TMDL Summary Table

(to be included in report preceding executive summary)

EPA/MPCA Required Elements	Summary			TMDL Page #
Location	Upper Mississippi Drainage Basin, Hennepin County, MN			
303(d) Listing Information	Waterbody: Lake Sarah Lake Assessment Unit ID: 27-0191-01 (Lake Sarah - West Bay) and 27-0191-02 (Lake Sarah - East Bay) Affected Use: Aquatic Recreation Pollutant or Stressor: nutrient/eutrophication biological indicators (Phosphorus) Original Listing: 2004, Category ??? Subsequent Changes: ??? Priority Ranking: ???			
Applicable Water Quality Standards/ Numeric Targets	Class 2B Eutrophication Standards (Lakes and Reservoirs in North Central Hardwood Forest Ecoregion): Phosphorus, total: 40 µg/L Chlorophyll-a: 14 µg/L Secchi disc transparency: not less than 1.4 m Source: Minnesota Rule 7050.0222 Subp. 4.			
Loading Capacity (expressed as daily load)	1356 lbs/yr Total Phosphorus (TP) representing an annual average daily load of 3.74 lbs TP/day Critical condition is defined as the summer growing season.			
Wasteload Allocation	Total WLA = 1155 lbs/yr (2.77lbs/day)			
	Source	**Permit #**	**Individual WLA**	
	Corcoran	MS400081	0.28 lbs/day	
	Independence	MS400095	0.48 lbs/day	
	Loretto	MS400030	0.05 lbs/day	
	Median	MS400105	0.27 lbs/day	
	Hennepin County	MS400138	0.01 lbs/day	
	MN DOT (Metro)	MS400170	0.02 lbs/day	
	Reserve Capacity	NA	0 lbs/day	
	Industrial Stormwater*	NA	NA	

	Construction Stormwater	MN R 100001	0.004 lbs/day	
	* No known industrial discharges			
Load Allocation	Total Load Allocation = 148 lbs/yr (0.41 lbs/day)			
	Source	**LA**		
	Atmospheric Deposition	0.41 lbs/day		
	Greenfield	1.65 lbs/day		
	Internal Loading	0 lbs/day *		
	* represents 0 lbs P above background levels implicitly represented in the models			
Margin of Safety	Explicit Margin of Safety = 198 lbs/yr (0.54 lbs/day) MOS established to achieve an in-lake TP concentration of 36, 4 µg/L lower than the water quality standard.			
Seasonal Variation	Seasonal variation is being addressed by using average growing-season conditions to quantify in-lake condition (thereby integrating intraseasonal variability) and by basing watershed assessments on 10-year average conditions (thereby integrating interseasonal variability).			
Reasonable Assurance	Reasonable assurance is provided through: 1) required adoption of the TMDL into local Stormwater Pollution Prevention Plans (SWPPP); 2) required alignment of Local Surface Water Management Plans with the *Pioneer-Sarah Creek Watershed Commission (PSCWC) 2nd Generation Plan;* and 3) cooperative efforts of the PSCWC and local municipalities in implementing Best Management Practices			
Monitoring	A comprehensive monitoring plan is included to assess: 1) progress toward the completion of TMDL implementation activities; 2) progression of the lake toward compliance with water quality standards; 3) sources of uncertainty within the TMDL analysis; 4) effectiveness of current BMPs; and 5) design of future BMPs			
Implementation	A detailed implementation plan is included that addresses a range of implementation options, likely phosphorus reductions and anticipated costs			
Public Participation	The Lake Sarah TMDL has had an extensive public process that has included 10 general Stakeholder Meetings and 14 directed meetings with City Council and Planning Commissions.			

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Introduction

1.1 Purpose

The goal of this Total Maximum Daily Load (TMDL) analysis is to quantify the phosphorus reduction that will be required to meet the water quality standards established for Lake Sarah and identify phosphorus reduction strategies in accordance with section 303(d) of the Clean Water Act.

Lake Sarah was identified as a priority resource in the *Pioneer-Sarah Creek Watershed Commission 2nd Generation Plan*. A Lake Sarah Project Report and implementation plan was completed in December, 1996 that suggested a number of projects to enhance lake quality. This list of projects included estimates of associated cost, expected effectiveness, predicted longevity, and technical feasibility for each proposed management alternative. Selection of actions for implementation required public discussion and cooperation between many concerned parties to evaluate and select the most acceptable management alternatives from this list. Through cooperative efforts between Three Rivers Park District, local municipalities, and the Minnesota Pollution Control Agency (MPCA), this diagnostic/feasibility study evolved into the Lake Sarah Phosphorus TMDL.

1.2 Problem Statement – 303d Listing

In 2004, Lake Sarah was identified for impairment of aquatic recreation (swimming) and placed on the MPCA 303(d) list of impaired waters. Inclusion in the 303(d) list was based excess nutrients - the Lake Sarah mean growing-season phosphorus concentration was consistently in excess of the MPCA State water quality standard of 40 μg/L (applicable for deep lakes). See the water quality monitoring section below for a more detailed discussion of the data supporting the 303d listing.

1.3 Applicable Water Quality Standards

Lake Sarah is located in the North Central Hardwood Forest Ecoregion, and is designated as a Class 2B water under Minnesota Rule 7050.0430. Class 2 waters are defined as:

> *Aquatic life and recreation. Aquatic life and recreation includes all waters of the state that support or may support fish, and other aquatic life, bathing, boating, or other recreational purposes and for which quality control is or may be necessary to protect aquatic or terrestrial life or their habitats or the public health, safety, or welfare (Minnesota Rule 7050.0140).*

Numeric water quality criteria applicable to deep (i.e., 15 feet maximum depth and less than 80% littoral area) lakes and reservoirs in the North Central Hardwood Forest Ecoregion are (Minnesota Rule 7050.0222 Subp 4):

- Phosphorus, total: 40 μg/L
- Chlorophyll-a: 14 μg/L
- Secchi disc transparency: not less than 1.4 m

Conditions for impairment are based on:

> *Eutrophication standards are compared to data averaged over the summer season (June through September). Exceedance of the total phosphorus and either the chlorophyll-a or Secchi disk standard is required to indicate a polluted condition (Minnesota Rule 7050.0222 Subp. 4a)*

1.4 Description of Lake Sarah and the Surrounding Watershed

1.4.1 History

Lake Sarah (East and West Bays; MNDNR Lake ID# 27-0191-01 and 27-0191-02) is a 561-acre lake located approximately 24 miles west of Minneapolis in west central Hennepin County (Figure 1.1). The Lake Sarah watershed was dominated by woodlands, grassland and wetlands before initial European settlement of the Greenfield area (then Greenwood) in the 1850s. Lake Sarah was named after the wife or sweetheart of an unknown pioneer in 1855. It was alternately called Union Lake and Long Lake before Lake Sarah became the accepted name. The onset of agriculture brought the removal of the hardwood forests and the draining of wetlands and small lakes in the watershed. Agriculture has continued to dominate the landscape in the Lake Sarah Watershed, though agricultural parcels are being subdivided to accommodate rural residential development on 2 to 40 acre lots.

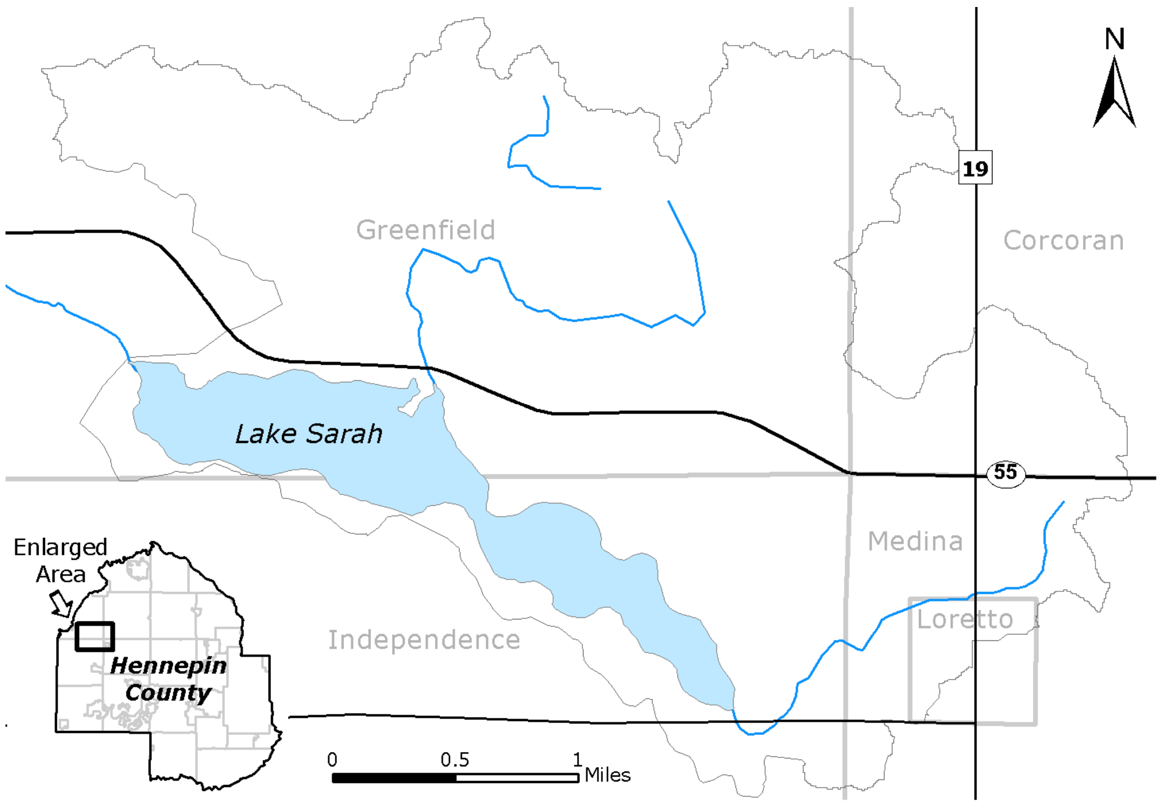

Figure 1.1. Locator map for the Lake Sarah watershed.

The Lake Sarah watershed has been heavily influenced by its proximity to Minneapolis, 24 miles to the east. The Soo Line Railroad was laid through the Greenfield, Loretto, and Medina in the 1880s and Lake Sarah became a popular summer destination for vacationers from Minneapolis. The downturn in the resort industry occurred with the onset of the Second World War and the resort buildings were converted to homes or removed to make way for shoreline development. The final resort was closed in 1993. The main automobile route in the area, State Highway 55, was paved in the 1940s and provides automobile traffic to and from Minneapolis. The current trend towards rural residential development is a continuation of the expansion of Minneapolis suburban development to the west.

1.4.2 Land Use

Lake Sarah receives runoff from a 5,005-acre mixed-use watershed which drains land from portions of five municipalities – Greenfield, Independence, Corcoran, Loretto, and Medina (Figures 1.1 and 1.2). The primary land uses are agriculture (23%), rural residential (22%), medium density residential (7%), wetland (21%) and commercial (3%). Approximately 3% of the land in the watershed is dedicated to pasture and feedlots for horses and cattle. Most of the shoreline land is occupied by single family residential homes, but the shoreline also includes a horse farm, a cattle farm, wetland areas, and parkland. Property along the western shoreline of the lake is within Lake Sarah Regional Park, operated by Three Rivers Park District.

In recent years, agricultural land has been increasingly converted into residential and commercial developments in the Lake Sarah watershed. Development of agricultural land into low density residential, medium density residential and commercial land uses is expected to continue. The Metropolitan Council's 2030 land use plan includes substantial areas that will be zoned for residential and commercial development.

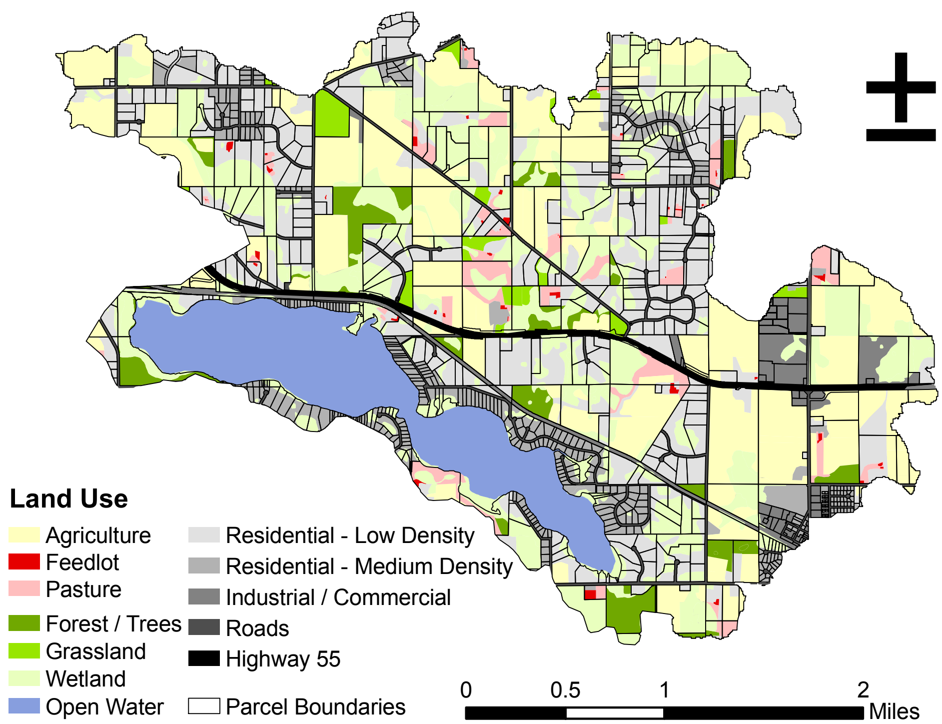

Figure 1.2. Land use throughout the Lake Sarah watershed for 2008.

1.4.3 Climate

Lake Sarah and its surrounding watershed are located within the Northern Central Hardwood Forest ecoregion. The closest weather station to the Lake Sarah Watershed is the cooperative observer station at Rockford, MN (COOP ID 217020). Average annual precipitation for this station from 1979 to 2008 is 754 mm (29.7 inches; Table 1.1). Approximately 72% of the precipitation falls as rain during the six-month growing season of May to October. Yearly ice cover records have not been kept on Lake Sarah, but typically ice cover is established in the end of November and disappears the first week of April.

Based on current trends in Minnesota, regional climate is expected to experience increases in: precipitation, dew points, winter overnight temperatures, and rainfall intensities during convective storms (Seeley, 2003). Increased rainfall intensities and precipitation amounts are expected to result in increased runoff and potential for phosphorus transport.

Table 1.1. Annual and growing season precipitation for Rockford, MN.

Period	Annual precipitation, mm	May to October precipitation, mm
1979-2008, average	754	546
2007	732	527
2008	547	397

1.4.4 Geology and Soils

The topography of the Lake Sarah watershed, like much of Hennepin and the surrounding counties, is the product of glacial processes and ice wasting during and after the last glacial maxima, approximately 14,000 years ago. Soils in the Lake Sarah watershed were formed from glacial till parent material (Steffen, 2001) and include some relatively clay-rich lenses compared with other tills in Hennepin County. The till units found in the watershed are loamy tills and clayey tills associated with the Des Moines Lobe. There are also some small areas of lacustrine clay and silt deposited by glacial lakes. Soils in the Lake Sarah watershed overlay approximately 100 to 300 feet of unconsolidated glacial material. The Franconia Formation, an Upper Cambrian dolomitic sandstone and shale, is the first bedrock layer below the unconsolidated material.

The Lake Sarah watershed includes soils in four soil orders: Mollisols, Histosols, Alfisols, and Entisols. The dominant orders in the non-wetland areas are Mollisols and Alfisols. Small areas along the lake shore and in Loretto are classified as Entisols. Soils classified as Histosols dominate the wetland areas. Textures range from sandy over loamy to fine, but the majority of the soils are fine-loamy.

Soils in the Lake Sarah watershed are within the entire spectrum of well drained (soil hydrologic group A) to poorly drained (soil hydrologic group D). The majority of the watershed area is in the B soil hydrologic group (Table 1.2) and classified as moderately well drained. Soils in the A/D, B/D, and C/D soil hydrologic groups are wetland soils and the two hydrologic group classifications refer to the normal and wetted drainage of the soil. Because of the variation in natural drainage in the watershed, there are some tile lines in place to drain agricultural fields.

Table 1.2. Soil areas in each of the soil hydrologic groups in the Lake Sarah watershed.

Soil Hydrologic Group	Area, acres
None (Water or Urban land)	546
A/D	741
B	2922
B/D	732
C	327
C/D	78

1.4.5 Demographic Information

The five municipalities in the Lake Sarah watershed are experiencing population growth and residential development (Table 1.3). The portion of three of these communities, Greenfield, Medina, and Corcoran, that is in the Lake Sarah watershed is currently in rural land uses and is anticipated (based on 2030 Comprehensive Plans) to continue to develop significantly in future years. The remaining two communities, Loretto and Independence, are predominantly developed within the watershed boundary and will only undergo small amounts of further development.

Table 1.3. Populations of the five municipalities in the Lake Sarah watershed from 1990 to 2030.

	Population				
Place	1990 Census	2000 Census	2010 Projected	2020 Projected	2030 Projected
Loretto	404	570	690	700	700
Independence	2,822	3,236	4,000	4,480	4,900
Medina	3,096	4,005	5,800	9,200	12,700
Corcoran	5,199	5,630	11,600	19,900	24,600
Greenfield	1,450	2,544	3,190	4,050	4,300
Total	12,971	15,985	25,280	38,330	47,200

1.4.6 Lake Morphometry and Hydrology

Lake Sarah is a deep (maximum depth of 59 feet and a mean depth of 9.7 feet), elongated lake of glacial origin with two bays: a west bay and an east bay. Water flows down gradient in the lake from east to west, where the outlet is located. In 2004, the lake outlet was set at 985.42 feet. Lake Sarah is fed by three surface water inlets and direct runoff from surrounding areas (Figure 1.3). Precipitation and shallow groundwater also contribute water directly to the lake. Information about the morphometry, watershed, and observed water quality are found in Table 1.4.

Table 1.4. Lake Sarah physical characteristics.

Morphometry and Watershed	
Lake area (acre)	561
Maximum depth - (feet)	59
Mean depth (feet)	9.7
% Littoral (% of basin 15 feet or less in depth)	65
Drainage area (total acre)	5,006
Watershed: lake area ratio	8.9
Water residence time (years)	1.95
Thermally stratified in summer?	Yes
Does lake have surface outlet?	Yes
Is the lake a "created" lake?	No
Is the lake managed as a reservoir?	No

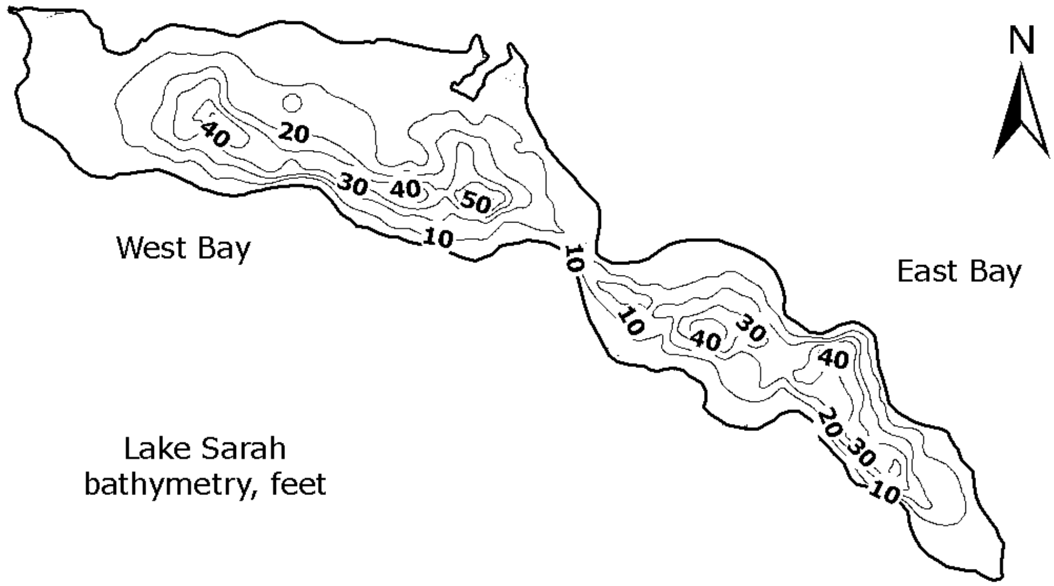

Figure 1.3. Lake Sarah depth contours in feet.

1.4.7 Lake Water Quality

Lake Sarah has been monitored biweekly during the ice-free season in 1991 and yearly from 1996 to 2008 with the exception of 1999, 2001, and 2003. Monitoring efforts have characterized changes in total phosphorus (TP), soluble reactive phosphorus (SRP), chlorophyll-*a* (Chl-*a*), temperature, conductivity, dissolved oxygen (DO) and secchi depth. All in-lake data have been collected by Three Rivers Park District water resource staff following standard procedures for eutrophic lake assessment (Heiskary 1994 and MPCA 2007). Based on the monitoring data, Carlson's Trophic State Index (TSI; Carlson, 1977) range from 54 to 70.7 (eutrophic to hypereutrophic; Table 1.5). Average annual total phosphorus concentration (Figure 1.4) show no trend throughout the data record, but average chlorophyll-*a* concentration (Figure 1.5) has increased annually and average secchi depth (Figure 1.6) has decreased, indicating a trend towards larger algae populations. In any given year, water quality changes significantly throughout the summer, generally resulting in increased algal blooms and reduced water clarity by late summer (Figure 1.7). Lake Sarah did not meet the state standard for average annual total phosphorus for recreational contact in any year it was monitored.

Table 1.5. Average observed water quality for Lake Sarah.

Observed WQ - Summer mean	
TP ppb (CV)	101 (0.22)
Chl-a ppb (CV)	41.9 (0.30)
Secchi m (CV)	1.52 (0.33)

Lake Sarah has two bays, a west bay with a maximum depth of 59 feet and an east bay with a maximum depth of 53 feet. From 1991 to 2007 only the west bay was monitored. Both bays were monitored in 2008 to examine potential water quality differences. Water quality and stratification were very similar in both bays throughout 2008; and thus, data gathered in the west bay was used to represent the water quality condition of the entire lake (Appendix A).

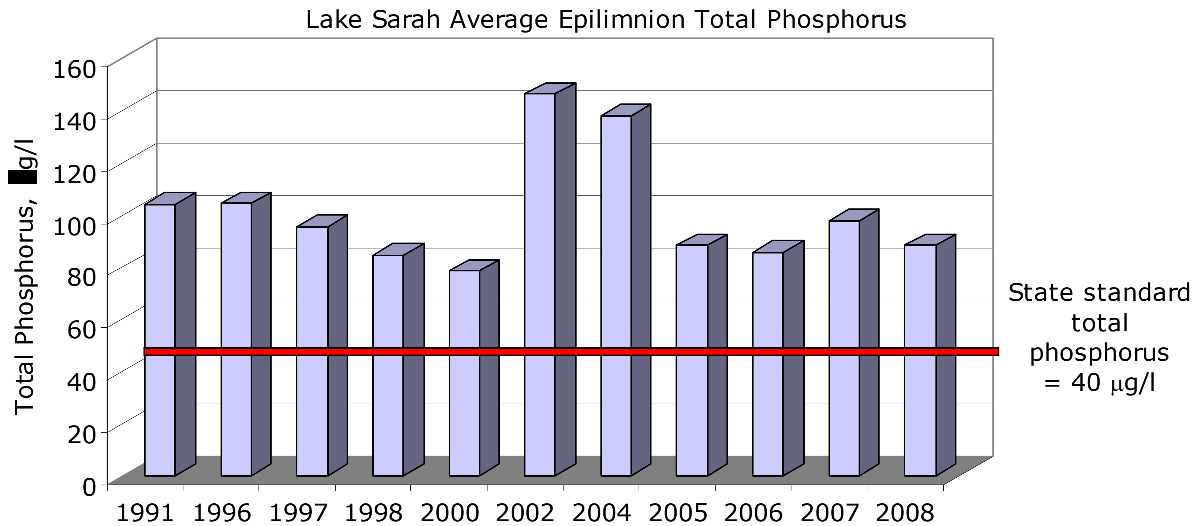

Figure 1.4. Average growing season epilimnion total phosphorus for Lake Sarah.

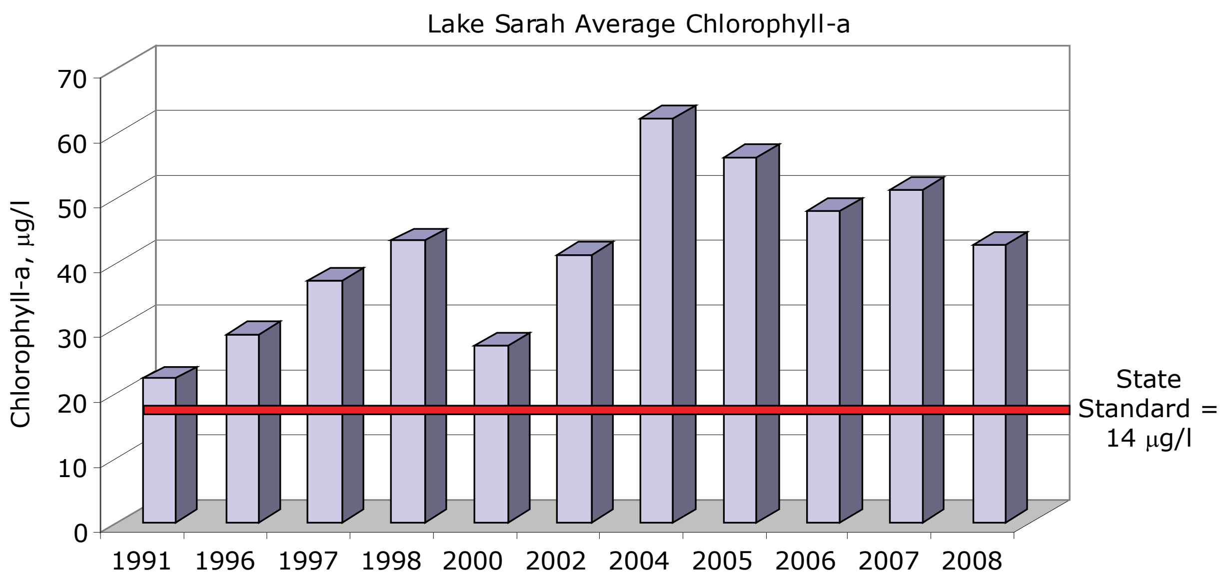

Figure 1.5. Average growing season epilimnion chlorophyll-a for Lake Sarah.

