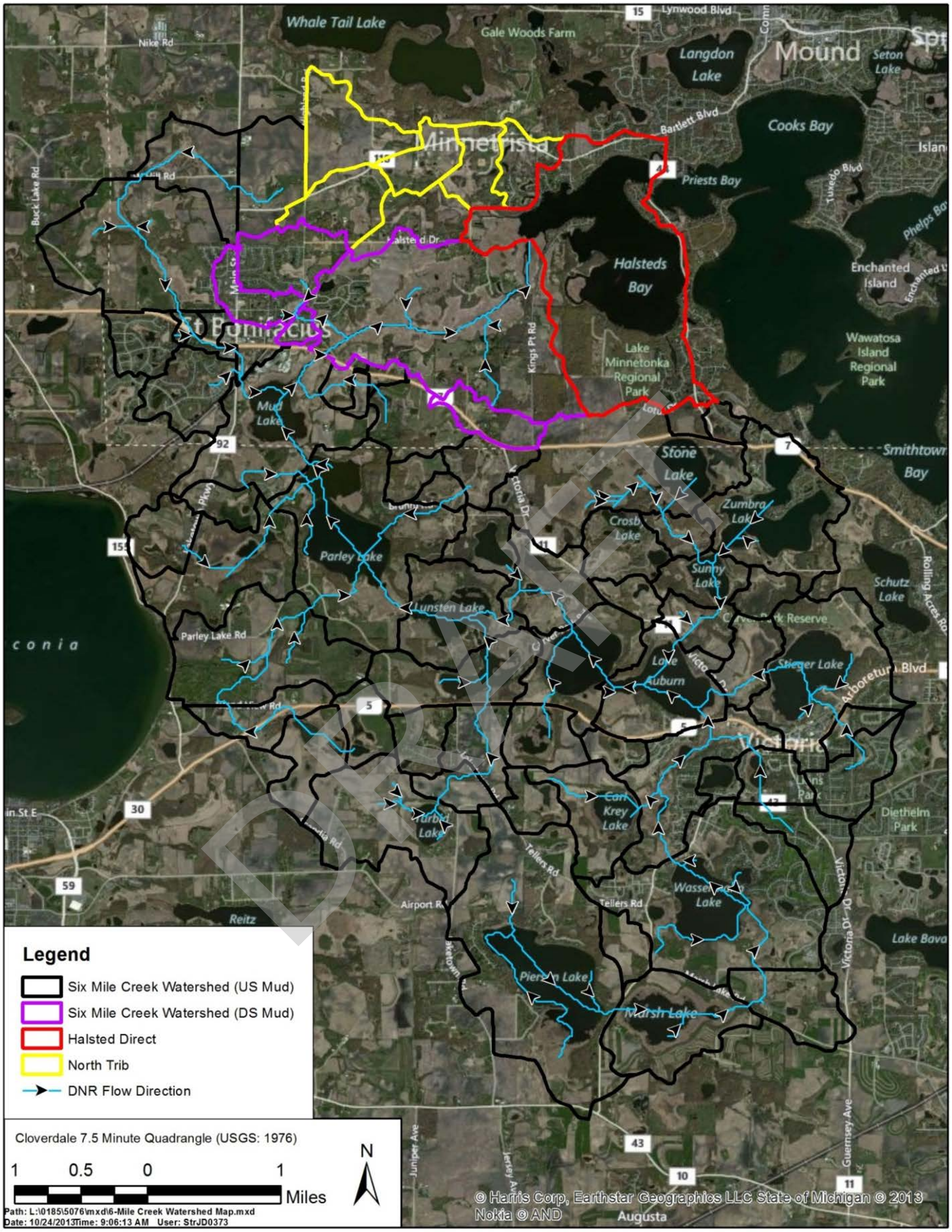



**Figure 3-1. Halsted Bay Watershed.**

### 3.2.2 Water Quality

Lake water quality is typically measured by assessing the amount of algal growth and water clarity during the summer growing season. When excess algae grow in a lake, water clarity is reduced and noxious smells can emit. These are symptoms of lake eutrophication. When lakes become hyper eutrophic (excess nutrients leading to heavy algae growth), the entire food web is affected. Changes are found in the algal community and water quality, including depletion of dissolved oxygen and decreased water clarity. A healthy lake has a balanced growth of algae supporting the base of the food chain without degrading water quality or harming biological organisms.

Lake water quality samples have been collected by Minnehaha Creek Watershed staff in Halsted Bay since 2000. In general, lake monitoring was conducted bi-weekly from May through September for Secchi depth, total phosphorus (TP) and chlorophyll-a, and temperature and dissolved oxygen measurements.

*Phosphorus*

Algal growth (measured as total chlorophyll-*a*) is typically limited by the amount of phosphorus in the water column. Therefore, TP is considered the causative factor for algal growth. Water clarity is affected by the amount of algae as well as suspended and dissolved particles in the water column. Since 2000, summer average TP concentrations have ranged from 70-130 µg/L and have exceeded the 40 µg/L NCHF deep lake standard every year (Figure 3-2).

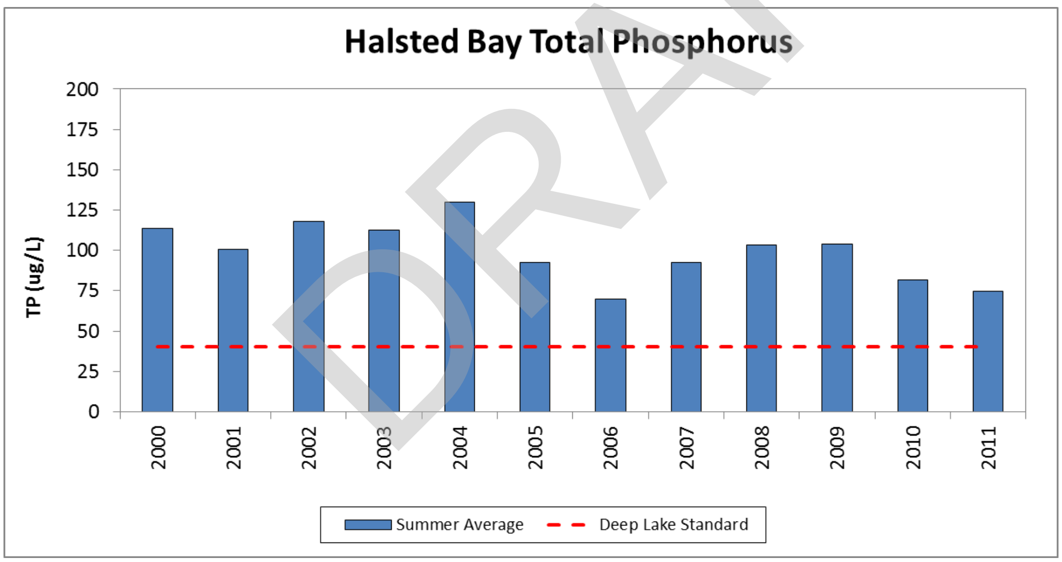



**Figure 3-2. Summer average total phosphorus concentrations for Halsted Bay.**

*Chlorophyll-a*

Chlorophyll-a is the primary pigment in aquatic algae and has been shown to have a direct correlation with algal biomass. Chlorophyll-a is a simple measurement and is often used to evaluate algal abundance rather than expensive cell counts. The greater the algal biomass and corresponding chlorophyll-*a* values, the more green and productive a lake appears with worst case scenarios including algal scum and foul odors. These conditions are considered nuisance algal blooms and are both aesthetically unpleasing but also potentially bad for fish and other biological organisms. Nuisance algal blooms cause poor smells and aesthetics and can lead to more severe problems such as summer fish kills. Ultimately, lakes should have a modest amount of algal productivity with light penetrating approximately 15 feet into the water column. Summer average chlorophyll-a concentrations in Halsted Bay have ranged from 24 µg/L to as high as 83 µg/L (Figure 3-3). Chlorophyll-a concentrations over 14 µg/L exceed state water quality standards for deep lakes in the NCHF ecoregion. Average chlorophyll-a concentrations have exceeded the state standard every year since 2000 indicating nuisance algae blooms are common in Halsted Bay during the summer months.

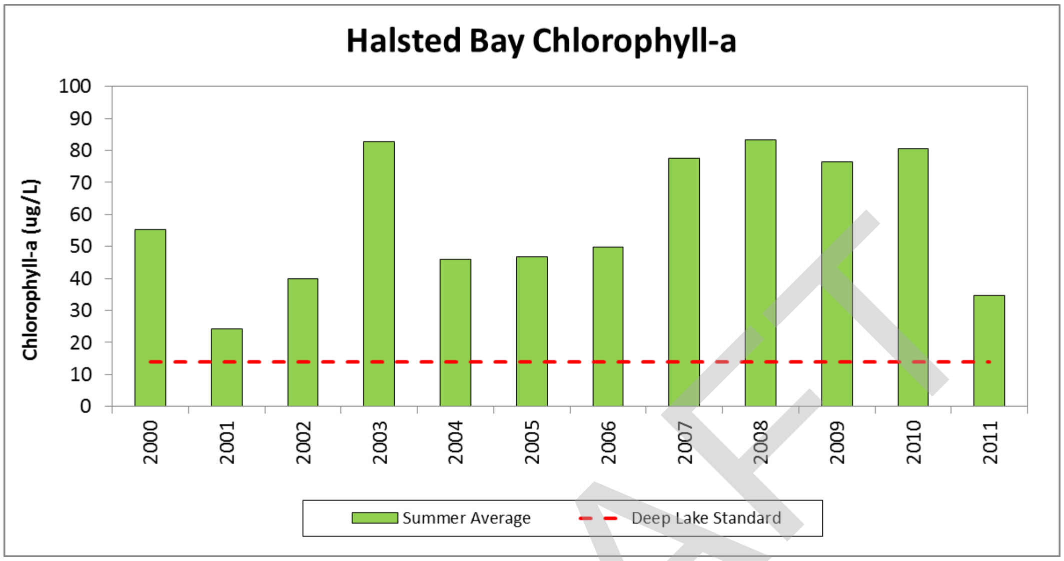



**Figure 3-3. Summer average chlorophyll-a concentrations for Halsted Bay.**



*Water Clarity*

Water clarity in lakes is typically measured using a Secchi disk. A Secchi disk is a black and white disk that is lowered into the water column until it can no longer be seen. The depth at which the disk disappears is known as the Secchi depth and is considered the depth where 90% of the light is extinguished.

Water clarity in lakes is controlled by several factors including the amount of algae in the water column as well as other suspended particles such as suspended sediment as a result of wind resuspension and bioturbation (such as carp). Since Halsted Bay is considered a deep lake, wind mixing is likely only a concern in shallow areas (<15 feet) where mixing can reach the sediments and stir up particles into the water column. Halsted Bay also has a large carp population that feeds and roots around in the sediments causing a fair amount of sediment disturbance in the shallow areas throughout the bay.

Secchi depth measurements in general follow the same trend as chlorophyll-a concentrations in Halsted Bay. Since 2000, the average summer Secchi depth has not met the 1.4 meter water quality standard for deep lakes (Figure 3-4). Mean summer values ranged from 1.2 meters to 0.5 meters between 2000-2011.

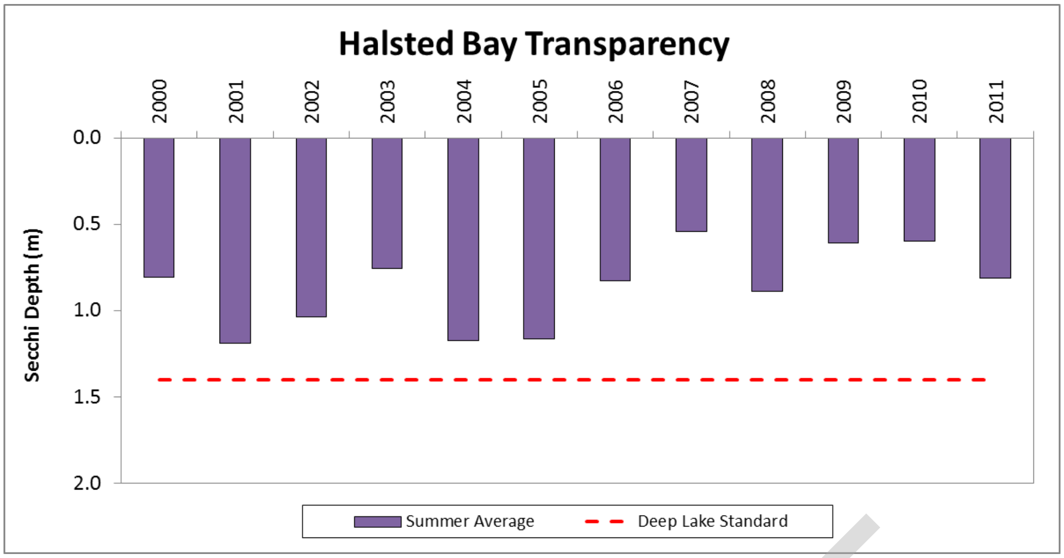



**Figure 3-4. Summer average Secchi depth values for Halsted Bay.**

### 3.2.3 Fisheries

Fish survey reports for Halsted Bay were provided by the DNR Area Fisheries Office in Shakopee, Minnesota. The first DNR fish survey conducted specifically for Halsted Bay was performed in 1992. Standard survey methods used by the DNR include gill net and trap nets. These sampling methods do have some sampling bias, including focusing on game management species (i.e., northern pike and walleye), under representing small minnow and darter species presence/abundance, and under representing certain management species such as largemouth bass. The current methods also likely under represent carp populations in lakes. However, when carp are present in a lake, the sampling methods do capture some of the population. So, although carp density is likely under represented, the methods do provide a reasonable year to year comparison.

Fish community data for Halsted Bay was summarized by trophic groups (Figures 3-5 and 3-6). Species within a trophic group serve the same ecological process in the lake (i.e., panfish species feed on zooplankton and invertebrates; may serve as prey for predators). Analyzing all the species as a group is often a more accurate summary of the fish community then analyzing individual species trends. Results indicate panfish to be the most abundant species in Halsted Bay. Total biomass in Halsted Bay appears to shift year to year between panfish and top predators. Common carp were present during both surveys and represented a sizable portion of the total catch biomass (18% in 1992 and 5% in 1997). Rough fish, particularly common carp, have both direct and indirect effects on aquatic environments. Carp uproot aquatic macrophytes during feeding and spawning and re-suspend bottom sediments and nutrients. These activities can lead to increased nutrients in the water column ultimately resulting in increased nuisance algal blooms.

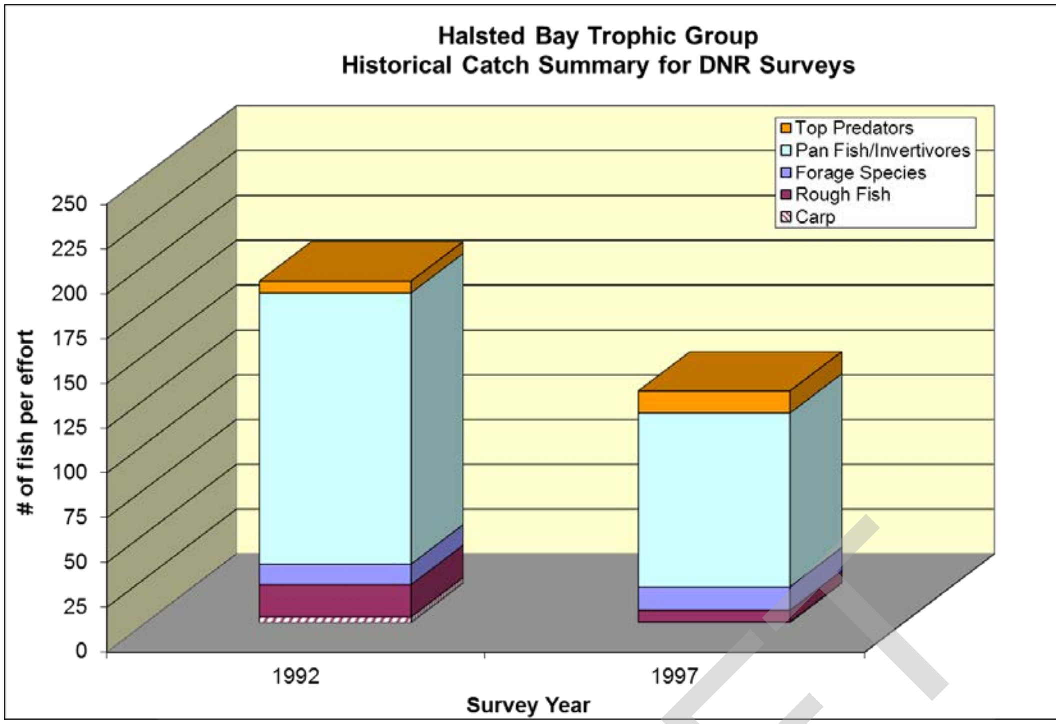



**Figure 3-5. Trophic group abundance based on historic MN-DNR fish survey results.**

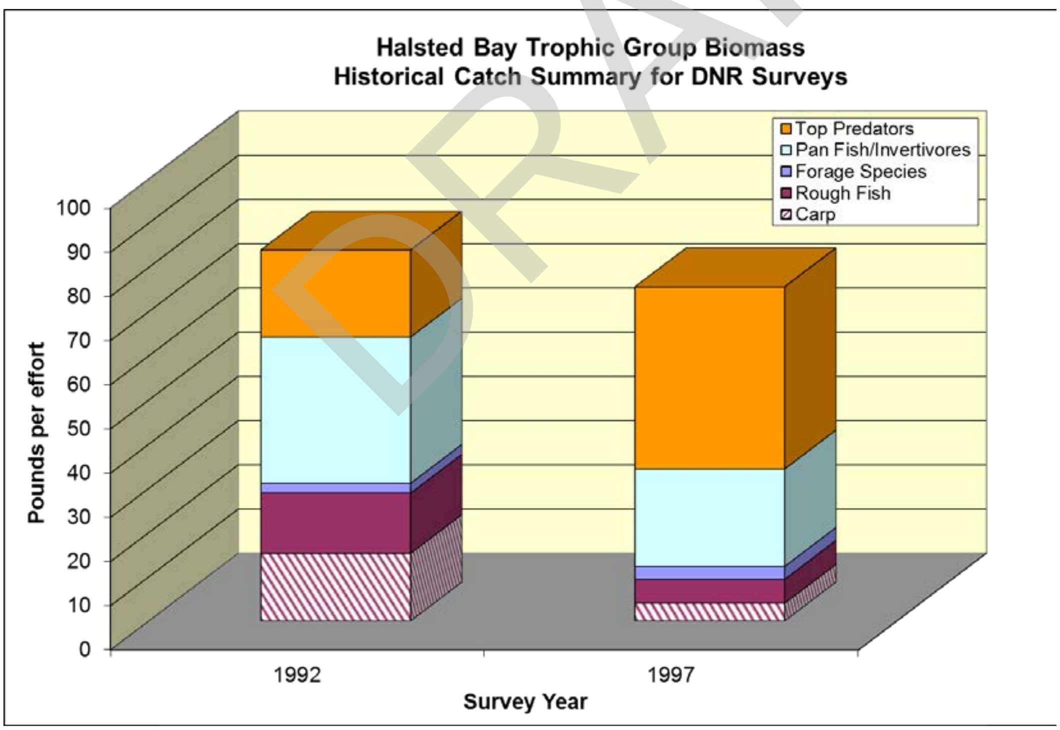



**Figure 3-6. Trophic group biomass based on historic MN-DNR fish surveys.**

### 3.2.4 Aquatic Vegetation

A point-intercept survey was conducted by Wenck staff on June 19, 2013 using methodology developed by the Minnesota Department of Natural Resources (DNR). Wenck staff identified all plant species found within a one square meter of each survey point. A weighted sampling hook attached to a rope was used to survey vegetation not visible from the surface. All vegetation species observed were identified to the species level where possible. This early summer survey was conducted specifically to estimate the distribution and abundance of curly-leaf pondweed.

Curly-leaf pondweed is a non-native plant species that can outcompete native plant species and disrupt lake ecosystems by changing the dynamics of internal phosphorus loading. Curly-leaf pondweed is a perennial submersed aquatic plant that was first noted in Minnesota around 1910. Curly-leaf pondweed has the ability to grow slowly throughout the winter, even under thick ice and snow cover. Thus by the time other species start growing in the spring, curly-leaf plants are large enough to block light penetration to the bottom. By late spring, curly-leaf pondweed can form dense surface mats which interfere with recreation activities. By mid-summer, these dense mats senesce and die back, releasing nutrients that can contribute to undesirable algae blooms. Before curly-leaf pondweed plants die back, they form hardened stem tips called turions, which serve the function of vegetative reproduction. These turions sprout in the fall and begin the plant's cycle again.

The frequency of occurrence of each species during the June 10, 2013 (near mid-season) and August 12, 2013 (late season) surveys is summarized in Table 3-2. Seven species of submerged and floating aquatic vegetation were documented at sample stations during these surveys. The most common species observed during the surveys were Eurasian water milfoil and coontail. Curly-leaf pondweed was relatively common in June, but had died off as it normally does by August. In general, species diversity and abundance was poor during both surveys and no vegetation was observed at many sample points less than 15 feet deep where submerged vegetation should grow and thrive.

**Table 3-2. Halsted Bay Vegetation Survey Results.**

| Species | June 10, 2013 Survey (frequency of occurrence) | August 12, 2013 Survey (frequency of occurrence) |
|---|---|---|
| Eurasian Water Milfoil | 14.5% | 13.0% |
| Coontail | 11.4% | 7.2% |
| Curly-leaf pondweed | 11.0% | 0.0% |
| White waterlily | 7.3% | 13.2% |
| Narrowleaf pondweed group | 0.4% | 0.2% |
| Yellow waterlily | 0.0% | 0.4% |
| Sago pondweed group | 0.0% | 0.7% |

# 4.0 Halsted Bay Nutrient Budget

## 4.1 INTRODUCTION

The first step in developing restoration options for Halsted Bay is to develop a nutrient budget for the bay along with a lake response model. A lake response model for Halsted Bay was previously developed for the Minnehaha Creek Lakes TMDL (Wenck 2013). For this study, additional data were collected including sediment cores to estimate internal phosphorus release. The lake response models were subsequently updated.

## 4.2 PHOSPHORUS SOURCES

One of the primary drivers for lake productivity or algal growth is phosphorus. To better understand what is driving water quality in Halsted Bay, a detailed phosphorus budget was developed to identify both the sources and magnitude of the phosphorus loading. Phosphorus sources to lakes include agricultural and stormwater runoff, internal sediment release of phosphorus, and direct atmospheric deposition of phosphorus to the lakes surface. In this section, a brief description of the potential source of phosphorus to Halsted Bay is provided.

### 4.2.1 Atmospheric Deposition

Precipitation picks up dust particles that contain phosphorus that can ultimately end up in Halsted Bay as a result of direct input on the basin surface or as a part of stormwater runoff from impervious surfaces in the watershed. Although they must be accounted for in development of a nutrient budget, atmospheric inputs are difficult if not impossible to control and are usually small compared to other sources (internal and external).

Atmospheric inputs of phosphorus from wet and dry deposition are estimated using rates set forth in the MPCA report “Detailed Assessment of Phosphorus Sources to Minnesota Watersheds” (Barr Engineering, 2004), and are based on annual precipitation. The values used for dry (< 25 inches), average, and wet precipitation years (>38 inches) for atmospheric deposition are 24.9, 26.8, and 29.0 $kg/km^2$-year, respectively. These values are equivalent to 0.22, 0.24, and 0.26 pounds/acre-year for dry, average, and wet years in English units, respectively.

### 4.2.2 Groundwater

Groundwater flow and phosphorus load was estimated using groundwater elevations from the Hennepin County, MN Geologic Atlas published by the Minnesota Geologic Survey, 1989. Surficial geology was also interpreted from the Geologic Atlas. Elevation difference between Lake Minnetonka’s Ordinary High Water Level (929 ft) listed on the DNR LakeFinder website and the region’s surficial geology (940 ft) indicates groundwater flow to Halsted Bay. Groundwater flow to Halsted Bay was determined using the following equation:

$Q = KiA$

Where Q is the flow, K is the hydraulic conductivity (3.28 x 10^-8 ft/s for loamy soils), i is the difference in lake surface and groundwater elevation divided by 10 feet, and A is the lake area. A mean groundwater concentration of 84 µg/L was used for the Halsted Bay lake response model as listed in Table A.17 of Baseline Water Quality of Minnesota's Principal Aquifers: Twin Cities Metropolitan Region (MPCA 1999).

### 4.2.3 Watershed Runoff

Phosphorus transported by agricultural runoff and urban stormwater represents some of the largest external contributors of phosphorus to surface waters in Minnesota. Ditching through crop and pasture land, impervious surfaces and storm sewer systems in the watershed improve the efficiency of runoff and phosphorus moving to streams, wetlands and lakes. Phosphorus in agricultural runoff and urban stormwater is a result of crop residue, field erosion, leaves and grass clippings, manure and fertilizers, sediments, pet waste, excessive lawn watering, automobiles, failing septic systems and illicit sanitary sewer connections. Managing agricultural runoff and stormwater is a high-priority concern for all Minnesota lakes and streams.

The first step in estimating the phosphorus load from a lake's watershed is to calculate the watershed's hydrologic budget. MCWD staff has attempted to monitor continuous flow at various locations along Six Mile Creek. Backwater conditions in Six Mile Creek upstream of Halsted Bay and other lakes throughout the watershed make it difficult to develop reliable long-term rating curves. Refer to Appendix A for more details on flow information. In 2013, Wenck Associates converted an XPSWMM model for Six Mile Creek previously developed by the District to EPA SWMM. This model predicts water elevations, runoff, flow and routing throughout the entire watershed. The EPA SWMM model was calibrated to gaged flow data collected by MCWD staff from 2001-2012 on Six Mile Creek near the outlet of Mud Lake. Using this model, Wenck was able to predict annual flow rates and volumes at various points along Six Mile Creek, including the creek's outlet to Halsted Bay. The Halsted Bay direct watershed and the tributary that enters Halsted Bay north of Six Mile Creek (Figure 3-1) were not included in the Wenck EPA SWMM model. Six Mile Creek runoff depths were used to represent the Halsted Bay direct watershed and the north tributary as it was assumed runoff from these subwatersheds is similar to Six Mile Creek.

EPA SWMM flow analysis suggests Six Mile Creek represents approximately 93% of the Halsted Bay water budget (Figure 4-1). The Six Mile Creek Watershed is approximately 17,033 acres in size and accounts for 87% of the Halsted Bay Watershed. The Halsted Bay direct watershed (1,350 acres) and the north tributary to Halsted Bay (1,106 acres) represent only 2% and 3% of the lakes overall water budget, respectively. Groundwater flow to Halsted Bay is also believed to be small and represent only 2% of the overall water budget. Direct precipitation and lake evaporation are approximately the same and there is not believed to be any net gain from the atmosphere on an annual basis.

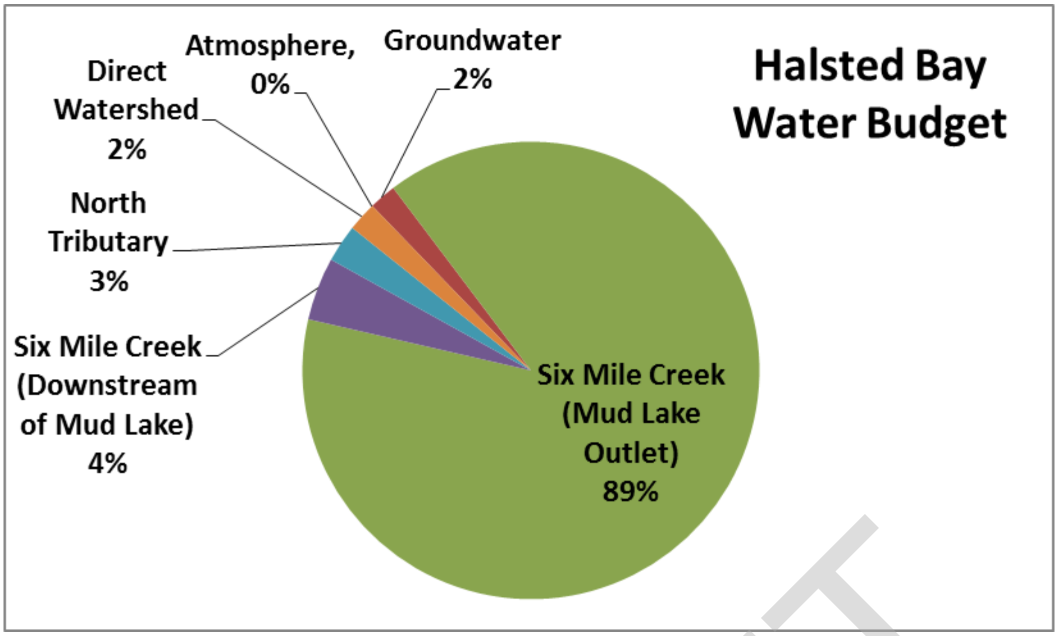



**Figure 4-1. Water budget for Halsted Bay.**

#### 4.2.3.1 Six Mile Creek Watershed

MCWD staff has collected total phosphorus and ortho-phosphorus grab samples at various Six Mile Creek mainstem and tributary monitoring stations since 1997 (Figures 4-2 and 4-3). Six Mile Creek monitoring station S003-752 located near the outlet of Mud Lake is the furthest downstream Six Mile Creek station before the creek's outlet to Halsted Bay (Figure 4-4). Water quality data collected at this station from 1997-2012 indicate TP has ranged from 38 µg/L to 467 µg/L while ortho-phosphorus has ranged from less than 5 µg/L to 303 µg/L. Grouping the TP and ortho-phosphorus data based on flow conditions indicates Six Mile Creek phosphorus concentrations do not vary significantly between flow regimes.

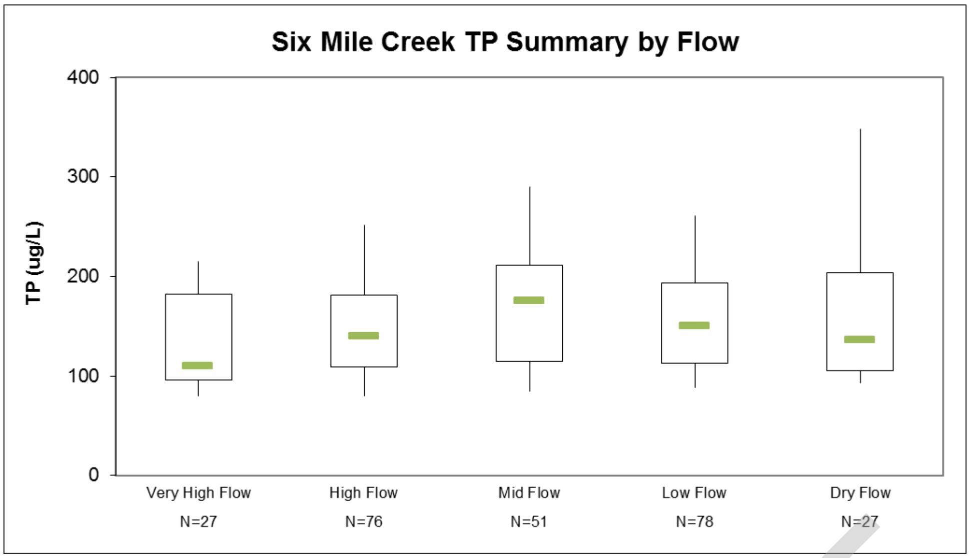



**Figure 4-2. Six Mile Creek TP concentrations at the outlet of Mud Lake from 1997-2012. The upper and lower edge of each box represents the 75th and 25th percentile of the data range for each flow zone. Error bars above and below each box represent the 95th and 5th percentile of the datasets. The green dash is the median DO concentration of all data collected in each flow zone.**

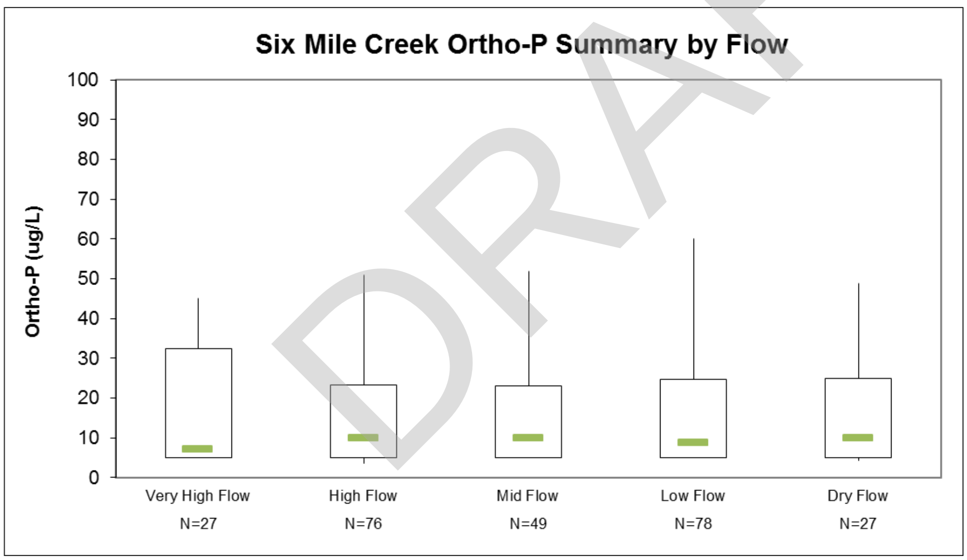



**Figure 4-3. Six Mile Creek ortho-phosphorus concentrations at the outlet of Mud Lake from 1997-2012. The upper and lower edge of each box represents the 75th and 25th percentile of the data range for each flow zone. Error bars above and below each box represent the 95th and 5th percentile of the datasets. The green dash is the median DO concentration of all data collected in each flow zone.**

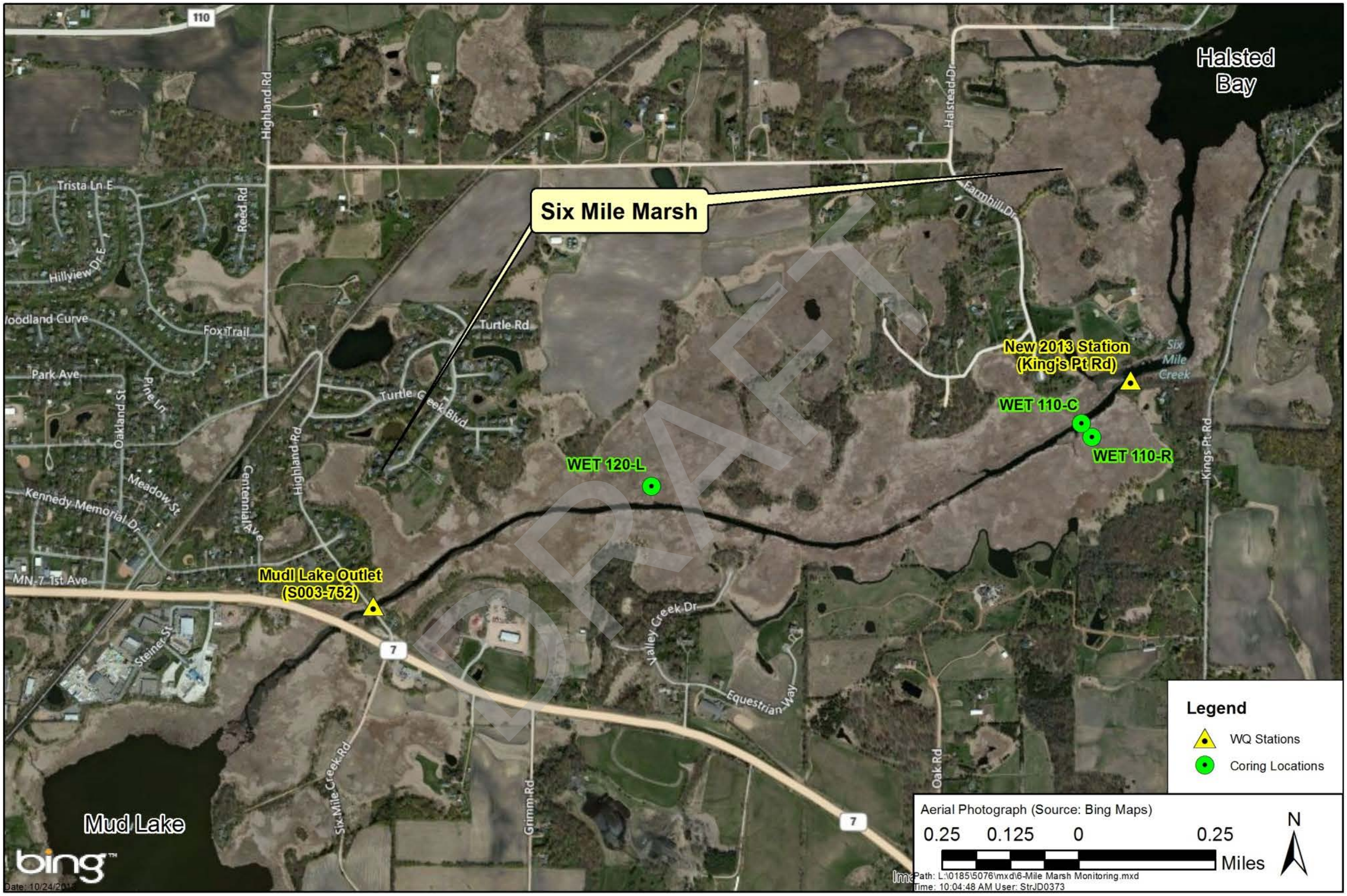



**Figure 4-4. Six Mile Creek sampling locations.**

### 4.2.3.2 Six Mile Marsh

In 2013, MCWD staff began monitoring TP and ortho-phosphorus in Six Mile Creek downstream of the Mud Lake outlet station (S003-752) at King's Point Road closer to the creek's outlet to Halsted Bay (Figure 4-4). Prior to 2013, there had been no phosphorus data collected in or downstream of the area between Mud Lake and Halsted Bay referred to as Six Mile Marsh. The channel through Six Mile Marsh is ditched and straightened through a large wetland complex. Flow through this section is very slow and is often subject to backwater conditions from Halsted Bay where large areas of the wetland complex are covered in standing water. The purpose of the 2013 sampling at King's Point Road was to determine if Six Mile Marsh is a source or sink of the phosphorus release from Mud Lake. Phosphorus data was collected between mid-April and early September 2013. Early in the season (March – mid June), there was very little change in TP and ortho-phosphorus between the Mud Lake outlet station and the Six Mile Marsh station at King's Point Road. Beginning in late June, however, the outlet station was increasingly higher in both total and ortho-phosphorus suggesting that the wetland is likely acting as a phosphorus source to Halsted Bay (Figures 4-5 and 4-6). Final flow data will need to be evaluated to determine the magnitude of the phosphorus source since it appears to occur mostly during low flow periods.

