A Subwatershed Assessment, Water Quality Management and BMP Retrofit Analysis for the

Arctic Lake Subwatershed

Shakopee Mdewakanton Sioux Community

Prior Lake-Spring Lake Watershed District

City of Prior Lake

10/03/2013

HDR

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1 Summary

The Shakopee Mdewakanton Sioux Community (SMSC), Prior Lake – Spring Lake Watershed District (District) and City of Prior Lake (City) (hereafter referred to as *Partners*) entered into an agreement to investigate the relationship between Arctic Lake and its watershed. Review of best management practice (BMP) options by site, type and design were modeled to estimate changes in water quality of subwatershed runoff and in-lake water quality. The results of this work provides the Partners with clear guidance towards the implementation of appropriate best management practices (BMPs), specific site-driven design and performance optimization considerations, precision BMP siting and arrangement within the subwatershed, and a related cost analysis of implementation strategies.

The analysis was comprised of four phases:

1. A review of current data related to the lake and its subwatershed for quantity and quality (*Existing Data Review*)
2. A modeling effort describing the hydrology and water quality of the subwatershed as well as lake water quality modeling (*Hydrologic/Water Quality and Lake Models*)
3. An assessment of the subwatershed's current likely impacts on lake water quality and an analysis of the effect of various stormwater BMP implementation strategies on subwatershed runoff water quality (Water Quality Impacts and Opportunities - Subwatershed)
4. An assessment of Arctic Lake's current and historical water quality and opportunities available for in-lake management (Water Quality Impacts and Opportunities – In-Lake)

The data reviewed for analyzing the watershed and lake were sufficient to precisely locate and conceptually design specific stormwater BMPs that will minimize the subwatershed's contribution of total phosphprus (TP) and total suspended solids (TSS) (as well as nitrogen, metals, hydrocarbons, bacteria and organic debris) to the lake. The current estimated loading of TP to the lake from the watershed was 62 LBS/year considering modeled existing treatment of 5 City ponds (21% - 51% annual TP removal). Urban areas are expected to contribute approximately half of the subwatershed load to the lake (32.7 LBS-TP/yr) while making up 8% of the total drainage area. Optimal treatment of this runoff was determined to be a combination of existing pond modification, agricultural sedimentation and filtration BMPs and urban bioretention. Although several significant gullies were noted along bluff lines both directly and indirectly connected to Arctic Lake, it was beyond the scope of work to produce field verified estimates of TSS and associated TP delivery. Further investigation into their contributions of loading are recommended. The recommended urban BMP retrofit strategy is estimated to annually remove 11.4 LBS-TP (35% reduction). An estimated annual removal of 5.5 LBS-TP (26% reduction) results from the recommended agricultural BMPs while a proposed enhanced wetland restoration is estimated to annually remove approximately 19.7 LBS-TP (90% reduction). All combined, the subwatershed strategy outlined in this report reduces the annual load of TP to Arctic Lake by approximately 37 LBS (60% removal).

Although the data provided by SMSC proved vital for investigation of Arctic Lake's water chemistry as well as for estimating watershed load from the western 2/3rds of its watershed, only a preliminary lake model could be constructed. Four of the years (2005, 2006, 2007 and 2010) were modeled for this analysis and compared to measured annual average concentrations from the epilimnion. These models consistently underestimated observed concentrations of phosphorus with an average of 26.5% (13.8% – 42.0%). The years 2006 and 2007 yielded the most accurate net concentrations (13.8% and 14.4%, respectively), while both 2005 and 2010 ranged above 36% error. The years 2005 and 2010 produced approximately 10 more inches of rain than 2006 and 2007 and were close to the 30 year normal precipitation depth. With the exception of 5 data points, taken in the late winter/early spring of 2013, from the drainage channel draining the western 2/3rds of the subwatershed, no flow data was available for the agricultural and urban contributing areas. As such, only modeled flows and water quality values could be used for lake response models. Therefore, it was not possible to calibrate subwatershed inputs and water budgets for these models. It is recommended that the current lake modeling effort be continued and supplemented with additional monitoring data for inflows and outflows to perform a calibration and sensitivity analysis for normal, dry and wet years, if possible. It may then be possible to estimate lake responses to subwatershed load reduction strategies.

Implementation of in-lake water quality treatment strategies are presented and recommended for Arctic Lake given existing historic, water chemistry and plant survey data even in the absence of a stable lake water quality model. SMSC Monitoring data suggests epilimnion TP concentrations well above what is considered regionally normal. Consistent fall turnover events likely drive a late summer algal bloom while snow melt and spring runoff from 2/3rds of the watershed via a drainage ditch had significantly elevated TP and low dissolved oxygen levels in samples taken in April 2013. The complete absence of submerged plant life and the abundance of bottom feeding fish species are know to increase suspended sediments from the benthic environment. Oxygen levels within the hypolimnion are constantly low to undetectable until apparent breakup of a thermocline normally occurring during late September to mid October. In 2007, an average hypolimnion TP concentration was 0.37 mg/L (0.11 – 0.61 mg/L from 6/4/2013 – 7/17/2013) while the epilimnion averaged 0.121 mg/L (0.045 – 0.320 mg/L, non-winter seasons of years 2004 - 2012). Historic aerial photography, dating back to 1937, shows a directly adjacent agriculturally-dominated landscape until the 21st century with the strong likelihood of this land use occurring as far back as the 1850's. University of Minnesota remote sensing research suggests very shallow Secchi depths for Arctic Lake from 1975 to 2008 (0-0.75m). Review of this data suggests the likelihood of internal dynamic drivers on water quality and clarity at least on par with subwatershed influences.

At this time, the recommended initial implementation strategy for recovery of Artic Lake's water quality is:

1. Develop and implement an in-lake, inflow and outflow monitoring program to better understand nutrient dynamics within Arctic Lake (e.g., internal loading)
2. Retrofit the recommended subwatershed opportunities to achieve the estimated TP load reductions
3. Assess directly connected gullies below the medium density residential areas southeast of the Lake for stability and estimate the total annual TP for each with a simulated, continuous, physics-based 2D model

4. Initiate a carp removal and exclusion effort for the lake

2 Background

The SMSC has an interest in managing the water quality of Arctic Lake. Although the lake is not currently listed as an impaired water body by the State of Minnesota, the Community wants to do what it can to restore clarity and quality of this resource to regional standards for aquatic recreational use. It is expected that the remaining agricultural fields north and west of Arctic Lake will be developed to medium density residential land use in the next couple decades. Similarly, the District and City have a vested interest in Arctic Lake's water quality. The District manages water quality within its jurisdiction and Arctic Lake drains to Upper Prior Lake, a lake with an approved total maximum daily load (TMDL) (Spring/Upper Prior TMDL, 2011). The City is an MS4 community and is accountable for stormwater discharges to surface waters of the State of Minnesota (State). Arctic Lake also sits within the currently developed Spring Lake Regional Park which is owned and operated by Scott County Parks and Recreation with similar conservation interests. Considering the multiple entity interest in Arctic Lake, the SMSC partnered with the City and District to undertake a lake and subwatershed analysis to identify implementation strategies that would promote water quality levels in the lake more closely aligned with State targets.

Arctic Lake is located in Scott County, MN within the boundaries of the SMSC, the City and District. Its outlet is positioned approximately 0.25 miles west of Upper Prior Lake, to which it drains. The lake is approximately 23 acres in size with a maximum depth of 30 feet (average of 9.5 feet). Arctic Lake's 507 acre subwatershed is comprised dominantly of woodlands, along with corn/soybean production land uses, and low to medium-density residential uses (Figure 1, Table 1). Future (2030) land use for the area is expected to become low-density residential but it is uncertain as to the timing and extent of development (*pers. comm*. Scott Walz, SMSC Hydrologist). There is at least one drain tile entering the lake from the adjacent agricultural area, and a drainage channel enters the lake contributing run-on from wetlands and a small, shallow lake/wetland to its northwest. Lastly, soil erodibility for the subwatershed is considered high given its topography with moderate capacity for infiltration. Slopes tend to become steepest in the areas within 0.25 miles of Arctic Lake.

Figure 1. Arctic Lake subwatershed and land use/cover

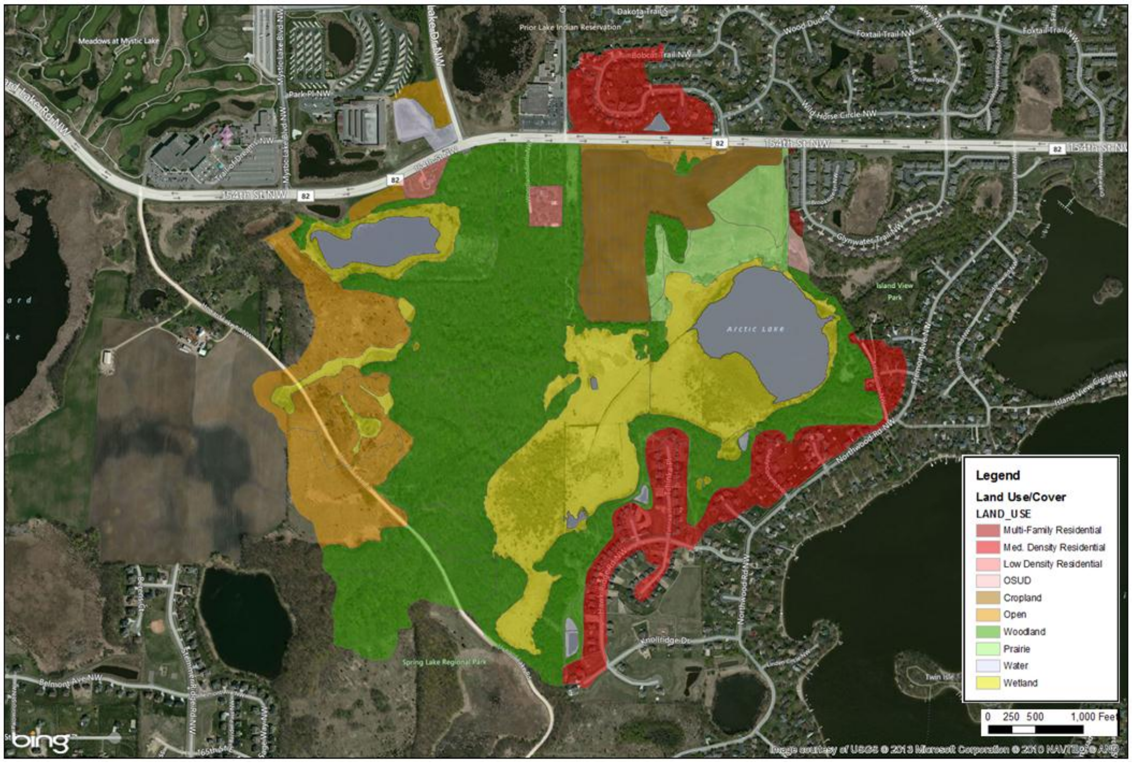


Table 1. Land cover and use in the Arctic Lake subwatershed (in acres)

Catchment	Cropland	LDR	MDR	MFR	Open Space	Park	Prairie	Water	Wetland	Woodland	Total
1	0.68		9.14	0.58		1.37	10.36	23.28	26.51	16.32	88.24
2			12.93					0.28	1.30	6.18	20.68
3			6.18					0.35		0.50	7.03
4			11.12					0.91		1.45	13.47
5	2.84		3.04				0.01	0.55	50.16	42.61	99.19
6									0.00	22.13	22.13
7					18.55					10.49	29.04
8					9.25				1.90	20.07	31.22
9		2.17			25.95			9.04	12.74	45.90	95.80
10					2.69			3.95			6.64
11	3.21	2.79			0.17				0.01	24.13	30.31
12			4.17								4.17
13			14.71					0.55			15.26
14	12.51						1.64			1.26	15.41
15	8.55		0.02		1.51		0.35			1.79	12.21
16	6.57		0.07	0.09	1.25	0.00	8.13			0.54	16.65
Total	34.36	4.96	61.36	0.67	59.37	1.37	20.47	38.91	92.62	193.36	507.46

LDR = Low density residential; MDR = Medium density residential; MFR = Multi-family residential

Arctic Lake's watershed has morphed from its native big woods to cultivation and urbanized landscapes starting approximately 160 years ago. The nearby Credit River watershed was cleared and cultivated sometime in the mid 1850's (Inter-fluv, 2008). Between that period and the first aerial photographic record of the landscape, the predominant contributing land cover was crops. It is possible that the major drainage gullies cutting through the hill slopes to the north, west and south of the lake saw increased incision during this period. The channel draining the wetland adjacent to Arctic lake to the west was established during this period as well, likely shortly after the turn of the 20th century. The remnant woodlands in the watershed's western portion (now incorporated as County Parkland), as well as the wooded bluff lands to the lake's south, remained mostly in-tact and are more or less similar in distribution today. By sometime before 1937, however, the predominant land use surrounding the Lake was agricultural.

Although a comprehensive historical analysis of the watershed's hydrology was beyond the scope of this study, it is safe to say that the establishment of County Road 83, between 1980 and 1990, likely altered its drainage patterns. It was during this period that the bluff-tops to the lake's south and east were being converted into low-to-medium density residential development. By the year 2000, the lands to Arctic Lake's northeast and the SMSC lands to the northwest were being developed into commercial, industrial and residential land uses. However, it is likely that the land conversions mentioned for this period altered the drainage to the lake beyond what the County Road may established prior to this conversion (i.e., the County Road may have cut off outlying farmstead lands which were then converted to urbanized landscapes).

The immediate watershed to Arctic Lake appears to have reduced its agricultural land uses from the years 1980 through 1990. The adjacent, major wetland complex to the lake's west appears to have been taken out of agricultural production during this time as well although it is possible that the area was used for grazing livestock. With the exception of the urbanization of the relatively smaller portion of the watershed area north of CR-83, the lake's drainage area land cover has not changed much since this period. The residential areas north of CR-83 were still in agriculture land use until a point between 2000 and 2003 and were likely drained directly under CR-83 to the current agricultural field north of the lake. These areas both drained directly to the lake until the SMSC began establishing a prairie buffer towards the end of the 2000-2003 period. Runoff from the newly urbanized areas north of CR-83 and the remaining agricultural fields south of CR-83 are now routed through a long prairie swale before reaching Arctic Lake (before entering the swale, the residential runoff is treated by a detention pond, then routed under CR-83 to a small wetland that overflows to the swale).

The *Spring/Upper Prior Lake TMDL* describes Arctic Lake's contributions of phosphorus to Upper Prior Lake. Upland drainages carry sediment and phosphorus loads to Arctic Lake that are passed along to Upper Prior Lake. The annual amount of phosphorus being conveyed from Arctic Lake to Upper Prior Lake, from 1998-2006, ranged from 28-212 Lbs-TP (*mean* = 118.22, *s.d.* = 68.47). This represents a portion of an expected 4 percent contribution to Upper Prior Lake's total load coming from all upstream lakes except for Spring Lake. The SMSC has collected lake water quality and elevation data since 1999 using several sample point locations as well as protocols. In addition, the University of Minnesota's Remote Sensing Laboratories has analyzed historical data to interpret water clarity for Arctic Lake dating back to 1975. The compiled data suggest that water quality/clarity of Arctic Lake was very poor as early as 1975 and continues to be well above State standards for the region it resides in (North Central Hardwoods Forest; *see* 4.1. Existing Data Review).

3 Methods

3.1 Existing Data Review

Existing data was used to generate, calibrate and validate landscape loading and treatment models as well as lake modeling to assist in the development of a restoration implementation plan for Arctic Lake. Data availability, resolution and quality were considered to identify gaps. When gaps existed, new sources of data were pursued including the collection of new field data. The following identifies the data used, their sources and describes their utility.

