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March 2015

Okabena Lake Diagnostic Study

Prepared for:

OKABENA OCHEDA WATERSHED DISTRICT

Minnesota Pollution Control Agency

CLEAN WATER LAND & LEGACY AMENDMENT

WENCK ASSOCIATES

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1.0 Purpose and Scope

Okabena Lake is a 776-acre water body located in southwestern Minnesota in the City of Worthington. The lake has poor water clarity due to high levels of suspended sediment (TSS), and algae growth caused by excessive nutrients. The purpose of this study is to use historic data along with data collected by the Okabena-Ocheda Watershed District in 2014 to improve the understanding of Lake Okabena's sediment and phosphorus sources. Specifically, this study investigates the following sources of sediment and phosphorus to Okabena Lake: dry and wet deposition on the lake surface; runoff from the City of Worthington; rural runoff from animal agriculture, field erosion and streambank erosion; and internal loading of phosphorus from the lake sediments. These sources were estimated using a combination of monitoring data, literature rates, and modeling exercises. The sediment and phosphorus source assessment presented in this report is intended to support development of the Okabena Lake TMDL and help identify source areas for best management practice (BMP) planning and implementation strategies.

2.0 Site Description

2.1 WATERSHED DESCRIPTION

Okabena Lake (DNR# 53-0028-00) is located entirely within the city limits of Worthington, in southwestern Minnesota. Okabena Lake's drainage area covers approximately 9,437 acres. A majority of the lake's watershed, approximately 7,999 acres (85%), is located outside the City of Worthington municipal boundary in rural portions of Nobles County. There are nine major subwatersheds that discharge to the lake through storm sewer pipes or small ditches and tributary channels (Figure 2-1). The largest surface water inflow to Okabena Lake is Okabena Creek which drains approximately 5,306 acres of land north of the lake. The second largest inflow to the lake is from an unnamed tributary to Sunset Bay that drains 2,628 acres of land west of the lake. The remainder of the watershed is made up of smaller subwatersheds that drain to city stormwater ponds, and direct runoff that enters the lake through overland flow and small storm sewer catchments. Dominant land cover in the Okabena Lake watershed is corn/soybean rotations, which are primarily located in the Okabena Creek and Sunset Bay tributary subwatersheds. The City of Worthington, roadways, and other developed land account for approximately 18% of watershed land cover. Table 2-1 presents current land cover throughout the Okabena Lake watershed.

Table 2-1. Land cover in the Okabena Lake watershed.

Land cover[1]	Acres	Percent
Corn/Soybeans	6,374	67%
Developed	1,698	18%
Grass/Pasture	937	10%
Wetlands	257	3%
Forest	169	2%
Other Crops	2	<1%
Total	**9,437**	**100%**

[1]Land cover calculated using 2013 National Agricultural Statistics Service (NASS) GIS database

There are several unique hydrologic features located throughout the Okabena Lake watershed. One of these features is the Boote-Herlein Marsh located approximately four miles northwest of Okabena Lake that drains approximately 4,200 acres west of Okabena Creek. Prior to 2014, outflow from the marsh was directed toward Okabena Creek through a ditched channel west of Nystrom Avenue. A dam was constructed in early 2014 across the outflow channel and the Boote-Herlein Marsh now outlets to the west and away from Okabena Creek and the Okabena Lake watershed.

Downstream of the Boote-Herlein Marsh, Okabena Creek flows through the Prairie View Golf Links public golf course located approximately one mile northwest of the City of Worthington along County Road 25. During development of the golf course, several large ponds were incorporated into the design to store and treat upstream flow and pollutant loads (Figure 2-2).

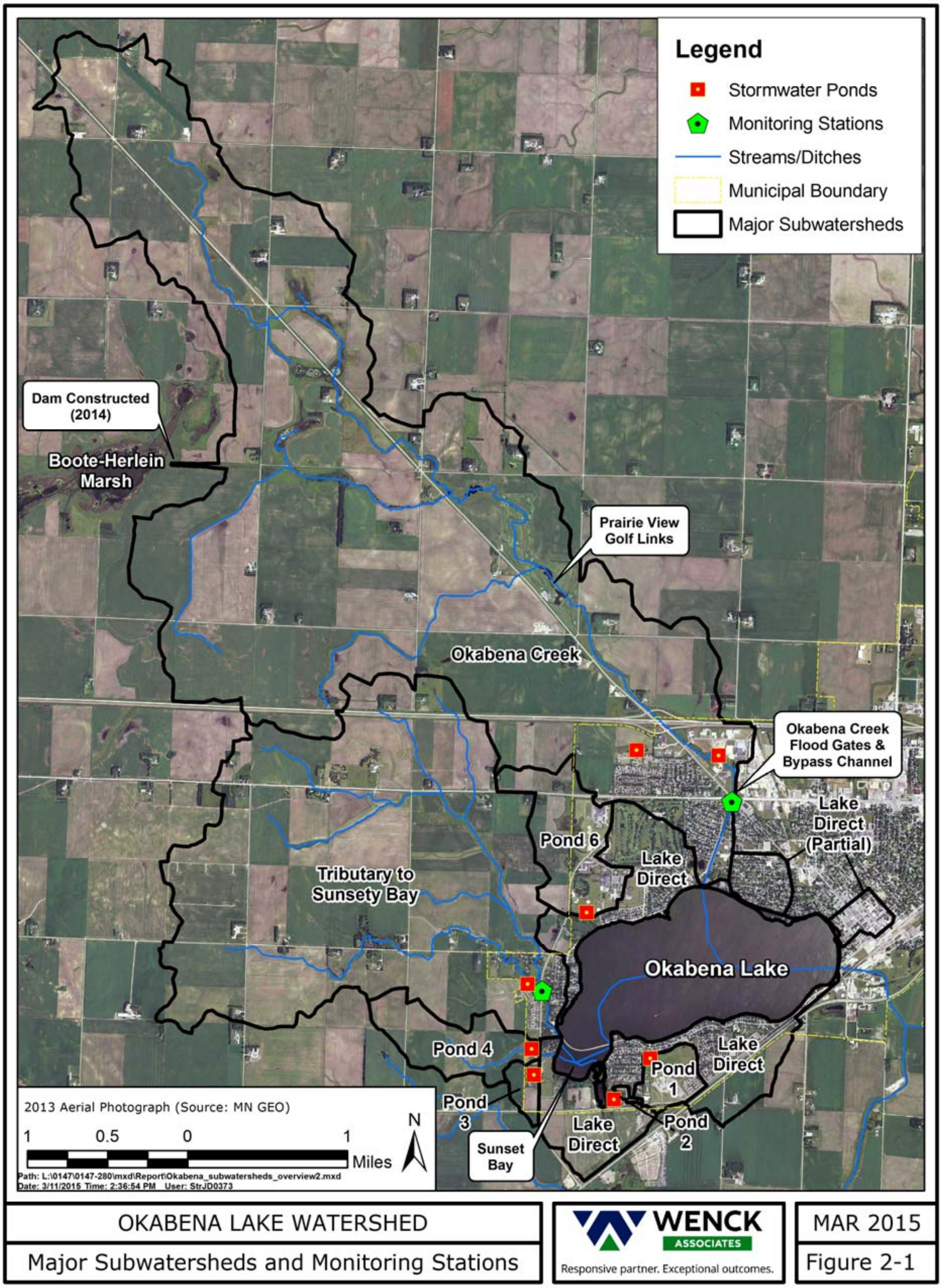


Figure 2-1. Okabena Lake watershed.

In the 1950's a U.S. Army Corp flood control project was completed to upgrade an existing flood diversion of Okabena Creek to Okabena Lake. The Army Corp project increased the capacity of the existing manmade diversion and established a fixed diversion of flows to Okabena Lake with a lesser portion of flows continuing to Okabena Creek (County Ditch 12). At a later date the City of Worthington added flood gates (Figure 2-3) to the Okabena Creek side of the diversion at Oxford Street to allow 100% of the Okabena Creek flow to be routed to Okabena Lake. It should be pointed out that the natural course for Okabena Creek is through Worthington then northeast toward Heron Lake. The portion of Okabena Creek between the Oxford Street flood gates and the lake is referred to as "Whiskey Ditch" and now provides for diversion to Okabena Lake. Historical maps show that the Okabena Lake outlet used to be located at the Whiskey Ditch inlet and flowed northeasterly toward Okabena Creek.

To the west there is a large tributary that drains mostly agricultural land and discharges into Sunset Bay. Sunset Bay is technically a part of Okabena Lake, however it likely acts as a settling basin since it is isolated from the main body of the lake by the South Shore Drive causeway. This basin likely provides some water quality treatment of the western tributary.

Figure 2-2. Okabena Creek ponds located at the Prairie View Golf Links (Image Source: Google Earth)

Figure 2-3. Okabena Creek bypass flood gates at Oxford Street.

2.2 OKABENA LAKE INFORMATION

2.2.1 Lake Morphometry

The Minnesota Department of Natural Resources (DNR) defines the littoral zone as areas of a lake less than 15 feet where light should be able to penetrate to the bottom and plant growth can be expected. With a maximum depth of about 16 feet and littoral area of 97%, Okabena Lake is considered a shallow lake by Minnesota rules and standards (Table 2-2). The lake has approximately 6.5 miles of shoreline that is completely developed. Okabena Lake has a moderate watershed to lake surface area ratio of 12:1 suggesting that the lake is likely sensitive to both external (watershed) and internal nutrient and pollutant sources.

Table 2-2. Physical Features of Okabena Lake.

Parameter	Result
Surface Area (acres)	776
Average Depth (ft)	6.6
Maximum Depth (ft)	16
Volume (acre-feet)	5,129
Littoral Area (acres)	752
Littoral Area (%)	97%
Watershed (acres)	9,437

2.2.2 Water Quality

Lake water quality is typically judged by assessing 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. Water clarity is also affected by the amount of total suspended sediment (TSS) in the water column. High TSS can be the result of excessive algae growth, but can also come from sediment re-suspension from the bottom of the lake caused by wind or fish activity. When lakes become hyper eutrophic (excess nutrients leading to heavy algae growth) or have high levels of TSS, the entire food web is affected. Changes are found in the algal, fish and aquatic plant communities, as well as the overall water quality, including depletion of dissolved oxygen. A healthy lake has good water clarity and a balanced growth of algae supporting the base of the food chain without degrading water quality or harming other biological organisms.

Under Minn. R. 7050.0150 and 7050.0222, subp. 4, Okabena Lake is a shallow lake located within the Western Corn Belt Plain (WCBP) Ecoregion with numeric water quality targets listed in Table 2-3. In addition to meeting phosphorus limits, chlorophyll-a and Secchi depth (water clarity) standards must also be met for the lake to be considered "fully supporting" its designated use. In developing the nutrient standards for Minnesota lakes (Minn. R. 7050), the MPCA evaluated data from a large cross-section of lakes within each of the state's ecoregions (MPCA, 2005). Relationships were established between the causal factor TP and the response variables chlorophyll-a and Secchi disk.

Table 2-3. Numeric standards for lakes in the WCBP Ecoregion.

Parameters	Western Corn Belt Plain Standards (Shallow Lakes[1])
Total Phosphorus (μg/L)	≤90
Chlorophyll-*a* (μg/L)	≤30
Secchi Disk Transparency (meters)	≥0.7

[1] Shallow lakes are defined as lakes with a maximum depth of 15 feet or less, or with 80% or more of the lake area shallow enough to support emergent and submerged rooted aquatic plants (littoral zone).

Lake water quality samples were collected by Okabena-Ocheda Watershed District staff since 1998. In general, lake monitoring was conducted one time per month from May through October for water clarity (Secchi depth), total phosphorus (TP), chlorophyll-*a* and TSS.

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.

As discussed previously, water clarity in shallow lakes is controlled by several factors including the amount of algae in the water column as well as other suspended particles caused by watershed loading, wind resuspension and bioturbation (such as carp). Since Okabena Lake is a large shallow lake, wind resuspension may be a significant driver of reduced clarity in areas where wind and wave action is able to reach the sediments and stir bottom particles into the water column.

Average summer growing season (June through September) Secchi depth has not met the 0.7 meter water quality standard for shallow lakes in the Western Corn Belt Plain (WCBP) ecoregion in 14 of 17 years since 1998 (Figure 2-4). During this time, mean summer values have ranged from 0.3 meters to 0.8 meters. Below is a more in-depth discussion of the primary factors causing poor water clarity in Okabena Lake, algae (chlorophyll-a) and TSS.

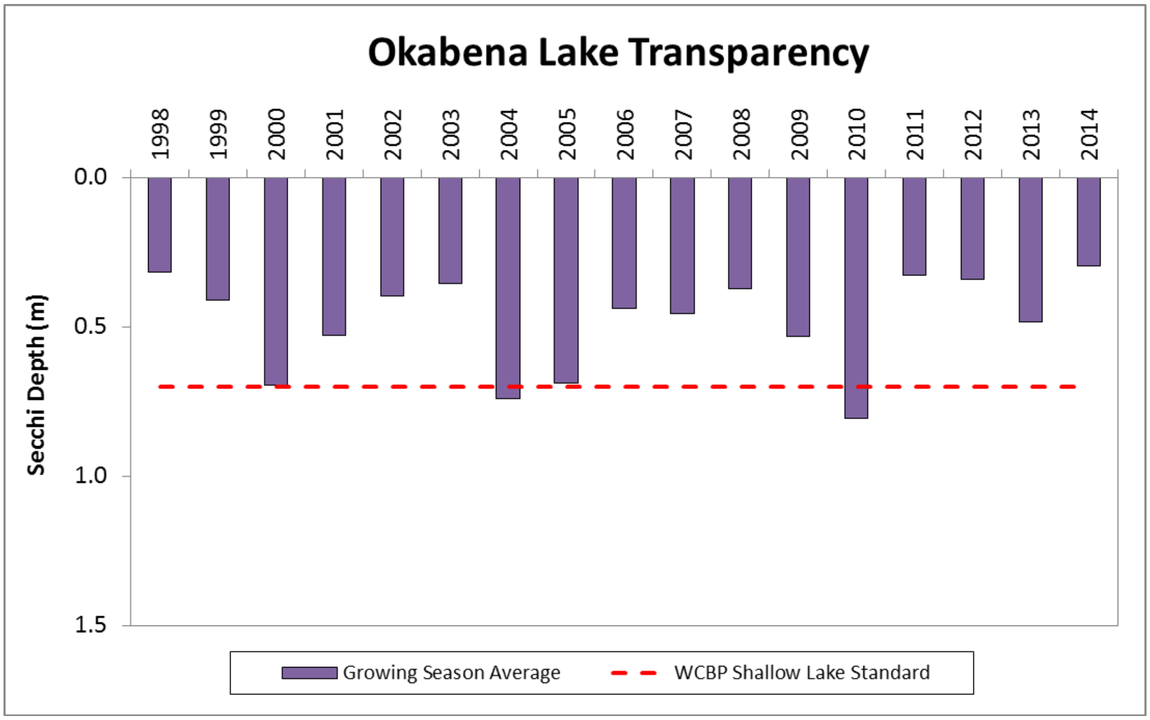


Figure 2-4. Summer average Secchi depth values for Okabena Lake.

Chlorophyll-a and Phosphorus

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. 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.

Okabena Lake summer growing season average TP concentrations have ranged from 91-307 µg/L. Average summer TP concentrations have exceeded the WCBP 90 µg/L shallow lake standard every year since 1998 (Figure 2-5). This suggests phosphorus levels are consistently high in Okabena Lake and available to support excessive algae growth. However, Figure 2-6 shows summer average chlorophyll-*a* concentrations in Okabena Lake have ranged from 6 µg/L to as high as 58 µg/L and have exceed WCBP shallow lake water quality standards in only 7 of 17 years since 1998. This indicates nuisance algae blooms do occur in Okabena Lake.

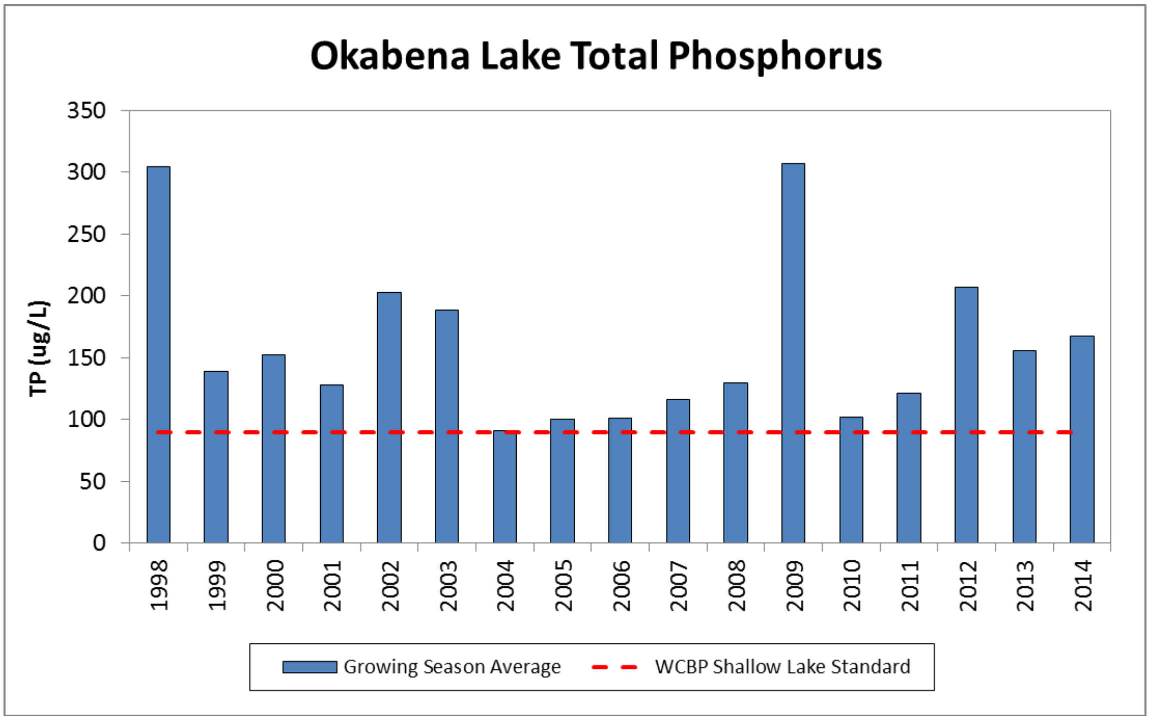


Figure 2-5. Summer average total phosphorus concentrations for Okabena Lake.

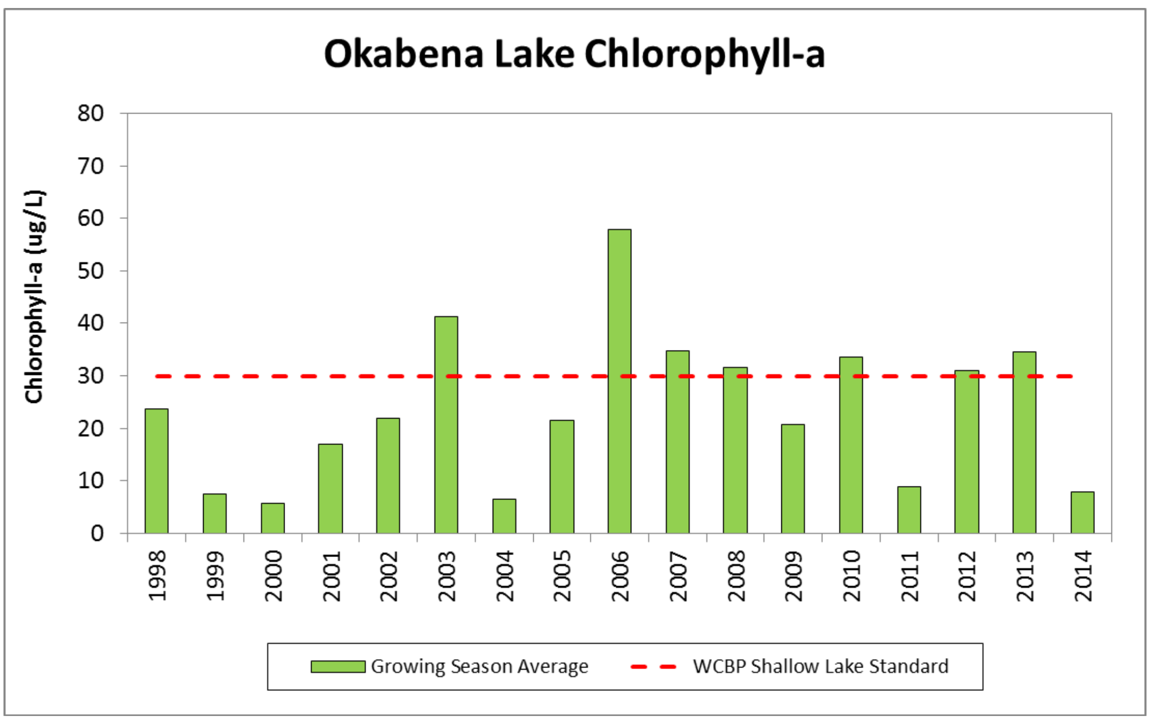


Figure 2-6. Summer average chlorophyll-*a* concentrations for Okabena Lake.

TSS

As discussed previously, TSS measured near the surface of the lake is typically driven by algal biomass and sediment re-suspension from the bottom of the lake. Okabena Lake is a shallow lake with very little submerged vegetation and a large surface area which leaves the lake vulnerable to sediment re-suspension during windy days. Summer average TSS in Okabena Lake has ranged from 9 mg/L to as high as 48 mg/L (Figure 2-7). Comparing Figures 2-4, 2-6 and 2-7 shows that in some years, such as 1999, 2011 and 2014, water clarity was poor even though chlorophyll-*a* levels were very low. In these years, TSS concentrations were high despite low chlorophyll-*a* indicating non-algal sources of turbidity. The high non-algal turbidity is likely a result of wind mixing and/or bioturbation. This suggests non-algal turbidty likely plays as big of a role as algae growth in affecting water clarity in Okabena Lake. Restoring water clarity in Okabena Lake will need to focus on decreasing in-lake sediment resuspension, as well as decreasing phosphorus loading and the potential for nuisance algae blooms. In order to reduce in-lake sediment resuspension, aquatic vegetation in Okabena Lake will need to be re-established. This will be a difficult process that may require drastic measures and in-lake management techniques.

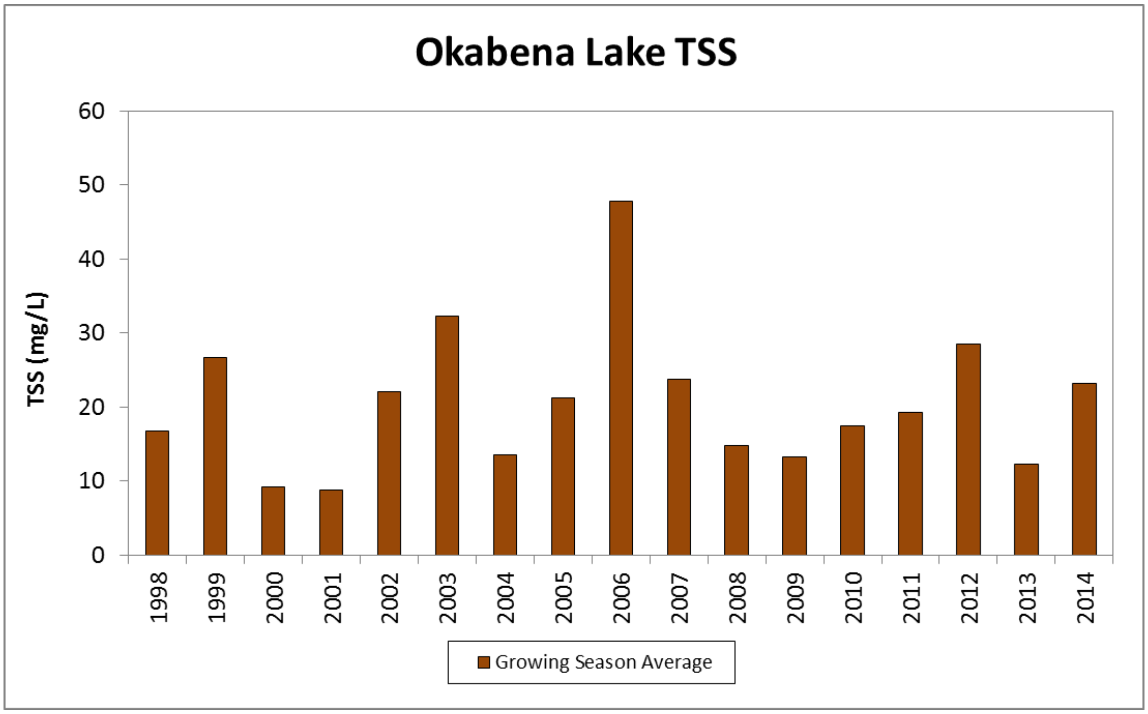


Figure 2-7. Summer average TSS concentrations for Okabena Lake.

3.0 Ecological Review

3.1 VEGETATION

To this point, no formal plant community surveys have been performed on Okabena Lake. Local knowledge has indicated Okabena Lake has very little submerged and emergent plant growth, particularly in late summer when water clarity is poor. With over 97% of the lake considered littoral (15 feet or less), most of Okabena Lake should be able to support aquatic vegetation as water clarity improves.