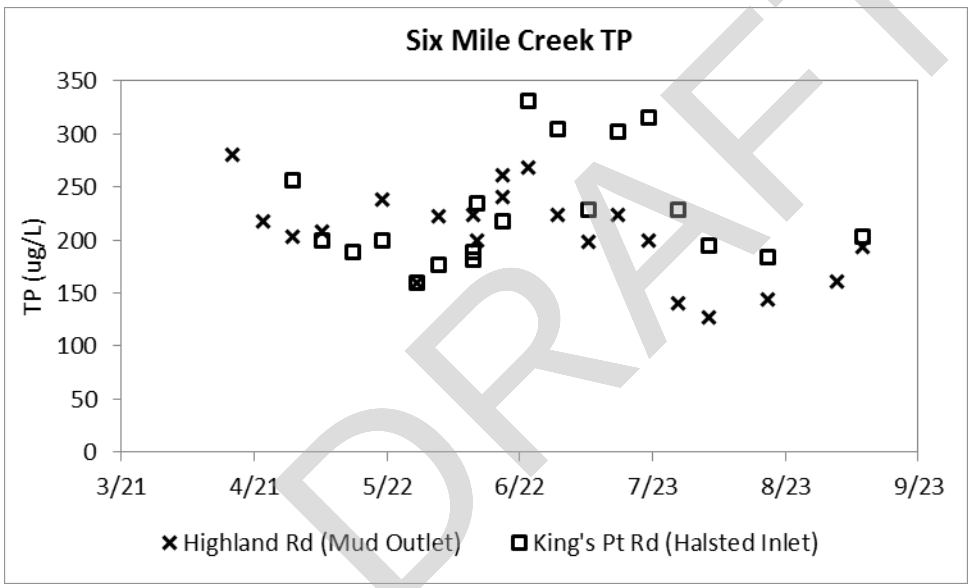



**Figure 4-5. 2013 Six Mile Creek TP data.**

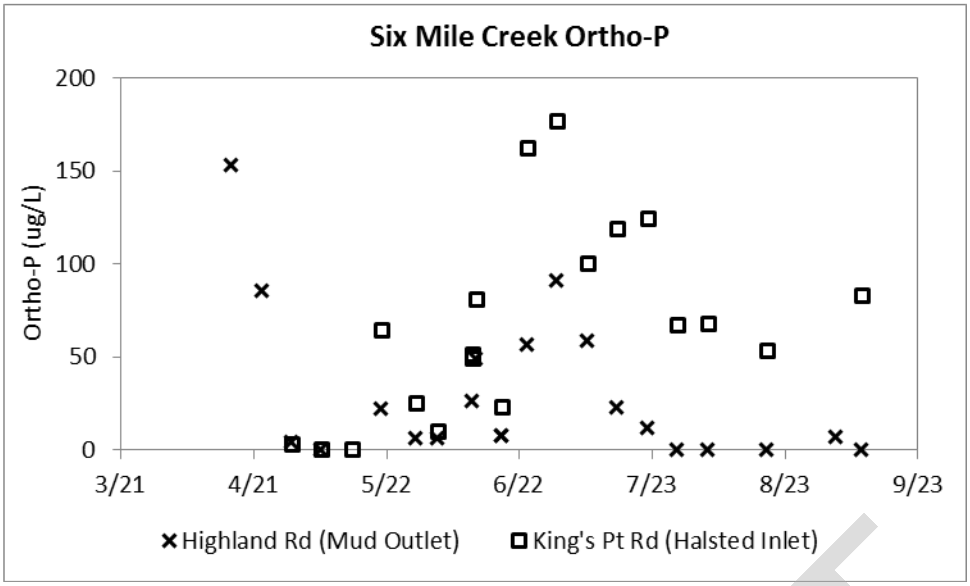



**Figure 4-6. 2013 Six Mile Creek Ortho-phosphorus data.**

Sediment cores were collected from the channel that flows through Six Mile Marsh in May 2013 to determine potential phosphorus release from the marsh's sediments. Results indicate moderately high phosphorus loading under both oxic and anoxic conditions further suggesting that the marsh could be a potential phosphorus source to Six Mile Creek and Halsted Bay (Table 4-1). Thus, sampling at both monitoring stations should continue to determine potential phosphorus loading from Six Mile Marsh during the late summer months when water temperatures increase and flow in Six Mile Creek is significantly lower.

**Table 4-1. Six Mile Marsh sediment phosphorus release.**

| Site | Oxic Release ($mg/m^2/day$) | Anoxic Release ($mg/m^2/day$) |
|---|---|---|
| WET 110-C | 5.7 | 5.9 |
| WET 110-R | 1.0 | 2.7 |
| WET 120-L | 2.9 | 7.2 |

#### 4.2.3.3 Watershed Phosphorus Load

Phosphorus loading to Halsted Bay from Six Mile Creek was calculated by multiplying Mud Lake outlet station's annual flow weighted mean TP concentration by the modeled flow volume estimated by the XPSWMM at the outlet to Halsted Bay. No phosphorus data has been collected in the direct watershed or the tributary north of Six Mile Creek. Thus, phosphorus loads from these subwatersheds were estimated using the Mud Lake outlet flow weighted mean TP concentration and XPSWMM model runoff depths.

### 4.2.4 Internal Loading

Over time, basins tend to accumulate phosphorus in their bottom sediments. One of the primary bonds for phosphorus is with iron. When oxygen is depleted near the sediment surface (water concentration less than 2.0 mg/L), phosphorus-iron bonds and other chemical bonds are broken, releasing dissolved phosphorus for transport into the water column. This phosphorus is in a dissolved form that is readily available to algae and plants.

Internal phosphorus loading from sources already in basins has been demonstrated to be an important aspect of the phosphorus budgets of basins. However, measuring or estimating internal loads can be difficult, especially in shallow lakes that mix several times throughout the year and in deep lakes that have long fetches and deep mixing depths. To estimate internal loading, an anoxic factor (Nürnberg 2004), which estimates the period where anoxic conditions exist over the sediments, is estimated from the dissolved oxygen profile data. The anoxic factor is expressed in days but is normalized over the area of the lake. Once the anoxic factor has been calculated, an oxic factor may be estimated which represents the number of days the lake's sediments are well oxygenated (oxygen concentration greater than 2.0 mg/L). For Halsted Bay, the oxic factor was calculated by subtracting the length of the summer growing season (122 days) by the anoxic factor. This calculation assumes the lake's sediments shift between oxic and anoxic conditions throughout the summer growing season. The anoxic and oxic factors are then used along with anoxic and oxic sediment release rates to estimate the total phosphorus load from the sediments. Sediment release rates were estimated by collecting sediment cores in the north and south basins of Halsted Bay and incubating the sediment in the lab under oxic and anoxic conditions (James, 2012; Appendix B). The laboratory measured rate of phosphorus release from anoxic and oxic sediments for each basin are presented in Table 4-2. These rates were then multiplied by the total area of each basin to estimate the gross internal load for each basin.

**Table 4-2. 2005-2011 average annual internal load estimates for Halsted Bay.**

| Basin | Oxic Release ($mg/m^2/day$) | Anoxic Release ($mg/m^2/day$) | Oxic Factor (days) | Anoxic Factor (days) | Total Internal Load (lbs/year) |
|---|---|---|---|---|---|
| Halsted North | 3.6 | 11.0 | 87 | 35 | 2,041 |
| Halsted South | 1.6 | 8.0 | 103 | 19 | 664 |
| Total | 2.7 | 10.1 | 93 | 29 | 2,705 |

## 4.3 PHOSPORUS BUDGET AND LOAD REDUCTIONS

The following is a description of the primary sources of phosphorus to Halsted Bay based on the phosphorus source inputs and lake response (BATHTUB) modeling.

### 4.3.1 Lake Phosphorus Budget

Average annual phosphorus budget for model years 2005-2011 is presented in Figure 4-7. Loading from the Halsted Bay drainage area, particularly Six Mile Creek, represents a majority of the annual TP load to the lake. Internal load from the lake's sediments represents the second largest source of TP. Internal load can play a significant role during the warm summer months when TP load from the watershed is low. Phosphorus inputs from the atmosphere and groundwater each account for only 2% of the overall budget.

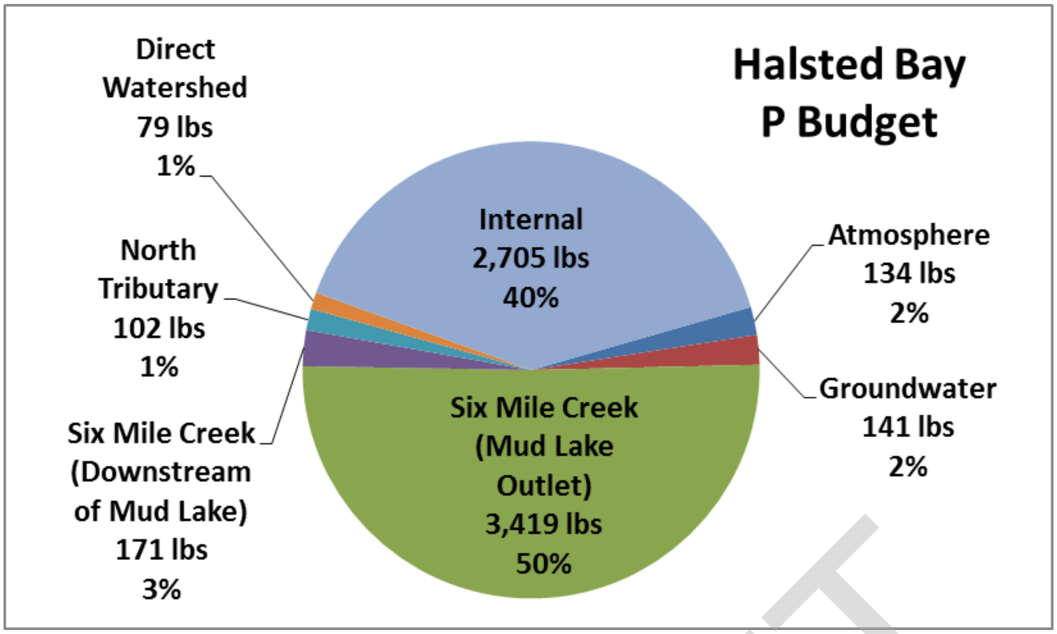



**Figure 4-7. Halsted Bay phosphorus budget.**

### 4.3.2 BATHTUB Model

Once the nutrient budget has been developed, the response of the lake to those nutrient loads must be established. The focus of the lake response modeling is on total phosphorus, chlorophyll-a and Secchi depth. For Halsted Bay, the BATHTUB model was selected to link phosphorus loads with in-lake water quality. A publicly available model, BATHTUB was developed by William W. Walker for the U.S. Army Corps of Engineers (Walker 1999). BATHTUB has been used successfully in many lake studies in Minnesota and throughout the United States. BATHTUB is a steady-state annual or seasonal model that predicts a lake's summer (June – September) mean surface water quality. BATHTUB's time-scales are appropriate because watershed phosphorus loads are determined on an annual or seasonal basis, and the summer season is critical for lake use and ecological health. BATHTUB has built-in statistical calculations that account for data variability and provide a means for estimating confidence in model predictions.

Halsted Bay BATHTUB lake response model was constructed using the nutrient budget methods and results previously described in this section. In-lake phosphorus data for Halsted Bay was available from 2005-2011, therefore these years were used to validate the assumptions of the model. Several models (subroutines) are available for use within the BATHTUB model. The selection of the subroutines is based on past experience in modeling lakes in Minnesota and is focused on subroutines that were developed based on data from natural lakes. The Canfield-Bachmann natural lake model was chosen for the phosphorus model. For more information on these model equations, see the BATHTUB model documentation (Walker 1999) or the MPCA report (MPCA 2005). Halsted Bay lake response model performance is summarized in Figure 4-8. Seven years were modeled for TP and the model predicted within 2% - 17% of the in-lake monitored TP values. Lake models are included in Appendix C.

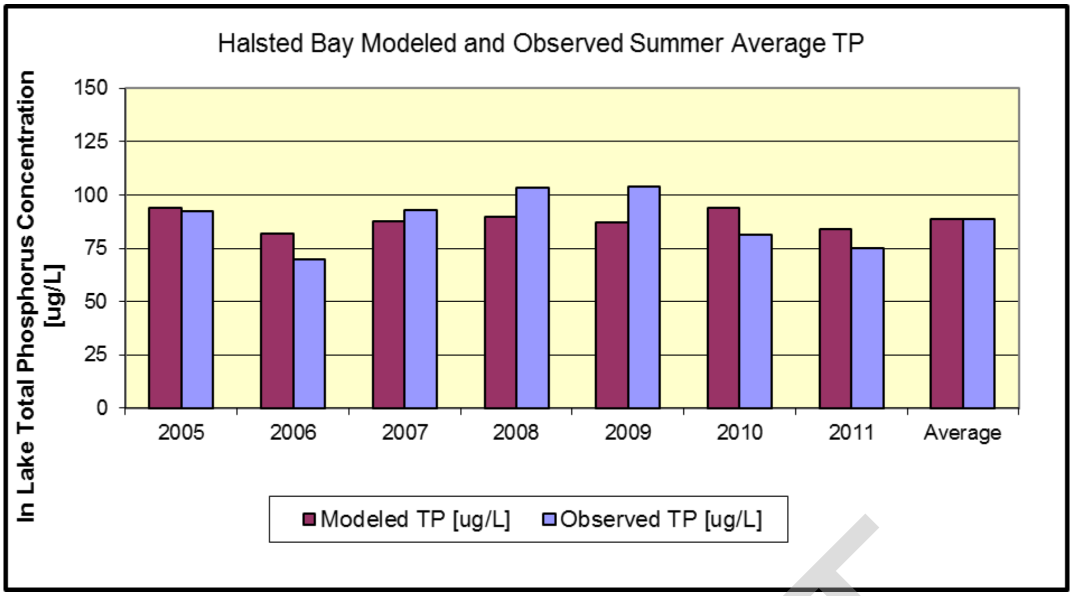



**Figure 4-8. Observed versus BATHTUB model-predicted total phosphorus for Halsted Bay.**

### 4.3.3 Phosphorus Load Reductions

To determine the required phosphorus loads to meet State water quality standards for deep lakes in the North Central Hardwood Forest Ecoregion (NCHF; Table 4-3), the average condition model run (2005-2011) phosphorus budget was used to determine the response of Halsted Bay to total phosphorus reductions.

**Table 4-3. Numeric water quality goals for Halsted Bay.**

| Intended Use | Average June-September Values | | |
|---|---|---|---|
| | Total Phosphorus (µg/L) | Chlorophyll-*a* (µg/L) | Secchi Depth (m) |
| Indirect Contact Recreation | ≤40 | ≤14 | ≥1.4 |

First, internal phosphorus loading was reduced to a rate of 0.7 mg/m$^2$/day based on other reference lakes. Then, watershed loads were reduced until the baseline lake response model predicted a summer average of 40 µg/L total phosphorus.

To meet this water quality goal, modeling suggests a total reduction of 4,459 pounds of phosphorus loading to Halsted Bay needs to occur with 2,181 pounds coming from the watershed and 2,278 pounds reduction through internal loading. The majority of watershed loading comes from Six Mile Creek through Mud Lake. Therefore, the restoration of Mud and Parley Lake is critical to the restoration of Halsted Bay. Table 4-4 breaks the watershed loading into subwatershed reduction requirements.

**Table 4-4. Halsted Bay TP load reductions.**

| Source | Existing TP Load [1] | TP Load at 40 µg/L | Load Reduction | |
|---|---|---|---|---|
| | (lbs/year) | (lbs/year) | (lbs/year) | % |
| Drainage Areas (Six Mile Marsh, north tributary and direct watershed) | 353 | 171 | 182 | **52%** |
| Upstream Lakes (Mud Lake @ 60 µg/L) | 3,419 | 1,421 | 1,999 | **58%** |
| Atmosphere | 134 | 134 | 0 | **0%** |
| Groundwater | 141 | 141 | 0 | **0%** |
| Internal Load | 2,705 | 427 | 2,278 | **84%** |
| **TOTAL** | **6,753** | **2,294** | **4,459** | **66%** |

# 5.0 IDENTIFICATION OF BEST MANAGEMENT PRACTICES

## 5.1 INTRODUCTION

The purpose of this Feasibility Study was to assess engineering alternatives to reduce nutrient loading to Halsted Bay and ultimately improve water quality.

## 5.2 ALTERNATIVES NOT FURTHER ASSESSED

The first step in the process was to eliminate alternatives that are not feasible or cost effective. Four alternatives were determined to be either infeasible or too costly to implement. Those alternatives are further described below.

### 5.2.1 Abstraction by Deep Infiltration

Abstraction by deep infiltration requires a significant area with high infiltration and percolation capacity. This alternative was eliminated due to lack of areas in the lower part of the Halsted Bay watershed that have these characteristics.

### 5.2.2 Temporary Drawdown of Halsted Bay

One of the standard restoration techniques for shallow lakes to restore submerged aquatic vegetation is whole lake draw down. Drawdowns typically occur during the summer months (June through September) and expose as much sediment as feasibly possible. Winter drawdowns are also used at times; however these are more targeted at Curly Leaf Pondweed control. Halsted Bay is not a typical shallow lake (max depth >15 feet or more that 85% less than 15 feet), and will likely not respond as strongly to a drawdown as a more traditional shallow lake, although plant establishment will be necessary for long term restoration of the bay. Drawdown is also very difficult due to the large contributing watershed to the bay as well as the connection to Lake Minnetonka. Since Halsted Bay is a highly used recreational lake and the overall efficacy of drawdown appears to be limited, this option was eliminated from consideration.

### 5.2.3 Microtunnel Bypass from Lundsten

Microtunneling a waterway underground from Lundsten Lake to Halsted Bay was initially considered. This waterway would allow Halsted Bay inflow to bypass Parley Lake, Mud Lake, and the large wetland between Mud Lake and Halsted Bay. This would reduce phosphorus in Halsted Bay by eliminating most of the phosphorus entering the bay from Six Mile Creek. The problem with this option is that it is very costly (approximately $23 million) and not likely feasible in terms of permitting or public approval.

### 5.2.4 Dredging Hypolimnion Sediments

Due to the high phosphorus concentration in the sediments of the hypolimnion, dredging the hypolimnion is an option for restoration. Dredging is enticing as it would physically remove the phosphorus, rather than suppressing the effects of high phosphorus concentration (aeration, alum dosing, alum injection). It has historically been considered for Jennings Bay, but not recommended due to the same considerations below.

The depth of the high concentration of phosphorus in the sediment is relatively unknown and may extend to depths greater than six feet. A cost estimate for eight feet of dredging results in $30 million. In addition, the disposal of the dredged slurry becomes a significant obstacle. Setting up detention basins close to Halsted Bay would require the purchasing land for large, open basins. There would be an odor concern to the surrounding residents.

Due to cost, relatively unknown phosphorus concentration at depths greater than six feet, and the land considerations, this alternative was eliminated.

## 5.3 ALTERNATIVE THAT NEEDS MORE INFORMATION

### 5.3.1 Hydrologic Restoration of Six Mile Marsh

There is some evidence, based on historical modeling, that Six Mile Marsh may be contributing phosphorus to surface waters as water moves from Mud Lake into Halsted Bay. Recent monitoring (2013) has not validated phosphorus release from Six Mile Marsh (see Section 4.2.3.2) but the sediment did demonstrate significant phosphorus release under both oxic and anoxic conditions. Since restoring Six Mile Marsh may be a very expensive project, further data and analysis are required prior to assessing the feasibility of this project to Halsted Bay. If the marsh is verified as a significant nutrient source to surface waters, a diagnostic study needs to be completed to identify the mechanism causing the wetland to export phosphorus so that an appropriate solution can be developed. One current theory for wetlands that export phosphorus is that the hydrology of the wetland has been significantly altered such that the soil wet and dry cycles are extended increasing the phosphorus release from the soils.

The District is currently monitoring Six Mile Marsh for flow and water quality to help determine if the marsh is really a significant source of phosphorus. If the wetland is determined to be a net phosphorus exporter, further monitoring and study may be required including piezometers, groundwater wells, and other water quality monitoring to determine an appropriate solution for Six Mile Marsh.

## 5.4 SELECTED ALTERNATIVES – INTERNAL LOAD

Five alternatives were evaluated for internal nutrient controls.

### 5.4.1 Alum Treatment of Halsted Bay

Internal phosphorus loading accounts for 40% of the phosphorus budget to Halsted Bay or roughly 2,705 pounds. An 84% reduction (2,278 pounds) is targeted for internal load reduction for Halsted Bay to meet water quality goals. It is important to note that internal nutrient load reductions alone will not achieve water quality goals for Halsted Bay.

One approach to reduce or eliminate internal phosphorus loading in lakes is chemical addition to permanently bind phosphorus in a form unavailable for algal uptake. Currently, the most common chemical used to permanently bind phosphorus is aluminum sulfate or alum. The alum phosphorus bond is insensitive to sediment redox processes keeping the phosphorus from releasing into the water column even if sediment becomes anoxic. Furthermore, research demonstrates that the longer the alum is in the lake sediment, the more stable it becomes, assuring the long term viability of phosphorus sequestration.

The process of applying alum to a lake typically includes injection of liquid alum just below the surface of the lake. The alum quickly forms a floc and settles to the bottom of the lake, forming a sediment seal while stripping phosphorus from the water column on the way down to the sediments. The undisturbed floc provides a sediment barrier that binds any phosphorus released from the sediment, essentially eliminating internal phosphorus loading from that portion of the lake.

To evaluate the appropriateness and cost of an alum treatment in Halsted Bay, Wenck, in conjunction with the University of Wisconsin-Stout, collected sediment cores from numerous locations in Halsted Bay. The cores were transported back to the University's lab and analyzed for sediment chemistry, phosphorus release under both anaerobic and aerobic conditions, and alum binding efficiency (UW-Stout 2013). More details on the methods used for alum dosage calculations can be found in Appendix B.

Two scenarios were evaluated for alum treatment to Halsted Bay including Scenario 1 where only the area of the lake that experiences anoxia is treated (Figure 5-1), and Scenario 2 where additional areas of aerobic phosphorus release is high are also treated (Figure 5-2). Scenario 1 is the more traditional approach with alum that targets the areas of the lake that have the potential to go anoxic. This approach can reduce internal loading by approximately 1,308 pounds, only a little more than half of the target reduction. This is because the shallower areas demonstrated a relatively high oxic (aerobic) release rate. If the shallow western areas (6 to 14 feet) are also targeted for alum, an additional 599 pound reduction can be achieved. The long term effectiveness in the shallower areas will likely be less than the deeper areas due to fish activity and wind resuspension (5 to 10 years). However, the treatment may help establish submerged aquatic vegetation that will stabilize and protect sediments from mobilization lengthening the benefits of the alum treatment. The ability to treat the shallow areas of the lake presents a stark advantage over other internal load approaches that only address the anoxic areas of the lake.

Multiple treatments of lower alum concentrations over a period of years (i.e., 1-2 year intervals) have been successful (Tiefwarensee, Germany) and have merit as a viable treatment schedule for Halsted Bay. First, splitting the overall alum dosage into 2 or 3 years would ensure that application does not lower pH temporarily to < 6.0. Second, costs are spread out over a period of several years and may be easier to finance. Third, since each incremental dosage is low relative to the final target dose, the alum floc has a greater chance of becoming saturated with sediment phosphorus immediately after application. Other research has suggested that alum binding efficiency for phosphorus declines with time as the alum reacts to form more orderly Al~(OOH) polymer chains (Berkowitz et al. 2005, de Vicente et al. 2008). Sediment redox-phosphorus and aluminum-bound phosphorus could be monitored after each application for effectiveness in control of sediment phosphorus. Subsequent alum applications might ultimately be lower if previously applied alum flocs have efficiently inactivated most of the redox-phosphorus in the surface sediment layers, resulting in overall cost savings. To ensure this approach can be considered, we used a 7% mobilization cost that should be sufficient to cover multiple applications.

*Regulatory Considerations*

Currently, there are no required permits to conduct an alum treatment on a lake in Minnesota; however the Minnesota Pollution Control Agency does request a letter outlining the project details for their review. The MPCA requests that the letter address the prescribed alum dose, pH considerations and other projects being considered to address external loading as well as internal loading. The MPCA continues to work toward developing a permitting process for alum treatments in Minnesota.

### 5.4.2 Hypolimnetic Aeration with Chemical Injection

Lake hypolimnetic aeration controls internal loads by aerating hypolimnetic waters (cold, dense water trapped at the bottom of a deep lake) to maintain oxic (oxygenated) conditions in the hypolimnion and sediment surface. It is the anoxic (no dissolved oxygen) condition of the hypolimnetic sediments which contribute to the internal phosphorus load. Hypolimnetic aeration only aerates water of the hypolimnion without causing it to mix with the epilimnion. This prevents the lake from destratifying and limits the amount of water to be aerated.

For this alternative, various aeration units would be placed throughout the bay. Diffused air would be introduced at the bottom of the aerator in the hypolimnion. The buoyancy of the air-water mixture lifts the water through the central pipe to the top of the aerator. The air bubbles leave the water and are vented to the water surface, while the oxygenated water returns to the hypolimnion by sinking through the external tube.

Addition of ferric chloride (an iron salt) solution may be necessary if iron becomes the limiting constituent in the deactivation of soluble phosphorus release. Therefore, both aeration and ferric chloride lines (other chemicals can be used too) would be installed in the lake during the initial construction.

Some additional implementation and design issues would need to be considered. For instance, the location and number of aeration units would need to be refined through further analysis. Also, the project team would need to determine if the aeration could take place year round. If aeration is used through the winter, it has the disadvantage of destroying ice cover or causing open water, posing a hazard for winter bay use. If year-round aeration is not an option, storage of the aeration units would need to be investigated. Therefore, additional safety measures or an increase of operation and maintenance practices will have to be factored into the final design.

*Regulatory Considerations*

A hypolimnetic aeration project would likely require review and comment from several local and state agencies. Two permits are required from the Minnesota DNR for a hypolimnetic aeration project. The first is from the Division of Fisheries. The second is the General Work in Public Waters Permit. The typical timeframe to acquire a General Work in Public Waters permit is 60 days. However, depending on the complexity of the project and the potential for controversy with the lake shore residents and/or general public the permitting process could take considerably longer. Typical processes for obtaining these permits can last from a period of many months to many years and involve a technical advisory committee to approve final design. DNR shoreline set-back requirements may apply to certain aspects of the project construction. The MPCA would also need to review the project in conjunction with the DNR permit.

### 5.4.3 Withdrawal, Alum Treatment, and Replacement

Hypolimnetic withdrawal is where anoxic bottom water is removed from the lake and either discharged downstream or treated and returned to the lake. In this alternative the water would be returned to the lake to minimize an overall decrease in lake water volume. Water would be pumped out of the hypolimnion into a pump house constructed on shore. A force main would be laid on the bottom of the lake with a screen at the intake.

Once water reaches the pump house, it is aerated over a cascade of concrete weirs into a basin. The water in the hypolimnion of Halsted Bay likely contains hydrogen sulfide ($H_2S$) and the aeration process releases hydrogen sulfide ($H_2S$) gas into the air, creating a very potent "rotten egg" smell. Due to the close proximity of residential neighborhoods, the hydrogen sulfide gas would need to be reduced to a suitable level before leaving the pump house. To reach this level, a series of air filters will be required. Along with the air filters in the pump house building, air monitoring equipment will also be required because even at low concentrations, hydrogen sulfide is potentially dangerous to maintenance personnel working in the building.

Dosing for this option will vary from the amounts calculated in Section 5.4.1 as the dosages for this option are based on water quality and not soil chemistry. More detailed methods including bench testing should be used to develop specification if Withdrawal and Alum Treatment is the internal load reduction option selected. Also, in-lake alkalinity and pH would need to be examined on a detailed level. If an inappropriate alum dose is used and the pH of Halsted Bay drops below 6.0, aquatic toxicity may occur which would be harmful to aquatic life. Application of a buffer solution, such as liquid sodium aluminate, may be required to keep pH levels above the toxicity threshold.

The long-term effectiveness of this method of alum treatment is determined by several factors including depth of treatment, presence of rough fish, long term storage and release of phosphorus in sediments, external loading rates, and application or injection techniques.

*Regulatory Considerations*

Hypolimnetic withdrawal implementation would require a General Work in Public Waters permit. The typical time frame to acquire a General Work in Public Waters permit is 60 days. However, depending on the complexity of the project and the potential for controversy with the lake shore residents and/or general public the permitting process could take considerably longer. Typical processes for obtaining these permits can last from a period of many months to many years and involve a technical advisory committee to approve final design. DNR shoreline set-back requirements may apply to certain aspects of the project construction. The MPCA would also need to review the project in conjunction with the DNR permits.

Additionally, a Water Appropriations permit will be necessary for the withdrawal of water, even if the water is being pumped back into the bay. However, a permit through the Minnesota DNR's Division of Fisheries for a Partial Drawdown Waters Work permit will not be necessary.

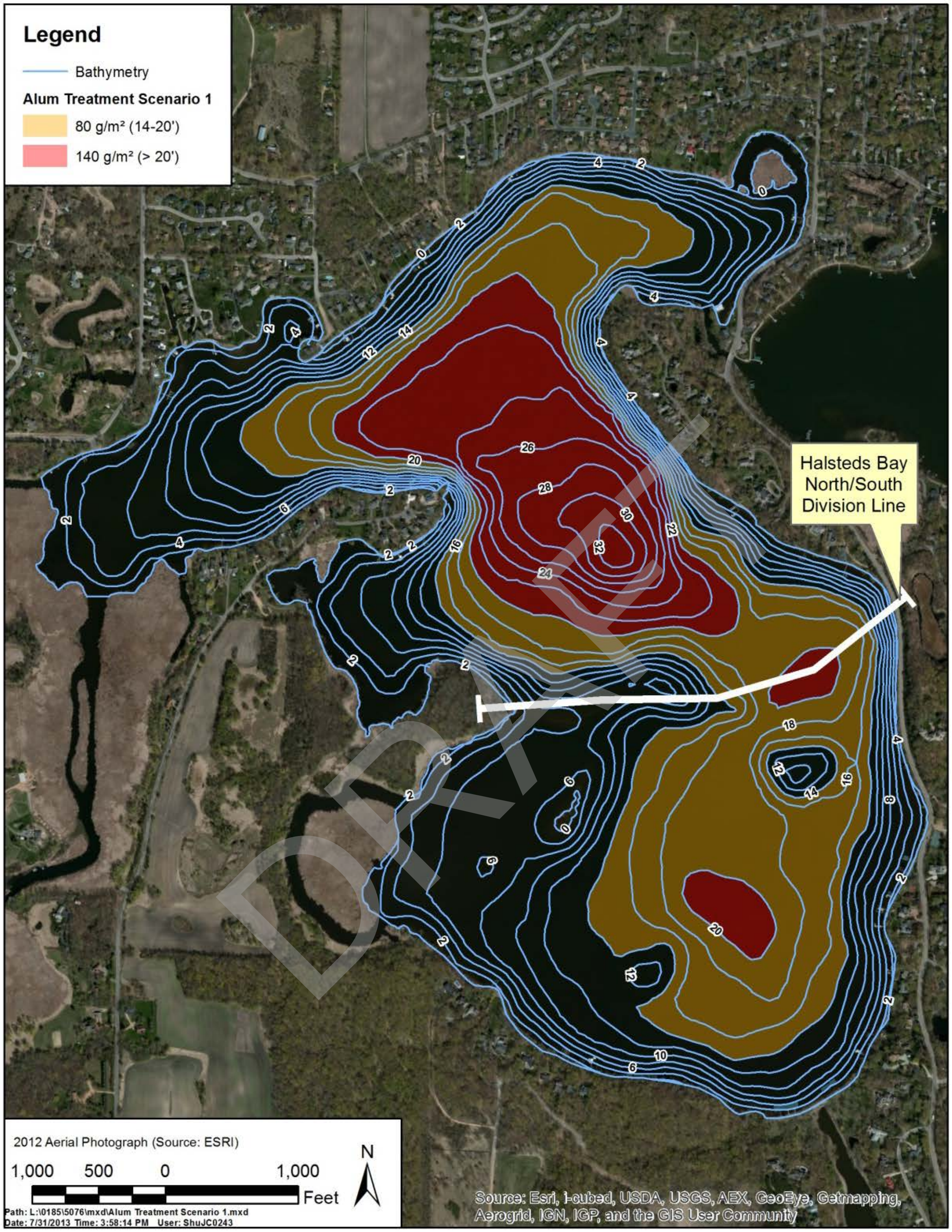



**Figure 5-1. Scenario 1: Alum treatment in the anoxic areas of Halsted Bay.**

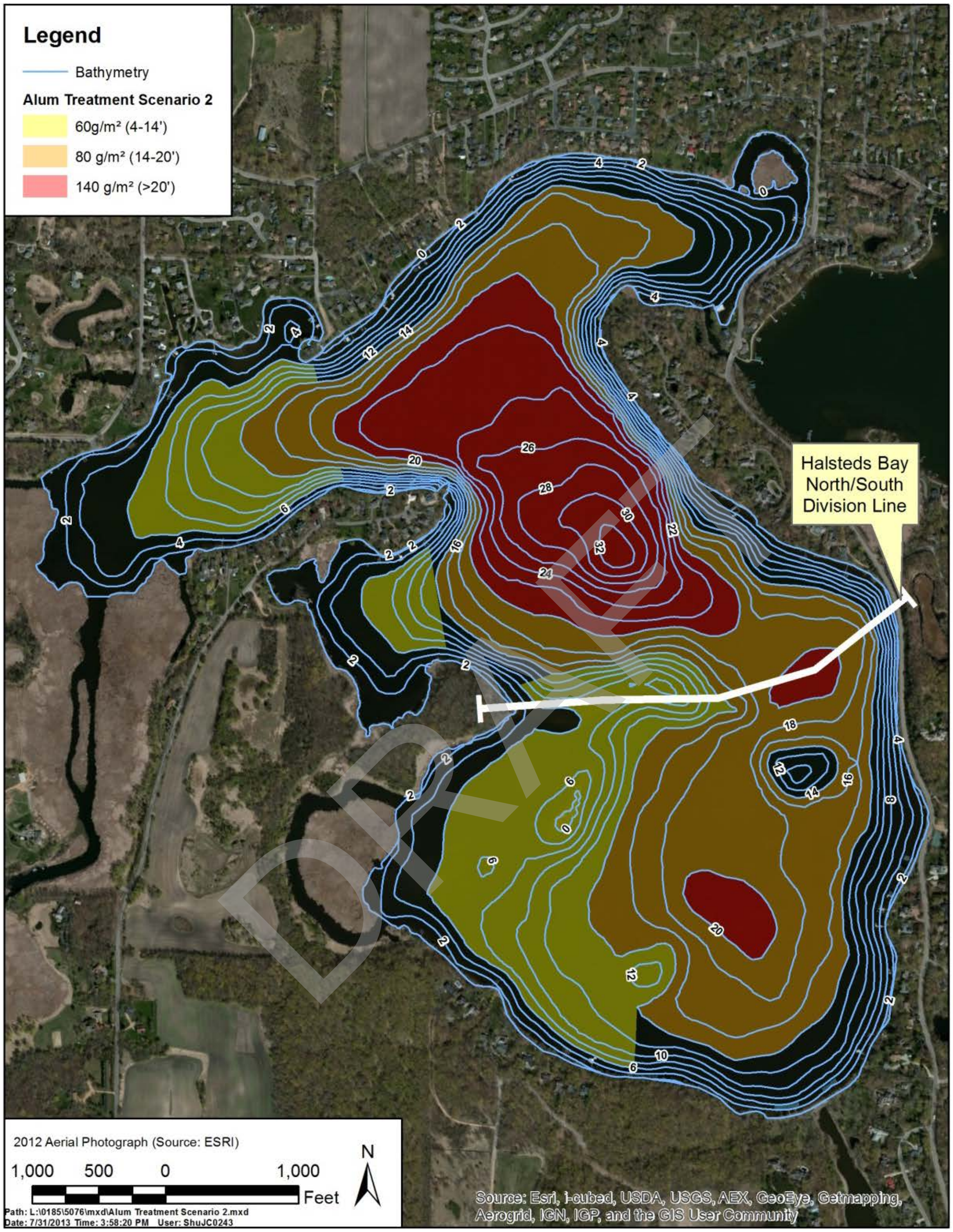



**Figure 5-2. Scenario 2: Alum treatment in the anoxic and shallow western areas of Halsted Bay.**

## 5.5 SELECTED ALTERNATIVES – EXTERNAL LOAD CONTROL

### 5.5.1 Off-line Alum Treatment

The off-line treatment alternative consists of a clarification system designed to remove phosphorus from the creek water entering Halsted Bay. The phosphorus is removed through the addition of a flocculant (alum) to the influent creek water to create large particles (floc) containing the phosphorus. The influent travels through the clarifier where the floc settles to the bottom, leaving cleaner water (effluent) near the top of the clarifier. The effluent is then discharged into Halsted Bay while the floc is disposed of through a sanitary sewer or to holding ponds.

For this alternative, raw water would be drawn from an intake structure placed at the bottom of Six Mile Creek. The water would be pumped to a splitter box which would control the flow rate to two 48-foot diameter clarifiers. Each clarifier would be equipped with a perimeter rake on the bottom of the structure and perimeter skimmer on the top of the water. The rake assists with the sludge disposal while the surface skimmer removes surface floc and prevents it from being discharged to Halsted Bay.

The plant would be designed for a flow rate of 5 cfs (2,250 GPM). At this rate, it is estimated that approximately 11,000 gpd of sludge would be generated. The sludge discharge rate from the clarifier is greater than the capacity of the two lift stations and therefore, two equalization tanks would be used to temporarily store sludge flow. The sludge would then be discharge to a sanitary sewer or to holding ponds.

