Storm Water Management Prioritization for the Watershed of Lake Windsor
Minnetonka, MN

Prepared by

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1- Introduction

1.1 Project Overview

The purpose of this report is to prioritize and investigate the most effective and cost sensitive methods of decreasing the quantity, and increasing the quality, of stormwater runoff to Windsor Lake in Minnetonka, MN. Specifically, the reduction of total suspended solids, phosphorus, and peak discharge values to the lake will be taken into consideration.

In order to achieve this prioritization, research into stormwater treatment and management methods was undertaken. Computer models were also built to simulate the effectiveness of these methods on the actual watershed.

Windsor Lake and its contributing watersheds are located entirely within the city limits of the city of Minnetonka, MN. The lake has a surface area of approximately 7 acres, with the contributing watershed totaling an area of approximately 198 acres. These watersheds are part of the larger Minnehaha Creek Watershed District (see *Figure 1*) Windsor Lake is considered by the city of Minnetonka and the Minnehaha Creek Watershed District to be at Level III lake, with a goal of supporting wildlife and waterfowl. However, Windsor Lake does not meet all the requirements to be classified as a Level III lake. (Barr Engineering Water Quality Study) The Minnesota Pollution Control Agency also assessed the lake in 2007 and found it to be impaired because of “the presence of nutrients such as phosphorus”. (MPCA) In 2011, the lake also received a grade of F (on an A-F scale) from the Minnehaha Creek Watershed District, ranking it in the lowest 10% for water quality relative to lakes in the area.

As a result of the impairments to Lake Windsor, recreation such as fishing and boating is not suggested by the MPCA. It is therefore desirable to investigate improving the quality of runoff to the lake. A TMDL for the lake is scheduled to be completed by the MPCA in the year 2017. Until then, preliminary steps may still be taken in order to achieve a reduction in desired pollutants.

The sub-watersheds draining into Lake Windsor are located in a primarily residential area. Medium density lots ranging in size from 1/3 to 1/2 acre in size are accompanied by wetlands and at least one large parking lot area. There is also an extensive stormwater conveyance system already in place in the watershed.