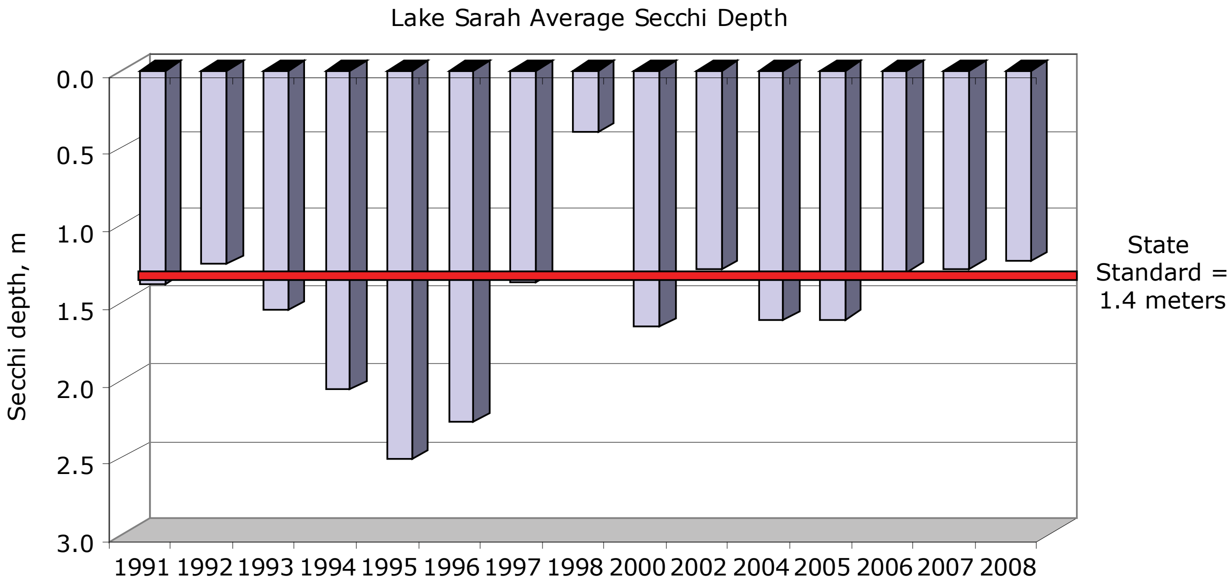

Figure 1.6. Average growing season secchi depth for Lake Sarah. Secchi depth was monitored 1992-1995 when total phosphorus and chlorophyll-*a* were not monitored.

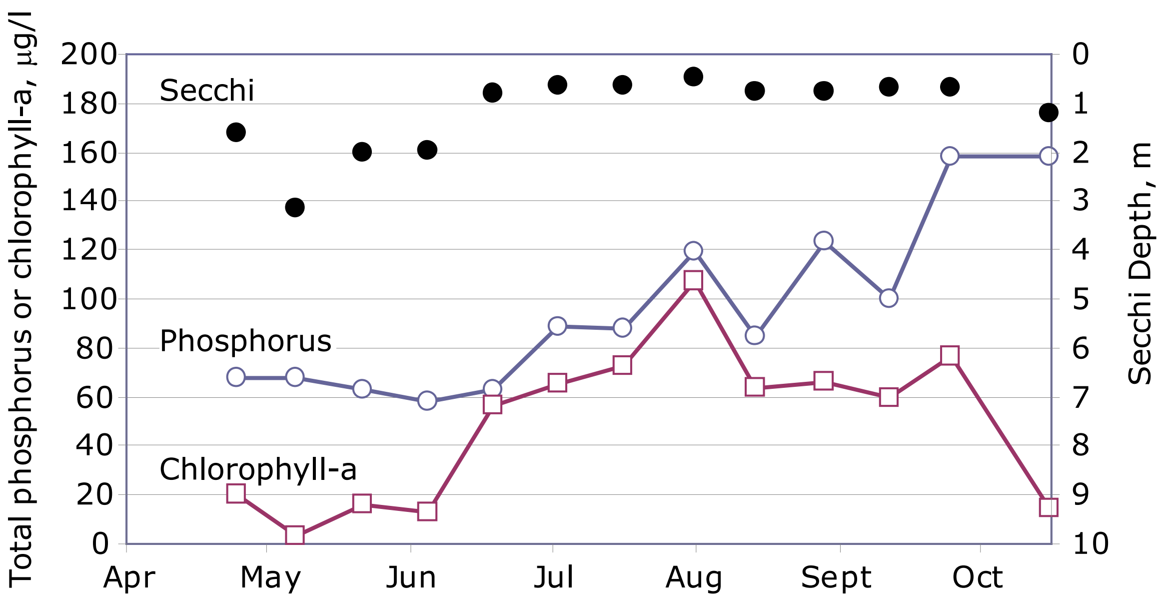

Figure 1.7. Bi-weekly monitoring data from 2007 for Lake Sarah showing typical annual variations of secchi depth, total phosphorus, and chlorophyll-*a*.

1.4.8 <u>Fishery Status</u>

Lake Sarah is heavily used by anglers and supports a high-quality northern pike fishery, in addition to abundant bluegill and crappie. Other fish species sampled by Minnesota Department of Natural Resources (MN DNR) in 2007 include black bullhead, bowfin, common carp, golden shiner, hybrid sunfish, largemouth bass, pumpkinseed, yellow bullhead and yellow perch. Lake Sarah was also stocked with walleye fry in 2006 and 2007. There are fish consumption guidelines for bluegill sunfish, bullhead, carp, crappie, and northern pike based on mercury contamination.

1.4.9 Aquatic Vegetation

Five aquatic vegetation surveys of the littoral areas of Lake Sarah (Table 1.6) have been completed between June, 2006 and September, 2008. Lake Sarah supports an aquatic vegetation community that includes Coontail, Muskgrass, Canada waterweed, Star duckweed, Common milfoil, Yellow waterlily, White waterlily, Sago pondweed, Water celery and two nuisance exotic species: Curlyleaf pondweed and Eurasian milfoil. The relatively short time period over which the surveys were conducted was not sufficient to detect long-term trends, but it is clear that the three most common species sampled were Coontail, Eurasian milfoil and curlyleaf pondweed. All surveys have been conducted by Three Rivers Park District water resource staff following standard methods (e.g., Madsen, 1999).

The presence of large populations of curlyleaf pondweed and Eurasian milfoil have different effects on the lake ecosystem. Eurasian milfoil, which was confirmed in Lake Sarah in 1990, is primarily an impediment to navigation and recreation. Eurasian milfoil reaches its peak during the late summer and forms dense mats near the surface and obstructs motorboat traffic. In addition, Eurasian milfoil shades and outcompetes native plants – often dominating the aquatic plant community in mid to late summer. Alternatively, curlyleaf pondweed begins growth under the ice and is established before ice-out. Thus, shading from curlyleaf pondweed gives it a competitive advantage and hinders the establishment of native plants. Curlyleaf pondweed naturally senesces in June/July and its subsequent decomposition releases soluble phosphorus into the water column where it is available for uptake by algae and often contributes to water quality degradation.

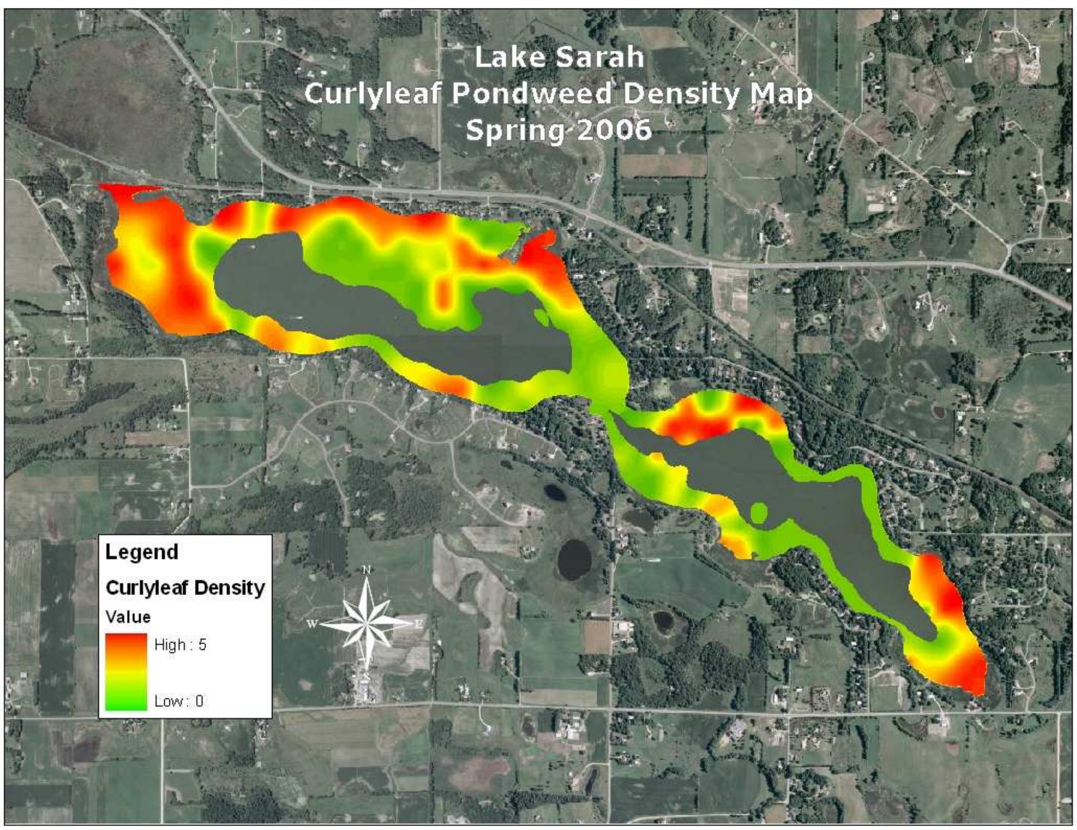

Figure 1.8. Curlyleaf pondweed density through the littoral zone of Lake Sarah during the spring survey of 2006.

Table 1.6. Species found during aquatic vegetation surveys of Lake Sarah.

		Percent Occurrence				
Scientific Name	Common Name	June, 2006	September, 2006	June, 2007	June, 2008	September, 2008
Ceratophyllum demersum	Coontail	12	13	10	18	32
Chara	Muskgrass	0	0	0	0	2
Elodea canandensis	Canada waterweed	0	1	0	0	2
Lemna trisulca	Star duckweed	0	3	0	15	16
Myriophyllum exalbescens	Common milfoil	0	0	0	0	3
Myriophyllum spicatum	Eurasian milfoil	11	24	16	21	32
Nuphar spp.	Yellow waterlily	1	5	3	0	0
Nymphaea spp.	White waterlily	1	7	6	0	4
Potamogeton crispus	Curly-leaf pondweed	59	8	19	44	12
Potamogeton pectinatus	Sago pondweed	0	1	0	0	8
Vallisneria americana	Water celery	0	1	0	0	3

Watershed Monitoring

To understand the relative sources of phosphorus from the watershed, water quality was monitored throughout the Lake Sarah watershed from April to November in both 2007 and 2008. The East and West Tributary sites were monitored during both 2007 and 2008 and the East Upstream and West Upstream sites were monitored from June to November, 2008 (Figure 2.1). The West Upstream site was not included in the analysis because equipment problems produced an inconsistent record.

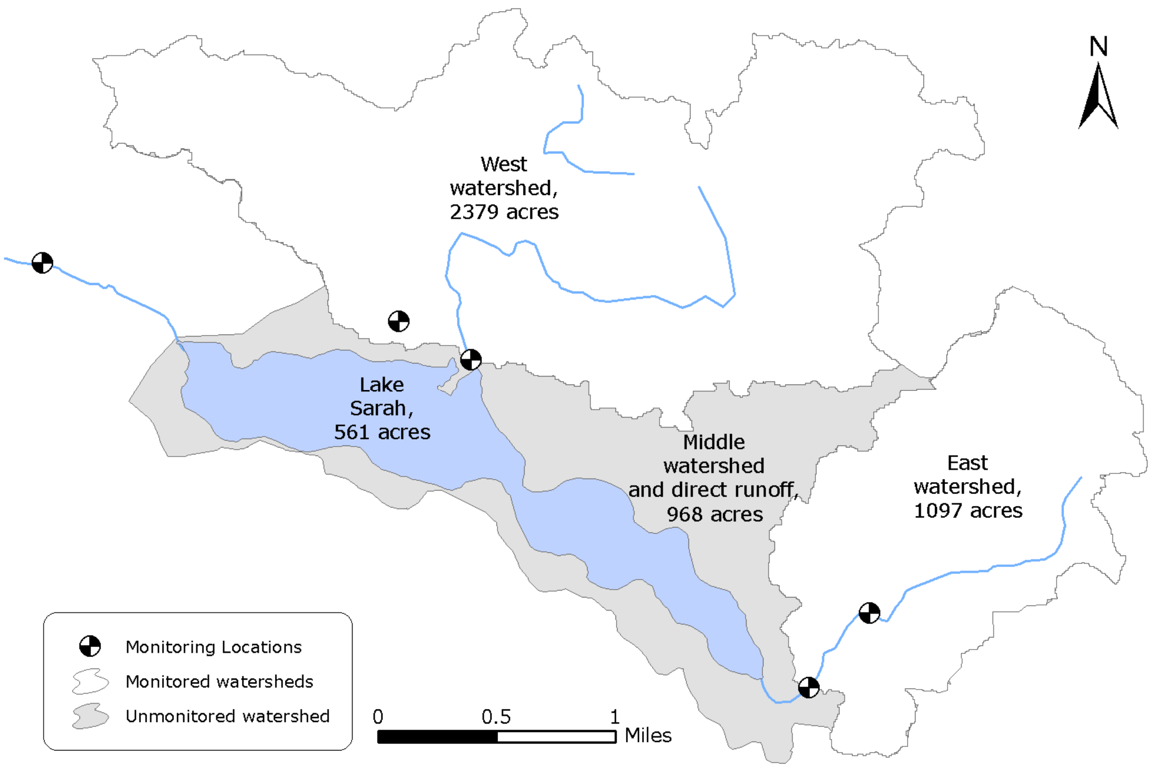

Figure 2.1. Watersheds for Lake Sarah tributaries and direct runoff.

Continuous level and velocity in each of the streams were measured every 15 minutes during the monitoring period with Isco Area-Velocity probes communicating with Isco 4150 data loggers (Teledyne Isco, Inc., Lincoln, NE). Area-Velocity probes were monitored and maintained approximately twice per week during the sampling period. The East Tributary site was located at a concrete box culvert flowing under County Road 11 and the West Tributary site was located at a metal 36-inch culvert flowing under a grass path extension to the east end of North Shore Drive in Greenfield. The East Upstream site was at a 60” metal culvert flowing under Townline Road and the West Upstream site was located at an 18” metal culvert flowing under Greenfield Road. Flows were calculated for each of the sites using Isco Flowlink version 4.16 (Teledyne Isco, Inc., Lincoln, NE) and the measured level, velocity, and culvert diameter. All streamflow measurement was conducted by Three Rivers Park District water resource staff following previously described protocols (Walker, 1996).

Water quality samples (composite and grab) were collected in conjunction with streamflow measurements throughout the sampling period. A 10-Liter GLS Compact Composite sampler (communicating with the 4150 datalogger; Teledyne Isco, Inc., Lincoln, NE) was used to collect composite water quality samples during storm events. Auto samplers were set to collect flow-weighted composite samples that characterize average concentration throughout the rising and falling limbs of the hydrograph (Isco, 2007). Baseflow and stormflow grab water quality samples were also collected to determine phosphorus loading during base flow and validate autosampler collection.

All samples were analyzed for TP, SRP, Total Nitrogen (TN) and Total Suspended Solids (TSS). Loads of each nutrient were calculated with the FLUX32 Load Estimating Software version 2.11 (Table 2.1) for the tributary outlet sites. Concentrations from both years were used to determine the relationship between concentration and flow that was applied to the whole time period. All sample analysis and data processing was conducted by the Three Rivers Park District laboratory (certified by Minnesota Department of Health) following Standard Methods for Analysis of Water and Wastewater 21st Ed. (2005).

2.1 Hydrologic Results

Precipitation during the two monitoring years was lower than the long-term average and included long periods of non-flowing, stagnant conditions during the summer months (Figure 2.1). Given the limited sampling period (2-years), it is unclear if this streamflow pattern is consistent across average precipitation patterns or a product of two years of below average flow. Modeling and assessment of average conditions is described in detail in the (SWAT modeling section below).

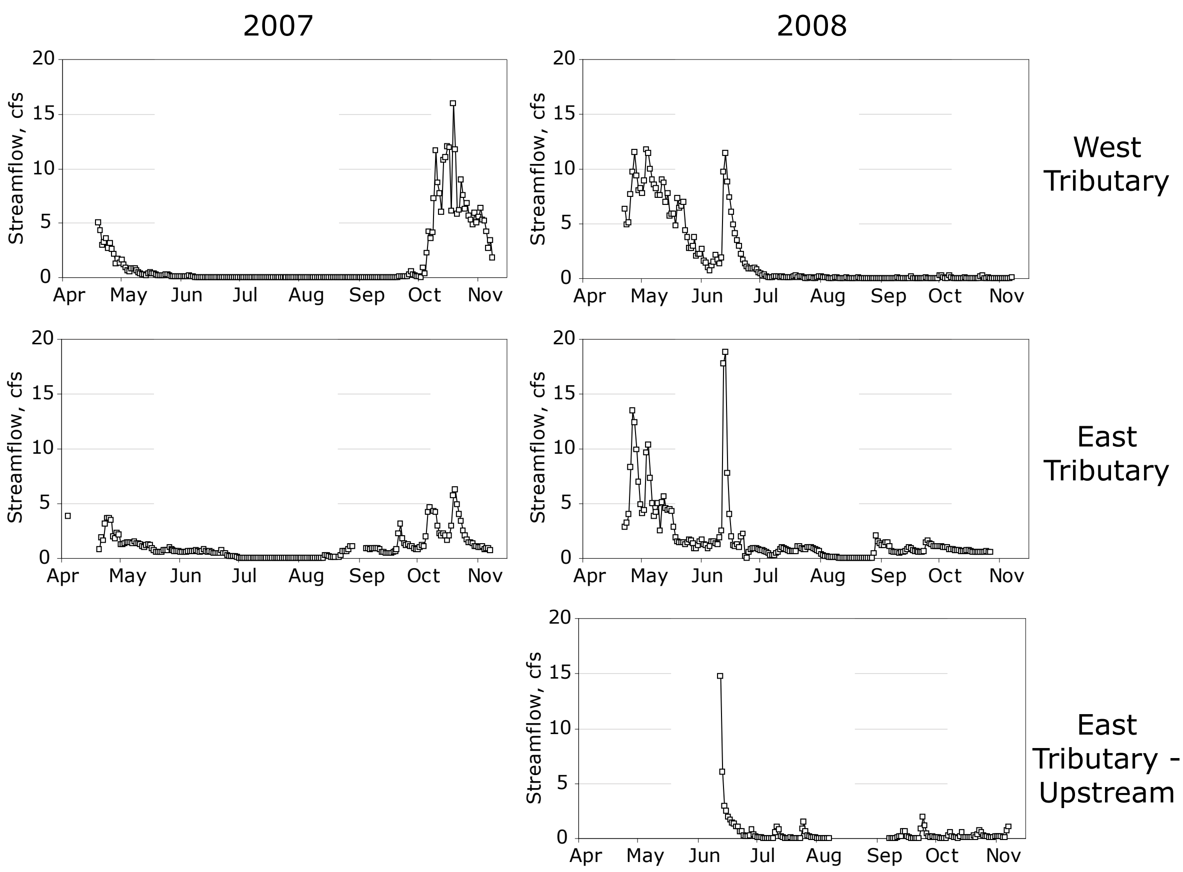

Figure 2.2. Daily mean streamflow for the East and West Tributaries in 2007 and 2008.

The hydrographs for 2007 and 2008 illustrate how differing hydrology in the two watersheds affects streamflow (Figure 2.1). The East Tributary is a flashier system that has steeper storm recessions, possibly because the East watershed is more developed and includes more connected impervious areas than the West watershed. Both the East and West Tributaries flow through wetlands above the monitoring sites, but the wetland areas in the West watershed are larger and more directly connect to the stream system.

2.2 Watershed Monitoring Results

Water quality and nutrient loading varied significantly between sites and years (Table 2.1). In general, nutrient loads were highest in the western tributary and higher in 2008 than 2007. However, nutrient concentrations within each tributary were highly variable, depending on the instream flow that was present prior to a precipitation event. Under low-flow conditions, nutrient concentrations were higher than high-flow conditions, likely as a result of sediment release during anoxic conditions. However, despite high concentration, the total nutrient load associated with low flow is relatively low compared with high flow events.

Table 2.1. Loads of total nitrogen, total phosphorus, and soluble reactive phosphorus estimated with FLUX for 2007 and 2008.

		Monitored Load, lbs		
Site	Constituent	2007	2008	Coefficient of Variation
West Tributary	Total Nitrogen	4,050	5,136	0.07
	Total Phosphorus	414	611	0.17
	Soluble Reactive Phosphorus	406	515	0.26
East Tributary	Total Nitrogen	1,725	3,866	0.14
	Total Phosphorus	269	539	0.06
	Soluble Reactive Phosphorus	159	335	0.12

Pollutant Sources

Phosphorus in Lake Sarah originates from two primary sources – watershed runoff and in-lake nutrient cycling (i.e., internal loading). The models used to describe the relative contribution of these different phosphorus sources are described below.

3.1 Watershed Modeling

The Lake Sarah watershed was modeled using a combination of models (Figure 3.1). Individual models were selected to best represent the diverse landscape and land-use types throughout the watershed. The Soil and Water Assessment Tool (SWAT) was selected to represent the majority of the watershed because of the strength in modeling agricultural landscapes. The Program for Predicting Polluting Particle Passage through Pits, Puddles, and Ponds (P8) was selected to model the urbanized areas in Loretto because it has the capacity to represent urban routing (including flow) through multiple detention ponds. The Source Loading and Management Model (SLAMM) was selected to represent residential and rural residential development areas of the watershed directly contributing to the lake because of its successful application of estimating urban runoff throughout the Midwest.

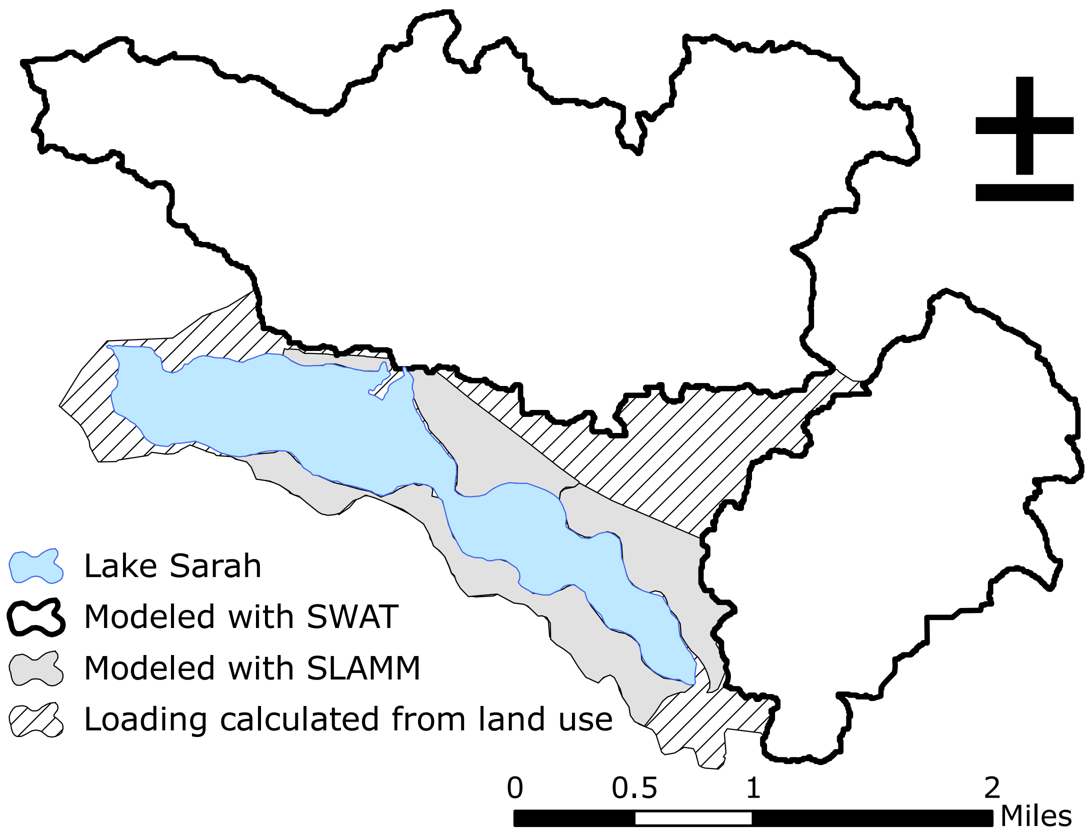

Figure 3.1. Describes the modeling approach used for each subwatershed.

3.1.1 <u>P8 Model</u>

A P8 model was used to estimate the pollutant loading from the urban areas within the Lake Sarah watershed (Figure 3.2). P8 has been used to model urban areas (i.e., residential and commercial) to design and evaluate runoff treatment schemes for existing or proposed urban developments in a number of TMDL efforts throughout the region (e.g., Bonestroo, 2009). P8 estimates watershed phosphorus loading using particle concentrations in the runoff. Particle loads from pervious and impervious areas are computed using a sediment rating model and particle accumulation and washoff equations – which are derived from the EPA Stormwater Management Model (SWMM; Huber and Kikinson, 1988). The water quality components of the model are based upon weight distributions across particle classes. A default file (NURP50.PAR) for particle classes and water quality components was used to estimate watershed loads of total phosphorus, total nitrogen, and total suspended solids. Watershed runoff and loading in the model is transported directly to downstream devices. A continuous water-balance and mass-balance calculations are performed to determine nutrient removal efficiencies for each device. In the Lake Sarah watershed, P8 was specifically used to evaluate the urban and residential drainage areas within the City of Loretto.

The P8 model developed for the City of Loretto was an interconnected, one-dimensional network of watersheds and treatment devices (Figure 3.3). Seven subwatersheds were defined in the model as the primary sources contributing to runoff and particle transport. The pervious and impervious areas for each subwatershed were digitized from aerial photography images and defined within the model (Figure 3.3; Table 3.1). Curve numbers for the pervious and impervious areas were estimated using the TR-55 Curve Number technique (USDA-NRCS, 2004).

In P8, watershed runoff is routed to specified devices such as storm sewer pipes, open channels, and detention ponds to model their effect on water quality. The City of Loretto drainage area included four treatment devices - three detention ponds and one wetland. The morphology of each treatment device was characterized using development plans supplied by the City of Loretto and were incorporated into the P8 model (Table 3.2). There were several pipes and open channels also identified as devices within the model; however these devices were assumed to have negligible particle removal efficiencies.

Continuous hourly precipitation is required in P8 to simulate runoff from the drainage area. Runoff from pervious areas is computed using the SCS curve number technique (USDA-NRCS, 1964). Antecedent moisture conditions are adjusted based upon 5-day antecedent precipitation and season. Runoff from impervious areas starts after the cumulative storm rainfall exceeds the specified depression storage. A precipitation file was developed and executed to simulate runoff conditions in 2007 and 2008. Run-off volume, nutrient concentration, and nutrient loading generated using 2007 and 2008 precipitation data were used as inputs to the watershed-wide SWAT model. Calibration and validation were performed as a component of SWAT modeling efforts (see the SWAT modeling section for greater detail).