*Regulatory Considerations*

The City of Minnetrista owns and operates the local wastewater collection system, but ultimately conveys its wastewater to MCES interceptor sewers that transport wastewater to regional treatment plants for final disposal. MCES requires an industrial discharge permit for all facilities using water in its treatment process and one would be required for this system. Historically, MCES has granted industrial discharge permits for similar facilities, but as phosphorus limits are reduced at their regional treatment facilities, there is a strong possibility permits will not be granted in the future. Additionally, industrial discharge permits are reviewed on a regular basis and MCES can revoke the permit in the future.

In the event MCES does not authorize an industrial discharge permit, a sludge holding pond system would need to be utilized. Sludge ponds would be designed to hold the sludge and allow drying. The ponds would need to be dredged as sludge builds up over time.

The treatment facility would withdraw water from and return it to public water; therefore a National Pollutant Discharge Elimination System (NPDES)/State Disposal System (SDS) permit will be required from the MPCA. Similar facilities have been permitted in the past, and water quality monitoring may be required by the permit (WSB & Associates, 2013).

### 5.5.2 In-line Alum Injection

In-line alum injection line is very similar to the off-line alum injection, except that it eliminates the need for clarifiers and an intake structure with associated pumps. The in-line injection system would introduce alum to the high-phosphorus concentrated Six Mile Creek flow. The alum would mix with the phosphorus and settle to the bottom of Halsted Bay.

A pump house would still be necessary for this alternative to house the injection pumps and the alum storage tanks, but it would have a much smaller footprint than the off-line alum injection alternative.

*Regulatory Considerations*

Permitting of in-line alum injection is very doubtful. It will be difficult to convince regulators that continuous injection of alum will not cause environmental impacts downstream.

### 5.5.3 Iron Filtration

Iron filtration involves passing phosphorus rich water through a sand and iron particle filter. Iron reacts with the phosphorus and removes it from the water. For this alternative, it is assumed 15 cfs of water from Six Mile Creek is pumped to a 15-acre lined, sand/iron filtration area. Once the water has passed through the filter it is collected in an under drain and routed back to the creek. The cost effectiveness is based on 85 percent removal efficiency.

Regulatory Considerations

Iron filtration is a relatively new best management practice, but it has been used in several locations in the metro area. There are no significant regulatory issues beyond that fact that this system is relatively large. The size may result in local concerns related to its appearance and possible odor.

## 5.6 OTHER RESTORATION CONSIDERATIONS

The projects evaluated in this report are focused on phosphorus reductions since these will have the greatest impact on water quality in Halsted Bay. However, several other factors need to be considered for these projects to be effective and sustainable for the long term. Following is a description of these factors.

### 5.6.1 Vegetation Management

Submerged aquatic vegetation (SAV) play a critical role in water quality especially in shallow areas of lakes. Submerged aquatic vegetation provide habitat for fish, stabilize sediments preventing wind resuspension and turbid water, and represent a food source and habitat for macroinvertebrates. Halsted Bay lacks a robust SAV population which may inhibit good water quality in the Bay.

Restoration of SAV typically involves whole-lake drawdown to consolidate sediments and invigorate the native seed bank. However, whole lake draw down is not feasible in Halsted Bay due to its littoral depth, large watershed, and recreational uses. Consequently, the best approach for restoring native vegetation is to improve water clarity and control invasive vegetation so that the native vegetation can establish.

One approach to increasing water clarity is the addition of alum (see Section 5.4.1). The increased water clarity will help the native plants establish, although Curly Leaf Pondweed and Eurasian Water Milfoil will respond too. A vegetation management plan should be developed prior to implementing water quality projects expected to have immediate impacts on water clarity. The invasive plants need to be controlled or they will choke out the natives, decreasing the value of the SAV in the lake. The increased water clarity and SAV abundance may also lead to some recreational constrains for swimming and boat access.

From a water quality perspective, only Curly Leaf Pondweed poses a major threat because it senesces mid-summer exposing sediments for release and resuspension. Management should focus on Curly Leaf Pondweed to protect the investment in the alum application or other internal control measures. There are other reasons to manage Eurasian Water Milfoil, including improved habitat and recreational access, although it is not critical for water quality. This report focuses on the management of Curly Leaf Pondweed.

The two most common approaches for managing vegetation include herbicide applications and mechanical removal. Typically, the most effective approach is a mix of mechanical removal and herbicide application.

### 5.6.2 Rough Fish Management

One of the keys to restoring Halsted Bay is the restoration of Parley and Mud Lakes as well as ensuring Six Mile Marsh is not discharging phosphorus. Almost 90% of the water entering Halsted Bay comes through Parley and Mud Lakes, extolling a large influence on Halsted Bay.

One of the key considerations for restoring Mud and Parley Lake is the removal and control of carp in the lakes. Carp cause significant damage in shallow lakes, uprooting submerged vegetation, stirring up sediments, and ultimately driving the lake into a turbid state. Carp likely migrate up into Mud and Parley Lake from Halsted Bay through Six Mile Marsh. Consequently, a carp barrier between Halsted Bay and Six Mile Marsh may need to be considered for the long term restoration of Mud and Parley Lakes. However, it is important to note that carp could still move down from the upper watershed through Lundsten Lake. So, restoration needs to focus on both sources.

Wenck reviewed locations for a potential carp barrier between Halsted Bay and Six Mile Marsh. The best location occurs just west of Halsted Bay where a constriction of the creek occurs (see location of new King's Point Road water quality station in Figure 4.4). Another area just north of this constriction may need to be considered for a fish barrier depending on water depths and fish movement potential.

The University of Minnesota is currently working with the District to develop a watershed-wide carp management plan for the Six Mile Creek Watershed. This study will evaluate the long term viability of controlling carp in the watershed and ultimately determine whether there is a need for a carp barrier between Halsted Bay and Six Mile Marsh. However, carp management is critical to restoring Mud and Parley Lake and ultimately Halsted Bay.

# 6.0 Nutrient Reduction Cost and Effectiveness

## 6.1 MODELING ALTERNATIVES AND EVALUATING COST/BENEFITS

Table 6-1 provides a summary of the costs related to the selected alternatives presented in this report. Refer to Appendix D for more details on cost estimates.

**Table 6-1. Physical Features of Halsted Bay.**

| Alternative Description | Capital Cost | 20-Yr Life Cost | Phosphorus Removal (lbs/yr) | Phosphorus Removal ($/lb-yr) |
|---|---|---|---|---|
| **Internal Alternatives (2,278 lb Annual P Reduction Goal)** | | | | |
| Alum Treatment of Halsted Bay - Scenario 1 | $1,046,000 | $1,054,000 | 1,308 | $40 |
| Alum Treatment of Halsted Bay - Scenario 2 | $1,134,000 | $1,142,000 | 1,907 | $30 |
| Hypolimnetic Aeration with Chemical Injection | $1,112,000 | $2,672,000 | 1,308 | $102 |
| Hypolimnetic Withdrawal, Alum Treatment, and Replacement | $8,277,000 | $11,577,000 | 1,308 | $443 |
| Hypolimnetic Alum Circulation | $1,663,000 | $4,363,000 | 1,308 | $167 |
| **External Alternatives (2,278 lb Annual P Reduction Goal)** | | | | |
| Off-line Alum Injection | $7,728,000 | $13,932,568 | 1,617 | $431 |
| In-line Alum Injection | $851,000 | $1,060,000 | 1,396 | $38 |
| Iron Filtration | $4,789,000 | $5,490,000 | 900 | $305 |
| **Other Restoration Considerations** | | | | |
| Fish Migration Barrier | $109,000 | $204,000 | Does not remove P, but is necessary for lake restoration. | |
| Vegetation Management | $0 | $396,000 | | |

### 6.1.1 Internal Load Reductions

The most cost effective approach for reducing sediment phosphorus release from Halsted Bay is sediment phosphorus inactivation using alum. The treatment of hypolimnetic water through an alum injection plant is very expensive and requires significant operation and maintenance over a 20 year life cycle. Hypolimnetic circulation with alum microfloc addition can achieve similar results as an alum treatment, but requires significant long term operation and maintenance costs versus an alum treatment. The only advantage to this approach is that the certainty of eliminating phosphorus flux to the epilimnion is much higher because you are continually dosing the hypolimnion and stripping phosphorus out of the water column. However, treating the sediments with alum provides the advantage of treating the shallow areas that demonstrated significant phosphorus release. Also, even of the alum treatment needs to be repeated at year 10 at the full dose (which is unlikely), the overall treatment cost is still significantly less than the microfloc addition. Alum treatment of sediments including identified shallow areas appears to provide the best long term control of internal phosphorus release at the lowest cost.

### 6.1.2 External Load Reductions

Of the three external load reductions alternatives, only off-line alum treatment and iron filtration are likely to get a permit. In-line alum treatment appears to be very cost effective, but there are too many unknown environmental impacts at this point in time.

In comparison to internal load reduction alternatives, external load reduction alternatives are significantly more expensive. These alternatives rely on facilities that are costly and require significant operation and maintenance costs.

Off-line alum treatment may have higher cost effectiveness, but has the advantages of a higher removal capacity and significantly smaller footprint. It should also be noted that the infrastructure required for off-line alum treatment may be used for some of the internal load reduction alternatives as well. The costs in Table 6-1 assume each alternative is separate. If the treatment required in hypolimnetic withdrawal, treatment, and replacement is done in conjunction with off-line alum treatment, the overall cost can be greatly reduced. Only one treatment facility is needed. There will be additional processes to add to accommodate both alternatives in one facility, but these costs are small relative to cost of the building.

### 6.1.3 Other Restoration Considerations

To restore Halsted bay, two ecological factors must be considered including carp and vegetation management. It is unclear if carp are impacting Halsted Bay currently, but the Bay is devoid of submerged aquatic vegetation, a key component to maintaining good water quality. For Halsted Bay to be ecologically healthy, a healthy submerged vegetation population needs to be established in areas less than 15 feet in depth. The presence of carp can hinder plant establishment and long term establishment of submerged vegetation. Furthermore, the long term restoration of Halsted Bay requires that both Parley and Mud Lake meet water quality standards which are nearly impossible with the current carp populations. Carp can also impact the long term effectiveness of alum in shallower areas because they stir up sediments which can bring phosphorus rich sediment to the surface. Overall, carp management will be critical in establishing long term internal phosphorus load control. To that end, the District is working with the University of Minnesota to evaluate carp in the Six Mile Creek Watershed to identity long term management strategies.

Another factor that must be considered is the presence of invasive species in Halsted Bay including Curly Leaf pondweed and Eurasian Water Milfoil. Curly Leaf Pondweed can have long term negative impacts on water quality in shallow lakes because it senesces in midsummer leaving sediments exposed of phosphorus release and resuspension. Furthermore, as the water clarity is increased through the implementation of nutrient reduction projects, both of the invasive species can be expected to respond with aggressive increases in abundance. Controls should be in place prior to implementing the nutrient reduction projects.

Table 6.1 provides some estimated costs associated with both carp control (if a barrier is needed) and Curly Leaf Pondweed maintenance. Vegetation management is assumed to be chemical and mechanical control of Curly Leaf Pondweed. Costs included for carp management just include the cost of a carp barrier at the outlet of Six Mile Creek if one is determined to be needed. However, long term costs for removal and management may be necessary. These costs will be much clearer once the University of Minnesota completes their carp study on Six Mile Creek.

## 6.2 DISCUSSION OF RESULTS

Lake response modeling indicates that both watershed loading and internal loading need to be aggressively pursued to reach the goal in Halsted Bay. One key factor is that 90 percent of the water comes through Mud Lake which only has a target of 60 µg/l while Halsted Bay has a target of 40 µg/l. This means additional reductions may need to be found in other parts of the watershed.

Restoration of upstream Mud and Parley Lakes will be critical in restoring Halsted Bay. Both of these lakes are very shallow and carp infested. To reach water quality goals in these lakes, the carp need to be addressed, plants reestablished in the lakes and nutrients reduced. This is an extensive undertaking.

Addressing external sources, accomplishing the goals of the Six Mile Creek Diagnostic Study, is going to be a long process with uncertain outcomes. The process could take 30 years or more and is dependent on numerous landowners. A large engineering project, such as an off-line phosphorus removal plant, provides the water quality benefits immediately however at a significant cost.

# 7.0 References


Airport Cooperative Research Program. *Guidebook on Preparing Airport Greenhouse Gas Emissions Inventories.* Transportation Research Board. Report 11. Washington, DC. 2009.

Energy Information Administration, www.eia.doe.gov/oiaf/1605/coefficients.html

FAA. *Emissions and Dispersion Modeling System (EDMS) User's Manual*. Federal Aviation Administration (FAA) Office of Environment and Energy (AEE). FAA-AEE-07-01, January 2007.

ICF International, *Greenhouse Gas Emission Inventory Methodologies for State Transportation Departments*, July 2011.

Intergovernmental Panel on Climate Change (IPCC). *2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Volume 2, Energy. Chapter 3, Mobile Combustion. Section 3.6, Civil Aviation, 2006.

Intergovernmental Panel on Climate Change (IPCC). *Aviation and The Global Atmosphere*, Chapter 8.3.3 "Intermodality", 1999.

International Council for Local Environmental Initiatives (ICLEI), http://www.iclei.org

Metropolitan Airports Commission. *Case Studies at the Minneapolis-St. Paul International Airport (MSP)*. Fuhrmann, August 2008.

Minnesota Pollution Control Agency, *Update on Air Monitoring Near the Minneapolis St. Paul International Airport*, May 2006.

Minnesota Pollution Control Agency, *Air Quality in Minnesota – Challenges and Opportunities*, 2007 Report to Legislature.

Wenck Associates Inc. Minnehaha Creek Watershed District Upper Watershed Nutrient and Bacteria TMDL Study. September 2013.

# Appendices

# Appendix A

# Water Surface Elevations and Flow Data

### Monitoring Locations and Equipment

The water surface elevations were monitored at three locations as shown in Figure A-1. Continuous flow data was also recorded at the Mud Lake Outlet location. The monitoring equipment used at Halsted Bay and Kings Point Road was a BaroTROLL by In-Situ Inc. The monitoring equipment used at Mud Lake Outlet was a SonTek-IQ ADV.


**Figure A-1. Monitoring Locations.**

### Water Surface Survey Data

The change in water surface elevation between the monitoring locations is small. Six Mile Creek between Halsted Bay and Mud Lake (and even Parley just upstream) act as an extension of Halsted Bay. The surrounding lakeshore and marsh are very flat. The data collection systems at Halsted Bay and Kings Point Road require that the data loggers be removed to download information. As a result, offsets occurred in the collected water surface data between each collection period. To correlate, compare, and correct the data collected at the three monitoring locations, multiple survey points were taken to determine the water surface elevation at each location. All three locations were surveyed on the same day and the average of the survey points was used as the water surface elevation. The surveyed water surface elevations are detailed in Table A-1. Using the time stamps associated with the survey points, the water surface elevation data were matched to the surveyed elevations and corrected for any offsets that occurred in the data during downloads.

**Table A-1. Survey data collected on July 23, 2013.**

| | Water Surface Survey Elevation (ft) | | | | | |
|---|---|---|---|---|---|---|
| Location | Point 1 | Point 2 | Point 3 | Point 4 | Average | Approximate Time Stamp |
| Halstead Bay | 930.35 | 930.13 | - | - | 930.24 | 2:37pm |
| Kings Point Road | 930.31 | 930.20 | 930.22 | - | 930.24 | 3:36pm |
| Mud Lake Outlet | 930.39 | 930.17 | 930.40 | 930.27 | 930.31 | 3:07pm |

**Flow Data**

Continuous water surface elevation data was collected every 15 minutes at the three monitoring locations. Figure A-2 shows the water surface elevations at the three monitoring locations throughout the monitoring duration. Continuous flow data was also measured every 15 minutes at the Mud Lake Outlet monitoring location using the SonTek-IQ ADV. While collecting measurements, the ADV was unable to collect flow measurements during the period of time from 6/21/2013 through 7/12/2013 because the depth of flow exceeded the limits of the channel geometry input into the ADV. It was also noticed that the SonTek-IQ did not report flow measurements when the mean channel velocity was within the range of approximately 0.1 ft/s to -0.1 ft/s. Within this range, the velocity results were reported as 0 ft/s and the corresponding flow was also 0 cfs. As a result, a low reverse flow could have occurred over periods of time where 0 cfs was reported if the flow did not reach the measureable limits of the ADV.

There is also an inconsistency in the Mud lake Outlet data over the period of time from 5/23 to 6/2 likely due to debris that affected the ADV measurements. The large variations in the Halsted Bay data over the period of time from 6/23 to 7/6 were likely caused by an interference with the measuring instrument. Reverse flow was measured at several different periods of time during monitoring. Precipitation data from the MSP airport was compared to the flow data at Mud Lake Outlet, and it is clear that reverse flow conditions correlate with large precipitation events which can be seen in Figure A-3.



Figure A-4 compares the water surface elevation with measured reverse flow conditions and there is a correlation between abrupt increases in the water surface elevation and measured reverse flow conditions. During the later months of the summer when precipitation was less frequent, the base flow rate lowered to less than 10 cfs and the mean channel velocity dropped to within the range that the ADV did not report velocities and flow rates. During that time, many of the periods of time that report 0 cfs and no measured reverse flows do not indicate the potential of reverse flow. This is especially true if the period of time does not correlate with a precipitation event.

Figure A-5 shows the difference between the water surface elevations at the monitoring stations in Six Mile Creek with the water surface elevations at Halsted Bay. Figures A-6a and A-6b are examples that show the difference in the water surface elevation minimizes during times of reverse flow.

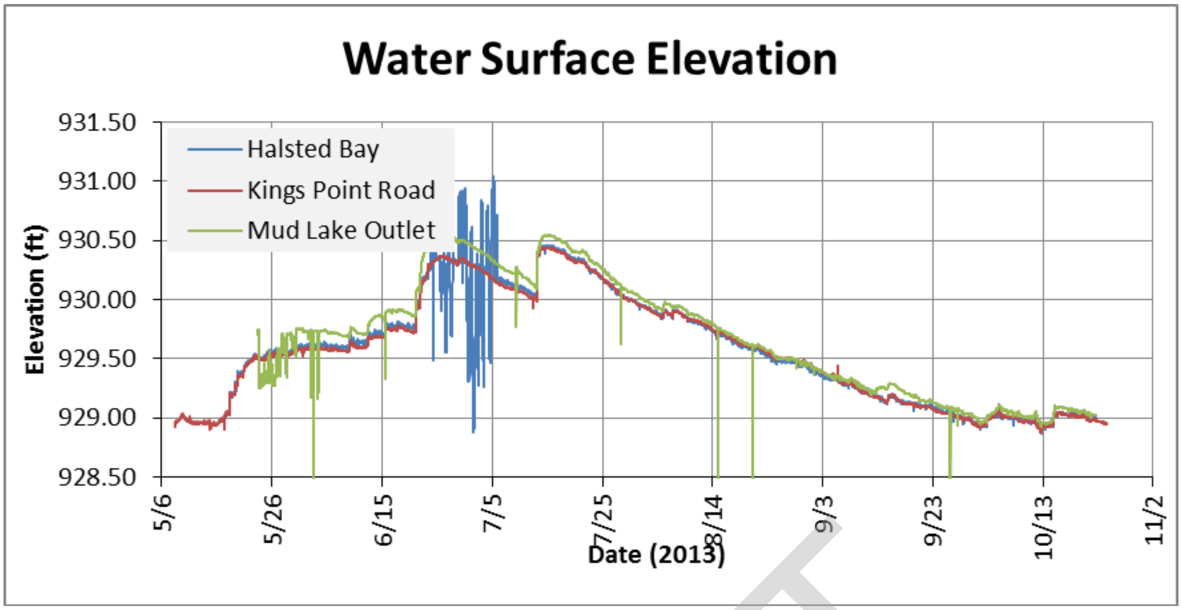



**Figure A-2. Water surface elevation comparison.**

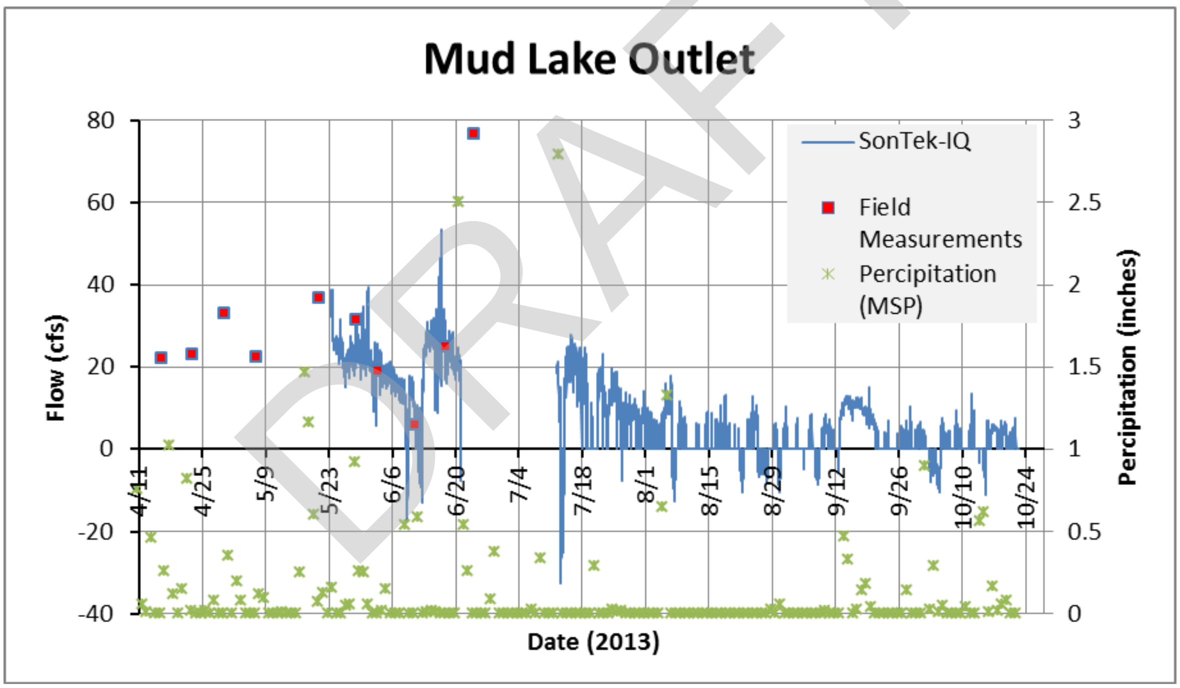



**Figure A-3. Mud Lake Outlet flow measurements and precipitation comparison.**

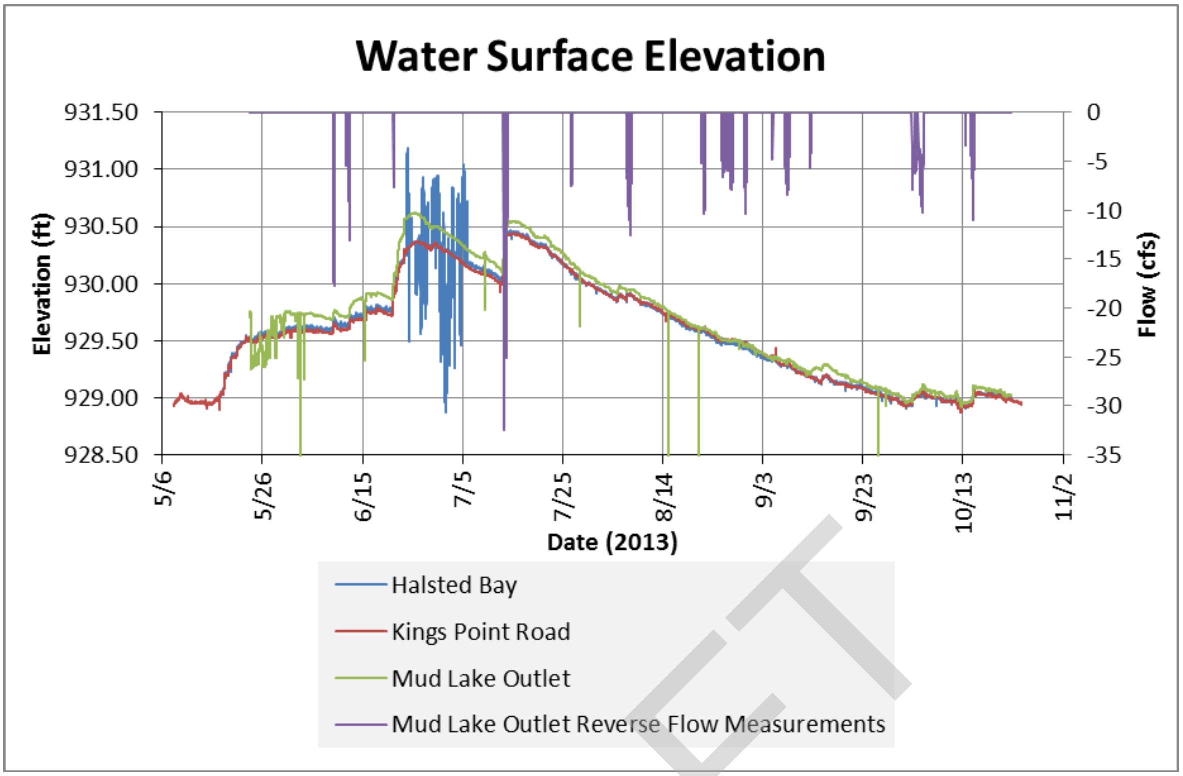



**Figure A-4. Water surface elevations compared to measured reverse flow conditions.**

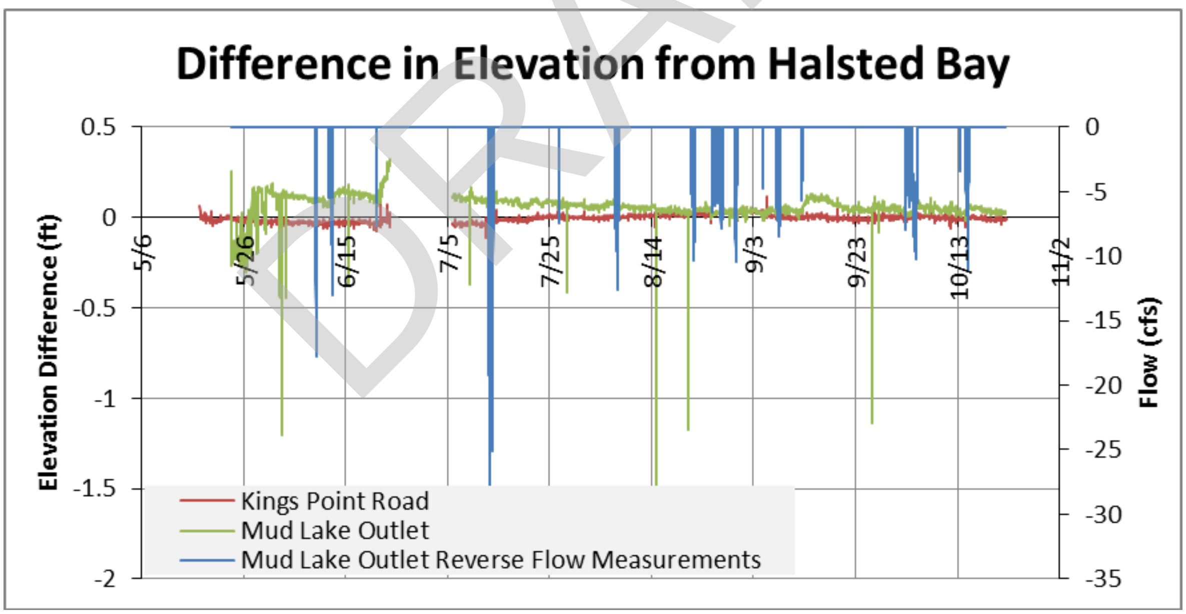



**Figure A-5. Difference in Elevation from Halsted Bay.**

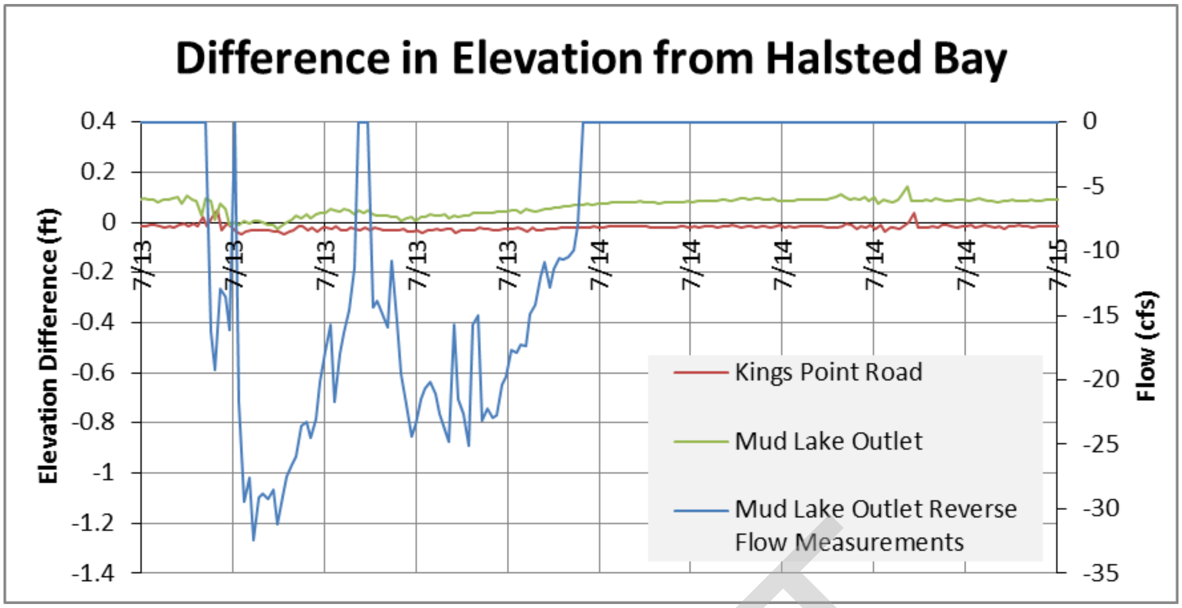



**Figure A-6a. The differences in the water surface elevation minimizes during periods when reverse flow was measured.**

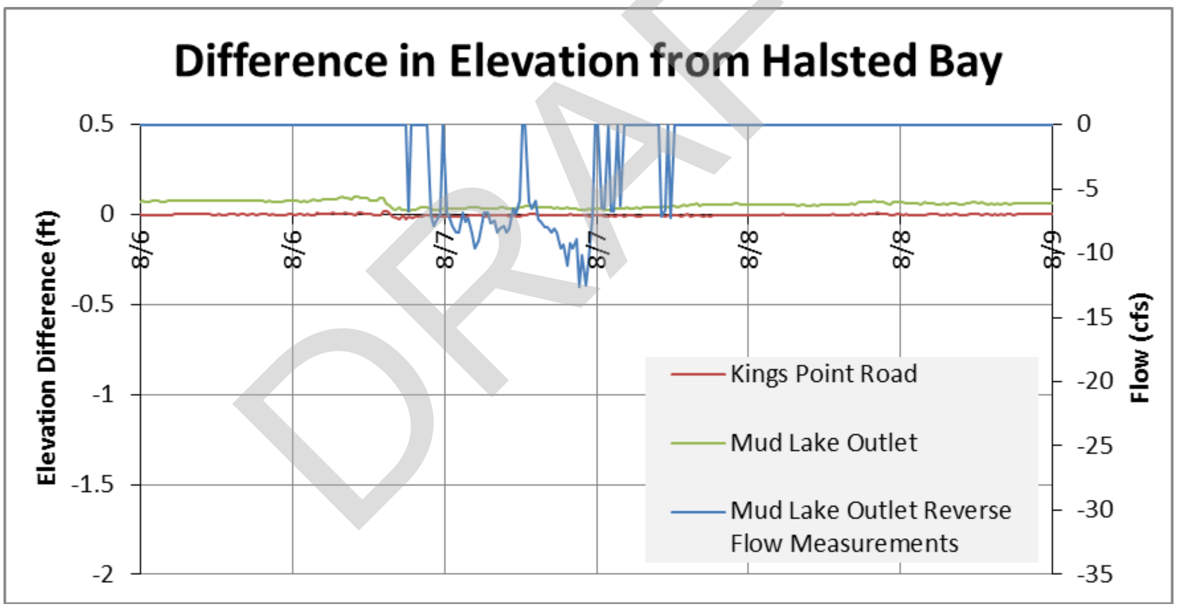



**Figure A-6b. The differences in the water surface elevation minimizes during periods when reverse flow was measured.**

# Appendix B

# Alum Dosage Considerations

# Alum Dosage Considerations for Halsted Bay, Lake Minnetonka, Minnesota



12 July, 2013

University of Wisconsin – Stout
Discovery Center - Sustainability Sciences Institute
123E Jarvis Hall
Menomonie, Wisconsin 54751
715-338-4395
williamfjames@charter.net
jamesw@uwstout.edu

Wenck Associates, Inc.
1800 Pioneer Creek Center
P.O. Box 249
Maple Plain, MN 55359
jbischoff@wenck.com

## OBJECTIVES

The objectives of these investigations were to examine rates of phosphorus (P) flux from sediments located in the wetland inlet and in Halsted Bay (Lake Minnetonka, Minnesota) and to estimate the aluminum sulfate dosage required to control sediment anaerobic internal phosphorus (P) loading in the bay. The specific outcomes and deliverables of this research were to,

1. determine rates of P flux from intact sediment cores under laboratory-controlled temperature and redox (i.e., aerobic and anaerobic) conditions,
2. examine vertical variations in biologically-labile (i.e., subject to recycling via Eh, pH, and bacterially-mediated reactions in the sediment; loosely-bound, iron-bound, and labile organic P) and refractory (i.e., relatively inert to recycling and subject to burial) phosphorus fractions from various stations in the bay to estimate the thickness of the sediment layer potentially active in sediment anaerobic internal P loading,
3. estimate aluminum sulfate (as aluminum; Al) dosage for binding redox-sensitive P (i.e., the loosely-bound and iron-bound P fractions) in the upper sediment layer, and,
4. provide a cost estimate for Al treatment based on treatment areas in the bay.

# APPROACH

### *Sediment coring stations and gravity coring methodology*

Sediment coring stations in the wetland inlet and Halsted Bay, along with numbers of replicate cores collected, are identified in Table 1 and Figure 1. Three replicate intact sediment cores were collected in the deep north and south basins of Halsted Bay (stations HB 20 and HB 30) for determination of rates of P flux under anaerobic conditions (Figure 2). Stratified conditions and hypolimnetic anoxia develop in the summer at these sites. At the shallow littoral stations HB 40 and 50, triplicate sediment cores were collected to measure rates of P flux under aerobic conditions. These representative stations were chosen for determination of P release under aerobic conditions because oxygenated conditions generally occur in the epilimnion and at depths < 12 ft throughout the bay during the summer period. Intact sediment cores were also collected in the wetland tributary channel (WET 110-C) and in the wetland complex (WET 110-R and WET 120-L) for P flux measurements.

For evaluation of spatial variations in sediment textural characteristics and biologically labile and refractory P fractions, sediment cores (i.e., one at each station) were collected at all stations in the wetland inlet and Halsted Bay for sectioning in the laboratory. For wetland sediment cores, the upper 10-cm section was examined for sediment constituents listed in Table 2. Halsted Bay sediment cores were sectioned at 5-cm intervals over the upper 10-cm for determination of the same constituents (Table 2).

Sediment cores collected at HB 10, HB 20, and HB 30 were sectioned vertically over the upper 20-cm layer to evaluate the thickness of the active sediment layer associated with internal P loading. Cores were sectioned at 1-cm intervals over the first 4 cm, 2-cm intervals between 4 and 10 cm, 2.5-cm intervals between 10 and 15 cm, and 5-cm intervals thereafter (Table 2). The upper 5-cm section of an additional core collected at each of these stations was used for estimation of Al dosage required to control internal P loading.

A gravity sediment coring device (Aquatic Research Instruments, Hope ID) equipped with an acrylic core liner (6.5-cm ID and 50-cm length) was used to collect sediment in May, 2013. The core liners, containing both sediment and overlying water, were immediately sealed using rubber stoppers and stored in a covered container in a cool location until analysis. Additional lake water was collected for incubation with the collected sediment. Sediment cores were sectioned within 24 hours of collection. Fresh sediment sections were stored in heavy-duty quart freezer bags and refrigerated until analysis.

*Rates of phosphorus flux from sediment*

Intact sediment cores were drained of overlying water and the upper 10 cm of sediment was transferred intact to a smaller acrylic core liner (6.5-cm dia and 20-cm ht) using a core remover tool. Surface water collected from the bay was filtered through a glass fiber filter (Gelman A-E), with 300 mL then siphoned onto the sediment contained in the small acrylic core liner without causing sediment resuspension. Sediment incubation systems consisted of the upper 10-cm of sediment and filtered overlying water contained in acrylic core liners that were sealed with rubber stoppers. They were placed in a darkened environmental chamber and incubated at a constant temperature (20 to 25 $^{o}$C). The oxidation-reduction environment in the overlying water was controlled by gently bubbling air (oxic) or nitrogen (anoxic) through an air stone placed just above the sediment surface in each system. Bubbling action insured complete mixing of the water column but did not disrupt the sediment.



Water samples for soluble reactive P were collected from the center of each system using an acid-washed syringe and filtered through a 0.45 µm membrane syringe filter (Nalge). The water volume removed from each system during sampling was replaced by addition of filtered lake water preadjusted to the proper oxidation-reduction condition. These volumes were accurately measured for determination of dilution effects. Soluble reactive P was measured colorimetrically using the ascorbic acid method (APHA 2005). Rates of P release from the sediment ($mg/m^2\ d^1$) were calculated as the linear change in mass in the overlying water divided by time (days) and the area ($m^2$) of the incubation core liner. Regression analysis was used to estimate rates over the linear portion of the data.

*Sediment chemistry*

A known volume of sediment was dried at 105 $^{o}$C for determination of moisture content and bulk density and burned at 500 $^{o}$C for determination of loss-on-ignition organic matter content (Håkanson and Jansson 2002). Phosphorus fractionation was conducted according to Hieltjes and Lijklema (1980), Psenner and Puckso (1988), and Nürnberg (1988) for the determination of ammonium-chloride-extractable P (loosely-bound P), bicarbonate-dithionite-extractable P (i.e., iron-bound P), and sodium hydroxide-extractable P (i.e., aluminum-bound P). A subsample of the sodium hydroxide extract was digested with potassium persulfate to determine nonreactive sodium hydroxide-extractable P (Psenner and Puckso 1988). Labile organic P was calculated as the difference between reactive and nonreactive sodium hydroxide-extractable P.