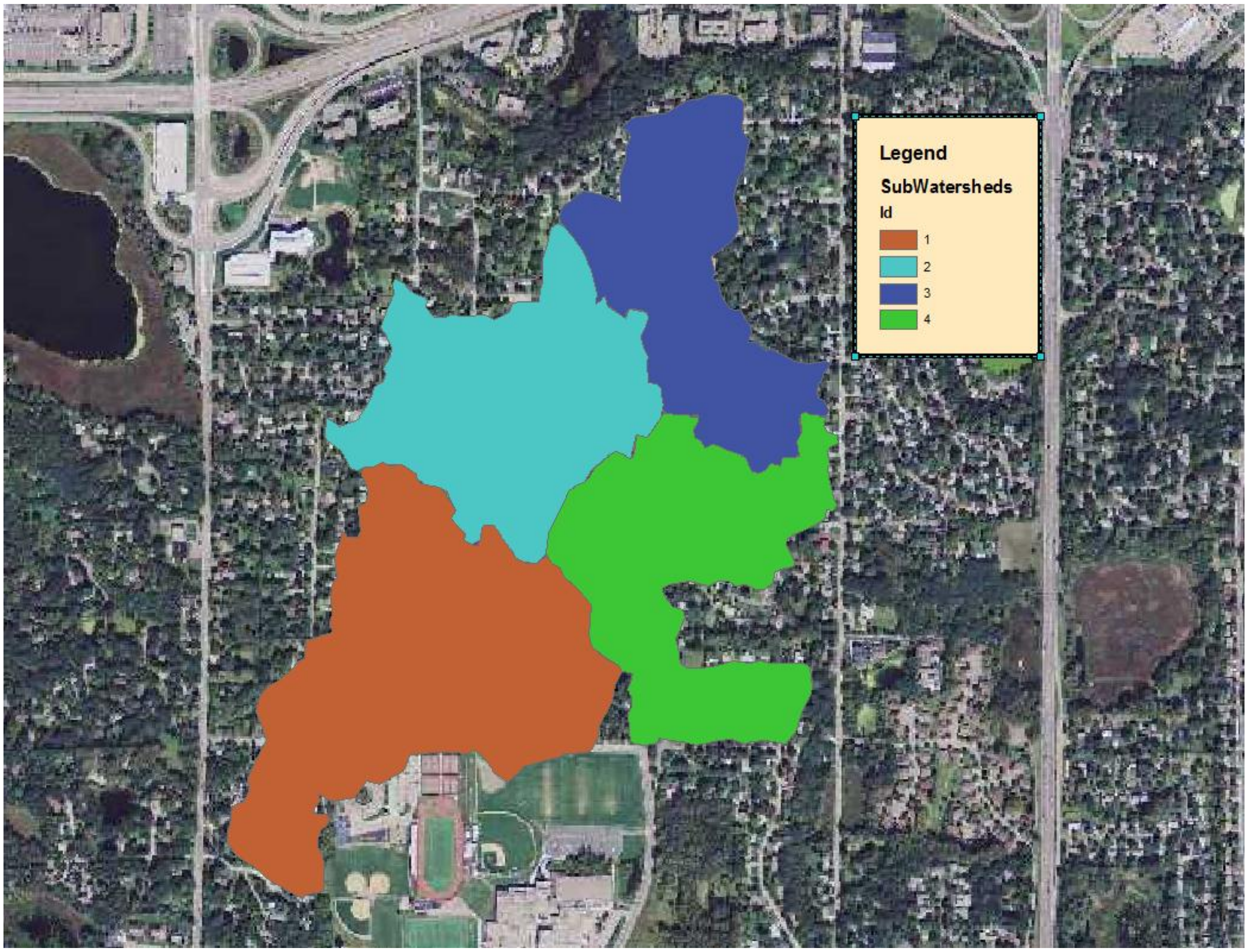

Figure 1: Map of Windsor Lake Subwatersheds (Minnetonka GIS Data, 2013)

2 – Methods

2.1 – Traditional BMPs

The following section investigates the costs and effectiveness of six different stormwater best management practices (BMPs) which have been traditionally used in stormwater treatment. This section considers dry detention basins, wet retention basins, sand filters, bio-retention filters, constructed wetlands, and infiltration trenches. The purpose of this analysis is to produce a metric that allows comparison between these traditional stormwater treatment practices and other proposed practices in this paper.

2.1.1 Water Quality Volume

The process of determining costs and effectiveness of the six stormwater treatment practices in this section, was laid out by Weiss, et al. (2007). The first step in this process is to determine the Water Quality Volume (WQV) of the Lake Windsor Watershed. This was done by using the following set of equations.

$$WQV = 100 * P * R_v * A$$

P = design rainfall precipitation depth (cm)
R_v = ratio of runoff to rainfall in the watershed
A = watershed area (ha)

$$R_v = 0.05 + 0.009 * (I)$$

I = percent (0-100) of the watershed that is impervious

The design rainfall used was determined to be 1.15 in. or 2.92 cm, which is the suggested MPCA design storm. The percent impervious for the Lake Windsor Watershed was estimated using GIS data, and was found to be approximately 29.5%.

Using this WQV, project costs, and removal efficiencies can be estimated for each particular BMP to treat this entire WQV. Using this approach, the costs and removal efficiency of each BMP were calculated based on the assumption that the entire impervious area of the watershed was treated by the BMP in consideration. We are not suggesting that the entire watershed should be treated only using one type of BMP, but this method offers a useful tool for investigating the feasibility of each BMP option.

2.1.2 Total Present Cost

Equations and figures are presented in Weiss, et al. (2007) that can be used to determine the cost of each stormwater practice for construction and maintenance. First the unit costs of construction for each stormwater practice were developed. The total present construction cost was then determined by multiplying the unit construction cost of the practice by the WQV of the watershed. Operation and maintenance costs, as a percentage of construction costs, were then determined for each stormwater management practice. These costs were then calculated for 20 years and properly adjusted to represent the present value. These two costs were then summed to determine the average total present cost of construction and operation and maintenance for 20 years.

This process was completed for four sub-watersheds. We divided the watershed to create four smaller WQV's that more closely matched the WQV's used to determine the pricing data in the paper. Once the costs were determined for each practice in each sub-watershed, the costs were totaled. For example the total wet basin cost is the sum of the wet basin costs of treating the WQVs of Area 1, Area 2, Area 3, and Area 4.