3.2 FISHERIES

Fish survey reports for Okabena Lake were provided by the DNR Area Fisheries Office in Windom, Minnesota. The first DNR fish survey conducted for Okabena Lake was performed in 1982. 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 Okabena Lake was summarized by trophic groups (Figures 3-1 and 3-2). Species within a trophic group serve the same ecological process in the lake (i.e., pan fish 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 pan fish, and in some years rough fish, are the most abundant species in Okabena Lake. Total biomass in Okabena Lake appears to shift year to year between top predators and rough fish, particularly common carp.

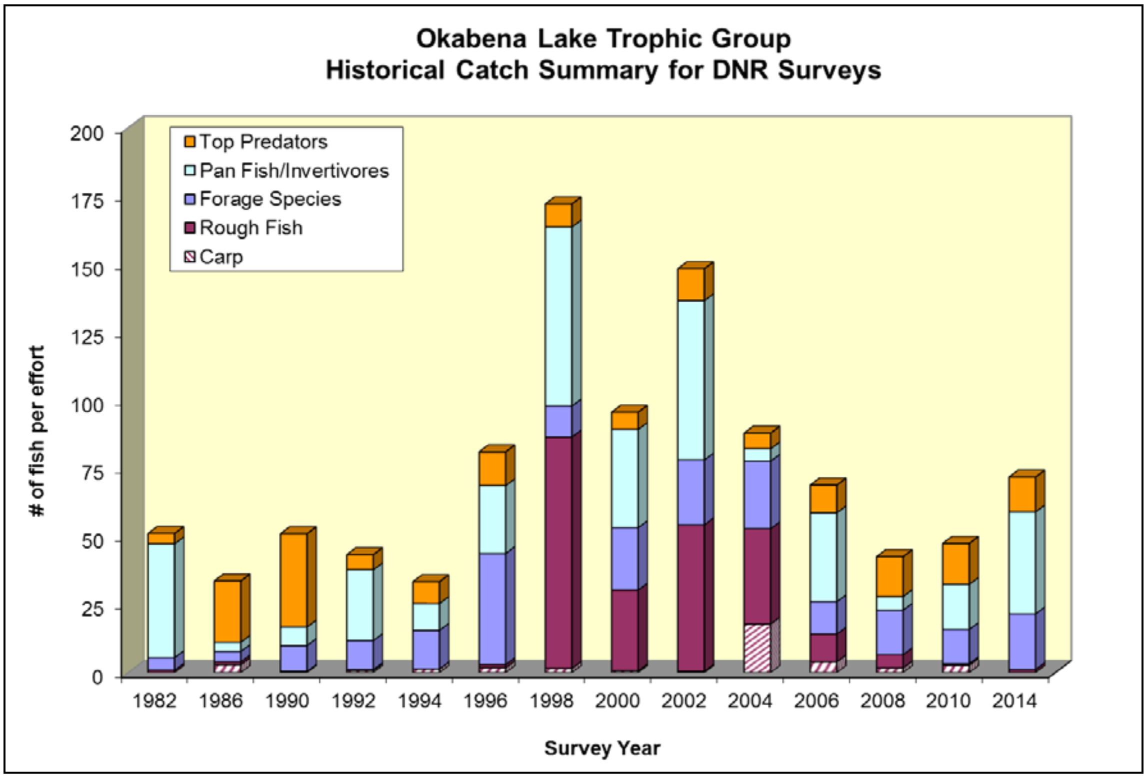


Figure 3-1. Trophic group abundance based on historic MN-DNR fish survey results.

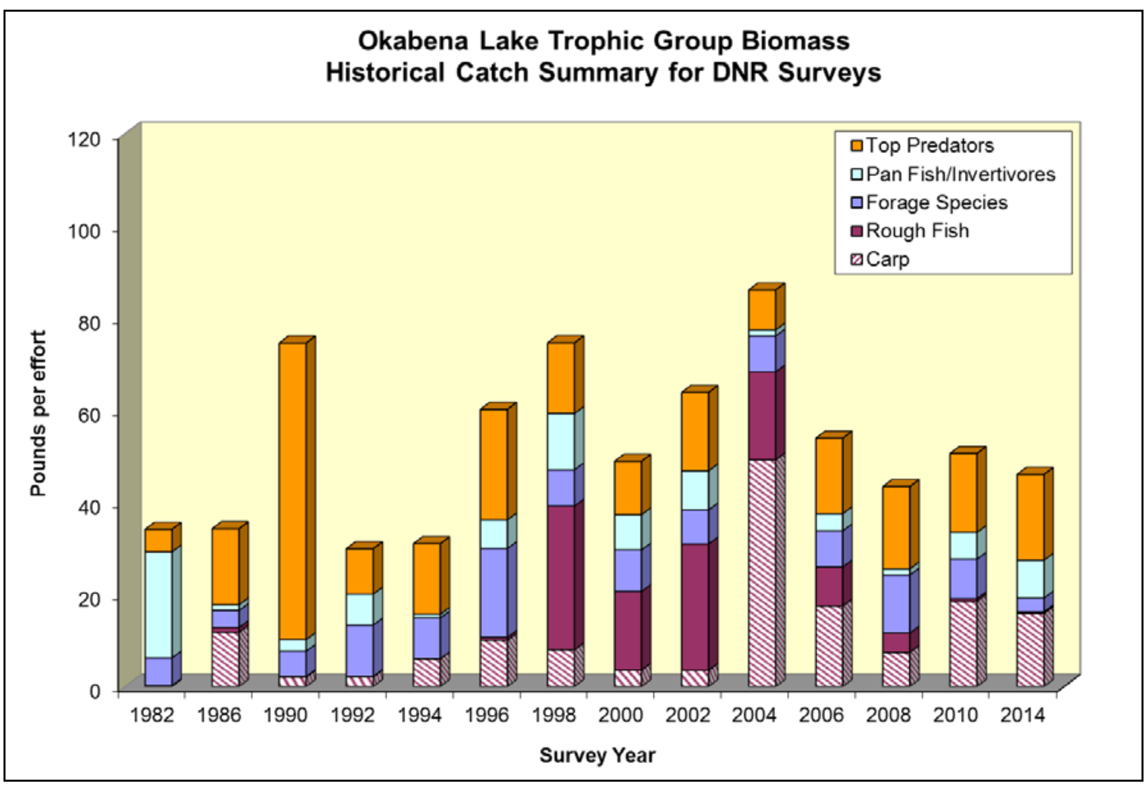


Figure 3-2. Trophic group biomass based on historic MN-DNR fish surveys

Common carp and other rough fish 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. During spring spawning, carp aggressively move into marshes, ponds, wetlands, and other shallow, winterkill prone basins that are connected to the main lake through small streams and waterways. These shallow basins are typically free of predators and therefore allow common carp a reproductive advantage. In lakes with a significant amount of carp, disrupting fish access to potential spawning areas by installing fish barriers and other structures can be effective in limiting reproduction and managing carp populations.

Common carp were present during every survey since 1986 and have typically accounted for a low percent of the total catch count (<1%-20%), but a significant portion of the total catch biomass (3% - 57%). This indicates there are a few large carp present in the lake and their overall presence and relative size could be a factor in the lake's water clarity and re-establishing the plant community. It is difficult to determine the level to which common carp are reproducing in Okabena Lake and its watershed. The Boote-Herlein Marsh may have been one potential common carp spawning habitat, however a dam was built at the outlet of the marsh in 2014 and it is no longer connected to Okabena Creek. Other potential spawning locations include the Okabena Creek ponds located at the Prairie View Golf Links (Figure 2-2) and a small, shallow backwater area connected to Sunset Bay on the southwest corner of the lake (Figure 3-3). There have been several attempts by commercial fisherman dating back to 1926 to harvest and remove carp and other fish, primarily buffalo, bullhead, sucker, and catfish from the lake. However, it is unclear what affect these attempts (Figure 3-4) have had on carp populations and biomass in Okabena Lake.

Figure 3-3. Potential common carp spawning habitat near Sunset Bay (Image Source: Google Earth).

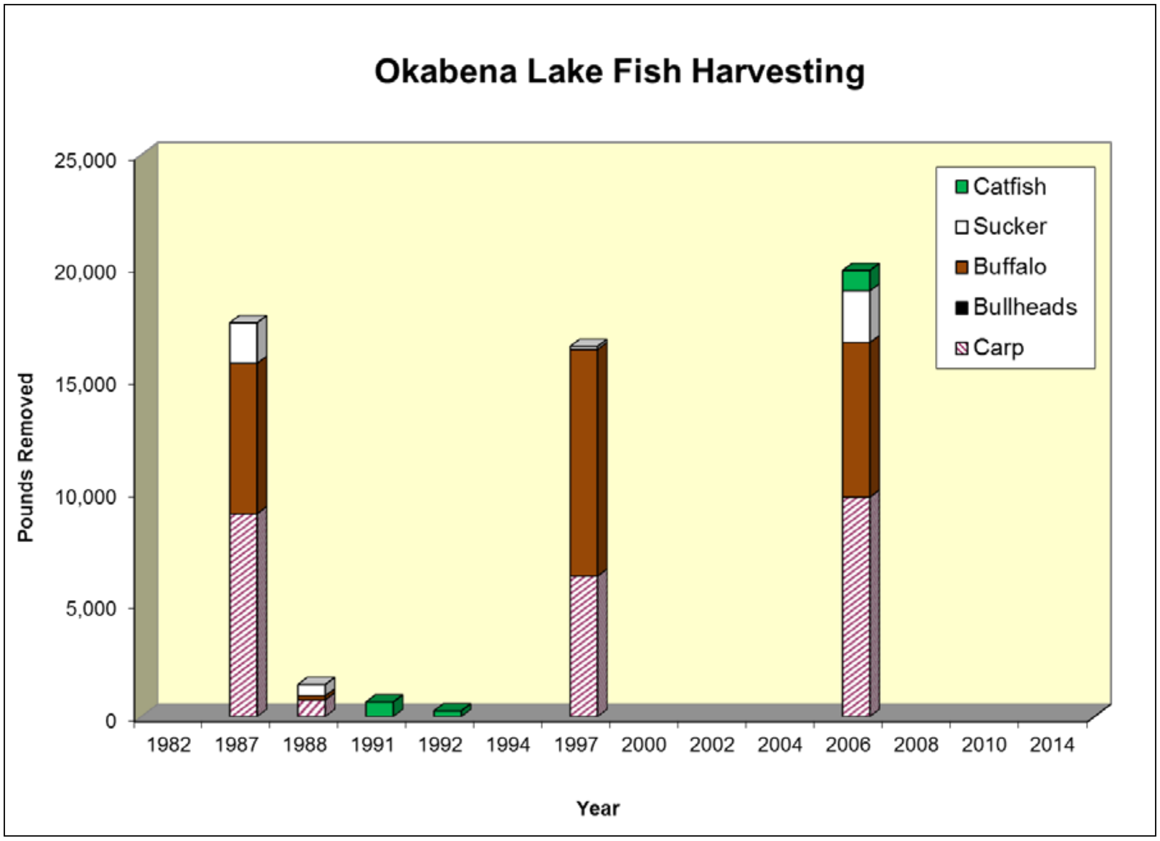


Figure 3-4. Okabena Lake fish harvesting since 1982.

4.0 External Source Assessment

4.1 INTRODUCTION

The primary purpose of this study is to develop a detailed sediment and phosphorus source assessment for Okabena Lake to better understand what is driving lake water quality. Sediment and phosphorus loading to lakes may come from external sources, as well as in-lake sources. This section examines the external sources of sediment and phosphorus to Okabena Lake including dry and wet deposition, and watershed runoff from the urban and rural portions of the watershed.

4.2 LAKE SURFACE DEPOSITION

4.2.1 Dry Deposition

Studies have shown deposition of wind-blown sediment, also referred to as dry deposition, can represent a significant proportion of a lake's total sediment and nutrient load. Dry deposition of sediment and phosphorus are often equal to, and in many cases greater than the sediment and phosphorus delivered from rainwater (wet deposition) via direct precipitation (Hicks et al, 1993). Wind erosion from human activities are often the biggest sources of wind-blown sediment. Some of these include: mining operations, agricultural practices, unpaved roads, aggregate storage piles and heavy construction activities. Depending on wind speed and soil particle size, wind-blown sediment from these sources may travel great distances before being deposited. Land cover in the 5 mile radius surrounding Okabena Lake is dominated by agriculture (85%), suggesting dry deposition of sediment and phosphorus on the lake is likely driven by farming practices. Studies in other agricultural regions have shown strong seasonal patterns of sediment and phosphorus deposition, with highest depositional rates coinciding with spring (April-June) and fall (October-November) planting and harvesting operations (Anderson and Downing, 2006; Cassel et al, 2000).

Estimating the amount of sediment and phosphorus that settles out and is deposited on land and water surfaces is a complex and poorly understood process. To do this for Okabena Lake, literature rates and methodology set forth in an MPCA report (Barr Engineering, 2007) were used that estimate dry deposition throughout different regions of Minnesota (Appendix A). Results of this analysis suggest average annual dry deposition of wind-blown sediment to Okabena Lake is approximately 195.6 tons per year, and dry deposition of phosphorus is 199 pounds per year (Table 4-1). These loading rates are moderately high, but are within the typical range for lakes in southwest Minnesota and agricultural areas throughout the Midwest (Anderson and Downing, 2006; Barr Engineering, 2007).

High potential wind erosion areas near Okabena Lake were identified using the Wind Erosion Prediction System (WEPS) model. WEPS is a process-based, daily time-step model that simulates weather, field conditions, and wind erosion. The model was designed by a multi-agency team of experts and is intended to provide users a tool for inputting initial field conditions to calculate soil loss for conservation planning and designing erosion control systems. WEPS model setup and assumptions for the 5 mile area surrounding Okabena Lake are presented in Appendix A. Model output results indicate wind-blown sediment losses from soybean fields near Okabena Lake ranged from 2.8 to 6.6 tons per acre per year, and were consistently higher than corn fields (1.2 – 3.6 tons per acre per year). Overall, approximately 2.8 tons per acre per year of sediment is potentially lost to wind erosion from the agricultural fields within 5 miles of Okabena Lake. This rate is also moderately high, but is within typical ranges estimated by the Natural Resources Conservation Service (NRCS) for cropland in southwestern Minnesota and other agricultural regions (NRCS, 2000). A map showing potential wind-blown sediment erosion hotspots near Okabena Lake is presented in Appendix A.

4.2.2 Wet Deposition

Wet deposition refers to the amount of sediment and phosphorus delivered to the surface of a lake from direct precipitation. Since phosphorus in rainwater has not been directly measured in or around the Okabena Lake watershed, it was calculated using a regression relationship between calcium and phosphorus concentrations in rainwater developed by the MPCA for Minnesota monitoring stations (Appendix A; Swain, 2003; Barr Engineering, 2007). Applying this regression to Okabena Lake estimates average annual wet deposition of phosphorus to the lake is 185.4 pounds per year, which is approximately 48% of the total dry+wet phosphorus deposition (Table 4-1). It was assumed sediment (TSS) concentrations in rainfall are small and any deposition of sediment during storm events is accounted for in the estimates for dry deposition.

4.2.3 Summary of Wet and Dry Deposition

Table 4-1 summarizes average annual TSS and TP to Okabena Lake from dry deposition and wet deposition sources. Since wind-blown sediment can travel great distances before being deposited, these sources will be difficult to control for Okabena Lake. That said, results of the WEPS model did identify several high potential wind erosion areas near Okabena Lake (Figure A-1 in Appendix A). These areas could be targeted for wind-erosion BMPs such as installing wind breaks/barriers, cover crops, creating soil ridges, and increasing crop residue through conservation tillage. Wet deposition of phosphorus is extremely difficult if not impossible to control and therefore no actions are suggested to manage these sources.

Table 4-1. Dry and wet deposition of sediment and phosphorus on Okabena Lake.

Parameter	Deposition Type	Average Areal Deposition Rate	Average Annual Deposition to Okabena Lake
Sediment (TSS)	dry	0.252 tons/acre/year	195.6 tons/year
Sediment (TSS)	wet	Assumed small or negligible	
Phosphorus (TP)	wet	0.239 lbs/acre/year	185.4 lbs/year
Phosphorus (TP)	dry	0.255 lbs/acre/year	197.9 lbs/year

4.3 WATERSHED SOURCES

Sediment and phosphorus transported by urban stormwater and agricultural runoff represents some of the largest external contributors of these pollutants to surface waters in Minnesota. Ditching through crop and pasture land and storm sewer systems in urban areas improve the efficiency of runoff, sediment and phosphorus moving to streams, wetlands and lakes. Sediment and phosphorus in runoff is a result of leaves and grass clippings, pet waste, excessive lawn watering, automobiles, illicit sanitary sewer connections, crop residue, field erosion, manure and fertilizers, and failing septic systems. The following sections describe the modeling and monitoring data used to estimate watershed runoff, sediment and phosphorus loading to Okabena Lake from urban and rural portions of the watershed.

4.3.1 Urban Sources

Urban land within Worthington's city limits accounts for approximately 15% of Okabena Lake's total watershed area. A P8 model (Program for Predicting Polluting Particles Passage thru Pits, Puddles & Ponds; Walker, 1996) was developed to estimate watershed loading from the City of Worthington. P8 is a public domain (http://wwwalker.net/p8/) industry standard model developed to assess pollutant loading in urban watersheds. P8 was developed using National Urban Runoff Program (NURP) data and provides loading estimates based on data collected as part of the NURP program. The model estimates the build-up and wash-off of particulates from impervious surfaces in the watershed. The NURP 50th percentile particle file was used to estimate watershed pollutant loading for the City of Worthington portion of the Okabena Lake watershed. The P8 model was also setup and used to estimate watershed loading from the rural (non-city) portions of the watersheds. Section 4.4.3 provides a summary and discussion of the rural portion of the P8 model. All inputs, assumptions, and calibration adjustments for the Okabena Lake watershed P8 model are presented in Appendix B.

The City of Worthington P8 model was developed for the most recent ten years (2005-2014) in which lake water quality was monitored. The model predicts 10-year average annual runoff volume, TSS load and TP load for the City of Worthington portion of each major subwatershed (Table 4-2). Appendix B also contains maps showing average annual TSS and TP loading rates by subwatershed. Results indicate the overall load contribution from the City of Worthington is relatively small compared to the rural portion of the watershed. Approximately 20% of the runoff from the City of Worthington is treated by one of eight city stormwater ponds before it enters the lake. Model output suggests these ponds perform relatively well in reducing sediment and phosphorus loads from these portions of the watershed. Currently, runoff from the Lake Direct, Lake Direct (Partial), and portions of the Okabena Creek and Sunset Bay Tributary subwatersheds is not retained or treated by any of the city stormwater ponds before entering the lake. In general, these subwatersheds exhibited higher areal TSS and TP loading rates (Table 4-2 and Appendix B).

Table 4-2. Model predicted average annual flow, TSS and TP loads for the City of Worthington portion of the Okabena Lake watershed.

Subwatershed	City Portion (acres)	Flow (acre-ft/yr)	TSS Load		TP Load	
			tons/yr	tons/acre/yr	lbs/yr	lbs/acre/yr
Pond 1	80	45	2.3	0.03	25.1	0.31
Pond 2	7	3	<0.1	0.01	1.1	0.16
Pond 3	18	7	0.4	0.02	5.4	0.30
Pond 4	8	2	0.3	0.03	2.3	0.29
Pond 6	130	79	2.6	0.02	39.2	0.30
Okabena Creek	438	257	39.0	0.09	218.7	0.50
Sunset Bay Tributary	112	44	6.8	0.06	42.3	0.38
Lake Direct (Partial)	126	60	9.4	0.07	48.4	0.38
Lake Direct	520	260	40.0	0.08	215.6	0.41
Totals	**1,439**	**757**	**100.8**	**0.07**	**598.1**	**0.42**

4.3.2 Rural Sources

4.3.2.1 Watershed Monitoring and Modeling

In 2014, Okabena-Ocheda Watershed District staff collected periodic gauged flow measurements and water quality grab samples in Okabena Creek and the Sunset Bay tributary. The monitoring station locations are shown in Figure 2-1 and were selected to characterize the flow and water quality coming from the rural portions of the Okabena Lake watershed. Water quality samples were analyzed for TP, ortho-P, TSS and Volatile Suspended Solids (VSS). Appendix C provides a detailed description of the 2014 sampling results for each monitoring station.

Figures 4-1 and 4-2 show the 2014 TSS and TP sampling results for both monitoring stations and how they relate to average daily flow. Results indicate TSS and TP levels were low and below proposed state standards (TP = 150 ug/L; TSS = 65 mg/L) when stream flow was less than 5 cubic feet per second (cfs). A series of large storm events between June 14 and June 28 delivered over 7 inches of rainfall – about 32% of the total precipitation recorded at the Worthington Municipal Airport in 2014. During this time period, stream flow went from less than 5 cfs to well over 100 cfs in Okabena Creek and the Sunset Bay tributary. Also during this time TSS and TP measurements were very high and well above proposed state standards at both monitoring stations.

TSS, TP and ortho-P loads for 2014 were estimated by calculating each parameter's monitored flow-weighted mean (FWM) concentration and multiplying this by the total annual flow volume. The 2014 FWMs and loading calculations for Okabena Creek and the Sunset Bay Tributary are presented in Appendices B and C. These estimates were used to adjust and calibrate the rural portion of the Okabena watershed P8 model. The TP and ortho-P loading results indicate that only 19%-28% of the TP load from the rural portion of the watershed is in dissolved form (ortho-P). This suggests a majority of the phosphorus delivered to Okabena Lake is in particulate form, likely attached to soil and TSS particles. Thus, targeting BMPs to decrease sediment loading from rural areas should have a significant impact on TP loading as well. Overall, the 2014 loading estimates show that between 56% and 73% of the total flow, TSS load and TP load from Okabena Creek and the Sunset Bay Tributary came during the two week high flow event in late June. This indicates flow and pollutant loading from the rural portions of the watershed are event driven and very sensitive to large, early season storm events.

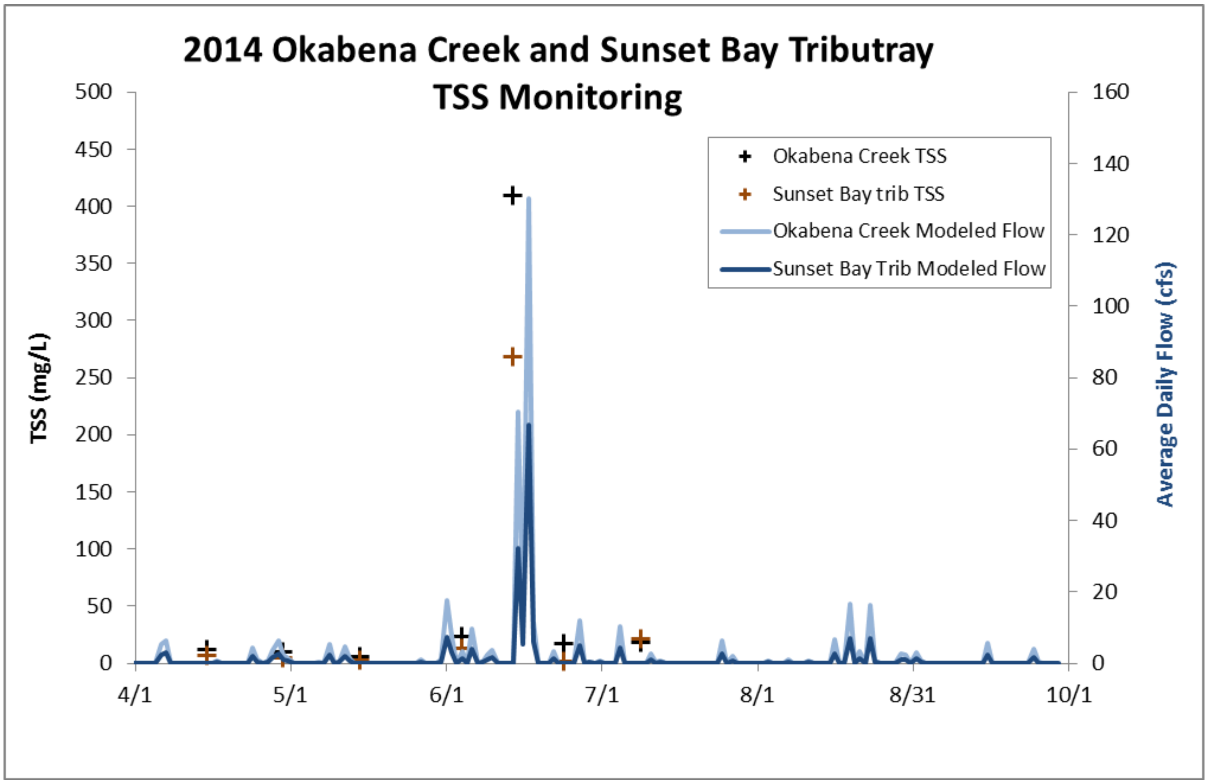


Figure 4-1. Stream TSS monitoring results for 2014.