The loosely-bound and iron-bound P fractions are readily mobilized at the sediment-water interface as a result of anaerobic conditions that lead to desorption of P from sediment and diffusion into the overlying water column (Mortimer 1971, Boström 1984, Nürnberg 1988; Table 2). The sum of the loosely-bound and iron-bound P fraction represents redox-sensitive P (i.e., the P fraction that is active in P release under anaerobic and reducing conditions; redox-P). In addition, labile organic P can be converted to soluble P via bacterial mineralization (Jensen and Andersen 1992) or hydrolysis of bacterial polyphosphates to soluble phosphate under anaerobic conditions (Gächter et al. 1988, Gächter and Meyer 1993, Hupfer et al. 1995). The sum of redox-P and labile organic P collectively represent biologically-labile P. This fraction is active in recycling pathways that result in exchanges of phosphate from the sediment to the overlying water column and potential assimilation by algae. In contrast, aluminum-bound, calcium-bound, and refractory organic P fractions are more chemically inert and subject to burial rather than recycling.

### *Al dosage determination*

Mixed sediment from the upper 5-cm section of an additional sediment core collected at HB 10, HB 20, and HB 30 was subjected to a range of aluminum sulfate (as Al) concentrations to determine the dosage required to inactivate the redox-P fraction (Rydin and Welch 1999). Alum (as aluminum sulfate; $Al_2(SO_4)_3 \cdot 18\ H_2O$) was combined with 0.1 M sodium bicarbonate ($NaHCO_3$) to a concentration of 0.7 g Al/L to form an aluminum hydroxide ($Al(OH)_3$) floc. Aliquots of this solution, diluted to a final volume of 10 mL with distilled water, were added to centrifuge tubes containing the equivalent of 0.025 g dry weight (DW) of fresh sediment to obtain Al concentrations ranging from 0 (i.e., control) to ~ 50 mg Al/g DW sediment. The assay tubes were shaken for a minimum of 2 hours at 20 $^{o}$C in a darkened environmental chamber, centrifuged at 500 g to concentrate the sediment, and decanted for redox-P determination (see *Sediment chemistry* above).

Al dosage was estimated as the concentration (g/m$^2$) required to bind at least 90% of the redox-P. The dry mass concentration of redox-P (mg/g) was converted to an areal concentration (g/m$^2$) as,

$$\text{Redox-P (g/m}^2\text{)} = \text{Redox-P (mg/g)} \cdot \rho \text{ (g/cm}^3\text{)} \cdot \theta \cdot h \text{ (m)} \cdot 1{,}000{,}000 \text{ (cm}^3\text{/m}^3\text{)} \cdot 0.001 \text{ (g/mg)} \qquad 1)$$

where, $\rho$ is sediment bulk density (g/cm$^3$), $\theta$ is the percentage of sediment solids (100 – percent moisture content; dimensionless), and $h$ is sediment thickness (m). The Al concentration (g/m$^2$) was estimated as,

$$\text{Al (g/m}^2\text{)} = \text{Redox-P (g/m}^2\text{)} \cdot \text{Al:P}_{90\%} \qquad 2)$$

where, Al:$P_{90\%}$ is the binding ratio required to adsorb at least 90% of the redox-P in the sediment.



### *Maximum allowable Al dosage based on alkalinity and pH in the bay*

Addition of aluminum sulfate to a lake leads to hydrolysis and the liberation of hydrogen ions which lowers the pH of the water column. Since Al toxicity to the biota can occur if the pH falls below ~4, maintaining a pH ≥ 6.0 as a margin of safety should also be considered in dose determination (Cooke et al. 2005). For situations where alkalinity is low or the required dosage exceeds the maximum allowable dosage to maintain pH ≥ 6.0, a buffered aluminum sulfate-sodium aluminate treatment will be needed to maintain pH near neutrality. Surface water collected from the lake was analyzed for total alkalinity and pH according to APHA (2005). A titration procedure was used to determine the maximum allowable dosage of aluminum sulfate that can be added and yet maintain pH above 6.0 (Cooke et al. 2005). A 1.25 g Al/L solution of $Al_2(SO_4)_3 \cdot 18\ H_2O$ was used as the titrant and 1.0 mL additions to 500 mL of lake water were each equivalent to 2.5 mg Al/L. Lake water was titrated with the Al solution until an endpoint of pH 6 was reached. A 1.0 mL aliquot of this solution added to 500 mL of lake water is equivalent to 2.5 mg Al/L. The total volume of Al solution needed to titrate lake water to pH 6 was multiplied by 2.5 mg Al/L to estimate the maximum allowable concentration. This calculation was then compared with estimates based on sediment redox-P to ensure that the latter was at or below the maximum allowable dosage. Caution needs to be used because a vertical alkalinity and pH profile over the entire vertical water column needs to be estimated in order to more accurately evaluate the maximum allowable dosage.

# RESULTS AND INTERPRETATION

## Halsted Bay

### *Sediment phosphorus fluxes*

Phosphorus mass and concentration increased linearly in the overlying water column under anaerobic conditions in replicate incubation systems collected in the north and south basins of Halsted Bay (i.e., stations HB 20 and HB 30; Figure 3). Mean SRP concentrations in the overlying water column at the end of the incubation period were high at 1.467 mg/L (±0.329 standard error; SE) and 0.984 mg/L (±0.088 SE) for HB 20 and HB 30, respectively. The mean rate of P release under anaerobic conditions was greatest at the deeper HB 20 (10.9 mg/m$^2$ d ± 1.6 SE) versus HB 30 (8.0 mg/m$^2$ d ± 0.9 SE; Table 3). When compared to linear regression relationships developed between iron-bound P or redox-P versus the anaerobic P release rate for other lakes in the region, Halsted Bay fell within the overall range of values (Figure 4), suggesting that iron-phosphorus chemistry was playing a role in anaerobic P release. Overall, the higher mean anaerobic P release rate at HB 20 coincided with higher iron-bound P and redox-P in the sediment versus HB 30.

Soluble phosphorus accumulation in the overlying water column was much more variable for sediment cores collected at shallow littoral sites in Halsted Bay (i.e., HB 40 and HB 50) and incubated under aerobic conditions (Figure 5). Phosphorus concentrations generally increased in a linear pattern starting near ~ day 5 then leveled off to constant vales near the end of the incubation period. Mean rates of P release under aerobic conditions were lower at these shallow stations versus rates under anaerobic conditions determined at the deeper stations. Nevertheless, aerobic P release rates were relatively high at 3.6 mg/$m^2$ d (± 1.4 SE) and 1.6 mg/$m^2$ d (± 0.7 SE) for HB 40 and HB 50, respectively (Table 3). The maximum P concentration attained in the overlying water column toward the end of the incubation period was a mean 0.310 mg/L (± 0.046 SE) for HB 40 and 0.254 mg/L (± 0.031 SE) for HB 50 aerobic incubation systems, which was moderately high and could represent an important available P source for assimilation by algae.

### *Sediment vertical phosphorus profiles*

Patterns in sediment physical-textural characteristics were similar at the three vertical profile stations (Figure 6). At HB 10 and HB 20, moisture content was greater than 90% over the upper 6 cm and declined steadily to ~83% below that depth. This vertical pattern is common and related to compaction of deeper sediment layers as new sediment accumulates over time. In particular, moisture content was greater that 92% in the upper 3 cm layer, indicating very flocculent, fine-grained sediment. Wet bulk density was less than 1.04 g/$cm^3$ within this layer due to high porosity (i.e., high interstitial volume). HB 30, located in the shallower south basin (>20 ft), exhibited a similar vertical pattern in moisture content. Sediment organic matter content at these stations was moderate, ranging between 21 and 27%. It was generally highest in the upper 4-6 cm sediment layer and declined linearly at deeper depths, a pattern resulting from the gradual anaerobic decomposition of organic matter by microbial communities residing in the sediment.

Although loosely-bound P accounted for < 25% of the biologically-labile P, concentrations were unusually high at 0.08 to 0.15 mg/g at HB 10-30 and nearly constant throughout the vertical profile (Figure 7). In contrast, iron-bound and labile organic P co-dominated the biologically-labile P fraction. Iron-bound P concentrations were usually highest in the upper 8-cm sediment layer and declined in concentration below that depth. In the upper sediment layer, iron-bound P concentrations were highest at the deeper stations HB 20 and HB 30, ranging between 0.30 and 0.38 mg/g. Labile organic P concentrations were also greatest in the upper sediment layer and declined with increasing depth below the sediment-water interface. Indeed, labile organic P exceeded iron-bound P in the surface sediment layer at station 10, versus the other stations where concentrations of these constituents were similar.

Overall, biologically-labile P exhibited peak concentrations near the sediment-water interface and declined to nearly constant concentrations below ~ 10-cm depth (Figure 8). Typically, biologically-labile P concentrations are elevated and exhibit a distinct maxima in the upper layer versus deeper layers of eutrophic lake sediments due to accumulation of sediment P that is recycled in excess of burial and diagenesis (Carey and Rydin 2011). Most or all of this excess P can be mobilized during summer hypolimnetic anoxia and generally represents the internal P load to lake systems (Rydin et al. 2011). Biologically-labile P in excess of background concentrations occurred over the upper 5 cm at station 10. Excess concentrations at this station declined to background levels at the 5-cm depth and then increased slightly below that depth. At stations 20 and 30, excess biologically labile P concentrations occurred over the upper 8 cm.

### *Spatial variations in sediment phosphorus*

Surface sediments (upper 5 cm) at various stations in Halsted Bay typically exhibited high moisture content and low dry bulk density indicative of flocculent sediment with high porosity (Table 4). Organic matter content was greatest for sediment located in the shallow littoral zone (i.e., stations 40 and 50) and percentages were high at ~ 48 to 60%. It was more moderate at ~ 21 to 33% for sediment located at deeper depths in the north and south basins.

Labile organic P tended to account for a major portion of the biologically-labile P fraction at most stations followed by iron-bound P (Table 5 and Figure 9). Overall, redox-P and labile organic P each represented ~ 50% of the biologically-labile P fraction (Table 5). Highest mean concentrations of biologically-labile P fractions occurred in the deep north and south basins with a trend of declining means as a function of decreasing depth, when values within various depth contours were averaged (Table 6). This spatial pattern is typical in lake basins and attributable to processes that result in the focusing of fine-grained, more nutrient-rich sediments, from shallow erosional regions to deeper zones of sediment accumulation. For instance, mean iron-bound P concentrations ranged between 0.105 mg/g at depths < 15 ft to 0.219 mg/g at depths > 20 ft. Estimated mean anaerobic P release rates, predicted from redox-P (Figure 4), varied from 3.4 $mg/m^2$ d at shallow, littoral sites to ~ 8.0 $mg/m^2$ d at the deep basin sites. Mean labile organic P concentrations followed a similar pattern of increasing concentration as a function of increasing depth.



### *Aluminum sulfate dosage and cost*

The Al:P ratio (i.e., parts of Al required to bind one part of redox-sensitive P), used to calculate the Al dosage needed to inactivate sediment P (*see* equation 1 in APPROACH), was estimated from assays that examined the binding of iron-bound P onto precipitated $Al(OH)_3$ floc as a function of Al concentration (Figure 10). I did not include the loosely-bound P fraction in the Al:P ratio determination because it was unusually high for Halsted Bay sediments and leads to underestimation of the ratio and Al dose needed to bind the iron-bound P (i.e., results in a lower that predicted ratio; James unpublished data). Binding of the loosely-bound P fraction was, however, factored into the overall Al dosage estimation for Halsted Bay. In general, iron-bound P declined exponentially as a function of increasing Al concentration due to binding onto the $Al(OH)_3$ floc (Figure 10). Loosely-bound P declined very rapidly at relatively low Al doses. The measured Al:P ratios required to bind 90% of the iron-bound P for various stations in Halsted Bay fell within regression relationships developed from several lakes in the region (Figure 11).

To calculate Al dosage for the bay, an Al:P ratio was estimated for each lake station from regression relationships developed between iron-bound P and the Al:P ratio (Figure 12). The thickness of the sediment layer to be inactivated was set at 8 cm for sediment located at depths > 20 ft, based on excess biologically-labile P (Figure 8). For sediments located at depths < 20 ft, I assumed a sediment thickness of 5 cm in the dosage calculation, based on vertical trends in excess biologically-labile P at station 10. The Al dosage was ~ 60 $g/m^2$, 80 $g/m^2$, and 140 $g/m^2$ for sediments < 15 ft, between 15 and 20 ft, and > 20 ft, respectively (Table 6).

Al dosage and cost scenario is shown in Table 7. The sediment area located at depths > 14 ft was chosen for treatment because this contour represents the maximum extent of summer anoxia in the hypolimnion and, thus, the potential of anaerobic P release from sediments. Sediment between the 14- and 20-ft depth contours would be treated with 80 g $Al/m^2$ while sediments deeper than 20 ft would be treated with an Al dosage of 140 $g/m^2$ to control internal P loading. Total cost, including a generic setup fee of $10,000 was $761,471.

Shallow sediments (i.e., between ~ 5 and 14 ft), particularly along the western shoreline and near the wetland inlet region, might also be considered for Al treatment because rates of P release under aerobic conditions were relatively high in this region of the bay. This internal P loading source could subsidize algal productivity and slow recovery.The effectiveness and benefits of an Al treatment in shallow regions can be problematic if sediment resuspension and focusing occurs. Under these conditions, the Al floc may be eroded to deeper accumulation zones during periods of high winds and overturn (Huser 2012). However, since the western littoral region of the bay has a much shallower slope and is more protected from northern and western winds than the steeper east littoral zone, the Al floc might be less susceptible to transport. In addition, sediment moisture content was relatively high, while wet bulk density was low, at HB 40 and HB 50 (Table 4). These patterns indicated that sediments were likely composed of fine-grained sediments, suggesting a lower erosion potential in this area of the bay. Since the Al floc is typically denser than surface sediments with high moisture content, it would likely sink several cm and further consolidate the sediment from erosion.

The proposed hypolimnetic Al dosage for Halsted Bay, based on the weighted average dose of the two sediment areas, was 105 g/m$^2$. Recent lake Al treatments that have resulted in very effective and successful control of sediment internal P loading and improved water quality have generally ranged between ~ 95 g Al/m$^2$ and ~140 g Al/m$^2$ (Table 8). These more recent Al dosage ranges are generally higher compared to historical ranges (Huser 2012) and were targeted toward inactivation of the excess P pool in the sediment. The proposed Al dosages for Halsted Bay fall within these recent ranges reported in the literature.

Al dosage estimation for Halsted Bay accounted for binding of the more rapidly mobilized redox-sensitive P and did not account for gradually released labile organic P and slower P diffusion upward from deeper sediments or downward from sediment freshly deposited on top of the Al floc. There is currently some uncertainty regarding whether simply increasing Al dosage to account for these future P sources will result in the desired longer-term control. de Vicente et al. (2008) showed that aging of the $Al(OH)_3$ floc without previously sorbed $PO_4^{-3}$ could result in substantially reduced future binding efficiency (up to 75% reduction in adsorption capacity over 90 d) due to changes in crystalline structure of the floc (Berkowitz et al. 2005). They suggested that smaller doses spread out over several years, versus one large dose, might maintain higher binding efficiencies for these future P sources. For Halsted Bay, Al dosage could be adjusted to account for these potential additional sources of P, but more research is needed to clarify both dosage estimation and application strategies for longer-term control of labile organic P and P diffusion from adjacent sediment layers. However, the overall Al dosage proposed for Halsted Bay should be more than sufficient to bind these future, more gradually released, P sources because the initial Al:P ratio is high.

The total alkalinity for Halsted Bay was relatively high at 139 mg $CaCO_3$/L, suggesting a high buffering capacity for moderating pH during alum application. Al binding of P is most efficient within a pH range of 6 to 8. As pH declines below 6, Al becomes increasingly soluble (as $Al^{3+}$) and toxic to biota. The maximum allowable Al dosage for Halsted Bay, determined via jar tests (Cooke et al. 2005), was high at 18.75 mg Al/L (Table 9). Cooke et al. (2005) reported that treatment longevity (i.e., years of successful P control) generally coincided with Al dosages greater than ~ 12 to 18 g/$m^3$ for stratified lakes (range = 11.7 to 30 g/$m^3$; Table 9). The overall estimated volume-based Al dosage of 17 mg/L for Halsted Bay fell well within that reported finding. However, treatment with the proposed areal Al dosages of 80 and 140 g/$m^2$ would be equivalent to volumetric dosages of 19 mg/L at depths > 20 ft. Thus, Al dosage is at the maximum allowable for depths > 20 ft and there would be potential concerns regarding low pH during application. This concern could be alleviated by splitting the application into at least 2 years (see below). An additional alkalinity-pH vertical profile would need to be examined during the spring to early summer period to verify and refine the maximum allowable Al dose.



### *Aluminum sulfate treatment schedule considerations*

Multiple treatments of lower Al concentrations over a period of years (i.e., 1-2 year intervals) have been successful (Tiefwarensee, Germany) and have merit as a viable treatment schedule for Halsted Bay. First, splitting the overall Al dosage into 2 or 3 years would ensure that application does not lower pH temporarily to < 6.0. Second, costs are spread out over a period of several years and may be easier to finance. Third, since each incremental dosage is low relative to the final target dose, the Al floc has a greater chance of becoming saturated with sediment P immediately after application. Other research has suggested that Al binding efficiency for P declines with time as the Al reacts to form more orderly Al~(OOH) polymer chains (Berkowitz et al. 2005, de Vicente et al. 2008).

Sediment redox-P and aluminum-bound P could be monitored after each application for effectiveness in control of sediment P. Subsequent Al applications might ultimately be lower if previously applied alum flocs have efficiently inactivated most of the redox-P in the surface sediment layers, resulting in overall cost savings.

## Wetland Inlet

### *Anaerobic and aerobic phosphorus release rates*

Under anaerobic conditions, P mass and concentrations generally increased rapidly and linearly over most of the incubation period (Figure 13). An exception occurred in one of the WET120-L systems where P was essentially undetectable in the overlying water column throughout the incubation. Anaerobic P release rates were relatively at all the wetland stations (Table 10) with no readily apparent pattern as a function of sampling location. For instance, the anaerobic P release rates were high both in the wetland channel at WET100-C and at both off-channel sites. Maximum overlying water concentrations were also elevated at the end of the incubation period, ranging between 0.875 mg/L (±0.010 SE) For WET110-C and ~ 0.350 mg/L to 0.391 mg/L for WET110-R and WET120-L, respectively. In particular, wetland sediments can rapidly become anaerobic under low flow and stagnant conditions and, thus, represent a potentially important P source to the Bay during storm inflows and flushing. P mass and concentration also increased rapidly and linearly in the overlying water column of systems incubated under oxic conditions (Figure 14). Aerobic rates of P release were substantial, ranging between a mean 1.0 and 5.7 $mg/m^2$ d (Table 10).

### *Wetland sediment chemistry*

Aerobic and anaerobic P release from wetland sediments was probably driven more by microbial breakdown and transformation of organic matter versus iron-phosphorus chemistry as iron-bound P concentrations were moderate relative to the magnitude of P release. Wetland sediment both in the thalweg and off channel exhibited very high moisture content and low wet and dry bulk density (Table 11). Organic matter content was greater than 50% at all stations and exceeded 80% at many stations. High organic matter content was related to extensive thick root mass and accumulated detritus. Labile organic P, which can be recycled via microbial transformations, dominated the biologically-labile P pool in the sediment at 45% to 70% (Table 12 and Figure 15). In contrast, iron-bound P accounted for only 17% to 36% of this pool. Loosely-bound P concentrations were also notably high at 0.049 mg/g to 0.096 mg/g and could represent an important P pool for nutrient flux from sediment.

## Implications for Phosphorus Management

### *Overall recommendations for aluminum sulfate treatment of Halsted Bay*

Laboratory-based rates of P release under anaerobic conditions are high in the two deep basins of Halsted Bay and indicative of eutrophic conditions. I recommend that the Al treatment scenario presented in Table 7 to control this internal P load be split into at least two applications to minimize concerns over low pH during application and to increase the sediment P binding efficiency (i.e., attempt to completely saturate binding sites with sediment P with each application). Aluminum sulfate applications could be conducted during consecutive years or during year 1 and 3. It should be noted that internal P loading reduction will not be completely reduced during the first year of application due to the split dosage scenario, and will not be completely controlled until the final Al application. Ideally, each application should occur in May or early June, before the onset of P accumulation in the hypolimnion and when P concentrations in the water column are relatively low. The goal of the aluminum sulfate treatment is to primarily bind sediment P on the $Al(OH)_3$ floc and minimize filling of these binding sites with P originating from the water column.

Aerobic rates of P release were also relative high for sediment cores collected in the shallow, littoral portion of the bay and could subsidize algal productivity after Al treatment. Potential contributions from this sediment source should be incorporated into the P budget for Halsted Bay for evaluation. It is more difficult to manage shallow sediments with Al because the floc tends to focus to deep accumulation zones (Huser 2011). However, application of 60 g Al/m$^2$ might be considered for shallow sediments located along the western shoreline of the bay between ~ 5- and 14-ft depth contours to temporarily control sediment P flux at locations near the wetland inlet (Table 6). A desirable management outcome would be improved underwater light penetration and re-establishment of native submersed macrophyte communities in this region of the bay to ultimately stabilize the Al floc for continued control of aerobic P release, reduce sediment resuspension, and promote habitat for invertebrates, fish larvae, and young of the year fish.

*Wetland sediment phosphorus contributions to Halsted Bay*

Similar to the shallow, littoral sediments in Halsted Bay, sediments located in the wetland inlet appear to be a potential source of internal P loading and may subsidize algal blooms. Although the mechanism of P release is not precisely known (i.e., may be driven more by microbial breakdown), rates are, nevertheless, relatively high under both aerobic and anaerobic conditions. More information is needed to better understand P contributions and fluxes from these sources in order to develop sound management decisions. Studies include:

1. quantifying hydrological conditions, water level stages, and flows in the wetland complex to determine periods of wetland soil flooding, desiccation, and potential P fluxes,
2. quantifying the role of vegetation breakdown in P recycling and flux to the bay, and
3. continuously monitoring temperature, dissolved oxygen, and pH at various locations in the wetland complex to determine periods of anoxia for more accurate sediment P flux determination.

## REFERENCES


APHA (American Public Health Association). 2005. Standard Methods for the Examination of Water and Wastewater. 21th ed. American Public Health Association, American Water Works Association, Water Environment Federation.

Berkowitz J, Anderson MA, Graham R. 2005. Laboratory investigation of aluminum solubility and solid-phase properties following alum treatment of lake waters. Wat Res 39:3918-3928.

Carey CC, Rydin E. 2011. Lake trophic status can be determined by the depth distribution of sediment phosphorus. Limnol Oceanogr 56:2051-2063.

Cooke GD, Welch EB, Peterson SA, Nichols SA. 2005. Restoration and management of lakes and reservoirs. 3rd ed. Boca Raton (FL): CRC Press.

de Vicente I, Huang P, Andersen FØ, Jensen HS. 2008. Phosphate adsorption by fresh and aged aluminum hydroxide. Consequences for lake restoration. Environ Sci Technol 42:6650-6655.

Dugopolski RA, Rydin E, Brett MT. 2008. Short-term effects of buffered alum treatment on Green Lake sediment phosphorus speciation. Lake Reserv Manage 24:181-189.

Gächter R., Meyer JS, Mares A. 1988. Contribution of bacteria to release and fixation of phosphorus in lake sediments. Limnol. Oceanogr 33:1542-1558.

Gächter R, Meyer JS. 1993. The role of microorganisms in mobilization and fixation of phosphorus in sediments. Hydrobiologia 253:103-121.

Håkanson L, Jansson M. 2002. Principles of lake sedimentology. The Blackburn Press, Caldwell, NJ USA.

Hjieltjes AH, Lijklema L. 1980. Fractionation of inorganic phosphorus in calcareous sediments. J Environ Qual 8: 130-132.

Hoyman T. 2012. East Alaska Lake, Wisconsin. LakeLine 32(4):34-41.

Huser B. 2012. Variability in phosphorus binding by aluminum in alum treated lakes explained by lake morphology and aluminum dose. Wat Res 46:4697-4704.

Hupfer M, Gächter R., Giovanoli R. 1995. Transformation of phosphorus species in settling seston and during early sediment diagenesis. Aquat Sci 57:305-324.

James WF, Barko JW, Eakin HL, Helsel DR. 2000. Distribution of sediment phosphorus pools and fluxes in relation to alum treatment. J Am Wat Resour Assoc 36:647-656.

James WF. 2011. Variations in the aluminum:phosphorus binding ratio and alum dosage considerations for Half Moon Lake, Wisconsin. Lake Reserv Manage 27:128-137.

Jensen HS, Kristensen P, Jeppesen E, Skytthe A. 1992. Iron:phosphorus ratio in surface sediment as an indicator of phosphate release from aerobic sediments in shallow lakes. Hydrobiologia 235/236:731-743.

Lewandowski J, Schauser I, Hupfer M. 2003. Long term effects of phosphorus precipitations with alum in hypereutrophic Lake Süsser See (Germany). Wat Res 37:3194-3204.

Mortimer CH. 1971. Chemical exchanges between sediments and water in the Great Lakes – Speculations on probable regulatory mechanisms. Limnol Oceanogr 16:387-404.

Nürnberg GK. 1988. Prediction of phosphorus release rates from total and reductant-soluble phosphorus in anoxic lake sediments. Can J Fish Aquat Sci 45:453-462.

Psenner R, Puckso R. 1988. Phosphorus fractionation: Advantages and limits of the method for the study of sediment P origins and interactions. Arch Hydrobiol Biel Erg Limnol 30:43-59.

Wauer G, Gonsiorczyk T, Hupfer M, Koschel R. 2009. Phosphorus balance of Lake Tiefwarensee during and after restoration by hypolimnetic treatment with aluminum and calcium salts. Lake Reserv Manage 25:377-388.

**Table 1. Station identification labels (HB = Halsted's Bay; WET = wetland inlet; L = north side of wetland tributary, C = center of wetland tributary channel, R = south side of wetland tributary) and numbers of sediment cores collected for determination of rates of phosphorus (P) flux under aerobic or anaerobic conditions, biologically-labile and refractory P fractions (see Table 1), and the dosage of aluminum (Al) required to bind redox-sensitive P.**

| Station | P Flux | | P fractions | | Al dosage |
|---|---|---|---|---|---|
| | Aerobic | Anaerobic | upper 5 to 10 cm | Vertical profile | |
| HB 10 | | | 1 | 1 | 1 |
| HB 20 | | 3 | 1 | 1 | 1 |
| HB 30 | | 3 | 1 | 1 | 1 |
| HB 40 | 3 | | 1 | | |
| HB 50 | 3 | | 1 | | |
| HB 60 | | | 1 | | |
| HB 70 | | | 1 | | |
| HB 80 | | | 1 | | |
| HB 90 | | | 1 | | |
| WET 100-L | | | 1 | | |
| WET 100-C | | | 1 | | |
| WET 100-R | | | 1 | | |
| WET 110-L | | | 1 | | |
| WET 110-C | 2 | 2 | 1 | | |
| WET 110-R | 2 | 2 | 1 | | |
| WET 120-L | 2 | 2 | 1 | | |
| WET 120-C | | | 1 | | |
| WET 120-R | | | 1 | | |

**Table 2. Sediment physical-textural characteristics, phosphorus species, and metals veriable list.**

| Category | Variable |
|---|---|
| **Physical-textural** | Moisture content |
| | Wet and dry sediment bulk density |
| | organic matter content |
| **Phosphorus species** | Loosely-bound P |
| | Iron-bound P |
| | Labile organic P |
| | Aluminum-bound P |
| | Calcium-bound P |
| | Refractory organic P |
| | Total P |
| **Metals** | Iron[1] |
| | Aluminum[2] |

[1]For the surface 5-cm section from all stations

[2]For vertical sections collected at HB 10, HB 20, and HB 30

**Table 3. Mean (1 standard error in parentheses; n = 3) rates of phosphorus (P) release under oxic (aerobic) and anoxic (anaerobic) conditions for sediments collected in Halsted's Bay.**

| Station | Diffusive P flux | |
|---|---|---|
| | Oxic ($mg\ m^{-2}\ d^{-1}$) | Anoxic ($mg\ m^{-2}\ d^{-1}$) |
| HB 20 | | 10.9 (1.6) |
| HB 30 | | 8.0 (0.9) |
| HB 40 | 3.6 (1.4) | |
| HB 50 | 1.6 (0.7) | |

**Table 4. Textural characteristics in the upper sediment layer for various stations in Halsted's Bay.**

| Station | Moisture Content (%) | Wet Bulk Density ($g/cm^3$) | Dry Bulk Density ($g/cm^3$) | Organic Matter (%) |
|---|---|---|---|---|
| HB 10 | 90.6 | 1.045 | 0.099 | 25.5 |
| HB 20 | 90.5 | 1.046 | 0.100 | 24.3 |
| HB 30 | 89.2 | 1.054 | 0.115 | 22.8 |
| HB 40 | 93.1 | 1.018 | 0.072 | 59.5 |
| HB 50 | 91.5 | 1.028 | 0.089 | 48.4 |
| HB 60 | 91.7 | 1.036 | 0.087 | 33.0 |
| HB 70 | 89.9 | 1.049 | 0.108 | 25.6 |
| HB 80 | 90.9 | 1.044 | 0.096 | 25.2 |
| HB 90 | 88.3 | 1.060 | 0.126 | 21.2 |

**Table 5. Concentrations of biologically labile and refractory P in the upper 5-cm sediment layer for various stations in Halsted's Bay. DW = dry mass, FW = fresh mass.**

| Station | Redox-sensitive and biologically labile P | | | | Refractory P | | |
|---|---|---|---|---|---|---|---|
| | Loosely-bound P (mg/g DW) | Iron-bound P (mg/g DW) | Iron-bound P (ug/g FW) | Labile organic P (mg/g DW) | Aluminum-bound P (mg/g DW) | Calcium-bound P (mg/g DW) | Refractory organic P (mg/g DW) |
| HB 10 | 0.127 | 0.161 | 15 | 0.306 | 0.070 | 0.122 | |
| HB 20 | 0.106 | 0.308 | 29 | 0.303 | 0.085 | 0.131 | |
| HB 30 | 0.096 | 0.188 | 20 | 0.301 | 0.067 | 0.329 | |
| HB 40 | 0.042 | 0.095 | 7 | 0.248 | 0.091 | 0.077 | |
| HB 50 | 0.088 | 0.115 | 10 | 0.300 | 0.074 | 0.107 | |
| HB 60 | 0.114 | 0.162 | 14 | 0.336 | 0.083 | 0.149 | |
| HB 70 | 0.124 | 0.141 | 14 | 0.262 | 0.065 | 0.165 | |
| HB 80 | 0.089 | 0.259 | 24 | 0.299 | 0.079 | 0.100 | |
| HB 90 | 0.112 | 0.167 | 20 | 0.258 | 0.065 | 0.134 | |

**Table 6. Predicted anaerobic phosphorus (P) release, loosely-bound P, iron-bound P labile organic P, redox-P biologically-labile P, the estimated aluminum:phosphorus (Al:P) binding ratio, estimated thicknes of the excess sediment P layer to be treated with aluminum sulfate (as aluminum; Al), and the areal Al dosage estimate for various stations in Halsted'ds Bay. Means for these variables are presented at the bottom of the table for depths < 15 ft, between 15 and 20 ft, and > 20 ft.**

| Depth contour (ft) | Station | Predicted anaerobic P release ($mg/m^2$ d) | Loosely-bound P (mg/g) | Iron-bound P (mg/g) | Labile organic P (mg/g) | Redox-P (mg/g) | Biologically-labile P (mg/g) | Estimated Al:P ratio[1] | Treated sediment thickness (cm) | Al dose ($g/m^2$) |
|---|---|---|---|---|---|---|---|---|---|---|
| <15 | HB 40 | 2.9[2] | 0.042 | 0.095 | 0.248 | 0.137 | 0.385 | 104 | 5 | 50 |
| <15 | HB 50 | 3.9[2] | 0.088 | 0.115 | 0.300 | 0.203 | 0.503 | 76 | 5 | 67 |
| 15-20 | HB 60 | 4.6[2] | 0.114 | 0.162 | 0.336 | 0.276 | 0.612 | 59 | 5 | 70 |
| 15-20 | HB 70 | 5.2[2] | 0.124 | 0.141 | 0.262 | 0.265 | 0.527 | 61 | 5 | 86 |
| 15-20 | HB 80 | 5.8[2] | 0.089 | 0.259 | 0.299 | 0.348 | 0.647 | 49 | 5 | 80 |
| 15-20 | HB 90 | 6.0[2] | 0.112 | 0.167 | 0.258 | 0.279 | 0.537 | 58 | 5 | 101 |
| >20 | HB 10 | 5.2[2] | 0.127 | 0.161 | 0.306 | 0.288 | 0.594 | 57 | 8 | 128 |
| >20 | HB 30 | 8.0[3] | 0.096 | 0.188 | 0.301 | 0.284 | 0.585 | 57 | 8 | 138 |
| >20 | HB 20 | 10.9[3] | 0.106 | 0.308 | 0.303 | 0.414 | 0.717 | 42 | 8 | 148 |
| < 15 | Average | 3.4 | 0.065 | 0.105 | 0.274 | 0.170 | 0.444 | 90 | 5 | 59 |
| 15-20 | Average | 5.4 | 0.110 | 0.182 | 0.289 | 0.292 | 0.581 | 57 | 5 | 84 |
| > 20 | Average | 8.0 | 0.110 | 0.219 | 0.303 | 0.329 | 0.632 | 52 | 8 | 138 |

[1]Based on the regression equation shown in Figure 12 but substituting the redox-P concentration into the calculation.

[2]Estimated from regression relationships between redox-P and the anaerobic P release rate (Figure 4).

[3]Measured mean anaerobic P release rate from Table 3.