Table 3.1. Areas and curve numbers for the Loretto subwatersheds.

	Pervious		Impervious		Total
Watershed	Acres	CN	Acres	CN	Acreage
Loretto A	7.7	80	6.2	98	13.9
Loretto B	3.4	80	3.5	98	6.9
Loretto C	12.9	80	3.8	98	16.7
Loretto Industrial North	4.4	80	7.0	98	11.4
Loretto Industrial South	6.7	80	6.6	98	13.3
Ballfield North	5.9	80	2.1	98	8.0
Ballfield South	6.4	80	1.6	98	8.0

Table 3.2. Morphological characteristics of the four nutrient removal devices in the P8 model of Loretto.

Device	Bottom Area (acres)	Permanent Pool		Flood Pool		Infiltration (in/hr)
		Area (ac)	Volume (ac-ft)	Area (ac)	Volume (ac-ft)	
Pond A	0.70	0.23	1.15	0.38	2.66	
Pond B	0.45	0.83	3.32	1.03	6.18	
Pond C	0.06	0.41	2.46	0.76	6.08	
Wetland	1.00	1.50	6.00	3.00	12.00	0.06

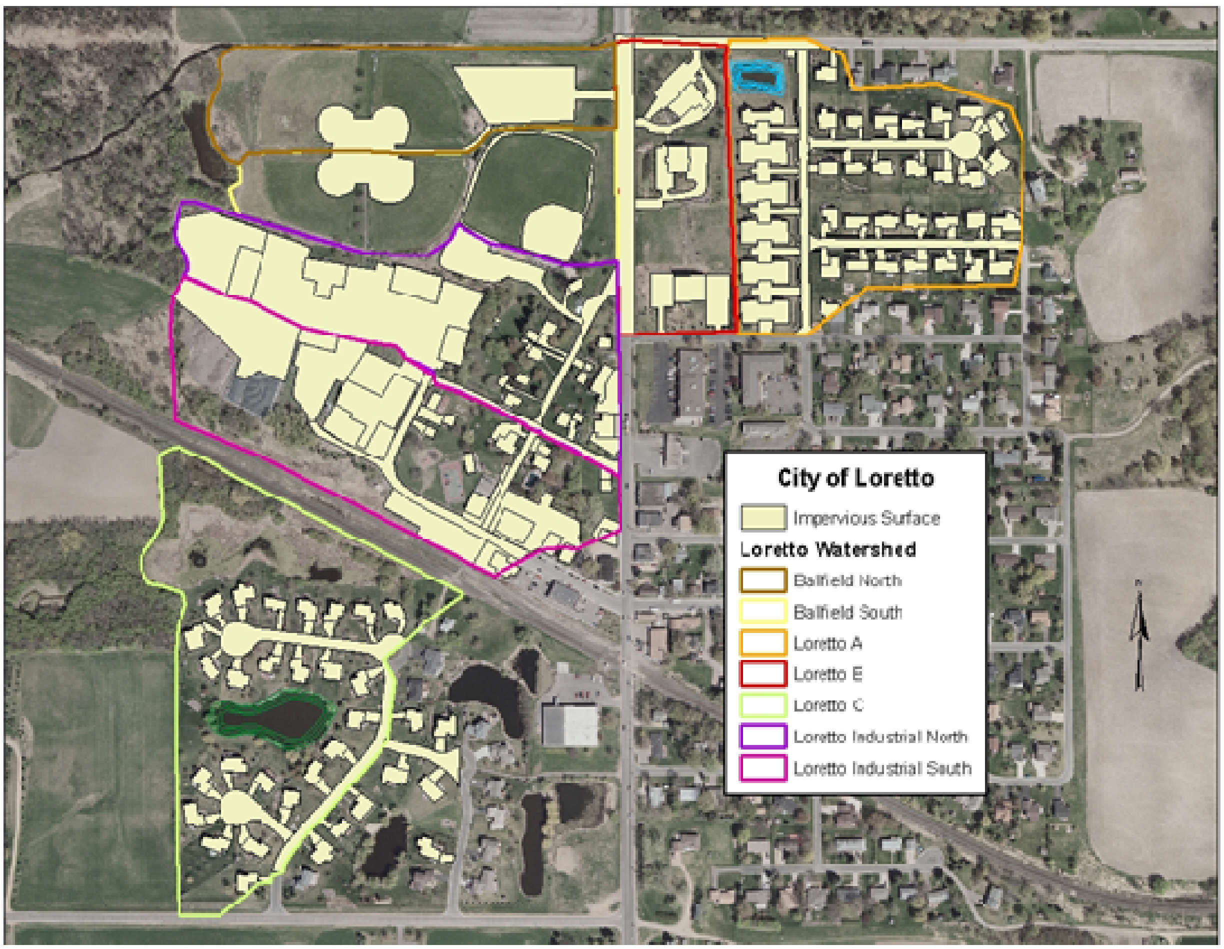

Figure 3.2. Subwatersheds in Loretto characterized using P8.

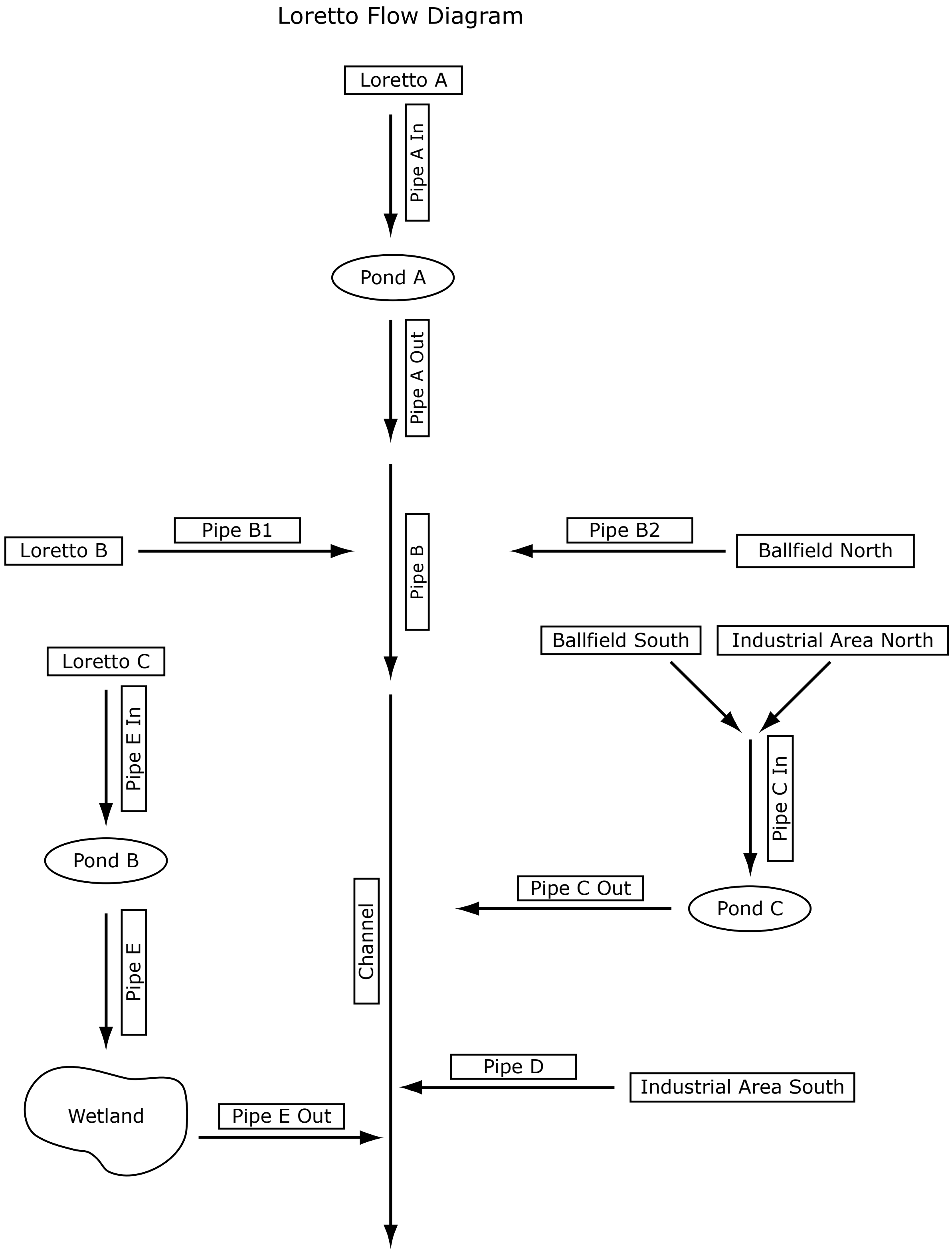

Figure 3.3. Conceptual flow diagram for the P8 model of Loretto.

3.1.2 SLAMM Model

The Source Loading and Management Model (SLAMM) was used to estimate phosphorus loading from residential, rural residential areas and transportation corridors that contribute runoff to Lake Sarah. The SLAMM model uses empirical relationships between phosphorus build-up, precipitation and runoff to estimate the phosphorus loading that would be expected from different urban land uses (e.g., roofs, sidewalks, driveways, parking lots, streets, etc.) under different precipitation patterns (Pitt and Voorhees, 1995). The SLAMM model computes nutrient loading using the cumulative mass loads and runoff volumes. Outputs from SLAMM were integrated into SWAT and BATHTUB to describe the relative contribution of urban sources of phosphorus throughout the watershed. All calibration and validation was performed as part of the SWAT and/or BATHTUB routines (see the SWAT and BATHTUB model section below for further description).

Direct Drainage Sub-Watershed Areas

Four subwatersheds that provide direct runoff to Lake Sarah were identified and modeled using SLAMM. For direct drainage from urban lands, build-up of nutrients prior to wash-off is based on anticipated land use exports (based on a runoff coefficient) and atmospheric deposition. Runoff is generated using a precipitation file that represents average conditions for the region. The different source area parameters that contributed to nutrient loading were identified for each sub-watershed and digitized from aerial photography images. Summary statistics of each parameter were input into the SLAMM model (Table 3.3).

SLAMM Model Land Uses

Impervious Areas
Roof = Roof Acres for Houses and Buildings
Driveway = Driveway Acres
Street = Paved and Gravel road Acres
Commercial = Industrial/Commercial Acres (i.e. railroad)

Pervious Areas
Small Landscape Areas = Residential Manicured Lawn Acres
Large Landscape Areas = Rural Residential Manicured Lawn Acres
Undeveloped = Acres without development that are open fields

Open Water Areas
Isolated Wetlands = Wetland Acres that were considered isolated

Table 3.3. Impervious and pervious source parameter acres input into the SLAMM model.

		Sub-watershed (acres)			
Surface	Source Area	Northwest	North	Northeast	South
Impervious	Roof	1.65	3.85	6.46	5.95
	Driveway	0.58	4.55	6.52	6.24
	Street	1.22	3.24	6.12	3.93
	Commercial	2.32	9.45	6.03	0.00
Pervious	Small Landscape (Residential)	6.16	30.57	66.24	40.31
	Large Landscape (Rural Residential)	0.00	34.69	20.00	8.40
	Undeveloped	0.92	5.35	10.66	68.67
Open Water	Isolated Wetlands	2.29	16.16	19.48	50.69

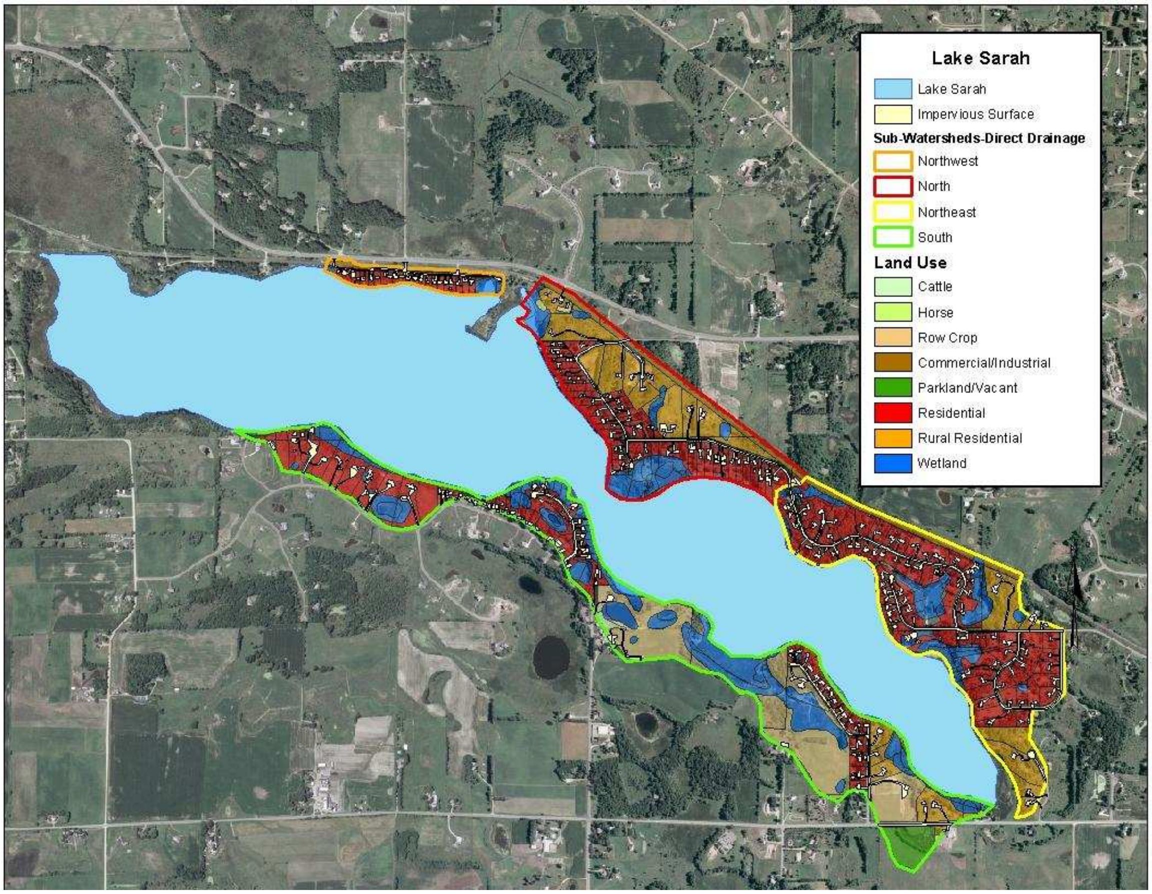

Figure 3.4. The subwatershed areas that provided direct run-off and nutrient loading to Lake Sarah.

Major Roadways

Phosphorus loading from two County Roads (CR11 and CR19) and one state Highway (Hwy 55) were modeled using SLAMM (Figure 3.4). For drainage from roadways, build-up of nutrients prior to wash-off is based empirical relationships between particle accumulation and daily traffic patterns (Tables 3.3 and 3.4) and runoff is generated using a precipitation file that represents average conditions for the region. Inputs for impervious surface area and roadway length for the County Roads and State Highway were digitized from aerial photography images. The average daily traffic volumes for each roadway were determined from the most recent published transportation information from the Minnesota Department of Transportation and Hennepin County (2008).

Table 3.4. County Road and State Highway inputs into the SLAMM model.

Roadway	Impervious (Acres)	Freeway Length (miles)	Average Daily Traffic (# Vehicles/day)
County Road 11	4	1.03	4,800
County Road 19	7	1.4	5,150
State Highway 55	24.5	3.8	16,200

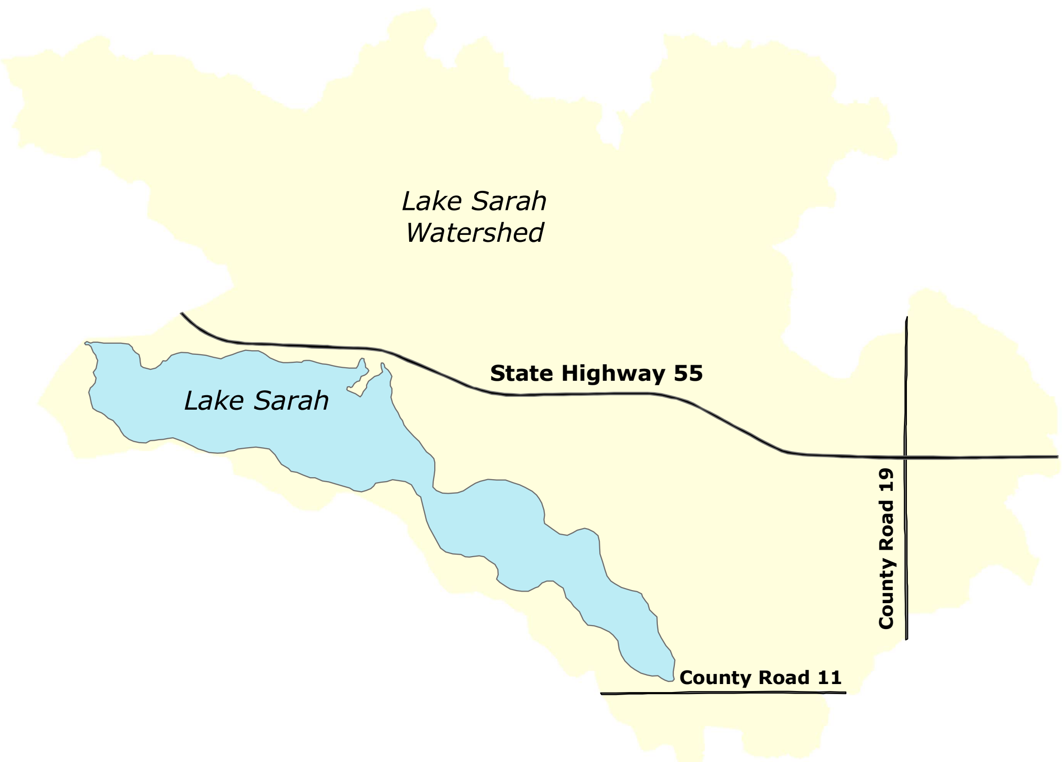

Figure 3.5. Major Roadways within the Lake Sarah Watershed.

SLAMM Results

Estimated phosphorus runoff from directly draining subwatersheds ranged from 5.9 lbs/yr to 48.5 lbs/yr (Table 3.5). Estimated phosphorus runoff from transportation corridors ranged from 4.7 lbs/yr to 62 lbs/yr (Table 3.6).

Table 3.5. SLAMM model estimates of run-off volume and phosphorus load from subwatersheds providing direct drainage to Lake Sarah.

Subwatershed	Runoff Volume, hm^3	TP concentration, ppb	TP load, lbs
Northwest	0.016	194	6.7
North	0.069	325	49.5
Northeast	0.082	344	62.2
South	0.072	329	52.3

Table 3.6. SLAMM estimates of run-off volume and nutrient loading for major roadways within the Lake Sarah Watershed.

Roadway	Runoff volume, hm^3	TP concentration, ppb	TP load, lbs
State Highway 55	0.059	395	61.9
County Road 19	0.017	183	6.8
County Road 11	0.01	221	4.7

3.1.3 SWAT Model

The Soil and Water Assessment Tool (SWAT) was used to model runoff from the agricultural subwatershed draining to Lake Sarah (East, Middle Direct and West Direct; Figure 2). SWAT is a partially physically-based and partially empirically-based watershed model (Neitsch et al., 2005) developed at the U.S. Department of Agriculture Agricultural Research Service (SWAT is currently supported by the Blacklands Research and Extension Center at Texas A&M University). SWAT runs on a daily time step and is intended to model large agricultural watersheds. It has been calibrated and validated to many watersheds in the United States and around the world (Gassman, 2007). SWAT has progressed through several development releases. The release selected for this project was ArcSWAT 2.3.4 for ArcGIS 9.3.1. This interface release was run with an updated version of the base 2.0.0 executable code release. The 2.0.0 executable file was updated by to eliminate a code anomaly which affected phosphorus settling in stream channels during low flow conditions (the unmodified version overpredicted instream phosphorus settling). All SWAT modeling and field assessments were conducted by Three Rivers Park District staff. Calibration and validation of the updated model is described below.

SWAT simulates the hydrologic cycle accounting for the following processes: precipitation, overland runoff, infiltration, percolation through one or more soil layers, evaporation, plant transpiration, interaction with the shallow aquifer, and loss to a deep aquifer (Arnold et al., 1998). Water is delivered to the stream as overland runoff, lateral flow, and groundwater flow and routed through defined stream channels to the watershed outlet. SWAT also models off-channel, surface-water bodies such as wetlands and ponds and on-channel bodies such as reservoirs.

Sediment export from uplands is calculated in SWAT with the Modified Universal Soil Loss Equation (MUSLE; Williams, 1975). While the original Universal Soil Loss Equation (USLE) predicts annual erosion on a field, the MUSLE includes a peak flow component that is used to determine the amount of eroded sediment reaching the stream from a uniform land area during a single storm event. Factors that control sediment export predicted by the MUSLE are surface runoff, peak flow, soil erodibility, biomass and residue present, cropping practices, slope length, and percentage of coarse fragments (i.e., stones) of soil.

Simulation of phosphorus and nitrogen cycles in SWAT uses inputs of inorganic fertilizer, organic fertilizer, plant residue, and, for nitrogen, rainwater. Nitrogen is partitioned between five mineral and organic pools within the soil and is transferred between and out of these pools through export, decay, mineralization, nitrification and denitrification, volatilization, and plant uptake. Similarly, SWAT models five soil phosphorus pools, with transfer between and out of these pools through export, decay, mineralization, immobilization and plant uptake. Nitrogen and phosphorus are exported via overland runoff, lateral flow, and groundwater flow to the stream channel, though they are only tracked through overland runoff and lateral flow. In the stream reaches, in-stream nutrient processes can be simulated with the imbedded QUAL2E submodel, or the nutrients can be delivered to the reach outlet undisturbed. Plant growth is modeled directly in SWAT based on simplified crop growth equations from the Erosion Productivity-Impact Calculator (EPIC) with controlling inputs including temperature, solar radiation, nutrient availability, and water.

SWAT allows input of specific management rotations for agricultural land, providing opportunities for modeling alternative scenarios to guide management decisions. Each day, the crop biomass, weight of residue present, and soil moisture are recalculated for each hydrologic response unit (HRU; the basic model unit that includes a unique combination of soil and land use). Agricultural crops can be rotated by year, and crops that continue to grow over several years, such as alfalfa, can be represented in the model.

SWAT Spatial Inputs

Spatial inputs for the Lake Sarah SWAT model included digital elevation, land use, and soils. All data for the Lake Sarah watershed were projected into the Universal Transverse Mercator Zone 15, with the North American Datum, 1983. The Lake Sarah watershed and subbasins were delineated from the National Elevation Dataset 10-meter gridded digital elevation model (DEM). This delineation was updated with water routing information from the Loretto department of public works and field observations. Soil Survey Geographic (SSURGO) soil data were downloaded from the US Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS) Soil Data Mart website. These data are organized by county and are the most detailed available for the watershed. The SSURGO dataset included 61 soils in the Lake Sarah watershed and was overlain with the municipality to allow analysis of the resulting HRUs by town. Land use input for the Lake Sarah SWAT model was generated from the 2006 Hennepin County parcel dataset, which includes land use as it relates to the tax code. These land uses were updated and subdivided using the 2006 high-resolution Hennepin County aerial photographs and field observations. The resulting land use dataset was converted to a grid.

The subbasins in the East and West watersheds were initially created with the Automatic Delineation feature in ArcSWAT. Subbasins were refined using field observations and known locations of stream channels and ponds. The final subbasin configuration included 14 subbasins in the East watershed ranging from 4.5 to 100.4 hectares in the East watershed and 13 subbasins ranging from 10.6 to 175.5 hectares in the West watershed. The West and East watersheds had 560 and 389 HRUs, respectively.

Agriculture

Agriculture is a major land use in the Lake Sarah watershed. The majority of producers grow corn-grain, soybeans and occasionally wheat in rotation. There are also several farms that grow corn-grain, soybeans, alfalfa, and corn-silage for a mix of grain crops and animal consumption. Hay and alfalfa are grown on other fields throughout the watershed for animal consumption.

Agricultural management operations were applied to each of the agricultural parcels modeled in SWAT. A variety of tillage schedules are used by producers in the Lake Sarah watershed. The majority of producers chisel plow in the fall after harvest. Spring field treatment varies and approximately half of the fields have some residue remaining from the previous year’s crop and the remainder has no residue at the time of planting (Jim Kujawa, Hennepin County Environmental Services, pers. comm.) Specific fertilizer rates were not available for the Lake Sarah watershed; fertilizer application rates were estimated based on a study in nearby St. Croix County, Wisconsin (Almendinger and Murphy, 2005).

Two surveys of animal locations and densities in the watershed were conducted in March and July, 2008. Animals that could not be seen during the windshield surveys were estimated from aerial photographs taken in 2006. All of the animals were associated with dirt, vegetation-free feedlots that were delineated from the aerial photographs. These areas were incorporated into the land use map and pastures associated with each of the feedlots were identified.

In surveys in spring of 2008, 38 parcels with animals were identified – the majority of which were horses (33). Seven parcels had cattle and three had goats. In these totals are several parcels that had more than one type of animal. There were 129 horses, 103 cattle, four goats and a donkey observed. Manure from the goats and donkey were not included in the watershed model.

Most animal operations in the Lake Sarah watershed are hobby horse farms with between 1 and 11 horses. The majority of these operations include a small, dirt feedlot and an area of associated pasture. Manure on small horse farms is not collected from the pasture. Manure is collected out of the barn and occasionally scraped from the feedlot and stockpiled. Stockpiled manure was not modeled directly in SWAT; rather, half of the manure from each operation was applied to the feedlot and the other half to the pasture. The feedlot manure was assumed to include both the dirt feedlot and the manure stockpile. In the three operations without obvious pastures, the entire quantity of manure was applied to the feedlot. The continuous fertilization function in SWAT applied manure to the landscape daily.

The specific manure management activities of the dairy and beef producers are unknown. For modeling purposes, it was assumed that 50% of the manure from these operations was collected, based a herd size of fewer than 25 animals (Powell et al., 2005). The collected manure was applied to nearby agricultural fields. Solid manure and bedding application to agricultural fields was observed in the watershed from February to April, 2009. The remaining, uncollected manure was assumed to remain – half to each the pasture and the feedlot associated with the operation.

Residential and Urban Land Uses

A variety of urban and residential land uses are present in the Lake Sarah watershed. The percentage of impervious area in each of the land uses guided how the land use type was represented in the SWAT model. SWAT is better structured to represent agricultural landscapes, so the P8 model of Loretto and the SLAMM model of the roadways were developed in parallel to provide a calibration check for these major areas with impervious land (see the SWAT and SLAMM model sections above for further description).