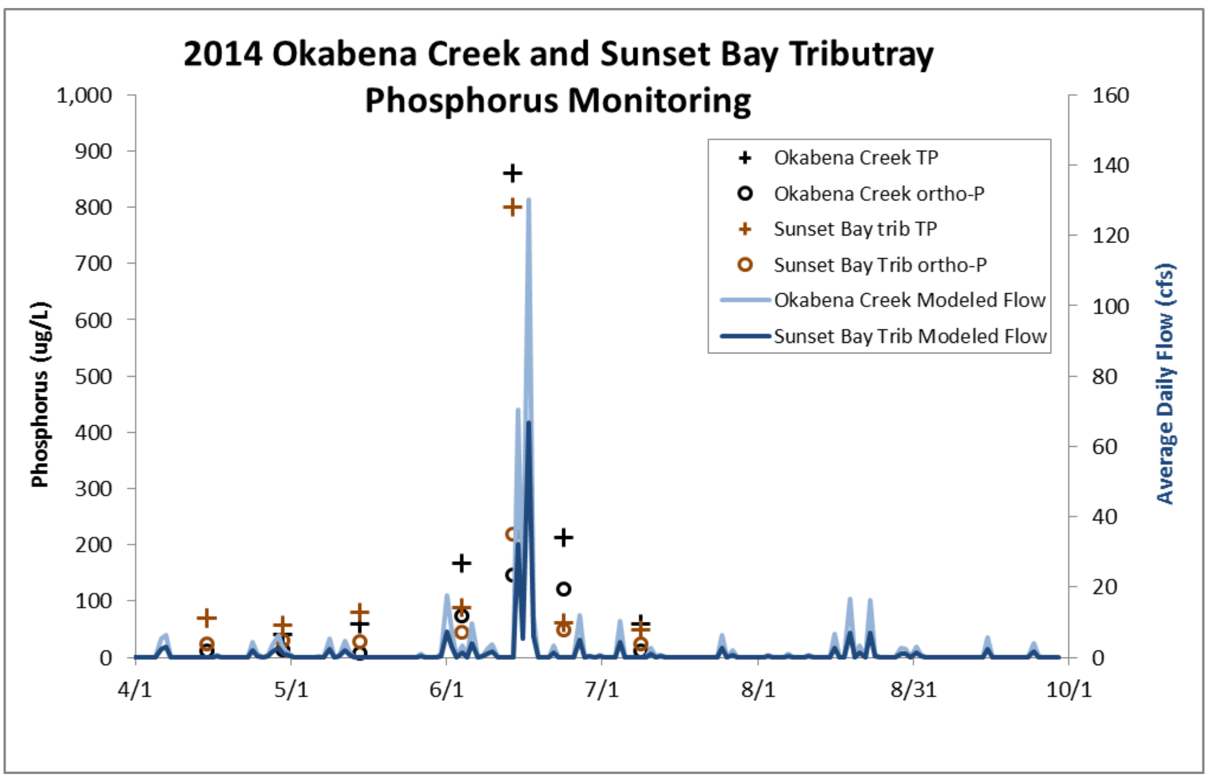


Figure 4-2. Stream TP and ortho-P monitoring results for 2014.

The 2014 monitoring data was used in conjunction with the P8 model to estimate average annual flow, TSS and TP loading from the rural portions of the Okabena Lake watershed. Appendix B provides a complete discussion of the model inputs, assumptions and loading adjustments used for the rural portion of the P8 model. Similar to the urban portion of the model, the rural P8 model was setup and run for the most recent ten years (2005-2014) in which lake water quality was monitored. The model predicted 10-year average annual runoff volume, TSS load and TP load for the rural portion of each major subwatershed are presented in Table 4-3. Appendix B also contains maps showing average annual TSS and TP loading rates by subwatershed.

Model results suggest the total flow, sediment and phosphorus loads from rural areas are significantly greater than loads from the urban portion of the watershed. Overall, approximately 88% of the watershed TSS load comes from rural areas, while city stormwater accounts for 12% of the TSS load. Similarly, 89% and 11% of the watershed TP load comes from rural and city runoff, respectively. Subwatershed loading analyses indicate a majority of the rural watershed TSS and TP load comes from Okabena Creek (61%) and the Sunset Bay Tributary (34%).

Areal loading rates were highest in the Okabena Creek, Sunset Bay Tributary, and Lake Direct subwatersheds. Loading rates for the rural portions of the watershed that flow to city stormwater ponds (Pond 1-4 and 6) were slightly less depending on subwatershed size and treatment efficiency of the pond.

Table 4-3. Model predicted average annual flow, TSS and TP loads for the rural portion of the Okabena Lake watershed.

Subwatershed	Rural Portion (acres)	Flow (acre-ft/yr)	TSS Load		TP Load	
			tons/yr	tons/acre/yr	lbs/yr	lbs/acre/yr
Pond 1	<1	1	<0.1	0.03	0.3	0.30
Pond 2*	--	--	--	--	--	--
Pond 3	22	6	0.7	0.03	11.2	0.51
Pond 4	200	53	13.5	0.07	135.5	0.68
Pond 6	149	42	3.1	0.02	57.9	0.39
Okabena Creek	4,868	1,397	472.1	0.10	3,026.5	0.62
Sunset Bay Tributary	2,517	718	259.6	0.10	1,706.4	0.68
Lake Direct (Partial)*	--	--	--	--	--	--
Lake Direct	241	71	23.3	0.10	148.3	0.62
Totals	**7,998**	**2,288**	**772.3**	**0.10**	**5,086.1**	**0.64**

* These subwatersheds do not contain any land outside the City of Worthington municipal boundary

The following sections are intended to provide a better understanding of potential loading from animal agriculture, upland field erosion, and streambank erosion throughout the rural portions of the Okabena Lake watershed.

4.3.2.2 Animal Agriculture

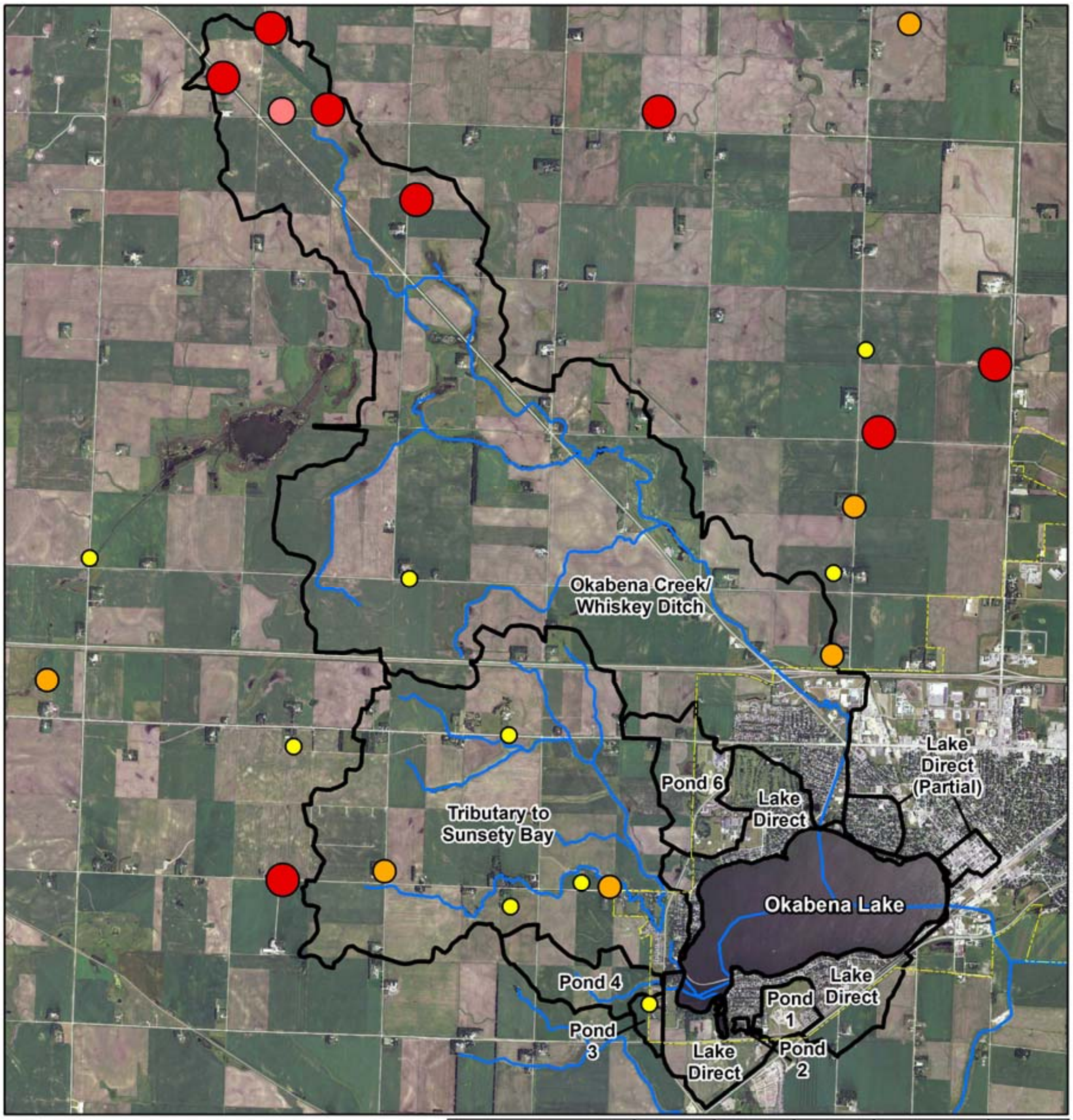
To assess the relative role of manure management on surface water nutrient concentrations and loads, an inventory of all registered agricultural animals in the Okabena Lake watershed was conducted. The MPCA maintains a statewide GIS database of registered feedlots throughout the state of Minnesota. The MPCA categorizes feedlots based on the number of registered animal units, which are the standardized measurement of animals for various agricultural purposes. Figure 4-3 shows all registered feedlots in the Okabena Lake watershed.

There are currently 12 registered feedlot operations and more than 2,700 total animal units throughout the Okabena Lake watershed. It should be pointed out that these numbers reflect each operator's permitted limit, and local knowledge has indicated some of these operations are not currently operating at full capacity. There are several large feedlot operations located just outside the Okabena Lake watershed boundary. A feedlot owner is required to apply for an National Pollutant Discharge Elimination System (NPDES) feedlot permit when a new or expanding facility will have a capacity of 1,000 animal units or more; or if it meets or exceeds the EPA Large Concentrated Animal Feedlot Operation (CAFO) threshold. There is currently one NPDES permitted feedlot operation in the Okabena Lake watershed. This operation contains approximately 3,000 pigs (900 animal units) and is located in the northern portion of the Okabena Creek subwatershed. There are several smaller, non-NPDES registered feedlot operations located throughout the watershed, mostly in the Okabena Creek and Sunset Bay tributary sub watersheds (Figure 4-3). Three operations alone in the Okabena Creek subwatershed account for over 83% of the animal units throughout the watershed.

Manure produced by the animals in the watershed is typically deposited on pasture lands and/or applied to fields for fertilizer as well as general manure management. Manure that is applied to fields during sensitive portions of the year or beyond the nutrient uptake ability of the crops may move easily into the surface waters adding to eutrophication and nutrient loads.

Total mass of phosphorus produced by each animal unit category can be estimated using literature values (Evans et al 2002). Based on these estimates, over 300,000 pounds of phosphorus are potentially applied to land in the form of manure throughout the Okabena Lake watershed (Table 4-4). To put this in perspective, average annual watershed loading to Okabena Lake from rural areas throughout the watershed is typically around 5,086 pounds or approximately 2% of the phosphorus potentially applied to the land throughout the watershed. Only a small proportion of this phosphorus need make its way to the lake to cause serious eutrophication issues.

The Okabena Lake watershed P8 model does not explicitly model phosphorus contributions from manure spreading. The model does, however, implicitly account for animal contributions by calibrating to water quality data collected at the Okabena Creek and Sunset Bay tributary monitoring locations. The watersheds draining to these sites are the largest surface inflows to Okabena Lake and should be representative of the surrounding non-monitored watersheds assuming manure practices are similar and spreading occurs close to where the animals are contained.



Subwatershed	Bovines	Swine	Horses	Goat/Sheep	Total
Pond 1	--	--	--	--	--
Pond 2	--	--	--	--	--
Pond 3	--	--	--	5	5
Pond 4	--	--	--	--	--
Pond 6	--	--	--	--	--
Okabena Creek	185	2,327	--	--	2,512
Sunset Bay Tributary	92	90	5	--	187
Lake Direct (Partial)	--	--	--	--	--
Lake Direct	--	--	--	--	--
Total	**277**	**2,417**	**5**	**5**	**2,704**

OKABENA LAKE WATERSHED

MPCA Registered Feedlots

WENCK ASSOCIATES
Responsive partner. Exceptional outcomes.

MAR 2015

Figure 4-3

Figure 4-3. MPCA registered feedlots and animal units in the Okabena Lake watershed.

Table 4-4. Agriculture animal phosphorus production by subwatershed.

Subwatershed	Agriculture Land (acres)	Total P (lbs/year)	Total P (lbs/acre/yr)
Pond 1	46	--	--
Pond 2	1	--	--
Pond 3	29	361	12.4
Pond 4	199	--	--
Pond 6	169	--	--
Okabena Creek	4,266	293,768	68.9
Sunset Bay Tributary	2,346	17,794	7.6
Lake Direct (Partial)	<1	--	--
Lake Direct	257	--	--
Total	**7,313**	**311,923**	**42.7**

4.3.3 Field Erosion

Average upland soil loss for the rural portions of the Okabena Lake watershed was modeled using the Revised Universal Soil Loss Equation (RUSLE). This model provides an assessment of existing soil loss from upland sources and the potential to assess sediment loading through the application of Best Management Practices (BMPs). RUSLE predicts the long term average annual rate of erosion on a field slope based on rainfall pattern, soil type, topography, land use and management practices. A description of RUSLE model setup and adjustments is provided in Appendix D. Model results predict a watershed-wide gross average annual soil loss of 3,273.4 tons per year (Table 4-5). While this is a significant amount, much of the soil loss occurring on the fields is not fully transported off site to the stream channels as it is trapped by buffers, ditches ponds and wetlands throughout the watershed. Since RUSLE does not take these factors into account, a sediment delivery ratio (Appendix D) was used to estimate the amount of upland soil loss delivered downstream. After applying this factor, it is estimated about 21% of the gross soil loss, or 700.8 tons is delivered and transported downstream. This value represents approximately 91% of the average annual sediment load from rural areas predicted by the P8 model (772.3 tons/year). Results show Okabena Creek and the Sunset Bay Tributary are responsible for a majority of the TSS delivered to Okabena Lake from field erosion (Table 4-5). However, areal loading rates indicate potential soil loss is also high in the Pond 4 subwatershed. Figure 4-4 shows several modeled erosion hotspots where potential field erosion is greater than 3 tons/acre/year. These hotspots, particularly those in the Okabena Creek and Sunset Bay Tributary subwatersheds, could be targeted to reduce/minimize soil loss. Possible BMPs include increased buffers, grassed waterways, conservation and/or contour tillage, cover crops, and water and sediment control basins.

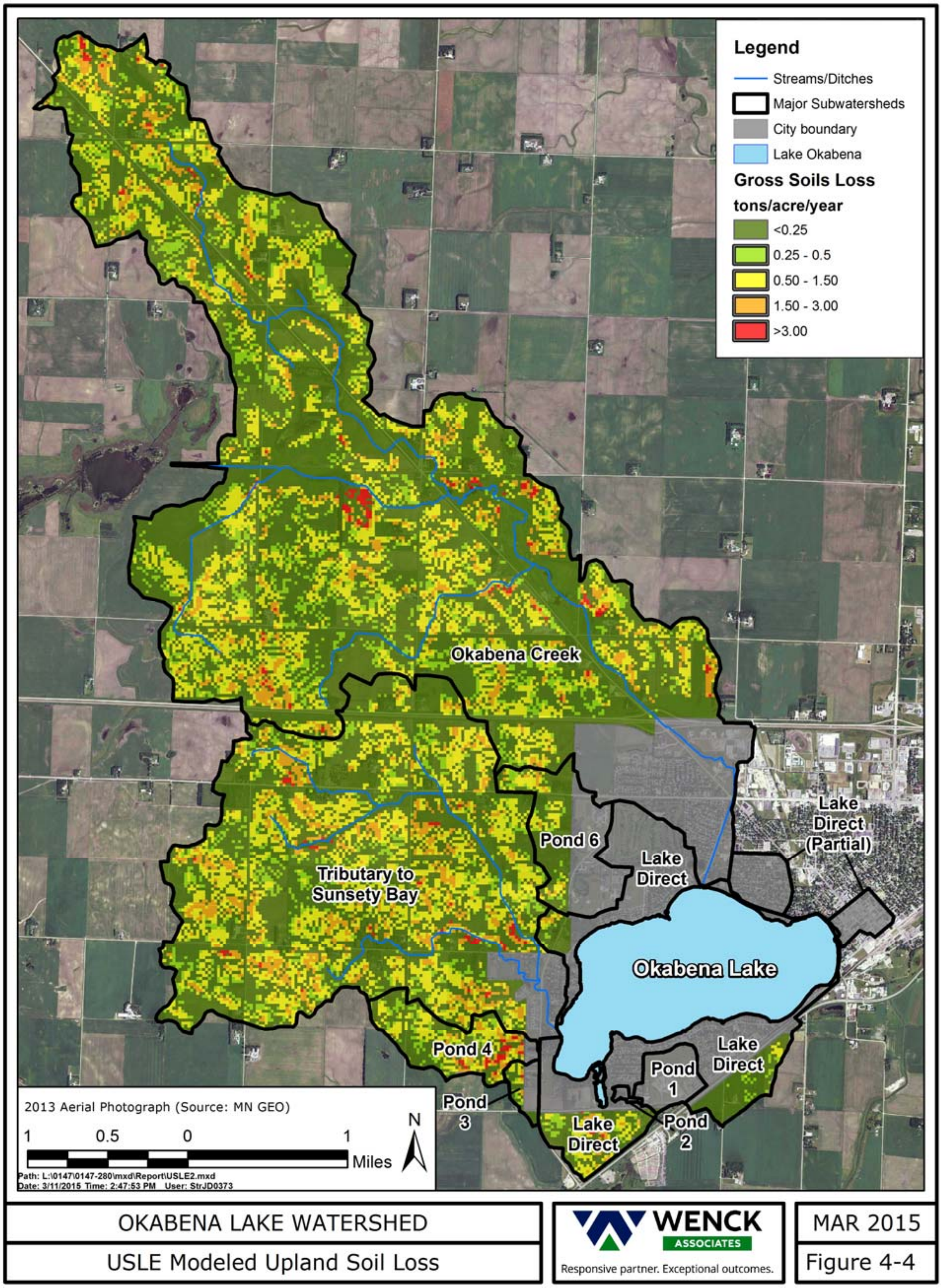


Figure 4-4. Potential rural upland soil loss in the Okabena Lake Watershed.

Table 4-5. Potential soil loss by subwatershed.

Watershed	Rural Portion (acres)	Gross Soil Loss (tons/acre/yr)	Gross Soil Loss (tons/yr)	Soil Loss Delivered to Streams (tons/yr)
Pond 1	<1	<.01	<0.1	<0.1
Pond 2*	--	--	--	--
Pond 3	22	0.37	7.9	2.2
Pond 4	200	0.66	132.0	36.1
Pond 6	149	0.25	37.5	4.1
Okabena Creek	4,868	0.37	1,804.2	334.8
Sunset Bay Tributary	2,517	0.48	1,215.1	278.8
Lake Direct (Partial)*	--	--	--	--
Lake Direct	241	0.32	76.7	44.8
Totals	**7,998**	**0.41**	**3,273.4**	**700.8**

* These subwatersheds do not contain any land outside the City of Worthington municipal boundary

4.3.4 Stream Bank Erosion

Land cover changes in the riparian zone may weaken stream banks by reducing or eliminating long-rooted native vegetation that strengthens and stabilizes the banks. Changes in flow regime may also destabilize stream banks that are exposed to prolonged periods of wetting or wet-dry cycles. A streambank assessment was performed by Okabena-Ocheda Watershed District staff to assess bank conditions as a potential source of sediment to Okabena Lake. Okabena Creek and the major tributary to Sunset Bay were walked, and erosion features were noted and measured (Appendix D).

Streambank conditions were variable, with some banks relatively stable, and others with moderate amounts of slumping and sloughing, especially on outer bends. Along Okabena Creek, the sections demonstrating significant bank erosion were located between Oxford Street and the Prairie View Golf Links (Appendix D). This section of Okabena Creek is situated downstream of the golf course's in-channel treatment ponds and is relatively buffered with some small meanders and channel sinuosity. Upstream of Prairie View Golf Links, Okabena Creek becomes more intermittent and flows through a series of ponded areas and gently sloped ditches buffered by tall grasses and emergent wetland vegetation. This section of Okabena Creek is relatively straight with very few sharp bends that often lead to unstable banks. No major bank erosion features were noted in the upper portions of Okabena Creek during the 2013 survey.

In general, the major tributary to Sunset Bay displays very little streambank erosion. The only section demonstrating significant bank erosion was the tributary's south branch between 260th Street and Oliver Avenue (Appendix D). Similar to Okabena Creek, most of the upper portions of this tributary are comprised of relatively straight, gently sloped ditches or grass waterways that receive intermittent flow.

Stream bottom sediments ranged from very fine muck to small gravel, often within the same sub reach. Some aggradation, deposition, and braiding were observed on the stream walking survey, particularly in areas with either bank sloughing or mass wasting. To evaluate whether soil loss from streambank erosion may be contributing significantly to sediment load, Okabena Creek and the tributary to Sunset Bay were evaluated for stability and amount of observed soil loss. Average annual soil loss for Okabena Creek and the Sunset Bay tributary were estimated using a method developed by the Natural Resources Conservation Service referred to as the “NRCS Direct Volume Method,” or the “Wisconsin method,” (Wisconsin NRCS 2003). Description of this method and how it was applied to Okabena Creek and the Sunset Bay tributary is discussed in more detail in Appendix D.

During the stream bank survey, watershed district staff noted and measured 15 bank erosion “problem areas” along Okabena Creek, and 4 problem areas along the Sunset Bay tributary (Appendix D). Using the Wisconsin Method, it was estimated these problem areas contribute approximately 31.1 tons of sediment per year to the stream channels. This value is relatively small compared to field erosion (700.8 tons/year) and only about 4% of the average annual sediment load from rural areas predicted by the P8 model (772.3 tons/year). Streams do experience some sediment loss each year from natural processes. According to the Wisconsin NRCS and based on their surveys of a number of streams throughout Wisconsin, a stream that is relatively undisturbed and at low risk for erosion typically experiences lateral recession of 0.01-0.05 feet per year. Therefore, it was assumed the remaining sediment load after the field erosion and problem area bank erosion estimates were subtracted from the total rural sediment load represents “natural background” stream bank erosion. Thus, about 57% (40.4 tons per year) of the sediment load delivered from the stream banks throughout the Okabena Lake watershed could be considered natural background, while 43% (31.1 tons per year) is considered “excess” sediment load. These results suggest that even though there are a few isolated areas of bank erosion occurring throughout the watershed, BMP planning and implementation to address upland field erosion should be a higher priority.

4.4 EXTERNAL LOADING CONCLUSIONS

Table 4-6 below summarizes the average annual external sediment and phosphorus loads to Okabena Lake based on the analyses and modeling presented in this section. Results indicate a majority of external sediment and phosphorus loading to Okabena Lake comes from the rural portions of the Okabena Lake watershed. Upland field erosion was by far the biggest external source of sediment to Okabena Lake, accounting for approximately 65% of the total load. At this time, there is not enough data/information available to estimate the amount of sediment and phosphorus loading from animal agriculture practices. That said, estimates of the average annual phosphorus produced by livestock in the Okabena Lake watershed suggest animal agriculture and manure spreading could be a significant source. While this study was able to quantify sediment loading from field erosion and streambank erosion, the amount of phosphorus associated with these sediment loads was not estimated. 2014 monitoring data showed most of the phosphorus load from the rural portions of the watershed is in particulate form, likely attached to sediment particles that are delivered during large storm events. Thus, it is safe to assume a large portion of the rural phosphorus load also comes from upland field erosion and the greater the amount of manure applied to this soil, the greater the resultant phosphorus load will be.

Table 4-6. External loading summary for Okabena Lake.

Source	Sediment (TSS)		Phosphorus (TP)	
	tons/year	**Percent**	**lbs/year**	**Percent**
Dry Deposition	195.6	18%	197.9	3%
Wet Deposition	0	0%	185.4	3%
City Runoff	100.8	10%	598.1	10%
Rural Runoff (Total)	772.3	72%	5,086.1	84%
- Animal Agriculture	?	?	?	?
- Field Erosion	700.8	65%	?	?
- Streambank Erosion	71.5	7%	?	?
Total	**1,068.7**		**6,067.5**	

5.0 Internal Source Assessment

5.1 SEDIMENT CHEMISTRY

Sediment cores were collected by Okabena-Ocheda Watershed District staff and Wenck Associates at four locations in Okabena Lake on February 19, 2014 (Figure 5-1). The sediment cores were transported to the Discovery Center – Sustainability Sciences Institute Laboratory at the University of Wisconsin – Stout where the top 10 centimeters of each core were analyzed for sediment chemistry. Sediment core chemical analysis included moisture content, organic matter content, sediment density, total iron, and phosphorus (P) content and fractionation. A complete description of the laboratory methodology and results are included in Appendix E (University of Wisconsin – Stout and Wenck Associates, 2014). Sediment chemistry results measured in the top 5 centimeters showed some spatial variability between the four Okabena Lake sampling sites. Moisture and organic matter content were slightly higher and dry bulk density was lower at the Sunset Bay site compared to the three sites located in the lake's main basin. These results suggests Sunset Bay has effectively settled and accumulated more flocculent, fine-grained sediment particles from the tributary that drains the western portion of the lake's watershed. Sites 1, 3 and 4 in the main basin exhibited very low organic matter content (6.9% to 7.5%), moderately low moisture content (64% to 68%) and relatively high sediment dry bulk densities (0.402 g/cm^3 to 0.457 g/cm^3). This suggests the sediment throughout the lake's main basin is relatively compacted and primarily composed of clay and fine silt particles.