**Table 7. Approximate cost scenario to treat two sediment areas with different concentrations of aluminum sulfate.**

| Variable | Sediment area 14-20 ft contour | Sediment area > 20 ft contour |
|---|---|---|
| Acres | 167 | 100 |
| Al dosage ($g/m^2$) | 80 | 140 |
| Alum ($) | $366,435 | $385,036 |
| Setup ($) | $10,000 | |
| Total ($) | $761,471 | |

| Table 8. Recent and proposed alum (as Al) dosages for various lakes. An asterisk denotes a future treatment. | | |
|---|---|---|
| Lake | Al Dose ($g\ Al\ m^{-2}$) | Reference |
| Halsted's Bay[1] | 105 | Present study |
| Tiefwarensee, Germany | 137 | Wauer et al. (2009) |
| East Alaska, Wisconsin | 132 | Hoyman (2012) |
| Squaw, Wisconsin* | 120 | James (unpubl. Data) |
| Cedar, Wisconsin[*2] | 116 | James (unpubl. Data) |
| Half Moon, Wisconsin[3] | 115 | James (2011) |
| Susser See, Germany | 100 | Lewandowski et al. (2003) |
| Green, Washington | 94 | Dugopolski et al. (2008) |

[1]Average of a stratified treatment at 140 and 80 $g/m^2$

[2]Average of a stratified treatment at 130 and 100 $g/m^2$

[3]West and east arm dosages were 150 and 75 $g/m^2$, respectively

**Table 9. A comparison of the maximum allowable Al dose, based on a titration assay (Cooke et al. 2005) and the the areal sediment redox-P based Al dosage converted to a concentration for Halsted Bay. Al dosages and longevity for other unstratified and stratified lakes are from Cooke et al (2005).**

| Lake | | Al Dose ($g\ Al/m^3$) | Observed Longevity (years) |
|---|---|---|---|
| Halsted's Bay | Maximum allowable | 18.8 | |
| | 140 $g\ Al/m^2$ below 20-ft contour | 19.1 | |
| | 80 $g\ Al/m^2$ between the 14 and 20 ft contour | 15.3 | |
| | Combined Al concentration below the 14-ft depth contour | 17.1 | |
| Unstratified lakes | Long Kitsap County | 5.5 | 11 |
| | Pickerel | 7.3 | <1 |
| | Long Thurston County North | 7.7 | >8 |
| | Pattison North | 7.7 | 7 |
| | Wapato | 7.8 | <1 |
| | Erie | 10.9 | >8 |
| | Campbell | 10.9 | >8 |
| Stratified lakes | Eau Galle | 4.5 | <2 |
| | Morey | 11.7 | 8 |
| | Cochnewagon | 18 | 6 |
| | Dollar | 20.9 | 18 |
| | Annabessacook | 25 | 13 |
| | West Twin | 26 | 18 |
| | Irondoquoit Bay | 28.7 | 5 |
| | Kezar | 30 | 9 |

**Table 10. Mean (1 standard error in parentheses; n = 2) rates of phosphorus (P) release under oxic (aerobic) and anoxic (anaerobic) conditions for sediments collected in the wetland inlet.**

| Station | Diffusive P flux | |
|---|---|---|
| | Oxic ($mg\ m^{-2}\ d^{-1}$) | Anoxic ($mg\ m^{-2}\ d^{-1}$) |
| WET110-C | 5.7 (1.2) | 5.9 (<0.1) |
| WET110-R | 1.0 (<0.1) | 2.7 (0.3) |
| WET120-L | 2.9 (0.7) | 7.2[1] |

[1]n = 1; undetected rate for the other rep

**Table 11. Textural characteristics in the upper sediment layer for various stations in the wetland Inlet.**

| Station | Moisture Content (%) | Wet Bulk Density ($g/cm^3$) | Dry Bulk Density ($g/cm^3$) | Loss-on-ignition (%) |
|---|---|---|---|---|
| WET100-L | 91.7 | 1.011 | 0.087 | 78.0 |
| WET00-C | 92.4 | 1.018 | 0.079 | 62.3 |
| WET100-R | 92.5 | 1.011 | 0.078 | 76.7 |
| WET110-L | 92.8 | 1.008 | 0.075 | 83.2 |
| WET110-C | 90.8 | 1.024 | 0.096 | 57.8 |
| WET110-R | 92.5 | 1.012 | 0.078 | 73.9 |
| WET120-L | 91.3 | 1.010 | 0.090 | 81.3 |
| WET120-C | 92.7 | 1.019 | 0.076 | 58.3 |
| WET120-R | 92.7 | 1.006 | 0.736 | 98.3 |

**Table 12. Concentrations of biologically labile and refractory P in the upper 10-cm sediment layer for various stations in wetland inlet. DW = dry mass, FW = fresh mass.**

| Station | Redox-sensitive and biologically labile P | | | | Refractory P | | |
|---|---|---|---|---|---|---|---|
| | Loosely-bound P (mg/g DW) | Iron-bound P (mg/g DW) | Iron-bound P (ug/g FW) | Labile organic P (mg/g DW) | Aluminum-bound P (mg/g DW) | Calcium-bound P (mg/g DW) | Refractory organic P (mg/g DW) |
| WET100-L | 0.089 | 0.172 | 6 | 0.405 | 0.126 | 0.107 | |
| WET00-C | 0.096 | 0.167 | 7 | 0.351 | 0.125 | 0.144 | |
| WET100-R | | | | | | | |
| WET110-L | | | | | | | |
| WET110-C | 0.049 | 0.066 | 5 | 0.266 | 0.099 | 0.048 | |
| WET110-R | | | | | | | |
| WET120-L | | | | | | | |
| WET120-C | 0.091 | 0.176 | 7 | 0.217 | 0.104 | 0.074 | |
| WET120-R | | | | | | | |

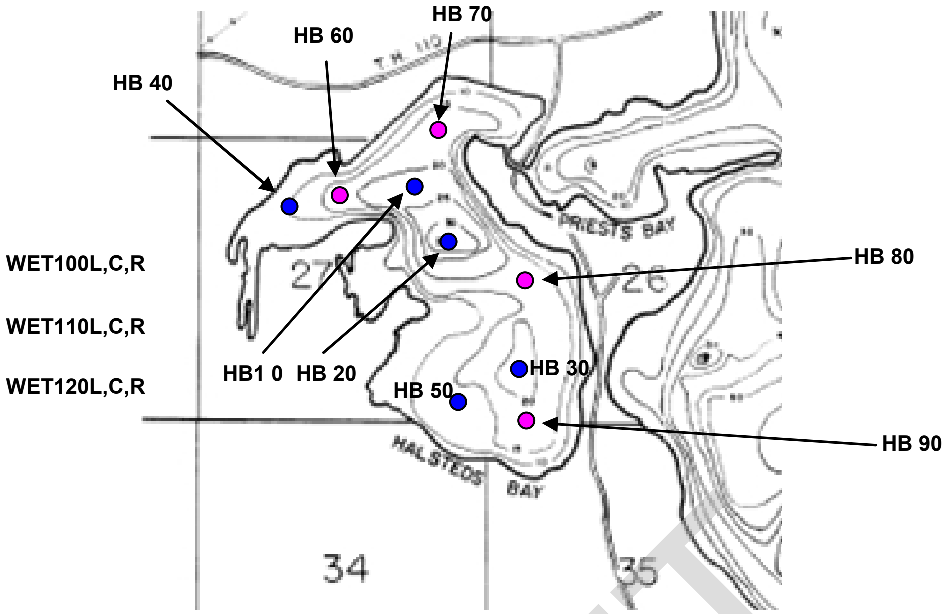



*Figure 1. Sediment core station identification and location.*

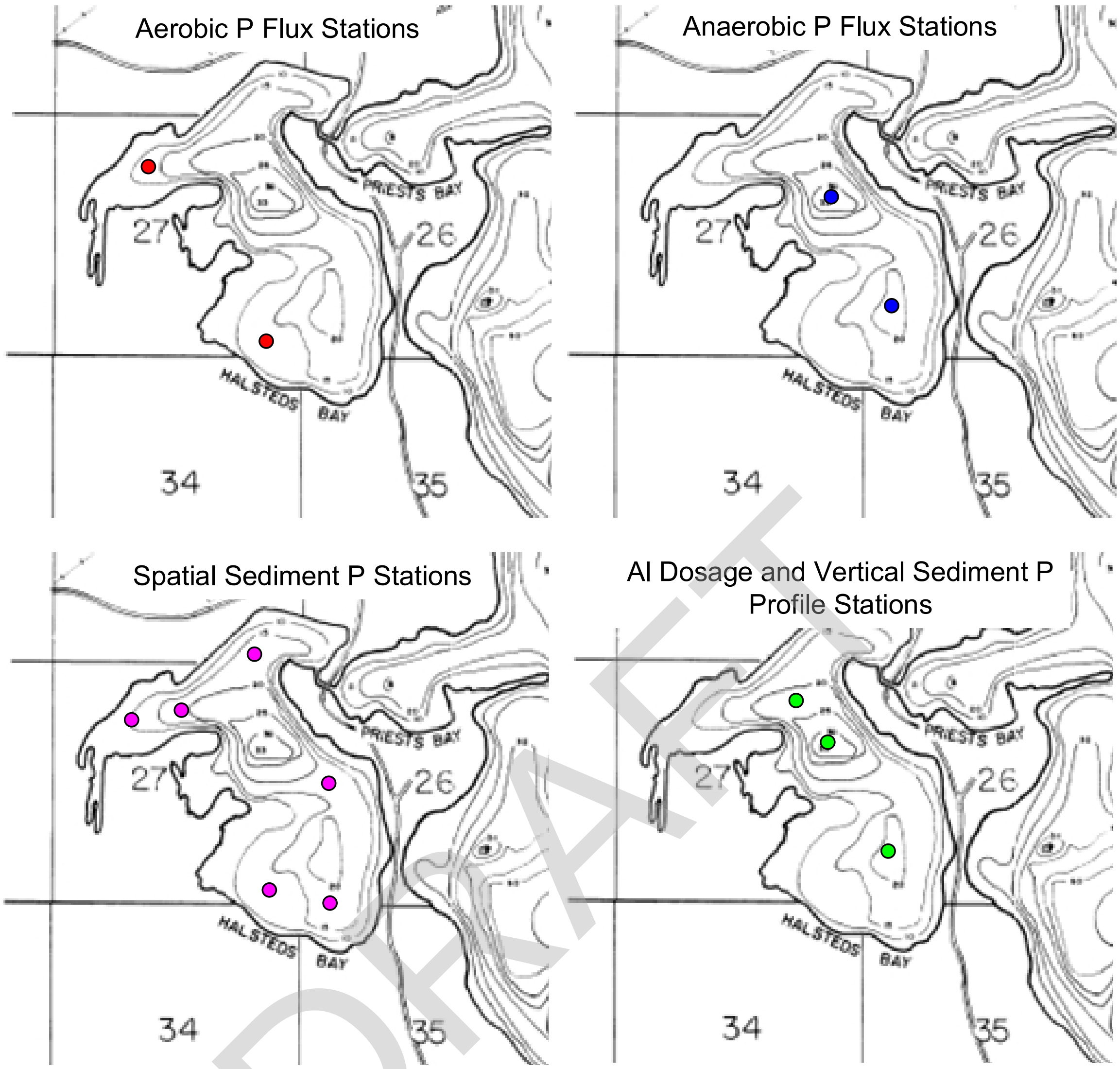



*Figure 2. Locations of sediment coring stations for the various studies. Upper left – location of shallow, littoral stations for determination of phosphorus (P) release from sediment under aerobic conditions, Upper right – stations for determination of anaerobic P release from sediment, Lower left – stations for determination of spatial variations in sediment physical-textural and chemical characteristics, Lower right - stations for determination of aluminum (Al) sulfate dosage and vertical variations in sediment physical-textural and chemical characteristics.*

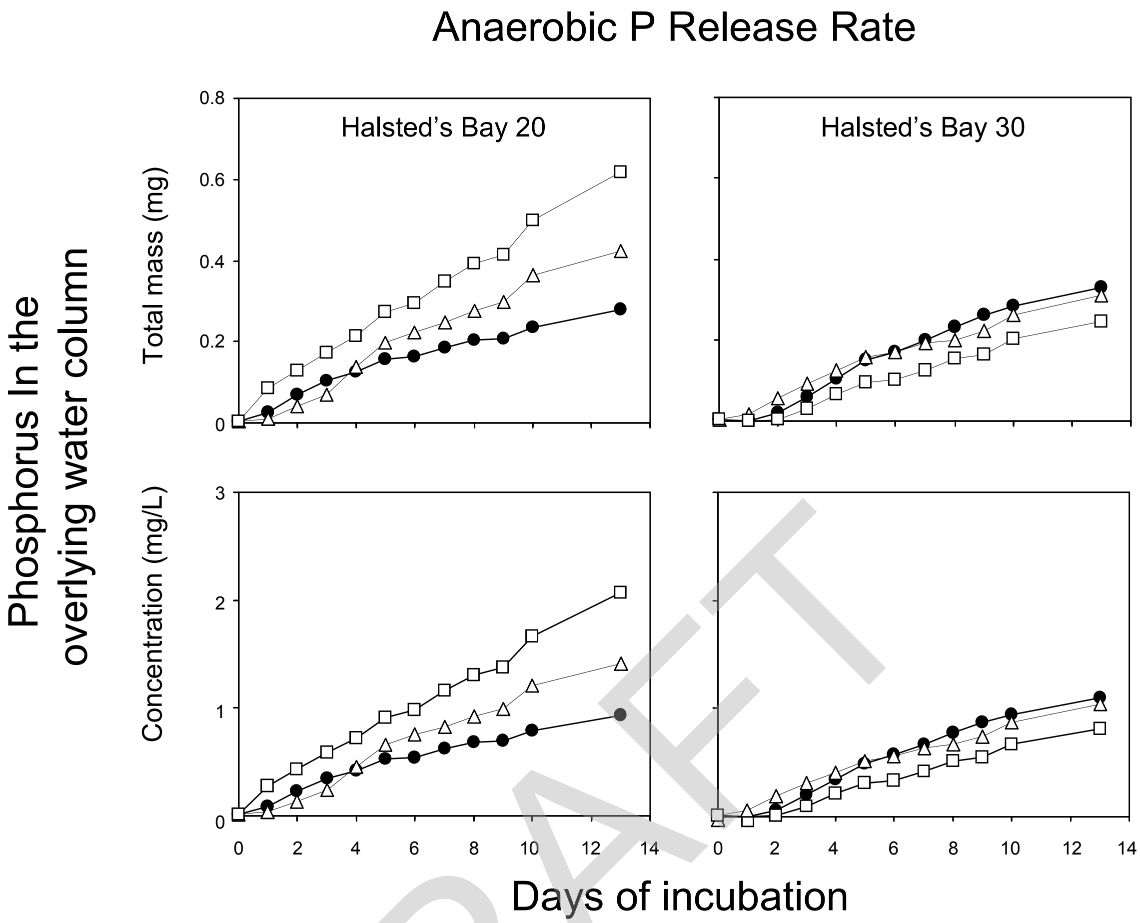



*Figure 3. Changes in soluble reactive phosphorus mass (upper panels) and concentration (lower panels) in the overlying water column under anaerobic conditions versus time for sediment cores collected in Halsted Bay.*

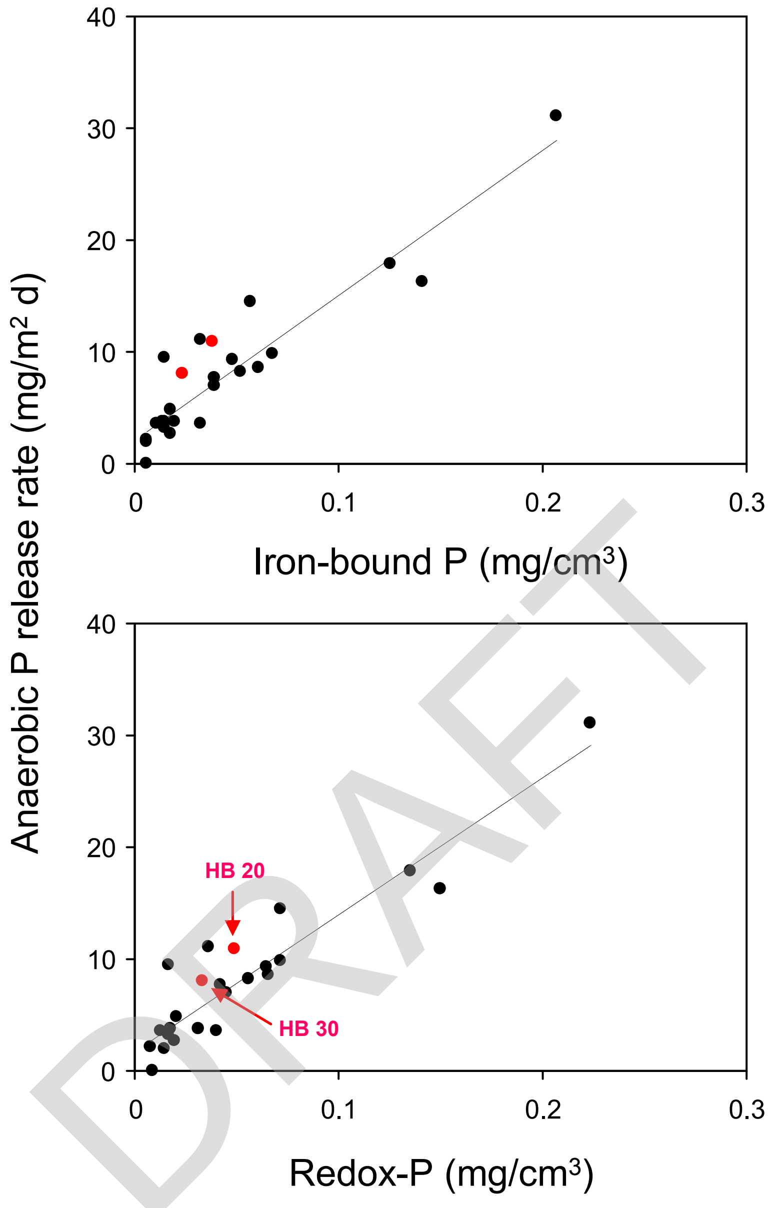



*Figure 4. Relationships between iron-bound phosphorus (P; mg/cm$^3$ dry bulk density) and rates of P release from sediments under anaerobic conditions for various lakes in the region.*

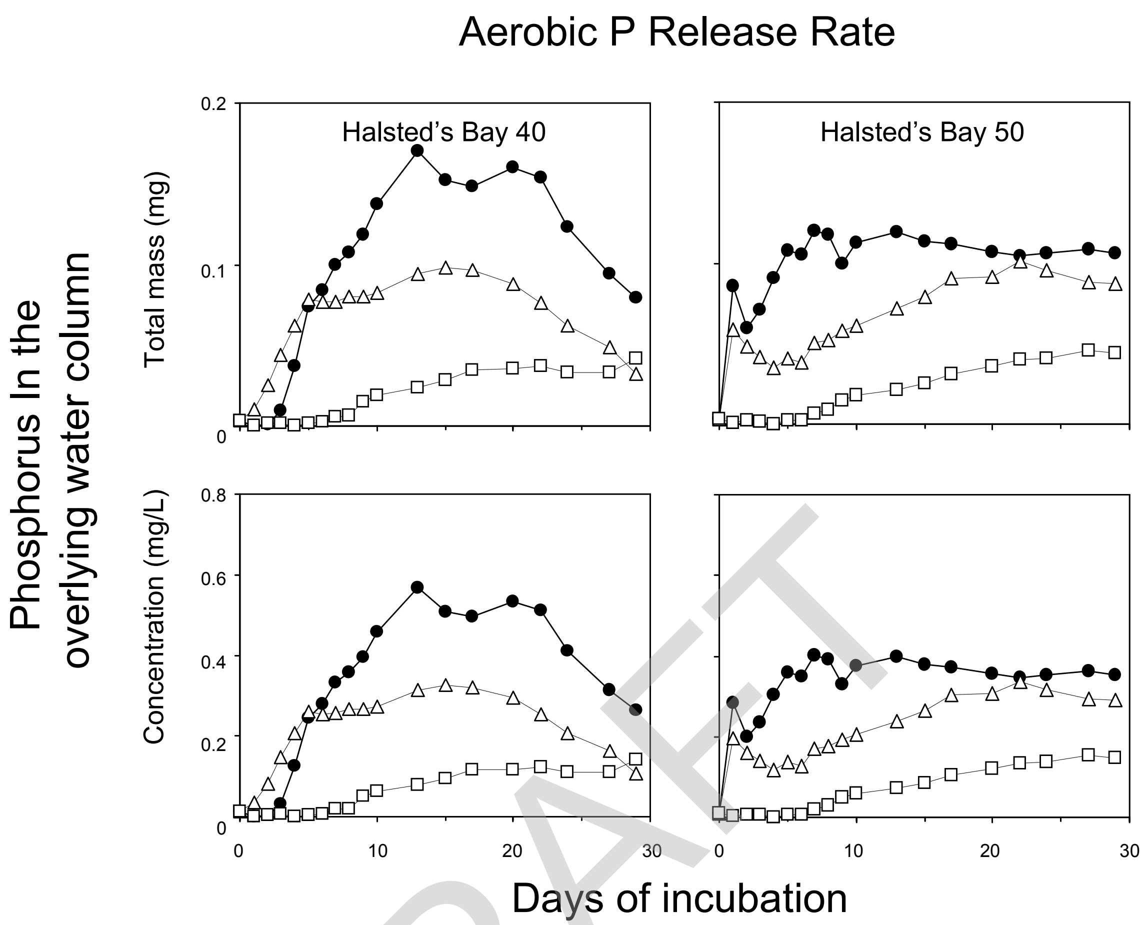



*Figure 5. Changes in soluble reactive phosphorus mass (upper panels) and concentration (lower panels) in the overlying water column under aerobic conditions versus time for sediment cores collected in Halsted Bay.*

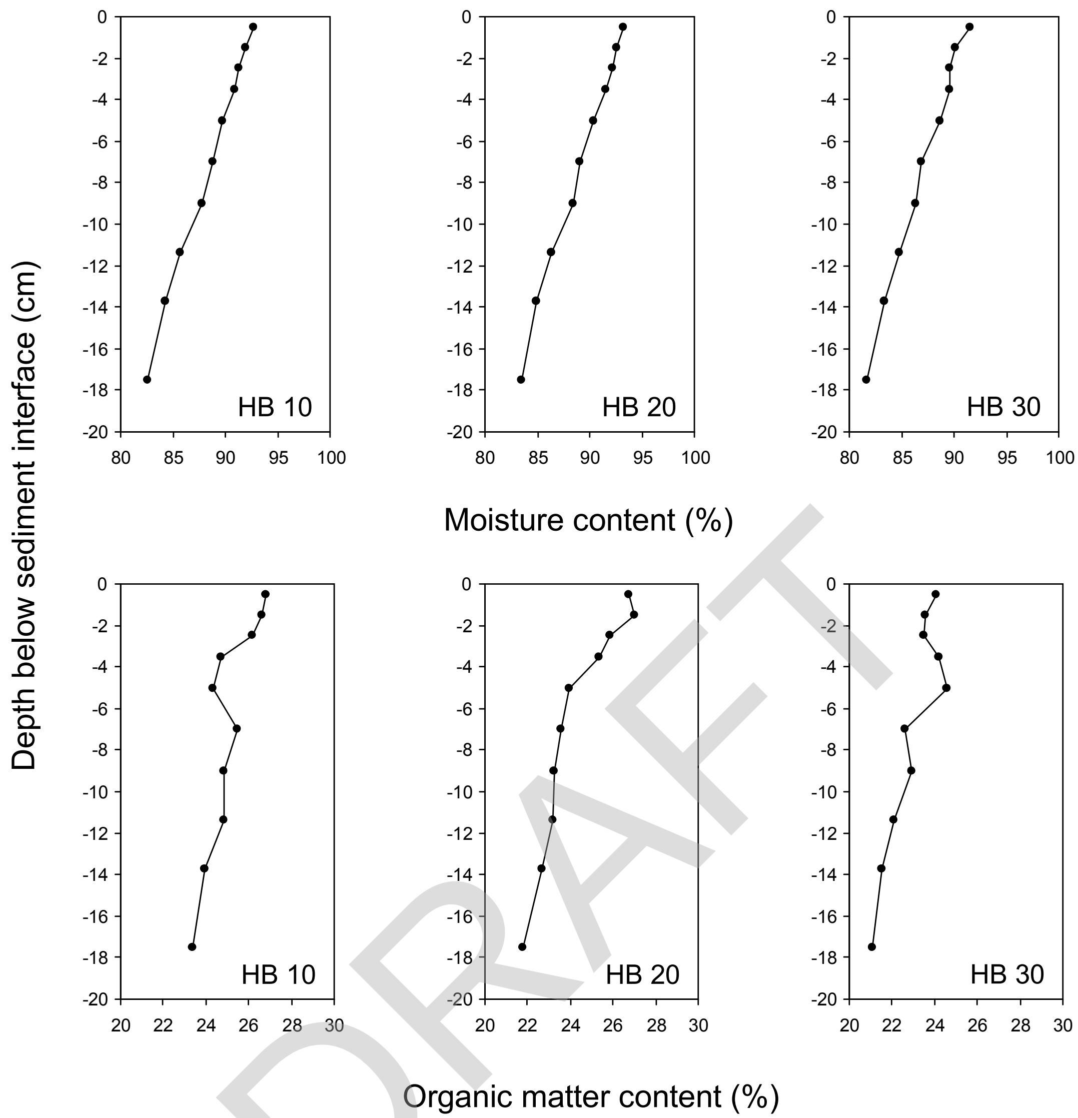



*Figure 6. Vertical variations in sediment moisture (upper panels) and organic matter content (lower panels) at Halsted Bay (HB) stations HB 10, HB 20, and HB 30.*

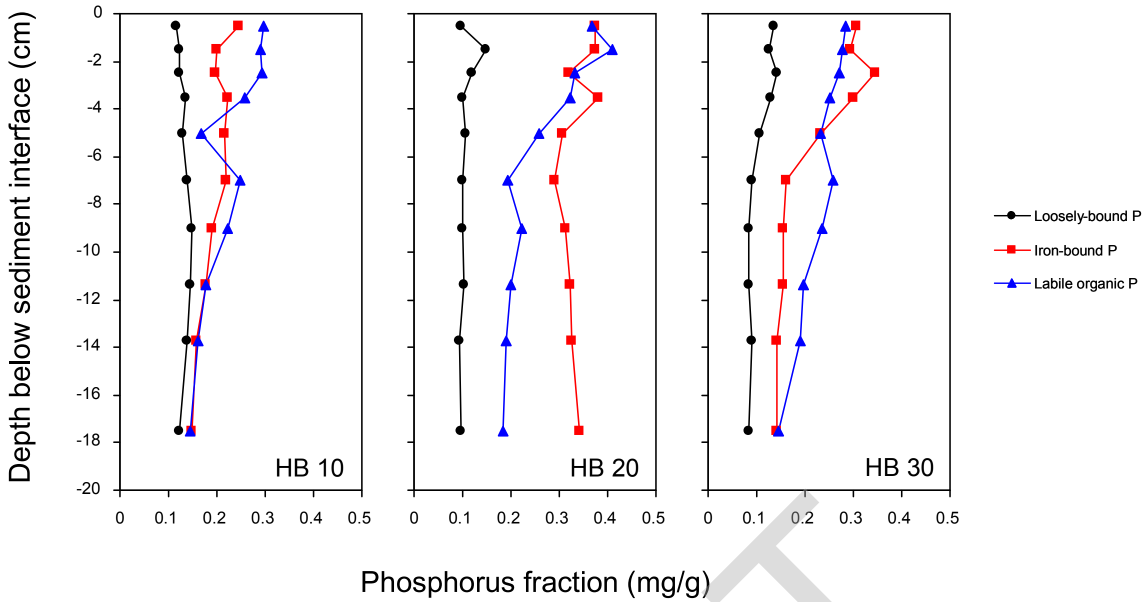



*Figure 7. Vertical variations in loosely-bound phosphorus (P), iron-bound P, and labile organic P concentrations at Halsted Bay (HB) stations HB 10, HB 20, and HB 30.*

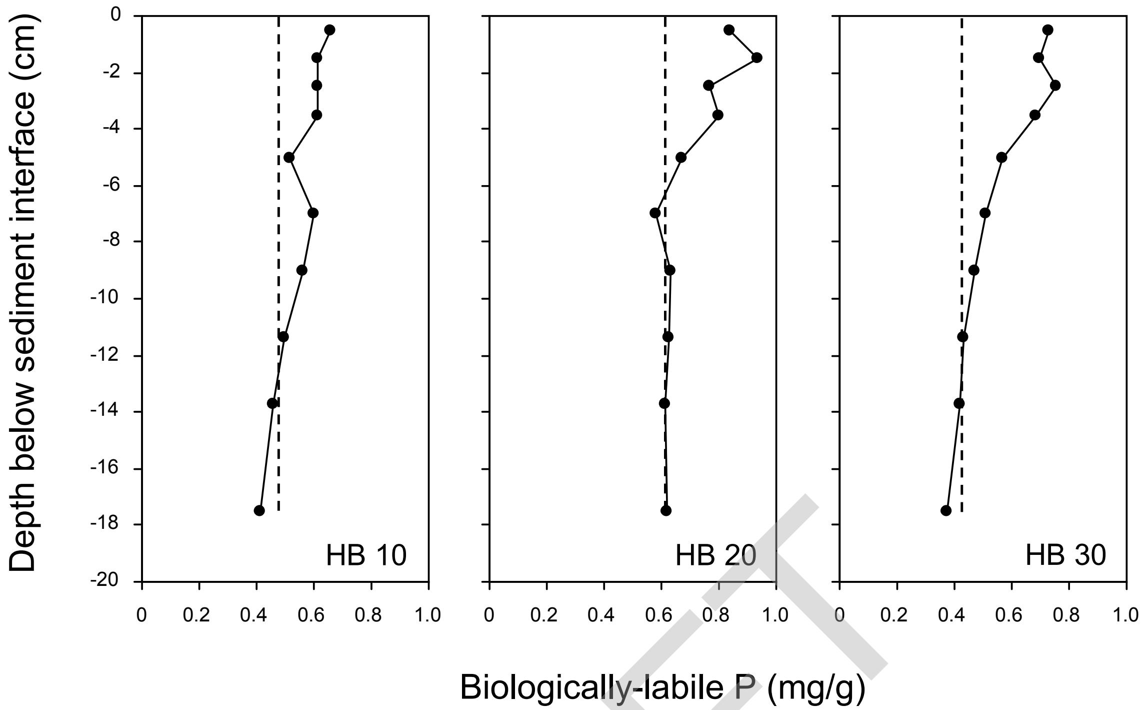



*Figure 8. Vertical variations in biologically-labile phosphorus (P; i.e., the sum of loosely-bound, iron-bound P, and labile organic P concentration) and thickness of the sediment layer with excess P (above background concentrations) that is subject to diffuse P flux into the overlying water column under anaerobic conditions.*

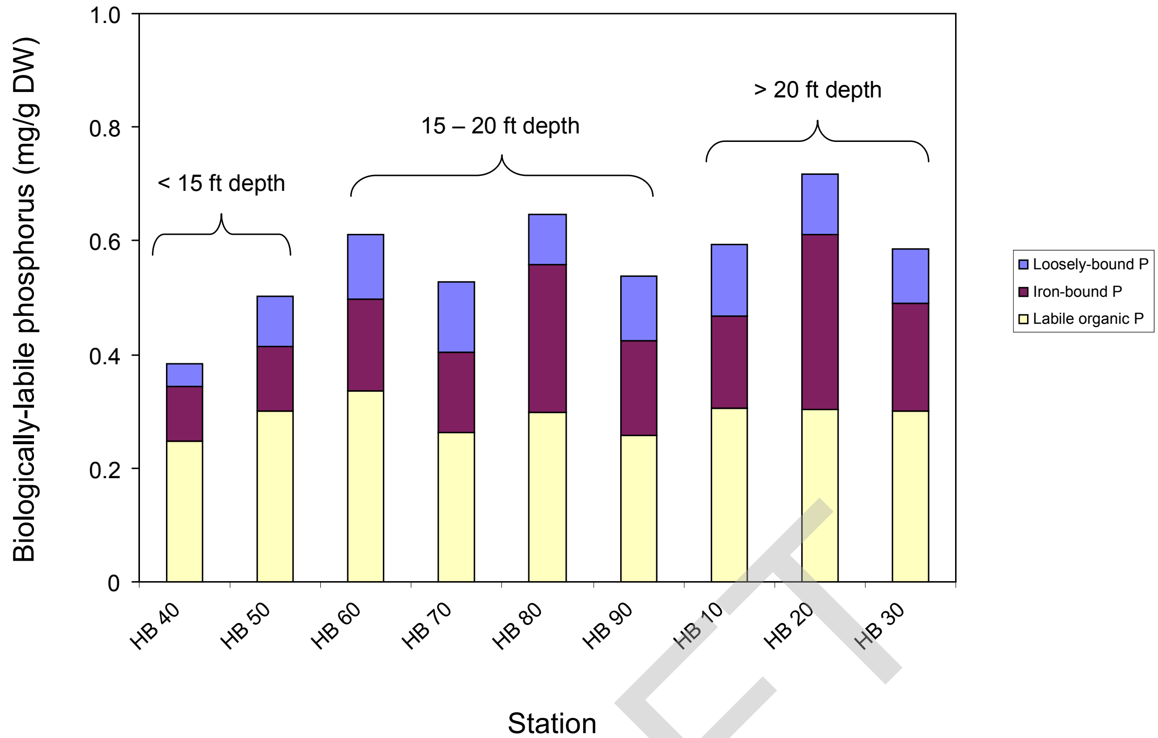



*Figure 9. Composition of the biologically-labile phosphorus (P) pool in the upper 5-cm sediment layer at various stations in Halsted Bay. Depth brackets represent various depth contour strata in the bay.*

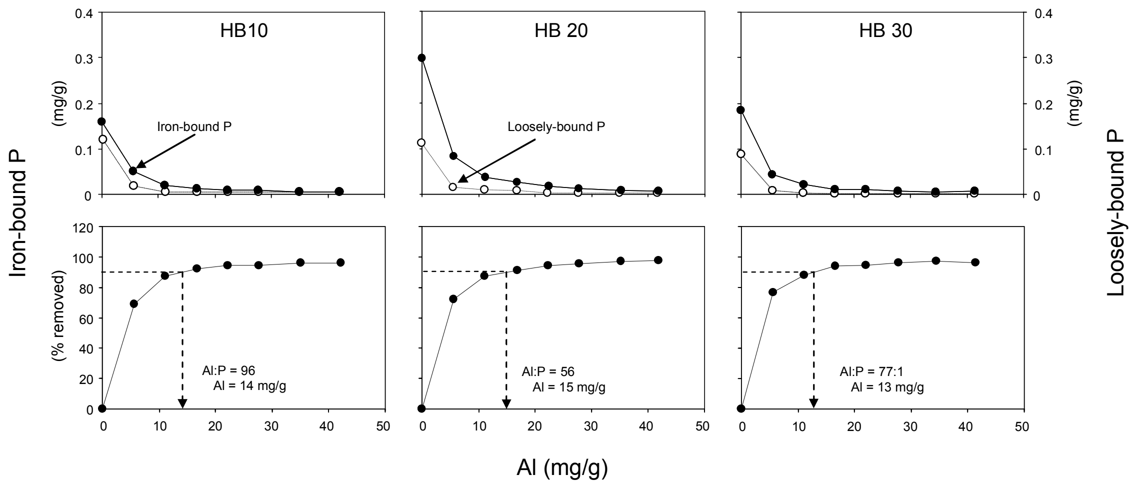



*Figure 10. Variations in the concentration of loosely-bound and iron-bound phosphorus (P; upper panels) and percent removed or adsorbed to the aluminum (Al) floc (lower panels) as a function of increasing Al concentration.*

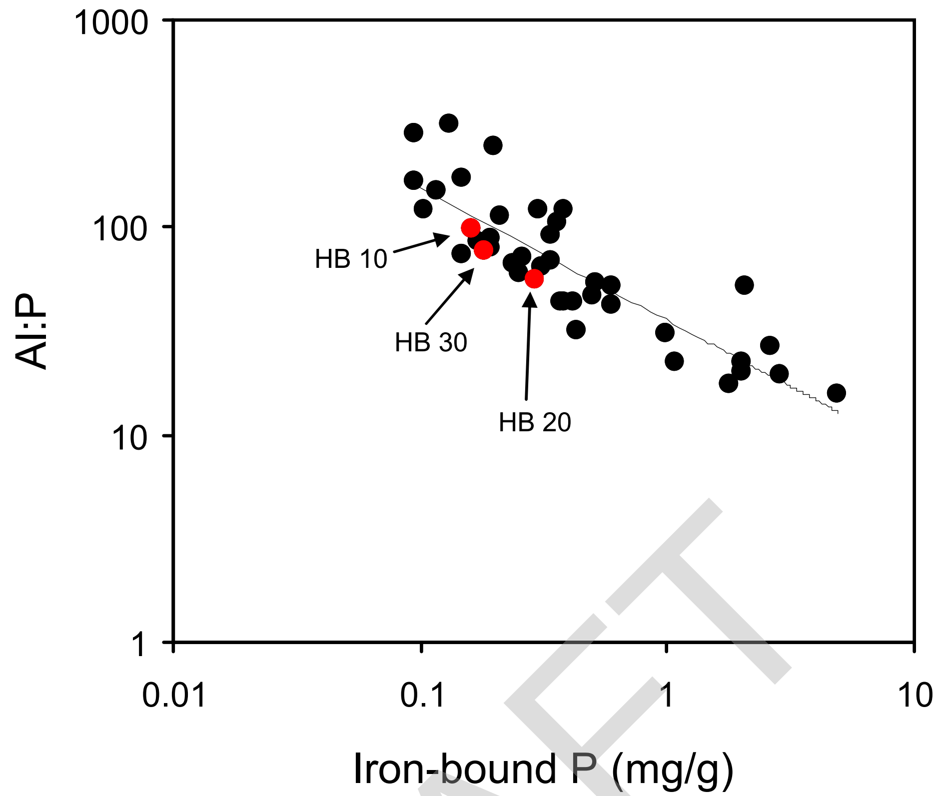



*Figure 11. Regression relationships between iron-bound phosphorus (P) concentration and the aluminum:phosphorus (Al:P) ratio for Halsted Bay sediments and sediments collected from various lakes in the region.*

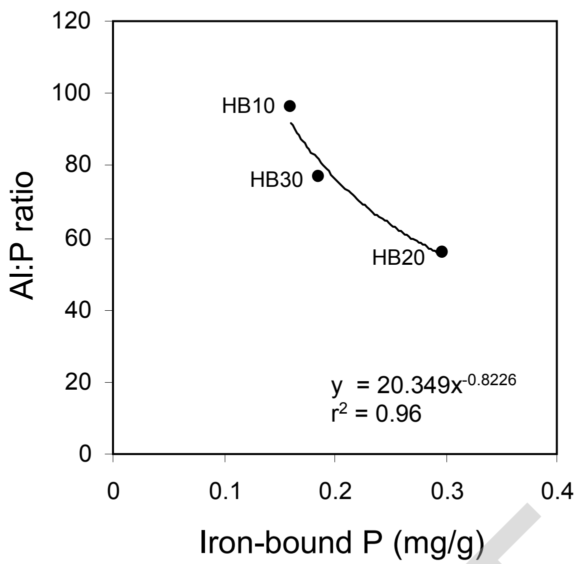



*Figure 12. Regression relationships between iron-bound phosphorus (P) concentration and the aluminum:phosphorus (Al:P) ratio for Halsted Bay sediments.*

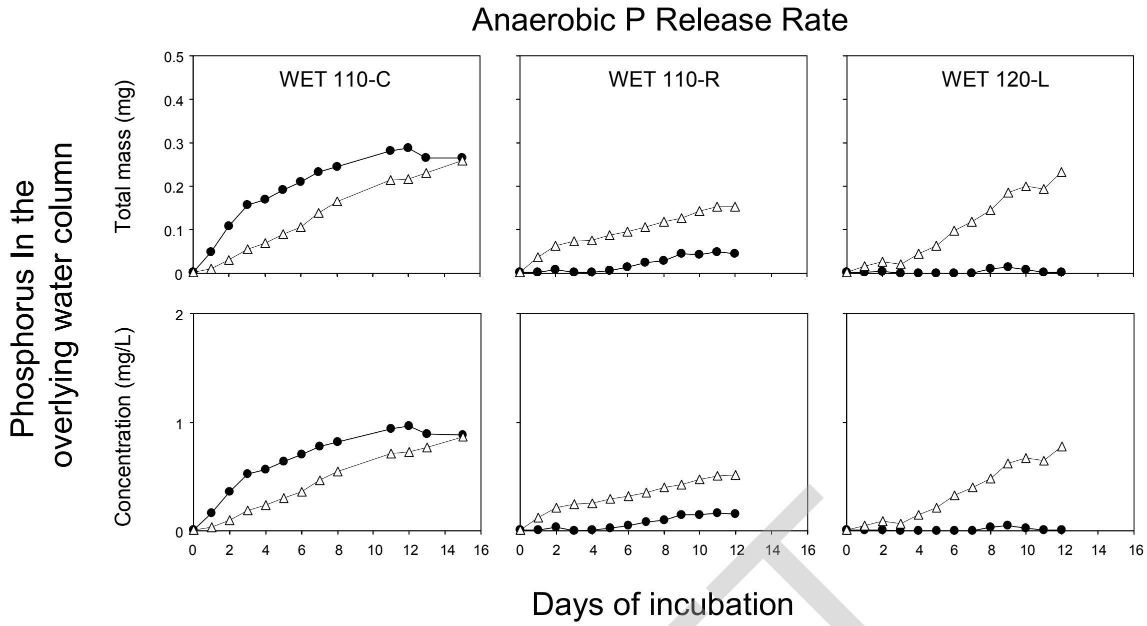



*Figure 13. Changes in soluble reactive phosphorus mass (upper panels) and concentration (lower panels) in the overlying water column under anaerobic conditions versus time for sediment cores collected in the wetland inlet.*