3.1.1 Precipitation and Lake Levels

SMSC collected precipitation and lake elevation data from June 7th in the first year (2004), otherwise starting in April in the remaining years, and continued through November in all years with the exception of 2012 (Appendix 6.1.1). Rainfall data from the Minneapolis-St, Paul airport (MSP) for the period 1981-2011 was used for determining a 30-yr average.

Outlet (an active beaver dam) elevation information was provided for the years 2004-2008 and for 2012. The elevation was established via survey in 2004 and then visually inspected the following years and reported as an inferred elevation. This was then checked against lake elevation data for the final assignment of outlet elevation. The outlet shifted its elevation from 276.60 MASL for the years 2004-2008 to 277.28 MASL in 2012. It is very likely that beaver dam construction increased sometime after 2007 as an upward trend in lake levels is most notable after this year. The spatially and temporally non-uniform dam outlet configuration proved to be a confounding factor in establishing a reliable water budget for this analysis.

SMSC precipitation data collected at the outlet was compared against the 30-yr average MSP record to identify average, dry and wet years to aid in lake modeling.

3.1.2 Lake Water Quality

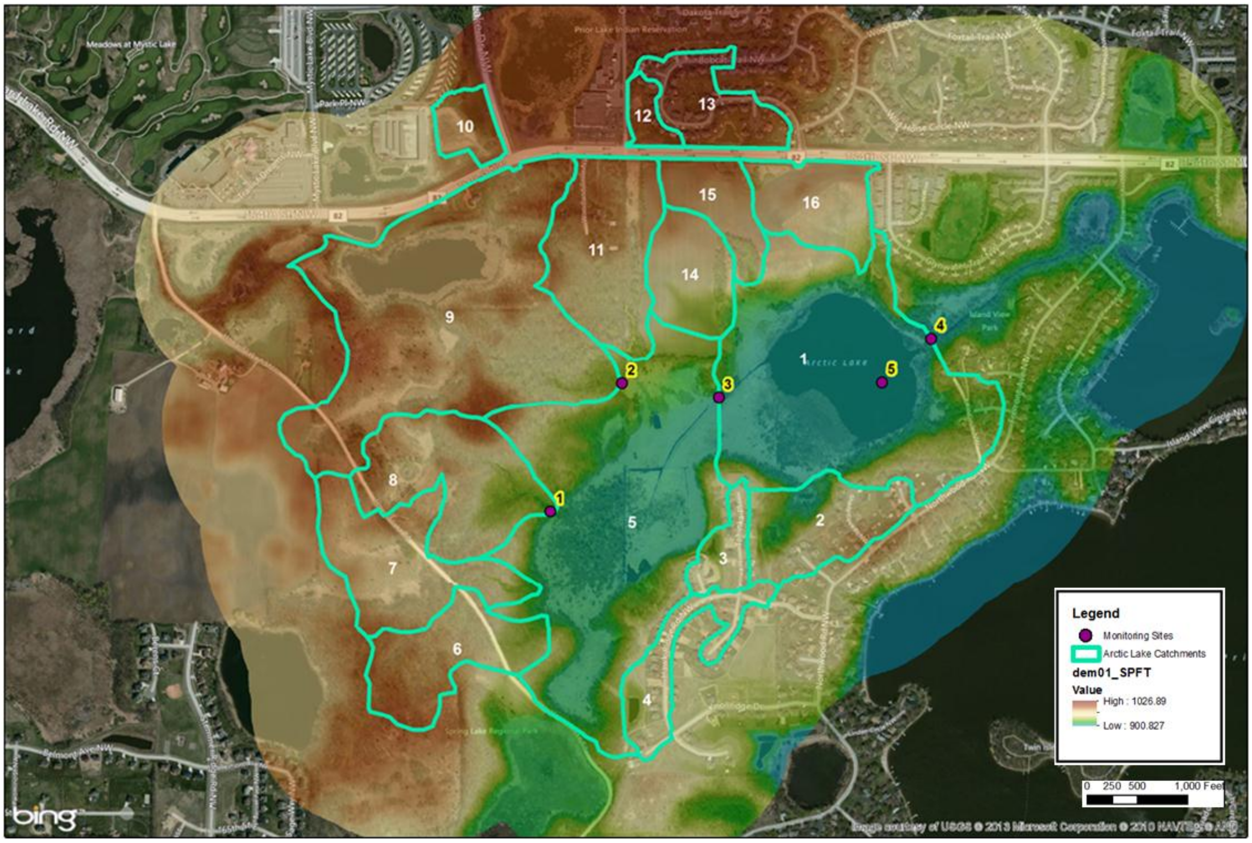
SMSC provided HDR with four MS Excel files containing water quality data. Each set provided data for several sampling sites within the lake. The data was quality controlled and used to develop annual average concentrations of TP for the epilimnion and hypolimnion for input into lake modeling as well as to observe temporal and potential cross strata (load mixing between the epilimnion and hypolimnion) nutrient dynamics for each year. To facilitate this analysis, water quality parameters were individually plotted against time for each year with both epilimnion and hypolimnion data to identify signs of stratification and mixing.

Data from the University of Minnesota's Remote Sensing Lab (UMNRSL) provided estimates of water clarity (estimated secchi depth) that were used to consider historic trends preceding SMSC data.

3.1.3 Inflow to Arctic Lake

Initially, no inflow volume, rate or water quality data existed for inflowing channels, gullies or ponds to Arctic Lake. In April of 2013, SMSC collected flow and water quality (temperature, specific conductivity, total dissolved solids, pH, orthophosphorus, percent dissolved oxygen and dissolved oxygen concentration) data for the drainage channel inlet to the lake as well as at the outfall of two of the major gullies draining the upper watershed (Figure 2). From 4/5/2013-4/25/2013 water quality and flow data for inflow to the lake via the drainage channel was provided. An additional day of flow in the channel was provided for 4/30/2013. For the 2 monitored gullies, flow was measured on 4/25/2013 and 4/30/2013 at approximately the same time as for the outlet channel sampling point. These data were used to preliminarily calibrate in-lake as well as watershed models. Future monitoring will allow for a more complete calibration.

Figure 2. Sampling locations, catchment delineations and topography of the Arctic Lake Subwatershed



The City of Prior Lake provided As-Built plan sets and hydrologic/hydraulic model inputs (in the form of previous HydroCAD analyses performed for the developments within the study area) for the stormwater ponds within the Arctic Lake subwatershed (catchments 2, 3 and 4, and 13, Figure 2). Th data were field verified by HDR staff and City staff to develop stormwater devices within WinSLAMM (*see* Section 3.2).

3.1.4 Outflow from Arctic Lake

Initially, no volume, rate or water quality data existed for Arctic Lake's outlet channel. However, SMSC provided 30-minute interval lake level data starting from 6/7/2004 through 9/26/2012. No winter data was provided. Since the initiation of the analysis, SMSC collected flow and water quality data for the outlet of the Lake for the dates 4/23/2013, 4/25/2013 and 4/3012013. These data were used to assist in preliminarily calibrating in-lake models, as described in 3.1.3.

3.1.5 Watershed Loading

To develop watershed loads for both rural and urban areas, two approaches were taken that utilized unique data sets. For the rural watershed areas, the District provided its TMDL Load Distribute ArcGIS shapefile to be used as a means of estimating loading. This file was created from the 2012 TMDL Implementation Plan (IP) for the Spring and Upper Prior Lake TMDL (Spring/Upper Prior 2011). Its Unit Area Loads (UAL) for land cover/use were originally developed by first calibrating published UAL's against monitored flows within Minnesota Highway 13's drainage channel (within the District boundary, south of the Arctic Subwatershed). This occurred during the relatively wetter years of 1999 and 2002. To adjust the UAL's for estimation of an expected "normal" year, load factors for the years 1998 through 2006 were generated based on their flows compared to 1999. The average load factor from that period was 0.583. This coefficient was applied to the initial UAL's within the TMDL Load Distribute shapefile to represent the Normal year's UAL value.

No local pollutant build-up or wash off data were available for the urbanized portions of the subwatershed. Therefore, pollutant probability, runoff coefficient, particulate solids concentration and land use class (n = 6) street delivery files within WINSLAMM (PV and Associates) were adopted to represent expected loading from urbanized land cover. This data was collected and analyzed by the developers of WinSLAMM in several urbanized cities from multiple sources (e.g., rooftops, streets, sidewalks, turf, etc). For WinSLAMM settings associated with this data see appendix 6.1.2.

Although several gullies exist within the subwatershed, an accurate estimate of annual loading of sediment and phosphorus was beyond the scope of this study.

3.1.6 Topography

The most current topographic information was provided to HDR by SMSC in the form of 2-foot contours based on LIDAR data (1.5 points per square meter; Twin Cities Metro Region, Minnesota 2011). This data set is state of the science and, in as such, meets the needs of modern hydrology and terrain analysis procedures. This data was used in conjunction with SMSC and City of Prior Lake stormwater utility shapefiles, as well as in-field verification, for quality control of the existing Arctic Lake subwatershed, catchment delineation, non-contributing area identification, gully identification and for identification of storm-flow focal points in rural land use areas.

Adjustments to the District's subwatershed boundary for the study area were made by first running the LiDAR data through standard GIS watershed methodology via ArcHYDRO (ESRI). Delineation of smaller catchments within the subwatershed were similarly constructed using supplemental spill points then corrected using the stormwater infrastructure. All delineations were then field verified for final definition of catchments.

Identification of non-contributing areas for this small watershed was carried out by generating a graduated DEM for visual inspection. If a pit was detected, HydroCAD would be used to route a 10-yr storm event from the drainage area to a pond device representing the pit within the landscape. Allowance for infiltration and time of concentration would be made based on the existing soils, topography and land cover data using standard hydrological methods. If the pit did not overflow, its drainage area would be considered non-contributing and excluded from both loading estimates for the lake as well as for siting BMPs.

Gullies were identified through visual inspection of the graduated DEM then field verified to the extent possible (chiefly, those areas where permission was granted for property access). Several gullies, located on private property, were later identified and visited by City Staff. Rapid visual assessments (qualitative) of stability and/or extent of erosion were made in consideration of delivery to the lake.

3.1.7 Soils

Scott County SSURGO soils data was selected to provide relevant soils attributes such as hydraulic conductivity and hydrologic soils classification. This data set meets the needs of modeling, screening and conceptual BMP treatment efficacy studies. The data set will not serve final BMP design and performance needs, however, and the final selection of infiltrating BMPs is best determined by performing, at least, soil boring investigations or, ideally, hydraulic conductivity testing of all sites called out in the final report.

3.1.8 Land Use/Cover

The PLSLWD TMDL Load shapefile as well as the SMSC Planning shapefile will be used to model both existing conditions and treatment options for Arctic Lake's watershed. The TMDL Load file was originally generated for a less resolute scale than this study proposes to use. In as such, land cover/use will be re-delineated using high resolution pictometry and the values for "adjusted load" from the original file will be correlated to the new working file. No adjustments were made to the Planning shapefile's linework but values for expected acreages of source areas will be assigned using WINSLAMM's Low-Density Residential Standard Land Use file.

3.1.9 Stormwater Utilities

Both the SMSC and the City provided stormwater utility data in the form of shapefiles. The City also provided As-Built designs and modeling information (Hydrology and Hydraulics) for the existing stormwater ponds within the study area. It is likely that some points listed as manholes will be found to be inlets (catch basins) during field investigation (not every manhole was field verified). In those cases, as with other error checking results, conflicting or missing information was noted and provided to the data owner for database updates.

After review of the pond models from the City, several errors and unanswerable questions regarding their assumptions led to their abandonment for use in this study. As-built plans were then field checked by City Staff and corrected field notes were provided to HDR. This corrected information was then be used to build existing ponds within WinSLAMM for existing conditions and treatment models.

3.1.10 Land Ownership

A parcel shape file was provided by the City of Prior Lake. Ownership information aided the selection and siting of new BMPs and for modification of older, existing BMPs. The undeveloped agricultural field immediately north of Arctic Lake used existing conditions in the model runs. This area is slated for Low-Density-Residential development and it is assumed, given the SMSC's proven dedication to Low Impact Development, will be done so in a fashion at least meeting State and Federal water quality standards when converted.

3.1.11 Aquatic Vegetation

A previous study surveying the presence and abundance of both native and invasive plant species was conducted by Blue Water Science and reported on in January 2013 (McComas and Stuckert, 2012a). The survey was completed on September 5, 2012 and found no species of rooted submerged plants within the lake. It was suggested that low-light levels during the growing season as well as the presence of bottom feeding fish species limit, or exclude, the ability of submerged, rooted plants to take hold and survive within the lake. It was speculated that the removal of carp would encourage new plant growth to occur.

3.1.12 Fish

A fish survey was conducted by Blue Earth Science on September 18-20, 2012 (McComas and Stuckert, 2012b). Ten species of fish were sampled using standard trapnets with Bluegill sunfish and Yellow Bullheads being predominant. An average of 6.7 carp per net were sampled and was considered reflective of high abundance. Both Snapping and Painted Turtles were also sampled and considered common in the lake.

Mini-trapnets were used to sample smaller fish. A total of eight species were sampled with Bluegills again representing the dominant species in terms of abundance. Fathead Minnows and Golden Shiners were also sampled, but at a slightly higher rate than found in the regular trap nets. Yellow and Black Bullheads were sampled at lower rates than Carp and Suckers, while no small Yellow Perch were captured. The report found that minnow populations were low within Arctic Lake for the year 2012.

The report suggests that Carp are likely contributing to poor water quality given that their benthic scavenging behavior stirs up sediments thereby contributing to internal loads. Similarly, the scavenging activity of benthic feeders likely has contributed to the absence of submerged, rooted vegetation further exacerbating sediment re-suspension and internal loading magnitude. Because no piscivorous fish were sampled within the lake, predatory pressure on planktivorous and herbivorous species is likely not present causing their populations to grow with likely limited controls on their populations beyond carrying capacity. Winter kill conditions were suggested to occur with limited frequency given the depth of Arctic Lake, though observation of such events have occurred in the past with the most recent being in 2010-2011. The report found a diverse range of age classes in its sampling suggesting that either these conditions are infrequent, not extensive or migration for Upper Prior Lake is frequent. All three conditions may be true.

Although the report suggests the Beaver Dam limits, possibly excludes migration in some years (such as suggested for 2012 for Carp), the study was not designed to assess that function and its inference was purely speculative.

3.1.13 Lake Sediment Fertility

Blue Water Science completed an analysis of sediment fertility for Arctic Lake and submitted a report of their findings on February 2013 (McComas and Stuckert, 2012c). The study analyzed sediment in two ways: release potential based on the ratio of total iron to total phosphprus as well as a prediction for potential support of Curlyleaf Pondweed and Eurasion Watermilfoil (as predicted by pH, iron and sediment bulk density and by ammonia and organic matter, respectively).

This report suggests that given the high ratio of iron to phosphprus in all six sampling locations, it is unlikely that internal loading from sediment is the highest contributor to phosphprus concentrations throughout the lake. Rather, it suggests that the likely heaviest contributors are watershed inputs and fish activities (i.e., stirring of sediments causing re-suspension).

However, initial review of the water quality monitoring data from SMSC suggests that in-lake conditions may promote internal loading. Although the SMSC data does not provide enough temperature data, by incremental depths, for the majority of years to directly detect a thermocline, low DO levels in the data support a hypothesis that internal loading should not necessarily be discounted as one source of loading to the lake. Currently, the Science Museum of Minnesota is analyzing a sediment core sample from the deepest part of the lake that may provide insight into the distribution, abundance and availability of phosphprus as related to potential internal loading contribution. That analysis may also provide information about the potential effectiveness of flocculent treatment BMP options.

The Blue Water Science report also suggests that conditions for both Curlyleaf Pondweed and Eurasion Watermilfoil are present, at all six of its sampling sites, that would support light to moderate growth.