The biggest drivers of phosphorus release from lake sediments are the amount of phosphorus in the sediment, and the type of chemical bonds that bind phosphorus to other particles in the sediment. Phosphorus bonds can be very strong and difficult to break, or weak and easy to break depending on conditions within the sediment porewater and overlying water column. For example, phosphorus forms a weak bond with iron that is easily broken when water near the sediment surface is anaerobic (low oxygen and redox potential). When this occurs, phosphorus is released from the sediment in dissolved form to the overlying water column. In lakes, dissolved phosphorus is rapidly taken up by algae which can lead to severe algae blooms. Loosely bound phosphorus and labile organic phosphorus are two other phosphorus fractions that tend to form weak bonds and are easily released from the sediment. In contrast, there are several phosphorus fractions that have stronger chemical bonds that are more difficult to break, such as aluminum and calcium. Collectively, these fractions are often referred to as refractory P and are subject to burial rather than recycling. Quantifying all of the aforementioned forms of phosphorus in lake sediments is an effective way to predict the potential phosphorus release under various conditions.

Sediment core phosphorus analyses indicate Okabena Lake sediment total phosphorus content at all four sites is low and below the 25th percentile measured in lakes throughout Minnesota. Total phosphorus concentration in Sunset Bay was slightly lower than the main basin sites, however Sunset Bay did display higher fractions of iron bound, loosely bound and labile organic phosphorus (Figure 5-2). This suggests Sunset Bay may have a higher potential for sediment phosphorus release compared to the other sites in the main part of the lake. Total iron concentrations in the surface sediment layer at all four sites were near the median compared to other lakes in Minnesota. Okabena Lake iron:phosphorus ratios were high, ranging between 25:1 and 37:1. In general, lakes with iron:phosphorus ratios less than 15:1 tend to display high rates of sediment phosphorus release.

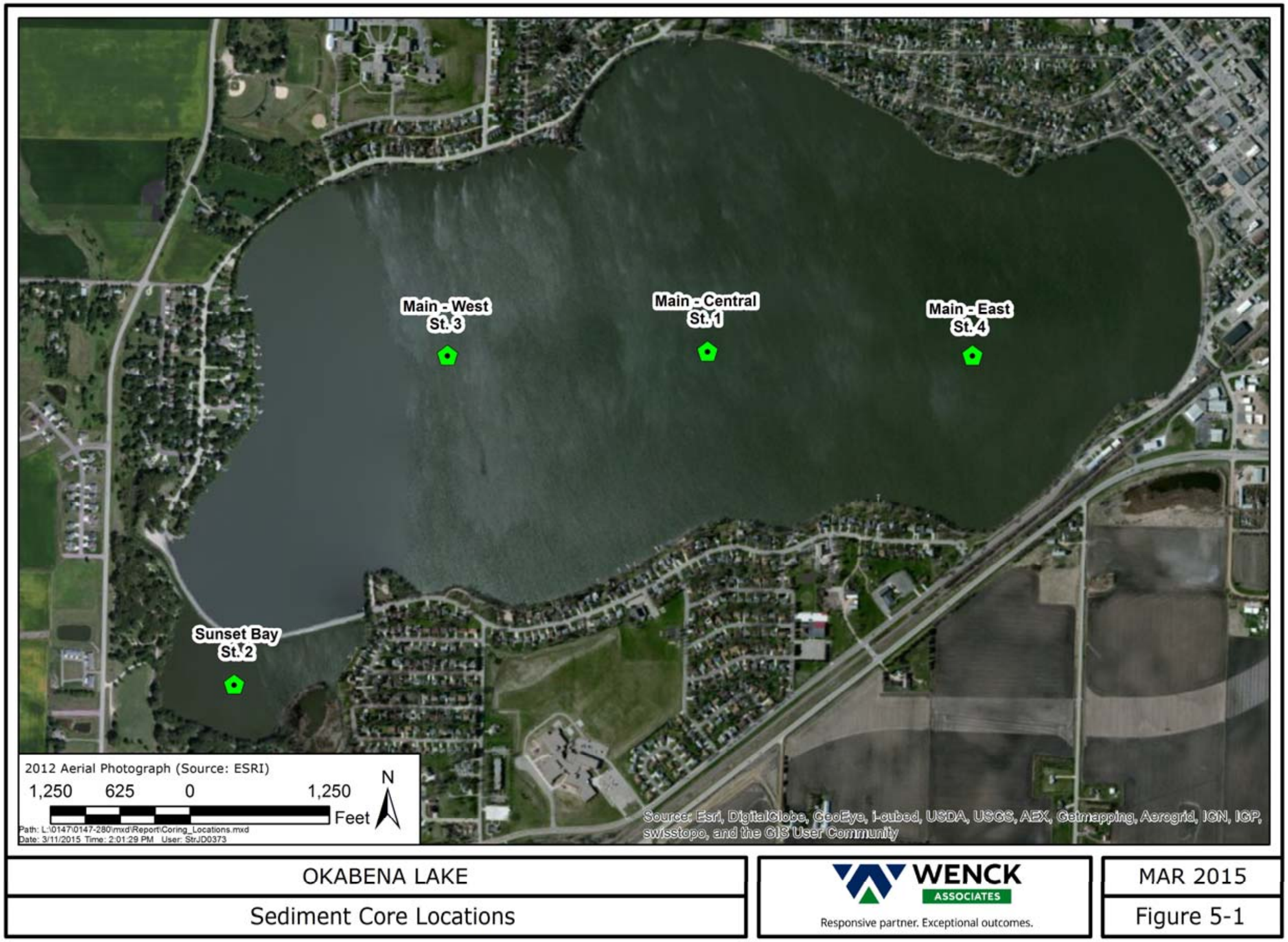


Figure 5-1. Okabena Lake sediment core sites.

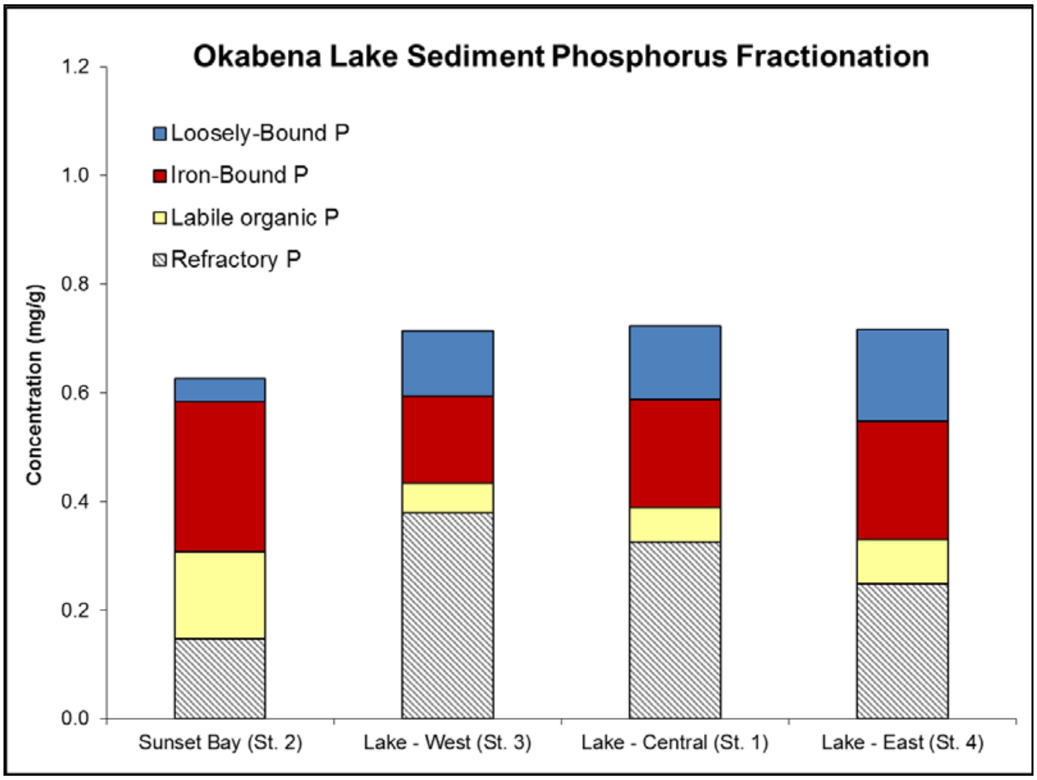


Figure 5-2. Okabena Lake sediment phosphorus fractionation for each monitoring station. Iron-bound P, loosely-bound P, and labile organic P are the fractions most susceptible to recycling and phosphorus release from sediment.

5.1.1 Sediment Phosphorus Release

Internal phosphorus loading from lake sediments can be a major component of a lake's phosphorus budget. In order to estimate internal phosphorus loading in Okabena Lake, sediment from the top 10 centimeters at the central main basin site (Site 1, Figure 5-1) were incubated for approximately 20 days in the lab at 20°C under both anaerobic (low oxygen) and aerobic (oxygenated) conditions. The lab measured phosphorus release rate under anaerobic conditions for Site 1 was 2.7 $mg/m^2/day$ (Appendix E). This rate is moderate compared to other lakes in Minnesota, falling in the lower 25% quartile. The mean phosphorus release rate under aerobic conditions was 0.62 $mg/m^2/day$. While this rate is lower than the anaerobic release rate, the aerobic release rate is relatively high compared to other lakes in Minnesota (upper 25% quartile). Typically, rates of phosphorus release are higher under anaerobic versus aerobic conditions, due to weak binding of phosphorus to iron in the sediment under aerobic conditions. Since Okabena Lake is shallow and exposed to wind-generated mixing, aerobic conditions likely regulate phosphorus release from sediments throughout much of the year.

Using the lab measured release rates to calculate annual internal loading for the entire lake can be difficult, especially in shallow lakes that mix several times throughout the year. To estimate total internal load, an anoxic factor (Nürnberg 2004) is used which estimates the period where anoxic conditions exist over the sediments. The anoxic factor is expressed in days but is normalized over the area of the lake and is typically calculated using dissolved oxygen (DO) profile data. Bottom water DO measurements were collected by Okabena-Ocheda Watershed District staff at least once per month at three separate Okabena Lake monitoring sites in 2013 and 2014. However; no anoxia (DO less than 2.0 mg/L) was observed at any of the sites during the 2013 and 2014 summer growing season. It is important to note that shallow lakes can often demonstrate short periods of anoxia due to instability of stratification. This instability can last a few days or even a few hours, and are often missed by periodic field measurements. Thus, the following equation was used to estimate the anoxic factor for Okabena Lake (Nürnberg, 2005):

$$AF_{shallow} = -35.4 + 44.2 \log(TP) + 0.95\, z/A^{0.5}$$

Where TP is the average summer phosphorus concentration of the lake, z is the mean depth (m) and A is the lake surface area (km^2). 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 Okabena Lake, 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 multiplied by the anaerobic and aerobic sediment release rates and the total area of the lake to estimate gross internal load. The laboratory measured release rates, anoxic and oxic factors, and total estimated internal load for Lake Okabena under both conditions are presented in Table 5-1.

Table 5-1. 2005-2014 average annual internal load estimates for Okabena Lake.

Parameter	Oxic Release	Anoxic Release
Oxic/Anoxic factor (days)	60	62
Release Rate (mg/m^2/day)	0.62	2.7
Total Internal Load (lbs/year)	256	1,157
	1,413 lbs/year	

Figure 5-3 displays all Okabena Lake surface TP measurements since 1998 summarized by month using box plots. In-lake phosphorus is relatively low during the wet months, April and May, and begins steadily increasing from June through October. Typically, by early August watershed inputs to the lake are low and therefore internal load is likely driving high in-lake TP values. So even though the annual internal phosphorus load to Okabena Lake is less than external sources of phosphorus (6,067.5 pounds), it is still an important source during certain times of the year (Aug–Oct) that may need to be addressed.

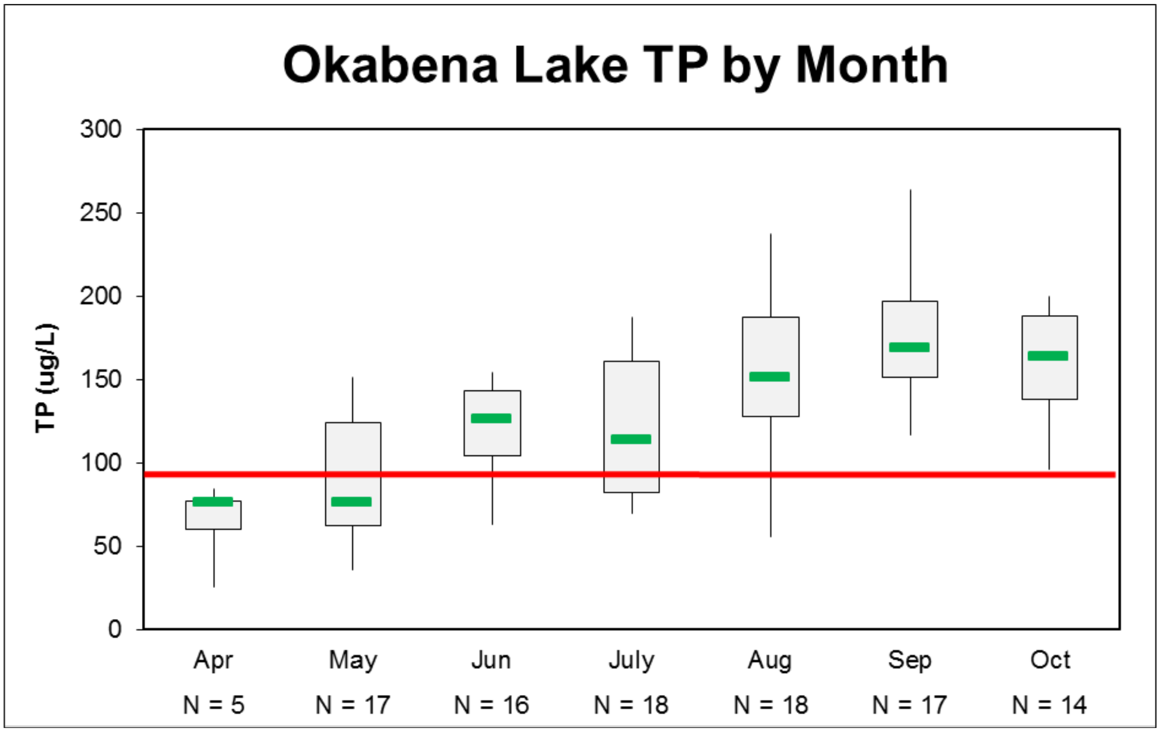


Figure 5-3. Box plots showing monthly surface TP monitoring for Okabena Lake.
Note: The upper and lower edge of each box represent the 75th and 25th percentile of the data range for each month. Error bars above and below each box represent the 95th and 5th percentile of the dataset. The green dash is the median TP concentration of all data collected. The solid red line shows the TP standard (90 µg/L) for shallow lakes in the Western Corn Belt Plains Ecoregion.

6.0 Recommendations and Conclusions

Water quality data for Okabena Lake indicate the lake is currently not meeting state water quality standards for water clarity, TP and chlorophyll-a. These data suggest both excessive algae growth due to high nutrient levels (TP) and sediment (TSS) resuspension are the main factors driving poor water clarity in Okabena Lake. Thus, restoring water quality in Okabena Lake will need to focus on decreasing phosphorus loading to the lake, as well as decreasing external TSS loading and the potential for in-lake sediment resuspension.

The primary purpose of this study was to improve the understanding of Lake Okabena's sediment and phosphorus sources. Specifically, this study investigated the following sources of sediment and phosphorus: dry and wet deposition on the lake surface; runoff from the City of Worthington; rural field erosion, streambank erosion, and animal agriculture; and internal loading of phosphorus from the lake sediments. These sources were estimated using a combination of monitoring data, literature rates, and modeling exercises. Average annual sediment and phosphorus loading to Okabena Lake is presented in Table 6-1 and Figures 6-1 and 6-2. These results support the following conclusions:

- Dry deposition accounts for approximately 18% of the annual sediment load and 3% of the phosphorus load to Okabena Lake. Modeling suggests potential wind erosion rates in areas surrounding Okabena Lake is moderately high, but within typical range for lakes in southwest Minnesota and agricultural areas throughout the Midwest. Dry deposition sources are difficult to control, however areas with high wind-erosion potential could be targeted for BMPs such as wind breaks/barriers, cover crops, soil ridges, and increasing crop residue through conservation tillage.
- It is estimated that only 2% of the phosphorus load comes from wet deposition (rainfall). For this study, it was assumed sediment (TSS) concentrations in rainfall are small and any deposition of sediment during storm events is accounted for in the estimates for dry deposition.
- Sediment and phosphorus loading from the City of Worthington accounts for about 10% and 8% of the total load to Okabena Lake, respectively. There are currently 8 stormwater ponds located throughout the city that provide storage and treatment for some of the city stormwater before entering the lake. Runoff from the Lake Direct, Lake Direct (Partial), and portions of the Okabena Creek and Sunset Bay Tributary subwatersheds is not retained or treated by any of the city stormwater ponds before entering the lake. These subwatersheds exhibited higher areal TSS and TP loading rates and could be assessed and targeted for stormwater BMP retrofit opportunities.
- It is recommended that water quality (TP and ortho-P) be monitored during the summer growing season in at least 2-3 city stormwater ponds for 1-2 years. Priority should be given to constructed ponds with larger drainage areas to validate modeling results and determine pond efficiency, maintenance needs and/or potential improvements.
- Approximately 85% of the Okabena Lake watershed is located outside of the City of Worthington in rural Nobles County. Runoff from rural areas is the largest contributor of sediment and phosphorus to Okabena Lake. The primary rural sources of sediment and phosphorus to Okabena Lake include field erosion, streambank erosion, and animal agriculture.
- Monitoring data collected in 2014 indicate runoff from rural areas is event driven and most of the pollutant load is delivered during large, early season storm events.

Therefore, rural BMP planning and design must focus on treating these high flow conditions. This may require exploring opportunities for additional retention and treatment for Okabena Creek and the Sunset Bay Tributary, along with continuing to implement upland BMPs and responsible farming practices. It is recommended that the 2014 watershed monitoring program be extended for at least 1-2 more years in order to develop a more robust database with multiple years of data to better estimate stream flow, TSS and TP loading from the rural portions of the watershed.

- Upland field erosion accounts for a majority (65%) of the sediment load to Okabena Lake. Most of the upland sediment is delivered by Okabena Creek and the Sunset Bay Tributary during large storm events. Rural areas with high erosion potential should be targeted for BMPs such as increased buffers, grassed waterways, conservation and/or contour tillage, cover crops, and water and sediment control basins.
- Streambank erosion accounts for only 7% of the sediment load to Okabena Lake. While there are a few problem areas throughout the watershed that could be targeted for repairs, it does not appear they are a significant contributor.
- This study did not estimate the exact amount of phosphorus delivered from upland field erosion and streambank erosion. However, 2014 stream monitoring data suggests a majority of the phosphorus from rural areas is attached to sediment particles and therefore most of the rural phosphorus load likely comes from upland field erosion.
- It was estimated that over 300,000 pounds of phosphorus is produced by livestock in the Okabena Lake watershed each year. While this study was not able to determine the exact amount of livestock phosphorus that reaches the lake, these results suggest manure spreading is likely a significant source and local farmers should continue implementing responsible manure management practices.
- In-lake sediment phosphorus fractionation analyses showed Sunset Bay had higher fractions of phosphorus that are susceptible to recycling and phosphorus release from the sediment compared to three sites in the main lake basin. It is recommended that surface water quality samples (TP and ortho-P) be collected in Sunset Bay during the summer growing season to determine if Sunset Bay is experiencing high levels of sediment phosphorus release.
- Phosphorus release from lake sediments represents approximately 19% of the total phosphorus load to Okabena Lake. While Okabena Lake's lab measured release rates were moderate compared to other lakes, in-lake monitoring data indicates internal phosphorus release likely plays a significant role during the late summer months when TP load from the watershed is low. Additionally, phosphorus loading from sediments is released in dissolved form which is rapidly taken up by algae and can lead to severe algae blooms.

Table 6-1. Average annual sediment and phosphorus loading to Okabena Lake by source.

Source	Sediment (TSS)		Phosphorus (TP)	
	tons/year	**Percent**	**lbs/year**	**Percent**
Dry Deposition	195.6	18%	197.9	3%
Wet Deposition	--	--	185.4	2%
City Runoff	100.8	10%	598.1	8%
Rural Runoff (Total)	772.3	72%	5,086.1	68%
- Animal Agriculture	?	?	?	?
- Field Erosion	700.8	65%	?	?
- Streambank Erosion	71.5	7%	?	?
P Release from Sediments	--	--	1,413.0	19%
Total	**1,068.7**		**7,480.5**	

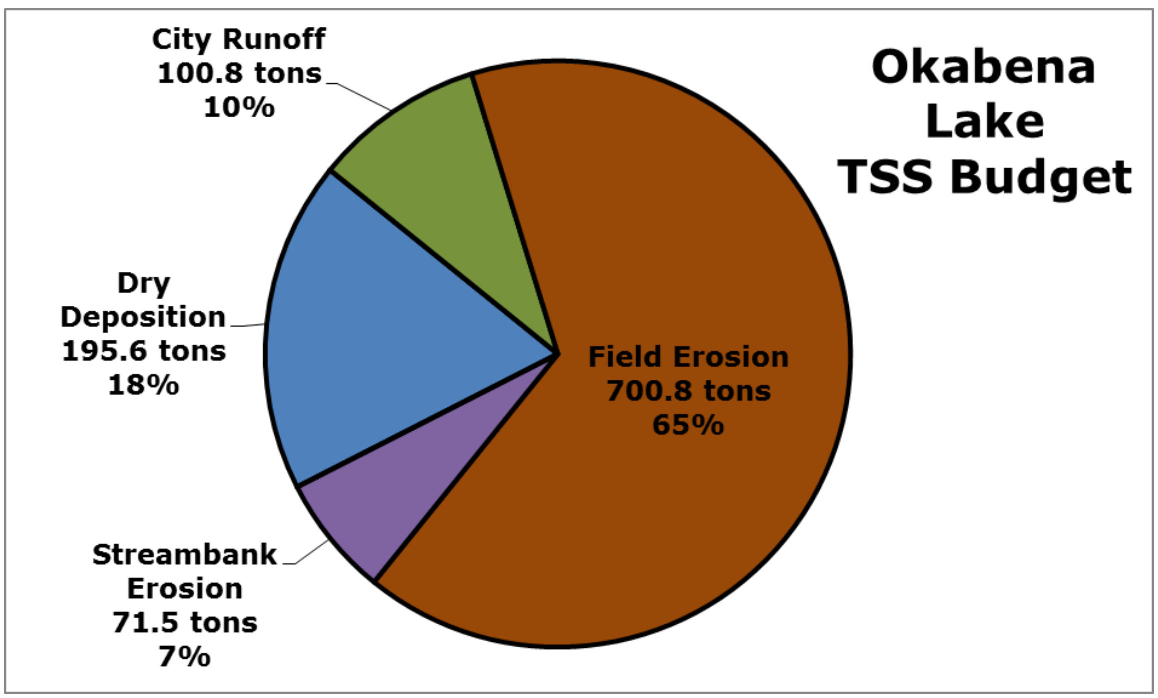


Figure 6-1. Okabena Lake sediment budget

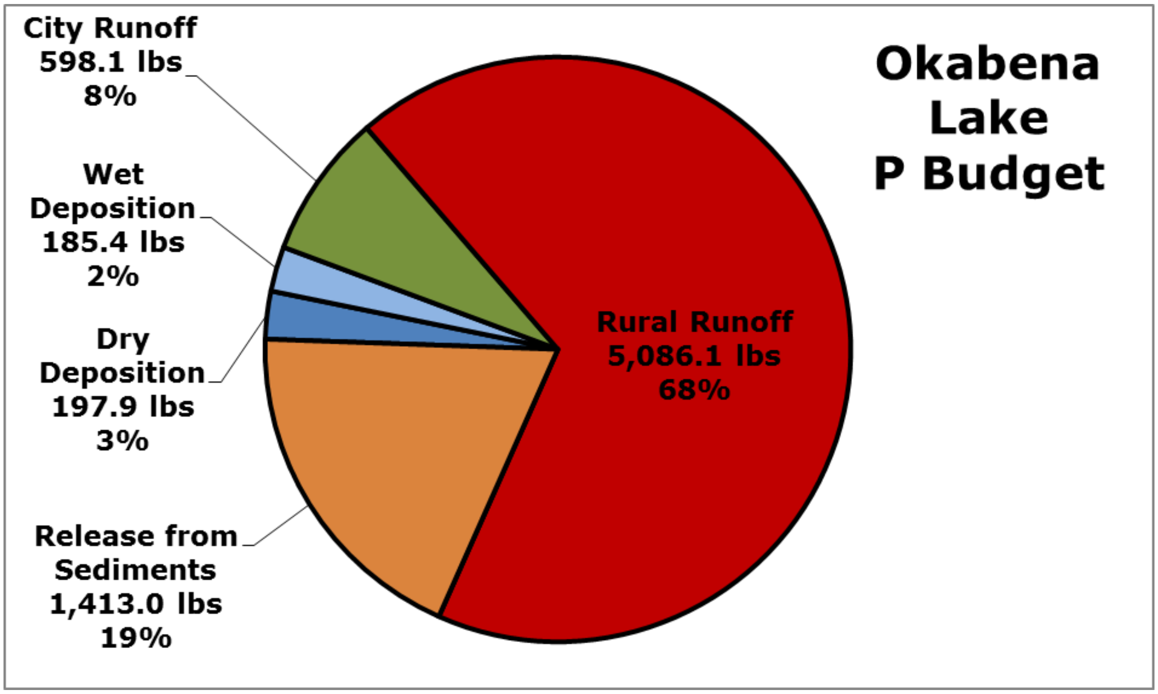


Figure 6-2. Okabena Lake phosphorus budget

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Deposition Modeling

Wind Erosion - WEPS Model Setup and Results

Four main inputs are required to run a simple WEPS model simulation: field size and orientation, latitude and longitude (for weather data/simulation), SSURGO soil type, and a land management scenario. Simple WEPS model simulations were run for all unique NASS (2013) agricultural land cover and SSURGO soil type combinations within a 5 mile radius of Okabena Lake. GIS data limitations and time constraints made it impossible to determine the exact size and orientation of each field within a 5 mile radius of Okabena Lake. So, for this exercise it was assumed each unique land cover-soil type combination is made up of one large (250 acres) square field, positioned perfectly east to west. Since nearly all of the NASS agricultural land cover types were either corn (50%) or soybean (40%), a general corn/soybean crop rotation management file was selected within WEPS that includes spring till and seeding, followed by a fall harvest and plow. Average annual wind-blown sediment erosion rates for the 30 most common agricultural land cover-soil type combinations in the Okabena Lake watershed are presented in Table A-1, and Figure A-1 is a map showing wind-blown sediment loading rates from agricultural areas in a 5 mile radius of Okabena Lake.