This average present value cost was created for 2005, so an average inflation rate over the past 8 years of 2.7% (Bureau of Labor Statistics) was used to adjust to 2013 costs. The results of these calculations are shown in Table 2.1.2a.

Table 2.1.2a: Average Present Value Construction, and 20 Year Operation/Maintenance Costs(2013 dollars)

Average Present Value Construction, and 20 year Operation/Maintenance Costs			
BMP	**Average Present Cost**	**Upper 67% CI**	**Lower 67% CI**
Dry Basin	$ 743,421	$ 1,551,775	$ 423,464
Wet Basin	$ 1,019,382	$ 1,698,863	$ 674,476
Sand Filters	$ 2,642,762	$ 5,937,720	$ 1,478,711
Bio-Infiltration Basins	$ 2,606,172	$ 4,352,287	$ 1,843,933
Wetland	$ 523,156	$ 1,035,178	$ 300,993
Infiltration Trenches	$ 5,148,509	$ 9,295,855	$ 3,263,561

(Note: CI = Confidence Interval)

The costs in Table 2.1.2a do not account for the price of the land needed for these practices. Weiss et al. (2007), includes a table that lists the average size of each practice based on the area of impervious land in the watershed. Using this table the necessary areas of each stormwater management practice were determined. Each BMP area was determined assuming that the practice(s) would be designed to treat the entire watershed. It is an unrealistic assumption for a bioretention filter to treat the entire 198 acre watershed, but the areas shown in Table 2.2 can be considered as the sum of the areas of practices necessary to treat the water. Next, it was found that in 2012, the average market value per acre of green area in Minnetonka was $75,000 (Minnesota Land Economics, 2013). Using this value multiplied by the average area needed for each practice the price for the land required was determined and shown in Table 2.1.2b. In the case of a range being given for the BMP area the highest value was used for a conservative estimate. The total cost for each practice was then calculated by summing the construction, operation, and maintenance costs with the land costs, and shown in Table 2.1.2c.

Table 2.1.2b: Average BMP Size and Land Prices for Lake Windsor Watershed

BMP	BMP Area (acres)	BMP Land Cost
Dry Basin	3.96	$297,315.00
Wet Basin	1.75	$131,391.59
Sand Filter	1.75	$131,391.59
Bio-Infiltration Basins	2.92	$218,985.98
Wetland	2.92	$218,985.98
Infiltration Trenches	1.75	$131,391.59

Table 2.1.2c: Total Present Cost (2013 dollars)

Total Present Cost			
BMP	**Average Present Cost**	**Upper 67% CI**	**Lower 67% CI**
Dry Basin	$ 1,040,736	$ 1,849,090	$ 720,779
Wet Basin	$ 1,150,774	$ 1,830,255	$ 805,868
Sand Filters	$ 2,774,154	$ 6,069,111	$ 1,610,103
Bio-Infiltration Basins	$ 2,825,158	$ 4,571,273	$ 2,062,919
Wetland	$ 742,142	$ 1,254,164	$ 519,979
Infiltration Trenches	$ 5,279,901	$ 9,427,247	$ 3,394,953

(Note: CI = Confidence Interval)

2.1.3 Removal Loads

The next step in creating a metric to compare these BMPs is estimating the 20 year removals of the pollutants. This was done in Weiss et al. 2007, for a watershed in Minneapolis using an average loading rate of 131 mg/L for TSS and an average loading rate of 0.55 mg/L for phosphorus. A relationship between the WQV of a watershed and the pollutant loads was created in the paper. Using these loading rates and the known average removal efficiencies we were able to determine the 20 year pollutant removals on the Lake Windsor Watershed, which is shown in Tables 2.1.3a and 2.1.3b. Keep in mind that these weights correspond to the situation where the entire watershed is being treated by one practice. This does not mean that we would suggest that for this watershed, it only means that by doing this we could come up with a quantitative metric to compare each BMP for the Lake Windsor watershed.