3.2 Hydrologic/Water Quality and Lake Models

The following section summarizes the methods used to develop an existing conditions watershed water quality model as well as an in-lake response model for Arctic Lake. Each major component of both the watershed and lake model are presented.

3.2.1 Modified PLSLWD TMDL Load Model for Rural Areas

The PLSLWD TMDL Load Distribute Tool (PLSLWD Tool) was used to estimate annual loading from the entire Arctic Lake subwatershed. This serves as a relativistic comparison of loading between all the land uses within the subwatershed, maintains the current standard operating procedure within the PLSLWD and provides an estimate of loading from rural areas to Arctic Lake otherwise not modeled within WinSLAMM.

Several modifications to the provided data relevant to the Arctic Lake’s subwatershed and land use/cover loading, as defined by the PLSLWD loading tool, were made to increase the resolution and quality of estimating watershed loads. The complete Arctic Lake subwatershed was redrawn referencing aerial photography, LIDAR (2-ft contours), SMSC and PLSLWD stormwater utility data and field verification. Similarly, smaller catchments were delineated within the Arctic Lake subwatershed by choosing points of potential BMP interest as spill points. For instance, one point of interest in the study was the culvert located within the main drainage channel within the wetland west of the Lake. This broken culvert system drains the bulk of the subwatershed’s rural, undeveloped component through a long dike.

The watershed was screened for non-contributing areas as well as to the expected frequency of effluent events from existing stormwater ponds. A shaded DEM was used to locate pits in the landscape and were reviewed in relation to their contributing drainage area. If a pit was found that had a drainage area more than twice its areal coverage, a HydroCAD model would be generated to determine the rain event which caused it to overflow. Those areas with pits overflowing during events less than the 10-yr frequency would be considered non-contributing areas to Arctic Lake.

Similarly, City archives of hydrologic and hydraulic storm pond models were reviewed for the sake of building existing treatment into the existing conditions model. When discrepancies or errors were detected in the review, correspondence with Pete Young, City of Prior Lake, led to his site review of the site and subsequent photographs and notes were used in place of the suspect data. Each pond's bathymetry and outlet configuration were to be incorporated into a WinSLAMM model for rate, volume and water quality treatment/behavior. When a pond did not overflow below a 10-yr event, its catchment was to be considered as non-contributing.

Approximately 2/3rds of the watershed draining to Arctic Lake flows through the ditched wetland complex adjacent to the west side of the Lake. Several gullies drain the various catchments within this area of the watershed (Figure 3). Understanding the relative flow from these gullies with respect to the common outlet of the wetland was necessary to evaluate the relative loads generated from various catchments. To understand the combined flows and TP loads as well as the relative proportion of catchment contributions, SMSC Hydrologist Scott Walz collected discharge and flow data at the mouth of two of the major gullies and the spill point of the wetland (points 1 and 2 Figure 2).

Figure 3. Location of gullies with the Arctic Lake subwatershed

3.2.2 WinSLAMM Model for Developed Areas

The Source Loading and Management Model for Windows (WinSLAMM; http://winslamm.com/default.html) was used to estimate runoff and pollutant loads from Arctic Lake's urbanized areas. This model was chosen partly because local governing units have adopted it as their urban watershed modeling software, but also because of the applicability of its empirical database related to source areas within each rain event. Standard Land Use files were selected that best fit observed land use types in the study area to provide definitions of the proportions of source area contribution as averaged over several similar Midwestern cities. This empirically-based model and its assumptions fit within the scope of this study and are preferable to physically-based models in this application (i.e., to semi-rapidly describe the relative contribution of loading the Lake from urban portions of its watershed).

WinSLAMM source files were selected with the following assumptions:

1. the pollutant mean and pollutant coefficients described in the pollutant probability file reflect conditions within the urban areas of the study
2. runoff coefficients (extensively calibrated within Midwestern sample sites) work with rain depths and land uses in a similar way in this study area to produce accurate runoff volumes
3. particulate solids concentration file provides source-area data (mg/l for individual rain events for each pollutant) that reflects those of the study area
4. the values related to sediment build up, washoff and pit-capture within the street delivery files reflect conditions found within the study area

The City of Prior Lake's storm pond data was used with supplemental correction notes supplied from Pete Young for accurate representation within the model. For catchments 2, 3, and 4, this meant revising pond bathymetry significantly from the hydraulic model information including outlet diameter and bathymetry. Bathymetry was re-created digitally using aerial photographs and replication of as-built contours. Similarly, catchment 13's pond bathymetry and normal elevation was recreated. No data was provided for 13's outlet configuration and was therefor assumed to be similar to that provided for catchment 3's pond.

Neither pond located within catchment 12 or 10 were modeled given that the drainage area to pond ratio was very close to one and was comprised of open space with very minimal loading. Lastly, WinSLAMM was used to estimate the existing treatment efficiency of the grassed swale in catchment 16.

3.2.3 BATHTUB Model for Arctic Lake

Bathtub Software was used to develop a comprehensive water quality model of Arctic Lake based on the lake's morphometry and the contributing watershed. Lake level and local precipitation data made initialing a water budget feasible, but inflow and outflow were only monitored for the spring of 2013 (April). Estimates of annual flow from the channel, agricultural field and urban areas were estimated as described below. Similarly, in-lake water quality sampling provided means for verification of model results as well as calibration, inflow concentrations from the watershed were provided at site 3 for April 2013 only. This data set proved very useful in verifying estimates for runoff quality from 2/3rds of the watershed.

Global variables were entered into the Bathtub model including precipitation and evaporation. Precipitation was gathered from the rain gauge data, and evaporation was determined based on studies by Thompson (1975) and Walker (1985). Evaporation estimates used temperature, wind speed, and dew point for each month. The atmospheric loads were adopted from an existing HDR metro-area model due to the relatively similar project locations and approach to each study.

Segment data contains calibration factors, internal loading, observed water quality, and the morphometry of each segment. For our study, Arctic Lake is the only segment. Initially, internal load and calibration factors were not used building the existing conditions model. Observed water quality was maintained from the metro-HDR study, mentioned above, due to the similar nature of the systems. Most of the morphometry information was gathered from GIS. Arctic Lake's bathymetry was used to find the surface area based on the outer contour, and the mean depth was found from stage-storage relationship according to the contours. The length is the distance along the lake's major flow axis, but has no effect on the last segment or a model like ours that has only one segment. The mixed-layer depth is a variable depth that changes seasonally. A rough estimate for a "representative" depth was 3 meters while Bathtub suggested using 2.9 meters. Because the values were very close, Bathtub's suggestion of 2.9 meters was adopted. The final variable is the hypolimnetic thickness which is simply the remaining lake depth beneath the mixed-layer.

Contributing watersheds are modeled as *tributaries* in the Bathtub program. Land uses in the watershed were digitized in ArcGIS. Three tributaries were used in the study: urban, cropland, and undeveloped. The cropland tributary is designed as a non-point source of runoff into Arctic Lake. Because it's non-point, flow rates and concentrations weren't entered in the tributary main screen. Instead, the land use tab was populated and the program adopts information from the cropland land use export coefficient. The export coefficient requires pollutant concentrations and a runoff value. The total phosphorus concentration comes from Minnesota Stormwater Manual guidance. The runoff value was found by using the Minnesota Hydrology Guide's contour map of Minnesota showing runoff values across the state. In Scott County, the average annual runoff was 4.5 inches and this considers that Arctic Lake's watershed is representative of a "typical" watershed being mostly undeveloped area (forest, crops and farmsteads, wetlands) with a small portion of medium-density residential. The 4.5 inches of runoff were applied over the total area of agricultural land use. The runoff value based on the Minnesota Hydrology Guide was 43 acre-feet. Other methods were considered to find the runoff value but proved ineffective. Lake level data and the "top of dam" data were considered over a series of time steps, but the top of dam elevation is dynamic and influenced regularly by other factors including beaver activity.

The remaining tributaries were urban and undeveloped. The urban tributary was labeled as a monitored inflow based on the results of a WinSLAMM model for urban catchments. This incorporates the total area of the urban watershed and the treatment BMPs that the runoff faces. WinSLAMM uses empirical data to estimate flow rates and pollutant concentrations, which were entered into Bathtub's tributary data.

The remaining undeveloped area was given a flow rate once again based on the Minnesota Hydrology Guide runoff value of 4.5 inches in Scott County over the digitized undeveloped land use acreage. The total phosphorus concentration was input based on available monitoring data in the channel upstream of Arctic Lake. When compared to the 5 flow measurements at Site 3, similar results were found suggesting that the MN Hydrology Guide may be used in the future with reasonable planning-level accuracy when no flow data is available. For this study, we used the limited flow data to estimate an annual average flow. To do this, a plot of flow versus rainfall was generated with a linear regression and formula. The fitted line's intersection was roughly equivalent to the measured base flow conditions observed in 2013. This formula was then used for each rain event in 2007 to generate estimated discharge for the entire year and averaged to provide an estimate of annual mean discharge.

3.3 Water Quality Impacts and Opportunities – Subwatershed

This section discusses the process used to identify and model possible opportunities for TSS and TP capture and treatment within the Arctic Lake subwatershed.

3.3.1 Undeveloped Areas

To identify and assess potential options for treating subwatershed runoff from the undeveloped (woodlands, prairies and wetlands) portion of Arctic Lake subwatershed, an initial screening of existing data in GIS was performed followed by site visits for verification of assumptions. To initiate this process, the DEM, land use and aerial photography were used to identify gullies, drainage ways and wetland restoration opportunities as well as BMP opportunities within-conveyance, at points above/below culverts, at outfalls and edge of agricultural field. Field observations provided on-site data that would lead to conceptual design treatment modeling affecting both cost and performance.

Once these potential opportunities were identified, iteratively-scaled solutions were analyzed for removal of TP using a combination of WinSLAMM and published data. This was accomplished by recreating the expected TP for each BMP's drainage area as defined by the District tool via adjustment of the acreage of an Open Space standard land use file in WinSLAMM. A BMP was then designed to estimate the expected TP removal. This process is recommended within the District's TMDL Implementation Plan (IP) for Spring/Upper Prior TMDL. The TMDL IP, however, suggests the use of P8 while this analysis chose WinSLAMM as the author feels it more accurately describes the distribution of phosphprus in runoff across the particle size and dissolved spectrum. This not only affects the p-distribution but also the BMPs performance considering the method by which it removes phosphorus from runoff.

For each scaled solution, estimates of a 30-year term cost were calculated to facilitate an Annualized Term-Cost Value as follows:

$$\frac{[\$Design + \$Installation/Materials + 30(\$Annual\ Maintenance)]}{[30(Annual\ LB\text{-}TP\ Reduction)]}$$

The values for each scaled solution were then compared to provide an implementation strategy that maximizes return on investment for the Partners.

3.3.2 Developed Areas

The process for developed areas mirrored that performed for the undeveloped areas with the exception of the potential BMPs proposed and their resulted treatment modeling. The developed area's proposed BMPs used the contributing catchment area model as defined for the existing conditions analysis. Again, several scaled solutions were modeled for the chosen BMP treatment strategy. The 30-yr annualized term-cost value was calculated in the same fashion.

3.4 Water Quality Impacts and Opportunities – In-Lake

SMSC lake water quality data was reviewed to assist in selection of potential management strategies for Arctic Lake. The following strategies were considered in light of this data and weighed against the practicality and estimated costs of implementation to provide recommended strategies:

- **Nutrient Management**
    - Flushing

      Flushing is the act of providing sufficient inflow of relatively clean water to the lake to cause existing waters, and its TP-mass, to be displaced through the outlet thereby "re-setting" a clean water state. A significant source of water is needed upstream of the lake's inlet for this to be viable.

    - Dredging

      Dredging is the act of removing sediment from the actively aggrading portions of the lake to remove associated phosphorus, thereby reducing the chance for internal loading via source removal. This is accomplished either by draw down and scooping/excavating or via suction.

    - Phosphorus precipitation

      Precipitation of phosphorus from the water column and/or top sediment layer, thereby making it unavailable to algae for growth, can be accomplished via the addition of iron ($FeCl_3$), aluminum or calcium.

- **Biomanipulation**

  Biomanipulation has been used to lower the trophic state of lake systems. The requirements for success are as follows (Scheffer, 2001):

    1. The existing fish stock must be dramatically reduced;
    2. The fish reduction must then establish a clear water state;
    3. Submerged plants must successfully re-establish dense stands; and
    4. This vegetation must stabilize the clear water state

  The following options are typically employed as strategies unified in the biomanipulation plan.

    - Carp removal

      Removal of benthic, foraging fishes assists in reduction of sediment re-suspension and improves the likelihood of submerged aquatic vegetation establishment. Aquatic plant re-establishment, in turn, can initiate an upward trophic cascade with the establishment of zooplankton refugia and subsequent increases in population and nutrient filtering from the water column.

    - Piscivore reintroduction

      Introduction of piscivorous fishes has been used to effect a downward trophic cascade via predatory pressure on planktivores. Population control of planktivores releases zooplankton from predatory pressure thereby increasing there populations and resulting filtering capacity of the lake.

  - Vegetation Restoration

    As mentioned above, the reintroduction of native, submerged aquatic vegetation provides controls on TP mass in several ways, indirectly and directly. Plant root structure stabilizes the benthic sediments buffering the effect of wave action that would normally lead to sediment re-suspension and subsequent phosphorus release and limitations of light penetration (impaired water clarity leading to reductions in plant density). Lastly, standing vegetative structure provide a refuge site for water filtering zooplankton, reducing the population stressors of plantivorous fishes. Benthic foraging fish removal and temporary, physical enclosures are required for successful establishment to occur. Temporary draw downs also promote vegetation restoration via protection from fish and increased access to light.

- **Hydrological Adjustments**
  - Draw down of water levels

    Similar to flushing, a drawdown involves the removal of the existing water column, but achieved via outlet modification of actively pumping to a downstream conveyance. Consideration of the time expected for the lake to refill itself must be made. Partial draw downs allow for shallow water aquatic vegetation restoration opportunities while complete draw downs allow for sediment removal form the lake's bottom.

- **Dredging**
  - As mentioned above, removal of lake sediment has the potential to restore its historic benthic environment to a point before sedimentation impacts occurred thereby removing accumulated phosphorus and providing the potential for vegetation restoration. The process focuses on areas of sediment accumulation via suction and/or mechanically scooping out material. It demands a flat, extensive open space for dewatering and removal to an offsite location.
- **Barley Straw**

  Barley straw has been used in shallow ponds to reduce phytoplankton biomass. Although the exact mechanism(s) driving algal reductions related to barley straw are relatively poorly understood, it is believed that the provision of refugia for zooplankton and beneficial bacteria are the primary drivers. As mentioned above, zooplankton (in particular Daphnia and other rotifers) filter the water column. It is believed that the bacteria residing on the straw uptake nutrients as well (Wingfield *et al*, 1985 *as cited by* Scheffer 2001). Another suggestion is that phytotoxic compound(s) found in barley straw have allelopathic effects on phytoplankton (Gibson *et al*., 1990; Pillinger et al, 1994 *as cited by* Scheffer, 2001). Barley Straw has been used, locally, outside of stormwater ponds (e.g., Powderhorn Park, Minneapolis) with anecdotal evidence of its efficacy, but not to the scale of Artic Lake's basin.