Table A-1. WEPS model predicted wind erosion for the largest landcover-SSURGO soil type combinations surrounding Okabena Lake.

2013 NASS Landcover type	SSURGO Soil Type	Total acres in 5 mile radius of Lake	Wind erosion (tons/acre/year)
soybeans	Omsrud-Storden complex 6-12%	684	6.62
soybeans	Delft, overwash-Delft complex, 1-4%	319	6.06
soybeans	Clarion-Crooks ford complex, 1-5%	356	5.25
soybeans	Canisteo-Glencoe, depressional, complex, 0 to 2 percent slopes	156	4.41
soybeans	Canisteo clay loam, 0-2%	762	4.41
soybeans	Nicollet Clay Loam 1-3%	4,155	4.24
soybeans	Clarion Loam 2-5%	4,876	4.21
soybeans	Webster Cla Loam 0-2%	5024	3.95
soybeans	Webster silty clay loam, 0-2%	359	3.95
corn	Omsrud-Storden complex 6-12%	1000	3.60
soybeans	Okabena silty clay loam, 1-3%	672	3.49
soybeans	Chetomba silty clay loam, 0-2%	303	3.37
soybeans	Waldorf Silt Clay Loam 0-2%	1,076	3.34
soybeans	Ocheda silty clay loam, 1-3%	622	3.15
soybeans	Glencoe silty clay loam, depressional, 0-1%	432	3.10
soybeans	Canisteo silty clay loam, 0-2%	520	2.88
soybeans	Nicollet silty clay loam, 1-3%	652	2.79
corn	Delft, overwash-Delft complex, 1-4%	432	2.76
corn	Clarion-Crooks ford complex, 1-5%	422	2.64

2013 NASS Landcover type	SSURGO Soil Type	Total acres in 5 mile radius of Lake	Wind erosion (tons/acre/year)
corn	Canisteo-Glencoe, depressional, complex, 0 to 2 percent slopes	344	1.93
corn	Canisteo clay loam, 0-2%	838	1.87
corn	Nicollet Clay Loam 1-3%	4,586	1.80
corn	Clarion Loam 2-5%	6,786	1.71
corn	Webster Cla Loam 0-2%	5,677	1.57
corn	Webster silty clay loam, 0-2%	320	1.57
corn	Okabena silty clay loam, 1-3%	902	1.50
corn	Canisteo silty clay loam, 0-2%	905	1.47
corn	Chetomba silty clay loam, 0-2%	509	1.39
corn	Glencoe silty clay loam, depressional, 0-1%	464	1.30
corn	Waldorf Silt Clay Loam 0-2%	1,077	1.27
corn	Nicollet silty clay loam, 1-3%	706	1.24
corn	Ocheda silty clay loam, 1-3%	627	1.19

Dry Deposition Calculations

Sediment and phosphorus deposition near Okabena Lake were estimated using measured 10 micrometer particulate matter (PM_{10}) and 2.5 micrometer particulate matter ($PM_{2.5}$) air quality data downloaded from the nearest Interagency Monitoring of Protected Visual Environments (IMPROVE) monitoring station at Blue Mounds State Park near Luverne, MN (http://vista.cira.colostate.edu/improve/). Phosphorus content of the airborne particulate matter was estimated based on MPCA laboratory phosphorus analyses of PM_{10} filter samples at three air quality monitoring stations with similar land cover characteristics as Okabena Lake watershed (Barr Engineering, 2007). Based on information from Meyers (2003) presented in the MPCA memo (Barr Engineering, 2007), particulate matter dry deposition settling velocities of 0.5 cm/s and 3 cm/s were applied to the fine ($PM_{2.5}$) and coarse (PM_{10} – $PM_{2.5}$) airborne particulate matter data downloaded at Blue Mounds State Park monitoring station. Using the above methodology, average annual dry sediment deposition to Okabena Lake is approximately 196 tons per year and annual phosphorus deposition is 199 pounds per year.

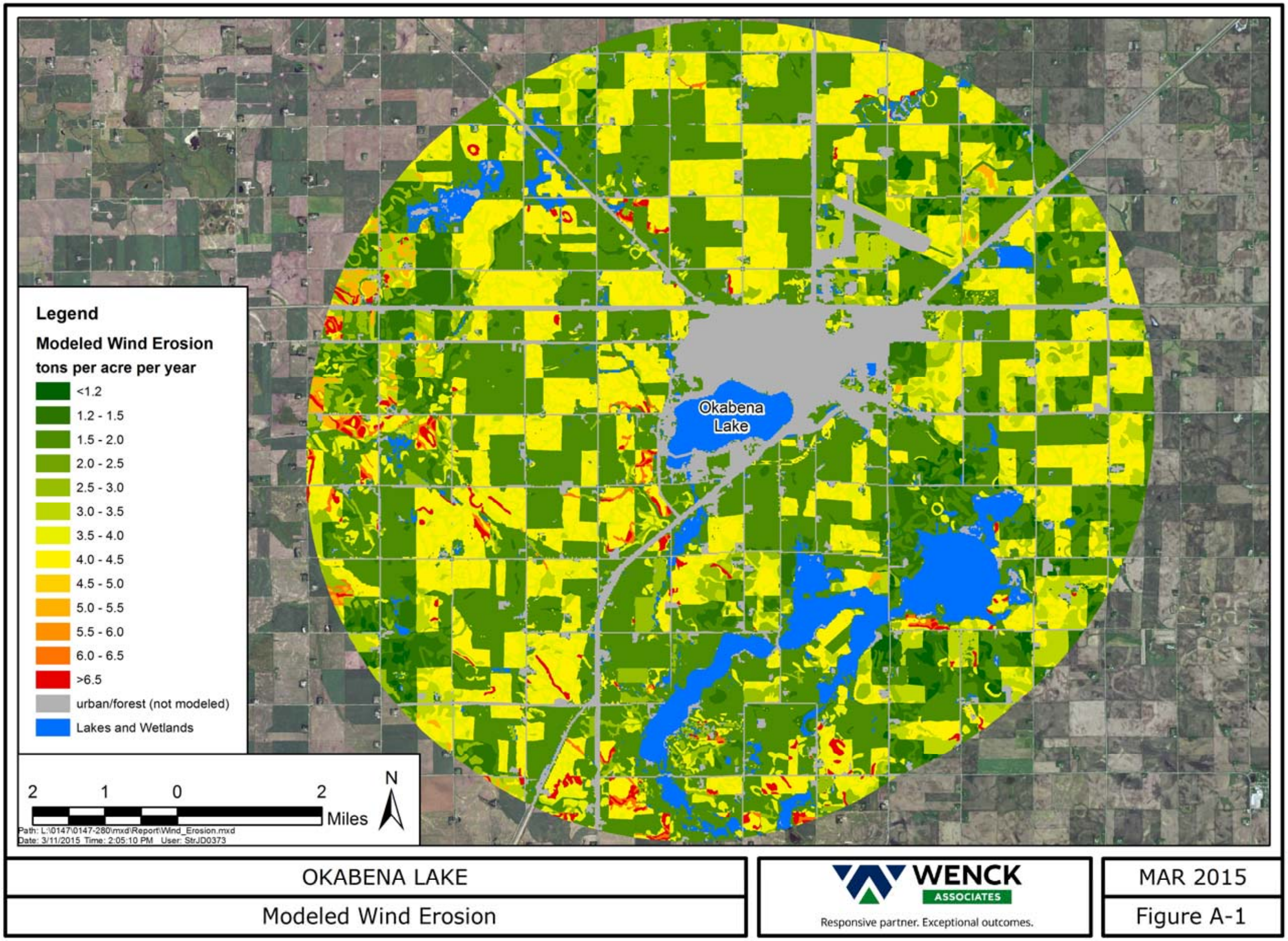

Figure A-1. WEPS model results for the 5 mile radius surrounding Okabena Lake.

Wet Deposition Calculations

Since phosphorus in rainwater has not been directly measured in or around the Okabena Lake watershed, wet deposition of phosphorus on the lake was calculated using the following regression relationship between calcium and phosphorus concentrations in rainwater at several stations throughout Minnesota developed by the MPCA (Swain, 2003; Barr Engineering, 2007):

$$y = 0.0671x - 0.4586$$

Where:

y = Total phosphorus in µg/L

x = dissolved calcium in rainwater in µg/L

Rainfall dissolved calcium data for the past 10 years was downloaded for the Lamberton, MN station which is the closest National Atmospheric Deposition Program (NADP) monitoring station to Worthington, MN (approximately 50 miles north). The calcium concentrations were used to estimate TP concentrations using the aforementioned equation and were then multiplied by daily rainfall totals in the Okabena Lake watershed recorded at the Worthington Municipal Airport. Results of the 10-year (2005-2014) annual wet deposition of phosphorus to Okabena Lake are presented in Table A-2.

Table A-2. Wet phosphorus deposition estimates to Okabena Lake.

Year	Total Precipitation (inches)	Phosphorus Loading Rate (lbs/acre/year)	Total Phosphorus Load to Lake (lbs/year)
2005	22.3	0.201	156
2006	33.4	0.248	193
2007	37.5	0.228	178
2008	29.6	0.150	117
2009	37.0	0.290	226
2010	29.0	0.309	240
2011	29.7	0.201	156
2012	36.0	0.260	202
2013	29.5	0.356	277
2014	24.1	0.265	206
Average	**29.7**	**0.239**	**186**

Appendix B

P8 Watershed Model

Model Setup

P8 model inputs include watershed characteristics and treatment devices. The Okabena Lake watershed was delineated into several smaller subwatersheds (Figure B-1) using storm sewer information provided by the City of Worthington and two foot LiDAR contours downloaded from the Minnesota Geospatial Information Office. In some cases, the subwatersheds were further divided using the City of Worthington's most recent municipal boundary GIS file in order to separate city and rural portions of the watershed. Overall, there were a total of 28 individual minor subwatersheds delineated for the Okabena Lake watershed P8 model. The 28 minor subwatersheds were then grouped into nine major subwatersheds (Figure B-1) that act as watershed pour points to the lake. The major subwatersheds discharge to the lake through storm sewer pipes or small ditches and tributary channels. The Lake Direct subwatershed represents runoff that enters the lake through overland flow and a few small storm sewer catchments immediately surrounding the lake. There are two small portions of the Lake Direct subwatershed located east and north of Okabena Lake that have interconnected collection systems with gravity outlets that drain away from the lake (toward County Ditch 12) and a storm lift that discharges to the lake. It was assumed approximately 50% of the stormwater runoff and pollutant load from these subwatersheds, referred to as Lake Direct (Partial), makes its way to Okabena Lake.

There are eight stormwater ponds in the Okabena Lake watershed that were included in the model with water quality treatment benefits. Partial as-built design specifications were available for all eight ponds. As-built information included outlet and basin bottom elevations, basin permanent pool and flood pool volumes, and outlet characteristics and dimensions. If basin information was not available, assumptions were made. For unknown outlet characteristics and dimensions, an 18-inch orifice was assumed for modeling purposes. If the outlet elevation and flood pool elevation were unknown, elevations were determined based on LiDAR and/or continuity with available basin information. If basin bottom elevation was unknown, the basin was assumed to have a depth of 7 feet. If the basin permanent pool volume was unknown, the volume was assumed to be the volume of runoff from the 2.5-inch event.

A GIS exercise was executed to intersect 2013 NASS Landcover and Soils Survey Geographic (SSURGO) database soil type information with the delineated subwatershed boundaries. The percent impervious fractions and pervious curve numbers for each subwatershed were estimated using current land cover and soil type information. Each land cover was assigned an impervious percent based on literature values and runoff curve numbers were determined by soil type.

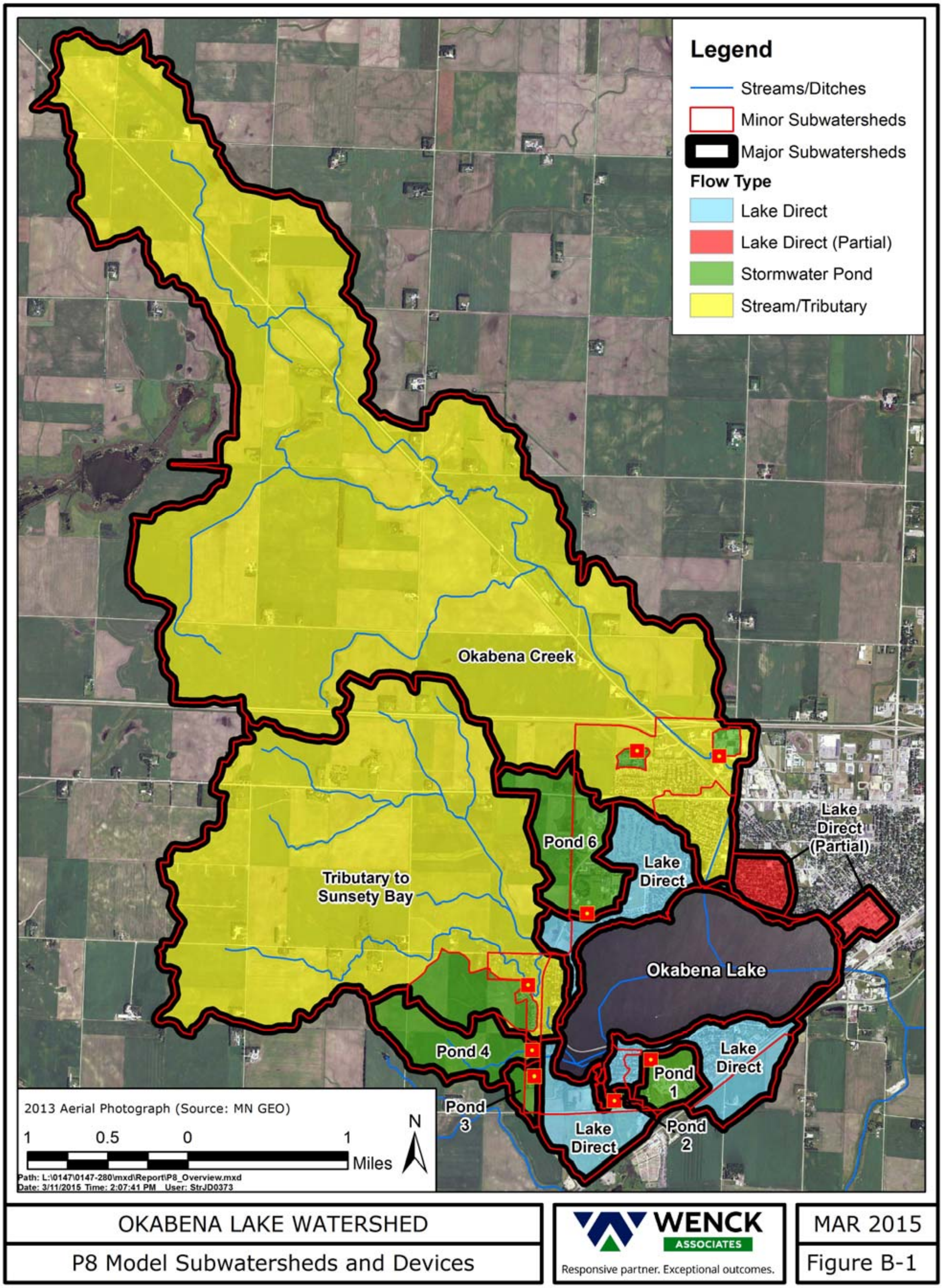

Figure B-1. P8 model major and minor subwatersheds.

Flow Adjustments

Initial runoff curve numbers slightly over-predicted total watershed inflow to Okabena Lake when compared to the 2014 lake inflow estimates (Table C-3) and gauged flow measurements at the Okabena Creek and Sunset Bay tributary monitoring stations. Runoff curve numbers for all subwatersheds were lowered by approximately 25% to match the 2014 data. Final flow calibration is presented in Figures B-2 through B-4.

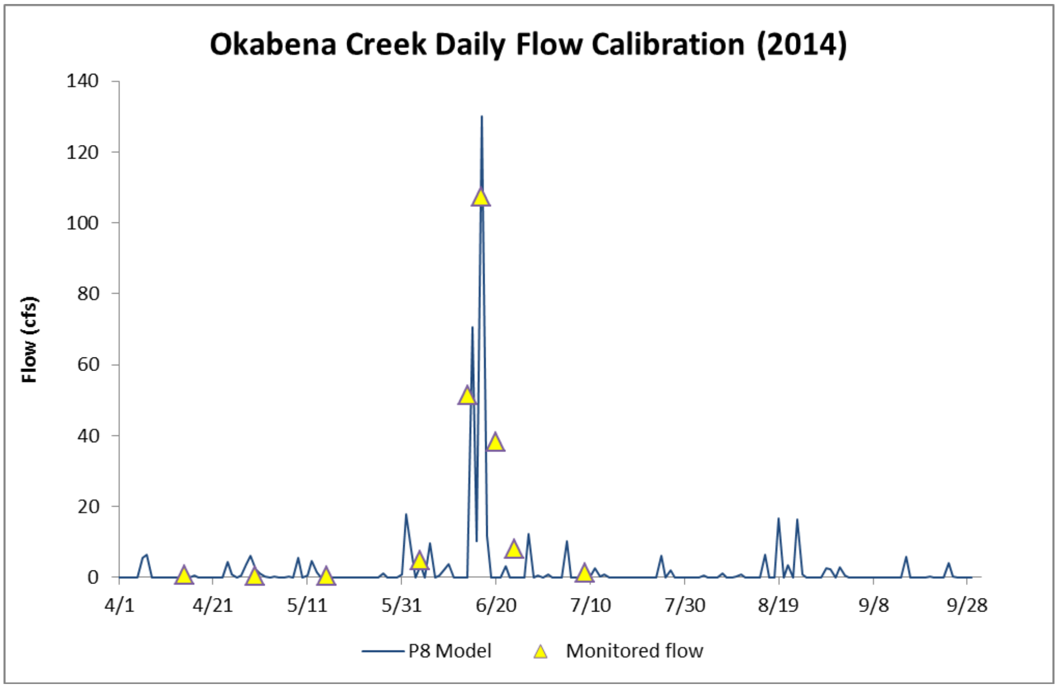

Figure B-2. P8 model average daily flow calibration for Okabena Creek.

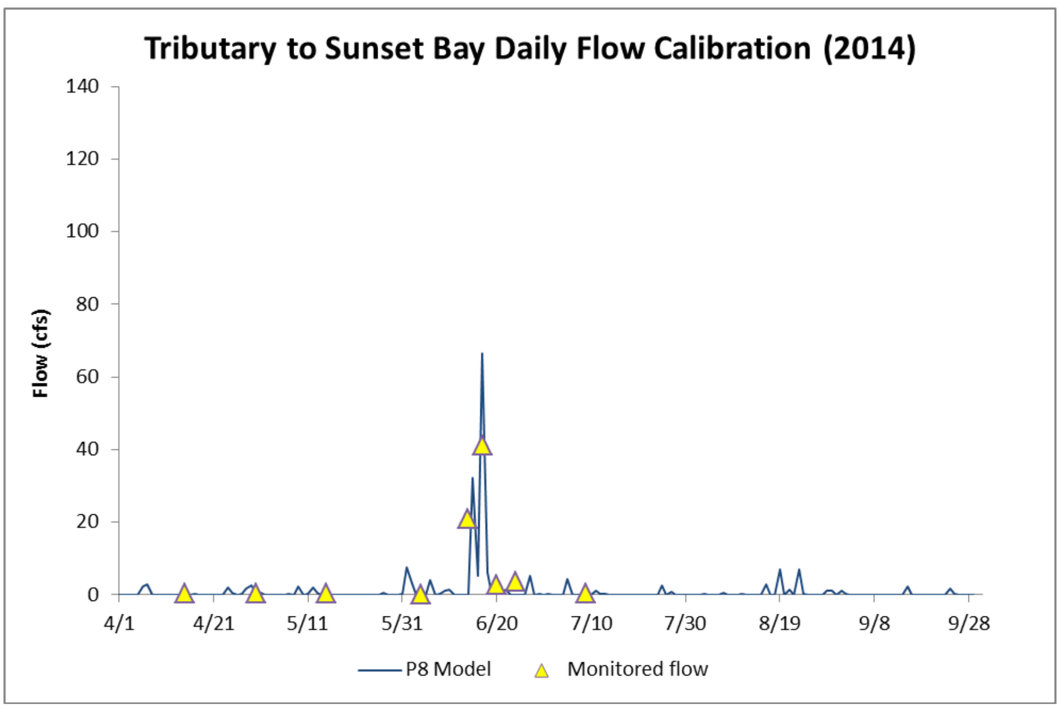

Figure B-3. P8 model average daily flow calibration for Sunset Bay Tributary.

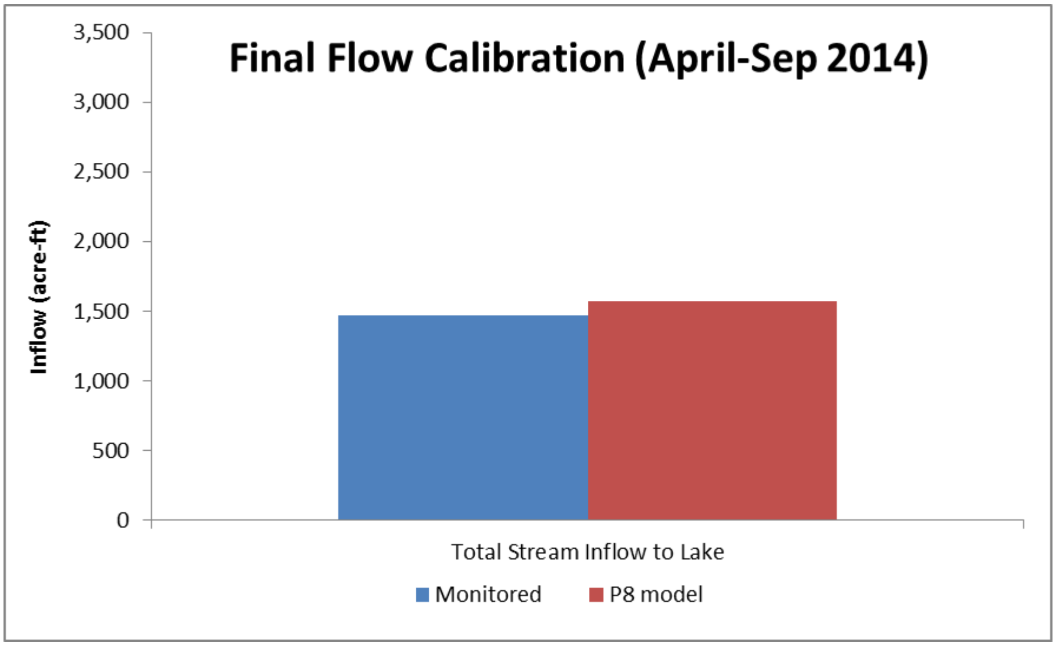

Figure B-4. Final P8 model flow calibration for the entire Okabena Lake watershed.