Wetlands

Wetlands exert a large hydrologic influence in the Lake Sarah watershed. On channel wetlands detain water, and settle nutrients. On channel wetlands were modeled as "reservoirs" in SWAT. Each "reservoir" was assigned to a subbasin and given the input parameters of the normal surface area, the emergency surface area, the normal volume and the emergency volume. The normal surface area was delineated as the pooled area for a given wetland, the emergency surface area was delineated using the National Wetland Inventory and visual inspection of aerial photographs as a guide. The normal and emergency volumes for the wetlands were used as calibration parameters to match the monitored hydrograph. Each wetland was parameterized with a number of days to return to the normal pool after exceeding the emergency pool volume.

Calibration

The SWAT models were calibrated to the two years of monitoring data for the East and West Tributaries. The model was initially calibrated to the first year of data and validated during the second year, but the validation was poor, so both years were used for calibration. The snowmelt parameters, the groundwater recession and delay parameters, the curve number, a soil evaporation parameter, and the in-stream detention parameters were calibrated to adjust the hydrologic response (Figure 3.6). The endpoint of calibration was determined from a visual inspection, an adequate Nash-Sutcliffe Coefficient of Efficiency for the daily modeled and monitored values, and corresponding modeled and monitored total flow volumes (Table 3.7).

Differences between the modeled and monitored hydrograph are influenced by variations in model application, model input data, and streamflow monitoring data. Using the Curve Number method, SWAT is a daily time step model and precipitation is input as daily values. Precipitation, as recorded by the cooperative observer at Rockford, is recorded as an 8 am to 8 am day. Streamflow is averaged as a midnight to midnight day. These differences in averaging, and unknown intensity of precipitation throughout the day likely account for much of the difference between the monitored and model streamflows.

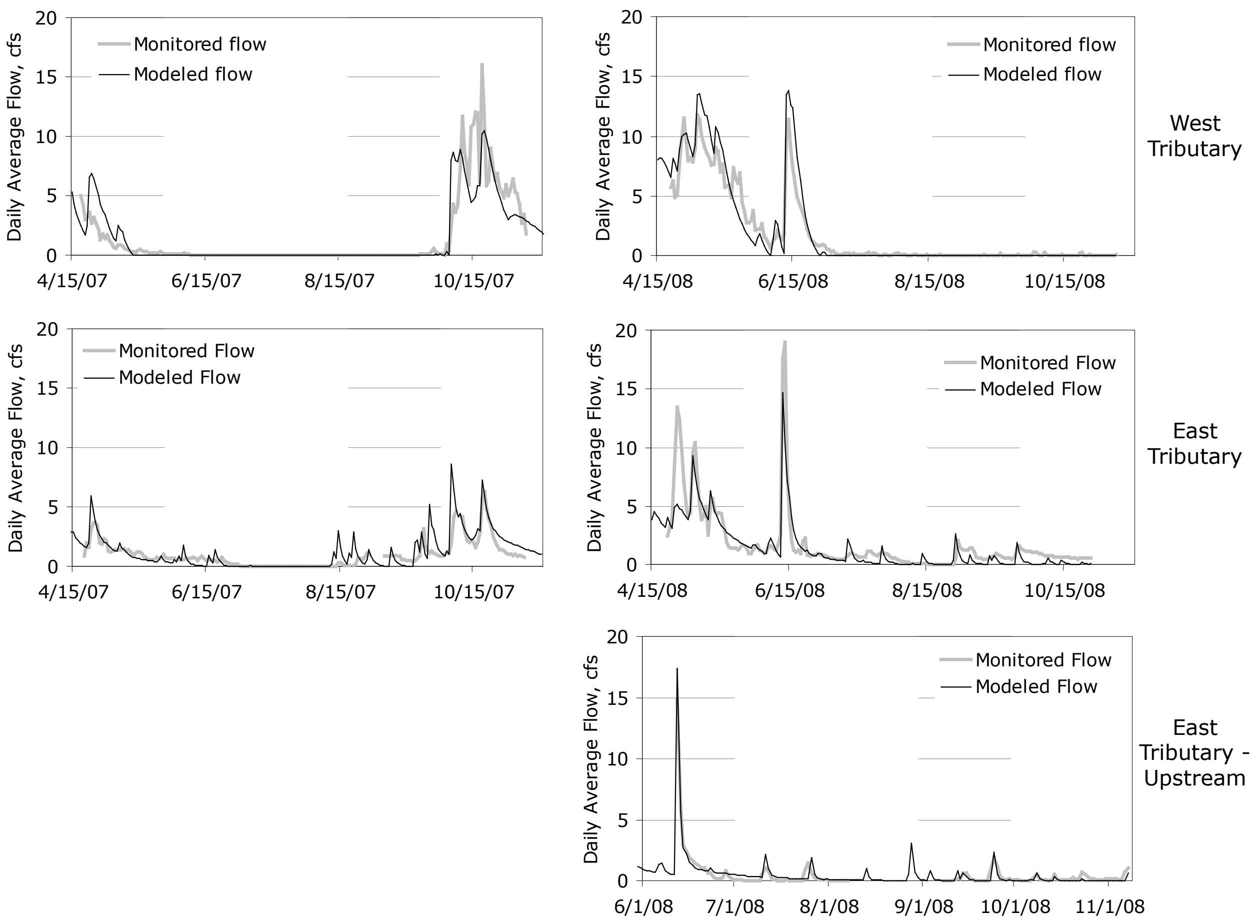

Figure 3.6. Modeled and monitored daily flows for the East and West Tributaries during the two monitoring seasons.

The SWAT model(s) for the two tributaries were calibrated to monitored phosphorus concentrations (Figure 3.7). Calibration parameters that affect landscape phosphorus export were set to the same values for both tributaries. The USLE P_factor was lowered significantly to reduce landscape phosphorus loads to expected quantities. Other parameters altered were the phosphorus soil partitioning coefficient and the width of vegetated field edges. The phosphorus sorption coefficient and the soil labile phosphorus concentration were calculated based on soil parameters in the Lake Sarah watershed (Vadas and White, unpublished). The phosphorus concentration in the groundwater was set to 150 μg/L – based on low-flow phosphorus concentrations (i.e., groundwater inputs) observed in adjacent watersheds. Finally, wetlands were assumed to settle phosphorus from August to May and release phosphorus in June and July – based on inspection of the monitoring data.

Table 3.7. Comparisons between modeled and monitored flows and volumes for the periods of record.

		Total Flow, hm^3			Nash-Sutcliffe
Site	Period	Monitored	Modeled	% Difference	Coefficient of Efficiency
West Tributary	2007	0.71	0.64	-9%	0.70
	2008	0.91	0.97	7%	0.88
	Whole Record	1.62	1.62	0%	0.80
East Tributary	2007	0.46	0.56	21%	0.39
	2008	0.81	0.64	-21%	0.75
	Whole Record	1.27	1.20	-6%	0.71
East Tributary - upstream	2008	0.11	0.11	1%	0.66

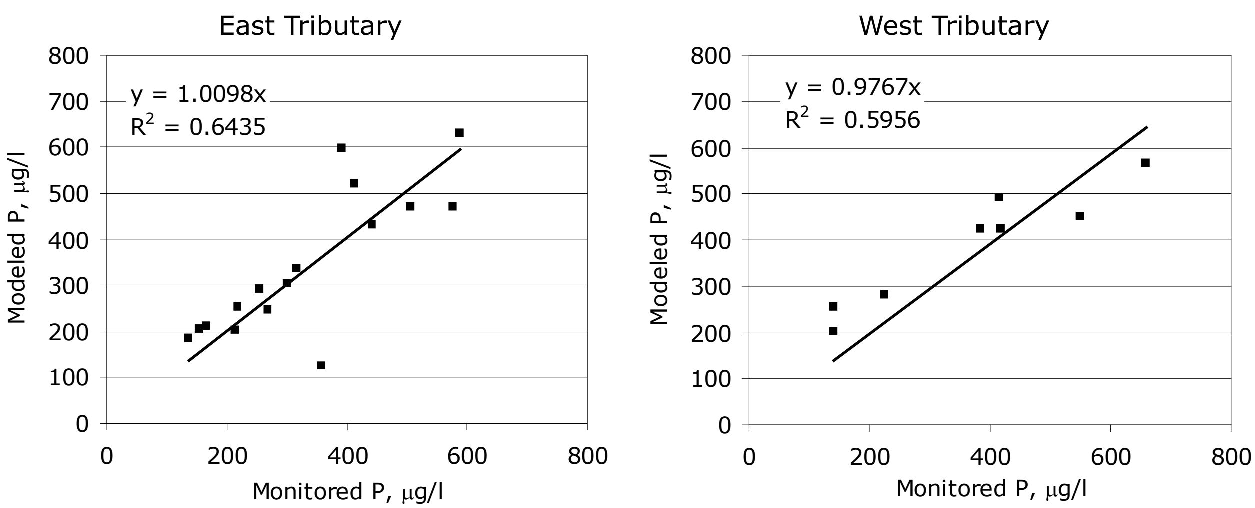

Figure 3.7. Monitored and modeled phosphorus concentrations for the East and West watersheds during 2007 and 2008.

After phosphorus concentrations were calibrated (Figure 3.7), daily and annual loads from SWAT and FLUX were compared for the two watersheds (Table 3.8). Total phosphorus concentrations for the two tributaries corresponded well (R^2 0.6 or greater). The West Tributary FLUX and SWAT phosphorus annual loads are closer than the East Tributary annual loads. Storm flows during 2007 were overestimated in the East Tributary model, while storm events during 2008 were underestimated in the East Tributary model, leading to the overestimate of total phosphorus load in 2007 and the underestimate of the total phosphorus load in 2008.

Phosphorus loads from the areas in the model that were not modeled with either SWAT or SLAMM were estimated with the SWAT output as a guide (Figure 3.1). First, the area in each land use was summed. Then, the average phosphorus export from SWAT was applied by land use to the unmodeled areas. The total average annual phosphorus load was reduced by 30% to estimate wetland removal – based on observed removal efficiencies throughout the remainder of the watershed. Water yield from the area was calculated proportionally to the water yield from the West Tributary. The resulting water yield and phosphorus concentration was included in the BATHTUB model.

Table 3.8. Phosphorus loads modeled with SWAT and estimated with FLUX for the 2007 and 2008 monitoring periods.

		Total Phosphorus, lbs		
Site	Period	FLUX	SWAT	% Difference
West Tributary	2007	414	419	1%
	2008	611	573	-6%
	Whole Record	1,026	1,075	5%
East Tributary	2007	268	296	10%
	2008	539	419	-22%
	Whole Record	807	688	-15%

Qualitative Model Uncertainty

There are three general areas of uncertainty in the watershed model: 1) snowmelt: 2) year-to-year variations in runoff; and 3) the influence of wetland and channel processes.

SWAT cannot explicitly model nutrient dynamics in wetland systems based on physical characteristics. However, SWAT does provide the capability to model phosphorus release/sequestration based on temporal patterns, so wetland nutrient dynamics were modeled based on monthly patterns observed in the monitoring data. Based on monitoring data, we hypothesized wetlands in the Lake Sarah watershed acted as phosphorus sinks during most of the year and were phosphorus sources during periods when water stagnated and anoxia caused the release of phosphorus from the sediments. The monitored and modeled phosphorus concentrations correspond well throughout the monitoring period (Figure 3.7), but these relationships should be confirmed in future monitoring efforts.

The snowmelt period (February to the middle of April) was not directly sampled in the Lake Sarah watershed in either of the monitoring years. This is a period of high flow, but the unpredictable period of thawing and refreezing often compromise field sampling equipment. These periods were modeled with SWAT, but based on visual observations. Studies in two adjacent watersheds have demonstrated that the initial streamflow after snowmelt has very high total phosphorus concentrations and future streamflow monitoring in the Lake Sarah system should include the period of snowmelt.

The two monitoring years, 2007 and 2008, both had lower than average total precipitation. Future monitoring efforts should attempt to capture runoff during high precipitation years to validate the model calibration throughout a wider range of environmental conditions.

3.2 Internal Loading

Internal loading in lakes refers to the phosphorus load that is released from the sediments into the water column. There are two primary sources of internal loading in Lake Sarah – direct sediment release and curlyleaf pondweed senescence.

3.2.1 Sediment Release Due to Hypolimnetic Anoxia

Water at the sediment-water interface remains hypoxic/anoxic for a significant portion of the growing season (Figure 3.8). Under low oxygen conditions, sediments release phosphorus, which accumulates in the hypolimnion (Figure 3.9). Phosphorus released from the sediments is mixed throughout the water column as stratification changes throughout the growing season. Typically, wind mixing and temperature changes are the primary mechanisms that alter stratification patterns within a lake. Increased phosphorus release to surface waters often results in more frequent and intense algal blooms and reduced water clarity (Figure 1.7).

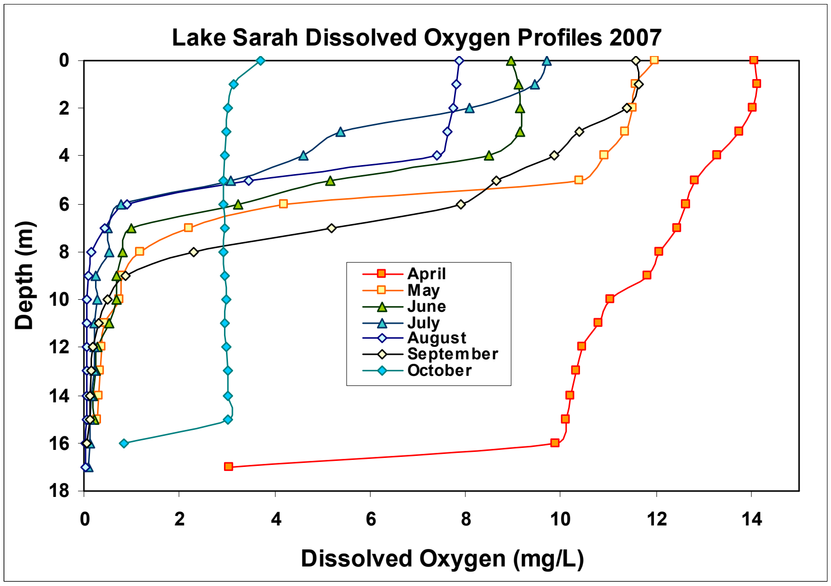

Figure 3.8. Lake Sarah Hypolimnetic Dissolved Oxygen Profile in 2007.

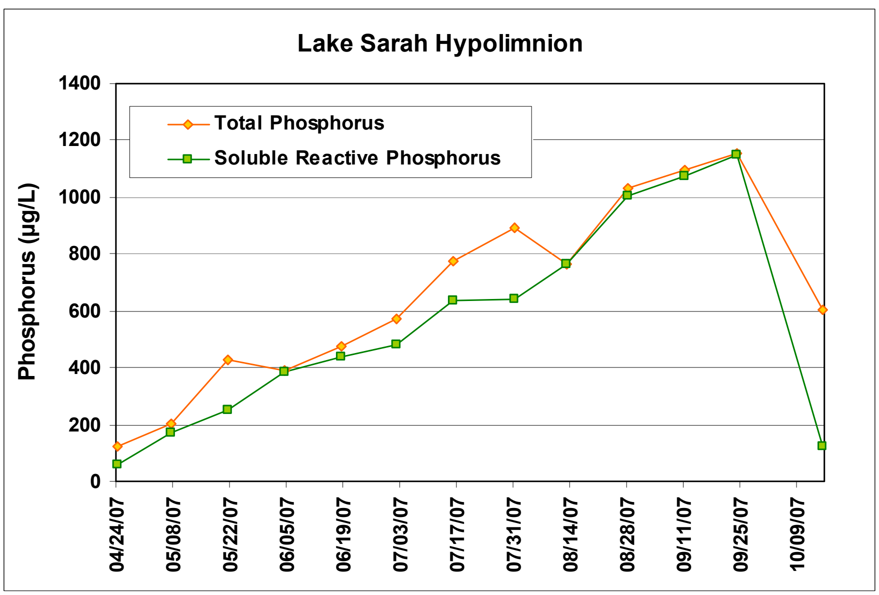

Figure 3.9. Lake Sarah Hypolimnetic Phosphorus Concentration in 2007.

Calculating Potential Internal Phosphorus Load from Sediment Release

Potential internal load of phosphorus from sediment release in Lake Sarah was calculated using methods described by Nürnberg (1985 and 1987). The Nürnberg equation estimates internal phosphorus load by multiplying an internal loading rate by the hypolimnetic anoxic area (Equation 3). Internal loading rate is calculated by multiplying the sediment release rates (RR; calculation of sediment release rates is described below) by an anoxic factor (AF; Equation 1). The anoxic factor represents the number of days that a sediment area, equal to the whole-lake surface area, is overlain by anoxic water (< 1 mg O_2/L). Nürnberg 1987 developed this relationship from a data set of lakes in central Ontario and eastern North America (Equation 2). Using the Nürnberg equation, the internal phosphorus load for Lake Sarah was estimated to be 2763 pounds.

Equation 1:
Internal Loading Rate (mg/m^2-yr) = AF * RR
AF = Anoxic Factor (days/year)
RR = Sediment Release Rate (mg/m^2-day)

Equation 2:
Anoxic Factor (days/yr) = -36.2 + 50.1 log (TP) + 0.762 * Z / A^0.5
TP = Average summer in-lake TP Concentration (µg/L)
z = lake mean depth (m)
A = lake surface area (km2)

Equation 3:
Internal Load = Internal Loading Rate (EQ1) * Hypolimnetic Anoxia Area (m^2)

Table 3.9. Simple TP Model User-Specified Constants

User-Specified Constants		
Description	**Value**	**Units**
Areal hypolimnetic oxygen demand	1.03	grams/(m^2 day)
Surface Area	2.27*10^6	M^2
Oxic/Anoxic DO cutoff value	2	grams/m^3
Epilimnion DO	8	grams/m^3
Thermocline dispersion	0.008	m^2/day
Epilimnion thickness	2.97	meters
Hypolimnion thickness	1.08	meters
Anoxic TP sediment flux	0.009	grams/(m^2 day)
Oxic TP sediment flux	0.000001	grams/(m^2 day)
Epilimnion Volume	6.74*10^6	M^3
Hypolimnion Volume	2.46*10^6	M^3
Settling Velocity	0.01	m/day
Initial Conditions: TP	0.06	grams/m^3
Initial Conditions: Date	12/31/2006	date

Calculating Sediment Release Rates

Sediment release rates for Lake Sarah were estimated using a Simple TP Model (LimnoTech 2009). The Simple TP Model uses mass balance calculations to track the estimated epilimnetic and hypolimnetic concentrations of total phosphorus on a time series basis. The initial model set-up requires constant inputs that define the morphological characteristics of the lake (Table 3.9). The model also requires the input of time series data that defines whether the lake is stratified (true or false), the watershed inflow and nutrient concentration, and the observed hypolimnetic and epilimnetic phosphorus concentrations. Mixing is specified on a daily basis as either full mixing within each layer, or complete mixing between layers.

The Simple TP model uses a series of algorithms to calculate the mass balance within and between each segment layer (epilimnion and hypolimnion) based on the in-lake stratification conditions. The model is calibrated to observed hypolimnetic and epilimnetic phosphorus concentrations by adjusting thermocline dispersion, settling velocity, and anoxic total phosphorus sediment flux. The model estimated hypolimnetic and epilimnetic phosphorus concentrations that were similar to observed conditions in 2008 (Figures 3.10 and 3.11). Based on the TP Model predictions, the anoxic total phosphorus sediment flux value that corresponded to in-lake conditions was 9 mg/m^2/day; this value was used as the sediment release rate within the Nürnberg equation to estimate internal loading (Equation 1). A sediment release rate of 9 mg TP/m^2/day is consistent with estimates from other eutrophic lakes throughout the region (average of 8.4 mg/m^2/day; Barr 1987)

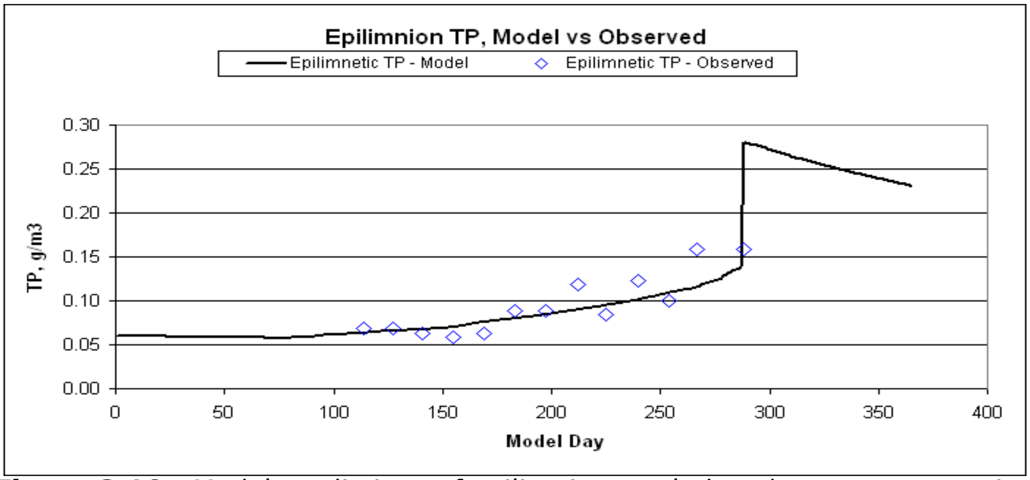

Figure 3.10. Model predictions of epilimnion total phosphorus concentrations in Lakes Sarah in 2008.

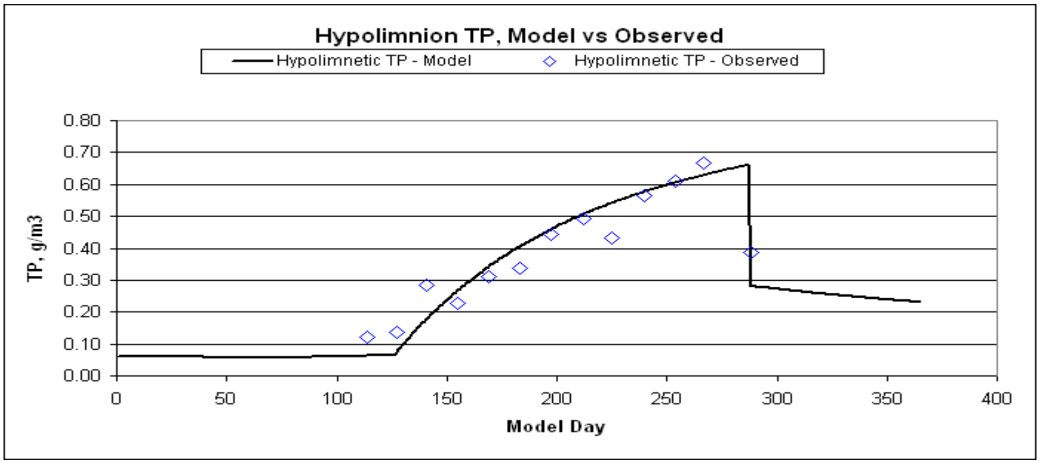

Figure 3.11. Model predictions of hypolimnetic total phosphorus concentrations in Lake Sarah in 2008.

3.2.2 Potential Internal Load Due to Curlyleaf Pondweed Senescence

Curlyleaf pondweed is likely a significant factor affecting water quality in Lake Sarah. Unlike most native aquatic plants, curlyleaf pondweed germinates in early fall, grows slowly during the winter months, and senesces by the end of June or early July the following year. This unique life-history allows curlyleaf pondweed to out-compete many native plant species and occupy large areas of the littoral zone – Lake Sarah often has up to 60% littoral surface area coverage of curlyleaf pondweed prior to senescence (Figure 1.8). Senescence of curlyleaf pondweed provides an internal source of nutrients within Lake Sarah. Senescence of curlyleaf pondweed and the coincident increase in total phosphorus concentration often correspond with increased algal growth and reductions in water clarity (Figure 3.12).

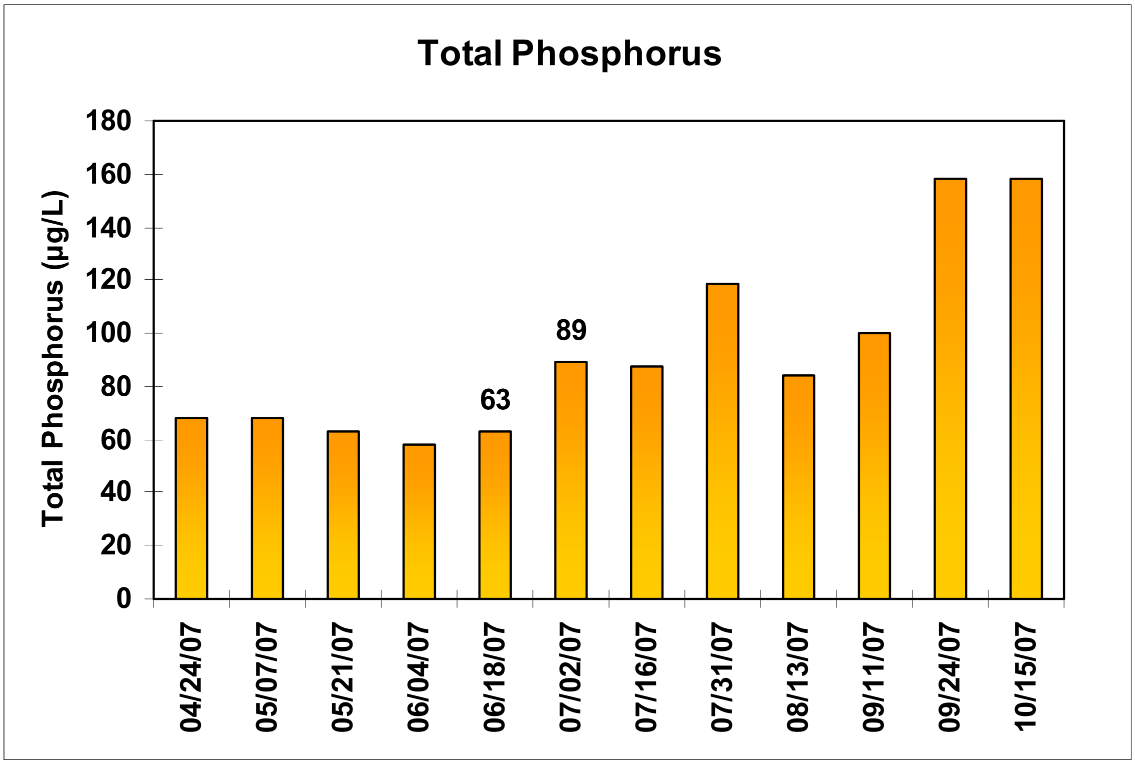

Figure 3.12. Lake Sarah total phosphorus concentrations corresponding to the senescence of curlyleaf pondweed.

Potential internal phosphorus loading from curlyleaf pondweed senescence was estimated using methods previously described by Vlach and Barten (2004). Following this procedure, the average total phosphorus concentration of 2.45 lbs/acre observed by Vlach and Barten (2004) was multiplied by the total acreage of curlyleaf pondweed coverage observed in Lake Sarah in 2007 to obtain an estimate of the potential phosphorus release from curlyleaf pondweed during senescence (Table 3.10). Based on these estimates, curlyleaf pondweed released approximately 914 pounds of phosphorus following senescence in 2007. Given the variability of curlyleaf pondweed densities from year to year and the wide range of reported lbs P/acre estimates, the total contribution of phosphorus from curlyleaf pondweed is likely variable from year to year. However, the data suggest that curlyleaf pondweed senescence may provide a significant source of internal phosphorus loading in Lake Sarah.