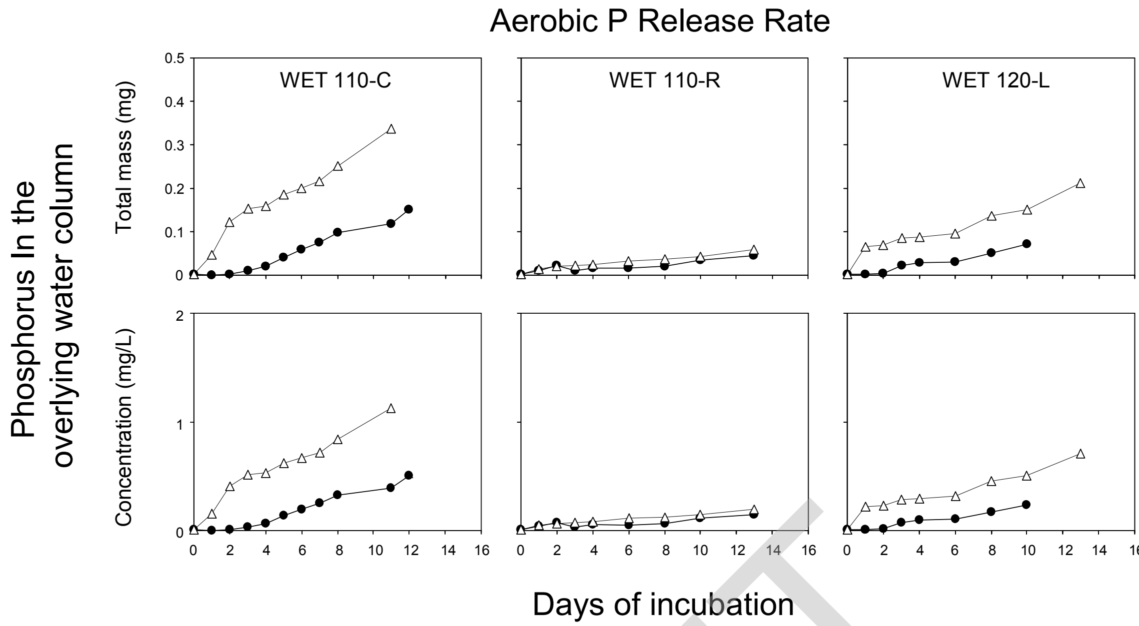



*Figure 14. Changes in soluble reactive phosphorus mass (upper panels) and concentration (lower panels) in the overlying water column under aerobic conditions versus time for sediment cores collected in the wetland inlet.*

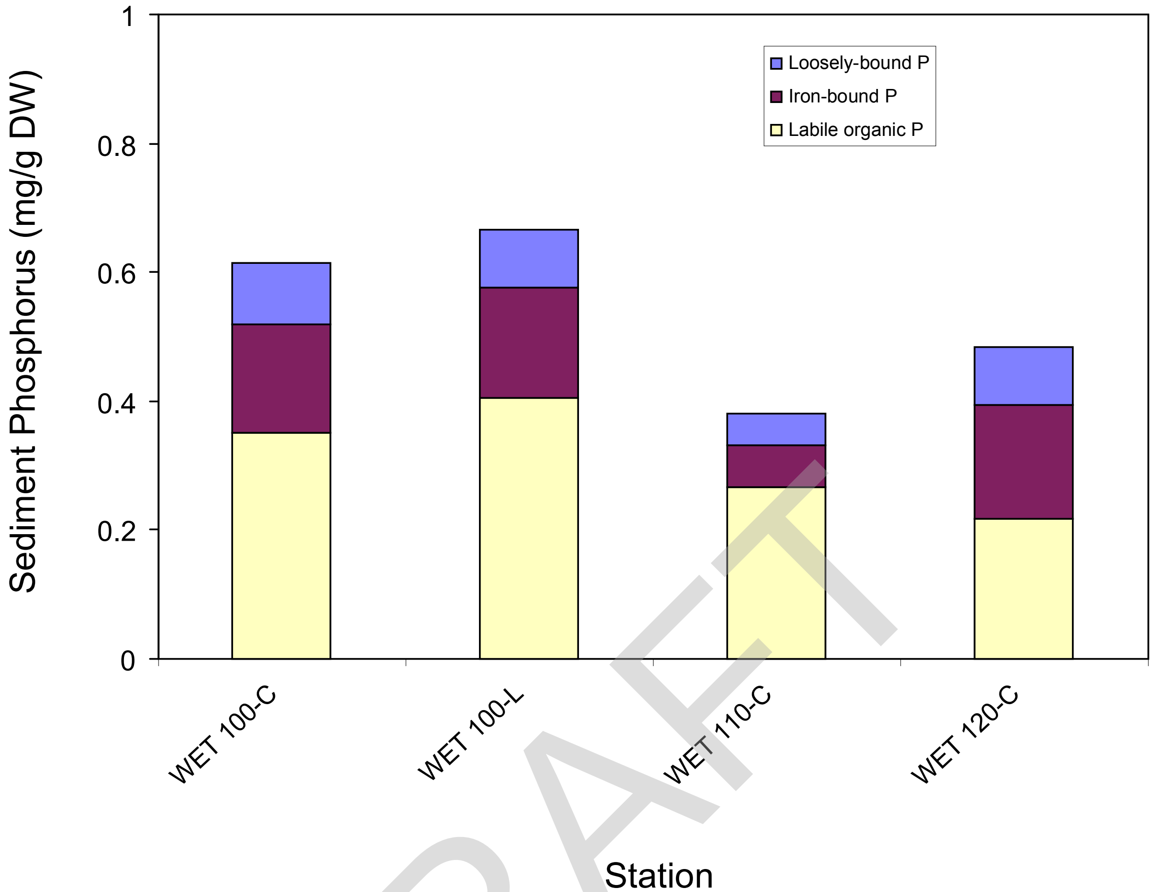



*Figure 15. Composition of the biologically-labile phosphorus (P) pool in the upper 10-cm sediment layer at various stations in the wetland inlet.*

# Appendix C

# Lake Response Model Results

# 2005 Loading Summary for Halsted Bay

| Water Budgets | | | | Phosphorus Loading | | |
|---|---|---|---|---|---|---|

### *Inflow from Drainage Areas*

| Name | Drainage Area [km$^2$] | Runoff Depth [m/yr] | Discharge [$10^6$ m$^3$/yr] | Phosphorus Concentration [ug/L] | Loading Calibration Factor (CF)[1] [--] | Load [kg/yr] |
|---|---|---|---|---|---|---|
| 1 Direct (Halsted's) | 3.2 | 0.10 | 0.330 | 160 | 1.0 | 53.0 |
| 2 6-Mile Creek (DS o | 6.9 | 0.10 | 0.712 | 160.4 | 1.0 | 114.2 |
| 3 North Trib | 4.1 | 0.10 | 0.425 | 160.4 | 1.0 | 68.2 |
| 4 | | | | | 1.0 | |
| 5 | | | | | 1.0 | |
| ***Summation*** | ***14*** | ***0*** | ***1*** | | | ***235.3*** |

### *Point Source Dischargers*

| Name | Discharge [$10^6$ m$^3$/yr] | Phosphorus Concentration [ug/L] | Loading Calibration Factor (CF)[1] [--] | Load [kg/yr] |
|---|---|---|---|---|
| 1 | | | 1.0 | |
| 2 | | | 1.0 | |
| 3 | | | 1.0 | |
| 4 | | | 1.0 | |
| 5 | | | 1.0 | |
| ***Summation*** | ***0.000*** | | | ***0.0*** |

### *Failing Septic Systems*

| Name | Total Systems | Failing Systems | Discharge [$10^6$ m$^3$/yr] | Failure [%] | Load [kg/yr] |
|---|---|---|---|---|---|
| 1 | | | | | |
| 2 | | | | | |
| 3 | | | | | |
| 4 | | | | | |
| 5 | | | | | |
| ***Summation*** | ***0*** | ***0*** | ***0.0*** | | ***0.0*** |

### *Inflow from Upstream Lakes*

| Name | Discharge [$10^6$ m$^3$/yr] | Estimated P Concentration [ug/L] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|
| 1 Mud Lake | 14.53 | 160.5 | 1.0 | 2,330.95 |
| 2 | | - | 1.0 | |
| 3 | | - | 1.0 | |
| ***Summation*** | ***14.53*** | ***160.5*** | | ***2,331*** |

### *Atmosphere*

| Lake Area [km$^2$] | Precipitation [m/yr] | Evaporation [m/yr] | Net Inflow [$10^6$ m$^3$/yr] | Aerial Loading Rate [kg/km$^2$-yr] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|---|
| 2.27 | 1.08 | 1.08 | 0.00 | 29.00 | 1.0 | 65.8 |
| | | | Dry-year total P deposition = | 24.9 | | |
| | | | Average-year total P deposition = | 26.8 | | |
| | | | Wet-year total P deposition = | 29.0 | | |
| | | | (Barr Engineering 2004) | | | |

### *Groundwater*

| Lake Area [km$^2$] | Groundwater Flux [m/yr] | Net Inflow [$10^6$ m$^3$/yr] | Phosphorus Concentration [ug/L] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|
| 2.27 | 0.3 | 0.76 | 84 | 1.0 | 64 |

### *Internal*

| Lake Area [km$^2$] | Anoxic Factor [days] | | Release Rate [mg/m$^2$-day] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|
| 2.27 | 95.7 | Oxic | 2.7 | 1.0 | 584 |
| 2.27 | 26.3 | Anoxic | 10.2 | 1.0 | 608 |
| ***Summation*** | | | | | 1,191 |

| | | | |
|---|---|---|---|
| **Net Discharge [$10^6$ m$^3$/yr] =** | **16.76** | **Net Load [kg/yr] =** | **3,888** |

NOTES
[1] Loading calibration factor used to account for special circumstances such as wetland systems, fertilizer use, or animal waste, among others, that might apply to specific loading sources.

# *2005 Lake Response Modeling for Halsteds Bay*

| Modeled Parameter | Equation | Parameters | Value [Units] |
|---|---|---|---|
| **TOTAL IN-LAKE PHOSPHORUS CONCENTRATION** | | | |

$$P = \frac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T\right)}$$

as f(W,Q,V) from Canfield & Bachmann (1981)

| Parameters | Value | Units |
|---|---|---|
| $C_P$ = | 1.04 | [--] |
| $C_{CB}$ = | 0.162 | [--] |
| b = | 0.458 | [--] |
| W (total P load = inflow + atm.) = | 3,888 | [kg/yr] |
| Q (lake outflow) = | 16.8 | [$10^6$ m$^3$/yr] |
| V (modeled lake volume) = | 9.1 | [$10^6$ m$^3$] |
| T = V/Q = | 0.55 | [yr] |
| $P_i$ = W/Q = | 232 | [µg/l] |

| | | |
|---|---|---|
| **Model Predicted In-Lake [TP]** | **94.1** | **[ug/l]** |
| **Observed In-Lake [TP]** | **92.6** | **[ug/l]** |

# 2006 Loading Summary for Halsted Bay

| Water Budgets | Phosphorus Loading |
|---|---|

### *Inflow from Drainage Areas*

| | Name | Drainage Area [$km^2$] | Runoff Depth [m/yr] | Discharge [$10^6$ $m^3$/yr] | Phosphorus Concentration [ug/L] | Loading Calibration Factor (CF)[1] [--] | Load [kg/yr] |
|---|---|---|---|---|---|---|---|
| 1 | Direct (Halsted's) | 3.2 | 0.07 | 0.233 | 124 | 1.0 | 28.9 |
| 2 | 6-Mile Creek (DS of | 6.9 | 0.07 | 0.503 | 123.8 | 1.0 | 62.3 |
| 3 | North Trib | 4.1 | 0.07 | 0.301 | 123.8 | 1.0 | 37.2 |
| 4 | | | | | | 1.0 | |
| 5 | | | | | | 1.0 | |
| | ***Summation*** | ***14*** | ***0*** | ***1*** | | | ***128.4*** |

### *Point Source Dischargers*

| | Name | Discharge [$10^6$ $m^3$/yr] | Phosphorus Concentration [ug/L] | Loading Calibration Factor (CF)[1] [--] | Load [kg/yr] |
|---|---|---|---|---|---|
| 1 | | | | 1.0 | |
| 2 | | | | 1.0 | |
| 3 | | | | 1.0 | |
| 4 | | | | 1.0 | |
| 5 | | | | 1.0 | |
| | ***Summation*** | ***0.000*** | | | ***0.0*** |

### *Failing Septic Systems*

| | Name | Total Systems | Failing Systems | Discharge [$10^6$ $m^3$/yr] | Failure [%] | Load [kg/yr] |
|---|---|---|---|---|---|---|
| 1 | | | | | | |
| 2 | | | | | | |
| 3 | | | | | | |
| 4 | | | | | | |
| 5 | | | | | | |
| | ***Summation*** | ***0*** | ***0*** | ***0.0*** | | ***0.0*** |

### *Inflow from Upstream Lakes*

| | Name | Discharge [$10^6$ $m^3$/yr] | Estimated P Concentration [ug/L] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|
| 1 | Mud Lake | 9.94 | 123.9 | 1.0 | 1,231.78 |
| 2 | | | - | 1.0 | |
| 3 | | | - | 1.0 | |
| | ***Summation*** | ***9.94*** | ***123.9*** | | ***1,232*** |

### *Atmosphere*

| Lake Area [$km^2$] | Precipitation [m/yr] | Evaporation [m/yr] | Net Inflow [$10^6$ $m^3$/yr] | Aerial Loading Rate [$kg/km^2$-yr] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|---|
| 2.27 | 0.68 | 0.68 | 0.00 | 26.80 | 1.0 | 60.9 |

Dry-year total P deposition = 24.9
Average-year total P deposition = 26.8
Wet-year total P deposition = 29.0
(Barr Engineering 2004)

### *Groundwater*

| Lake Area [$km^2$] | Groundwater Flux [m/yr] | Net Inflow [$10^6$ $m^3$/yr] | Phosphorus Concentration [ug/L] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|
| 2.27 | 0.3 | 0.76 | 84 | 1.0 | 64 |

### *Internal*

| Lake Area [$km^2$] | Anoxic Factor [days] | | Release Rate [$mg/m^2$-day] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|
| 2.27 | 97.8 | Oxic | 2.7 | 1.0 | 597 |
| 2.27 | 24.2 | Anoxic | 10.2 | 1.0 | 561 |
| ***Summation*** | | | | | 1,158 |

| | | | |
|---|---|---|---|
| **Net Discharge [$10^6$ $m^3$/yr] =** | **11.74** | **Net Load [kg/yr] =** | **2,643** |

NOTES
[1] Loading calibration factor used to account for special circumstances such as wetland systems, fertilizer use, or animal waste, among others, that might apply to specific loading sources.

# *2006 Lake Response Modeling for Halsteds Bay*

| Modeled Parameter | Equation | Parameters | Value | [Units] |
|---|---|---|---|---|
| **TOTAL IN-LAKE PHOSPHORUS CONCENTRATION** | | | | |
| $$P = \frac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T\right)}$$ | as f(W,Q,V) from Canfield & Bachmann (1981) | | | |
| | | $C_P$ = | 1.04 | [--] |
| | | $C_{CB}$ = | 0.162 | [--] |
| | | b = | 0.458 | [--] |
| | | W (total P load = inflow + atm.) = | 2,643 | [kg/yr] |
| | | Q (lake outflow) = | 11.7 | [$10^6$ $m^3$/yr] |
| | | V (modeled lake volume) = | 9.1 | [$10^6$ $m^3$] |
| | | T = V/Q = | 0.78 | [yr] |
| | | $P_i$ = W/Q = | 225 | [µg/l] |
| **Model Predicted In-Lake [TP]** | | | **81.8** | **[ug/l]** |
| **Observed In-Lake [TP]** | | | **70.0** | **[ug/l]** |

# 2007 Loading Summary for Halsted Bay

| | Water Budgets | | | Phosphorus Loading | | |
|---|---|---|---|---|---|---|
| ***Inflow from Drainage Areas*** | | | | | | |
| Name | Drainage Area [$km^2$] | Runoff Depth [m/yr] | Discharge [$10^6$ $m^3$/yr] | Phosphorus Concentration [ug/L] | Loading Calibration Factor (CF)[1] [--] | Load [kg/yr] |
| 1 Direct (Halsted's) | 3.2 | 0.07 | 0.227 | 145 | 1.0 | 32.9 |
| 2 6-Mile Creek (DS of | 6.9 | 0.07 | 0.491 | 144.6 | 1.0 | 70.9 |
| 3 North Trib | 4.1 | 0.07 | 0.293 | 144.6 | 1.0 | 42.3 |
| 4 | | | | | 1.0 | |
| 5 | | | | | 1.0 | |
| ***Summation*** | ***14*** | ***0*** | ***1*** | | | ***146.1*** |
| ***Point Source Dischargers*** | | | | | | |
| Name | | | Discharge [$10^6$ $m^3$/yr] | Phosphorus Concentration [ug/L] | Loading Calibration Factor (CF)[1] [--] | Load [kg/yr] |
| 1 | | | | | 1.0 | |
| 2 | | | | | 1.0 | |
| 3 | | | | | 1.0 | |
| 4 | | | | | 1.0 | |
| 5 | | | | | 1.0 | |
| ***Summation*** | | | ***0.000*** | | | ***0.0*** |
| ***Failing Septic Systems*** | | | | | | |
| Name | Total Systems | Failing Systems | Discharge [$10^6$ $m^3$/yr] | Failure [%] | | Load [kg/yr] |
| 1 | | | | | | |
| 2 | | | | | | |
| 3 | | | | | | |
| 4 | | | | | | |
| 5 | | | | | | |
| ***Summation*** | ***0*** | ***0*** | ***0.0*** | | | ***0.0*** |
| ***Inflow from Upstream Lakes*** | | | | | | |
| Name | | | Discharge [$10^6$ $m^3$/yr] | Estimated P Concentration [ug/L] | Calibration Factor [--] | Load [kg/yr] |
| 1 Mud Lake | | | 9.47 | 144.6 | 1.0 | 1,369.91 |
| 2 | | | | - | 1.0 | |
| 3 | | | | - | 1.0 | |
| ***Summation*** | | | ***9.47*** | ***144.6*** | | ***1,370*** |
| ***Atmosphere*** | | | | | | |
| Lake Area [$km^2$] | Precipitation [m/yr] | Evaporation [m/yr] | Net Inflow [$10^6$ $m^3$/yr] | Aerial Loading Rate [$kg/km^2$-yr] | Calibration Factor [--] | Load [kg/yr] |
| 2.27 | 0.72 | 0.72 | 0.00 | 26.80 | 1.0 | 60.9 |
| | | | Dry-year total P deposition = | 24.9 | | |
| | | | Average-year total P deposition = | 26.8 | | |
| | | | Wet-year total P deposition = | 29.0 | | |
| | | | (Barr Engineering 2004) | | | |
| ***Groundwater*** | | | | | | |
| Lake Area [$km^2$] | Groundwater Flux [m/yr] | | Net Inflow [$10^6$ $m^3$/yr] | Phosphorus Concentration [ug/L] | Calibration Factor [--] | Load [kg/yr] |
| 2.27 | 0.3 | | 0.76 | 84 | 1.0 | 64 |
| ***Internal*** | | | | | | |
| Lake Area [$km^2$] | Anoxic Factor [days] | | | Release Rate [$mg/m^2$-day] | Calibration Factor [--] | Load [kg/yr] |
| 2.27 | 93.9 | | Oxic | 2.7 | 1.0 | 572 |
| 2.27 | 28.1 | | Anoxic | 10.1 | 1.0 | 647 |
| ***Summation*** | | | | | | 1,220 |
| | | **Net Discharge [$10^6$ $m^3$/yr] =** | **11.24** | | **Net Load [kg/yr] =** | **2,861** |

NOTES

[1] Loading calibration factor used to account for special circumstances such as wetland systems, fertilizer use, or animal waste, among others, that might apply to specific loading sources.

# *2007 Lake Response Modeling for Halsteds Bay*

**Modeled Parameter** | **Equation** | **Parameters** | **Value [Units]**

**TOTAL IN-LAKE PHOSPHORUS CONCENTRATION**

$$P = \frac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T\right)}$$

as f(W,Q,V) from Canfield & Bachmann (1981)

| | | |
|---|---|---|
| $C_P$ = | 1.04 | [--] |
| $C_{CB}$ = | 0.162 | [--] |
| b = | 0.458 | [--] |
| W (total P load = inflow + atm.) = | 2,861 | [kg/yr] |
| Q (lake outflow) = | 11.2 | [$10^6$ $m^3$/yr] |
| V (modeled lake volume) = | 9.1 | [$10^6$ $m^3$] |
| T = V/Q = | 0.81 | [yr] |
| $P_i$ = W/Q = | 254 | [µg/l] |
| **Model Predicted In-Lake [TP]** | **87.8** | **[ug/l]** |
| **Observed In-Lake [TP]** | **92.7** | **[ug/l]** |

# 2008 Loading Summary for Halsted Bay

| Water Budgets | | | | Phosphorus Loading | | |
|---|---|---|---|---|---|---|

## *Inflow from Drainage Areas*

| Name | Drainage Area [km$^2$] | Runoff Depth [m/yr] | Discharge [$10^6$ m$^3$/yr] | Phosphorus Concentration [ug/L] | Loading Calibration Factor (CF)[1] [--] | Load [kg/yr] |
|---|---|---|---|---|---|---|
| 1 Direct (Halsted's) | 3.2 | 0.07 | 0.2 | 158 | 1.0 | 35 |
| 2 6-Mile Creek (DS of | 6.9 | 0.07 | 0.5 | 157.6 | 1.0 | 75 |
| 3 North Trib | 4.1 | 0.07 | 0.3 | 157.6 | 1.0 | 45 |
| 4 | | | | | 1.0 | |
| 5 | | | | | 1.0 | |
| ***Summation*** | ***14*** | 0.07 | ***1*** | 157.6 | | ***155*** |

## *Point Source Dischargers*

| Name | Discharge [$10^6$ m$^3$/yr] | Phosphorus Concentration [ug/L] | Loading Calibration Factor (CF)[1] [--] | Load [kg/yr] |
|---|---|---|---|---|
| 1 | | | 1.0 | |
| 2 | | | 1.0 | |
| 3 | | | 1.0 | |
| 4 | | | 1.0 | |
| 5 | | | 1.0 | |
| ***Summation*** | ***0.000*** | | | ***0.0*** |

## *Failing Septic Systems*

| Name | Total Systems | Failing Systems | Discharge [$10^6$ m$^3$/yr] | Failure [%] | Load [kg/yr] |
|---|---|---|---|---|---|
| 1 | | | | | |
| 2 | | | | | |
| 3 | | | | | |
| 4 | | | | | |
| 5 | | | | | |
| ***Summation*** | ***0*** | ***0*** | ***0.0*** | | ***0.0*** |

## *Inflow from Upstream Lakes*

| Name | Discharge [$10^6$ m$^3$/yr] | Estimated P Concentration [ug/L] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|
| 1 Mud Lake | 9.21 | 157.7 | 1.0 | 1,453 |
| 2 | | - | 1.0 | |
| 3 | | - | 1.0 | |
| ***Summation*** | ***9.21*** | ***157.7*** | | ***1,453*** |

## *Atmosphere*

| Lake Area [km$^2$] | Precipitation [m/yr] | Evaporation [m/yr] | Net Inflow [$10^6$ m$^3$/yr] | Aerial Loading Rate [kg/km$^2$-yr] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|---|
| 2.27 | 0.67 | 0.67 | 0.00 | 26.80 | 1.0 | 60.9 |
| | | | Dry-year total P deposition = | 24.9 | | |
| | | | Average-year total P deposition = | 26.8 | | |
| | | | Wet-year total P deposition = | 29.0 | | |
| | | | (Barr Engineering 2004) | | | |

## *Groundwater*

| Lake Area [km$^2$] | Groundwater Flux [m/yr] | Net Inflow [$10^6$ m$^3$/yr] | Phosphorus Concentration [ug/L] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|
| 2.27 | 0.3 | 0.76 | 84 | 1.0 | 64 |

## *Internal*

| Lake Area [km$^2$] | Anoxic Factor [days] | | Release Rate [mg/m$^2$-day] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|
| 2.27 | 97.0 | Oxic | 2.7 | 1.0 | 594 |
| 2.27 | 25.0 | Anoxic | 10.1 | 1.0 | 574 |
| ***Summation*** | | | | | 1,169 |

| | | | |
|---|---|---|---|
| **Net Discharge [$10^6$ m$^3$/yr] =** | **10.96** | **Net Load [kg/yr] =** | **2,902** |

NOTES

[1] Loading calibration factor used to account for special circumstances such as wetland systems, fertilizer use, or animal waste, among others, that might apply to specific loading sources.

# *2008 Lake Response Modeling for Halsteds Bay*

**Modeled Parameter** | **Equation** | **Parameters** | **Value [Units]**

**TOTAL IN-LAKE PHOSPHORUS CONCENTRATION**

$$P = \frac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T\right)}$$

as f(W,Q,V) from Canfield & Bachmann (1981)

| Parameters | Value | [Units] |
|---|---|---|
| $C_P$ = | 1.04 | [--] |
| $C_{CB}$ = | 0.162 | [--] |
| b = | 0.458 | [--] |
| W (total P load = inflow + atm.) = | 2,902 | [kg/yr] |
| Q (lake outflow) = | 11.0 | [$10^6$ m$^3$/yr] |
| V (modeled lake volume) = | 9.1 | [$10^6$ m$^3$] |
| T = V/Q = | 0.83 | [yr] |
| $P_i$ = W/Q = | 265 | [µg/l] |

| | | |
|---|---|---|
| **Model Predicted In-Lake [TP]** | **89.5** | **[ug/l]** |
| **Observed In-Lake [TP]** | **103.4** | **[ug/l]** |

# 2009 Loading Summary for Halsted Bay

| Water Budgets | | | | Phosphorus Loading | | |
|---|---|---|---|---|---|---|

### *Inflow from Drainage Areas*

| Name | Drainage Area [km$^2$] | Runoff Depth [m/yr] | Discharge [$10^6$ m$^3$/yr] | Phosphorus Concentration [ug/L] | Loading Calibration Factor (CF)[1] [--] | Load [kg/yr] |
|---|---|---|---|---|---|---|
| 1 Direct (Halsted's) | 3.2 | 0.08 | 0.250 | 136 | 1.0 | 34.0 |
| 2 6-Mile Creek (DS of Mı | 6.9 | 0.08 | 0.540 | 136.0 | 1.0 | 73.4 |
| 3 North Trib | 4.1 | 0.08 | 0.322 | 136.0 | 1.0 | 43.8 |
| 4 | | | | | 1.0 | |
| 5 | | | | | 1.0 | |
| ***Summation*** | ***14*** | ***0*** | ***1*** | 136.0 | | ***151.2*** |

### *Point Source Dischargers*

| Name | Discharge [$10^6$ m$^3$/yr] | Phosphorus Concentration [ug/L] | Loading Calibration Factor (CF)[1] [--] | Load [kg/yr] |
|---|---|---|---|---|
| 1 | | | 1.0 | |
| 2 | | | 1.0 | |
| 3 | | | 1.0 | |
| 4 | | | 1.0 | |
| 5 | | | 1.0 | |
| ***Summation*** | ***0.000*** | | | ***0.0*** |

### *Failing Septic Systems*

| Name | Total Systems | Failing Systems | Discharge [$10^6$ m$^3$/yr] | Failure [%] | Load [kg/yr] |
|---|---|---|---|---|---|
| 1 | | | | | |
| 2 | | | | | |
| 3 | | | | | |
| 4 | | | | | |
| 5 | | | | | |
| ***Summation*** | ***0*** | ***0*** | ***0.0*** | | ***0.0*** |

### *Inflow from Upstream Lakes*

| Name | Discharge [$10^6$ m$^3$/yr] | Estimated P Concentration [ug/L] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|
| 1 Mud Lake | 10.37 | 136.1 | 1.0 | 1,411.28 |
| 2 | | - | 1.0 | |
| 3 | | - | 1.0 | |
| ***Summation*** | ***10.37*** | ***136.1*** | | ***1,411*** |

### *Atmosphere*

| Lake Area [km$^2$] | Precipitation [m/yr] | Evaporation [m/yr] | Net Inflow [$10^6$ m$^3$/yr] | Aerial Loading Rate [kg/km$^2$-yr] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|---|
| 2.27 | 0.76 | 0.76 | 0.00 | 26.80 | 1.0 | 60.9 |
| | | | Dry-year total P deposition = | 24.9 | | |
| | | | Average-year total P deposition = | 26.8 | | |
| | | | Wet-year total P deposition = | 29.0 | | |
| | | | (Barr Engineering 2004) | | | |

### *Groundwater*

| Lake Area [km$^2$] | Groundwater Flux [m/yr] | Net Inflow [$10^6$ m$^3$/yr] | Phosphorus Concentration [ug/L] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|
| 2.27 | 0.3 | 0.76 | 84 | 1.0 | 64 |

### *Internal*

| Lake Area [km$^2$] | Anoxic Factor [days] | | Release Rate [mg/m$^2$-day] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|
| 2.27 | 91.1 | Oxic | 2.6 | 1.0 | 547 |
| 2.27 | 30.9 | Anoxic | 10.3 | 1.0 | 721 |
| ***Summation*** | | | | | 1,267 |

| | | | |
|---|---|---|---|
| **Net Discharge [$10^6$ m$^3$/yr] =** | **12.24** | **Net Load [kg/yr] =** | **2,955** |

NOTES

[1] Loading calibration factor used to account for special circumstances such as wetland systems, fertilizer use, or animal waste, among others, that might apply to specific loading sources.



# *2009 Lake Response Modeling for Halsteds Bay*

| Modeled Parameter | Equation | Parameters | Value | [Units] |
|---|---|---|---|---|
| TOTAL IN-LAKE PHOSPHORUS CONCENTRATION | $$P = \frac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T\right)}$$ | as f(W,Q,V) from Canfield & Bachmann (1981) | | |
| | | $C_P$ = | 1.04 | [--] |
| | | $C_{CB}$ = | 0.162 | [--] |
| | | b = | 0.458 | [--] |
| | | W (total P load = inflow + atm.) = | 2,955 | [kg/yr] |
| | | Q (lake outflow) = | 12.2 | [$10^6$ m$^3$/yr] |
| | | V (modeled lake volume) = | 9.1 | [$10^6$ m$^3$] |
| | | T = V/Q = | 0.75 | [yr] |
| | | $P_i$ = W/Q = | 241 | [μg/l] |
| **Model Predicted In-Lake [TP]** | | | **87.2** | **[ug/l]** |
| **Observed In-Lake [TP]** | | | **104.1** | **[ug/l]** |

# 2010 Loading Summary for Halsted Bay

| Water Budgets | | | | | Phosphorus Loading | | |
|---|---|---|---|---|---|---|---|

## *Inflow from Drainage Areas*

| | Name | Drainage Area [$km^2$] | Runoff Depth [m/yr] | Discharge [$10^6\ m^3/yr$] | Phosphorus Concentration [ug/L] | Loading Calibration Factor (CF)[1] [--] | Load [kg/yr] |
|---|---|---|---|---|---|---|---|
| 1 | Direct (Halsted's) | 3.2 | 0.09 | 0.271 | 156 | 1.0 | 42.4 |
| 2 | 6-Mile Creek (DS of | 6.9 | 0.09 | 0.585 | 156.1 | 1.0 | 91.4 |
| 3 | North Trib | 4.1 | 0.09 | 0.350 | 156.1 | 1.0 | 54.6 |
| 4 | | | | | | 1.0 | |
| 5 | | | | | | 1.0 | |
| | ***Summation*** | ***14*** | ***0*** | ***1*** | | | ***188.3*** |

## *Point Source Dischargers*

| | Name | Discharge [$10^6\ m^3/yr$] | Phosphorus Concentration [ug/L] | Loading Calibration Factor (CF)[1] [--] | Load [kg/yr] |
|---|---|---|---|---|---|
| 1 | | | | 1.0 | |
| 2 | | | | 1.0 | |
| 3 | | | | 1.0 | |
| 4 | | | | 1.0 | |
| 5 | | | | 1.0 | |
| | ***Summation*** | ***0.000*** | | | ***0.0*** |

## *Failing Septic Systems*

| | Name | Total Systems | Failing Systems | Discharge [$10^6\ m^3/yr$] | Failure [%] | Load [kg/yr] |
|---|---|---|---|---|---|---|
| 1 | | | | | | |
| 2 | | | | | | |
| 3 | | | | | | |
| 4 | | | | | | |
| 5 | | | | | | |
| | ***Summation*** | ***0*** | ***0*** | ***0.0*** | | ***0.0*** |

## *Inflow from Upstream Lakes*

| | Name | Discharge [$10^6\ m^3/yr$] | Estimated P Concentration [ug/L] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|
| 1 | Mud Lake | 12.27 | 156.2 | 1.0 | 1,916.59 |
| 2 | | | - | 1.0 | |
| 3 | | | - | 1.0 | |
| | ***Summation*** | ***12.27*** | ***156.2*** | | ***1,917*** |

## *Atmosphere*

| Lake Area [$km^2$] | Precipitation [m/yr] | Evaporation [m/yr] | Net Inflow [$10^6\ m^3/yr$] | Aerial Loading Rate [$kg/km^2$-yr] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|---|
| 2.27 | 0.92 | 0.92 | 0.00 | 26.80 | 1.0 | 60.9 |

Dry-year total P deposition = 24.9
Average-year total P deposition = 26.8
Wet-year total P deposition = 29.0
(Barr Engineering 2004)

## *Groundwater*

| Lake Area [$km^2$] | Groundwater Flux [m/yr] | Net Inflow [$10^6\ m^3/yr$] | Phosphorus Concentration [ug/L] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|
| 2.27 | 0.3 | 0.76 | 84 | 1.0 | 64 |

## *Internal*

| Lake Area [$km^2$] | Anoxic Factor [days] | | Release Rate [$mg/m^2$-day] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|
| 2.27 | 88.3 | Oxic | 2.7 | 1.0 | 535 |
| 2.27 | 33.7 | Anoxic | 10.1 | 1.0 | 775 |
| ***Summation*** | | | | | 1,310 |

**Net Discharge [$10^6\ m^3/yr$] = 14.24** **Net Load [kg/yr] = 3,539**

NOTES
[1] Loading calibration factor used to account for special circumstances such as wetland systems, fertilizer use, or animal waste, among others, that might apply to specific loading sources.

# *2010 Lake Response Modeling for Halsteds Bay*

| Modeled Parameter | Equation | Parameters | Value | [Units] |
|---|---|---|---|---|
| **TOTAL IN-LAKE PHOSPHORUS CONCENTRATION** | | | | |
| $$P = \frac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T\right)}$$ | as f(W,Q,V) from Canfield & Bachmann (1981) | | | |
| | | $C_P$ = | 1.04 | [--] |
| | | $C_{CB}$ = | 0.162 | [--] |
| | | b = | 0.458 | [--] |
| | | W (total P load = inflow + atm.) = | 3,539 | [kg/yr] |
| | | Q (lake outflow) = | 14.2 | [$10^6\ m^3/yr$] |
| | | V (modeled lake volume) = | 9.1 | [$10^6\ m^3$] |
| | | T = V/Q = | 0.64 | [yr] |
| | | $P_i$ = W/Q = | 249 | [µg/l] |
| **Model Predicted In-Lake [TP]** | | | **93.8** | **[ug/l]** |
| **Observed In-Lake [TP]** | | | **81.5** | **[ug/l]** |

# 2011 Loading Summary for Halsted Bay

| Water Budgets | | | | Phosphorus Loading | | |
|---|---|---|---|---|---|---|

### *Inflow from Drainage Areas*

| Name | Drainage Area [$km^2$] | Runoff Depth [m/yr] | Discharge [$10^6$ $m^3$/yr] | Phosphorus Concentration [ug/L] | Loading Calibration Factor (CF)[1] [--] | Load [kg/yr] |
|---|---|---|---|---|---|---|
| 1 Direct (Halsted's) | 3.2 | 0.07 | 0.213 | 122 | 1.0 | 26.0 |
| 2 6-Mile Creek (DS of | 6.9 | 0.07 | 0.459 | 122.0 | 1.0 | 56.1 |
| 3 North Trib | 4.1 | 0.07 | 0.274 | 122.0 | 1.0 | 33.5 |
| 4 | | | | | 1.0 | |
| 5 | | | | | 1.0 | |
| ***Summation*** | ***14*** | ***0*** | ***1*** | | | ***115.5*** |

### *Point Source Dischargers*

| Name | Discharge [$10^6$ $m^3$/yr] | Phosphorus Concentration [ug/L] | Loading Calibration Factor (CF)[1] [--] | Load [kg/yr] |
|---|---|---|---|---|
| 1 | | | 1.0 | |
| 2 | | | 1.0 | |
| 3 | | | 1.0 | |
| 4 | | | 1.0 | |
| 5 | | | 1.0 | |
| ***Summation*** | ***0.000*** | | | ***0.0*** |

### *Failing Septic Systems*

| Name | Total Systems | Failing Systems | Discharge [$10^6$ $m^3$/yr] | Failure [%] | Load [kg/yr] |
|---|---|---|---|---|---|
| 1 | | | | | |
| 2 | | | | | |
| 3 | | | | | |
| 4 | | | | | |
| 5 | | | | | |
| ***Summation*** | ***0*** | ***0*** | ***0.0*** | | ***0.0*** |

### *Inflow from Upstream Lakes*

| Name | Discharge [$10^6$ $m^3$/yr] | Estimated P Concentration [ug/L] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|
| 1 Mud Lake | 9.37 | 122.1 | 1.0 | 1,144.26 |
| 2 | | - | 1.0 | |
| 3 | | - | 1.0 | |
| ***Summation*** | ***9.37*** | ***122.1*** | | ***1,144*** |

### *Atmosphere*

| Lake Area [$km^2$] | Precipitation [m/yr] | Evaporation [m/yr] | Net Inflow [$10^6$ $m^3$/yr] | Aerial Loading Rate [$kg/km^2$-yr] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|---|
| 2.27 | 0.71 | 0.71 | 0.00 | 26.80 | 1.0 | 60.9 |
| | | | Dry-year total P deposition = | 24.9 | | |
| | | | Average-year total P deposition = | 26.8 | | |
| | | | Wet-year total P deposition = | 29.0 | | |
| | | | (Barr Engineering 2004) | | | |

### *Groundwater*

| Lake Area [$km^2$] | Groundwater Flux [m/yr] | Net Inflow [$10^6$ $m^3$/yr] | Phosphorus Concentration [ug/L] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|
| 2.27 | 0.3 | 0.76 | 84 | 1.0 | 64 |

### *Internal*

| Lake Area [$km^2$] | Anoxic Factor [days] | | Release Rate [$mg/m^2$-day] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|
| 2.27 | 90.0 | Oxic | 2.7 | 1.0 | 549 |
| 2.27 | 32.0 | Anoxic | 10.0 | 1.0 | 726 |
| ***Summation*** | | | | | 1,275 |

| | | | |
|---|---|---|---|
| **Net Discharge [$10^6$ $m^3$/yr] =** | **11.08** | **Net Load [kg/yr] =** | **2,660** |

NOTES

[1] Loading calibration factor used to account for special circumstances such as wetland systems, fertilizer use, or animal waste, among others, that might apply to specific loading sources.