Table 2.1.3a: Estimated 20 Year TSS Load Removed

Estimated 20 Year TSS Load Removed			
BMP	**Average TSS Removed (lb)**	**Upper 67% CI**	**Lower 67% CI**
Dry Basin	447517	739567	155467
Wet Basin	548123	889011	207235
Sand Filter	690241	976105	404540
Bio-Infiltration Basins	719381	1002641	435959
Wetland	574170	874848	273329
Infiltration Trenches	804033	1109107	498797

(Note: CI=Confidence Interval)

Table 2.1.3b: Estimated 20 Year Phosphorus Load Removed

Estimated 20 Year Phosphorus Load Removed			
BMP	**Average P Removed (lb)**	**Upper 67% CI**	**Lower 67% CI**
Dry Basin	833	1537	104
Wet Basin	1693	3021	365
Sand Filter	1485	2683	313
Bio-Infiltration Basins	2917	4819	1016
Wetland	1308	2579	130
Infiltration Trenches	2111	3883	339

(Note: CI = Confidence Interval)

2.2 – Small Scale Infiltration Basins

For the purposes of this analysis, in order to estimate the effectiveness of implementing small-scale infiltration basins (perhaps rain gardens) across the watershed, P8 modeling software was used. In the generated model, success of the infiltration elements was judged by comparing the overall TSS and phosphorus removal efficiencies of the watershed. After an analysis of the Lake Windsor watersheds, it was apparent to the engineering team that there was not enough detailed data available to accurately model the removal efficiencies of the existing system. For this reason, it was assumed in P8 that *no* other stormwater treatments were taking place besides the infiltration basins. The goal was to assess the effectiveness of these basins in treating the water *before* it came into contact with the existing treatment methods.

2.2.1-Surface Runoff

In order to simulate runoff from a watershed, P8 utilizes the SCS curve number method. In this scenario, the Lake Windsor watershed was divided into 4 subwatersheds, which were further divided in order to accurately depict the real world land uses. (*Figure 2.2.1a)* GIS data provided by the City of Minnetonka was used to assign curve numbers to each of the subwatersheds in question. Curve numbers were assigned using 'TR-55 Table 2-2a' (USDA) assuming B type soils. Weighted curve numbers for the pervious areas of the watershed were calculated based on the sub-subwatershed's land usage.