4 Results

4.1 Existing Data Review

4.1.1 Precipitation and Lake Levels

Figure 4. April - November annual rainfall (in inches) in Arctic Lake subwatershed (SMSC data)

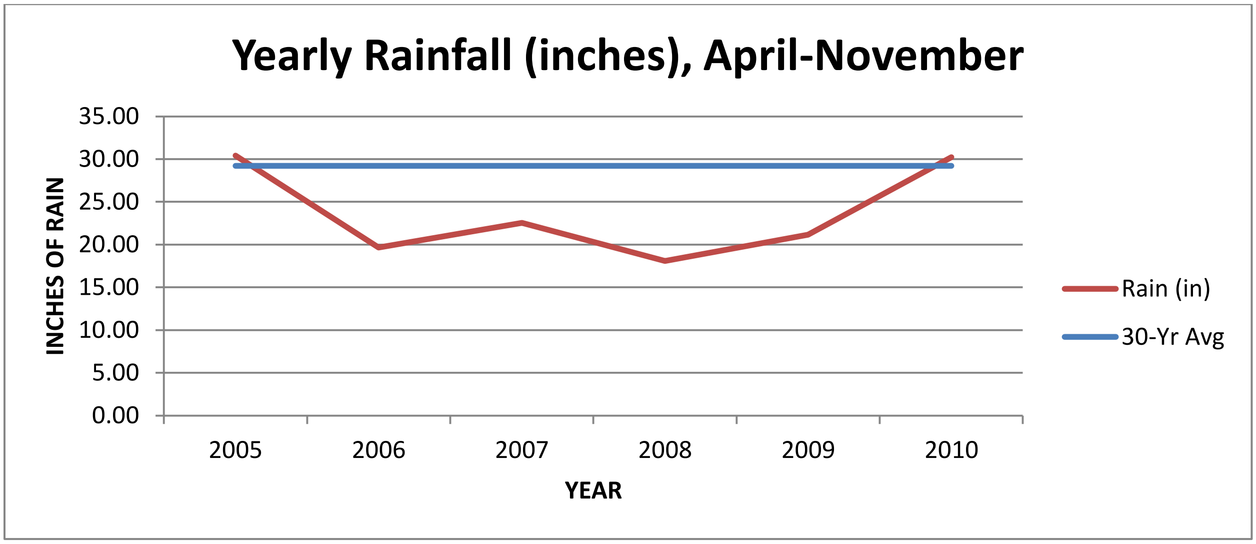
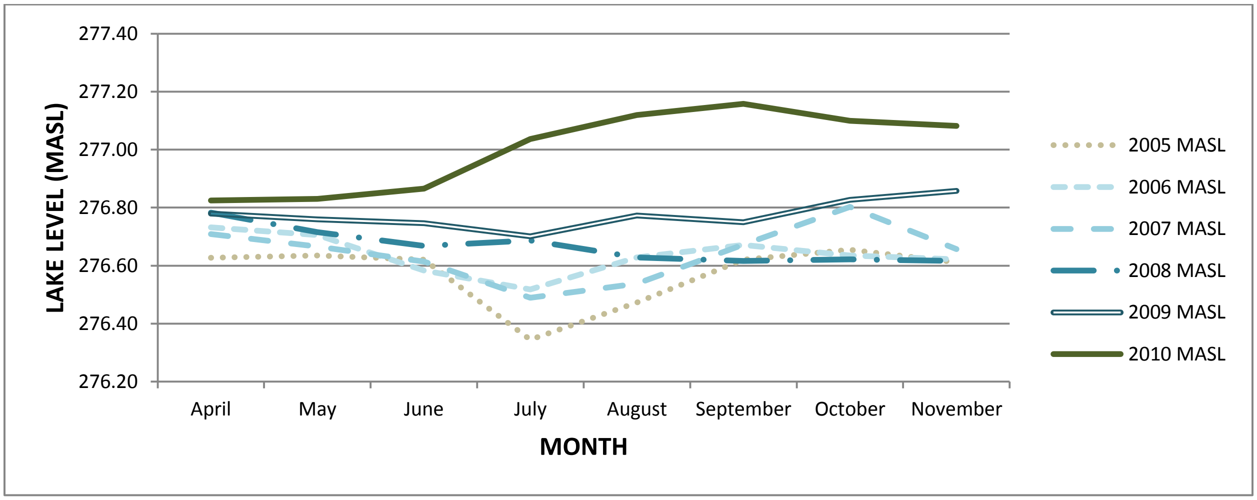


Figure 5. Arctic Lake average monthly lake levels (SMSC data)



4.1.2 Lake water quality

This section discusses the SMSC water quality data and how it was used for this analysis. There were four database files used in this study with an example summary of the resulting data (see Appendix 6.1.2 for additional data):

Arctic Lake Chemical Data.xlsx

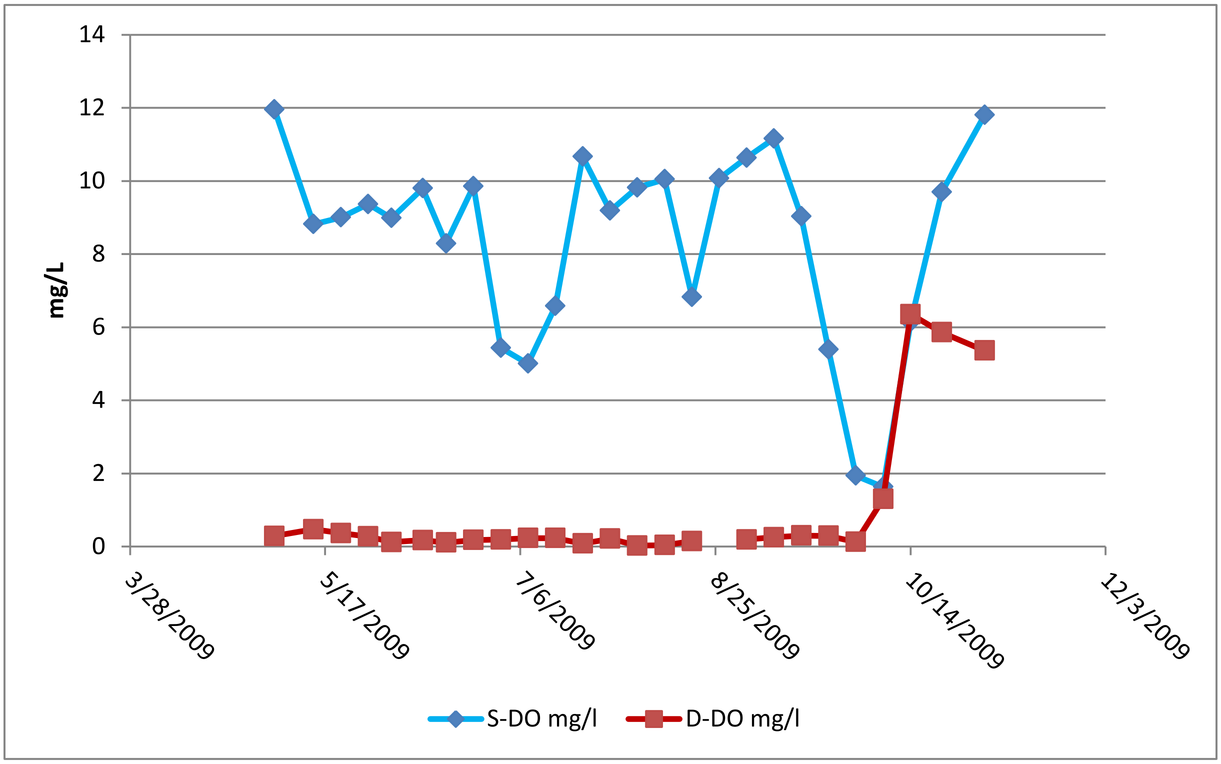
This file contains Arctic Lake data collected from May 5, 1999 through August 8, 2012. The "West Arctic" monitoring location was sampled only twice, in 1999. The "Central Arctic" monitoring location was sampled approximately 50 times from 1999 through 2006; a "top" sample and a "bottom" sample were taken during each sampling trip. The "East Arctic" monitoring location was sampled 112 times from 1999 through 2012, typically from late May/early June to late August/early September. These surface samples (1 meter below water surface) were typically taken 7-10 times per year from 1999 through 2007, and 12-14 times per year from 2008 through 2012.

Arctic Lake 1999-2012.xlsx

This file contains a number of parameters measured with a submersible, cabled probe (aka Sonde). The parameters were measured at the same depth as the water sample collection. Measured parameters include water temperature (degrees C), dissolved oxygen (mg/L), dissolved oxygen saturation (%), specific conductivity (micro Siemens/cm), total dissolved solids (g/L), pH, oxidation-reduction potential (millivolts), and barometric pressure (mm Hg). There are 182 data points available for most of these parameters from 2004 through 2012. Exceptions are for oxidation-reduction potential (181 points) and barometric pressure (40 points, primarily 2004-2005).

Thermocline identification is a necessity for development of in-lake response modeling (e.g., Bathtub). On review of the current data set, only the year 2012 provides data sufficient for this purpose as preceding years' data was collected in locations of the lake away from the deepest point, where a more definitive profile can be ascertained. For other years, a comparison of hypolimnion vs. epilimnion chemical and temperature parameters were used to estimate mixing event timing (Figure 6).

Figure 6. 2009 Shallow (S) versus Deep (D) dissolved oxygen in Arctic Lake



Arctic_2012.xlsx

This file contains quality assurance information for the Sonde data. It also contains water column profile data for the Sonde for three dates in 2012 (September 12th, 19th, and October 15th). This data can help identify important physical changes in the lake if collected over the course of the year.

Hydrolab_ChemicalProfile_ArcticLake.xlsx.

This file contains Sonde profile data for the year 2005 (22 monitoring events from April 4th through November 9th). The data was typically measured each foot from 1 foot off of the lake bottom to 7 feet off of the bottom.

Summary of Findings

SMSC's 2004 through 2012 water quality monitoring results suggest elevated concentrations of TP in the surface waters of Arctic Lake for the duration of the record with an average of 0.128 mg/L (0.045 – 0.320 mg/L; Figure 7). In 2007, SMSC collected water quality data at the deep part of the lake (East Arctic site). In that year, the concentration of TP averaged 0.368 mg/L (0.110 – 0.610 mg/L, *n*=6 from 6/4 though 7/17; Figure 8). In that year, the early to mid June concentrations in the epilimnion and hypolimnion effectively equivalent during two samples.

Sonde data collected during the years 2007-2012 showed consistently anoxic conditions (<0.4 mg/L DO) in the hypolimnion and dissimilar temperatures between it and the epilimnion. This trend repeated itself for each year until early to mid October (Appendix 6.1.2).

Figure 7. 2004 – 2012 Shallow TP (mg/L)

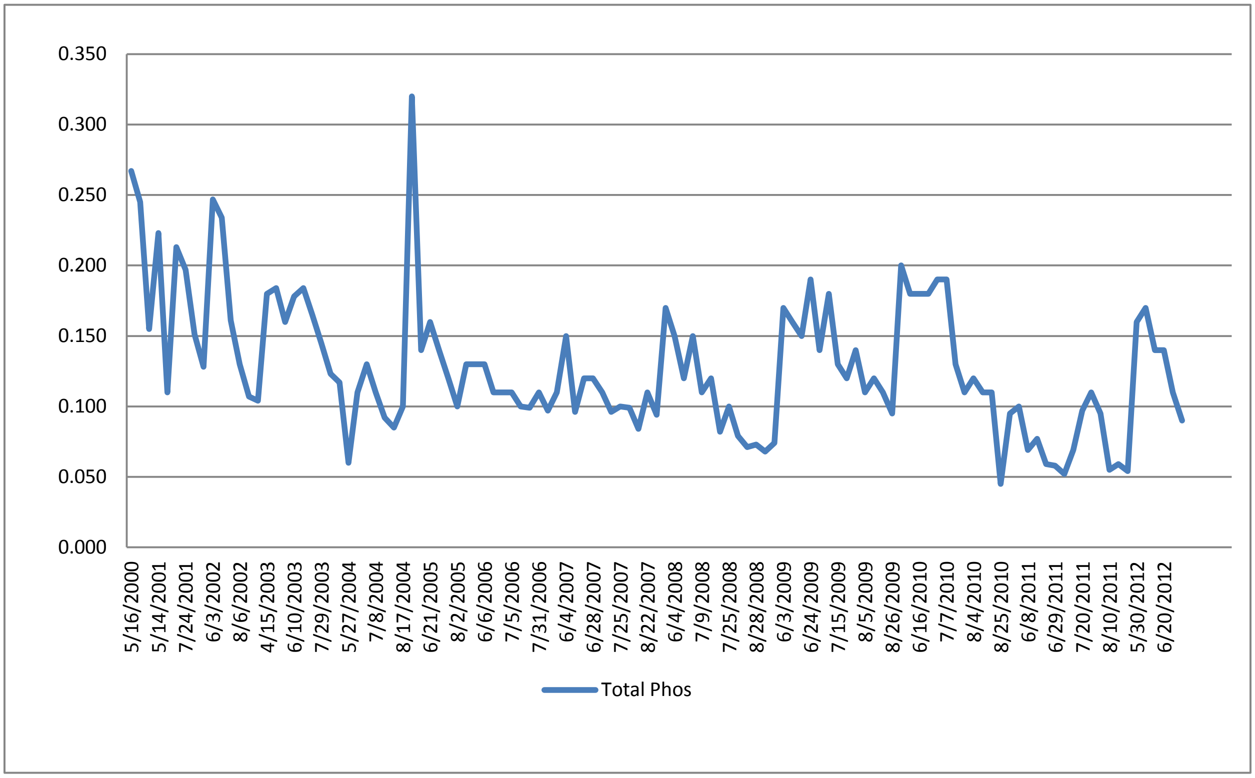
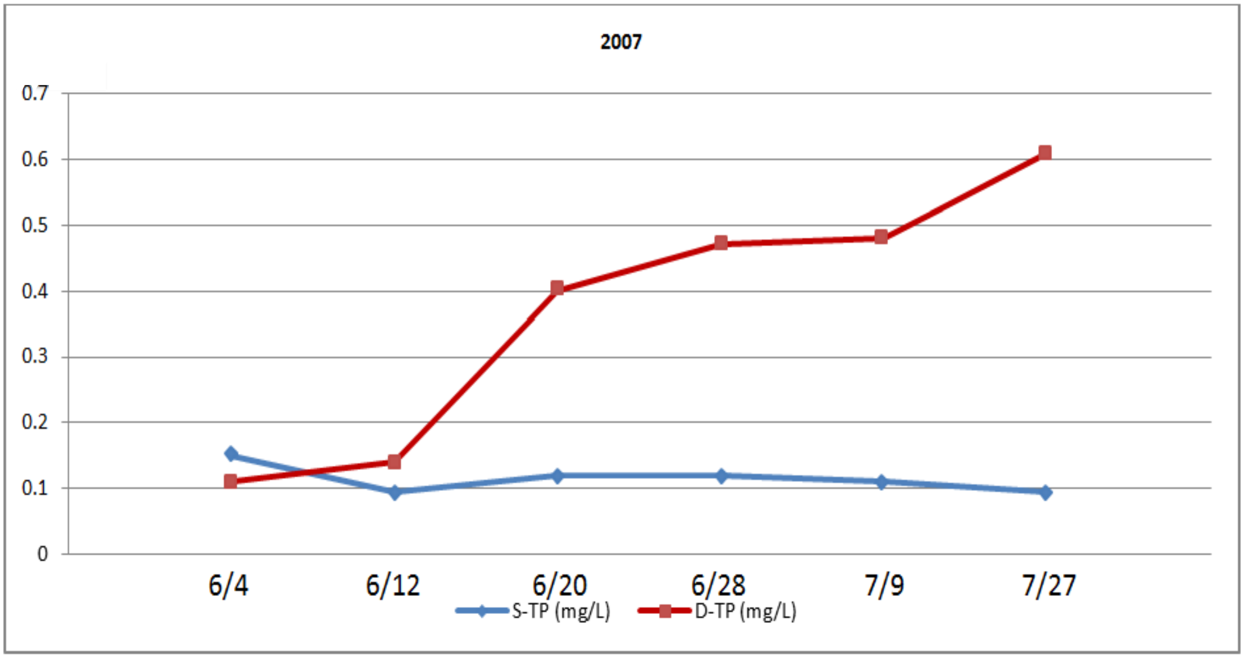


Figure 8. Shallow (S) and Deep (D) total phosphorus for 2007



The 2007 TP data, when compared to the Sonde data from 2007-2012, provides the best insight into the lake's behavior relative to establishment of a thermocline and its disruption. There is not enough data available to identify a thermocline in terms of temperature at this time. The shallow and deep water concentrations of Dissolved Oxygen (DO) highly differ from the earliest sampling (in most every year) until October. DO was nearly undetectable in the hypolimnion in most samples and consistently well above 4 mg/L in the epilimnion. The temperature between the shallow and deep measurements, on average, differed by 20°C suggesting a thermocline from June until October. Nearly each year (2007-2012), both the DO and Temperature measurements of the epilimnion and hypolimnion converged in early to mid October.