# *2011 Lake Response Modeling for Halsteds Bay*

**Modeled Parameter** **Equation** **Parameters** **Value [Units]**

**TOTAL IN-LAKE PHOSPHORUS CONCENTRATION**

$$P = \frac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T\right)}$$

as f(W,Q,V) from Canfield & Bachmann (1981)

| Parameters | Value | [Units] |
|---|---|---|
| $C_P$ = | 1.04 | [--] |
| $C_{CB}$ = | 0.162 | [--] |
| b = | 0.458 | [--] |
| W (total P load = inflow + atm.) = | 2,660 | [kg/yr] |
| Q (lake outflow) = | 11.1 | [$10^6$ $m^3$/yr] |
| V (modeled lake volume) = | 9.1 | [$10^6$ $m^3$] |
| T = V/Q = | 0.82 | [yr] |
| $P_i$ = W/Q = | 240 | [µg/l] |
| **Model Predicted In-Lake [TP]** | **83.9** | **[ug/l]** |
| **Observed In-Lake [TP]** | **74.9** | **[ug/l]** |

# Average Loading Summary for Halsted Bay

| Water Budgets | | | | Phosphorus Loading | | |
|---|---|---|---|---|---|---|

### Inflow from Drainage Areas

| Name | Drainage Area [km$^2$] | Runoff Depth [m/yr] | Discharge [$10^6$ m$^3$/yr] | Phosphorus Concentration [ug/L] | Loading Calibration Factor (CF)[1] [--] | Load [kg/yr] |
|---|---|---|---|---|---|---|
| 1 Direct (Halsted's) | 3.2 | 0.08 | 0.250 | 144.3 | 1.0 | 36.0 |
| 2 6-Mile Creek (DS of | 6.9 | 0.08 | 0.538 | 144.3 | 1.0 | 77.7 |
| 3 North Trib | 6.9 | 0.05 | 0.321 | 144.3 | 1.0 | 46.4 |
| 4 | | | | | | |
| 5 | | | | | | |
| ***Summation*** | ***17*** | ***0*** | ***1*** | | | ***160.0*** |

### Point Source Dischargers

| Name | Discharge [$10^6$ m$^3$/yr] | Phosphorus Concentration [ug/L] | Loading Calibration Factor (CF)[1] [--] | Load [kg/yr] |
|---|---|---|---|---|
| 1 | | | | |
| 2 | | | | |
| 3 | | | | |
| 4 | | | | |
| 5 | | | | |
| ***Summation*** | ***0.000*** | | | ***0.0*** |

### Failing Septic Systems

| Name | Total Systems | Failing Systems | Discharge [$10^6$ m$^3$/yr] | Failure [%] | Load [kg/yr] |
|---|---|---|---|---|---|
| 1 | | | | | |
| 2 | | | | | |
| 3 | | | | | |
| 4 | | | | | |
| 5 | | | | | |
| ***Summation*** | ***0*** | ***0*** | ***0.0*** | | ***0.0*** |

### Inflow from Upstream Lakes

| Name | Discharge [$10^6$ m$^3$/yr] | Estimated P Concentration [ug/L] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|
| 1 Mud Lake | 10.74 | 144.5 | 1.0 | 1,551 |
| 2 | | - | 1.0 | |
| 3 | | - | 1.0 | |
| ***Summation*** | ***10.74*** | ***144.5*** | | ***1,551*** |

### Atmosphere

| Lake Area [km$^2$] | Precipitation [m/yr] | Evaporation [m/yr] | Net Inflow [$10^6$ m$^3$/yr] | Aerial Loading Rate [kg/km$^2$-yr] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|---|
| 2.27 | 0.79 | 0.79 | 0.00 | 26.80 | 1.0 | 60.9 |

| | |
|---|---|
| Dry-year total P deposition = | 24.9 |
| Average-year total P deposition = | 26.8 |
| Wet-year total P deposition = | 29.0 |
| (Barr Engineering 2004) | |

### Groundwater

| Lake Area [km$^2$] | Groundwater Flux [m/yr] | Net Inflow [$10^6$ m$^3$/yr] | Phosphorus Concentration [ug/L] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|
| 2.27 | 0.3 | 0.76 | 84 | 1.0 | 64 |

### Internal

| Lake Area [km$^2$] | Anoxic Factor [days] | | Release Rate [mg/m$^2$-day] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|
| 2.27 | 93.4 | Oxic | 2.7 | 1.0 | 568 |
| 2.27 | 28.6 | Anoxic | 10.1 | 1.0 | 659 |
| ***Summation*** | | | | | 1,227 |

| | | | |
|---|---|---|---|
| **Net Discharge [$10^6$ m$^3$/yr] =** | **12.61** | **Net Load [kg/yr] =** | **3,063** |

NOTES

[1] Loading calibration factor used to account for special circumstances such as wetland systems, fertilizer use, or animal waste, among others, that might apply to specific loading sources.

# *Average Lake Response Modeling for Halsteds Bay*

| Modeled Parameter | Equation | Parameters | Value | [Units] |
|---|---|---|---|---|
| **TOTAL IN-LAKE PHOSPHORUS CONCENTRATION** | | | | |
| | $$P = \frac{P_i}{1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T}$$ | as f(W,Q,V) from Canfield & Bachmann (1981) | | |
| | | $C_P$ = | 1.04 | [--] |
| | | $C_{CB}$ = | 0.162 | [--] |
| | | b = | 0.458 | [--] |
| | | W (total P load = inflow + atm.) = | 3,063 | [kg/yr] |
| | | Q (lake outflow) = | 12.6 | [$10^6$ m$^3$/yr] |
| | | V (modeled lake volume) = | 9.1 | [$10^6$ m$^3$] |
| | | T = V/Q = | 0.72 | [yr] |
| | | $P_i$ = W/Q = | 243 | [µg/l] |
| **Model Predicted In-Lake [TP]** | | | **88.5** | **[ug/l]** |
| **Observed In-Lake [TP]** | | | **88.5** | **[ug/l]** |

# Loading Summary at the Standard for Halsted Bay

| Water Budgets | | | | Phosphorus Loading | | |
|---|---|---|---|---|---|---|

## *Inflow from Drainage Areas*

| Name | Drainage Area [km²] | Runoff Depth [m/yr] | Discharge [$10^6$ $m^3$/yr] | Phosphorus Concentration [ug/L] | Loading Calibration Factor (CF)[1] [--] | Load [kg/yr] |
|---|---|---|---|---|---|---|
| 1 Direct (Halsted's) | 3.2 | 0.08 | 0.250 | 70.0 | 0.49 | 17.5 |
| 2 6-Mile Creek (DS of | 6.9 | 0.08 | 0.538 | 70.0 | 0.49 | 37.7 |
| 3 North Trib | 6.9 | 0.05 | 0.321 | 70.0 | 0.49 | 22.5 |
| 4 | | | | | | |
| 5 | | | | | | |
| ***Summation*** | ***17*** | ***0*** | ***1*** | | | ***77.6*** |

## *Point Source Dischargers*

| Name | Discharge [$10^6$ $m^3$/yr] | Phosphorus Concentration [ug/L] | Loading Calibration Factor (CF)[1] [--] | Load [kg/yr] |
|---|---|---|---|---|
| 1 | | | | |
| 2 | | | | |
| 3 | | | | |
| 4 | | | | |
| 5 | | | | |
| ***Summation*** | ***0.000*** | | | ***0.0*** |

## *Failing Septic Systems*

| Name | Total Systems | Failing Systems | Discharge [$10^6$ $m^3$/yr] | Failure [%] | Load [kg/yr] |
|---|---|---|---|---|---|
| 1 | | | | | |
| 2 | | | | | |
| 3 | | | | | |
| 4 | | | | | |
| 5 | | | | | |
| ***Summation*** | ***0*** | ***0*** | ***0.0*** | | ***0.0*** |

## *Inflow from Upstream Lakes*

| Name | Discharge [$10^6$ $m^3$/yr] | Estimated P Concentration [ug/L] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|
| 1 Mud Lake | 10.74 | 60.0 | 0.42 | 644 |
| 2 | | - | | |
| 3 | | - | | |
| ***Summation*** | ***10.74*** | ***60.0*** | | ***644*** |

## *Atmosphere*

| Lake Area [km²] | Precipitation [m/yr] | Evaporation [m/yr] | Net Inflow [$10^6$ $m^3$/yr] | Aerial Loading Rate [kg/km²-yr] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|---|
| 2.27 | 0.79 | 0.79 | 0.00 | 26.80 | 1.0 | 60.9 |
| | | | Dry-year total P deposition = | 24.9 | | |
| | | | Average-year total P deposition = | 26.8 | | |
| | | | Wet-year total P deposition = | 29.0 | | |
| | | | (Barr Engineering 2004) | | | |

## *Groundwater*

| Lake Area [km²] | Groundwater Flux [m/yr] | Net Inflow [$10^6$ $m^3$/yr] | Phosphorus Concentration [ug/L] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|
| 2.27 | 0.3 | 0.76 | 84 | 1.0 | 64 |

## *Internal*

| Lake Area [km²] | Anoxic Factor [days] | | Release Rate [mg/m²-day] | Calibration Factor [--] | Load [kg/yr] |
|---|---|---|---|---|---|
| 2.27 | 93.4 | Oxic | 0.6 | 0.23 | 128 |
| 2.27 | 28.6 | Anoxic | 1.0 | 0.10 | 66 |
| ***Summation*** | | | 0.7 | | 194 |
| | | **Net Discharge [$10^6$ $m^3$/yr] =** | **12.61** | **Net Load [kg/yr] =** | **1,041** |

NOTES

[1] Loading calibration factor used to account for special circumstances such as wetland systems, fertilizer use, or animal waste, among others, that might apply to specific loading sources.

# *Average Lake Response Modeling for Halsteds Bay*

| Modeled Parameter | Equation | Parameters | Value [Units] |
|---|---|---|---|
| **TOTAL IN-LAKE PHOSPHORUS CONCENTRATION** | | | |

$$P = \frac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T\right)}$$

as f(W,Q,V) from Canfield & Bachmann (1981)

| Parameter | Value | Units |
|---|---|---|
| $C_P$ = | 1.04 | [--] |
| $C_{CB}$ = | 0.162 | [--] |
| b = | 0.458 | [--] |
| W (total P load = inflow + atm.) = | 1,041 | [kg/yr] |
| Q (lake outflow) = | 12.6 | [$10^6$ $m^3$/yr] |
| V (modeled lake volume) = | 9.1 | [$10^6$ $m^3$] |
| T = V/Q = | 0.72 | [yr] |
| $P_i$ = W/Q = | 83 | [µg/l] |
| **Model Predicted In-Lake [TP]** | **40.0** | **[ug/l]** |
| **Observed In-Lake [TP]** | **40.0** | **[ug/l]** |

# Appendix D

# Cost Estimates

Alum Treatment of Halsted Bay - Scenario 1
Summary of Pre-Design Estimated Costs

| Cost Component Description | Quantity | Units | Estimated Unit Price | Extension |
|---|---|---|---|---|
| Final Design (1.5%) | 2% | | Constr Cost | $20,020 |
| Permitting | 1 | lump sum | $10,000 | $10,000 |
| Bidding Documents | 1 | lump sum | $5,000 | $5,000 |
| Bidding Assistance | 1% | | Constr Cost | $10,010 |
| Construction Estimate: | | | | |
| Mobilization | 1 | lump sum | $70,000 | $70,000 |
| Chemicals [$AlSO_4$ and $NaAl(OH)_4$] | 1 | lump sum | $931,000 | $931,000 |
| **Total Construction** | | | | **$1,001,000** |

| | |
|---|---|
| **Capital Costs** | **$1,046,030** |
| Construction Contingency (10%) | $104,603 |
| Annualized O&M | $0 |
| Annualized Monitoring | $8,000 |
| **20-Year O&M/Monitoring:** | **$8,000** |
| **Capital + 20-year Total Costs:** | **$1,054,030** |
| 20-year TP Removal (lbs) | 26160 |
| $/lb TP Removal Over 20-year Life | **$40.29** |

Alum Treatment of Halsted Bay - Scenario 2
Summary of Pre-Design Estimated Costs

| Cost Component Description | Quantity | Units | Estimated Unit Price | Extension |
|---|---|---|---|---|
| Final Design (1.5%) | 2% | | Constr Cost | $21,720 |
| Permitting | 1 | lump sum | $10,000 | $10,000 |
| Bidding Documents | 1 | lump sum | $5,000 | $5,000 |
| Bidding Assistance | 1% | | Constr Cost | $10,860 |
| Construction Estimate: | | | | |
| Mobilization | 1 | lump sum | $75,000 | $75,000 |
| Chemicals [$AlSO_4$ and $NaAl(OH)_4$] | 1 | lump sum | $1,011,000 | $1,011,000 |
| **Total Construction** | | | | **$1,086,000** |

| | |
|---|---|
| **Capital Costs** | **$1,133,580** |
| Construction Contingency (10%) | $113,358 |
| | |
| Annualized O&M | $0 |
| Annualized Monitoring | $8,000 |
| **20-Year O&M/Monitoring:** | **$8,000** |
| | |
| **Capital + 20-year Total Costs:** | **$1,141,580** |
| 20-year TP Removal (lbs) | 38140 |
| $/lb TP Removal Over 20-year Life | **$29.93** |

## Hypolimnetic Aeration with Chemical Injection
## Summary of Pre-Design Estimated Costs

| Cost Component Description | Quantity | Units | Estimated Unit Price | Extension |
|---|---|---|---|---|
| Property Surveys | 1 | lump sum | $7,000 | $7,000 |
| Land Rights/Easements for Operation | 5 | acre | $10,000 | $50,000 |
| Land Rights/Easements for Access | 1 | acre | $35,000 | $17,500 |
| Preliminary Design (7%) | 10% | | Constr Cost | $78,000 |
| EAW | 1 | lump sum | $50,000 | $50,000 |
| Preliminary Permitting | 1 | lump sum | $20,000 | $20,000 |
| Final Design (1.5%) | 2% | | Constr Cost | $15,600 |
| Permitting | 1 | lump sum | $10,000 | $10,000 |
| Sediment Dosage Testing | 1 | lump sum | $25,000 | $25,000 |
| Bidding Documents | 3% | | Constr Cost | $23,400 |
| Bidding Assistance | 1% | | Constr Cost | $7,800 |
| Construction Estimate: | | | | |
| Mobilization/Demobilization | 1 | lump sum | $30,000 | $30,000 |
| Site Access Road, Grading and Drainage | 1 | lump sum | $50,000 | $50,000 |
| Compressor/Chemical Storage/Controls and Building | 1 | lump sum | $300,000 | $300,000 |
| Power Source, Utilities | 1 | lump sum | $50,000 | $50,000 |
| Aerator Units | 2 | Each | $125,000.00 | $250,000 |
| Miscellaneous Piping/Electrical/chemical Feeds | 1 | lump sum | $100,000.00 | $100,000 |
| **Total Construction** | | | | **$780,000** |
| Construction Management Estimate | 4 | weeks | $7,000 | $28,000 |

| | |
|---|---|
| **Capital Costs** | **$1,112,300** |
| Construction Contingency (10%) | $111,230 |
| | |
| Annualized O&M | $75,000 |
| Annualized Monitoring | $3,000 |
| **20-Year O&M/Monitoring:** | **$1,560,000** |
| | |
| **Capital + 20-year Total Costs:** | **$2,672,300** |
| 20-year TP Removal (lbs) | 26160 |
| $/lb TP Removal Over 20-year Life | **$102.15** |

Hypolimnetic Withdrawal, Alum Treatment, and Replacement

Summary of Pre-Design Estimated Costs

| Cost Component Description | Quantity | Units | Estimated Unit Price | Extension |
|---|---|---|---|---|
| Piping, Intake, Discharge, Pumps | | | | |
| Land Rights/Easements for Access | 1 | lump sum | $50,000 | $50,000 |
| Preliminary Design (10%) | 10% | | Constr Cost | $95,300 |
| Preliminary Permitting | 1 | lump sum | $5,000 | $5,000 |
| Final Design | 3% | | Constr Cost | $28,590 |
| Permitting | 1 | Lump sum | $5,000 | $5,000 |
| Construction Estimate: | | | | |
| HDPE Manifolds, 36" HDPE and PVC Pipe | 6,000 | LF | $80 | $480,000 |
| Power Source | 1 | lump sum | $8,000 | $8,000 |
| 2 Pumps, 25 HP, Housing | 1 | lump sum | $55,000 | $55,000 |
| PVC Piping from Alum Plant | 5,500 | LF | $70 | $385,000 |
| Discharge Structure | 1 | lump sum | $25,000 | $25,000 |
| **Total Construction** | | | | **$953,000** |
| Alum Treatment | | | | |
| Non-Construction Costs | | | | $2,380,000 |
| **Total Construction of 15 cfs Plant** | | | | **$4,760,000** |
| | | | | |
| **Capital Costs** | | | | **$8,276,890** |
| Construction Contingency (10%) | | | | $827,689 |
| | | | | |
| Power | | | | $5,000 |
| Annualized O&M | | | | $150,000 |
| Annualized Monitoring | | | | $10,000 |
| **20-Year O&M/Monitoring:** | | | | **$3,300,000** |
| | | | | |
| **Capital + 20-year Total Costs:** | | | | **$11,576,890** |
| 20-year TP Removal (lbs) | | | | 26160 |
| $/lb TP Removal Over 20-year Life | | | | **$443** |

Hypolimnetic Alum Circulation
Summary of Pre-Design Estimated Costs

| Cost Component Description | Quantity | Units | Estimated Unit Price | Extension |
|---|---|---|---|---|
| Property Surveys | 1 | lump sum | $7,000 | $7,000 |
| Land Rights/Easements for Operation | 5 | acre | $10,000 | $50,000 |
| Land Rights/Easements for Access | 1 | acre | $35,000 | $17,500 |
| Preliminary Design (7%) | 10% | | Constr Cost | $125,500 |
| EAW | 1 | lump sum | $50,000 | $50,000 |
| Preliminary Permitting | 1 | lump sum | $20,000 | $20,000 |
| Final Design (1.5%) | 2% | | Constr Cost | $25,100 |
| Permitting | 1 | lump sum | $10,000 | $10,000 |
| Sediment Dosage Testing | 1 | lump sum | $25,000 | $25,000 |
| Bidding Documents | 3% | | Constr Cost | $37,650 |
| Bidding Assistance | 1% | | Constr Cost | $12,550 |
| Construction Estimate: | | | | |
| Mobilization/Demobilization | 1 | lump sum | $30,000 | $30,000 |
| Site Access Road, Grading and Drainage | 1 | lump sum | $50,000 | $50,000 |
| Hypolimnetic Circulator | 10 | Each | $70,000 | $700,000 |
| Chemical & Storage/Controls and Building | 1 | lump sum | $250,000 | $250,000 |
| Power Source, Utilities | 1 | lump sum | $50,000 | $50,000 |
| Alum Storage Tank | 1 | lump sum | $25,000 | $25,000 |
| Pump Units | 1 | Each | $50,000 | $50,000 |
| Miscellaneous Piping/Electrical/chemical Feeds | 1 | lump sum | $100,000 | $100,000 |
| **Total Construction** | | | | **$1,255,000** |
| Construction Management Estimate | 4 | weeks | $7,000 | $28,000 |

| | |
|---|---|
| **Capital Costs** | **$1,663,300** |
| Construction Contingency (10%) | $166,330 |
| Annualized O&M | $125,000 |
| Annualized Monitoring | $10,000 |
| **20-Year O&M/Monitoring:** | **$2,700,000** |
| **Capital + 20-year Total Costs:** | **$4,363,300** |
| 20-year TP Removal (lbs) | 26160 |
| $/lb TP Removal Over 20-year Life | **$166.79** |

Off-line Alum Injection
Summary of Pre-Design Estimated Costs

## 6. OPINION OF PROBABLE COST

Based on the layout for each alternative, an engineer's opinion of probable cost, estimated MCES SAC charges, and estimated operation and maintenance cost (20 year present value) are shown in Table 6.1 below. These opinions of cost incorporate anticipated 2013 construction costs and include a 25% contingency and 25% for indirect costs. The indirect costs include legal, engineering, administrative, and financing items. Table 6.2, following 6.1, provides greater detail of annual operation and maintenance costs.

**Table 6.1 – Engineer's Opinion of Probable Cost and Estimated Operation and Maintenance Costs Present Value**

| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 |
|---|---|---|---|---|
| Total Project Cost | $7,203,695 | $10,079,406 | $5,013,695 | $7,469,406 |
| MCES SAC Charges | $94,945 | $258,942 | $94,945 | $258,942 |
| **Total Capital Cost** | **$7,298,640** | **$10,338,348** | **$5,108,640** | **$7,728,348** |
| | | | | |
| MCES Flow Charges (20 yr PV) | $58,915 | $160,677 | $58,915 | $160,677 |
| Labor, Power, Chemicals, and Depreciation Cost (20 yr PV) | $2,716,893 | $6,043,543 | $2,716,893 | $6,043,543 |
| **Total Operation and Maintenance Costs (20 yr PV)** | **$2,775,808** | **$6,204,220** | **$2,775,808** | **$6,204,220** |
| | | | | |
| **Total Project Cost (20 yr Present Value)** | **$10,074,448** | **$16,542,568** | **$7,884,448** | **$13,932,568** |

*It has been assumed an MCES Industrial Discharge Permit will be granted. Should sludge lagoons be required project costs would increase.
*Land purchase costs not included

In-line Alum Injection
Summary of Pre-Design Estimated Costs

| Cost Component Description | Quantity | Units | Estimated Unit Price | Extension |
|---|---|---|---|---|
| Property Surveys | 1 | lump sum | $7,000 | $7,000 |
| Land Rights/Easements for Operation | 5 | acre | $10,000 | $50,000 |
| Land Rights/Easements for Access | 1 | acre | $35,000 | $17,500 |
| Preliminary Design (7%) | 10% | | Constr Cost | $55,500 |
| EAW | 1 | lump sum | $50,000 | $50,000 |
| Preliminary Permitting | 1 | lump sum | $20,000 | $20,000 |
| Final Design (1.5%) | 2% | | Constr Cost | $11,100 |
| Permitting | 1 | lump sum | $10,000 | $10,000 |
| Sediment Dosage Testing | 1 | lump sum | $25,000 | $25,000 |
| Bidding Documents | 3% | | Constr Cost | $16,650 |
| Bidding Assistance | 1% | | Constr Cost | $5,550 |
| Construction Estimate: | | | | |
| Mobilization/Demobilization | 1 | lump sum | $30,000 | $30,000 |
| Site Access Road, Grading and Drainage | 1 | lump sum | $50,000 | $50,000 |
| Chemical & Storage/Controls and Building | 1 | lump sum | $250,000 | $250,000 |
| Power Source, Utilities | 1 | lump sum | $50,000 | $50,000 |
| Alum Storage Tank | 1 | lump sum | $25,000 | $25,000 |
| Pump Units | 1 | Each | $50,000 | $50,000 |
| Miscellaneous Piping/Electrical/chemical Feeds | 1 | lump sum | $100,000 | $100,000 |
| **Total Construction** | | | | **$555,000** |
| Construction Management Estimate | 4 | weeks | $7,000 | $28,000 |

| | |
|---|---|
| **Capital Costs** | **$851,300** |
| Construction Contingency (10%) | $85,130 |
| | |
| Annualized O&M | $50,000 |
| Annualized Monitoring | $3,000 |
| **20-Year O&M/Monitoring:** | **$1,060,000** |
| | |
| **Capital + 20-year Total Costs:** | **$1,911,300** |
| 20-year TP Removal (lbs) | 27918 |
| $/lb TP Removal Over 20-year Life | **$68.46** |

# Iron Filtration
## Summary of Pre-Design Estimated Costs

| Cost Component Description | Quantity | Units | Estimated Unit Price | Extension |
|---|---|---|---|---|
| Property Surveys | 1 | lump sum | $10,000 | $10,000 |
| Land Rights/Easements for Operation | 16 | acre | $35,000 | $560,000 |
| Land Rights/Easements for Access | 1 | acre | $35,000 | $35,000 |
| Preliminary Design (10%) | 10% | | Constr Cost | $336,650 |
| Preliminary Permitting | 1 | lump sum | $25,000 | $25,000 |
| Final Design | 3% | | Constr Cost | $100,995 |
| Permitting | 1 | lump sum | $10,000 | $10,000 |
| No Association Determination | 1 | Each | $1,000 | $1,000 |
| Phase 1 EA | 1 | Each | $2,500 | $2,500 |
| Certificate of Closure (COC) Plan Contingency | 1 | Each | 4,500 | $4,500 |
| COC Implementation Contingency | 1 | lump sum | $25,000 | $25,000 |
| Bidding Documents | 5% | | Constr Cost | $168,325 |
| Bidding Assistance | 1% | | Constr Cost | $33,665 |
| Construction Estimate: | | | | |
| Site Access | 1 | lump sum | $100,000 | $100,000 |
| Power, Utilities | 1 | lump sum | $50,000 | $50,000 |
| Site Grading and Development | 1 | lump sum | $100,000 | $100,000 |
| 7000 gpm Lift Station and Screen House | 1 | lump sum | $375,000 | $375,000 |
| Liner | 650,000 | SF | $0.55 | $357,500 |
| Under-drain | 70,000 | LF | $10.00 | $700,000 |
| Intake and Discharge Lines | 2,000 | LF | $50.00 | $100,000 |
| Intake and Discharge Structures | 2 | Each | $20,000.00 | $40,000 |
| Coarse Sand | 25,000 | CY | $15.00 | $375,000 |
| Geotextile | 660,000 | SF | $0.30 | $198,000 |
| Coarse Filter Agregate | 25,000 | CY | $35.00 | $875,000 |
| Top Dressing | 12,000 | CY | $8.00 | $96,000 |
| **Total Construction** | | | | **$3,366,500** |
| Construction Management Estimate | 12 | weeks | $5,000 | $60,000 |
| Environmental Remediation Contingency | 1 | lump sum | $50,000 | $50,000 |

| | |
|---|---|
| **Capital Costs** | **$4,789,135** |
| Construction Contingency (10%) | $478,914 |
| | |
| Annual Power | 5040 |
| Annualized O&M | $25,000 |
| Annualized Monitoring | $5,000 |
| **20-Year O&M/Monitoring:** | **$700,800** |
| | |
| **Capital + 20-year Total Costs:** | **$5,489,935** |
| 20-year TP Removal (lbs) | 17991.6 |
| $/lb TP Removal Over 20-year Life | **$305.14** |

Fish Migration Barrier
Summary of Pre-Design Estimated Costs

| Cost Component Description | Quantity | Units | Estimated Unit Price | Extension |
|---|---|---|---|---|
| Land Rights/Easements for Access | 1 | lump sum | $50,000 | $50,000 |
| Preliminary Design (10%) | 10% | | Constr Cost | $5,000 |
| Preliminary Permitting | 1 | lump sum | $500 | $500 |
| Final Design | 3% | | Constr Cost | $1,500 |
| Permitting | 1 | Lump sum | $1,500 | $1,500 |
| Construction Estimate: | | | | |
| Fish Barrier Device (using electric current) | 1 | lump sum | $50,000 | $50,000 |
| **Total Construction** | | | | **$50,000** |

| | |
|---|---|
| **Capital Costs** | **$108,500** |
| Construction Contingency (10%) | $10,850 |
| | |
| Annualized O&M | $4,000 |
| Annualized Monitoring | $750 |
| **20-Year O&M/Monitoring:** | **$95,000** |
| | |
| **Capital + 20-year Total Costs:** | **$203,500** |
| 20-year TP Removal (lbs) | na |
| $/lb TP Removal Over 20-year Life | **na** |
| $/lb TP Removal Over 20-year Life w/o Alum Plant | **na** |

Vegetation Management
Summary of Estimated ManagementCosts

| Annual Cost Component Description | Quantity | Units | Estimated Unit Price | Extension |
|---|---|---|---|---|
| Contract Harvester Treatment (1) (2) | 0 | AC | $300 | $0 |
| Contract Herbicide Treatment (2) | 40 | AC | $350 | $14,000 |
| Permitting | 1 | LS | $1,000 | $1,000 |
| Monitoring (3) | 1 | LS | $2,500 | $2,500 |
| Contract Management | 1 | LS | $500 | $500 |
| | | | | |
| | | | **Annual Treatement Costs** | **$18,000** |
| | | | Contingency (10%) | $1,800 |
| | | | **Annual Treatement Costs w/Contingency** | **$19,800** |

| | |
|---|---|
| **20-Year Total Costs:** | **$396,000** |
| 20-year TP Removal (lbs) | na |
| $/lb TP Removal Over 20-year Life | **na** |
| $/lb TP Removal Over 20-year Life w/o Alum Plant | **na** |

(1) Assumed no harvesting since the majority of aquatic vegetation less than 5ft
(2) Based on average of vendor quotes assumes treatment two times per year - 20ac/treatment
(3) Monitoring assumed 2 staff at $35/hr would be required to complete 60 hrs total of monitoring including vegetation sampling, water quality, and sediment sampling.

Wenck

Engineers • Scientists
Business Professionals

# FEASIBILITY STUDY

---

## NUTRIENT REMOVAL SYSTEM

## FOR THE
## MINNEHAHA CREEK WATERSHED DISTRICT

**July 19, 2013**

**Prepared By:**

**WSB & Associates, Inc.**
**701 Xenia Avenue South, Suite 300**
**Minneapolis, MN 55416**
**(763) 541-4800**
**(763) 541-1700 (Fax)**

# CERTIFICATION

I hereby certify that this plan, specification, or report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Engineer under the laws of the State of Minnesota.

Joseph C. Ward, PE

Date: July 19, 2013 Lic. No. 45855

Leslee L. Storlie, EIT

Date: July 19, 2013

Quality Control Review By:

Thomas A. Roushar, PE

Date: July 19, 2013 Lic. No. 12084

# TABLE OF CONTENTS

# 1.EXECUTIVE SUMMARY

This feasibility study is prepared as part of the Minnehaha Creek Watershed District (MCWD) and the City of Minnetrista's Halsted's Bay Phosphorus Reduction Project. Included is an evaluation of alternatives for the design of a nutrient removal system to improve water quality at Halsted's Bay of Lake Minnetonka. Halsted's Bay lies within Minnetrista, MN.

As part of this feasibility study, two site locations (Figure 1) were selected with two alternatives for process water flow rates at each location, resulting in four alternative designs. These alternatives are listed below.

- Alternative #1-West Location at 5 cfs (2,250 GPM)
- Alternative #2-West Location at 15 cfs (6,750 GPM)
- Alternative #3-East Location at 5 cfs (2,250 GPM)
- Alternative #4-East Location at 15 cfs (6,750 GPM)

Based on the project capital costs, staff operation and maintenance requirements, constructability, and removal efficiency Alternative #4 is recommended. The evaluation of operation and maintenance costs is included in Section 6. The engineer's opinion of probable capital costs is approximately $7,500,000.

Additional project design recommendations are listed below.

- Engineering and design of the nutrient removal system was based on water quality and treatment process from similar lakes in the metro area. It is recommended that pilot plant (jar) testing be completed to verify treatment process assumptions included in this study and resulting structure sizes and necessary equipment. Removal efficiencies and a more detailed evaluation can be completed following jar testing.

- Begin permitting process with Minnesota Pollution Control Agency (MPCA) and Metropolitan Council on Environmental Services (MCES). Sludge disposal is a critical issue with MCES and if it will not be permitted, then additional land should be purchased for lagoons for sludge storage.

- An evaluation should be completed at the recommended nutrient removal system site and near intake/effluent piping locations to confirm existing soils are adequate for facility construction or if additional geotechnical improvements are necessary.

## 2. PURPOSE AND SCOPE

The purpose of the Halsted's Bay Off-Line Phosphorus Removal Facility Feasibility Study is to evaluate potential treatment facility locations, and determine sizing and construction costs necessary for a nutrient removal system.

The feasibility study involves the evaluation, design, and cost estimation of a clarification system to remove phosphorus from 6 Mile Creek upstream of Halsted's Bay. Within the study, consideration to pumping capacity, operations flexibility, sludge handling, and removal efficiency were evaluated.

The scope of this report includes a description of existing conditions, a presentation of the four alternatives for removing phosphorus from the surface water, a discussion of probable cost, and recommendations.

## 3. PROCESS BACKGROUND AND PERMITTING

### A. PHOSPHORUS REMOVAL SYSTEM

Sedimentation systems have been used to effectively remove phosphorus from some metro area lakes. The sedimentation process consists of a clarification system that is designed to remove phosphorus from the creek water leading to Halsted's Bay. Addition of a flocculant (alum, ferric chloride, and/or in combination with a polymer) to the influent water forms large particles (floc) containing phosphorus. Water flows through a clarifier where the floc settles to the bottom, leaving cleaner water (effluent) near the top of the clarifier. The effluent is returned to the lake and the remaining floc (sludge), containing phosphorus, is disposed in the sanitary sewer or sludge holding lagoons.

### B. FLOCCULANT ADDITION AND ALTERNATIVES

Several alternatives are available for flocculant addition including, aluminum sulfate (alum), ferric chloride, and alum or ferric chloride polymer combinations. The optimal flocculant type and dosage should be determined through jar testing. Some advantages and disadvantages of each flocculant type are listed below.

- Alum is typically 50% less in cost than ferric chloride, however prices do fluctuate and are dependent on delivery quantities.
- Alum is less corrosive than ferric chloride. Ferric chloride delivery systems can be more expensive, replaced more often, and require more care for operators to work with.
- Alum does not stain as much as ferric chloride. Ferric chloride's color stains tanks (making it difficult to read levels), walls, floors, and requires more cleaning and care for operators to work with.
- Phosphorus removal through alum dosing results in pH decrease, therefore caustic soda must be added to the water to return the water to a neutral pH.
- Ferric chloride reacts better in colder temperatures than alum.
- Ferric chloride can be stored outside in cold temperatures, alum cannot.
- Addition of ferric chloride introduces chlorides into the water which MPCA may have objections to during the agency permitting process.

It is emphasized that jar testing will determine the optimal flocculant and dosage for Halsted's Bay water quality. For example, although ferric chloride costs approximately 50% more than alum, ferric chloride may have greater phosphorus removal capacity and require less to be added to the influent water. Therefore, there would be no net difference in cost between the two flocculants. Also, the flocculant can be changed once the facility is in operation depending on operator preferences.

Based on past removal data from similarly designed systems, the system may have the ability to remove approximately 1,617 lb (15 cfs) or 1,095 lb (5 cfs) of phosphorus per year of operation, however, jar testing and laboratory testing is necessary to determine actual phosphorus removal expectations.

## C. SLUDGE DISPOSAL AND PERMITTING

The sludge containing phosphorus floc remaining would likely consist of approximately 0.5 to 1% solids which are light and do not settle or dewater easily. Therefore, the most efficient method of disposal is by conveyance to the sanitary sewer system.

The City of Minnetrista owns and operates the local wastewater collection system, but ultimately conveys its wastewater to MCES interceptor sewers that transport wastewater to regional treatment plants for final disposal. MCES requires an industrial discharge permit for all facilities using water in its treatment process and one would be required for this system. Historically, MCES has granted industrial discharge permits for similar facilities, but as phosphorus limits are reduced at their regional treatment facilities, there is a strong possibility permits will not be granted in the future. Additionally, industrial discharge permits are reviewed on a regular basis and MCES can revoke the permit in the future.

In the event MCES does not authorize an industrial discharge permit, a sludge holding pond system would need to be utilized. A sludge lagoon would be designed to hold the sludge and allow drying. The ponds would need to be dredged as sludge builds up over time. Further sludge holding pond details are included in Section 8.

## D. TREATMENT PROCESS PERMITTING

The treatment facility would withdraw water from and return it to a public water, therefore a National Pollutant Discharge Elimination System (NPDES)/State Disposal System (SDS) permit will be required from the MPCA. Similar facilities have been permitted in the past, and water quality monitoring may be required by the permit.

## 4. PHOSPHORUS REMOVAL DESIGN ALTERNATIVES

### A. Alternative #1 (Figures 1 and 2) – West Location at 5 cfs (2,250 GPM)

This alternative is designed to treat water from 6 Mile Creek at a rate of 5 cfs at the West Location option as shown in Figure 1. Figure 2 shows the West Location options along with the necessary structures and piping layout for this design alternative.

Raw water would be drawn from an intake structure in 6 Mile Creek and pumped to a splitter box which would control the flow rate to each of the two clarifiers. At this stage flocculant would be added to improve the mixing of the water with the chemicals which can save on the volume of chemical needed during treatment.

Alternative #1 is designed using two 48' diameter clarifiers to allow the phosphorus floc to settle from the water. The use of two clarifiers instead of one allows for more flexibility in the operation of the facility. With two clarifiers available, operators would have the option of running the clarifiers in parallel or in series. During times of high water flow in the creek, the clarifiers could be run in parallel to treat the maximum volume of water. However, during times of low flow in the creek the clarifiers could be run in series allowing for better polishing of the water and better removal of phosphorus. In the future when phosphorus loading is reduced, the treatment system could be utilized in series to maximize removal, similar to creek low flow conditions.

Each clarifier would be equipped with a perimeter rake on the bottom of the structure and perimeter skimmer on the top of the water. The rake assists with the sludge disposal while the surface skimmer removes surface floc and prevents them from being discharged into Halsted's Bay.

Due to floc settling, a waste sludge is produced. It is estimated that approximately 11,000 gallons per day (gpd) sludge would be generated consisting of approximately 0.5 to 1% solids which are light and do not settle or dewater easily, so the sludge is mostly water and would flow from the bottom of the clarifier. The sludge discharge rate from the clarifier is greater than the capacity of the two lift stations that the sludge would ultimately flow to. Therefore, this design option would include two flow equalization tanks to temporarily store sludge flow which could then be pumped at a lower rate to the Minnetrista's sanitary sewer system and not exceed its capacity. Additionally, the flow equalization tanks would allow sludge to be pumped to the sanitary system during off-peak flow periods.