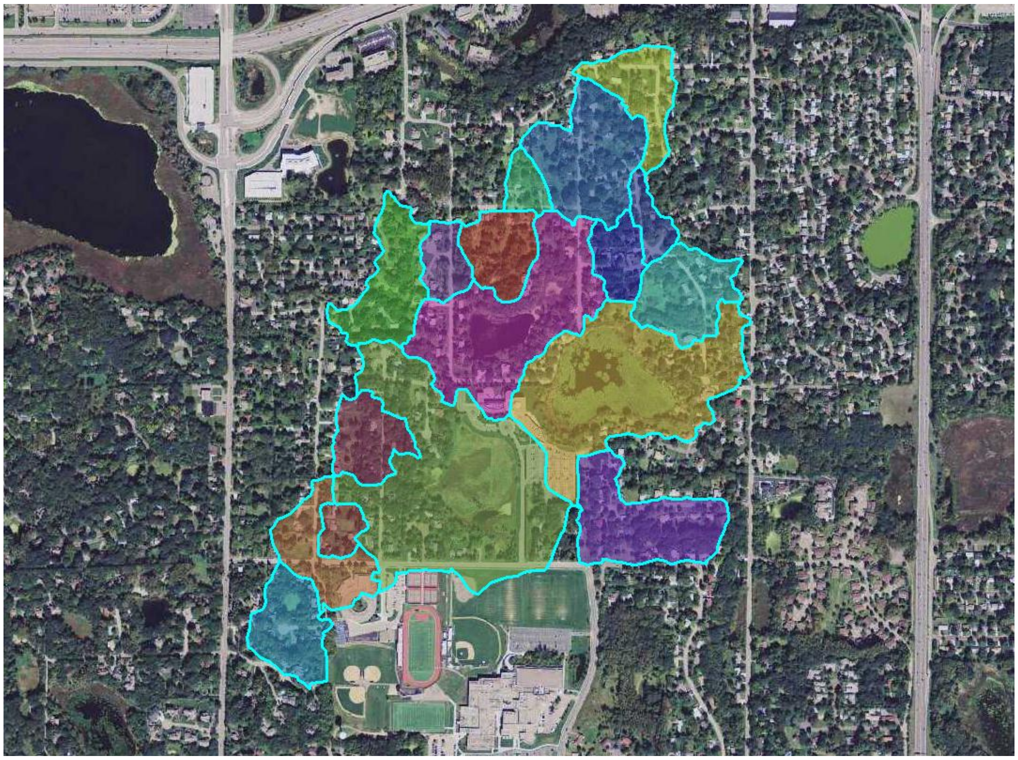

Figure 2.2.1a – Lake Windsor Sub-Subwatersheds

For each sub-subwatershed, a small portion of the total area was diverted and assumed to flow directly and completely to the modeled infiltration basins. To find this small area, first the total directly connected impervious area was determined by using the Sutherland equation for finding directly connected impervious area, or DCIA (Sutherland), assuming that the area is *highly connected*.

$$DCIA\ (\%\ of\ watershed) = 0.4 * (\%\ of\ Watershed\ is\ impervious)^{1.2}$$

With this equation, approximate total impervious areas were computed using the TR-55 table 2-2a values for average impervious areas in urban settings, based on lot sizes in that sub-subwatershed. The area to be diverted is then found by:

$$RR = DCIA - (\%\ of\ sub\ subwatershed\ made\ up\ of\ street)$$

If RR ever came to be less than 0, the value was assumed to be 1%.

Where RR the percent of the watershed assumed to be rooftops that are directly routed to the system. In order to calculate the area of these rooftops, the total area routed to the infiltration basins per watershed, the following equation is used-

$$Inf\ Basin\ Drainage\ Area = RR * Total\ area\ of\ sub\ subwatershed$$

In P8, this *Inf Basin Drainage Area* is then the "Total Area" input value for the watershed input screen for all of the respective watershed elements that are routed to infiltration basins. The pervious area curve number is assumed to be 98 for all of these elements, as it is assumed that almost all water directly flows to the outlet. The indirectly connected impervious fraction is assumed to be 0, and the scale factor for particle loads is assumed to be 1. No vacuum sweeping is assumed, so the connected impervious fraction for not swept areas is equal to 1.

In order to calculate the respective values for the non-infiltration basin sub-subwatersheds, that is to say the ones that are considered to be not treated at all the following is used:

$$Total\ Area_{non\ infiltration} = Sub\ Subwatershed\ Area - Inf\ Basin\ Drainage\ Area$$

In order to find the respective indirectly connected impervious fraction (*ICIF*) and the connected impervious fraction (*CIF*) for these non-infiltration areas, the following equations were used.

$$ICIF = (Total\ \%\ Sub\ Subwatershed\ Impervious) - DCIA$$

The Sutherland equation assumes that the area in question is all a residential area. It does not take into account the presence of large bodies of water such as wetlands, parking lots, or lakes, which will function as directly connected features. For the purposes of this investigation, this is still a good assumption as the vast majority of the watershed in question is residential land. However, the CIF must be augmented to account for the presence of these. Since all of the rooftops are assumed to be routed to the infiltration basins, the CIF for the non-infiltration sub-subwatersheds CIF is assumed to be:

$$CIF = DCIA - RR + (\%\ of\ watershed\ is\ wetland\ or\ lake\ or\ large\ parking\ lot)$$

Depression storage for all (even infiltration basin watersheds) is assumed to be 0.02 inches, and the impervious runoff coefficient and scale factor for particle loads is assumed to be equal to 1.

Each of the 4 subwatersheds is then routed to a corresponding infiltration basin. The default NURP-50 Water Quality Component file was used for particle loading on the watershed. The temperature and precipitation files, MSP4889.tmp and msp_4989.pcp respectively, were gained from the WWWalker website. (WWWalker) The simulation was then run for a period of 1 year.

2.2.2-Infiltration Basins

In a real world implementation, small infiltration basins would be interspersed throughout the watersheds. This is difficult to model in P8. Therefore, 4 large scale infiltration basins were modeled as 5% of the size of the area that drains to them. This size is via standards put forth by the Minnesota Pollution Control Agency. (MN Stormwater Manual) This drainage area was calculated as the sum of the sub-subwatershed *Inf Basin Drainage Area*s. The basins were all assumed to have a depth of 6 inches, a void volume of 100%, and an infiltration rate of 0.2 inches per hour. Infiltration and overflow were both routed to OUT.