The data suggests that

1. There is a very high likelihood a thermocline keeps shallow and deep water from mixing, in most years, until October when the similar temperatures and DO suggest a mixing event occur;
2. The extent of this mixing, in terms of TP and total load delivery to the epilimnion from the deep part of the lake, cannot be verified from the existing dataset;
3. The similarity between shallow and deep concentrations of TP, in June 2007, may suggest that TP levels start out uniformly in the beginning of the season and that anoxic conditions lead to an internal release of P throughout the remainder of the summer. Without a clear understanding of thermocline depth trough time, it is difficult to estimate the relative proportion of hypolimnion load related to a sinking thermocline (reduced volume of water in the hypolimnion) versus that related to the release of P from the sediment;
4. The shallow TP sampling at East Arctic ended before October for every year on the record (before the observed possible mixing event as detected via the Sonde data) so no interpretations can be made as to whether the hypolimnion's elevated TP-load is transferred into the shallow waters; and
5. Given the Sonde data, however, it appears likely that internal loading plays a significant role in the nutrient balance of the epilimnion. Unfortunately, however, the data does not allow us to tell to what extent.

Future sampling can serve to verify these findings by sampling temperature at each meter, along with the Sonde parameters currently being sampled, from ice out though ice in, or until a homogeneous temperature profile is established. Samples for TP should be taken each month as well. The total load of TP can then be calculated for the epilimnion and hypolimnion as the thermocline moves downwards and eventually whole lake mixing occurs.

4.1.3 **Inflow to Arctic Lake**

Event sampling of flow and water quality at three locations west of Arctic Lake allowed for insights into the spring runoff quality and quantity for 2013 (Figure 9). In addition, this data was used to assist in the Bathtub lake model.

Flow data, as shown in Table 2, from two sampling dates in the spring of 2013 were compared (sites 1 and 2) with respect to the flow from the entire western 2/3rds of the subwatershed (site 3). Sites 1 and 2 were located at the bottom of two major drainage gullies. They differ dramatically in their response to rainfall in terms of runoff generation, according the

SMSC flow data for their outlets. The much larger catchment 9, that drains to sample site 2, has disproportionately smaller runoff. It is somewhat surprising that even after the 3.42 inches of precipitation from 4/1/2013 through 4/15/2013 (see Table 3) site 2 registered zero runoff while site 1 (catchment 8) produced 21% of the entire drainage area running to sample site 3. Interestingly, catchment 9 did register runoff through its gulley outlet on 4/30/2013, but only represented 3% of the western drainage's total flow while catchment 8 produced 25%. It is possible that the shallow lake within catchment 9 was relatively low in the winter of 2013 compared to its outlet elevation and did not overflow for either or both of the sampling dates. Other possible explanations are that catchment 9 has more wetland coverage (storage potential) outside of its shallow lake drainage area as well as primarily woodland cover in the remaining portion, relative to catchment 8. Catchment 8 is 3/5ths woodland and 2/5ths newly developed parkland. In either case, the TMDL Load tool predicts negligible TP loads from both catchments.

Figure 9. Flow (cubic meters/second) at 3 sampling points west of Artic Lake

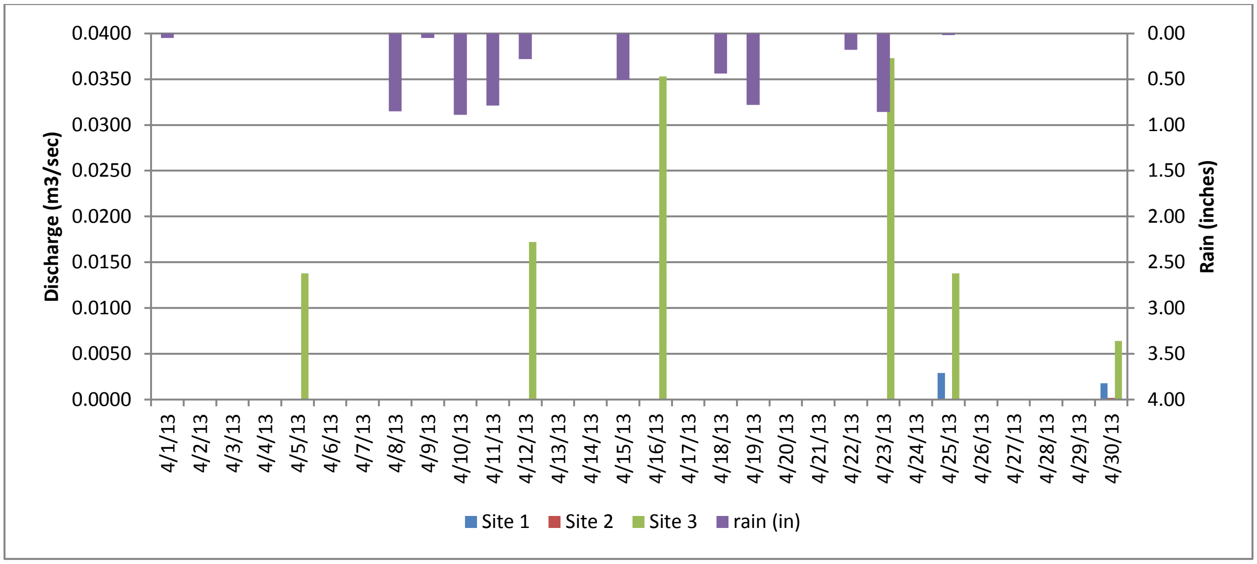


Table 2. Proportion of flow at three sampling locations within the western 2/3rds of the subwatershed for two spring, 2013, rain events

Date	Site	Acres Drained	Percent of Western 2/3rds of Subwatershed Area Draining to Site 3	Discharge (m³/s)	Ratio of Drainage Contributing to Site 3
4/25/2013	1	31.22	9%	0.00290	21%
4/30/2013	1			0.00180	28%
4/25/2013	2	95.84	28%	0.00000	0%
4/30/2013	2			0.00020	3%
4/25/2013	3	339.10	100%	0.01380	100%
4/30/2013	3			0.00640	100%

Table 3. Daily precipitation events related to the inflow sampling data collection in 2013

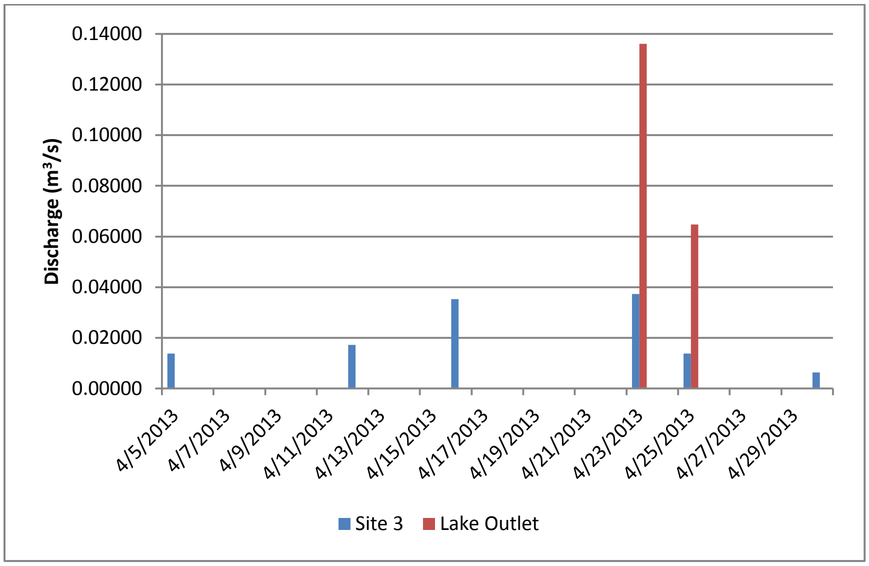
Date	Precip. (in)	Date	Precip. (in)
4/1/13	0.05	4/18/13	0.44
4/8/13	0.85	4/19/13	0.78
4/9/13	0.05	4/22/13	0.18
4/10/13	0.89	4/23/13	0.86
4/11/13	0.79	4/25/13	0.02
4/12/13	0.28	4/29/13	0.05
4/15/13	0.51		

Given the monitoring data, above, the remaining flow observed at site 3 is contributed by catchments 3, 4, 5, 6, 7, 10, 11 and 12. Catchments 3 and 4 were modeled in WinSLAMM while the remaining catchments were neither modeled nor monitored. Catchment 3 does not have any volume reduction capacity as its pond is filled with sediment to within a foot of the overflow and low enough to have nearly permanent ground water filling that stage storage. Catchment 4 has the capacity for minor infiltration and is expected to remove 15.7% of the volume draining to it annually. WinSLAMM, however, does not directly predict discharge. To estimate the rate of discharge provided by catchment 4, WinSLAMM precipitation records for Minneapolis, 1959 (representative normal year) provided a 7 day period generating 2.64 inches of rain. After the volume removal of the existing pond, this equated to an estimated 0.0163 m^3/s of flow for an event similar to that preceding the 4/30/2013 sampling date. Similarly, catchment 3 was determined to produce 0.0074 m^3/s of discharge. The sum of flows for catchments 3, 4, 8, 9 would then be estimated at 0.0275 m^3/s. If these relative numbers are accurate, the wetland complex in catchment 5 would need to be storing more volume than the ditch channel provides or the rate of flow from the outfalls of each catchment draining to it exceeds 7 days.

Of the remaining catchments, 10 is considered non-contributing given its very small drainage area to pond ratio and that it overflows to the seldom overflowing shallow lake found within catchment 9. Similarly, catchment 2 is primarily comprised of a small drainage area of natural cover feeding a wetland of nearly the same size that rarely overflows through 11. Catchments 6 and 7 may contribute proportionally to runoff of catchment 8 (71% and 93%), as would catchment 11 (98% the size of 8). These contributing areas combined would then account for 0.00472 m^3/s. The total sum of the contributing catchment's flows would then be 0.0322 m^3/s.

The relative contribution of the western 2/3rds of Arctic Lakes watershed (west of site 3) possibly contributes less than 1/3rd of the total flow to the lake, as evidenced by inflow versus outflow of the lake (Figure 10).

Figure 10. Spring 2013 measured discharge of the western 2/3rds of the arctic Lake's subwatershed versus the Lake's outlet



In addition to the relatively low estimates for flow and TP load from the western portion of Arctic Lake's watershed, monitoring data of site 3, albeit for a short period of record, suggest the possibility of seasonal variation in TP concentrations (Figure 11). Although it is possible that sampling in 2013 may have started after the initial late winter-early spring flush of wetland nutrients in the lands tributary to site 3, data from other wetlands within the District suggest similar seasonality in nutrient concentrations (e.g., CD-13). The tapering of TP concentrations during the month of April may be correlated not only to wetland flushing but to the fact that the water became more oxygenated during that time as evidenced by monitoring data (Table 4).

Figure 11. Spring 2013 measured flow versus TP concentrations at site 3

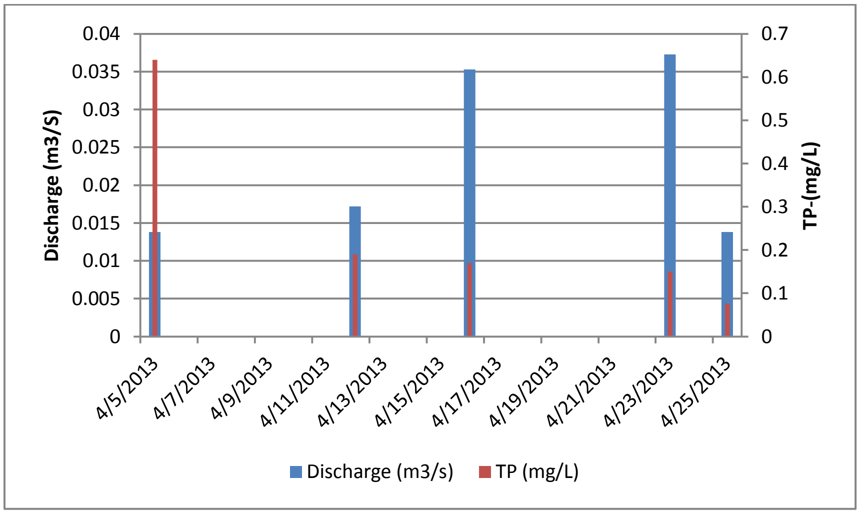


Table 4. Dissolved oxygen levels at site 3 in in 2013 monitoring data

Date	LDO (mg/L)	Time
4/05/2013	4.89	11:20 am
4/13/2013	5.62	11:11 am
4/16/2013	8.02	10:54 am
4/23/2013	8.32	10:24 am
4/25/2013	3.06	01:39 pm
4/30/2013	3.20	11:08 am

4.2 Hydrologic/Water Quality and Lake Models

4.2.1 TMDL Loading Tool Results

The modified TMDL Tool and modified land use/cover delineation overlay provided a slightly more refined estimate of the load produced for each catchment in the study area. The catchments with the highest predicted yields of TP were catchments 15 and 14, respectively. When combined, their collective 27.62 acres (5.4% of Arctic Lake's subwatershed) contributed 40% of the estimated TP generation from the subwatershed (Table 5). Both of these cultivated field-dominant catchments drain to minimal prairie buffer area across steep, gullied and exposed soils before entering the wetland fringe of Arctic Lake. A similar catchment (16), comprises 3% of the subwatershed area and potentially generates another 11% of the overall annually-expected yield of TP. Its yield is expected to be smaller (0.5-LB/ac/yr versus 1.34 and 0.82 Lbs/ac/yr for catchments 14 and 15, respectively) purely based on the fact that a significant portion of its area is restored prairie.

It is important to understand that the TMDL Tool only calculates the potential load generation from a site and does not take into account actual delivery of that load to the Lake. For instance, catchment 16's 6.57 acres of agricultural drainage area is routed through 1200-ln ft of fully vegetated 5% grade swale before reaching the Lake. The estimated 5.9 Lbs-TP generated by this field (70% of the catchment load) is expected to be reduced by 2.65 Lbs via the swale (a 45% reduction). Given this, catchment 16 is deemed partially connected (or, partially treated; Table 5).

To generate estimates of load reductions for partially connected catchments (partial water quality treatment in place), the TMDL Tool's expected loads were replicated in WinSLAMM and routed to an appropriate BMP(s).