Depending upon jar testing results, it may be possible to use the equalization tanks for sludge thickening which would reduce the total volume of sludge discharged to Minnetrista's sanitary sewer system. The reduction in volume of sludge discharged would result in lower MCES disposal charges (SAC and flow charges). Through the use of a thickening tank and a polymer to reduce settling time, the sludge would be given time to settle and better separate from the water. The cleaner water on the top of the tank would be decanted and recycled to the head of the facility while the remaining sludge at the bottom of the tank would be pumped to the sanitary sewer system. It is estimated that the sludge volume disposed of to the sanitary sewer could be as low as 3,000 gpd if thickening is possible.

Specifically, the sludge could be discharged to Minnetrista's Lift Station No. 12, which ultimately flows into Lift Station No. 13 and to the MCES interceptor system. Lift Station No. 12 has reserve peak flow capacity of approximately 110 GPM, so sludge flow to the lift station should be at a rate less than 110 GPM. However, if sludge is discharged to the lift station during off-peak hours the lift station may be able to accommodate the additional sludge flow.

Also included in this design is a chemical building to store and pump the necessary chemicals along with housing the controls for the treatment system. Chemical storage would allow for about 2-4 weeks of storage and would be delivered by tanker truck for optimal pricing. Based on experience at similar facilities in the region, chemical dosing rates were estimated at approximately 340 gallons (gal) of alum and 85 gal of caustic soda per day at an estimated cost of $550/day.

Based on previous permitting experiences it is assumed that MCES will grant an industrial discharge permit allowing sludge to be disposed of to their wastewater treatment system. If the permit is denied, a sludge lagoon would be designed to hold the sludge and allow drying. The sludge lagoons would be approximately 1 acre if sludge thickening is possible and 4 acres if it is not possible.

Advantages and disadvantages of this alternative are summarized in the Feasibility and Recommendation section.

**B. Alternative #2 (Figures 1 and 2) – West Location at 15 cfs (6,750 GPM)**

Alternative #2 would be the same as Alternative #1 except that it would have the ability to treat up to 15 cfs of surface water. The increased treatment capacity does not require any additional structures or facilities but would require larger structures. The clarifiers would have a designed diameter of 80' and would be equipped with the same flexibility as with Alternative #1. In addition, a larger influent pump station would be needed for the increased influent volume and a larger chemical building is needed to hold the greater volume of flocculant needed to treat the larger volume of water.

Based on experience at similar facilities in the region, chemical dosing rates were estimated at approximately 1,000 gal alum and 250 gal caustic soda per day, at an estimated cost of $1,630/day.

A similar sized splitter box would be utilized to split the flow evenly to the two clarifiers from the initial raw water pumping station. After the clarification process, the sludge would be handled in a similar manner as described in Alternative #1, however a greater volume of sludge would be produced (30,000 gpd). Sludge would be conveyed to Minnetrista's Lift Station No.12 which would have capacity to pump the increased sludge volume through the use of the equalization tanks.

Based on previous permitting experiences, it is assumed that MCES will grant an industrial discharge permit allowing sludge to be disposed of through their wastewater treatment system. If the permit is denied, a sludge lagoon would be designed to hold the sludge and allow drying. The sludge lagoons would be approximately 1 acre if sludge thickening is possible and 10 acres if it is not possible.

Advantages and disadvantages of this alternative are summarized in the Feasibility and Recommendation section.

### C. Alternative #3 (Figures 1 and 3) – East Location at 5 cfs (2,250 GPM)

This alternative is the same as Alternative #1 but is located at the East location option (Figure 1). It is equipped to effectively remove phosphorus from the surface water at a treatment rate of 5 cfs. Figure 3 shows the East location options along with the necessary structures and piping layout for this design alternative.

The only difference between Alternative #1 and Alternative #3 is the site location. Alternative #3 is located closer to 6 Mile Creek as well as Halsted's Bay allowing for shorter pipe lengths and less overall headloss throughout the system as displayed in Figure 1.

Advantages and disadvantages of this alternative are summarized in the Feasibility and Recommendation section.

### D. **Alternative #4 (Figures 1 and 3) – East Location at 15 cfs (6,750 GPM)**

This alternative is the same as Alternative #2 but is located at the East location option. Similar to Alternative #2, it could handle 15 cfs of surface water flow during treatment.

As with Alternative #3, due to the location, the pipe lengths and overall headloss are less for this option as compared to Alternatives #1 and #2.

Advantages and disadvantages of this alternative are summarized in the Feasibility and Recommendation section.

## 5. ENVIRONMENTAL CONSIDERATIONS

In an effort to reduce environmental impacts, the nutrient removal system would be designed with considerations for environmental impact. Included in each alternative design are the following environmental considerations: VFDs, water recycling, low impact site development, and solar power.

### A. Variable Frequency Drives (VFDs)

Through the use of VFDs, a reduction in speed, flow, energy, and headloss is achieved. These savings are possible because the VFD alters the speed of the pump motor. Changing the speed of the motor places less stress on the piping and pumping components and electrical savings are achieved.

### B. Water Recycling

Depending upon jar testing results, it may be possible to use the equalization tanks for sludge thickening which would reduce the total volume of sludge discharged to Minnetrista's sanitary sewer system. The reduction in volume of sludge discharged would result in lower MCES disposal charges (SAC and flow charges). Through the use of a thickening tank and a polymer to reduce settling time, the sludge is given time to settle and better separate from the water. The cleaner water on the top of the tank would be decanted and recycled to the head of the facility while the remaining sludge at the bottom of the tank would be pumped to the sanitary sewer system. It is estimated that the sludge volume disposed of to the sanitary sewer may be as low as 3,000 gpd if thickening is possible compared to approximately 30,000 gpd for the 15 cfs alternatives and 11,000 gpd for the 5 cfs alternatives.

### C. Low Impact Site Development-Visual and Physical

Each alternative design would be located in either a current residential location or a location that may become residential in the future. To assist in providing a site with low visual impact, the clarifier structures could be constructed as close to level with grade as possible. A minimal amount of the structure could be visible to residents as the majority of the structure would be underground. The clarifier could be equipped with a flat cover, rather than a domed cover to improve aesthetics and decrease the visual impact the site has on the surrounding residents if a cover is necessary. To improve aesthetics, architectural finishes can be used for the building and the site landscaped.

The physical impact of the site development could be minimized through minimal grading and the consideration of the natural ground slope in the design of the system's hydraulics. Wetland impacts could be minimized through the use of best management practices for storm water pollution prevention.

## D. Solar Panels

Along with the use of VFDs for electricity conservation, solar panels could also be installed and utilized to save energy. The solar energy could be used to provide a portion of power requirements and would be evaluated in greater detail during final design.

## 6. OPINION OF PROBABLE COST

Based on the layout for each alternative, an engineer's opinion of probable cost, estimated MCES SAC charges, and estimated operation and maintenance cost (20 year present value) are shown in Table 6.1 below. These opinions of cost incorporate anticipated 2013 construction costs and include a 25% contingency and 25% for indirect costs. The indirect costs include legal, engineering, administrative, and financing items. Table 6.2, following 6.1, provides greater detail of annual operation and maintenance costs.

**Table 6.1 – Engineer's Opinion of Probable Cost and Estimated Operation and Maintenance Costs Present Value**

| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 |
|---|---|---|---|---|
| Total Project Cost | $7,203,695 | $10,079,406 | $5,013,695 | $7,469,406 |
| MCES SAC Charges | $94,945 | $258,942 | $94,945 | $258,942 |
| **Total Capital Cost** | **$7,298,640** | **$10,338,348** | **$5,108,640** | **$7,728,348** |
| | | | | |
| MCES Flow Charges (20 yr PV) | $58,915 | $160,677 | $58,915 | $160,677 |
| Labor, Power, Chemicals, and Depreciation Cost (20 yr PV) | $2,716,893 | $6,043,543 | $2,716,893 | $6,043,543 |
| **Total Operation and Maintenance Costs (20 yr PV)** | **$2,775,808** | **$6,204,220** | **$2,775,808** | **$6,204,220** |
| | | | | |
| **Total Project Cost (20 yr Present Value)** | **$10,074,448** | **$16,542,568** | **$7,884,448** | **$13,932,568** |

*It has been assumed an MCES Industrial Discharge Permit will be granted. Should sludge lagoons be required project costs would increase.
*Land purchase costs not included

**Table 6.2 – Estimated**
**Operation and Maintenance Costs**

| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 |
|---|---|---|---|---|
| MCES Flow Charges | $3,960 | $10,800 | $3,960 | $10,800 |
| Labor | $36,000 | $36,000 | $36,000 | $36,000 |
| Power | $30,281 | $54,441 | $30,281 | $54,441 |
| Chemicals | $97,524 | $292,572 | $97,524 | $292,572 |
| Depreciation | $18,813 | $23,208 | $18,813 | $23,208 |
| | | | | |
| **Total Estimated Annual Operations and Maintenance Cost** | **$186,578** | **$417,021** | **$186,578** | **$417,021** |

*Depreciation includes equipment items only and does not include structures.

## 7. COST BENEFIT

It has been assumed that the loading rate from the 6 Mile Creek, leading to Halsted's Bay, is approximately 2,724 lb/yr as an average annual load with an average concentration of 146 µg/L.

Under an assumption that the Halsted's Bay Off-Line Phosphorus Removal Facility is operational for 180 days a year, about 90 % of the previously stated load would be available for treatment, providing 2,452 lb/yr.

Based on Diagram 7.1, flow and load "capture" can be determined for both the 5 cfs and 15 cfs design alternatives. Under the 5 cfs alternative, approximately 56% of the flow is captured at a load of 1378 lb/yr. For the 15 cfs alternative, approximately 83% of the flow is captured at a load of 2035 lb/yr.

Assuming a discharge concentration of 30 µg/L (more defined limit can be assumed after jar testing), the 5 cfs design option would be capable of removing approximately 1,095 lb/yr while the 15 cfs design option could be capable of removing approximately 1,617 lb/yr. As an approximation, the removal rate of the Halsted's Bay Off-Line Phosphorus Removal Facility would be about 80% of the captured load. It is important to note however, that jar testing should be completed to verify this assumption.

In an effort to determine the cost benefit of the Halsted's Bay Off-Line Phosphorus Removal Facility, the present worth calculations shown in Table 6.1 were divided by the removal capabilities described above. The cost benefits in $/lb phosphorus removed can be found in Table 7.1.

**Diagram 7.1 – 6 Mile Creek Flow Duration**

**<INSERT 6 MILE CREEK FLOW DURATION GRAPH>**

**Table 7.1 – Cost Benefit**

| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 |
|---|---|---|---|---|
| **Total Project Cost (20 yr PV)** | **$10,074,448** | **$16,542,568** | **$7,884,448** | **$13,932,568** |
| **Phosphorus Removed, lb (20 yr)** | 21,900 | 32,340 | 21,900 | 32,340 |
| **Cost Benefit, $/lb** | $460.02 | $511.52 | $360.02 | $430.82 |

## 8. FEASIBILITY AND RECOMMENDATION

Each design alternative includes advantages and disadvantages, which are summarized in Table 8.1 below based on site location and treatment capacity.

**Table 8.1 –Advantages and Disadvantages of Alternative Designs**

| | ***Location*** | | ***Treatment Capacity*** | |
|---|---|---|---|---|
| | **Alternative #1 or #2** | **Alternative #3 or #4** | **Alternative #1 or #3** | **Alternative #2 or #4** |
| | **West Location** | **East Location** | **5 cfs** | **15 cfs** |
| Advantages | high elevation | close to Halsted's Bay and existing lift station | smaller pumps | greater phosphorus removal |
| | separated from City | | smaller diameter pipes | flow flexibility |
| | flat site area near clarifier placement | | | large enough for drinking water consideration |
| Disadvantages | far from Halsted's Bay-long pipe lengths | near a new development | more likely to short circuit settling process | larger pumps |
| | great changes in elevation of road leading to bay | | | larger diameter pipes |

Based on the decision matrix presented above, Alternative #4 is recommended. This alternative is located at the East location and has capacity for the highest flow rate of 15 cfs. The recommendation of Alternative #4 over the other three alternatives is due to the following key reasons:

- Located close to 6 Mile Creek, Halsted's Bay, and the existing lift station allowing for shorter pipe lengths.
- The treated water effluent line follows a more regular terrain providing for more cost effective discharge piping and easier construction than the west location alternatives.
- At 15 cfs, the nutrient removal system includes greater capital costs due to the greater capacity but is marginally less than the 5 cfs alternative (Alternative #3) per unit of capacity due to economies of scale. For a tripling of capacity (from 5 to 15 cfs) the price increase is estimated to be approximately 50% higher making the 15 cfs option an economical treatment option.

Project design recommendations include:

- Engineering and design of the nutrient removal system was based on water quality and treatment process from similar lakes in the metro area. It is recommended that pilot plant (jar) testing be completed to verify treatment process assumptions included in this study to determine the resulting structure sizes and necessary equipment. Removal efficiencies and a more detailed evaluation can be completed following jar testing.

- Begin permitting process with MPCA and MCES. Sludge disposal is a critical issue with MCES and if it will not be permitted, then additional land should be purchased for lagoons for sludge storage.

- An evaluation be completed at the recommended nutrient removal system site and near intake/effluent piping locations to confirm existing soils are adequate for facility construction or if additional geotechnical improvements would be necessary.

## 9. OTHER CONSIDERATIONS

### A. Sludge Lagoons

In the event MCES does not authorize an industrial discharge permit, a sludge ponding system may be necessary. A sludge lagoon would be designed to hold the sludge and water mixture, allowing for the sludge to settle to the bottom and the water to separate. Within the lagoon structure, an adjustable decanting device could be used to pump the water back to the treatment facility for reuse, providing for a thicker sludge and greater volume of pond volume available for further sludge additions.

The lagoon system would be designed for flexibility in operation. It would contain extra volume for emergency use and to prevent overflow during normal operating conditions. To allow for sufficient drying, four ponds would be available to allow rotation every three months. After being used for three months, a pond would be allowed to dry for three months. In addition, to reduce the overall surface area needed for the lagoon system, a five year dredging schedule is initially contemplated. It is expected with this design that each pond would be cleaned every five years to maintain ample volume for sludge storage.

In total, the lagoon system would be different for the 15 cfs alternatives (10 acres) and 5 cfs alternatives (4 acres) as noted in the alternative descriptions. Also, if sludge thickening is possible (based on jar testing) it should be possible to greatly reduce the lagoon size to approximately 1 acre under both the 15 or 5 cfs alternative.

## B. Drinking Water Treatment Plant

In the event that the City of Minnetrista would like to expand the nutrient removal system for phosphorus into a drinking water treatment facility, there are processes and additional chemicals that would need to be added. In general, the processes of coagulation and clarification, disinfection, filtration, and distribution disinfection would be required. Through these additional process chemicals such as lime, soda ash, flocculants (alum or ferric chloride), polymer, polyphosphates, carbon dioxide, chlorine (or other disinfectant), ammonia, and fluoride may be necessary. These additional treatment processes could require an expansion in the chemical storage capabilities of the nutrient removal system to contain equipment such as lime slakers, lime silos, chemical batch tanks, sludge containment, chemical diffusers, pumps, and chlorine storage and containment. Table 9.1 provides a list of the potential processes and likely equipment that would be needed for a surface water drinking water treatment plant. Highlighted items indicate items included in the planned nutrient removal system at Halsted's Bay. It should be noted that existing water quality is unknown, but preliminary processes have been identified based on water quality from typical surface waters in the metro area.

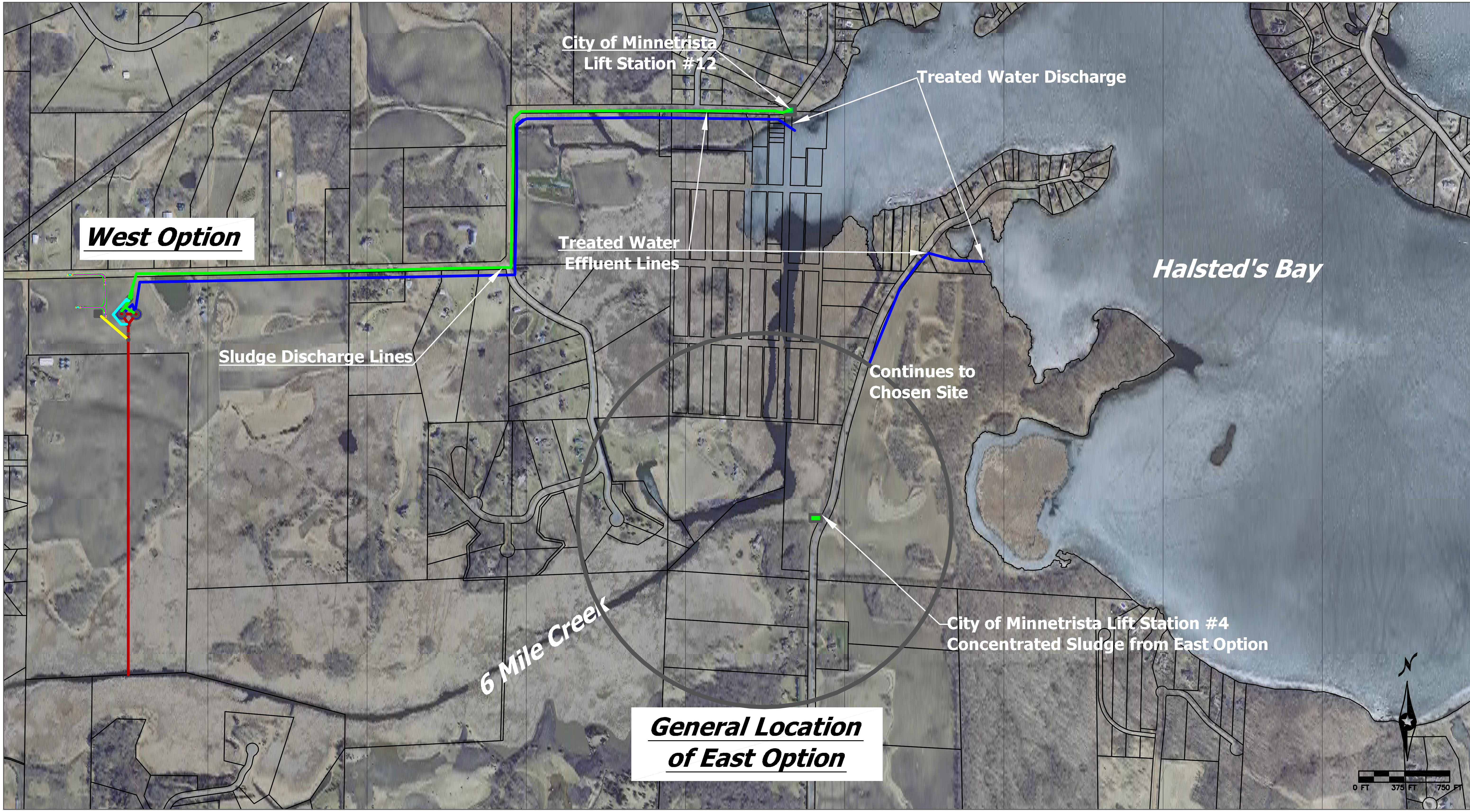
**Table 9.1 – Drinking Water Treatment Plant Considerations**

| *Surface Water Treatment Facilities* | | | |
|---|---|---|---|
| ***Processes*** | ***Chemicals*** | ***Equipment*** | |
| Coagulation | Lime | Lime Slakers | *Softening* |
| Softening | Soda Ash | Lime Silos | |
| Sludge Handling | Ferric or Alum | Soda Ash Batch Tanks | |
| Disinfection | Polymer | Polymer Mix Tanks | |
| Recarbonation | Polyphosphate | Center Mixer | |
| Filtration | Carbon Dioxide | Perimeter Rake | |
| Polishing | Ozone | Sludge Discharge | |
| Booster Station | Chlorine | Contact Chambers | *Ozone Disinfection* |
| | Ammonia | Fine Bubble Diffusers | |
| | Fluoride | Injection Pumps | |
| | Liquid Oxygen | Ozone Generators | |
| | Calcium Thiosulfate | PSA or LOX | |
| | | Ozone Compressors | |
| | | Ozone Destruct Units | |
| | | Backwash Pumps | *Filtration* |
| | | Air Scour Pumps | |
| Included in Off-Line Phosphorus Removal System | | Filter Waste Return Tank | |
| | | Chemical Building | *Chemicals* |
| | | Pumps for Chemicals | |
| | | Mix Tanks | |
| | | Day Tanks | |
| | | Dry Chemical Hoppers | |
| | | Chlorine Containment | |

An ozone disinfection system is illustrated in Table 9.1, however, a chlorine disinfection system would also be a possible form of disinfection.

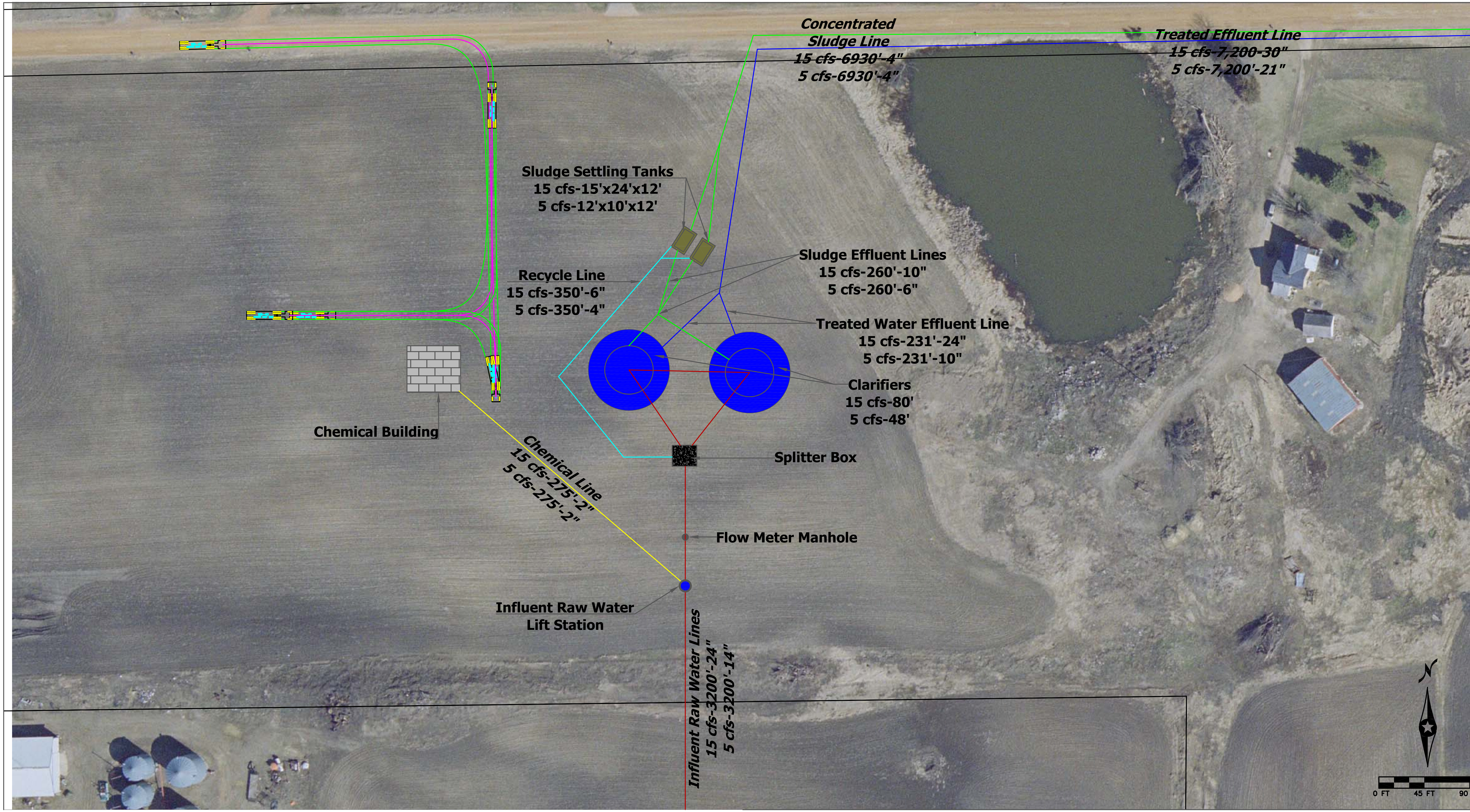
With the addition of the treatment processes described above, increases in cost to an approximate cost of about $5 million per million gallons per day (MGD) of treatment capacity. For example, to construct a facility to treat approximately 10 MGD (15.4 cfs) of water, a project cost of approximately $50 million could be expected.

# FIGURES




WSB & Associates, Inc. | Minnehaha Creek Watershed District | City of Minnetrista

**Figure 1: Overview**
**Halsted's Bay**
**Off-line Phosphorus Removal Facility**
**WSB Project No. 02213-000**




WSB & Associates, Inc.

Minnehaha Creek Watershed District

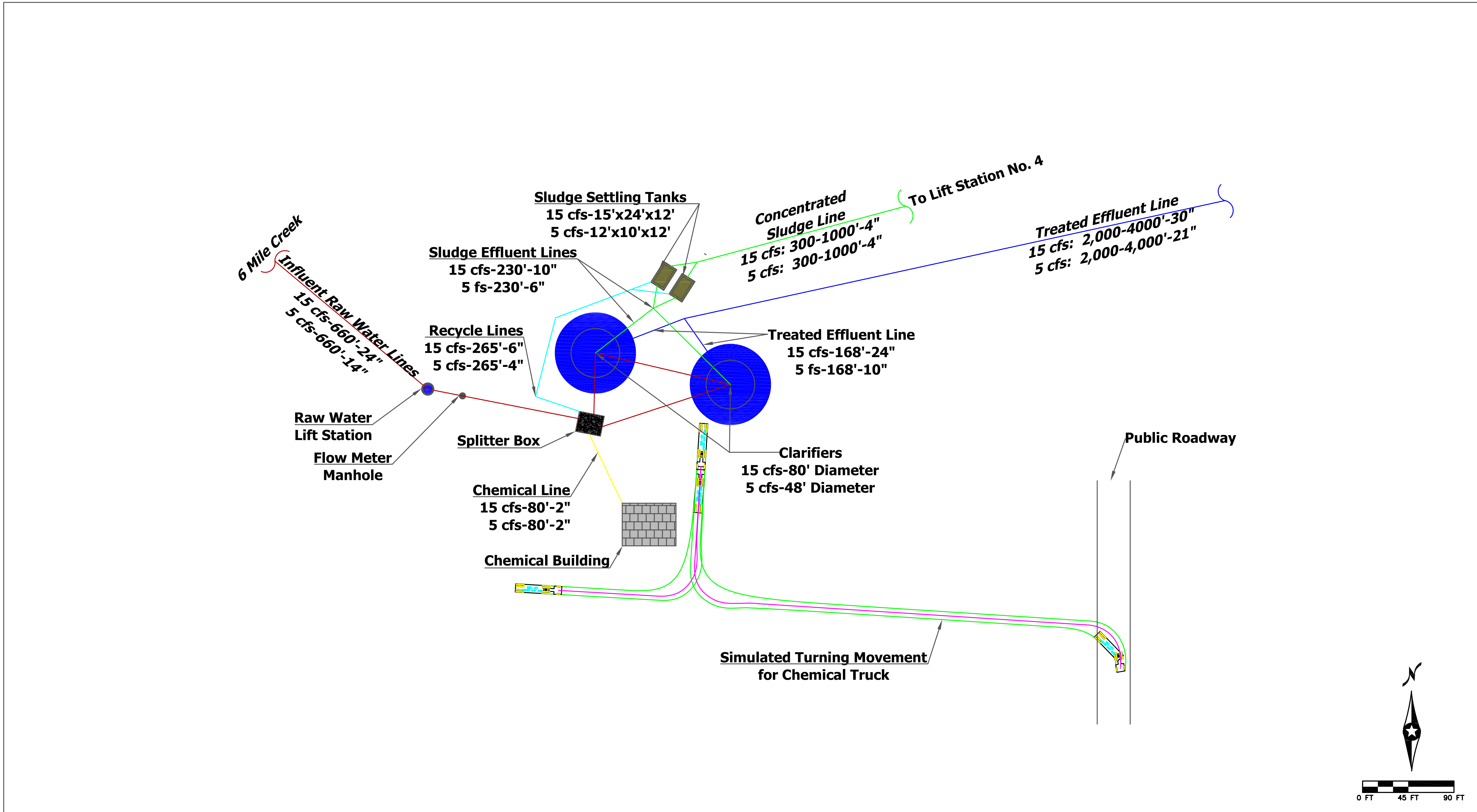
City of Minnetrista

**Figure 2: West Option**

**Halsted's Bay**

**Off-line Phosphorus Removal Facility**

**WSB Project No. 02213-000**

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Minnehaha Creek Watershed District

City of Minnetrista

**Figure 3: East Option-Generalized Site Plan**

**Halsted's Bay**

**Off-line Phosphorus Removal Facility**

**WSB Project No. 02213-000**

# APPENDIX A

# OPINION OF PROBABLE COSTS

# MCWD Halsted's Bay Nutrient Removal System

**Alternative #1 - West Location Option at 5 cfs**

**Cost Summary, Engineer's Opinion of Probable Cost**

| Item No. | Description | Estimated Construction Cost | Contingency Cost (25%) | Indirect Cost (25%) | Total Estimated Cost |
|---|---|---|---|---|---|
| 1 | 16" INFLUENT SUCTION (INTAKE TO SPLITTER BOX) | $271,500.00 | $67,875.00 | $67,875.00 | $407,250.00 |
| 2 | INFLUENT LIFT STATION AND METER MANHOLE | $301,000.00 | $75,250.00 | $75,250.00 | $451,500.00 |
| 3 | 28' X 52' X 13' MASONRY CHEMICAL BUILDING | $716,875.00 | $179,218.75 | $179,218.75 | $1,075,312.50 |
| 4 | SITE PIPING (BETWEEN CLARIFIERS, TANKS, BUILDING, | $90,500.00 | $22,625.00 | $22,625.00 | $135,750.00 |
| 5 | SITE SURFACE IMPROVEMENTS (ROADWAY, FENCING) | $178,500.00 | $44,625.00 | $44,625.00 | $267,750.00 |
| 6 | SPLITTER BOX | $97,300.00 | $24,325.00 | $24,325.00 | $145,950.00 |
| 7 | 2 - 48' DIA. CLARIFIERS | $1,247,288.00 | $311,822.00 | $311,822.00 | $1,870,932.00 |
| 8 | SETTLING TANKS (INCLUDING PUMPS, PIPING) | $140,000.00 | $35,000.00 | $35,000.00 | $210,000.00 |
| 9 | 4" SLUDGE PIPING FROM SETTLING TANK TO LIFT STATION | $292,000.00 | $73,000.00 | $73,000.00 | $438,000.00 |
| 10 | 21" EFFLUENT FROM CLARIFIER TO BANK (PVC) | $760,000.00 | $190,000.00 | $190,000.00 | $1,140,000.00 |
| 11 | 21" EFFLUENT FROM BANK TO OUTLET (PVC) | $67,500.00 | $16,875.00 | $16,875.00 | $101,250.00 |
| 12 | 2 - EFFLUENT INTERMEDIATE PUMP STATIONS | $640,000.00 | $160,000.00 | $160,000.00 | $960,000.00 |
| | **TOTAL** | ***$4,802,463.00*** | ***$1,200,615.75*** | ***$1,200,615.75*** | ***$7,203,694.50*** |

# MCWD Halsted's Bay Nutrient Removal System

**Alternative #2 - West Location Option at 15 cfs**

**Cost Summary, Engineer's Opinion of Probable Cost**

| Item No. | Description | Estimated Construction Cost | Contingency Cost (25%) | Indirect Cost (25%) | Total Estimated Cost |
|---|---|---|---|---|---|
| 1 | 24" INFLUENT SUCTION (INTAKE TO SPLITTER BOX) | $348,000.00 | $87,000.00 | $87,000.00 | $522,000.00 |
| 2 | INFLUENT LIFT STATION AND METER MANHOLE | $370,000.00 | $92,500.00 | $92,500.00 | $555,000.00 |
| 3 | 40' X 52' X 13' MASONRY CHEMICAL BUILDING | $882,500.00 | $220,625.00 | $220,625.00 | $1,323,750.00 |
| 4 | SITE PIPING (BETWEEN CLARIFIERS, TANKS, BUILDING) | $131,000.00 | $32,750.00 | $32,750.00 | $196,500.00 |
| 5 | SITE SURFACE IMPROVEMENTS (ROADWAY, FENCING) | $178,500.00 | $44,625.00 | $44,625.00 | $267,750.00 |
| 6 | SPLITTER BOX | $104,610.00 | $26,152.50 | $26,152.50 | $156,915.00 |
| 7 | 2 - 80' DIA. CLARIFIERS | $2,354,494.00 | $588,623.50 | $588,623.50 | $3,531,741.00 |
| 8 | SETTLING TANKS (INCLUDING PUMPS, PIPING) | $240,000.00 | $60,000.00 | $60,000.00 | $360,000.00 |
| 9 | 4" SLUDGE PIPING FROM SETTLING TANK TO LIFT STATION | $292,000.00 | $73,000.00 | $73,000.00 | $438,000.00 |
| 10 | 30" EFFLUENT FROM CLARIFIER TO BANK (PVC) | $976,000.00 | $244,000.00 | $244,000.00 | $1,464,000.00 |
| 11 | 30" EFFLUENT FROM BANK TO OUTLET (PVC) | $82,500.00 | $20,625.00 | $20,625.00 | $123,750.00 |
| 12 | 2 - EFFLUENT INTERMEDIATE PUMP STATIONS | $760,000.00 | $190,000.00 | $190,000.00 | $1,140,000.00 |
| | **TOTAL** | ***$6,719,604.00*** | ***$1,679,901.00*** | ***$1,679,901.00*** | ***$10,079,406.00*** |

# MCWD Halsted's Bay Nutrient Removal System

**Alternative #3 - East Location Option at 5 cfs**

**Cost Summary - Engineer's Opinion of Probable Cost**

| Item No. | Description | Estimated Construction Cost | Contingency Cost (25%) | Indirect Cost (25%) | Total Estimated Cost |
|---|---|---|---|---|---|
| 1 | 16" INFLUENT SUCTION (INTAKE TO SPLITTER BOX) | $89,500.00 | $22,375.00 | $22,375.00 | $134,250.00 |
| 2 | INFLUENT LIFT STATION AND METER MANHOLE | $301,000.00 | $75,250.00 | $75,250.00 | $451,500.00 |
| 3 | 28' X 52' X 13' MASONRY CHEMICAL BUILDING | $716,875.00 | $179,218.75 | $179,218.75 | $1,075,312.50 |
| 4 | SITE PIPING (BETWEEN CLARIFIERS, TANKS, BUILDING, | $90,500.00 | $22,625.00 | $22,625.00 | $135,750.00 |
| 5 | SITE SURFACE IMPROVEMENTS (ROADWAY, FENCING) | $178,500.00 | $44,625.00 | $44,625.00 | $267,750.00 |
| 6 | SPLITTER BOX | $97,300.00 | $24,325.00 | $24,325.00 | $145,950.00 |
| 7 | 2 - 48' DIA. CLARIFIERS | $1,247,288.00 | $311,822.00 | $311,822.00 | $1,870,932.00 |
| 8 | SETTLING TANKS (INCLUDING PUMPS, PIPING) | $140,000.00 | $35,000.00 | $35,000.00 | $210,000.00 |
| 9 | 4" SLUDGE PIPING FROM SETTLING TANK TO LIFT STATION | $34,000.00 | $8,500.00 | $8,500.00 | $51,000.00 |
| 10 | 21" EFFLUENT FROM CLARIFIER TO BANK (PVC) | $380,000.00 | $95,000.00 | $95,000.00 | $570,000.00 |
| 11 | 21" EFFLUENT FROM BANK TO OUTLET (PVC) | $67,500.00 | $16,875.00 | $16,875.00 | $101,250.00 |
| | **TOTAL** | ***$3,342,463.00*** | ***$835,615.75*** | ***$835,615.75*** | ***$5,013,694.50*** |

# MCWD Halsted's Bay Nutrient Removal System

**Alternative #4 - East Location Option at 15 cfs**

**Cost Summary, Engineer's Opinion of Probable Cost**

| Item No. | Description | Estimated Construction Cost | Contingency Cost (25%) | Indirect Cost (25%) | Total Estimated Cost |
|---|---|---|---|---|---|
| 1 | 24" INFLUENT SUCTION (INTAKE TO SPLITTER BOX) | $114,000.00 | $28,500.00 | $28,500.00 | $171,000.00 |
| 2 | INFLUENT LIFT STATION AND METER MANHOLE | $370,000.00 | $92,500.00 | $92,500.00 | $555,000.00 |
| 3 | 40' X 52' X 13' MASONRY CHEMICAL BUILDING | $882,500.00 | $220,625.00 | $220,625.00 | $1,323,750.00 |
| 4 | SITE PIPING (BETWEEN CLARIFIERS, TANKS, BUILDING) | $131,000.00 | $32,750.00 | $32,750.00 | $196,500.00 |
| 5 | SITE SURFACE IMPROVEMENTS (ROADWAY, FENCING) | $178,500.00 | $44,625.00 | $44,625.00 | $267,750.00 |
| 6 | SPLITTER BOX | $104,610.00 | $26,152.50 | $26,152.50 | $156,915.00 |
| 7 | 2 - 80' DIA. CLARIFIERS | $2,354,494.00 | $588,623.50 | $588,623.50 | $3,531,741.00 |
| 8 | SETTLING TANKS (INCLUDING PUMPS, PIPING) | $240,000.00 | $60,000.00 | $60,000.00 | $360,000.00 |
| 9 | 4" SLUDGE PIPING FROM SETTLING TANK TO LIFT STATION | $34,000.00 | $8,500.00 | $8,500.00 | $51,000.00 |
| 10 | 30" EFFLUENT FROM CLARIFIER TO BANK (PVC) | $488,000.00 | $122,000.00 | $122,000.00 | $732,000.00 |
| 11 | 30" EFFLUENT FROM BANK TO OUTLET (PVC) | $82,500.00 | $20,625.00 | $20,625.00 | $123,750.00 |
| | **TOTAL** | ***$4,979,604.00*** | ***$1,244,901.00*** | ***$1,244,901.00*** | ***$7,469,406.00*** |