Water Quality Adjustments

Model predicted sediment and phosphorus concentrations and loads for Okabena Creek and the Sunset Bay tributary were compared to stream water quality data collected in 2014. Initially, the 2014 model predicted TSS and TP flow weighted mean (FWM) concentrations were significantly lower than the monitored FWM concentrations at both monitoring stations (See Appendix C). It should be noted that P8 often struggles to accurately predict pollutant loading from agricultural areas since the model is primarily intended to be used in urban watersheds. Agriculture (row crops and pasture land) is the dominant land cover in the Okabena Creek (80%) and Sunset Bay Tributary (89%) subwatersheds. Thus, Okabena Creek and Sunset Bay Tributary TSS and TP runoff factors had to be increased in P8 in order to bring model predicted FWM concentrations closer to the 2014 monitored values. The runoff factor adjustments applied to both subwatersheds were scaled based on the amount of agricultural land within each watershed and were within the range of published data for agricultural land in Minnesota (Lin 2004; Reckhow et al. 1980). Once it appeared the Okabena Creek and Sunset Bay tributary model predicted FWM TSS and TP concentrations and annual loads matched 2014 monitored values, the agriculture scaled runoff factor adjustments were applied across the entire watershed. Final 2014 model predicted versus monitored FWM concentrations for Okabena Creek and the Sunset Bay tributary are presented in Figures B-5 and B-6. Maps showing average annual TP and TSS loading rates (in lbs/acre/year) by subwatershed are presented in Figure B-7 and B-8.

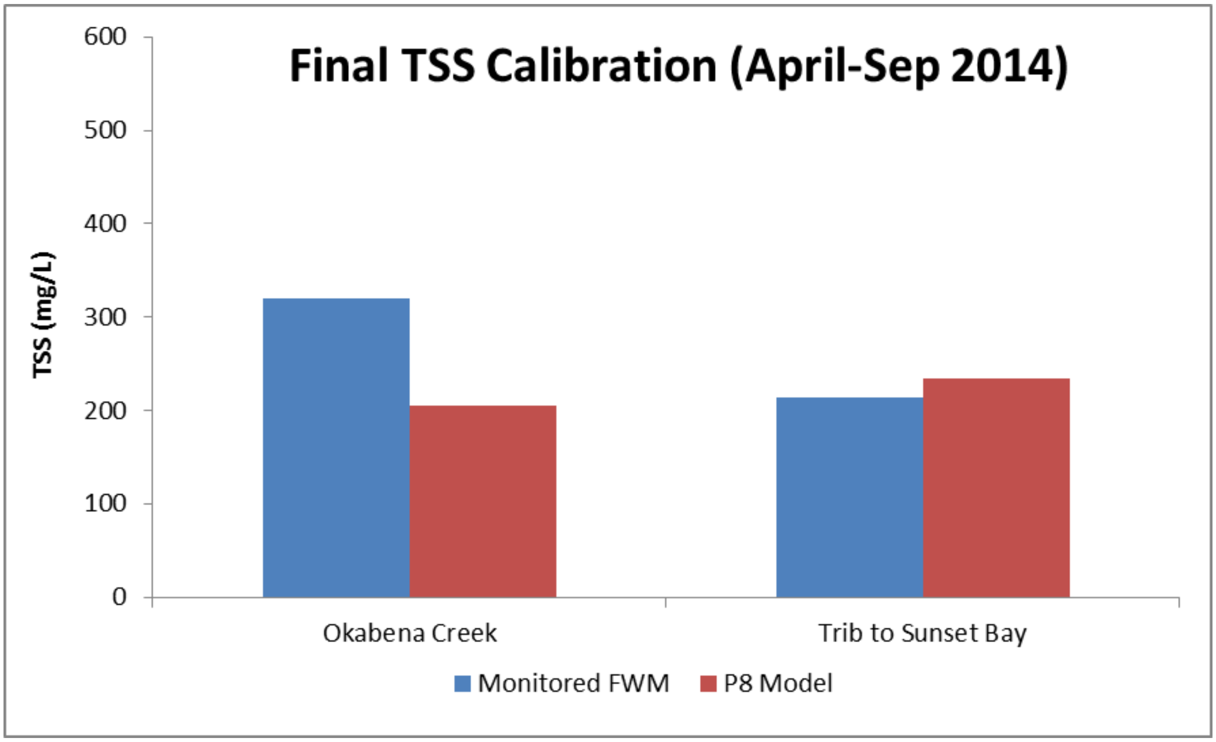

Figure B-5. P8 model TSS calibration.

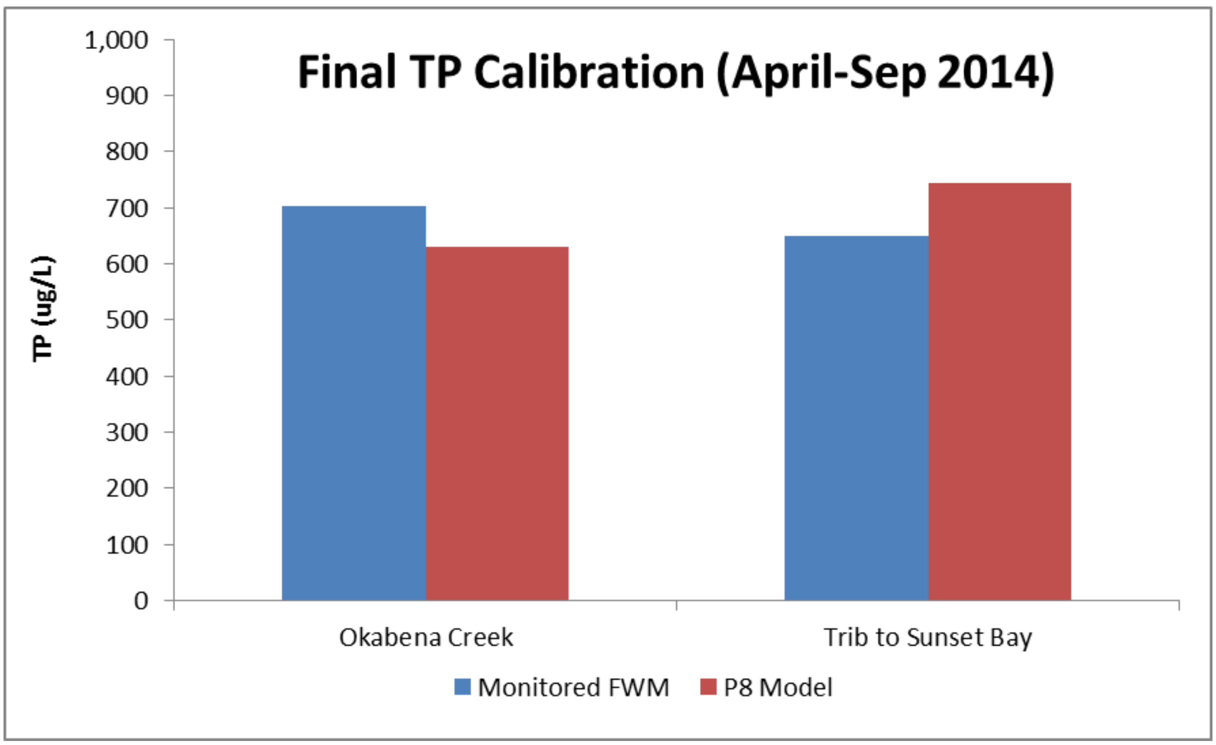

Figure B-6. P8 model TP calibration.

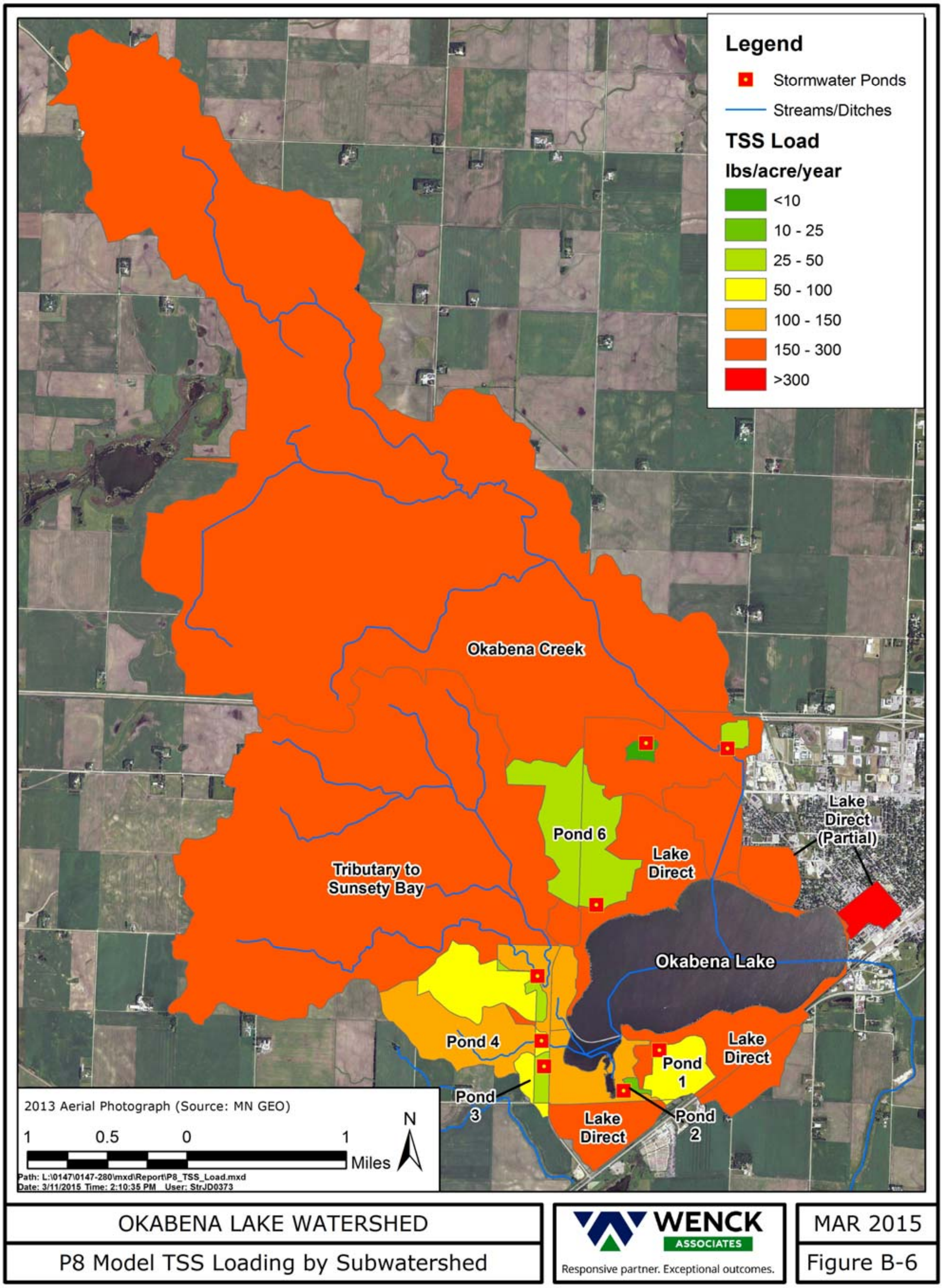

Figure B-6. P8 model TSS loading rates by subwatershed.

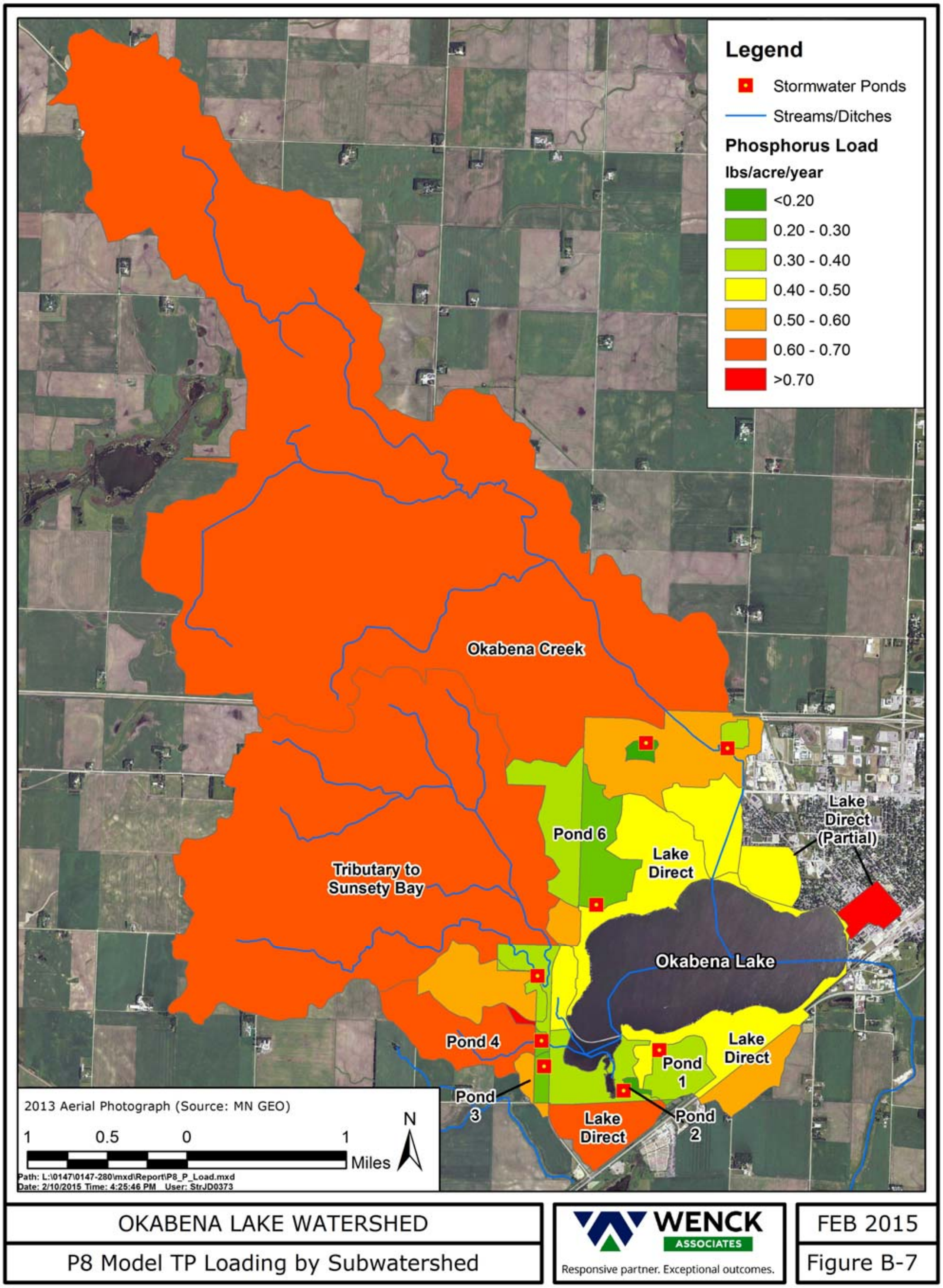

Figure B-7. P8 model TP loading rates by subwatershed.

Appendix C

Water Quality and Lake Level Monitoring

Monitoring Locations and Water Quality Results

Okabena-Ocheda Watershed District staff monitored two stream surface locations in the Okabena watershed in 2014: Okabena Creek/Whiskey Ditch downstream of Oxford Street , and the tributary flowing to Sunset Bay at County Road 10 (Crailsheim Drive) (Figure C-1). Seven water quality samples were collected in 2014 between April and early July (Tables C-1 and C-2). No samples were collected after July 9th due to low-flow and drought conditions. Samples at each site were analyzed for the following lab parameters: total suspended solids (TSS), volatile suspended solids (VSS), total phosphorus (TP), soluble ortho phosphorus (ortho-P), nitrate+nitrite and total Kjeldahl nitrogen (TKN). Additionally, the following field parameters were recorded during each site visit: stream stage (elevation), gauged flow, dissolved oxygen (DO), conductivity and transparency. Gauged flow measurements were made using a Hach FH950 Portable Velocity Meter. Two non-water quality sampling site visits were made during high flow conditions (6/17/2014 and 6/20/2014) to measure stream stage and flow. Results of the stream water quality and flow samples are presented in Tables C-1 and C-2.

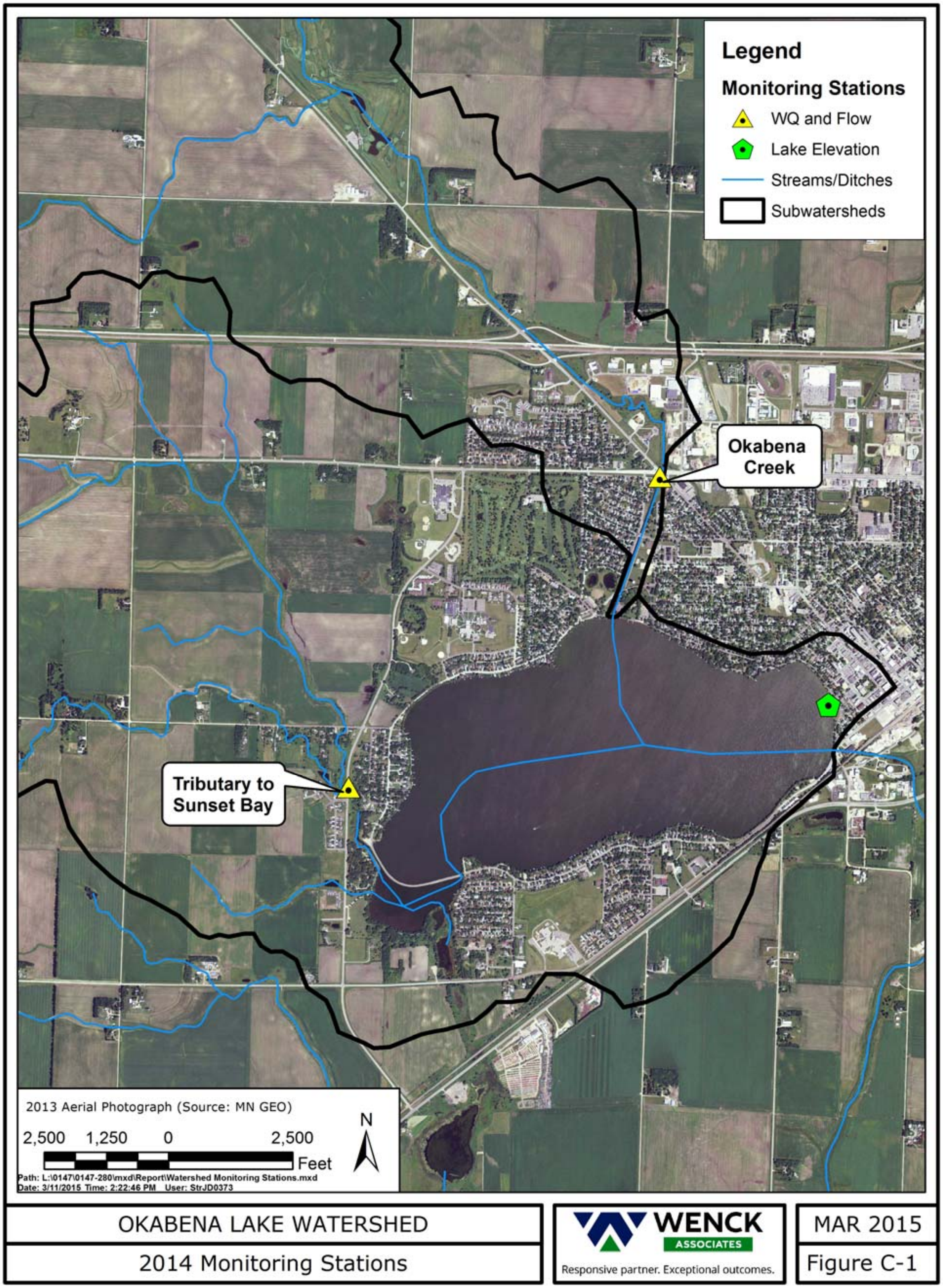

Figure C-1. 2014 Monitoring Stations.

Table C-1. 2014 Okabena Creek flow and water quality monitoring results.

Date	Gauged Flow (cfs)	TSS (mg/L)	VSS (mg/L)	TP (µg/L)	Ortho-P (µg/L)	TKN (mg/L)	Nitrate+Nitrite (mg/L)	DO (mg/L)	Conductivity (µs/cm)	Transparency (cm)
4/15/2014	0.7	12	8	69	11	1.50	1.56	17.45	764	60+
4/30/2014	0.3	10	2	40	13	1.00	0.64	13.47	977	60+
5/15/2014	<0.3	6	6	60	7	1.20	NA	11.36	908	60+
6/4/2014	4.9	23	14	168	74	1.40	2.32	10.58	886	52
6/14/2014	51.5	410	80	860	147	3.20	2.34	7.52	295	4
6/17/2014	107.5	NA	NA	NA	NA	NA	NA	6.72	399	8
6/20/2014	38.2	NA	NA	NA	NA	NA	NA	7.20	568	19
6/24/2014	7.9	122	9	213	122	1.50	7.97	8.41	674	29
7/9/2014	1.3	11	9	60	11	1.10	8.69	7.80	813	44
FWM concentration		**320**	**64**	**702**	**133**	**2.79**	**3.10**			

NA = denotes no water quality sample was collected

Table C-2. 2014 Sunset Bay tributary flow and water quality monitoring results.

Date	Gauged Flow (cfs)	TSS (mg/L)	VSS (mg/L)	TP (µg/L)	Ortho-P (µg/L)	TKN (mg/L)	Nitrate+Nitrite (mg/L)	DO (mg/L)	Conductivity (µs/cm)	Transparency (cm)
4/15/2014	<0.2	6	6	70	25	1.00	0.80	16.58	692	>60
4/30/2014	<0.2	5	5	58	30	1.00	0.65	12.18	807	>60
5/15/2014	<0.2	3	3	81	28	0.60	NA	11.82	970	>60
6/4/2014	0.2	13	12	89	45	1.00	1.53	15.08	896	>60
6/14/2014	20.8	268	52	800	220	3.00	4.05	8.17	236	4
6/17/2014	41.1	NA	NA	NA	NA	NA	NA	6.72	453	13
6/20/2014	2.8	NA	NA	NA	NA	NA	NA	8.17	710	>60
6/24/2014	3.5	2	2	62	49	1.20	15.90	9.25	739	>60
7/9/2014	0.4	21	6	49	25	0.80	13.40	8.37	748	>60
FWM concentration		**218**	**43**	**661**	**187**	**2.64**	**5.71**			

NA = denotes no water quality sample was collected

Lake Elevation Monitoring

Continuous lake elevation measurements were recorded in 2014 at one location from April 15th to September 25th using an In-Situ Rugged Troll 100 pressure transducer with internal logging capabilities. The transducer was housed in a metal pipe that was mounted to a concrete pier north of the lake's outlet near the intersection of Lake Street and 4th Avenue (Figure C-1). The transducer was set using depth to water measurements from a surveyed benchmark at the top of the pier. Site visits were made approximately once every 2-3 weeks to measure depth to water, and download data. Figure C-2 shows results of the 2014 lake elevation measurements.

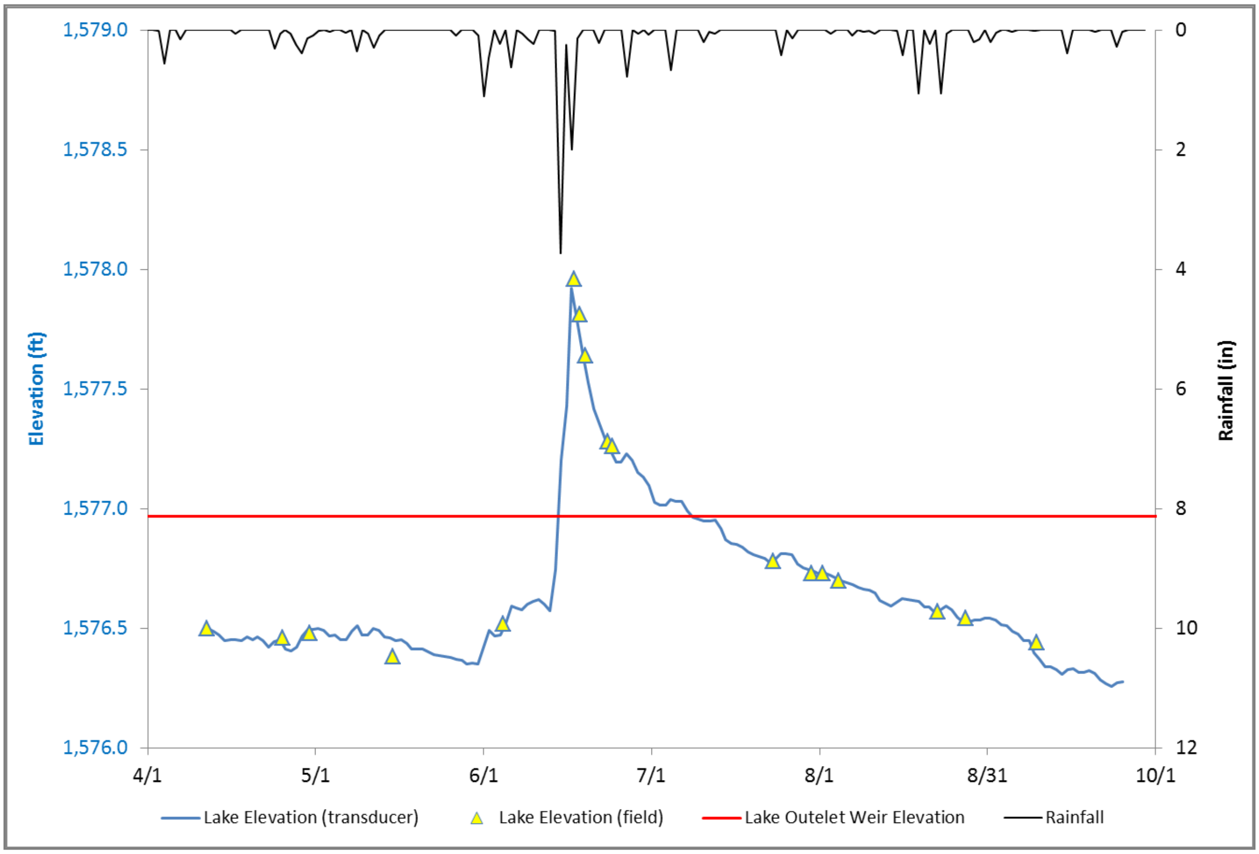

Figure C-2. 2014 Okabena Lake water level monitoring.