Table 5. Summary of TMDL tool watershed TP generation by catchment

Catchment	Acres	Portion of Subwatershed	LB-TP/Year[1]	LB-TP/AC/Year	Connection to Arctic Lake[2]	Post-Treatment Delivery to Lake (Lbs-TP/yr)[3]
1	88.27	17.39%	7.93	0.09	Full	7.93
2	20.68	4.07%	5.17	0.25	Partial	4.06
3	7.03	1.38%	2.47	0.35	Partial	1.32
4	13.5	2.66%	4.45	0.33	Partial	2.27
5	99.2	19.54%	5.74	0.06	Full	5.74
6	22.13	4.36%	0.00	0.00	Full	0.00
7	29.05	5.72%	0.00	0.00	Full	0.00
8	31.22	6.15%	0.00	0.00	Full	0.00
9	95.84	18.88%	0.22	0.00	Partial	0.00
10	6.64	1.31%	0.00	0.00	Non-contributing	0.00
11	30.31	5.97%	4.47	0.15	Full	4.47
12	4.18	0.82%	1.67	0.40	Non-contributing	0.00
13	15.40	3.03%	5.88	0.38	Non-contributing	0.00
14	15.41	3.04%	20.69	1.34	Full	20.69
15	12.21	2.40%	10.04	0.82	Full	10.04
16	16.65	3.28%	8.40	0.50	Partial	4.06
Total	507.72		77.12			60.58

[1] The PLSLWD TMDL load estimating tool assumes no loading from various natural land cover types such as open spaces, prairies, woodlands, water and wetlands.

[2] "Full" connection, here, is meant to describe a scenario where the landscape run off with no BMP in place before the Lake. "Partial' implies that some form of BMP is in place at some efficiency at handling rate, volume and/or water quality of the watershed-generated load (i.e., a portion of this load is treated; see WinSLAMM results, Section 2.2.). "Non-contributing", here, implies that either the catchment rarely overflows with enough volume to reach the Lake, or that significant treatment of that effluent is located between it and the Lake.

[3] Post-treatment delivery to lake was determined by generating an open space model in WinSLAMM that met the TMDL Tool's estimated load generation, then routing it through a grassed swale for catchment 16. For catchments 2, 3 and 4, the resulting WinSLAMM pollutant reduction percentage from the WinSLAMM model discussed for Urban Modeling (Section 2.2) was used to reduce the TMDL Tool's estimated load generation.

4.2.2 Urbanized Catchment Loading

The following Table of results describes estimated catchment loading and existing treatment potential for the small portion of urban area draining to Arctic Lake.

Table 6. Urban catchment loading estimates within the Arctic Lake subwatershed

Catchment	Acres	Portion of Subwatershed	LB-TP/Year[1]	LB-TP/AC/Year	Post-Treatment Delivery to Lake (Lbs-TP/yr)[3]	Percent Treatment
2	20.68	4.07%	13.26	0.64	10.42	21.40%
3	7.03	1.38%	6.38	0.91	3.40	46.77%
4	13.5	2.66%	13.07	0.97	6.42	50.90%
Total	41.21	8.11	32.71	0.79	20.24	38.12%

4.2.3 Lake Model Results

A preliminary Bathtub model was generated for the client that will be supplemented with additional inflow and outflow monitoring data in subsequent years. At present, four annual model runs were generated (Table 7). The model consistently underestimated epilimnion concentrations of TP with the most accuracy occurring for the slightly dry years of 2006 and 2007.

As more data comes in it may be possible to increase the accuracy of a normal, dry and wet year model as well as test sensitivity of each inflow to better understand the drivers of watershed load delivery to Arctic Lake.

Table 7. Bathtub model results for four years within Arctic Lake

Year	Variable	Predicted		Observed		Error
		Mean	CV	Mean	CV	
2005	Total-P (ppb)	89.9		155.00	4.74	-42.0%
	Secchi (m)	0.6		0.32	0.33	+47.0%
2006	Total-P (ppb)	93.4		108.44	0.10	-13.8%
	Secchi (m)	0.6		0.35	1.59	
2007	Total-P (ppb)	92.7		108.30	0.35	-14.4%
	Secchi (m)	0.6		0.32	0.92	+47.0%
2010	Total-P (ppb)	90.2		141.54	2.30	-36.3%
	Secchi (m)	0.6		0.30	0.40	

4.2.4 Lake Internal Phosphorus Loading

Potential internal loading was estimated by using monitored TP concentrations for the epilimnion and hypolimnion for the year 2007, the only time when TP was measured at the very bottom of the lake. The year 2007 provided 6 sampling events from 6/7/2013 to 7/17/2013. Knowing the location of the thermocline, the volumes of the epilimnion and hypolimion were calculated. Because temperature and DO profiles were not taken at the time, here we assume constant volumes for the epilimnion (14.6 ac-ft) and hypolimnion (77 ac-ft). For the 2007 estimate, the TP concentrations for the hypolimnion and epilimnion were multiplied against the estimated hypolimnion and epilimnion volumes to determine TP mass (Table 10). Although this method provides somewhat speculative results without the availability of bottom core laboratory analyses, some inferences can be made until said data is collected and analyzed.

Table 8. Estimated TP loads within the epilimnion and hypolimnion of Arctic Lake in 2007

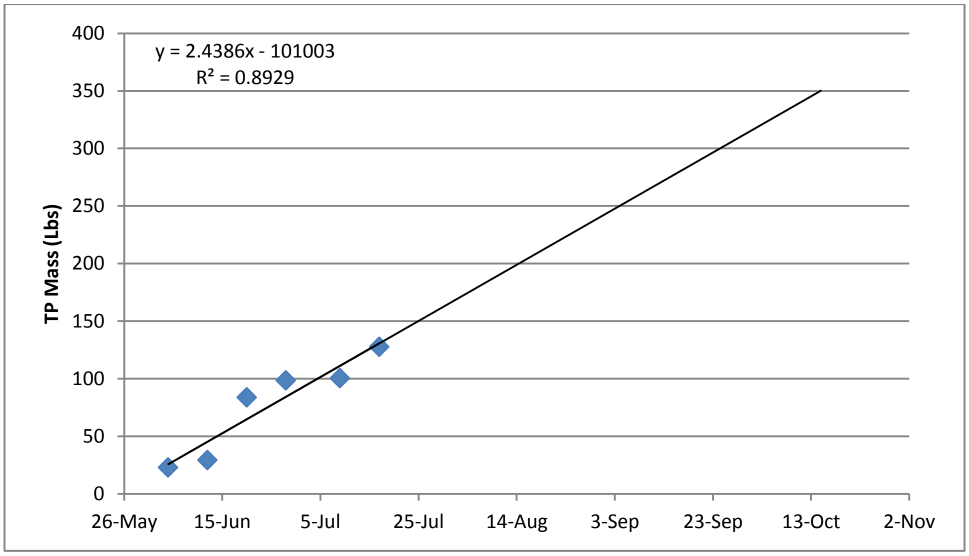
	Date	TP (mg/L)	Estimated TP Mass (Lbs)	TEMP (°C)	DO (mg/L)
Epilimnion (141.6 ac-ft)	6/4	0.15	57.8	N/A	N/A
	6/12	0.10	38.5	23.7	15.15*
	6/20	0.12	46.2	22.6	8.00
	6/28	0.12	46.2	24.2	8.07
	7/9	0.11	42.4	26.3	7.11
	7/17	0.10	38.5	25.2	9.33
	7/25	0.10	38.5	25.8	4.47
	8/2	0.10	38.5	27.1	6.88
	8/13	0.08	30.8	25.2	6.65
	8/22	0.11	42.4	21.0	6.86
	8/30	0.10	38.5	22.1	7.92
Hypolimnion (77 ac-ft)	6/4	0.11	23.0	N/A	N/A
	6/12	0.14	29.3	6.3	0.45
	6/20	0.40	83.8	5.4	0.82
	6/28	0.47	98.4	5.7	0.88
	7/9	0.48	100.5	6.3	0.40
	7/17	0.61	127.7	6.6	1.38

*This value may be the result of an error with the probe

Although the water chemistry monitoring for 2007 was limited to a mid-season period, limiting the ability to estimate internal loading (as per methods descried for nearby Fish Lake; Bischoff 2005), data suggests that anoxic conditions in the hypolimnion are present the majority of the season leading to a release of phosphorus (making up approximately 77% of the lake's total TP-load, mid-season). For the years 2007-2012, DO remained below 2 mg/L until an autumn mixing event between 10/7 and 10/31 in these years as evidenced by both DO and temperature (Appendix 6.1.2, Figures 15 and 16). A conservative estimate of potential internal loading would then be 105 lbs (the change in load from 6/4/2013 to 7/17/2013). This assumes the predicted hypolimnion depth is constant and accurate as well as that the mass remains unchanged between 7/17 and turnover 3 months later; which is highly unlikely.

To forecast hypolimnetic mass-TP through to the mixing event, a mass versus period regression was performed on the limited data set and compared to the nearby Fish Lake data (Figures 12, 13 and 14). Although a limited series of data is available, the results are more suggestive than definitive forecasts of hypolimnion mass and, therefore, potential load.

Figure 12. Predicted mass of TP (Lbs) in Arctic Lake's hypolimnion prior to autumn mixing.



When hypolimnion data from Fish Lake is similarly analyzed, a similar linear relationship and fit is shown for two discrete periods of the season, presumably separated by a mixing event (Bischoff 2005, Figures 13 and 14). The Fish Lake data show a reduction in slope for the second period of the season suggesting the potential for a potential non-linear relationship or weaker correlation between mass and time if no mixing event were to have occurred. It is possible, then that Artic Lake's hypolimnetic TP mass could range from 200-350 lbs by mid-October, the typical time when fall turnover occurs. Conservatively, then, the potential internal loading may range from 177-327 lbs-TP. Compared to external load estimates presented earlier (i.e. 61 lbs-TP) this represents 75%-84% of the annual lake TP loading.

Figure 13. Early season hypolimnion phosphorus mass (Kg) in Fish Lake

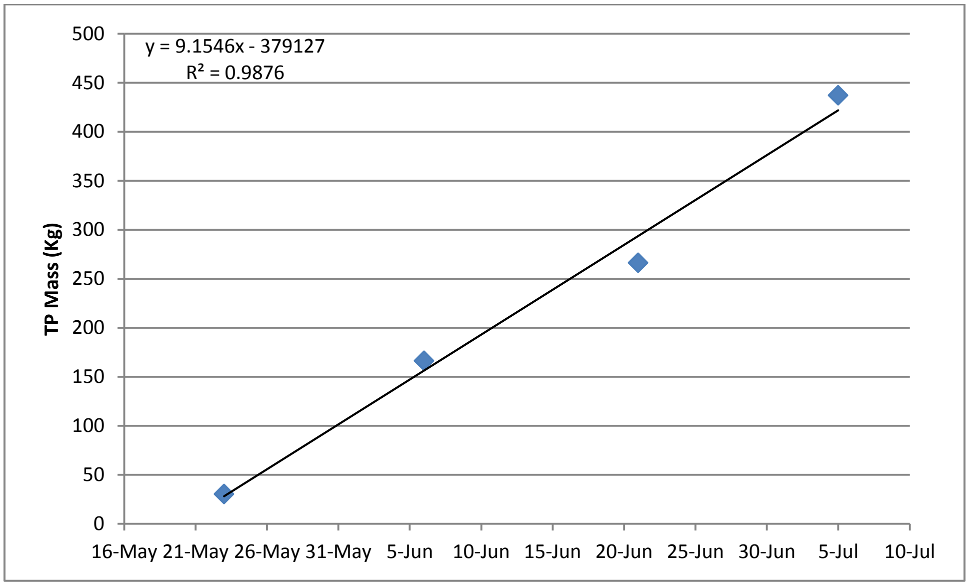
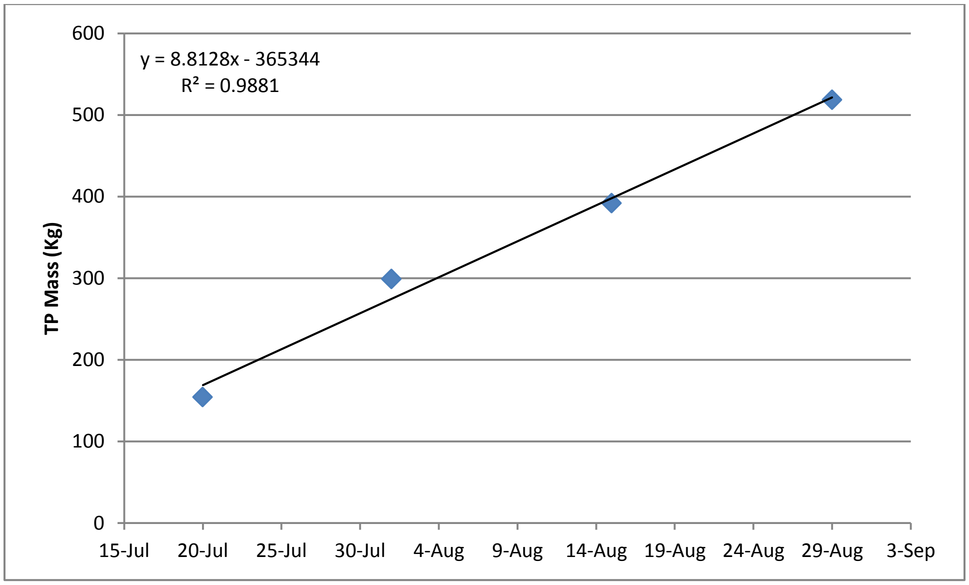


Figure 14. Late season hypolimnion phosphorus mass (Kg) in Fish Lake



4.3 Water Quality Impacts and Opportunities – Subwatershed

This section discusses possible opportunities for TP capture and treatment within the Arctic Lake subwatershed. Because both subwatershed and internal processes appear to play important roles in epilimnion concentrations of P, consideration of external loading treatment options is recommended for restoration strategies for Arctic Lake. A map of each identified strategy is found in Appendix 6.1.4.

4.3.1 Developed Areas

Several opportunities exist for the capture and treatment of stormwater runoff from the developed portions of Arctic Lake's subwatershed.

4.3.1.1 Pond Retrofits

The City of Prior Lake maintains several stormwater ponds within the Arctic Lake subwatershed. Three of these are well-suited for slight modifications that will improve their expected stormwater treatment capacity. The City is well known for its pond retrofit designs in relation to iron-enhanced sand filters (IESF) and has staff used to their maintenance. This, along with increased storage capacity, is likely the two best-fit retrofit modifications of ponds for these sites. See Table 9, Table 10 and Table 11for restoration estimates.

Table 9. Pond 03010101 (Catchment 2; site 6) - Existing treatment = 2.84 Lbs TP; potential treatment after restoration = 3.21 Lbs TP

Existing Watershed Load (13.26 Lbs TP)	Level 1 TP Treatment: Restored plus 15% increase in storage (0.08 Lbs TP)	Level 2 TP Treatment: Restored plus 30% increase in storage (0.16 Lbs TP)
Design and Installation	$5,243	$7,969
Annual Maintenance	$0	$0
Capacity Cost	$65,538	$49,807
Term Value (30-yr annualized)	$2,185	$1,660

Table 10. Pond 04020201 (Catchment 3; site 7) - Existing Treatment = 3.40 Lbs TP

Existing Watershed Load (6.38 Lbs TP)	Level 1 TP Treatment: IESF (2.32 Lbs TP)	Level 2 TP Treatment: Level 1 plus 15% increase in storage (0.06 Lbs TP)	Level 3 TP Treatment: Level 1 plus 30% increase in storage (0.11 Lbs TP)
Design and Installation	$5,000	$16,500*	$38,000*
Annual Maintenance	$150	$250	$500
Term Value (30-yr annualized)	$137	$13,333	$16,060

*Construction @ $25/yd³, Design @15% project

Table 11. Pond 04020202 (Catchment 4; site 8) - Existing Treatment = 6.42 Lbs TP

Existing Watershed Load (13.07 Lbs TP)	Level 1 TP Treatment: IESF (4.29 Lbs TP)	Level 2 TP Treatment: Level 1 plus 15% increase in storage (0.08 Lbs TP)	Level 3 TP Treatment: Level 1 plus 30% increase in storage (0.14 Lbs TP)
Design and Installation	$5,000	$54,000*	$108,000*
Annual Maintenance	$150	$250	$500
Term Value (30-yr annualized)	$74	$25,625	$29,285)

4.3.1.2 Boulevard Retrofits

The neighborhoods draining to the City stormwater ponds south and east of Arctic Lake are well-suited for inclusion of treatment systems within the right-of-way (Points 6-8, Figure 18, Appendix 6.1.4). The SMSC, City and WD all have a successful history of using curb-cut bioretention to treat stormwater both as sole owners of the systems and within public-private-partnerships. Priority locations for these systems are immediately uphill from catch basins in non-limiting spaces with gentle slopes. Each cell should treat, at minimum, 5 property's runoff (including the street), preferably as much as 8. Efficiencies are optimized by spreading, rather than "stacking," these systems in a distributed fashion through the neighborhoods. Pre-treatment is recommended as it assists in preserving treatment efficiency of the system as well as extends the life-cycle before soil replacement is necessary. This pre-treatment can include both frequent street sweeping and sediment forebays (e.g., Rainguardian©).