Table 3.10. Estimate of Internal Load from the Senescence of Curlyleaf Pondweed.

Acres	Biomass (g dry-wt/m^2)	TP Conc (mg/g dry-wt)	TP (lbs/acre)	TP Load (lbs)
373	76.7	3.93	2.45	913.9

3.2.3 Representing Internal Load in the TMDL

Estimates of potential internal phosphorus load from sediment release and curlyleaf pondweed senescence are being used to identify/quantify the potential benefits of different in-lake options for water quality management (described in detail in the Implementation section). However, the internal load value being used to establish the Load Allocation for the TMDL is was derived using the BATHTUB model (see the Loading Capacity section below for further detail).

3.3 Atmospheric Deposition

Atmospheric depositional loading was estimated within the BATHTUB model (described further in the Loading Capacity section below). The default BATHTUB estimate for atmospheric deposition is 0.27 lbs/acres-year (30 mg/m^2-yr). The BATHTUB default value is similar to other atmospheric TP loading rates observed in Minnesota watersheds (Barr, 2007). Since the total surface area of Lake Sarah is approximately 553.5 acres, the average annual atmospheric deposition of phosphorus was estimated to be 148 lbs/year for Lake Sarah. The atmospheric depositional loading was included in the overall lake nutrient balance.

Loading Capacity

4.1 Methods

A BATHTUB model (Army Corps of Engineers Version 6.1) was developed to describe water quality conditions and estimate the assimilative capacity for Lake Sarah. BATHTUB is an empirical model that estimates lake and reservoir eutrophication using several different algorithms. The model estimates in-lake water quality conditions based on the lake morphological characteristics and a mass-balance of nutrient loading to the lake. BATHTUB was selected to model Lake Sarah because the input requirements matched the available data and because of its successful application in previous lake nutrient TMDLs throughout the region (e.g., Bonestroo, 2009 and Johnson et al., 2007). Nutrient sources included in the model are atmospheric deposition, and both internal and watershed loading. The model was calibrated to a 4-year average of in-lake water quality conditions from 2005 through 2008; and validated to water quality conditions for two individual years (2007 and 2008). Following validation, an in-lake, load-response simulation was performed to determine the assimilative capacity for Lake Sarah. The load response procedure was used to estimate wasteload allocations that would result in compliance with the water quality goals for Lake Sarah.

4.1.1 BATHTUB Inputs

Physical-Chemical Parameters

BATHTUB modeling for Lake Sarah was based on over ten years of in-lake data (Figures 1.4 through 1.7). The BATHTUB model was developed to simulate average, growing-season, water-quality conditions (May through September) from 2005 through 2008 (Table 4.1). Water quality data from 2000, 2002 and 2004 were not included in the calibration dataset because they did not represent average conditions (2000 and 2002 represented years with extreme precipitation events and in 2004 lake water levels were affected by installation of a new outlet structure). Morphometry and observed water quality conditions for Lake Sarah were represented within the BATHTUB model as a spatially-averaged single segment (Tables 4.2 and 4.3). Although Lake Sarah has two geographically distinct areas (Figure 1.1), it was modeled as a single segment because the results from comparative sampling efforts suggested that there was not a significant difference in water quality between the two bays (see section Water Quality Monitoring Section for further detail).

Table 4.1. Lake Sarah observed water quality conditions used for calibration of the BATHTUB model.

Year	TP µg/L	Chl-*a* µg/L	Secchi M
2005	88.4	56.4	1.53
2006	80.5	46.7	1.31
2007	92.2	54.7	1.28
2008	83.8	44.9	1.23
Average	86.2	50.7	1.34
CV	0.2	0.1	0.10

Precipitation and evaporation values used in the model were based on average conditions for the Minneapolis, Minnesota. Evaporation loss was calculated using a PAN evaporation average (0.93 m) from the St. Paul Campus Climatological Observatory (from 1972 through

2008). The PAN evaporation average was converted to lake evaporation using a PAN coefficient of 74.5% (Minnesota Hydrology Guide, 1975). The atmospheric deposition TP loading rate used in BATHTUB was the default value (see the Atmospheric Deposition section for further detail).

Table 4.2: Lake Sarah morphometry inputs.

Morphometry Characteristics	
Surface Area	2.24 km^2
Mean Depth	4.1 m
Length	4.6 km
Mixed Layer Depth	4 m
Hypolimnetic Depth	11 m

Table 4.3. BATHTUB global input parameters.

Parameter	BATHTUB Input
Precipitation	0.74 m
Evaporation	0.69 m
Atmospheric precipitation TP load rate	30 mg/m^2-yr
Averaging period	1 year

Watershed Load

The watershed load entered into the BATHTUB model was developed from both modeling efforts and monitoring data (Table 4.4). The BATHTUB model calculates watershed load for each tributary by multiplying an annual flow by an average concentration. A ten-year average annual flow and TP concentration was calculated using the Lake Sarah SWAT model and used as input for the West, East, Middle Direct and West Direct tributaries (Figure 7; see the SWAT model section for further detail). Annual flow and TP concentration values for the tributaries providing direct drainage (Northeast, North, Northwest and South; Figure 3.3) were derived from SLAMM modeling efforts (see SLAMM modeling section for further detail).

Table 4.4. Lake Sarah Tributary Flow and Concentration for the BATHTUB model.

Tributaries	Flow hm^3/yr	TP µg/L
West	1.44	340
East	1.0	311
Northeast Direct	0.082	344
North Direct	0.069	325
Northwest Direct	0.016	194
South Direct	0.072	329
Middle Direct	0.27	249
West Direct	0.13	300

4.2 Calibration

The BATHTUB model was calibrated to a 4-year average condition from 2004 through 2008 (Table 4.4). The Canfield and Bachmann General Lakes TP sedimentation equation (option 9) was used for BATHTUB model simulations because it best predicted the observed water quality conditions in Lake Sarah (Table 4.5). Calibration of the BATHTUB model was initially attempted using internal loading rate of 0 (i.e., although a background level of internal loading is implicitly represented in BATHTUB, no additional internal load was added). However, calibration with an internal loading rate of 0 did not produce a strong fit between observed and modeled values. To achieve a stronger correlation between modeled and observed water quality conditions, an additional internal loading calibration adjustment was necessary.

4.2.1 Internal Load Calibrations

An internal loading calibration adjustment of 1.0 mg TP/m^2/day resulted in a strong correlation between the modeled and observed water quality conditions (Table 4.5). The internal load calibration resulted in an additional 1800 pounds of phosphorus to the overall mass balance equation. The additional internal load required to calibrate the BATHTUB model was consistent with the internal load estimated from the Nürnberg equation (2763 lbs of phosphorus) and curlyleaf pondweed senescence (977 lbs of phosphorus). The difference between the total estimated internal load (e.g., sum of the Nürnberg and curlyleaf pondweed estimates) and the additional internal load required to calibrate the BATHTUB model was 1940 pounds of phosphorus. This difference between the estimates likely represents some component of the internal load that is implicitly represented in the BATHTUB model. The internal load estimate calculated using the BATHTUB model (1800 lbs) was used in the overall lake nutrient balance.

4.2.2 Chlorophyll-a and Secchi Transparency Calibrations

The chlorophyll-*a* and secchi depth algorithms were selected based on the model option that best predicted the observed in-lake conditions. The chlorophyll-*a* model option used was P,N, Low-Turbidity (option 3). The default transparency vs. chlorophyll-*a* and turbidity model option (option 1) was used to characterize secchi depth. Chlorophyll-*a* and secchi depth model coefficients were adjusted incrementally to further calibrate to the observed in-lake water quality conditions (Table 4.5).

Table 4.5. BATHTUB model calibration to existing conditions.

Water Quality Parameters	Lake Sarah			
			Bathtub	
	Observed	Bathtub Predicted	Model Selection	Calibration Coefficients
TP (µg/L) Mean	97	96.9	9-Canfield Bachmann, Lakes	1
Chl-a (µg/L) Mean	52	52	3-P,N, Low-Turbidity	1.1
SD (m) Mean	1.4	1.4	1-vs. Chl-a & Turbidity	1.25

4.3 Validation

The calibrated BATHTUB model was validated using independent in-lake water quality data and SWAT/SLAMM watershed load estimates from 2007 and 2008 (Table 4.6). The correlation of BATHTUB model predictions with the 2007 and 2008 datasets (Table 23) suggests that the BATHTUB model (developed for average conditions) accurately predict changes in lake water quality in specific individual years (Table 4.7).

Table 4.6. BATHTUB Model watershed loading for 2007 and 2008.

	2007		2008	
Tributaries	Flow hm³/yr	TP µg/L	Flow hm³/yr	TP µg/L
West	1.43	307	1.4	288
East	1.02	279	0.95	182
Northeast Direct	0.09	372	0.06	292
North Direct	0.08	355	0.05	275
Northwest Direct	0.02	220	0.01	165
South Direct	0.08	356	0.05	286
Middle Direct	0.26	224	0.26	212
West Direct	0.12	276	0.12	254

Table 4.7. Validation results from independent water quality and watershed load data from 2007 and 2008 in Lake Sarah.

Bathtub Model Validation						
	2007			2008		
Parameter	Observed	Predicted	% Difference	Observed	Predicted	% Difference
TP (µg/L)	92.2	83.8	9.1	83.8	78.5	6.3
Chl-a (µg/L)	54.7	48.4	11.5	44.9	44.0	2.0
Secchi (m)	1.3	1.4	7.1	1.2	1.5	20.0

4.4 Load Response

A load response procedure was performed to evaluate the in-lake water quality response to varying phosphorus loads from the watershed. The load response procedure was used to estimate the wasteload allocation consistent with achieving specific water quality goals. The load response analysis was performed with the internal loading rate set to zero. Setting the internal loading rate of zero, does not imply there is no internal loading occurring within Lake Sarah. Instead, an internal loading rate of zero indicates that the maximum internal load that will result in compliance with the in-lake water quality goals can be no higher than the background levels of internal loading implicitly represented in the BATHTUB model (see the BATHTUB calibration section for further detail). With the internal load set to zero, the watershed phosphorus loads were incrementally reduced to identify the watershed load that resulted in an in-lake TP concentration of 40 µg/L. The output from the load response analysis also included predictions of chlorophyll-*a* concentration and secchi depth that would be anticipated when the in-lake phosphorus concentration reached the TMDL goal (with Margin of Safety).

4.5 Results

4.5.1 Existing Conditions

Water quality conditions in Lake Sarah are influenced by both watershed and internal loading processes. The Lake Sarah watershed contributes approximately 53% of the total annual phosphorus load to the lake, and internal loading accounts for 44% of the total annual load (Table 4.8). Atmospheric deposition accounts for only a small percentage (3%) of the total phosphorus loading to the lake.

Table 4.8. Volume and TP load source contributions: Existing conditions

Source	Volume (hm^3)	% Volume	TP Load (lbs/yr)	% TP Load
Watershed	3.1	65%	2166	53%
Atmospheric precipitation	1.6	35%	148	3%
Internal	0	0%	1800	44%

4.5.2 Assimilative Capacity

The load response simulation for Lake Sarah determined that reductions in both the watershed and internal loads will be necessary to meet the in-lake water quality goal of 40 µg/L. Initially, the load response simulation was run to estimate the water quality improvements that would result from a reduction in the watershed load alone (i.e., the internal loading rate was not reduced). This analysis suggested that a 100% reduction of the watershed load would result in an in-lake TP concentration of 53.5 µg/L – above the 40 µg/L goal (Figure 4.1). A second load-response simulation was run with the internal loading rate set to zero (i.e., the internal loading represented in the model was no greater than background levels implicitly represented by BATHTUB). Results from the second load-response analysis suggest that – when internal loading is controlled to background levels – in-lake water quality goals will be achieved when the total annual watershed phosphorus load to the lake does not exceed 1208 lbs TP/yr (Figure 4.2).

4.6 Margin of Safety

Margin of safety (MOS) for Lake Sarah is explicitly defined as 198 lbs. The MOS value was developed by identifying and adopting an in-lake phosphorus goal of 36 µg TP/L, 4 µg/L less than the Minnesota State standard of 40 µg TP/L. A primary input for the development of in-lake phosphorus standards in Minnesota was the relationship between user perception and in-lake TP concentrations (e.g., Heiskary and Wilson, 2005). Heiskary and Walker (1988) observed that 40 µg TP/L standard corresponds to an ~25% risk of experiencing "High Algae" conditions, "Swimming Impairment" and Chlorophyll-a concentrations of > 20 µg/L. An in-lake TP concentration of 36 µg TP/L corresponds to a reduced risk of these conditions of ~10%. The 198 lbs margin of safety represents 9 % of the existing total annual watershed load, 20% of the wasteload allocation and ~28% of the annual variability in watershed loading (standard deviation around the annual average watershed load is ~706 lb TP/yr).

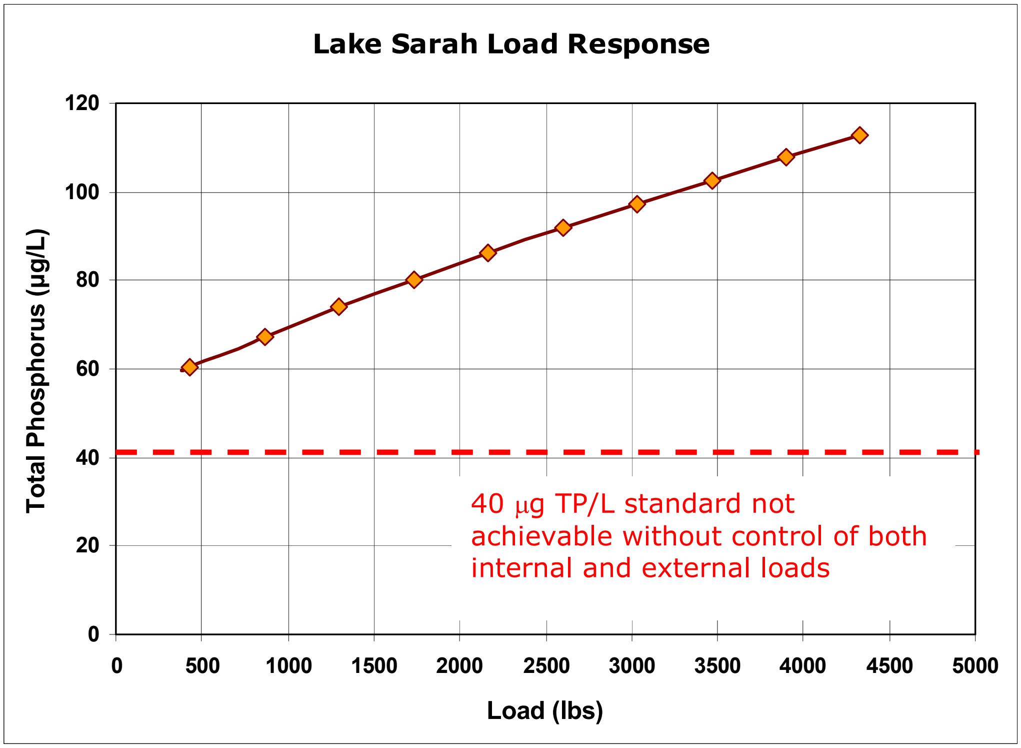

Figure 4.1. Lake Sarah load-response with an internal loading rate of 1.0 $mg/m^2/day$ and 10-year average watershed loading in the BATHTUB model.

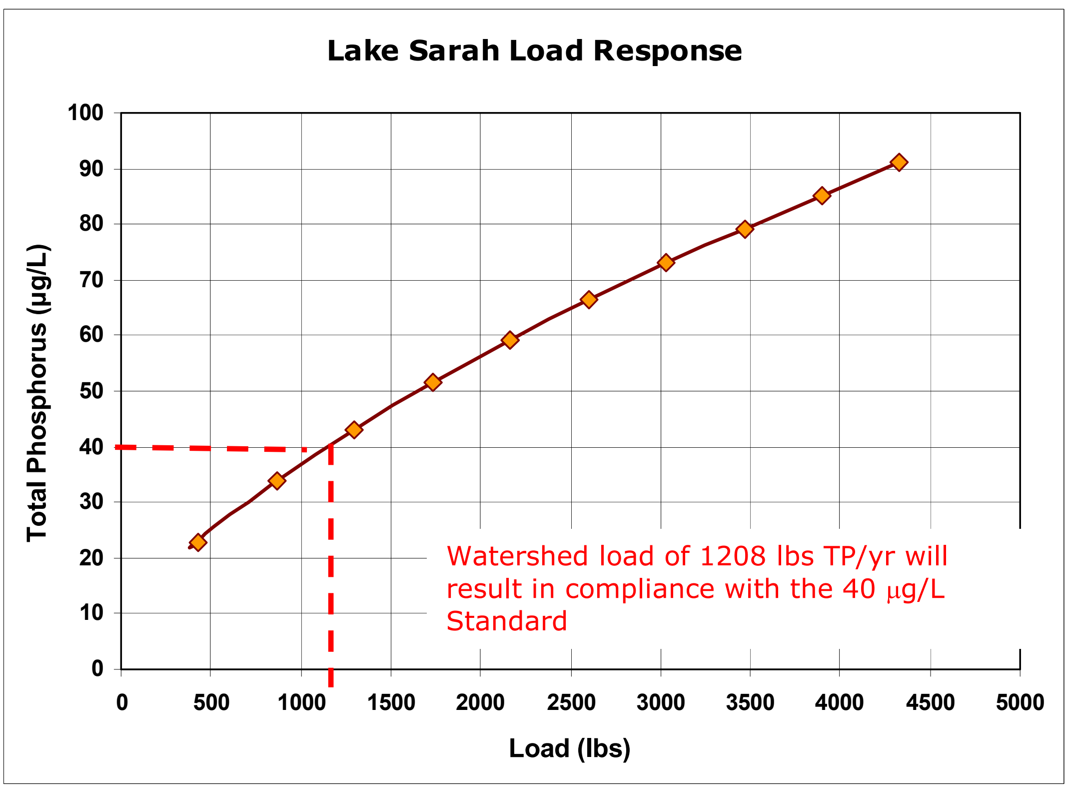

Figure 4.2. Lake Sarah load-response with internal loading set to zero in the BATHTUB model and average watershed loading based on the 10-year average.

4.7 Reserve Capacity

Reserve capacity for Lake Sarah is being set to zero in the TMDL. A reserve capacity of zero was determined based on the non-degradation policy described in the *Pioneer-Sarah Creek Watershed Commission 2nd Generation Plan* (section VI, A.21). This policy requires no increase in phosphorus discharge as a result of development and/or redevelopment activities.

4.8 Seasonal Variability

As described in Lake Water Quality and Watershed Monitoring sections, water quality in Lake Sarah and phosphorus loads from the surround watershed vary within and among years (Figures 1.4 through 1.7 and 2.1). Intra and interannual variability are both addressed in the TMDL. Intraannual variability is addressed in the TMDL by basing lake condition assessments on the average growing-season TP concentration. Although TP concentrations vary significantly throughout the summer months, the growing-season average integrates ecosystem variability over time. Interannual variability is reflected in the TMDL by basing the model calibration(s) on long-term averages in precipitation/watershed loading (10-year average) and in-lake response (4-year average) – which integrates long-term trends.

TMDL Allocations

The TMDL represents the total mass of phosphorus that can be assimilated into Lake Sarah while continuing to meet the state water quality standards. For purposes of implementation, the TMDL is described as an equation with four different components: Waste Load Allocation (WLA); Load Allocation (LA); Margin of Safety (MOS); and Reserve Capacity (RC). The WLA represents phosphorus loading from permitted sources such as permitted stormwater discharge from the various MS4s. The LA represents phosphorus from non-permitted sources such as non-MS4 municipalities, atmospheric deposition and internal lake loading. A portion of the TMDL is allocated to the MOS to account for uncertainty associated with modeling estimates and environmental variation. The RC represents the portion of the load that is set aside to account for future development.

$$TMDL = \sum WLA + \sum LA + MOS + RC$$

WLA = Wasteload Allocations
LA = Load Allocations
MOS = Margin of Safety
RC = Reserve Capacity

Values for the WLA, LA, MOS, and RC were summed to arrive at the overall TMDL goal for Lake Sarah (Equation 4).

Equation 4:

TMDL	**=**	**ΣWLA**	**+**	**ΣLA**	**+**	**MOS**	**+**	**RC**
1356	**=**	**406**	**+**	**752**	**+**	**198**	**+**	**0**

Based on the load-response simulation, the total annual watershed phosphorus load must not exceed 1208 lbs P/year to achieve the in-lake water quality goal (Figure 4.2). In addition, an explicit MOS of 198 pounds was included to ensure that water quality standards are achieved across a range of environmental conditions. Following the adjustment for the explicit MOS, the total annual watershed phosphorus load to the lake from permitted (WLA) and non-permitted (LA) sources must not exceed 1010 pounds of phosphorus per year (Table 5.1). Thus, the watershed load will need to be reduced by 1155 lbs (approximately 53%) to achieve the in-lake water quality goals.

Table 5.1. Lake Sarah phosphorus sources and required reductions necessary to achieve in-lake water quality goal.

TP Source	**TP Load (lbs/yr)**			**% Difference**
	Current	**TMDL**	**Difference**	
Watershed, Permitted (WLA)	986	406	580	59%
Watershed, Non-permitted (LA)	1180	604	576	49%
Atmospheric (LA)	148	148	0	0%
Internal (LA)	1800	0	1800	100% *
Margin of Safety (MOS)	-	198	-	-
Reserve Capacity (RC)	0	0	0	0%
Total	4114	1356	2758	67%

**Note: 100% of the internal load refers to the 1800 lbs identified as internal load above the background levels implicitly represented in the BATHTUB model.*

The BATHTUB model was used to predict the change in chlorophyll-*a* concentration and secchi-depth transparency that will correspond to the TMDL loading scenario (including MOS). With phosphorus loading at levels prescribed by the TMDL, secchi depth in Lake Sarah will increase to 3.9 m (Table 5.2) – meeting the state standard of 1.4 meters. However, the chlorophyll-*a* water quality standard will not be achieved with the load reductions prescribed by the TMDL. The BATHTUB model predicts that chlorophyll-*a* concentration will decrease to 14.7 µg/L, which is slightly above the chlorophyll-a water quality standard of 14 µg/L (Table 8). Assuming that the total phosphorus and secchi-depth transparency water quality standards are achieved, Lake Sarah will not be considered impaired due to excess nutrients and removed from the 303d impaired waters list.

Table 5.2. Lake Sarah predicted changes in water quality conditions for the TMDL modeled loading scenario.

Parameters	Loading Scenario		Water Quality Standard
	Existing Conditions	TMDL Modeled	
TP (µg/L)	86.2	36.0	40.0
Chl-a (µg/L)	50.4	14.7	14.0
Secchi (m)	1.3	3.9	1.4

5.1 Wasteload Allocations

5.1.2 Wasteload Allocations for Permitted MS4

The overall wasteload allocation was partitioned out into individual WLAs for each of the permitted MS4s throughout the watershed*. Individual WLAs were assigned based on watershed area. For example, if community "A" represents 10% of the watershed area, it was allocated 10% of the watershed load. WLAs and existing loads are described in detail in Table 5.3. **Note: Because the City of Greenfield is not currently a permitted MS4, its respective phosphorus load is included in the Load Allocation (see the Load Allocation Section below).*

5.1.3 Construction Stormwater

Stormwater from construction activities has been assigned a WLA of 1.46 lbs TP/yr (0.004 lbs TP/day). The construction stormwater WLA was estimated based on a 10-year estimate of the median number of construction site acres present throughout the Lake Sarah watershed. Ten-year median construction acres (6.45 in the Lake Sarah watershed) were divided by the total watershed area (4453 acres) to identify the percent watershed area anticipated to be in construction in any given year (0.145%). The 10-year median construction percentage was multiplied by the TMDL watershed load allocation to identify the construction WLA (1.46 lbs TP/yr). Construction stormwater activities are considered in compliance with provisions of the TMDL if they obtain a Construction General Permit under the NPDES program and properly select, install and maintain all BMPs required under the permit, including any applicable additional BMPs required in Appendix A of the Construction General Permit for discharges to impaired waters, or meet local construction stormwater requirements if they are more restrictive than requirements of the State General Permit.

5.1.4 Industrial Stormwater

Industrial stormwater has not been assigned a WLA. There are no known industrial discharges located in the Lake Sarah watershed. Any future industrial stormwater activities will be considered in compliance with provisions of the TMDL if they obtain an industrial stormwater general permit or General Sand and Gravel general permit (MNG49) under the NPDES program and properly select, install and maintain all BMPs required under the permit.

Table 5.3. Annual and daily wasteload allocations for permitted discharges in the Lake Sarah watershed.

Permitted Source	Permit Number	Existing Load		Acres Contributing to Wasteload		Wasteload Allocation		Wasteload Reduction
		Annual (lbs/yr)	Daily (lbs/day)	Acres	Percentage	Annual (lbs/yr)	Daily (lbs/day)	Annual (lbs/yr)
Corcoran	MS400081	223	0.610	458	25.5%	104	0.284	119
Independence	MS400095	300	0.822	780	43.4%	176	0.483	124
Medina	MS400105	342	0.937	429	23.9%	97	0.266	245
Loretto	MS400030	57	0.157	87	4.9%	20	0.054	38
MnDOT Metro	MS400170	51	0.139	25	1.4%	6	0.015	45
Hennepin County	MS400138	11	0.031	11	0.6%	2	0.007	9
Construction *	MN R 100001	1	0.004	6	0.4%	1.458	0.004	0
Industrial **	NA	NA	NA	-	-	NA	NA	0
TOTAL		**986**	**2.700**	**1797**		**406**	**1.112**	**580**

** Assuming compliance with NPDES general permits.*
*** No known industrial discharges in the Lake Sarah watershed*

5.2 Load Allocations

The Load Allocation (LA) represented in the BATHTUB model was 752 lbs TP/year (Table 5.1). The LA portion of the TMDL equation represents 604 lbs TP/yr from the City of Greenfield*, 148 lbs TP/yr from the atmosphere and 0 lbs TP/yr from internal loading. As described above, setting the internal load value in the TMDL equation to 0 does not imply there is no internal load. Instead, the 0 value indicates that the internal load that will allow Lake Sarah to meet water quality standards can be no higher than the background levels of internal loading already represented in the BATHTUB model (additional sources of internal load are described in more detail in the Internal Load section above). To meet water quality goals in all years (particularly those with high densities of curlyleaf pondweed), internal load will also have to be reduced by an average of 1800 lbs TP/year. **Note: Because the City of Greenfield is not currently a regulated MS4 community, its respective phosphorus load is included in the Load Allocation. Following classification as an MS4 community, the 604 lb TP/yr LA for the City of Greenfield will be converted to a WLA and included in the list of permitted sources.*

5.3 Reasonable Assurances

Implementation of the Lake Sarah TMDL will occur at federal, state and local levels. Given the ongoing commitment of the watershed communities, local residents and the Pioneer-Sarah Creek Watershed Management Organization, timely and effective implementation of water quality improvement projects is anticipated. All implementation efforts will be guided by a detailed implementation plan that was developed through ongoing discussion with watershed stakeholders.