Okabena Lake Water Balance

Okabena Lake water budget for the April through September 2014 monitoring period was calculated using the following equation with a daily time step:

$$(1)\ \Delta Lake_{volume} = Inflow_{streams} + Inflow_{precip} - Outflow_{streams} - Outflow_{evaporation}$$

Where $\Delta Lake_{volume}$ represents the average daily change in lake volume which is a function of inflow to the lake from surface water runoff ($Inflow_{streams}$), direct precipitation ($Inflow_{precip}$), evaporation from the lake surface ($Outflow_{evaporation}$) and surface outflow over the lake's outlet weir ($Outflow_{streams}$). This equation assumes all major changes in lake volume are regulated by these four main processes.

Okabena Lake volume was estimated using average daily lake elevation data recorded during the 2014 transducer deployment period (Figure C-2). Okabena Lake direct precipitation during this time period was calculated using Worthington Municipal Airport precipitation data downloaded from the cli-MATE website (http://mrcc.isws.illinois.edu/CLIMATE). Lake evaporation was estimated using the Lamberton, MN weather station weekly pan evaporation rates downloaded from the Minnesota Climatology Working Group website (http://climate.umn.edu). Surface outflow from Okabena Lake was estimated using the following flow equation for rectangular weirs:

(2) $Q = 2/3\ b\ (2g)^{1/2}\ H^{3/2}$

Where:

Q = flow over the weir (cfs)

b = length of Okabena outlet weir (54 ft)

g = acceleration due to gravity (32.2 ft/sec^2)

H = height of surface water above weir (ft)

Height above the weir was calculated based on the difference between the surveyed elevation at the top of the outlet weir (1,577.96 feet) and average daily lake elevation recorded by the pressure transducer. Figure C-2 shows the only time lake elevation exceeded the top of the weir was from June 15 – July 8 which was in response to 6.1 inches of rainfall the week of June 15th.

Once the other parameters were calculated, Equation 1 was solved to determine stream inflow to Okabena Lake. Table C-3 summarizes the lake water balance for the entire 2014 monitoring period. Results indicate total losses slightly exceeded inflows during the April 15th – September 25th monitoring period. Evaporation from the lake surface was the largest loss from the lake and exceeded both surface runoff to the lake and direct precipitation on the lake surface.

Table C-3. Okabena Lake water balance during the 2014 monitoring period.

Water Balance Parameter	Description	Acre-ft
$Inflow_{streams}$	Surface water inflow from watershed	(+) 1,467
$Inflow_{precip}$	Direct precipitation on lake surface	(+) 1,187
$Outflow_{streams}$	Outflow over lake weir	(-) 644
$Outflow_{evaporation}$	Evaporation from lake surface	(-) 2,171
$\Delta Lake_{volume}$	**Change in total lake volume**	**-161**

Field Erosion and Streambank Assessment Survey

Field Erosion - Universal Soil Loss Equation

Average upland sediment loss in the impaired reach watershed was modeled using the Revised Universal Soil Loss Equation (RUSLE). This model provides an assessment of existing soil loss from upland sources and the potential to assess sediment loading through the application of Best Management Practices (BMPs). RUSLE predicts the long term average annual rate of erosion on a field slope based on rainfall pattern, soil type, topography, land use and management practices. The general form of the RUSLE has been widely used in predicting field erosion and is calculated according to the following equation:

$$A = R \times K \times LS \times C \times P$$

Where A represents the potential long term average soil loss (tons/acre) and is a function of the rainfall erosivity index (R), soil erodibility factor (K), slope-length gradient factor (LS), crop/vegetation management factor (C) and the conservation/support practice factor (P). RUSLE only predicts soil loss from sheet or rill erosion on a single slope as it does not account for potential losses from gully, wind, tillage or streambank erosion.

For this exercise, it was assumed all agricultural practices are subject to maximum soil loss fall plow tillage methods and no support practices (P-factor = 1.00). Raster layers of each RUSLE factor were constructed in ArcGIS for rural areas in the Okabena Lake watershed study area and then multiplied together to estimate the average annual potential soil loss for each grid cell. It is important to note that model results represent the maximum amount of soil loss that could be expected under existing conditions. Thus, results are intended to provide a first cut in identifying potential field erosion hot spots based on slope, landuse and soil attributes. Areas with high potential erosion should be verified in the field prior to BMP planning and targeting.

Since this model does not take into account a stream's ability to transport suspended sediment, a sediment delivery ratio (SDR) (Vanoni 1975) was used to estimate how much upland soil loss may be delivered downstream:

$SDR = 0.451(b)^{-0.298}$
Where b = watershed size in square kilometers

Streambank Assessment Methodology and Results

Annual soil loss from streambank erosion was estimated using field collected data and a method developed by the Natural Resources Conservation Service referred to as the "NRCS Direct Volume Method," or the "Wisconsin method," (Wisconsin NRCS 2003). Soil loss is calculated by:

1. measuring the amount of exposed streambank in a known length of stream;
2. multiplying that by a rate of loss per year;

3. multiplying that volume by soil density to obtain the annual mass for that stream length; then
4. converting that mass into a mass per stream mile.

The Direct Volume Method is summarized in the following equation:

$$\frac{\text{(eroding area) (lateral recession rate) (density)}}{2{,}000 \text{ lbs/ton}} = \text{erosion in tons/year}$$

Data were compiled into a spreadsheet database that summarized stream length, total eroding area, Bank Condition Severity Rating, and soil texture. The estimated recession rate was multiplied by the total eroding area to obtain the estimated total annual volume of soil loss (Table D-1). To convert this soil loss to mass, soil texture was used to establish a volume weight for the soil. The total estimated volume of soil was multiplied by the assumed volume weight and converted into annual tons.

Table D-1. Okabena Creek and Sunset Bay Tributary streambank soil loss per year for identified problem areas.

Reach	Survey Segment	Eroding Bank Length (feet)	Eroding Bank Height (feet)	Area of Eroding Stream-bank (ft^2)	Lateral Recession Rate (Est.) (ft/yr)	Estimated Volume (ft^3) Eroded Annually	Soil Texture	Approx. Pounds of Soil per ft^3	Est. Soil Loss (tons/year)
Okabena Creek	OKA11	70	6.5	455	0.15	68.3	Silt Loam	85	2.9
Okabena Creek	OKA12	66	5.5	363	0.15	54.5	Silt Loam	85	2.3
Okabena Creek	OKA13	97	6.8	660	0.15	98.9	Silt Loam	85	4.2
Okabena Creek	OKA14	27	6.2	167	0.15	25.1	Silt Loam	85	1.1
Okabena Creek	OKA15	22	6.0	132	0.15	19.8	Silt Loam	85	0.8
Okabena Creek	OKA16	34	6.5	221	0.15	33.2	Silt Loam	85	1.4
Okabena Creek	OKA17	33	6.7	221	0.15	33.2	Silt Loam	85	1.4
Okabena Creek	OKA18	38	3.5	133	0.15	20.0	Silt Loam	85	0.8
Okabena Creek	OKA19	38	3.8	144	0.15	21.7	Silt Loam	85	0.9
Okabena Creek	OKA20	59	4.6	271	0.15	40.7	Silt Loam	85	1.7
Okabena Creek	OKA21	33	5.2	172	0.15	25.7	Silt Loam	85	1.1
Okabena Creek	OKA22	37	5.6	207	0.15	31.1	Silt Loam	85	1.3
Okabena Creek	OKA23	30	5.4	162	0.15	24.3	Silt Loam	85	1.0
Okabena Creek	OKA24	29	4.0	116	0.15	17.4	Silt Loam	85	0.7
Okabena Creek	OKA25	88	5.5	484	0.15	72.6	Silt Loam	85	3.1
Sunset Bay Trib	SB1R	13	6.5	85	0.18	15.2	Silt Loam	85	0.6
Sunset Bay Trib	SB2R	49	4.5	221	0.15	33.1	Silt Loam	85	1.4
Sunset Bay Trib	SB3L	12	4.0	48	0.20	9.6	Silt Loam	85	0.4
Sunset Bay Trib	SB4R	70	7.0	490	0.18	88.2	Silt Loam	85	3.7
Total Surveyed		**845**		**4,753**		**732.4**			**31.1**

Surveyed Bank Erosion Sites

The field photos and maps below document the areas that were observed to be actively eroding during the 2013 assessment survey. Table D-1 provides a complete summary of the average annual bank loss occurring at each sites.

Figure D-1. Okabena Creek streambank erosion location OKA11.

Figure D-2. Okabena Creek streambank erosion location OKA12.

Figure D-3. Okabena Creek streambank erosion location OKA13.

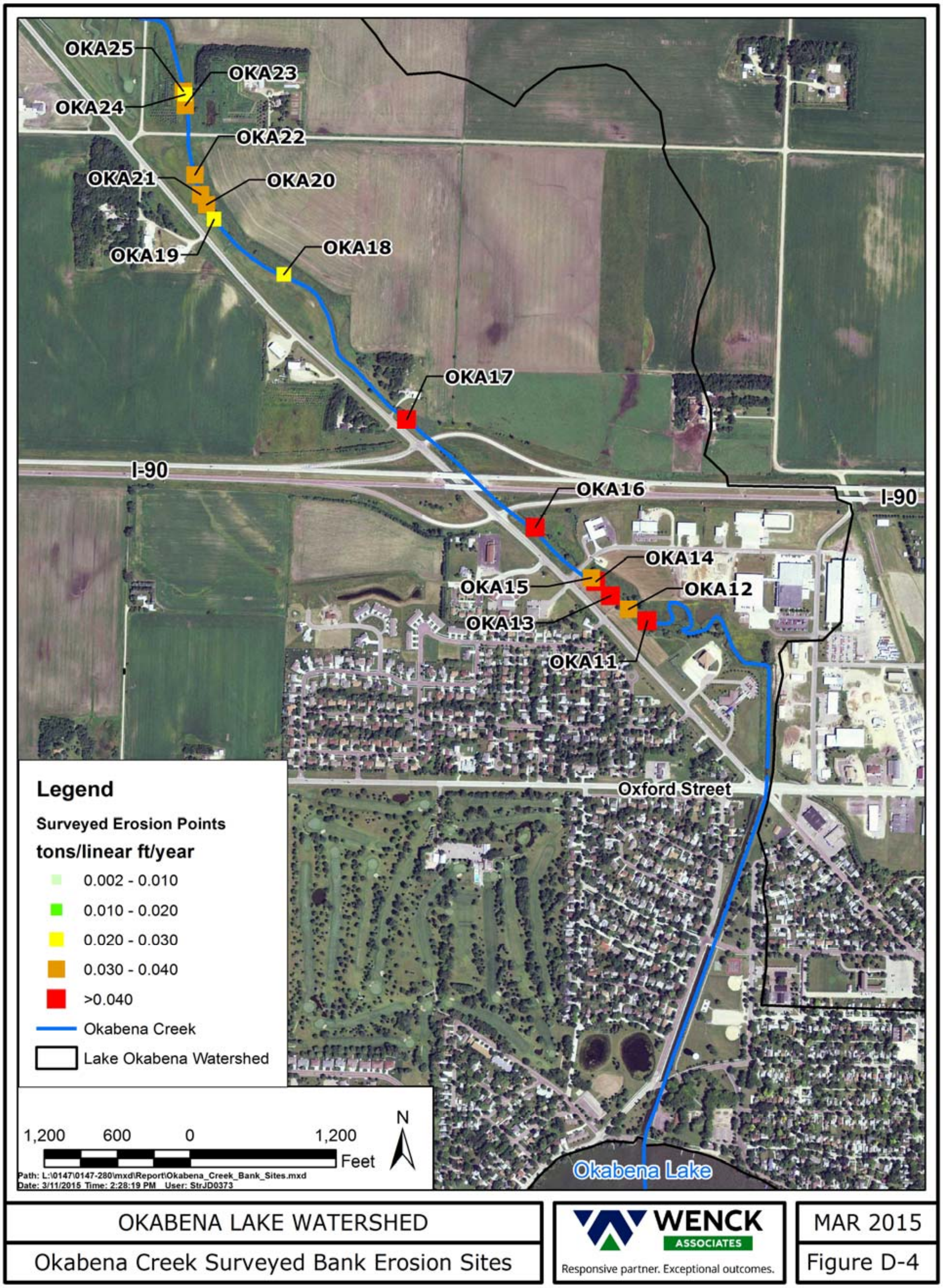

Figure D-4. Okabena Creek surveyed bank erosion locations.

Figure D-5. Sunset Bay tributary streambank erosion location SB1R.

Figure D-6. Sunset Bay tributary streambank erosion location SB2R.


Figure D-7. Sunset Bay tributary streambank erosion location SB3L.

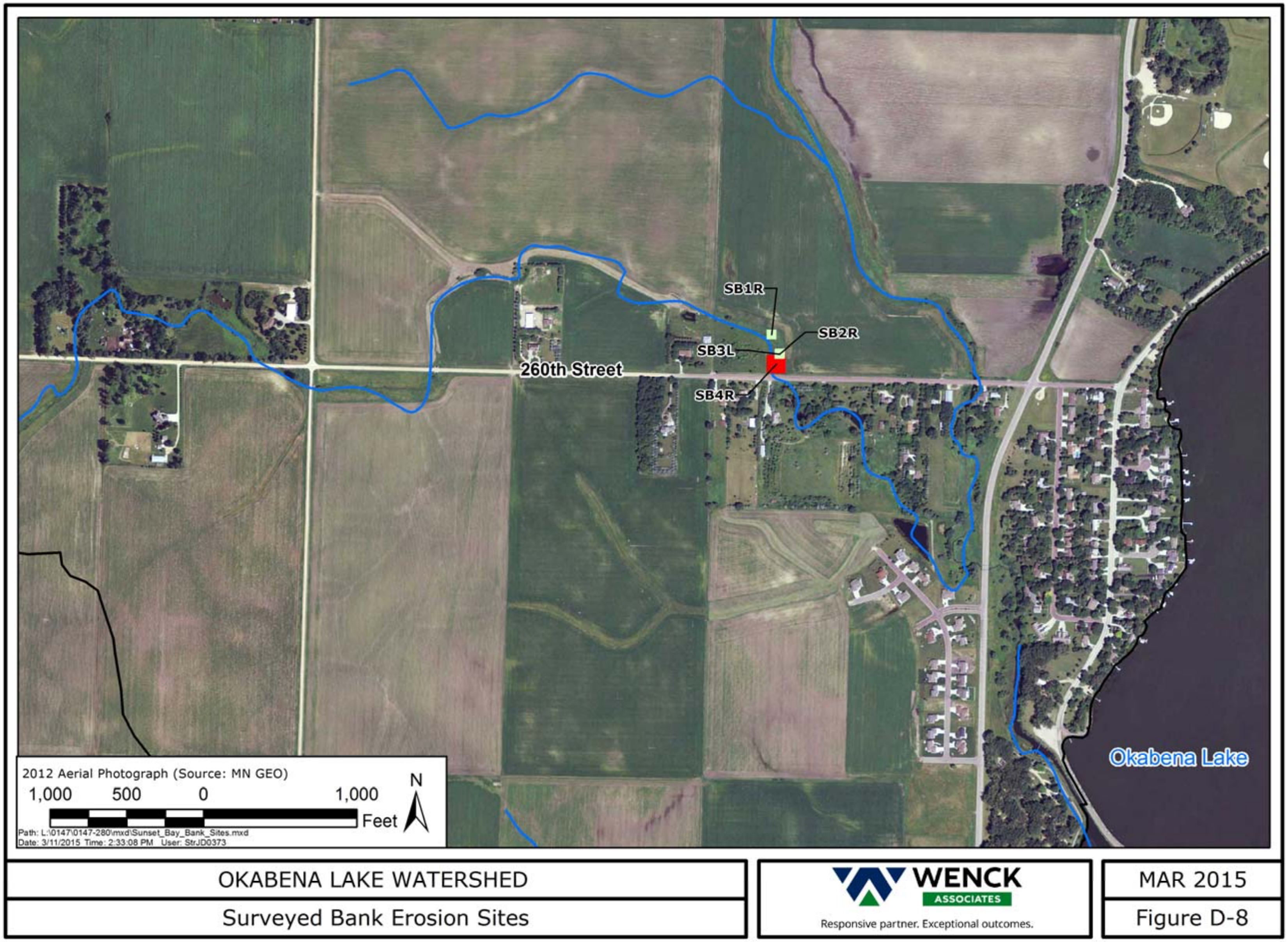

Figure D-8. Sunset Bay tributary surveyed bank erosion locations.

Appendix E

Internal Loading and Sediment Phosphorous Fractionation

Internal Phosphorus Loading and Sediment Phosphorus Fractionation Analysis for Lake Okabena, Minnesota

Google Maps

Wenck
Engineers • Scientists
Business Professionals

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10 May, 2014

OBJECTIVES

The objectives of this investigation were to determine rates of phosphorus (P) release from sediments under laboratory-controlled aerobic and anaerobic conditions and to quantify biologically-labile (i.e., subject to recycling) and refractory (i.e., biologically inert and subject to burial) P fractions for sediment collected in Lake Okabena, Minnesota.

APPROACH

Laboratory-derived rates of P release from sediment under anaerobic conditions: Sediment cores were collected by Wenck Associates, Inc. from centrally-located St. 1 in February, 2014, for determination of rates of P release from sediment under aerobic and anaerobic conditions (Figure 1 and Table 1). 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 lake 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 ^{o}C). The oxidation-reduction environment in the overlying water was controlled by gently bubbling nitrogen (anaerobic conditions, 3 replicates) or air (aerobic conditions, 3 replicates) 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) 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: In addition to St. 1, sediment cores were also collected in the dredged inlet area (i.e., St. 2; Figure 1) and at stations located in the western and eastern portion of Lake Okabena (Figure 1) for analysis of moisture content (%), sediment density (g/cm^3), loss on ignition (i.e., organic matter content, %), loosely-bound P, iron-bound P, labile organic P, total P, and total iron (Fe; all expressed at mg/g; Table 2). The sediment core collected at the centrally-located St. 1 was sectioned at 2-cm intervals over the upper 10 cm to examine vertical variations in sediment chemistry (Table 1). Sediment cores collected at St. 2, 3, and 4 were sectioned at 5-cm intervals over the upper 10 cm for analysis (Table 1). A known volume of sediment was dried at 105 ^{o}C for determination of moisture content and sediment density and burned at 550 ^{o}C for determination of loss-on-ignition organic matter content (Håkanson and Jansson 2002). Additional sediment was dried to a constant weight, ground, and digested for analysis of total P and Fe using standard methods (Anderson 1976, APHA 2005 method 4500 P.f., EPA method 3050B).

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 result in desorption of P from sediment and diffusion into the overlying water column (Mortimer 1971, Boström 1984, Nürnberg 1988). The sum of the loosely-bound and iron-bound P fractions represent redox-sensitive P (i.e., the P fraction that is active in P release under anaerobic and reducing conditions). 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-sensitive P and labile organic P collectively represent biologically-labile P. This fraction is generally 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.

RESULTS AND INTERPRETATION

P mass and concentration increased approximately linearly in the overlying water column of St. 1 sediment systems maintained under anaerobic conditions (Figure 2). Linear increases in P concentration were observed between day 3 and 14. The mean P concentration maximum in the overlying water end of the incubation period was moderate at 0.382 mg/L (± 0.049 standard error; SE; Table 2). The mean rate of P release under anaerobic conditions was also moderate at 2.7 mg/m^2 d (± 0.5 SE; Table 3), but indicative of eutrophic conditions (Nürnberg 1988). Overall, the mean anaerobic P release rate was lower relative to other lakes in the region, and fell in the lower 25% quartile (Figure 3).

Soluble phosphorus accumulation in the overlying water column was lower for sediment cores collected at St. 1 and incubated under aerobic conditions (Figure 4). However, the mean aerobic P release rate was moderately high at 0.62 mg/m^2 d (± 0.03 SE; Table 3) and fell within the upper 25% quartile compared to other lakes in the region (Figure 3). The maximum P concentration attained in the overlying water column toward the end of the incubation period was moderately high at 0.161 mg/L (± 0.014 SE). Typically, rates of P release are higher under anaerobic versus aerobic conditions, due to binding of P onto Fe~(OOH) in the sediment oxidized microzone under the latter condition and suppression of diffusive flux into the overlying water column. Since Lake Okabena is shallow and exposed to wind-generated mixing, aerobic conditions probably regulate P release rates from sediment throughout most if not all of the summer.

At St. 1, sediment moisture content was moderately low (range = 54% to 72%), while dry bulk density was relatively high (range = 0.340 g/cm^3 to 0.640 g/cm^3), suggesting that sediment was composed of compacted clays and fine silts (Table 4). Organic matter content was low at less than 10% (Table 4). Moisture content declined modestly, while sediment dry bulk density increased with increasing sediment depth at St. 1, suggesting compaction of deeper sediment layers (Figure 5). Organic matter content was homogeneous as a function of increasing depth (Figure 5). The surface sediment layer at St. 3 and 4 in the main basin of Lake Okabena exhibited similar patterns of low moisture content (64% to 67%), high sediment dry bulk density (0.42 g/cm^3 to 0.46 g/cm^3), and low organic matter content (7.0%), comparable to St. 1 characteristics. In contrast, St. 2 sediment, located in the dredged area of the lake, exhibited slightly higher moisture content, lower sediment dry bulk density, and higher organic matter content compared to the main basin sites (Table 4). This pattern probably reflected some accumulation of fine-grained, more flocculent, particulate sediment from the watershed drained by the western tributary.

In the main basin (i.e., St. 1, 3, and 4), loosely-bound P concentrations were relatively high, representing ~ 43% of the redox-sensitive P concentration (i.e., the sum of loosely-bound and iron-bound P) in the surface sediment layer (i.e., 0-5 cm; Table 5 and Figure

6). Iron-bound P accounted for ~ 57% of this mobile P fraction at the same main basin stations (Figure 6). Concentrations of loosely-bound P in the main basin were also high, while iron-bound P concentrations were moderate and fell within the lower 25% quartile, relative to other lakes in the region (Figure 7). In contrast, surface sediment in the dredged area of the lake (St. 2), exhibited much lower concentrations of loosely-bound P compared to main basin sediments (Figure 6). Iron-bound P concentrations at this station were moderate and similar to those in the main basin.

Labile organic P concentrations in the main basin surficial sediment layer were low relative to redox-sensitive P concentrations (~ 17% of the biologically labile P; Figure 6). Concentrations also fell below the 25% quartile compared to other lakes in the region (Figure 7), reflecting, perhaps, the overall low organic matter content in the sediment of this shallow lake. Surface sediment concentrations of labile organic P differed in the dredged area versus the main basin (Figure 6). Concentrations of this fraction were much higher at St. 2 compared to other stations, representing ~ 33% of the biologically-labile sediment P concentration. Like other surface sediment characteristics, this pattern coincided with station location near the inflow. Although higher compared to main basin stations, concentrations of labile organic P at St. 2 were moderate relative to other lakes in the region (Figure 7).

Total P concentration in the surface sediment layer was homogeneous for main basin stations and slightly lower at station 2 (Figure 6), ranging between 0.63 mg/g and 0.73 mg/g (Table 5). They were also low relative to other lakes in the region (Figure 8). Total iron concentrations in the surface sediment layer fell near the median compared to other lakes in the region (Figure 8). The Fe:P ratio was high, ranging between 25:1 and 37:1. Ratios greater than 10:1 to 15:1 have been associated with regulation of P release from sediments under oxic (aerobic) conditions due to efficient binding of P onto iron oxyhydroxides in the sediment oxic microzone (Jensen et al. 1992). Complete binding efficiency for P at these higher relative concentrations of Fe are suggested explanations for patterns reported by Jensen et al. At lower Fe:P ratios, Fe binding sites become increasingly saturated with P, allowing for diffusion of excess porewater P into the overlying water column, even in the presence of a sediment oxic microzone. P release rates for Lake Okabena sediments at St. 1 were moderate under aerobic conditions, a pattern that could be attributed to the Jensen et al. model.

Biologically-labile P and total P concentrations were homogeneous over the upper 10-cm sediment layer at St. 1 (Figure 9). In contrast, elevated concentrations in the upper 2- to 4-cm might indicate the accumulation of P in excess of burial, a pattern often associated with eutrophic lake sediments (Carey and Rydin 2012). Lake mixing and frequent periods of sediment resuspension/redeposition may play a role homogenizing the upper sediment layer in the lake.

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Table 1. Station identification labels and numbers of sediment cores collected in Lake Okabena for determination of rates of phosphorus (P) flux under aerobic or anaerobic conditions and biologically-labile and refractory P fractions (see Table 2).