The estimated value of boulevard bioretention assumed the following:

- Each cell would be 250 ft^2
- An installed cost of $1000 for a forebay
- Partial retaining walls
- Tree plantings
- An averaged annual cost of $75 per bioretention cell assuming mulch additions, weeding, plant replacement and 1 forebay maintenance event up to the cost of replacement
- An overall design and installation cost of $6250/ft^2

Table 12. Catchment 2 - Existing Treatment (2.84 Lbs TP)

Existing Watershed Load (13.26 Lbs TP)	**Level 1 TP Treatment:** **20% TP Reduction (4 BMPs, 2.00 Lbs TP)**	**Level 2 TP Treatment:** **40% TP Reduction (10 BMPs, 4.20 Lbs TP)**	**Level 3 TP Treatment:** **Pond 03010101 Level 1 plus Catchment 2 Level 1 (2.47 Lbs TP)**
Design and Installation	$25,000	$62,500	$30,243
Annual Maintenance	$300	$750	$300
Term Value (30-yr annualized)	$567	$675	$530

Table 13. Catchment 3 - Existing Treatment = 3.40 Lbs TP

Existing Watershed Load (6.38 Lbs TP)	**Level 1 TP Treatment:** **20% TP Reduction (3 BMPs, 0.57 Lbs TP)**	**Level 2 TP Treatment:** **40% TP Reduction (6 BMPs, 1.23 Lbs TP)**	**Level 3 TP Treatment:** **Pond 04020201 Level 1 plus Catchment 3 Level 1 (2.57 Lbs TP)**
Design and Installation	$18,750	$37,500	$42,500
Annual Maintenance	$225	$450	$600
Term Value (30-yr annualized)	$1491	$1,382	$785

Table 14. Catchment 4 - Existing Treatment (6.42 Lbs TP)

Existing Watershed Load (13.07 Lbs TP)	Level 1 TP Treatment: 20% TP Reduction (5 BMPs, 1.34 Lbs TP)	Level 2 TP Treatment: 40% TP Reduction (11 BMPs, 2.64 Lbs TP)	Level 3 TP Treatment: Pond 04020202 Level 1 plus Catchment 4 Level 1 (4.63 Lbs TP)
Design and Installation	$31,250	$68,750	$73,750
Annual Maintenance	$375	$825	$975
Term Value (30-yr annualized)	$1,057	$1,181	$749

4.3.2 Agricultural Areas

The remaining agricultural land use on the north and northwestern side of Artic Lake has opportunities for the stabilization of soils and filtration of surface runoff that should be considered. Given that the forecasted future land use for this area is low-density residential, recommendations for stormwater treatment are also provided.

4.3.2.1 Vegetated Swale

An existing drainage within the agricultural field northwest of Arctic Lake is suited for the establishment of a vegetated swale (Site 14, Figure 18, Appendix 6.1.4). Dense cover of non-clump forming native grass slows runoff causing sediment to fall from suspension as well as acting as a filter. In addition, their dense and extensive root zone improves the infiltration capacity of soils thereby reducing water volume and dissolved nutrient delivery to receiving water bodies. The vegetation should extend from the head of the drainage flow to the existing vegetated buffer along the wetland fringe of the lake.

Table 15. Swale treatment options

Existing Load 20.00 LB-TP/YR	Level 1 TP Treatment: Vegetated swale (3.11 LBS-TP/YR)	Level 2 TP Treatment: Level 1 plus 1000 ft^2 basin (2-ft storage) and 6-in standpipe (4.20 LBS-TP/YR)
Design and Installation	$2000	$3000
Annual Maintenance	$125	$150
Term Value (30-yr annualized)	$61.63	$59.52

4.3.2.2 Sediment Basin

A major gulley within the wooded windrow of the northern agricultural field is fed by hydrology that can be captured and metered via the use of a sedimentation basin at its head (Site 15, Figure 18, Appendix 6.1.4). A slight re-grading of the upland area to create a berm as well as the provision of a perforate stand pipe can be used to allow fallout of sediment and associated nutrients as well as provide the required attenuated flows for gulley stabilization. This system can also use conservation drainage practices (described below) to maintain optimal soil moisture of the root zone within the newly created basin.

Table 16. Sediment basin treatment options

Existing Load	Level 1 TP Treatment: Berm and stand pipe (1 LB)
Design and Installation	$7500
Annual Maintenance	$75
Term Value (30-yr annualized)	$325

4.3.3 Wetland Restoration

A somewhat rare opportunity exists to restore the hydrology and vegetation within the currently drained wetland, west of the Lake. The 50-acre area was drained prior to 1936 (likely near the turn of the 20th century) with a ditch that runs through a perpendicular levee via two culverts (Site 4, Figure 18, Appendix 6.1.4). A simple modification of these culverts can provide hydraulic control of the wetland to provide new storage. Scott County Parks plans on establishing a new walking path on top of the levee where an IESF could be included to receive primary overflow from the wetland. This filter would strip an estimated 85% dissolved-TP from the wetland effluent before passing its runoff to the culverts leading to Arctic Lake. The combined particulate and dissolved TP treatment would likely approach 90% for all waters coming to and leaving the wetland. Considering that this area makes up 2/3rds of the entire Arctic Lake subwatershed, and observed flow concentrations from the wetland are high in spring setting the stage for increased epilimnion loads, this proposed subwatershed modification is attractive. This simple and inexpensive solution also provides the added benefits associated with wetland restoration (i.e., habitat restoration and aesthetic enhancement).

Table 17. Wetland BMP options

Existing Load 21.92 LB-TP/YR	Level 1 TP Treatment: Box spillway at culvert (6.41 LB-TP/YR)	Level 2 TP Treatment: Gate-controlled spillway at culvert (6.41 LB-TP/YR)	Level 3 TP Treatment: Level 2 plus IESF (1,000ft²) (19.70 LB-TP/YR)
Design and Installation	$2000	$13,800	$23,800
Annual Maintenance	$75	$25	$125
Term Value (30-yr annualized)	$22.10	$75.66	$46.62

4.3.4 Gully Stabilization

Several gullies exist within the Arctic Lake subwatershed (Figure 3). The gullies located in catchments 6-11 drain to the wetland west of Arctic Lake and are in varying degrees of stability. As discussed earlier, the gulley draining the shallow lake within catchment 9 appears to flow infrequently and with little intensity when compared to those within catchments to its south (6, 7 and 8). Catchment 11's gully, although dramatic in its historic erosion, appears to have limited erosive hydrology, currently. However, its immediate drainage area may be causing on-going erosion given the degraded conditions. All the mentioned gullies rank low on a relativistic comparison based on immediate delivery to Arctic Lake and should be considered after the more attractive strategies called out within this document.

A few gullies drain directly to Arctic Lake with little to no sediment control buffering the lake. The gully located within catchment 15's wooded shelter belt should be considered for stabilization. Similarly, City Staff noted the formation of several small gullies within catchment 5 that need further site analysis as access to these private lands was not provided during this analysis (Figure 3 and Appendix 6.1.4).

4.4 Water Quality Impacts and Opportunities – In-Lake

Current data does not definitively describe the processes driving potential internal loading nor allow a reasonable estimate of its contribution to lake nutrient dynamics. However, given what is known of internal water chemistry, the subwatershed's history of agricultural dominance for over 140 years, that carp are found in high numbers, and that no rooted plant material was detected, internal loading likely does play a significant part of Arctic's water quality behavior. The Science Museum of Minnesota is currently analyzing a sediment core sample taken in the summer of 2013. It is expected that information coming from that study will supplement this analysis when considering the question of P-availability for release as well as the likelihood its successful precipitation (e.g., via alum treatment). In addition, it would be prudent to collect at least one more season's worth of profile data, as described earlier, to identify thermocline behavior and internal loading frequency and magnitude.

Until that occurs, the recommended in lake strategy is to:

1. <u>Develop an implement an in-lake, inflow and outflow monitoring plan for both water budget and lake nutrient dynamics study</u>
   Although the existing databases provided by SMSC proved highly valuable in this analysis, a more detailed monitoring effort of water temperature and chemistry at 1 m intervals throughout the growing season would greatly strengthen the understanding of nutrient dynamics within the lake. This information could be used to calibrate the BATHTUB model used for this study to assist in modeling lake responses to watershed management practices. To aid this effort, inflow and outflow hydrology and water chemistry should be monitored frequently. A well designed plan that specifies materials, methods and frequency of monitoring efforts would bolster the preliminary findings of this report.

2. <u>Harvest greater than 90% of the current carp population with the aid of a partial draw down</u>
   Given the high density of carp in Arctic Lake, a focused effort on their removal, perhaps aided by a partial draw down, should reduce the extent and frequency of sediment re-suspension and promote aquatic vegetation to re-establish. This is a relatively inexpensive option when compared to many of the options identified by this study and has a strong history of success in the State. It may be necessary to perform removal activities for 2-3 years with additional efforts as needed in the future, as dictated via capture-recapture sampling population analyses.

3. Install a fish barrier at Arctic Lake's culvert located at Freemont Ave NW (Site 3, Appendix 6.1.4)
   To help ensure that carp removal efforts are sustainable, installation of a carp barrier near the outlet of the lake is vital. Inexpensive solutions abound for culvert barrier designs that can be built and installed by the Partners' Staff.

4. Consider the efficacy and costs of an alum treatment via a detailed assessment of the benthic sediments via a core analysis
   An analysis of several sediment cores can lead to a go-no-go decision to precipitate phosphorus within the lake and its sediments. There currently is one such effort underway for the lake. The results should provide insights into this potential as well as describe historic sedimentation rates within the lake that could be used to justify dredging or alum treatment within the top layer of sediment. This is typically a relatively expensive, temporary solution, but needs to be considered in light of long-term management strategies such as biomanipulation.

After these efforts are completed, the following secondary tasks should be considered:

5. Re-establish native submerged vegetation with the help of the partial draw down as well as enclosures
   To aid in the maintenance of a clear, stable state, the promotion of submerged vegetation should be considered. This relatively inexpensive strategy has many benefits that, collectively, make this a valuable solution to lake and fisheries management.
6. Re-introduce piscivorous fish
   Once carp populations are reduced to a juvenile-dominated population, piscivorous fish should be reintroduced, monitored, managed and supplemented to ensure a balanced age-class population. This is a relatively inexpensive strategy that needs further assessment of potential efficacy before implementation.

Although several other alternatives were considered for Arctic Lake, either the impracticality, uncertainty and risks deemed them unfavorable. Given the minimal flow to the Lake and that it drains to an impaired water body, flushing or complete draw down are inadvisable. Any form of dredging is either going to be impractical or far too expensive. Barley straw tends work well in smaller lakes or ponds and the mechanisms of its TP removal are not yet fully understood, mostly theoretical.

Table 18. Estimated in-lake treatment costs

Strategy	**Estimated Cost**	**Notes**
Carp Harvest	$5000-$7000	Local commercial fisherman ($0.20/LB @ 20,000 LBS catch)
Culvert Fish Barrier	$100-$1500	A simple fish gate within a culvert (see http://www.seagrant.umn.edu/downloads/biocontrol/Integrated_Pest_Management_of_Invasive_Fish-Peter_Sorensen.pdf for an example of a very simple design; Przemyslaw Bajer, PhD, University of Minnesota, 612-626-4964)
Alum Treatment	$350,000-$700,000	Feasibility, design, dosing (Spring Lake Case Study: sediment coring, dosing map, community engagement = $18,000; bidding and oversight = $20,000; $1.50/gallon of Alum @ ~600,000 gallons)

5 References

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McComas, S. and J. Stuckert, 2012c. *Lake Sediment Fertility Assessment for Arctic Lake, Scott County, Minnesota*

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Spring/Upper Prior TMDL, 2011. MPCA. http://www.pca.state.mn.us/index.php/water/water-types-and-programs/minnesotas-impaired-waters-and-tmdls/tmdl-projects/minnesota-river-basin-tmdl/project-upper-prior-spring-lakes-excess-nutrients.html

UMNRSL, 2013, University of Minnesota's (UMN) remote sensing lab's Lake Browser (http://water.umn.edu/lakebrows.html)

6 Appendices

6.1 Appendix A - Existing Data Review

6.1.1 Precipitation and Lake Level

Figure 15. Precipitation, lake level and outlet elevation for the period 2004-2006

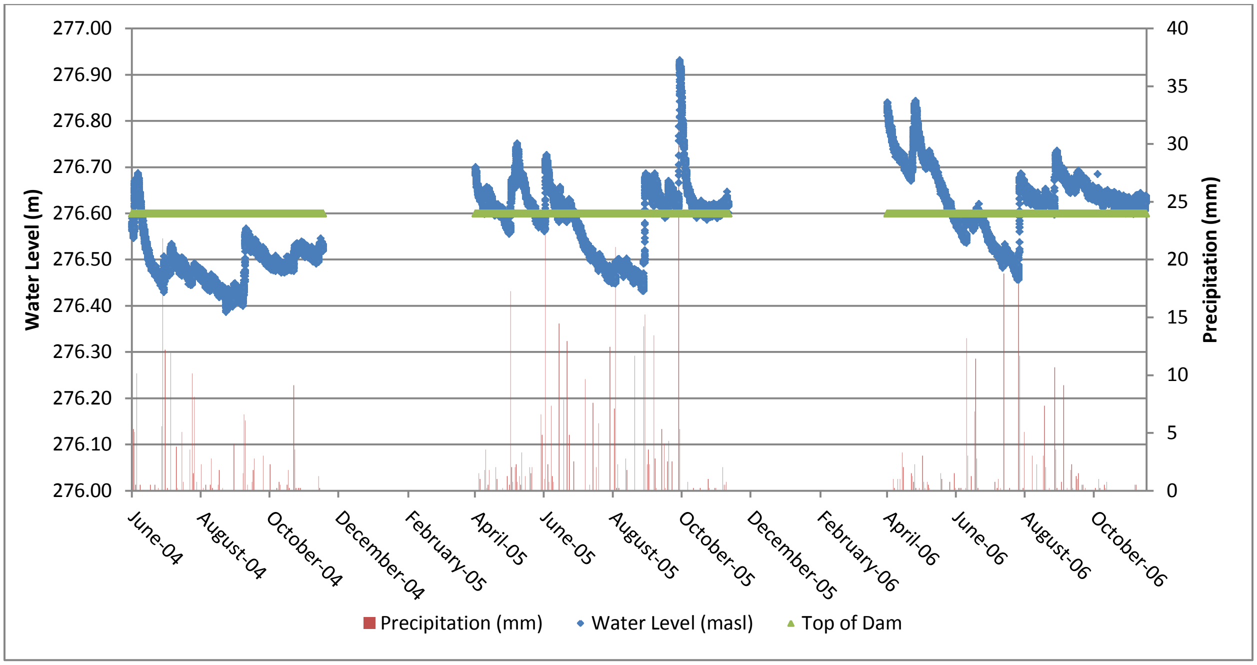


Figure 16. Precipitation, lake level and outlet elevation for the period 2007-2009