Since ~40% of the phosphorus runoff throughout the Lake Sarah watershed is a component of the WLAs for the permitted MS4s, much of the implementation will occur through the National Pollution Discharge Elimination System (NPDES) permit program. As part of the NPDES program, the Minnesota MS4 general permit requires that all regulated MS4s develop and implement a Stormwater Pollution Prevention Plan (SWPPP). Within 18 months of TMDL approval by EPA, each MS4 must update their individual SWPPP to reflect the WLAs and BMPs described in the TMDL and Implementation Plan. Individual SWPPPs are reviewed by MPCA every five years to track implementation activities.

Water quality in the Lake Sarah watershed is further managed through the local surface water planning process implemented by the Minnesota Board of Water and Soil Resources (BWSR). Minnesota Rules Chapter 8410 requires that watershed management plans be developed to address specific goals and policies that address: Water Quantity; Water Quality; Natural Resource Protection; Erosion and Sediment Control; Wetland Protection; Shoreland Management; and Floodplain Management. Watershed management plans are updated every ten years and reviewed by BWSR. Permitted MS4s are required to update their Local Surface Water Management Plans to align with the current Pioneer-Sarah Creek Watershed Management Plan. As described above, the *Pioneer-Sarah Creek Watershed Commission (PSCWC) 2nd Generation Plan* (section VI, A.21) contains a non-degradation policy that requires no increase in phosphorus discharge during development and redevelopment activities. Development, adoption and implementation of a shoreland management controls is also required and regulated by Minnesota Department of Natural Resources (MNDNR) for all riparian communities (*Minnesota Rules 6120.2500 – 3900*). Progress toward TMDL implementation will also be tracked through a comprehensive monitoring program (see the Monitoring Plan section below for further detail).

In addition the regulatory capacity of MPCA, BWSR and PSCWC, implementation (particularly for non-point sources) will be facilitated through incentive-based programs. Hennepin County Environmental Services (HCES), Natural Resource Conservation Service (NRCS) and the Lake Sarah Improvement Association (LSIA) have been actively involved in a number of projects throughout the watershed to engaging landowners in water resource stewardship activities. Previous incentive programs have included: cost-share grants for shoreline stabilization/restoration, erosion control, conservation buffers, technical assistance and rain garden installation. To increase voluntary participation in watershed stewardship activities, the PSCWC is also an active participant in the regional Education and Public Outreach Committee (EPOC).

Monitoring Strategy

To ensure effectiveness and efficiency of TMDL implementation, ongoing monitoring will be conducted. Monitoring will assess BMP implementation, in-lake condition, watershed loading and aquatic plant community composition.

BMP implementation monitoring will be conducted by the Pioneer-Sarah Creek Watershed Commission (PSCWC). Each year member communities will submit a summary of BMP projects and the anticipated phosphorus reductions to the PSCWC in conjunction with Stormwater Pollution Prevention Plan (SWPPP) reporting. BMPs will be cataloged to monitor progress toward the individual wasteload reduction goals.

In-lake monitoring will be conducted annually following completion of the TMDL. Samples will be collected biweekly (April thru October) following previously described protocols for eutrophic lake assessment (Heiskary, 1994 and MPCA, 2007). Based on this sampling frequency, there is a 75% probability that a 30% change in lake condition will be detected after 3 years of monitoring (90% after 6 yrs; MPCA, 2007). Monitoring will be continued at this frequency for a ten year period and/or until implementation efforts have been completed.

Five years after approval of the TMDL, a detailed watershed load monitoring study will be conducted to quantify the relative load reduction associated with various BMPs. Watershed monitoring will be conducted at the current TMDL monitoring sites following protocols described by Walker (1996). Follow-up monitoring will be conducted for a one to two year period (depending on precipitation patterns), every five years until wasteload reduction goals have been achieved. Watershed load monitoring will be structured to assess BMP effectiveness at a watershed scale (where applicable) to validate the predicted phosphorus removal efficiencies and facilitate an adaptive approach to the design/implementation of future BMPs. **Future watershed load monitoring efforts should include assessments of early season runoff associated with snow melt and early season rain events (particularly during seasons where rain on snow events are possible). Preliminary data suggests that early season runoff may be an important phosphorus source to the lake that is currently underrepresented in the model (see the modeling uncertainty section for further discussion).*

Sediment phosphorus levels will be assessed concurrently to watershed load monitoring efforts to better evaluate the applicability and potential cost-effectiveness of additional in-lake BMPs. Sediment phosphorus monitoring will be conducted following the protocol outlined by Pettersson et al. (1988).

Aquatic macrophyte monitoring will be conducted annually to assess: 1) the natural variability of the aquatic plant community; and 2) the efficacy of any future aquatic plant management programs. Monitoring will be conducted at ~200 points throughout the littoral zone using a point intercept survey (e.g., Madsen, 1999). Annual monitoring will be conducted until in-lake plant management activities have been completed.

Implementation Strategy

Implementation efforts will focus on reduction of both internal and external phosphorus loads. As described in the TMDL Allocation section, reductions of both the watershed (53 %) and internal (100 % - above background levels) loads are necessary to achieve water quality goals for Lake Sarah. To ensure that water quality improvements from internal load management efforts are sustained, implementation will initially focus on reducing watershed loading.

7.4 Watershed Load Reduction Strategies

To achieve the Wasteload Allocation (WLA) and Load Allocation (LA) goals (as described in the TMDL Allocation section), watershed load reduction efforts must remove 1155 lbs of phosphorus annually. Reduction of the watershed load will be achieved by implementing a series of BMPs related to row crop agriculture, feedlot and manure management, residential and commercial development and restoration of stream, wetland and shoreline habitat. To facilitate flexibility during implementation, the total acreages available for implementation, relative cost, and removal efficiencies of different BMP for each watershed community have been summarized (Appendix B).

As described in the Loading Capacity and SWAT modeling sections, the majority of the phosphorus load is delivered to the lake as a result of overland surface flow – primarily from spring snow-melt and early season precipitation. As a result, BMPs that focus on reducing surface runoff and/or erosion will have a greatest influence on water quality improvements. Recommendations described below are based a combination of a cost-benefit comparisons and direction from local city councils and planning commissions. Costs and associated pounds of phosphorus reduction are presented below as maximum or best-case scenario estimates. Total phosphorus reduction goals (either Wasteload Reductions, WLRs or Load Reduction, LRs) identified for each community are in excess of the respective individual WLAs or LAs. This excess is intended to account for partial implementation of different BMP types, overlap of BMP effectiveness and facilitate cost-sharing among communities and with transportation entities. BMPs described are intended for existing conditions and do not address anticipated changes in land use.

Medina (WLR 245 lbs P/yr)

The most cost-effective options for phosphorus load reduction in the City of Medina are BMPs related to row crop management and instream/wetland restoration. Specific, projects/activities recommended in Medina are:

1) nutrient management based on soil tests (up to 115 lbs P/yr; $2,881);
2) edge-of-field filter strips (buffers; up to 172 lbs P/yr; $8,600);
3) instream/wetland restoration of channelized reaches (up to 300* lbs P/yr; $320,000). **note: projected phosphorus reduction is based on a generalized formula and will be updated following completion of project design specifications*

Total potential P removal resulting from BMP implementation in Medina is **783 lbs P/yr**.

Independence (WLR 123 lbs P/yr)

The most cost-effective options for phosphorus load reduction in the City of Independence are BMPs related to row crop management, feedlot and manure management and shoreline restoration. Specific projects/activities recommended in Independence are:

1) manure application guidance (up to 19 lbs P/yr; $527);
2) nutrient management based on soil tests (up to 38 lbs P/yr; $950);
3) edge-of-field filter strips (buffers; up to 38 lbs; $1,890);
4) shoreline buffering (up to 25 lbs P/yr; $2,901);

5) barnyard management* (up to 76 lbs P/yr; $45,000) **note: for details, see Appendix B*
6) Urban raingarden installation (up to 64 lbs P/yr; $1,162,500)

Total potential P removal resulting from BMP implementation in Independence is **260 lbs P/yr**.

Greenfield (LR 576 lbs P/yr)

The most cost-effective options for phosphorus load reduction in the City of Greenfield are BMPs related to row crop and feedlot/manure management. Specific projects/activities recommended in Greenfield are:

1) manure application guidance (up to 27 lbs P/yr; $740);
2) nutrient management based on soil tests (up to 264 lbs P/yr; $950/yr);
3) edge-of-field filter strips (buffers; up to 519 lbs; $25,974);
4) barnyard management* (up to 162 lbs P/yr; $215,000) **note: for details, see Appendix B*

Total potential P removal resulting from BMP implementation in Greenfield is **972 lbs P/yr**.

Corcoran (WLR 119 lbs P/yr)

The most cost-effective options for phosphorus load reduction in the City of Corcoran are BMPs related to row crop, feedlot/manure and commercial runoff management. Specific projects/activities recommended in Corcoran are:

1) nutrient management based on soil tests (up to 64 lbs P/yr; $1,597/yr);
2) edge-of-field filter strips (buffers; up to 140 lbs; $7,002);
3) barnyard management* (up to 28 lbs P/yr; $25,000) **note: for details, see Appendix B*
4) Filtration of commercial runoff (up to 35 lbs P/yr; $1,027,500)

Total potential P removal resulting from BMP implementation in Corcoran is **267 lbs P/yr**.

Loretto (WLR 38 lbs P/yr)

The most cost-effective options for phosphorus load reduction in the City of Loretto are BMPs related to urban and residential stormwater management and instream/wetland restoration. Specific, projects/activities recommended in Loretto are:

1) instream/wetland restoration of channelized reaches (up to 300* lbs P/yr; $320,000) **note: projected phosphorus reduction is based on a generalized formula and will be updated following completion of project design specifications*

Total potential P removal resulting from BMP implementation in Loretto is **300 lbs P/yr**.

Minnesota Department of Transportation (MNDOT; WLR 45 lbs P/yr)

The most cost-effective options for phosphorus load reduction by MNDOT are the implementation of stormwater BMPs during roadway redevelopment projects and/or cost-sharing with local municipalities during BMP implementation.

Hennepin County (WLR 9 lbs P/yr)

The most cost-effective options for phosphorus load reduction by Hennepin County is the implementation of stormwater BMPs during roadway development/redevelopment projects and/or cost-sharing with local municipalities during BMP implementation.

7.5 Internal Load Reduction Strategies

Internal load reduction will be achieved through the implementation of a curlyleaf pondweed control program and/or in-lake phosphorus sequestration/removal. Effective control of internal loading will require the removal/sequestration of 1800 lbs P/year (described in further detail in the BATHTUB modeling section).

7.5.1 Curlyleaf Pondweed Control

As described in the introduction, curlyleaf pondweed is present in approximately 373 acres of the littoral zone, and this corresponds to a potential phosphorus load from senescence of approximately 914 pounds of phosphorus per year. Preliminary estimates suggest that a curlyleaf pondweed control program would need to treat a approximately 300 acres for a minimum of five years. Initial cost estimates for a lake-wide curlyleaf pondweed control program are $100,000 to $120,000 per year (cost would likely vary based on the efficacy of treatment from year to year). Prior to any whole-lake manipulation, the Lake Sarah Lake Vegetation Management Plan (LVMP) must be completed and approved by Minnesota Department of Natural Resources.

7.5.2 In-lake Phosphorus Sequestration/Removal

In addition to aquatic vegetation management, sediment release of nutrients during anoxia may need to be addressed. Potential options for internal load control that may be considered are alum treatment and hypolimnetic withdrawal and treatment/irrigation. Specific cost estimates for control of sediment release of phosphorus have not been identified in Lake Sarah, but costs of projects in similar lakes range between $280/acre and $700/acre. In-lake phosphorus control is not being proposed as a recurring management activity, but as a supplementary management tool that may be used in a “one-time” fashion to complement watershed and aquatic plant management efforts.

Public Participation

The Lake Sarah TMDL has been developed in conjunction with an extensive public participation process. Starting in January of 2008, ten stakeholder meetings were conducted to inform the TMDL development. Minutes and presentations from all TMDL stakeholder meetings are posted on the MPCA Lake Sarah TMDL project website http://www.pca.state.mn.us/water/tmdl/project-lakesarah-nutrients.html . Meetings have been coordinated by the Lake Sarah Stakeholders Committee and well attended by representatives from local governments, local citizens, the Lake Sarah Improvement Association, Pioneer-Sarah Creek Watershed Management Commission, Hennepin County Environmental Services, Board of Water and Soil Resources, Minnesota Department of Natural Resources, Minnesota Pollution Control Agency and Three Rivers Park District. *Note: starting in 2005, the Lake Sarah Stakeholders Committee began meeting independent of the TMDL process to discuss water quality management in Lake Sarah.*

In addition to the broad Stakeholder Group meetings, a series of directed stakeholder meetings/presentation (14 in total) have also been conducted with local government city councils and/or planning commissions to discuss the TMDL process and identify opportunities for BMP implementation. Directed stakeholder meetings have been conducted with City of Median, City of Loretto, City of Independence, City of Corcoran and City of Greenfield. Minutes and presentation from meeting with city councils and planning commissions are posted with the associated meeting summaries.

The official public comment period will begin…*following a 45-day, pre-draft review by all stakeholder representatives and inclusion of comments into the final draft. Following the 45-day, pre-draft comment period a public meeting will be held to present the draft report and address specific comments/questions from stakeholder representatives. Presentation of the draft TMDL to the public is expected in mid-January…*

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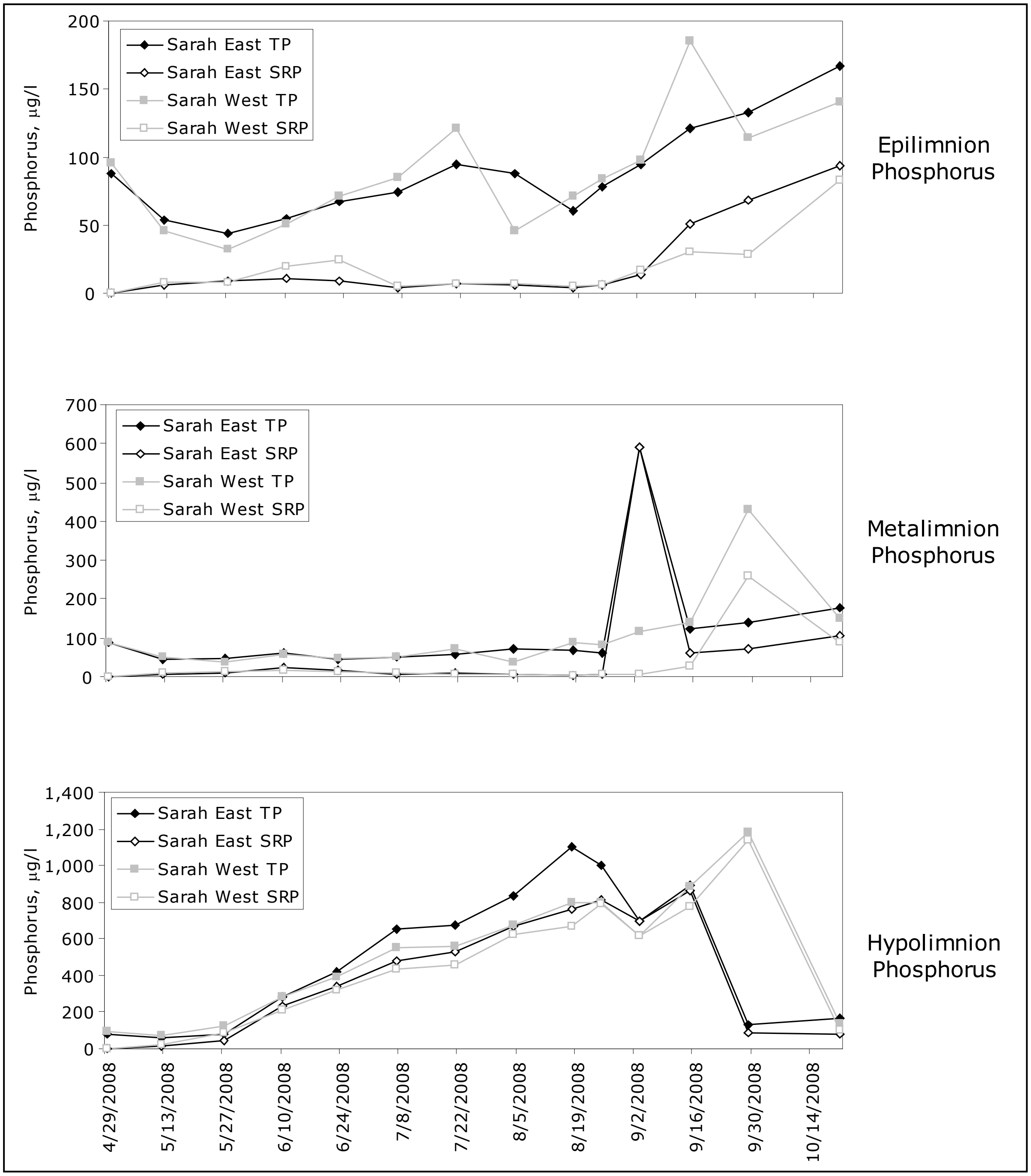
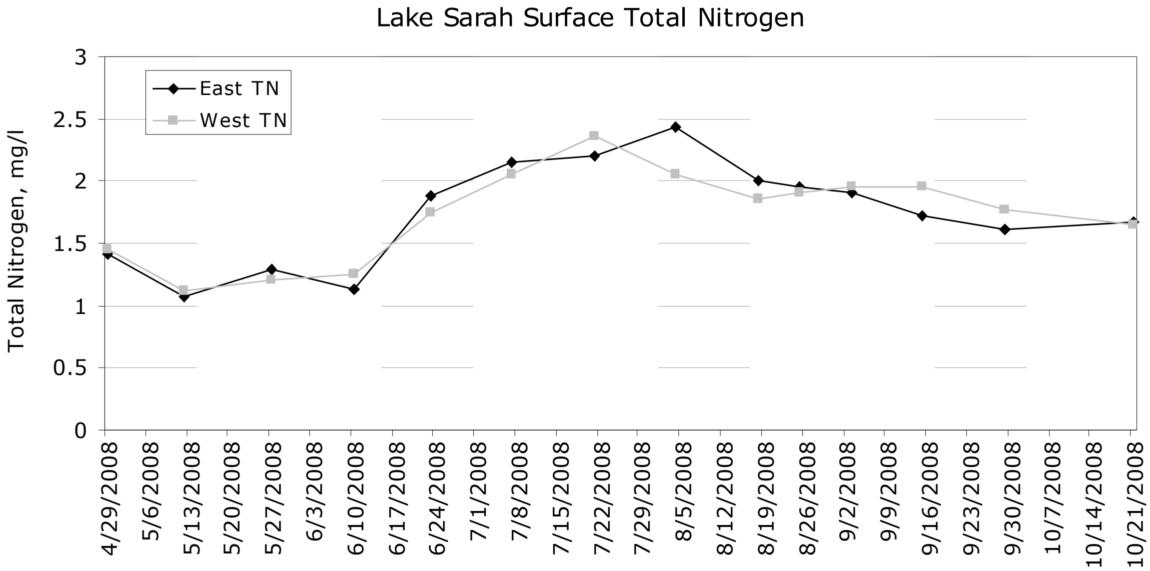
Appendix A – Comparison of General Water Quality Parameters
between the East and West Bays of Lake Sarah in 2008




Lake Sarah Surface Total Nitrogen
East TN
West TN
Total Nitrogen, mg/l
3
2.5
2
1.5
1
0.5
0
4/29/2008
5/6/2008
5/13/2008
5/20/2008
5/27/2008
6/3/2008
6/10/2008
6/17/2008
6/24/2008
7/1/2008
7/8/2008
7/15/2008
7/22/2008
7/29/2008
8/5/2008
8/12/2008
8/19/2008
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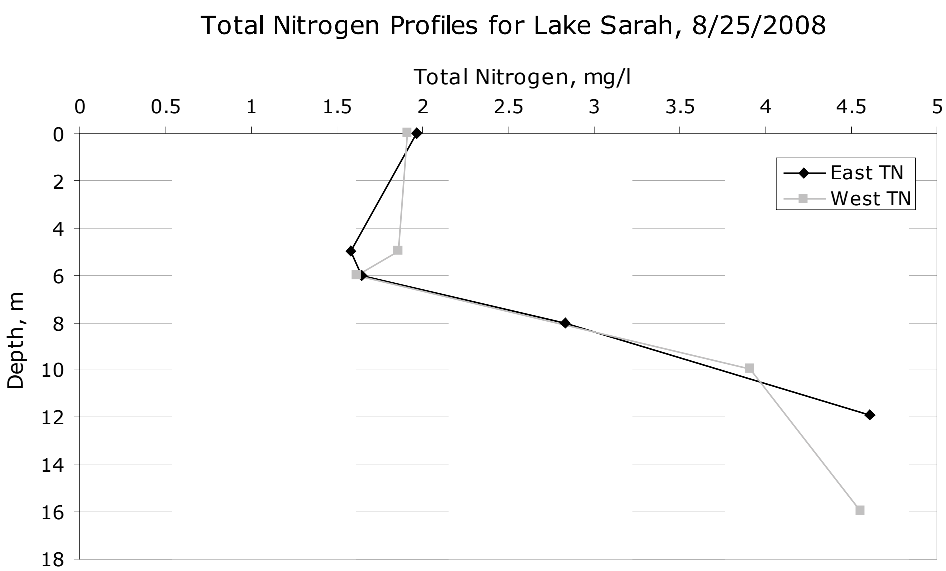
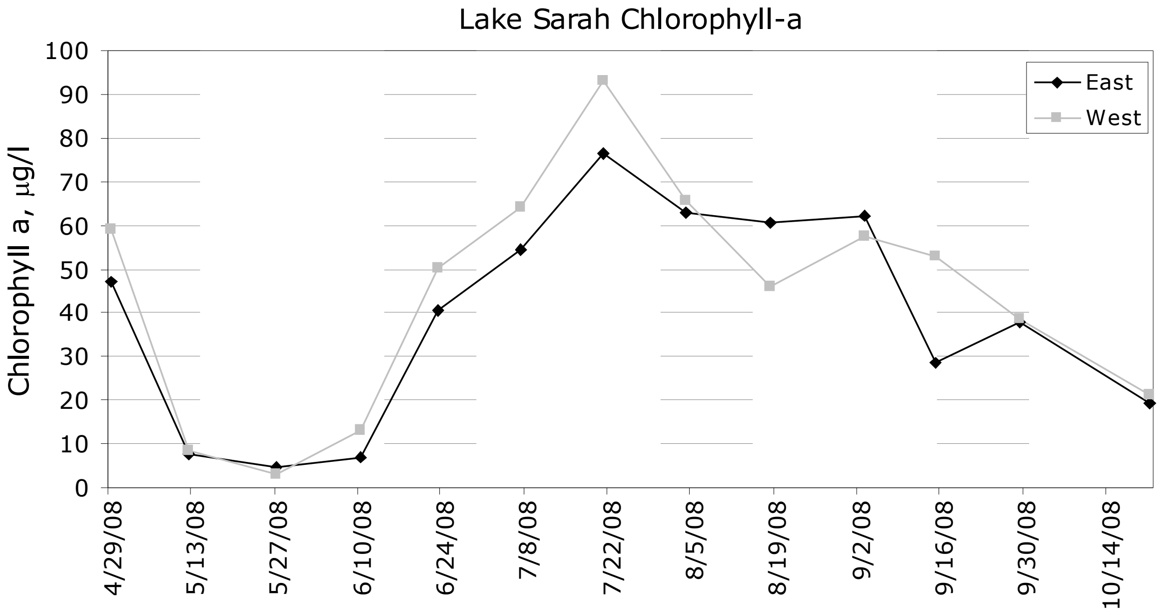
10/14/2008
10/21/2008


Total Nitrogen Profiles for Lake Sarah, 8/25/2008
Total Nitrogen, mg/l
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
East TN
West TN
Depth, m
0
2
4
6
8
10
12
14
16
18


Lake Sarah Chlorophyll-a
Chlorophyll a, µg/l
100
90
80
70
60
50
40
30
20
10
0
East
West
4/29/08
5/13/08
5/27/08
6/10/08
6/24/08
7/8/08
7/22/08
8/5/08
8/19/08
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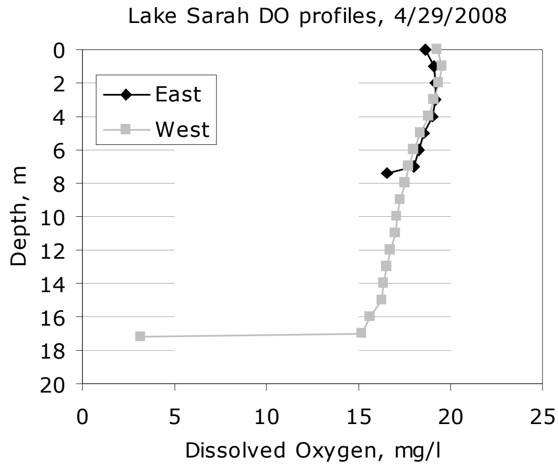
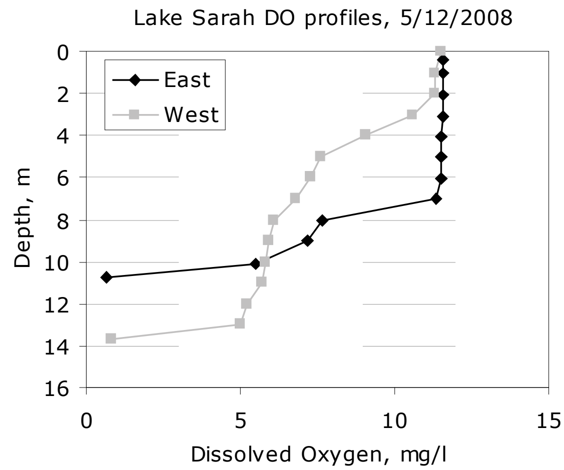
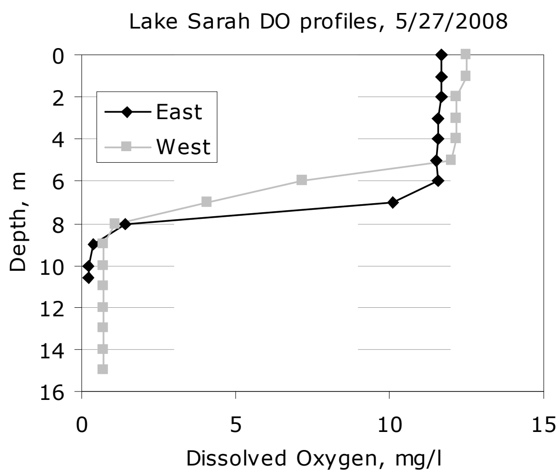
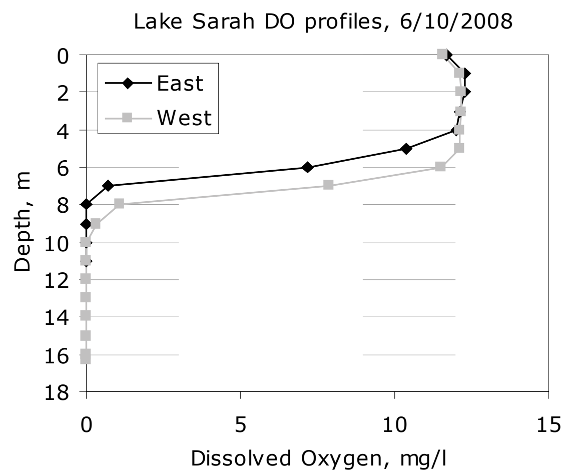
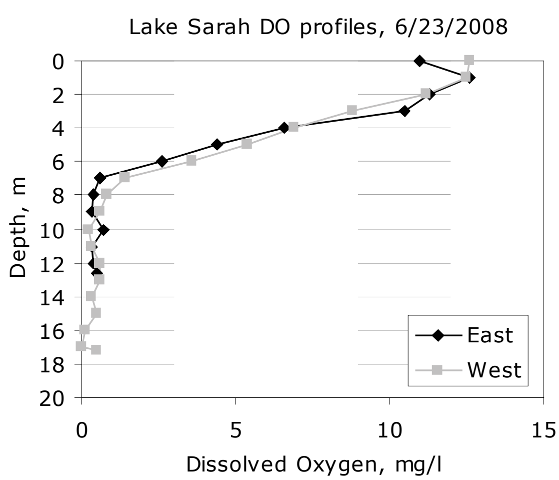
9/30/08
10/14/08