Station	P Flux		P fractions	
	Aerobic	Anaerobic	0- to 5-cm and 5- to 10-cm sections	Vertical profile
1	3	3		1
2			1	
3			1	
4			1	

Table 2. Sediment physical-textural characteristics, phosphorus species, and metals variable 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
	Total P
Metals	Total Fe

Table 3. Mean (1 standard error in parentheses; n = 3) rates of phosphorus (P) release under aerobic and anaerobic conditions for sediments collected at station 1 in Lake Okabena.

Station	Diffusive P flux	
	Oxic ($mg\ m^{-2}\ d^{-1}$)	Anoxic ($mg\ m^{-2}\ d^{-1}$)
1	0.62 (0.03)	2.68 (0.47)

Table 4. Textural characteristics in the upper sediment layer for various stations in Lake Okabena.

Station	Section (cm)	Moisture Content (%)	Wet Bulk Density (g/cm^3)	Dry Bulk Density (g/cm^3)	Organic Matter (%)
1	0 - 2	71.8	1.190	0.341	7.9
1	2 - 4	68.0	1.223	0.397	7.4
1	4 - 6	63.6	1.262	0.468	7.4
1	6 - 8	62.5	1.273	0.487	7.2
1	8 - 10	54.0	1.355	0.639	7.5
2	0 - 5	77.7	1.137	0.258	12.3
2	5 - 10	72.7	1.175	0.328	11.5
3	0 - 5	64.3	1.258	0.457	6.9
3	5 - 10	62.4	1.274	0.489	7.0
4	0 - 5	66.8	1.235	0.417	6.9
4	5 - 10	57.9	1.320	0.568	6.4

Table 5. Concentrations of total iron (Fe), total phosphorus (P), the Fe:P ratio, and biologically labile and refractory P for various stations and sediment sections in Lake Okabena. DW = dry mass, FW = fresh mass.

Station	Section	Total Fe	Total P	Fe:P	Redox-sensitive and biologically labile P			
					Loosely-bound P	Iron-bound P	Iron-bound P	Labile organic P
	(cm)	(mg/g DW)	(mg/g DW)		(mg/g DW)	(mg/g DW)	(ug/g FW)	(mg/g DW)
1	0 - 2	18.60	0.730	25.5	0.150	0.208	59	0.074
1	2 - 4	18.90	0.741	25.5	0.136	0.204	65	0.063
1	4 - 6	18.55	0.695	26.7	0.116	0.183	67	0.055
1	6 - 8	20.71	0.658	31.5	0.133	0.197	74	0.066
1	8 - 10	21.07	0.704	29.9	0.143	0.152	70	0.046
2	0 - 5	22.96	0.626	36.7	0.043	0.276	62	0.159
2	5 - 10	23.56	0.706	33.4	0.035	0.264	75	0.137
3	0 - 5	17.95	0.713	25.2	0.120	0.159	57	0.056
3	5 - 10	17.79	0.700	25.4	0.107	0.162	61	0.049
4	0 - 5	19.38	0.717	27.0	0.170	0.218	73	0.081
4	5 - 10	19.42	0.743	26.1	0.134	0.161	68	0.043

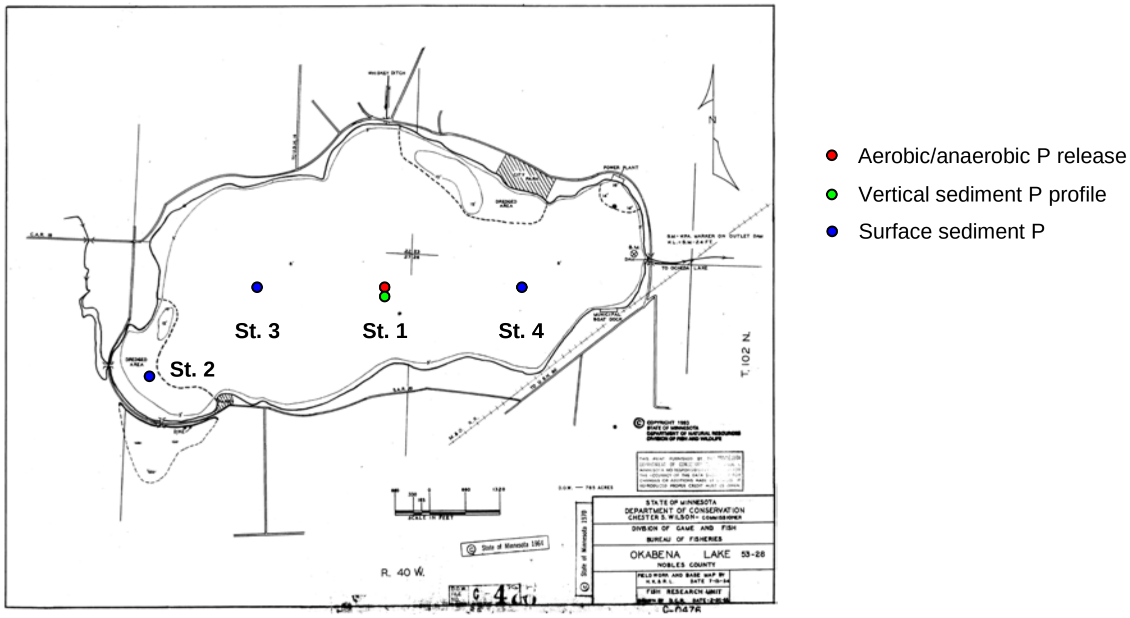

Figure 1. Station locations in Okabena Lake.

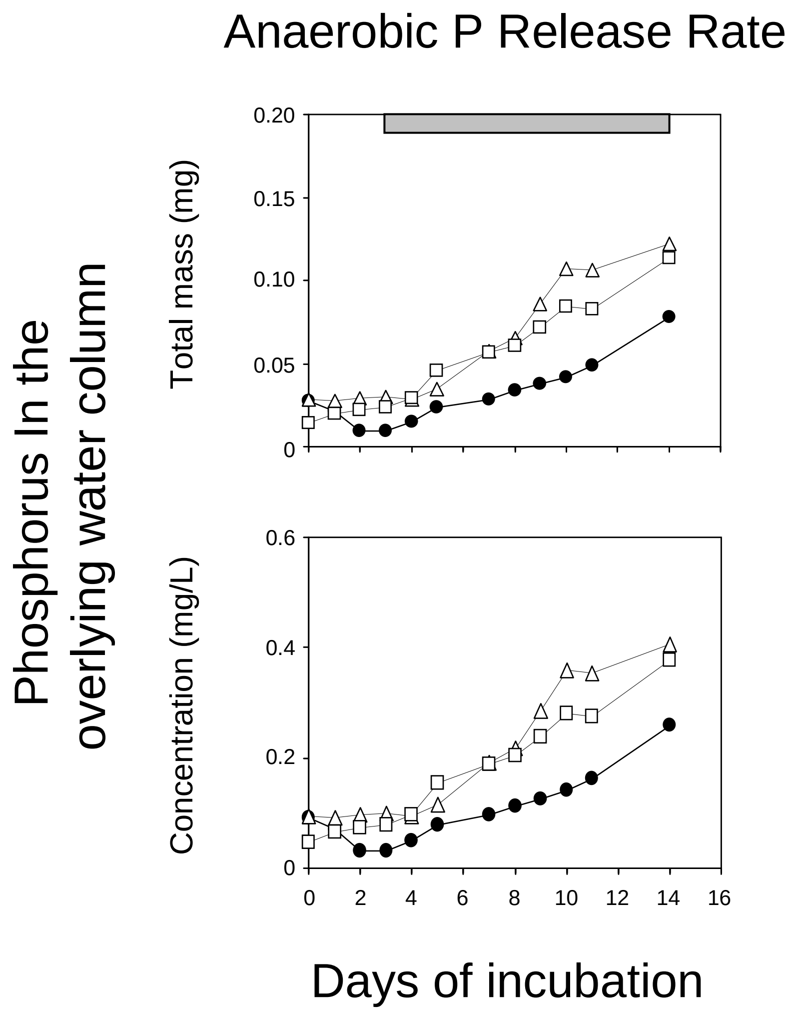

Figure 2. Changes in soluble reactive phosphorus mass (upper panel) and concentration (lower panes) in the overlying water column under anaerobic conditions versus time for sediment cores collected at station 1 in Okabena Lake. Gray horizontal bar denotes the time period used for rate estimation.

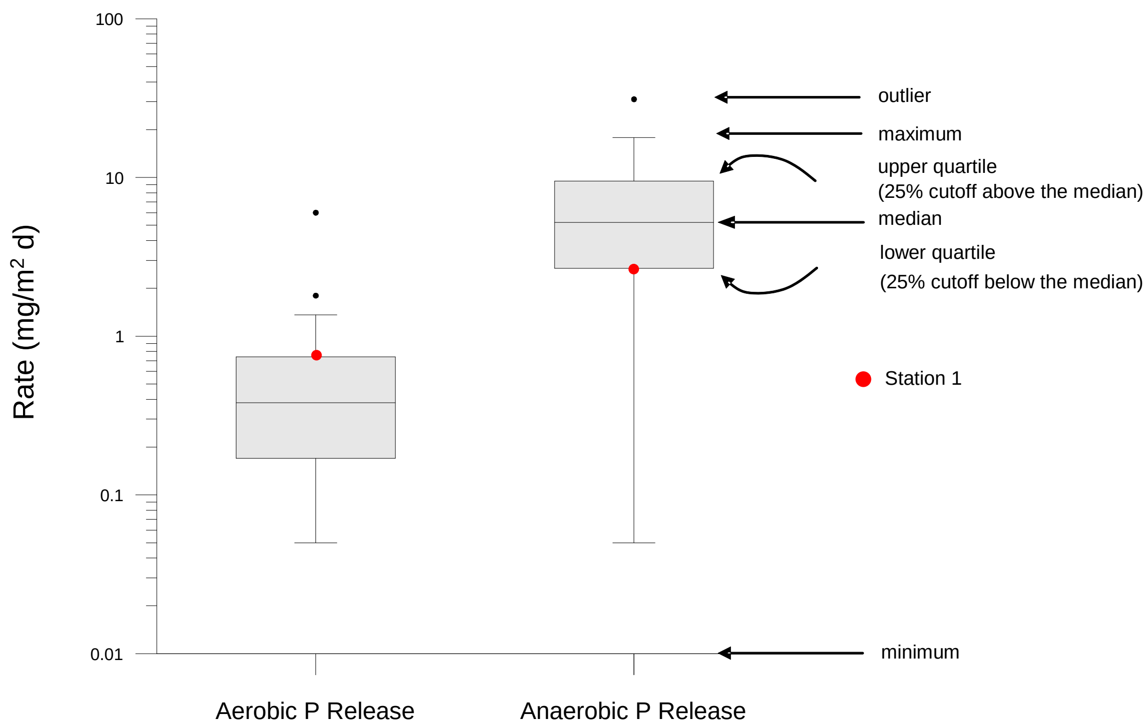

Figure 3. Box and whisker plot comparing the aerobic and anaerobic phosphorus (P) release rates measured for station 1 with statistical ranges for lakes in the region.

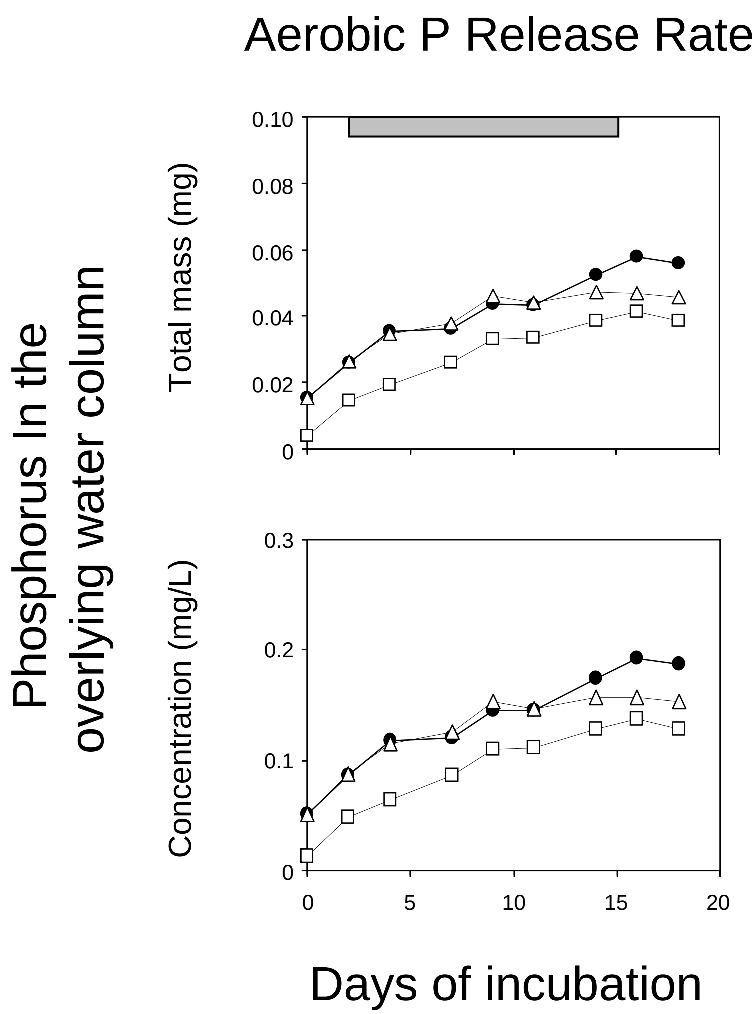

Figure 4. Changes in soluble reactive phosphorus mass (upper panel) and concentration (lower panels) in the overlying water column under aerobic conditions versus time for sediment cores collected from station 1 in Okabena Lake. Gray horizontal bar denotes the time period used for rate estimation.

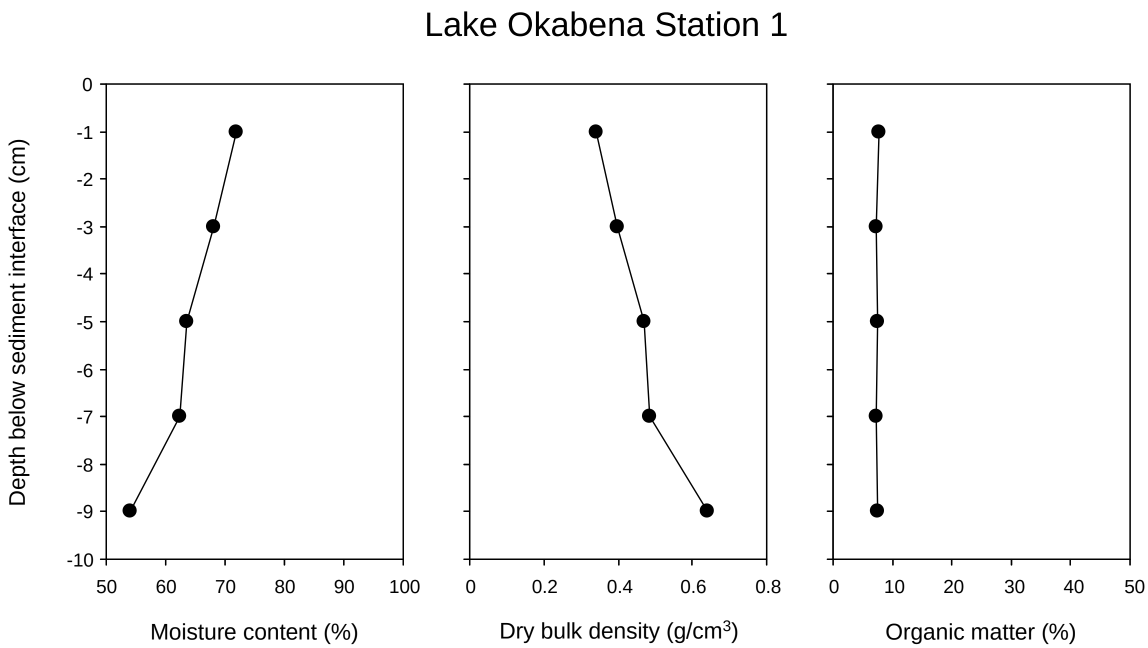

Figure 5. Variations in sediment moisture content, dry bulk density, and organic matter content as a function of depth below the sediment surface for a sediment core collected from station 1 of Okabena Lake.

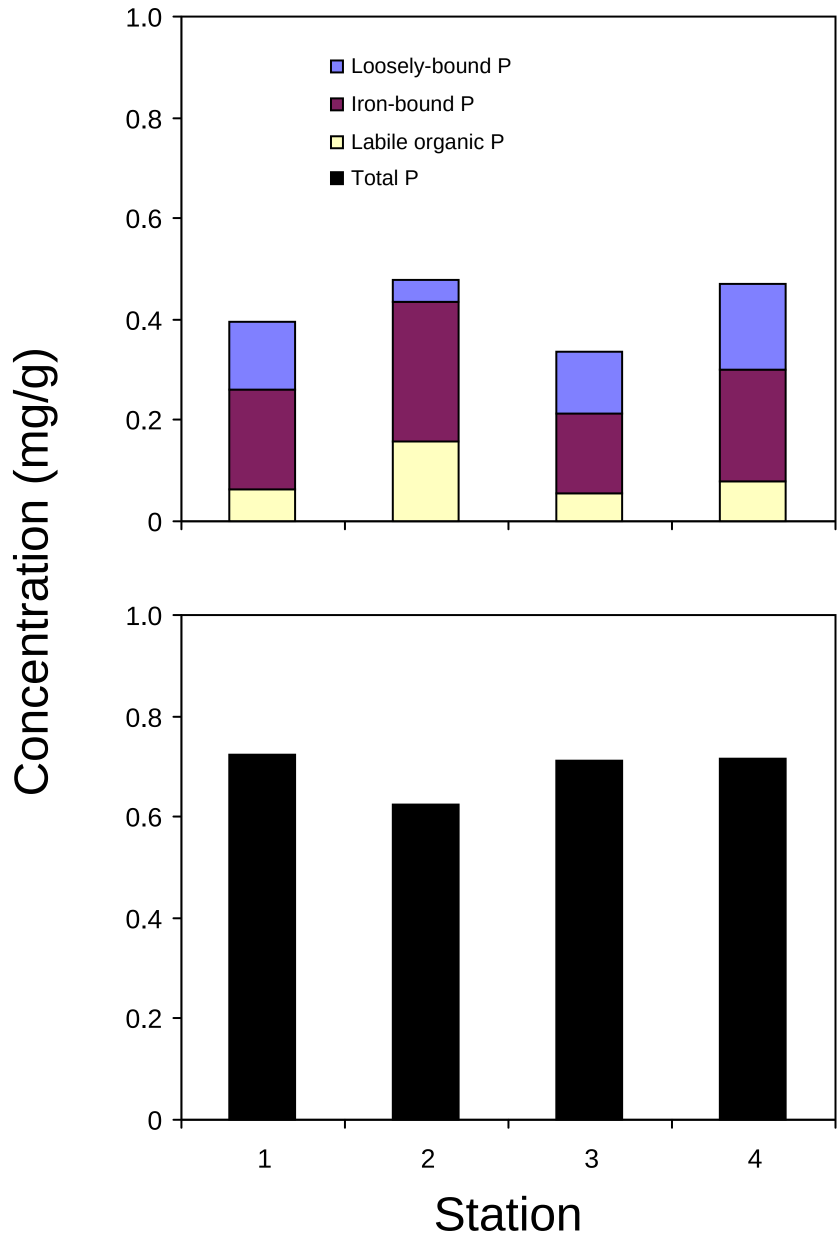

Figure 6. Variations in the concentration of biologically-labile phosphorus (P; i.e., subject to recycling with the overlying water column; sum of the loosely-bound, iron-bound, and labile organic P; upper panel) and total P (lower panel) in the upper 5-cm sediment layer for cores collected in Lake Okabena.

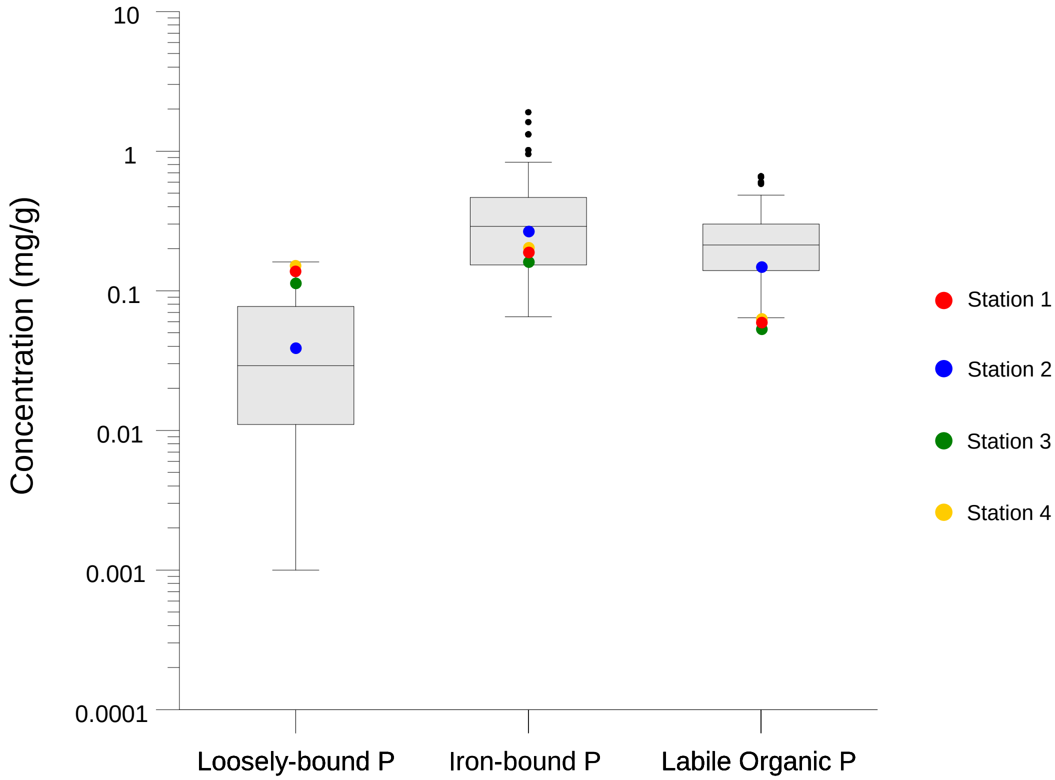

Figure 7. Box and whisker plot comparing various sediment phosphorus (P) fractions measured for various stations in Okabena Lake with statistical ranges for lakes in the region. Loosely-bound, iron-bound, and labile organic P are biologically-labile (i.e., subject to recycling). Please note the logarithmic scale.

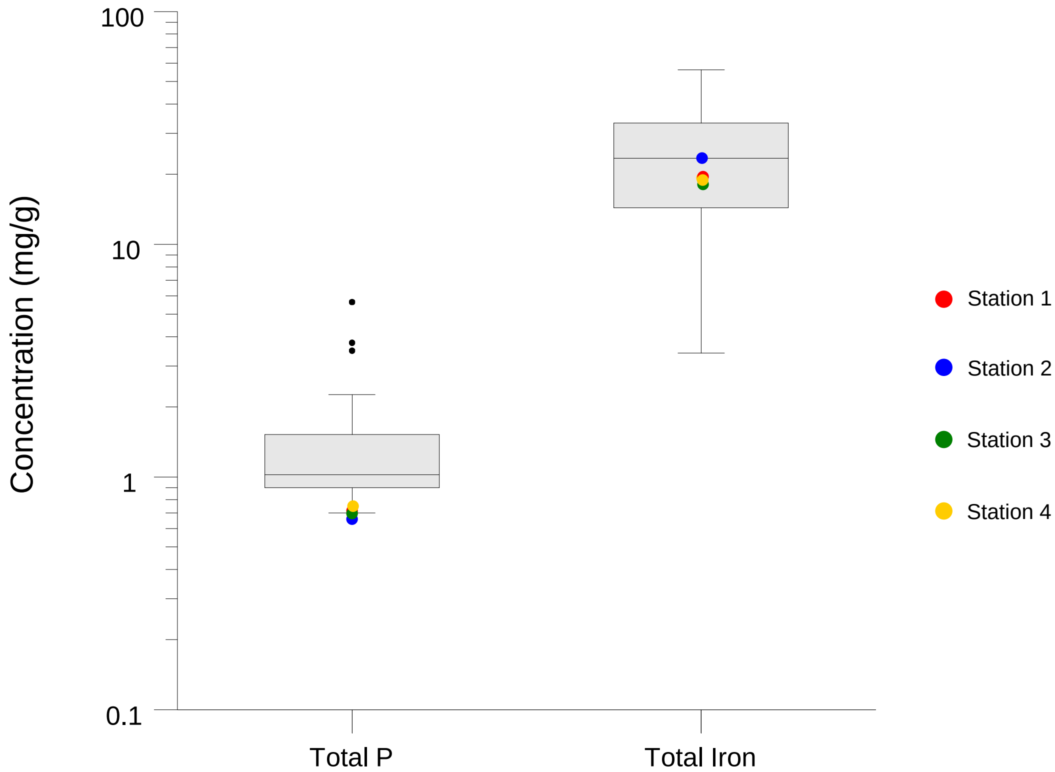

Figure 8. Box and whisker plot comparing total phosphorus (P) and total iron (Fe) measured for various stations in Okabena Lake with statistical ranges for lakes in the region. Please note the logarithmic scale.