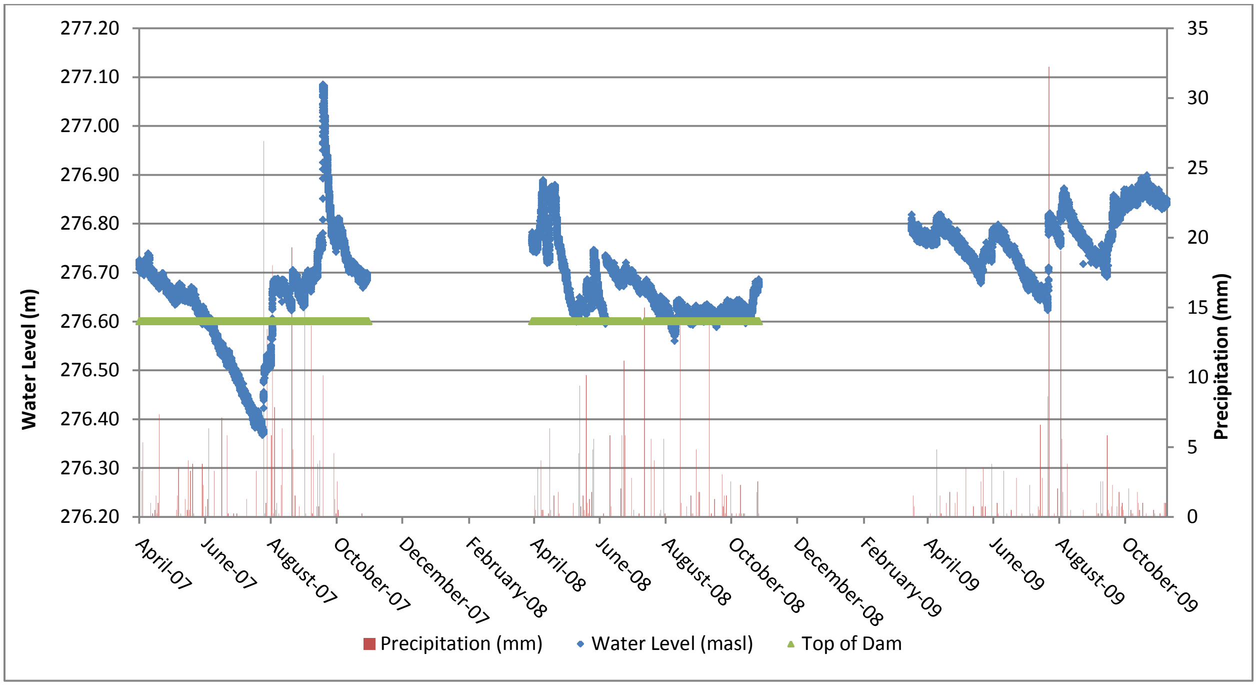
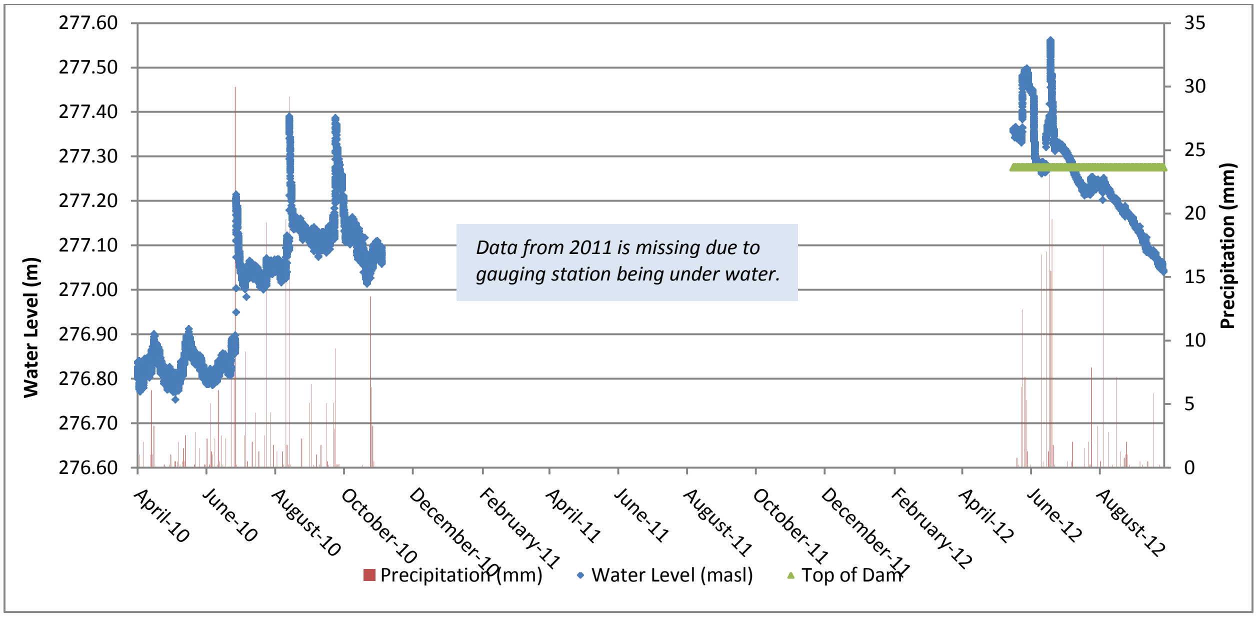


Figure 17. Precipitation, lake level and outlet elevation for the period 2010-2012



6.1.2 Lake water quality

Table 19. SMSC water quality sample metadata

	W. Arctic	*C. Arctic (top)*	*C. Arctic*	*C. Arctic (deep)*	*C. Arctic (bottom)*	*E. Arctic*	*E. Arctic (bottom)*
Sampling Events	2	26	25	25	23	112	6
Dates	1999	1999-2003	2004-2006	2000-2003	2004-2006	1999-2012	2007
Ave. Sample Depth (m)	0.7	1.2	0.9	2.9	2.3	1.0	7.1
Bottom Depth (m)	1.6-3.2	Most < 4	Most < 3	Most < 3	Most < 3	Most 6-9	6.1-7.9

Table 20. SMSC lake water quality parameter sample sizes by monitoring station

Parameter	*C. Arctic (surface)*	*C. Arctic (bottom)*	*E. Arctic (surface)*	*E. Arctic (bottom)*
Collection Dates	1999-2006	2000-2006	1999-2012	2007
Secchi Depth	47	39	101	6
Water Temperature	8	7	80	6
Chloride	0	0	51	0
Chlorophyll a	48	48	98	6
Nitrogen: Ammonia-	46	44	112	6
Nitrogen: Diss. Kjeldahl	3	4	0	0
Nitrogen: Nitrate/Nitrite	50	48	112	6
Nitrogen: Total Kjeldahl	48	48	110	5
Phosphprus: Ortho-P	50	48	112	6
Phosphprus: TP	48	48	110	6
Sodium	0	0	50	0
Solids: TSS	24	23	98	6

Figure 18. Surface (S) and Deep (D) water temperatures (Celsius) in Arctic Lake at East Arctic sampling site

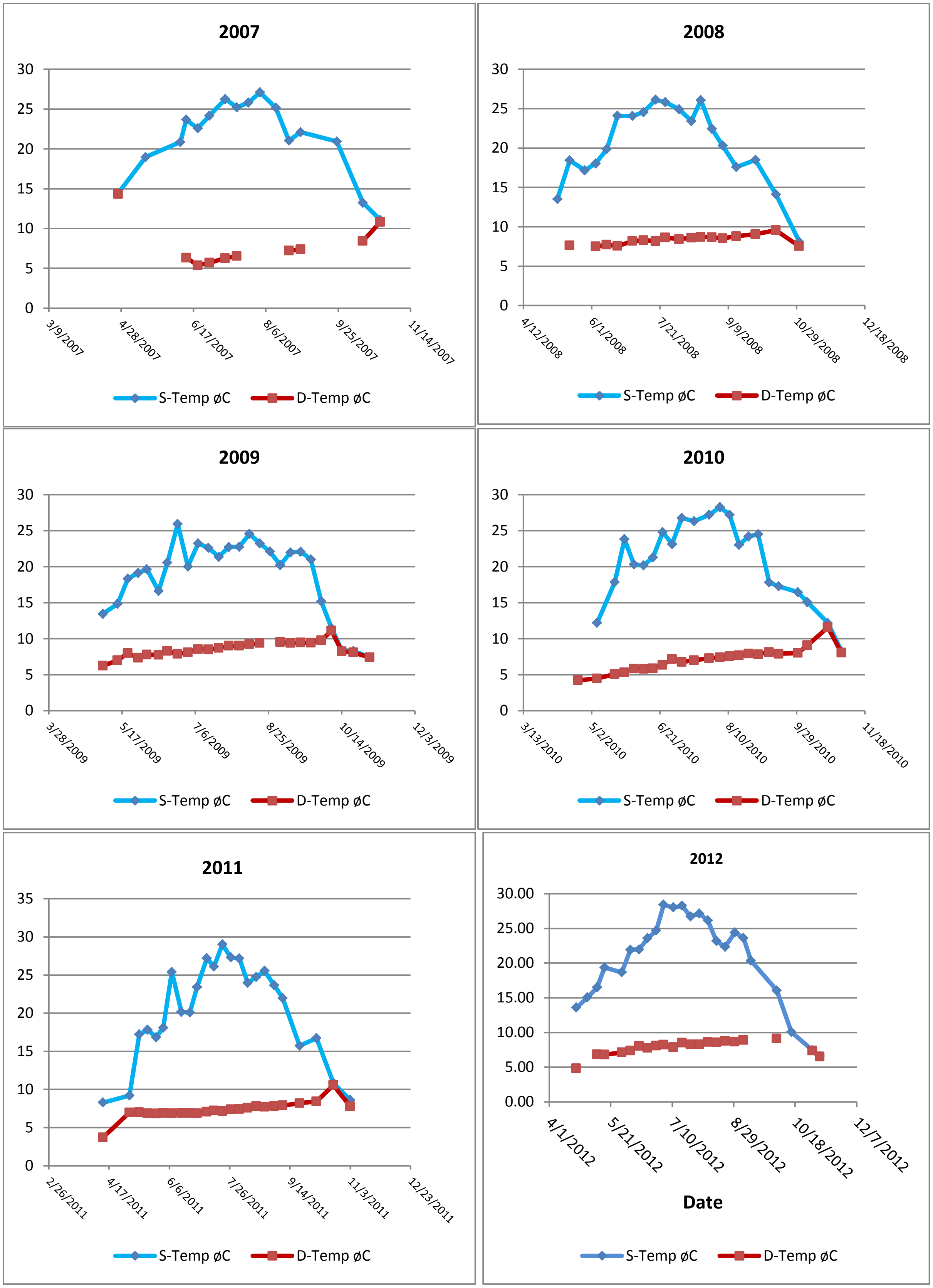
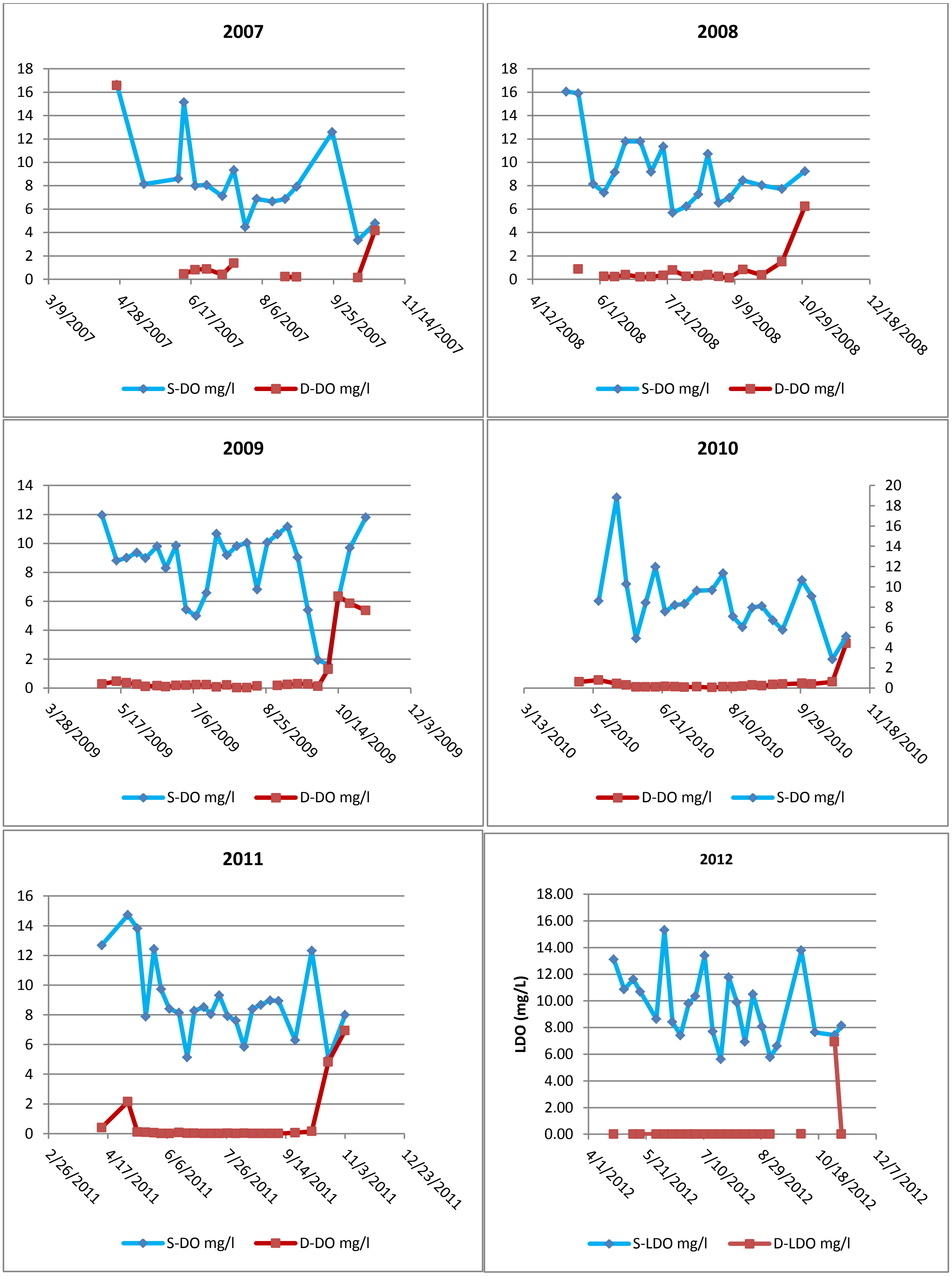


Figure 19. Surface (S) and Deep (D) dissolved oxygen (mg/L) in Arctic Lake at East Arctic sampling site



6.1.3 Watershed loading

Table 21. WinSLAMM settings used within urbanized landscapes of the Arctic Lake subwatershed

Data Type	*WINSLAMM Source File*
Pollutant Probability File	WI_GEO02
Runoff Coefficient File	WI_SL06 Dec06
Particulate Solids Concentration File	WI_AVG01
Street Delivery Files:	
Residential Land Use	WI_Res and Other Urban Dec06
Other Urban Land Use	WI_Res and Other Urban Dec06
Institutional Land Use	WI_Com Inst Indust Dec06
Commercial Land Use	WI_Com Inst Indust Dec06
Industrial Land Use	WI_Com Inst Indust Dec06
Freeways	Freeway Dec06

6.1.4 Potential BMP Locations

Figure 20. Sites of proposed BMPs