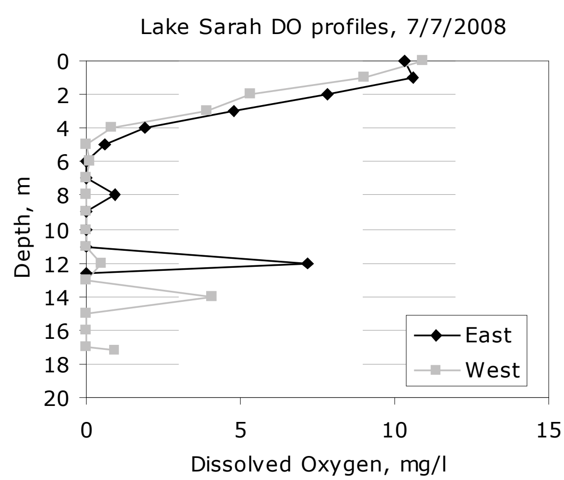

Lake Sarah DO profiles, 4/29/2008
East
West
Depth, m
Dissolved Oxygen, mg/l

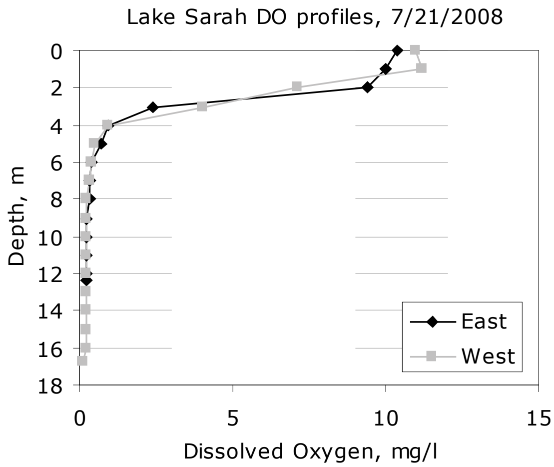

Lake Sarah DO profiles, 5/12/2008
East
West
Depth, m
Dissolved Oxygen, mg/l


Lake Sarah DO profiles, 5/27/2008
East
West
Depth, m
Dissolved Oxygen, mg/l


Lake Sarah DO profiles, 6/10/2008
East
West
Depth, m
Dissolved Oxygen, mg/l


Lake Sarah DO profiles, 6/23/2008
East
West
Depth, m
Dissolved Oxygen, mg/l


Lake Sarah DO profiles, 7/7/2008
East
West
Depth, m
Dissolved Oxygen, mg/l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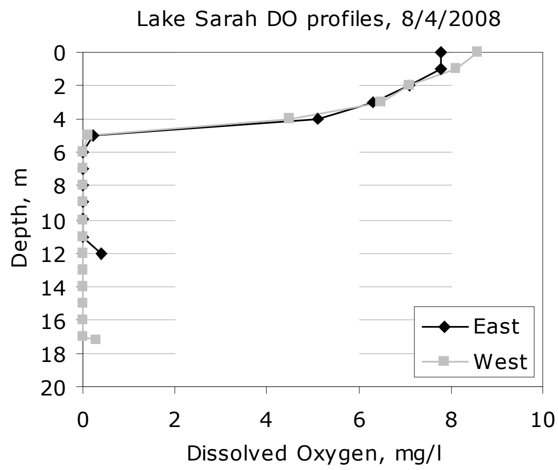
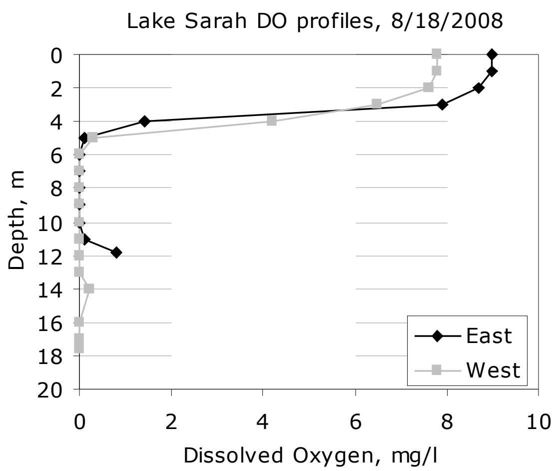
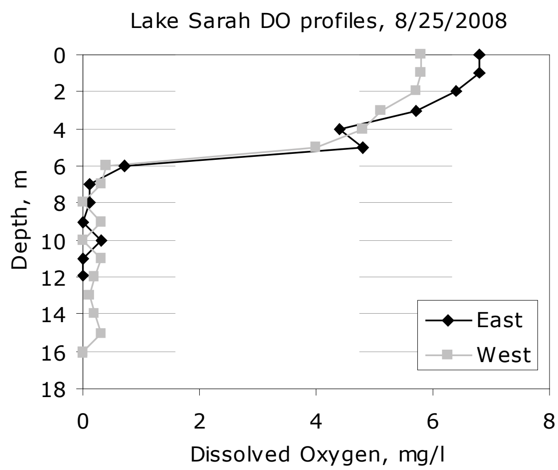
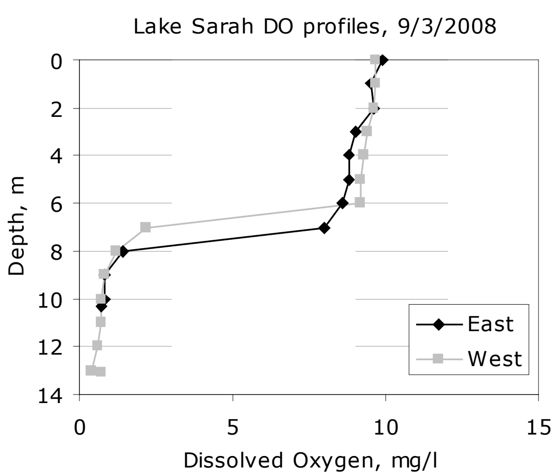
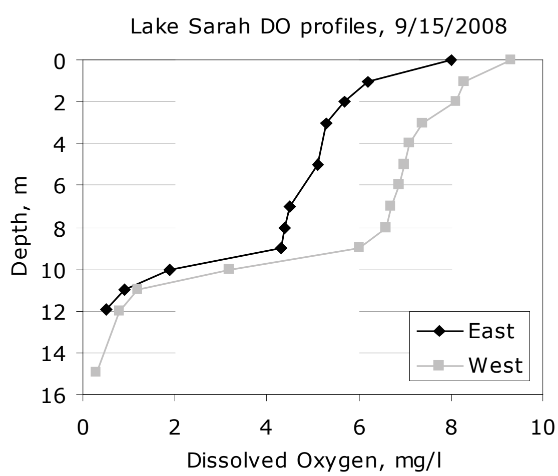
Depth, m
Dissolved Oxygen, mg/l
East
West

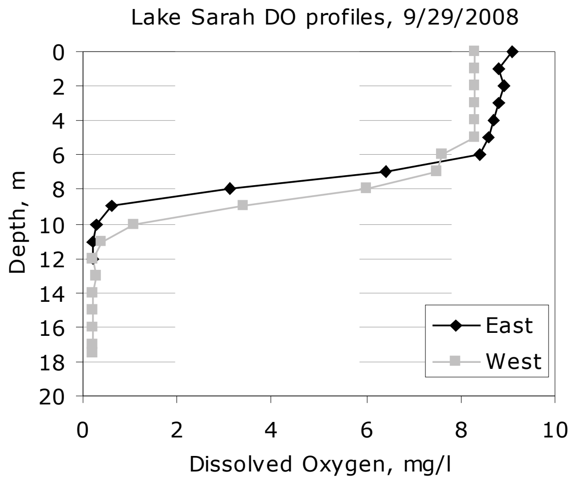

Lake Sarah DO profiles, 8/4/2008
Depth, m
Dissolved Oxygen, mg/l
East
West

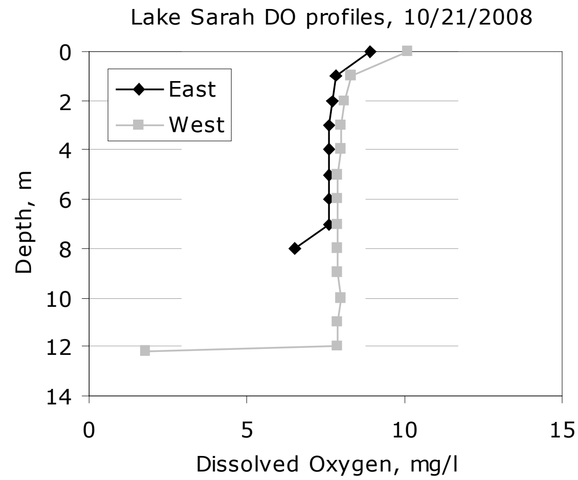

Lake Sarah DO profiles, 8/18/2008
Depth, m
Dissolved Oxygen, mg/l
East
West

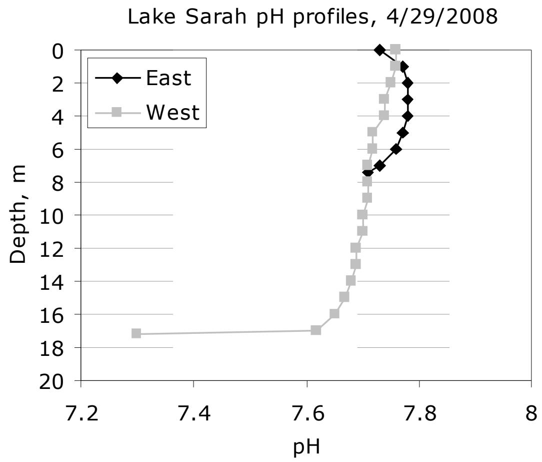

Lake Sarah DO profiles, 8/25/2008
Depth, m
Dissolved Oxygen, mg/l
East
West

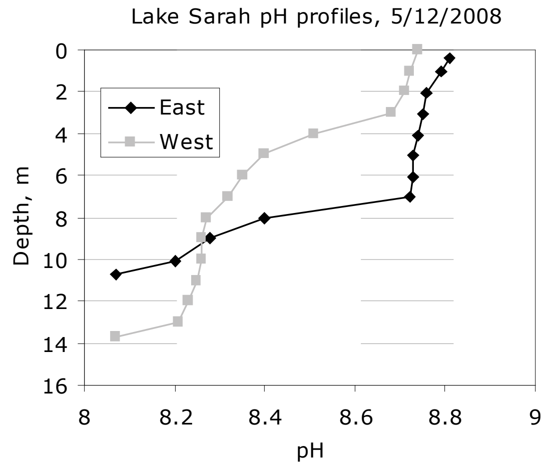

Lake Sarah DO profiles, 9/3/2008
Depth, m
Dissolved Oxygen, mg/l
East
West

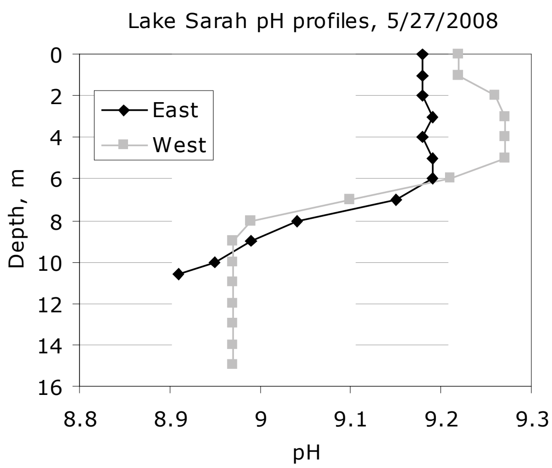

Lake Sarah DO profiles, 9/15/2008
Depth, m
Dissolved Oxygen, mg/l
East
West


Lake Sarah DO profiles, 9/29/2008
Depth, m
Dissolved Oxygen, mg/l
East
West
0
2
4
6
8
10
12
14
16
18
20
0
2
4
6
8
10


Lake Sarah DO profiles, 10/21/2008
Depth, m
Dissolved Oxygen, mg/l
East
West
0
2
4
6
8
10
12
14
0
5
10
15


Lake Sarah pH profiles, 4/29/2008
East
West
Depth, m
pH


Lake Sarah pH profiles, 5/12/2008
East
West
Depth, m
pH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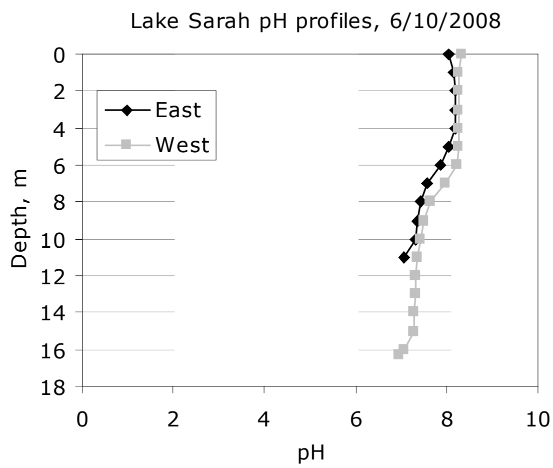
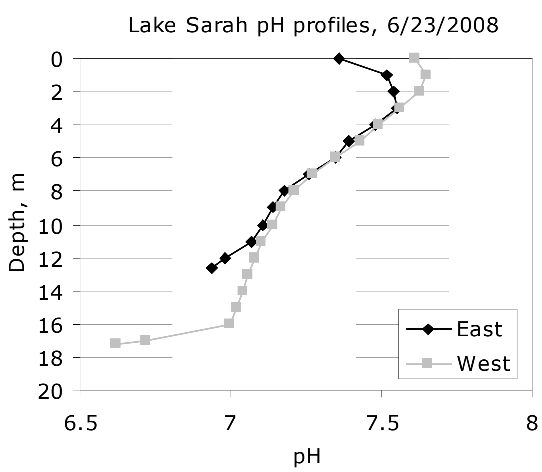
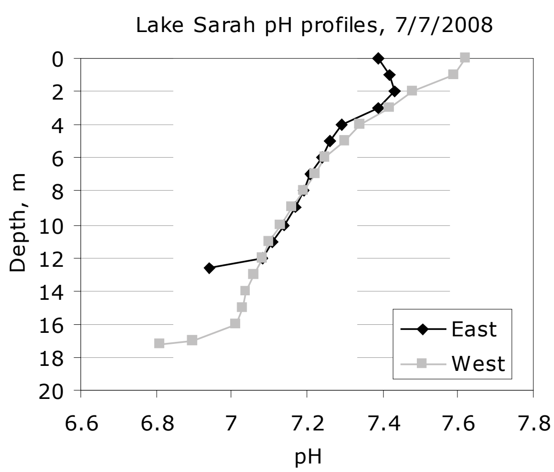
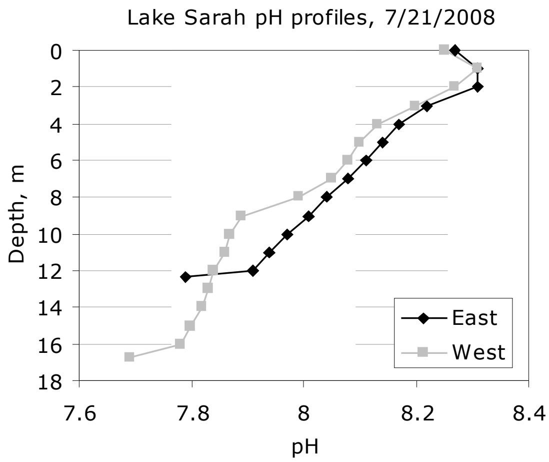
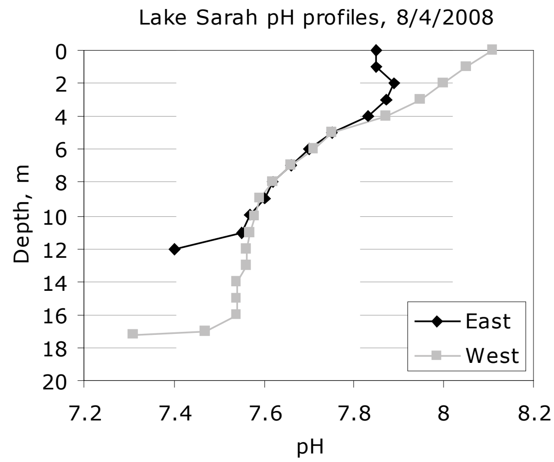
East
West
Depth, m
pH

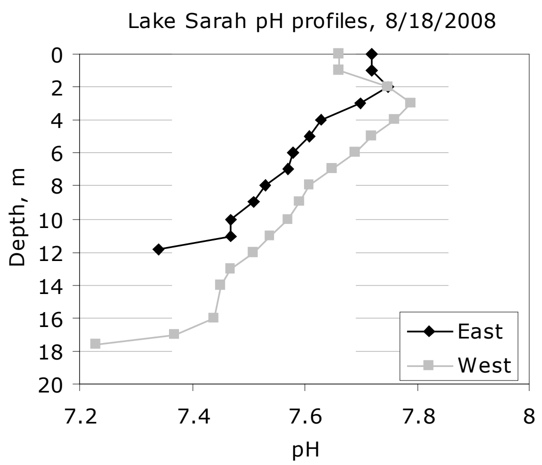

Lake Sarah pH profiles, 6/10/2008
East
West
Depth, m
pH

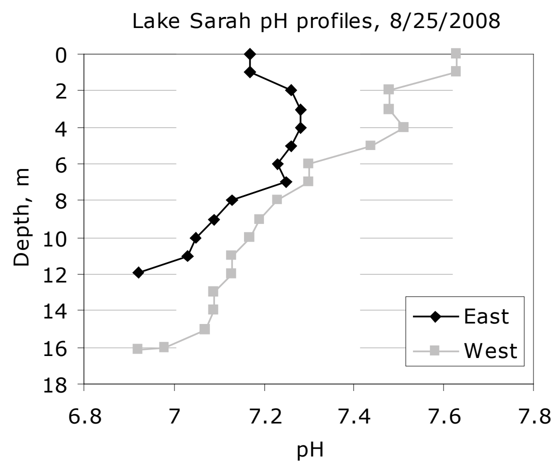

Lake Sarah pH profiles, 6/23/2008
East
West
Depth, m
pH

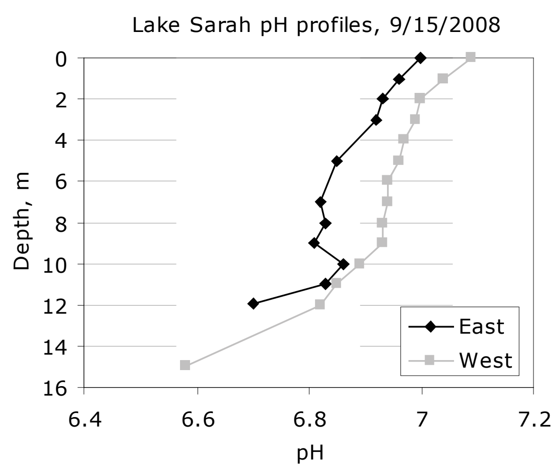

Lake Sarah pH profiles, 7/7/2008
East
West
Depth, m
pH

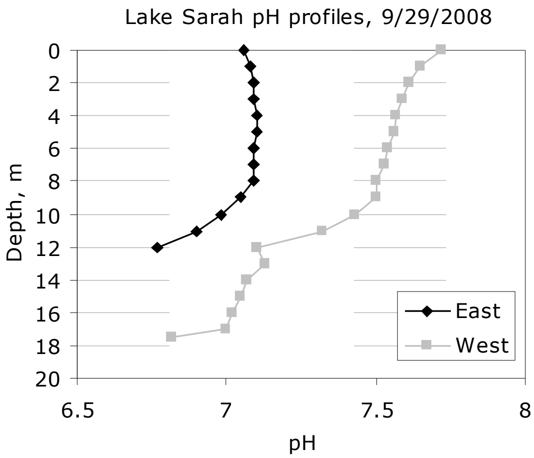

Lake Sarah pH profiles, 7/21/2008
Depth, m
pH
East
West


Lake Sarah pH profiles, 8/4/2008
Depth, m
pH
East
West


Lake Sarah pH profiles, 8/18/2008
Depth, m
pH
East
West


Lake Sarah pH profiles, 8/25/2008
Depth, m
pH
East
West


Lake Sarah pH profiles, 9/15/2008
Depth, m
pH
East
West


Lake Sarah pH profiles, 9/29/2008
Depth, m
pH
East
West
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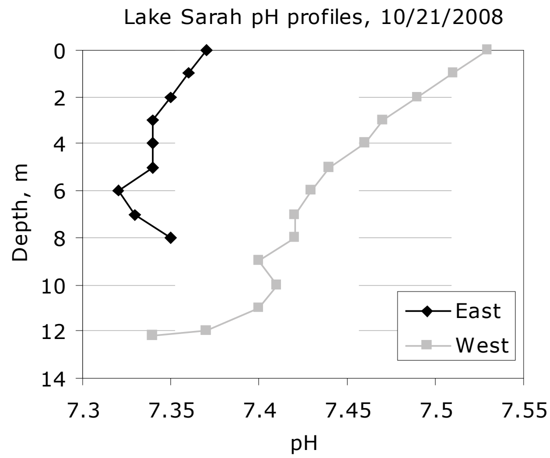
2
4
6
8
10
12
14
16
18
20
6.5
7
7.5
8


Lake Sarah pH profiles, 10/21/2008
Depth, m
pH
East
West
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4
6
8
10
12
14
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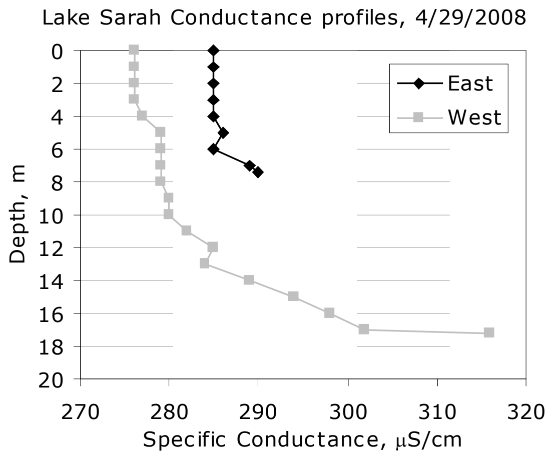
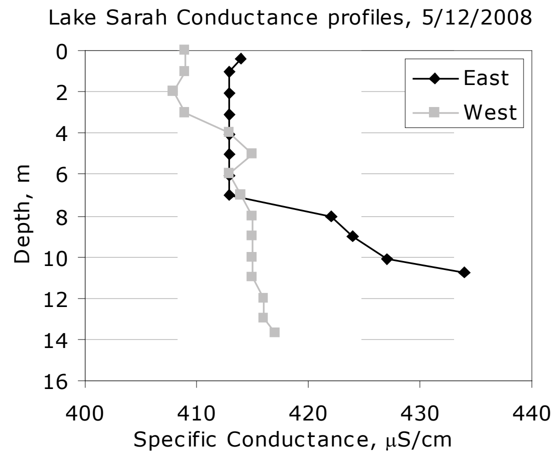
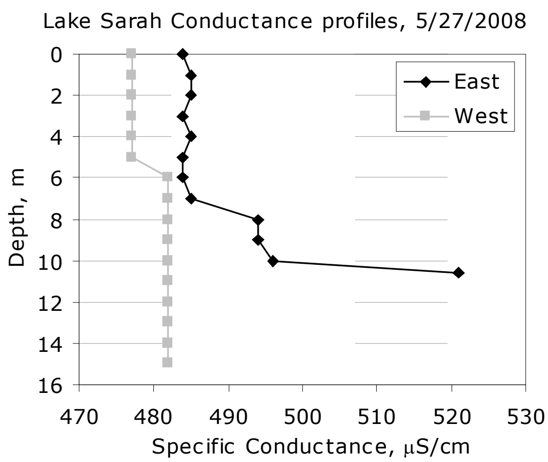
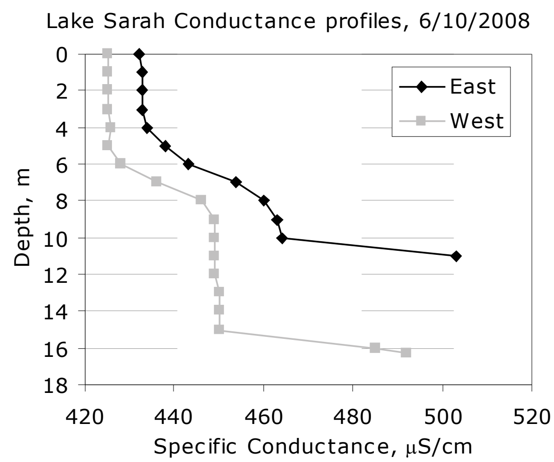
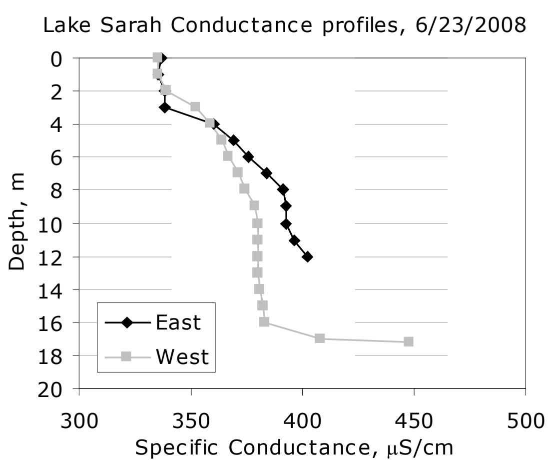
7.35
7.4
7.45
7.5
7.55

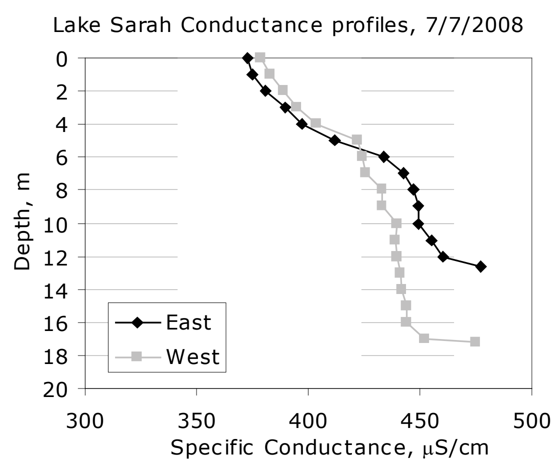

Lake Sarah Conductance profiles, 4/29/2008
East
West
Depth, m
Specific Conductance, µS/cm


Lake Sarah Conductance profiles, 5/12/2008
East
West
Depth, m
Specific Conductance, µS/cm

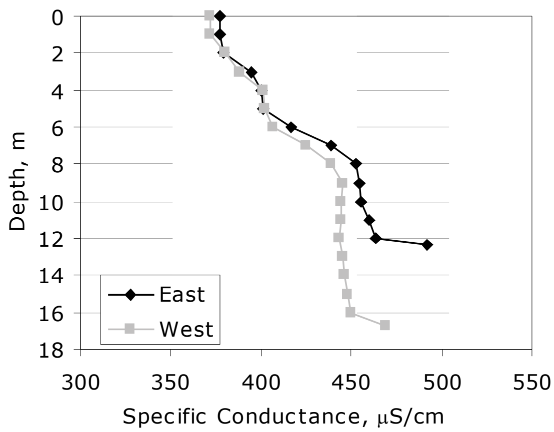

Lake Sarah Conductance profiles, 5/27/2008
East
West
Depth, m
Specific Conductance, µS/cm


Lake Sarah Conductance profiles, 6/10/2008
East
West
Depth, m
Specific Conductance, µS/cm

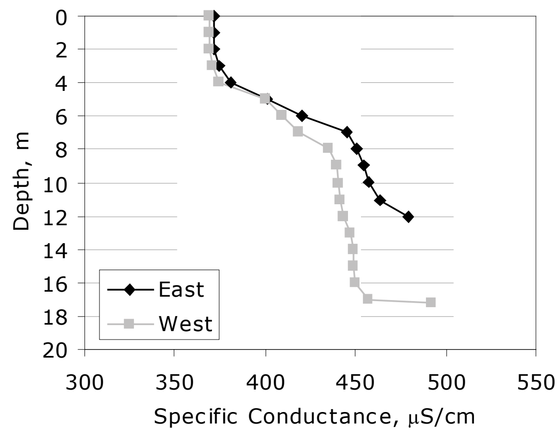

Lake Sarah Conductance profiles, 6/23/2008
East
West
Depth, m
Specific Conductance, µS/cm


Lake Sarah Conductance profiles, 7/7/2008
East
West
Depth, m
Specific Conductance, µS/cm

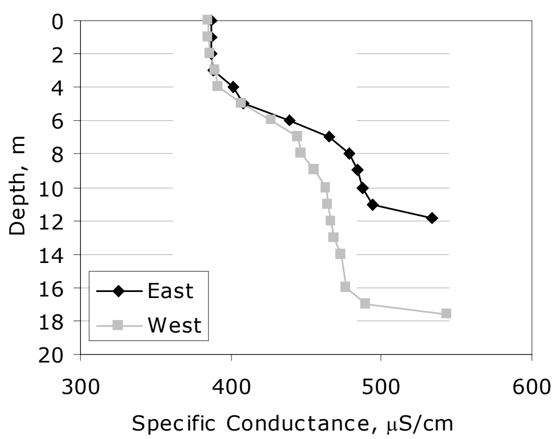
Lake Sarah Conductance profiles, 7/21/2008



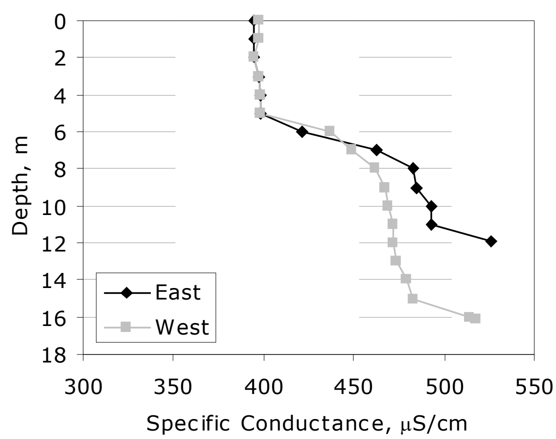
Lake Sarah Conductance profiles, 8/4/2008



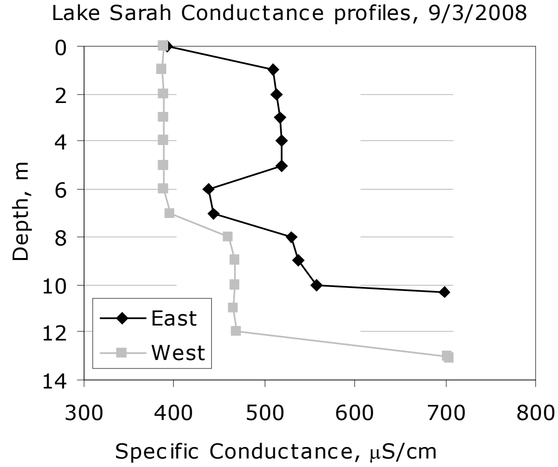
Lake Sarah Conductance profiles, 8/18/2008



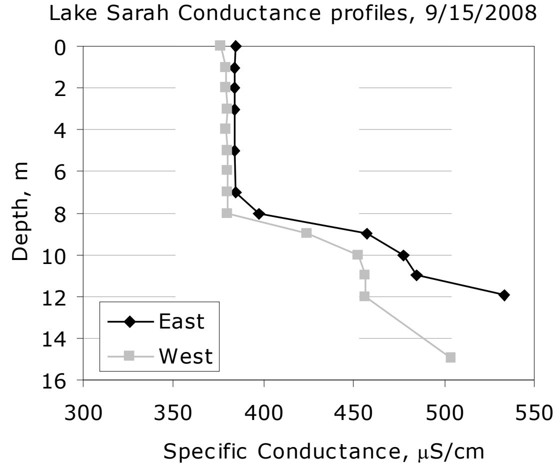
Lake Sarah Conductance profiles, 8/25/2008



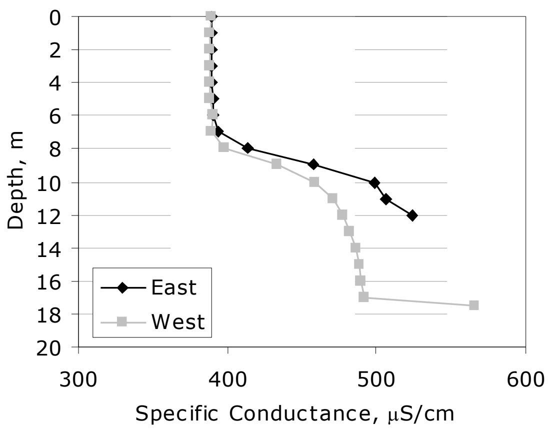
Lake Sarah Conductance profiles, 9/3/2008



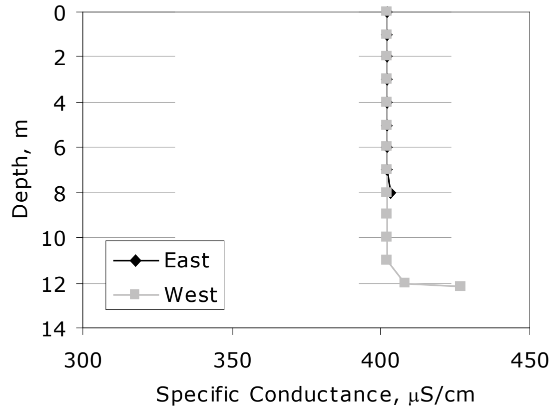
Lake Sarah Conductance profiles, 9/15/2008



Lake Sarah Conductance profiles, 9/29/2008



Lake Sarah Conductance profiles, 10/21/2008



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Appendix B – Summary of BMP Options for Individual Communities in the Lake Sarah Watershed

Best Management Practice	Expected reduction in total phosphorus export	Approximate cost	Independence		
			Area available for treatment	Total P reduction possible, lbs	Cost for best possible case
Row crop agriculture					
Conversion from moldboard plow to continuous no-till	40-80%	$20/acre	21 acres	8 - 17	$420
Conversion from moldboard plow to ridge till	50%	$20/acre	21 acres	11	$420
Conversion from moldboard plow to chisel plow (at least 30% surface residue at planting)	30-35%	$20/acre	21 acres	6	$420
Conversion from chisel plow to continuous no-till	10%-50%	$20/acre	21 acres	2 - 11	$420
Phosphate placement, broadcast to surface banding	20%	$9/acre	42 acres	8	$378
Phosphate placement, broadcast to injection/subsurface banding	30-50%	$9/acre	42 acres	13 - 21	$378
Nutrient management based on soil test phosphorus	up to 40%	$10/acre	95 acres	up to 38	$950
Setback zones for phosphorus fertilizer	up to 25%	$10/acre	15 acres	up to 4	$150
Edge-of-field filter strips (buffers)	8-90%	$210-$300/acre	42 acres	3 - 38	$1,323 - $1,890
Hill contour farming	30%	$7/acre	21 acres	6	$147
Grassed waterways	22-89%	$3700-$4300/acre	42 acres	9 - 37	$7,770 - $9,030
Critical area planting	up to 25%	$0-$300/acre	42 acres	up to 11	$12,600
Stripcropping	up to 70%	$7-$25/acre	42 acres	up to 29	$294 - $1,050
Cover cropping	7-15%	$15/acre	60 acres	4 - 9	$900
Add wheat into corn-soybean rotation	60%	$30-$50/ac	42 acres	6	$1,260 - $2,100
Add alfalfa into corn-soybean rotation	50%	$30-$50/ac	42 acres	6	$1,260 - $2,100
Permanent vegetative cover	up to 80%	$500/acre	95 acres	up to 76	$47,500

Best Management Practice	Expected reduction in total phosphorus export	Approximate cost	Greenfield		
			Area available for treatment	Total P reduction possible, lbs	Cost for best possible case
Row crop agriculture					
Conversion from moldboard plow to continuous no-till	40-80%	$20/acre	289 acres	115 - 231	$5,772
Conversion from moldboard plow to ridge till	50%	$20/acre	289 acres	144	$5,772
Conversion from moldboard plow to chisel plow (at least 30% surface residue at planting)	30-35%	$20/acre	289 acres	87	$5,772
Conversion from chisel plow to continuous no-till	10%-50%	$20/acre	289 acres	29 - 144	$5,772
Phosphate placement, broadcast to surface banding	20%	$9/acre	577 acres	115	$5,195
Phosphate placement, broadcast to injection/subsurface banding	30-50%	$9/acre	577 acres	173 - 289	$5,195
Nutrient management based on soil test phosphorus	up to 40%	$10/acre	661 acres	up to 264	$6,610
Setback zones for phosphorus fertilizer	up to 25%	$10/acre	192 acres	up to 48	$1,924
Edge-of-field filter strips (buffers)	8-90%	$210-$300/acre	577 acres	46 - 519	$18,182 - $25,974
Hill contour farming	30%	$7/acre	289 acres	87	$2,020
Grassed waterways	22-89%	$3700-$4300/acre	577 acres	127 - 514	$106,782 - $124,098
Critical area planting	up to 25%	$0-$300/acre	577 acres	up to 144	$173,160
Stripcropping	up to 70%	$7-$25/acre	577 acres	up to 404	$4,040 - $14,430
Cover cropping	7-15%	$15/acre	602 acres	42 - 90	$9,026
Add wheat into corn-soybean rotation	60%	$30-$50/ac	577 acres	87	$17,316 - $28,860
Add alfalfa into corn-soybean rotation	50%	$30-$50/ac	577 acres	87	$17,316 - $28,860
Permanent vegetative cover	up to 80%	$500/acre	661 acres	up to 529	$330,500

Best Management Practice	Expected reduction in total phosphorus export	Approximate cost	Medina		
			Area available for treatment	Total P reduction possible, lbs	Cost for best possible case
Row crop agriculture					
Conversion from moldboard plow to continuous no-till	40-80%	$20/acre	114 acres	45 - 91	$2,271
Conversion from moldboard plow to ridge till	50%	$20/acre	114 acres	57	$2,271
Conversion from moldboard plow to chisel plow (at least 30% surface residue at planting)	30-35%	$20/acre	114 acres	34	$2,271
Conversion from chisel plow to continuous no-till	10%-50%	$20/acre	114 acres	11 - 57	$2,271
Phosphate placement, broadcast to surface banding	20%	$9/acre	227 acres	45	$2,044
Phosphate placement, broadcast to injection/subsurface banding	30-50%	$9/acre	227 acres	68 - 114	$2,044
Nutrient management based on soil test phosphorus	up to 40%	$10/acre	288 acres	up to 115	$2,881
Setback zones for phosphorus fertilizer	up to 25%	$10/acre	96 acres	up to 24	$960
Edge-of-field filter strips (buffers)	8-90%	$210-$300/acre	191 acres	15 - 172	$6,020 - $8,600
Hill contour farming	30%	$7/acre	114 acres	34	$795
Grassed waterways	22-89%	$3700-$4300/acre	227 acres	50 - 202	$42,014 - $48,827
Critical area planting	up to 25%	$0-$300/acre	227 acres	up to 57	$68,130
Stripcropping	up to 70%	$7-$25/acre	191 acres	up to 134	$1,338 - $4,778
Cover cropping	7-15%	$15/acre	288 acres	20 - 43	$4,322
Add wheat into corn-soybean rotation	60%	$30-$50/ac	227 acres	34	$6,813 - $11,355
Add alfalfa into corn-soybean rotation	50%	$30-$50/ac	227 acres	34	$6,813 - $11,355
Permanent vegetative cover	up to 80%	$500/acre	288 acres	up to 230	$144,050

Best Management Practice	Expected reduction in total phosphorus export	Approximate cost	Corcoran		
			Area available for treatment	Total P reduction possible, lbs	Cost for best possible case
Row crop agriculture					
Conversion from moldboard plow to continuous no-till	40-80%	$20/acre	78 acres	31 - 62	$1,556
Conversion from moldboard plow to ridge till	50%	$20/acre	78 acres	39	$1,556
Conversion from moldboard plow to chisel plow (at least 30% surface residue at planting)	30-35%	$20/acre	78 acres	23	$1,556
Conversion from chisel plow to continuous no-till	10%-50%	$20/acre	78 acres	8 - 39	$1,556
Phosphate placement, broadcast to surface banding	20%	$9/acre	156 acres	31	$1,400
Phosphate placement, broadcast to injection/subsurface banding	30-50%	$9/acre	156 acres	47 - 78	$1,400
Nutrient management based on soil test phosphorus	up to 40%	$10/acre	160 acres	up to 64	$1,597
Setback zones for phosphorus fertilizer	up to 25%	$10/acre	52 acres	up to 13	$519
Edge-of-field filter strips (buffers)	8-90%	$210-$300/acre	156 acres	12 - 140	$4,901 - $7,002
Hill contour farming	30%	$7/acre	78 acres	23	$545
Grassed waterways	22-89%	$3700-$4300/acre	156 acres	34 - 138	$28,786 - $33,454
Critical area planting	up to 25%	$0-$300/acre	156 acres	up to 39	$46,680
Stripcropping	up to 70%	$7-$25/acre	156 acres	up to 109	$1,089 - $3,890
Cover cropping	7-15%	$15/acre	157 acres	11 - 24	$2,355
Add wheat into corn-soybean rotation	60%	$30-$50/ac	156 acres	23	$4,668 - $7,780
Add alfalfa into corn-soybean rotation	50%	$30-$50/ac	156 acres	23	$4,668 - $7,780
Permanent vegetative cover	up to 80%	$500/acre	160 acres	up to 128	$79,850

Best Management Practice	Expected reduction in total phosphorus export	Approximate cost	Independence		
			Area available for treatment	Total P reduction possible, lbs	Cost for best possible case
Feedlot/manure management					
Combination of barnyard practices: runoff diversion, solids settling, filter strip, restricting cattle from the stream. Each operation with have a different set of needs.	85%	$5,000 operation with <5 AU $15,000/operation with >5 AU	3 operations	76	$45,000
Use exclusion		$15/acre			
Fencing		$1.50-$5/ft			
Runoff diversion		$3.50/ft			
Water and sediment control basin		$4,000			
Filter strip		$210-300/acre			
Manure containment/composting		$6000/facility, $1000/individual system			
Manure application guidance (apply at low runoff potential)	up to 60%	$4-10/acre	53 acres	19	$211 - $527
Subsurface inject manure instead of surface spread	20%	$26/acre	53 acres	6	$1,370
Incorporate manure before a runoff event	20%	$7.50/acre	53 acres	6	$395
Reduce dietary P fed to cattle to NRC recommendations	up to 30%	$425	3 operations	27	$1,275
Intensive rotational grazing	up to 50%	varies	3 operations	45	varies
Pasture renovation	43%	$150-$200/acre	20 acres	7	$3,000 - $4,000

Best Management Practice	Expected reduction in total phosphorus export	Approximate cost	Medina		
			Area available for treatment	Total P reduction possible, lbs	Cost for best possible case
Feedlot/manure management					
Combination of barnyard practices: runoff diversion, solids settling, filter strip, restricting cattle from the stream. Each operation with have a different set of needs.	85%	$5,000 operation with <5 AU $15,000/operation with >5 AU	3 operations	31	$35,000
Use exclusion		$15/acre			
Fencing		$1.50-$5/ft			
Runoff diversion		$3.50/ft			
Water and sediment control basin		$4,000			
Filter strip		$210-300/acre			
Manure containment/composting		$6000/facility, $1000/individual system			
Manure application guidance (apply at low runoff potential)	up to 60%	$4-10/acre	61 acres	22	$244 $610
Subsurface inject manure instead of surface spread	20%	$26/acre	61 acres	7	$1,586
Incorporate manure before a runoff event	20%	$7.50/acre	61 acres	7	$458
Reduce dietary P fed to cattle to NRC recommendations	up to 30%	$425	3 operations	11	$1,275
Intensive rotational grazing	up to 50%	varies	1 operation	9	varies
Pasture renovation	43%	$150-$200/acre	14 acres	5	$2,100 - $2,800

Best Management Practice	Expected reduction in total phosphorus export	Approximate cost	Greenfield		
			Area available for treatment	Total P reduction possible, lbs	Cost for best possible case
Feedlot/manure management					
Combination of barnyard practices: runoff diversion, solids settling, filter strip, restricting cattle from the stream. Each operation with have a different set of needs.	85%	$5,000 operation with <5 AU $15,000/operation with >5 AU	29 operations	162	$215,000
Use exclusion		$15/acre			
Fencing		$1.50-$5/ft			
Runoff diversion		$3.50/ft			
Water and sediment control basin		$4,000			
Filter strip		$210-300/acre			
Manure containment/composting		$6000/facility, $1000/individual system			
Manure application guidance (apply at low runoff potential)	up to 60%	$4-10/acre	74	27	$296 - $740
Subsurface inject manure instead of surface spread	20%	$26/acre	74	9	$1,924
Incorporate manure before a runoff event	20%	$7.50/acre	74	9	$555
Reduce dietary P fed to cattle to NRC recommendations	up to 30%	$425	29 operations	57	$12,325
Intensive rotational grazing	up to 50%	varies	1 operation	15	varies
Pasture renovation	43%	$150-$200/acre	110 acres	38	$16,500 - $22,000

Best Management Practice	Expected reduction in total phosphorus export	Approximate cost	Corcoran: Area available for treatment	Corcoran: Total P reduction possible, lbs	Corcoran: Cost for best possible case
Feedlot/manure management					
Combination of barnyard practices: runoff diversion, solids settling, filter strip, restricting cattle from the stream. Each operation with have a different set of needs.	85%	$5,000 operation with <5 AU $15,000/operation with >5 AU	3 operations	28	$25,000
Use exclusion		$15/acre			
Fencing		$1.50-$5/ft			
Runoff diversion		$3.50/ft			
Water and sediment control basin		$4,000			
Filter strip		$210-300/acre			
Manure containment/composting		$6000/facility, $1000/individual system			
Manure application guidance (apply at low runoff potential)	up to 60%	$4-10/acre	4 acres	1	$16 - $40
Subsurface inject manure instead of surface spread	20%	$26/acre	4 acres	0	$104
Incorporate manure before a runoff event	20%	$7.50/acre	4 acres	0	$30
Reduce dietary P fed to cattle to NRC recommendations	up to 30%	$425	3 operations	10	$1,275
Intensive rotational grazing	up to 50%	varies	1 operation	13	varies
Pasture renovation	43%	$150-$200/acre	13 acres	4	$1,950 - $2,600

Best Management Practice	Expected reduction in total phosphorus export	Approximate cost	Independence		
			Area available for treatment	Total P reduction possible, lbs	Cost for best possible case
Shoreland					
Minimize pavement	varies	$\$1/ft^2$ + reseeding			
Shoreline stablization	varies	$1.50-$200/ft			
Shoreline native-vegetation buffer of 40 feet	60%	$210-300/acre	10 acres	25	$2,031 - $2,901
Shoreline native-vegetation buffer of 15 feet	28%	$210-300/acre	4 acres	12	$762 - $1,088

Best Management Practice	Expected reduction in total phosphorus export	Approximate cost	Greenfield		
			Area available for treatment	Total P reduction possible, lbs	Cost for best possible case
Shoreland					
Minimize pavement	varies	$\$1/ft^2$ + reseeding			
Shoreline stablization	varies	$1.50-$200/ft			
Shoreline native-vegetation buffer of 40 feet	60%	$210-300/acre	4 acres	8	$888 - $1,269
Shoreline native-vegetation buffer of 15 feet	28%	$210-300/acre	2 acres	4	$333 - $476

Best Management Practice	Expected reduction in total phosphorus export	Approximate cost	Independence		
			Area available for treatment	Total P reduction possible, lbs	Cost for best possible case
Residential and commercial					
Pervious pavement, residential	65%	$45,000-$100,000/acre (2x-4x traditional pavement)	15 acres	50	$688,500 - $1,530,000
Pervious pavement, commercial	65%	$45,000-$100,000/acre (2x-4x traditional pavement)	4 acres	9	$157,500 - $350,000
Rain gardens	85%	$3500 - $7500 each	155 lots	64	$542,500 - $1,162,500
Filtration - sand filter	50-55%	$5,000-$50,000/impervious acre served	19 acres	56	$94,000 - $940,000
Filtration - organic media filter	40-50%	$5,000-$23,000/impervious acre served	19 acres	55	$94,000 - $940,000

Best Management Practice	Expected reduction in total phosphorus export	Approximate cost	Medina		
			Area available for treatment	Total P reduction possible, lbs	Cost for best possible case
Residential and commercial					
Pervious pavement, residential	65%	$45,000-$100,000/acre (2x-4x traditional pavement)	1 acres	2	$31,500 - $70,000
Pervious pavement, commercial	65%	$45,000-$100,000/acre (2x-4x traditional pavement)	3 acres	7	$123,750 - $275,000
Rain gardens	85%	$3500 - $7500 each	3 lots	3	$10,500 - $22,500
Filtration - sand filter	50-55%	$5,000-$50,000/impervious acre served	3 acres	7	$17,250 - $172,500
Filtration - organic media filter	40-50%	$5,000-$23,000/impervious acre served	3 acres	6	$17,250 - $172,500

Best Management Practice	Expected reduction in total phosphorus export	Approximate cost	Loretto		
			Area available for treatment	Total P reduction possible, lbs	Cost for best possible case
Residential and commercial					
Pervious pavement, residential	65%	$45,000-$100,000/acre (2x-4x traditional pavement)	3 acres	11	$153,000 - $340,000
Pervious pavement, commercial	65%	$45,000-$100,000/acre (2x-4x traditional pavement)	7 acres	18	$303,750 - $675,000
Rain gardens	85%	$3500 - $7500 each	47 lots	5	$164,500 - $352,500
Filtration - sand filter	50-55%	$5,000-$50,000/impervious acre served	10 acres	22	$50,750 - $507,500
Filtration - organic media filter	40-50%	$5,000-$23,000/impervious acre served	10 acres	21	$50,750 - $507,500

Best Management Practice	Expected reduction in total phosphorus export	Approximate cost	Greenfield		
			Area available for treatment	Total P reduction possible, lbs	Cost for best possible case
Residential and commercial					
Pervious pavement, residential	65%	$45,000-$100,000/acre (2x-4x traditional pavement)	14 acres	46	$630,000 - $1,400,000
Pervious pavement, commercial	65%	$45,000-$100,000/acre (2x-4x traditional pavement)	7.5 acres	20	$337,500 - $750,000
Rain gardens	85%	$3500 - $7500 each	124 lots	58	$434,000 - $930,000
Filtration - sand filter	50-55%	$5,000-$50,000/impervious acre served	22 acres	58	$107,500 - $1,075,000
Filtration - organic media filter	40-50%	$5,000-$23,000/impervious acre served	22 acres	57	$107,500 - $1,075,000

Best Management Practice	Expected reduction in total phosphorus export	Approximate cost	Corcoran		
			Area available for treatment	Total P reduction possible, lbs	Cost for best possible case
Residential and commercial					
Pervious pavement, residential	65%	$45,000-$100,000/acre (2x-4x traditional pavement)	0 acres	1	$13,500 - $30,000
Pervious pavement, commercial	65%	$45,000-$100,000/acre (2x-4x traditional pavement)	20 acres	53	$911,250 - $2,025,000
Rain gardens	85%	$3500 - $7500 each	2 lots	1.173	$7,000 - $15,000
Filtration - sand filter	50-55%	$5,000-$50,000/impervious acre served	21 acres	35	$102,750 - $1,027,500
Filtration - organic media filter	40-50%	$5,000-$23,000/impervious acre served	21 acres	32	$102,750 - $1,027,500

Best Management Practice	Expected reduction in total phosphorus export	Approximate cost
Stormwater Pond	40-75%	$75,000 (1 acre-ft) - $1,930,000 (100 acre-ft)

Western Lake Sarah stream

Pond volume, acre-feet	Pond cost	Pond size, acres	Towns	Phosphorus removal, lbs
101	$2,000,000	15	Greenfield, Corcoran	660 - 1238

Eastern Lake Sarah stream

Pond volume, acre-feet	Pond cost	Pond size, acres	Towns	Phosphorus removal, lbs
48	$1,000,000	7	Medina, Loretto, Independence, Corcoran	302 - 568