2.3 – Street Sweeping

Since the movement of advancing street sweeping technologies in the 1970's, street sweeping and been one of the most widely used BMP's on the market. Sweeping was first introduced simply to clean up the sand and salt used on roadways during the winter but now is being researched more intensely as not only a way to remove solids from our waterways but also phosphorous. As mentioned earlier, two of the largest problems with the Lake Windsor watershed is the excess of phosphorous and solids flowing into the lake. Currently the city of Minnetonka street sweeps only once a year in the spring. With the emergence of new street sweeping technologies, the analysis of the efficiencies and cost is appropriate to see if street sweeping is a viable option/solution for the Lake Windsor watershed.

2.3.1 – Previous Study Analysis

Three different studies where analyzed while considering the effectiveness of street sweeping for this project. The studies considered were pilot studies performed in San Diego, California; Prior Lake, Minnesota; and the Ramsey-Washington Metro Watershed District (RWMWD).

The study conducted in San Diego, CA consisted of four phases. These four phases included (I) sweeping frequency, (II) machine technology, (III) median sweeping, and (IV) speed efficiency. The cities main goal is to optimize the cost-effectiveness of its street sweeping practices using these four phases (Brown, 2012). From this study the main goal is to figure out which type of sweeper works the best based purely off performance between mechanical, vacuum, and regenerative-air sweepers.

For the Prior Lake study, the goal was to quantify the information as a cost per pound of phosphorous removed (Kalinosky, 2013). Phosphorous is the limiting nutrient in most freshwater systems so finding out the amount of phosphorous removed for all Minnesota bodies of water is very crucial. The Prior Lake study consist of three different sweeping frequencies in three different canopy cover areas giving us a comparison for which areas should be swept more or less. This study was chosen in order to incorporate the physical characteristics of the watershed.

Finally the Ramsey-Washington Metro Watershed District study focuses on the cost effectiveness of mechanical and vacuum sweepers for multiple sweeping patterns (Schilling, 2005). The report also goes into further detail with cost analysis over the lifetime of the two machines to more accurately depict the most cost effective practice.

After gathering all the information from these reports, a cost analysis will be performed for each piece of equipment for the multiple scenarios presented in the studies. For most the information given in the reports, the total curb-length and tree canopy cover are the only characteristics of the watershed that are needed to transform the data to relate to a specific watershed. This data can then be related to the RWMWD study to give us cost predictions and efficiencies based off price for the practice. Based off the results, the plans best suited for the Lake Windsor Watershed will be recommended to the city of Minnetonka.

2.4 – Sump Retrofits

2.4.1 – Hydrodynamic Separators

Within the last 25 years, many cities, counties and watershed districts have turned to underground stormwater treatment devices to reach their goals. The standard sump (manhole) has been a key component of urban storm water management infrastructure. Sumps are placed at pipe junctions and provide access for storm sewer maintenance. Standard sumps may provide unintentional pretreatment by removing and retaining sediment from the flowing water, thereby causing sediment capture. This has implications for cleaning, which is the greatest cost in nonroutine maintenance activities (Howard et al., 2012). Standard sumps can remove sand and silt particles from stormwater, but have a high propensity for washout of the collected sediment. With appropriate maintenance these sumps may qualify as a stormwater BMP device for the removal of suspended sediment from stormwater runoff. To decrease the maintenance frequency and prevent standard sumps from becoming a source of suspended sediment under high flow conditions, a porous baffle, named the SAFL Baffle, has been designed and tested as a retrofit to the sump by Saint Anthony Falls Laboratory, University of Minnesota (Stormwater research at SAFL, 2011). The performed experiments on the SAFL Baffle indicate that with the right baffle dimensions and porosity, sediment washout from the sump at high flow rates can be almost eliminated, and removal efficiency can be significantly increased at low flow rates (Howard et. al, 2011). Figure 2.4.1a illustrates a schematic of two standard sump manholes retrofitted with SAFL Baffles. For retrofit projects like the current study, the cost of SAFL Baffle and its installation will be between $3,000 and $5,000depending on the SAFL Baffle model (Upstream Technologies, Inc.).

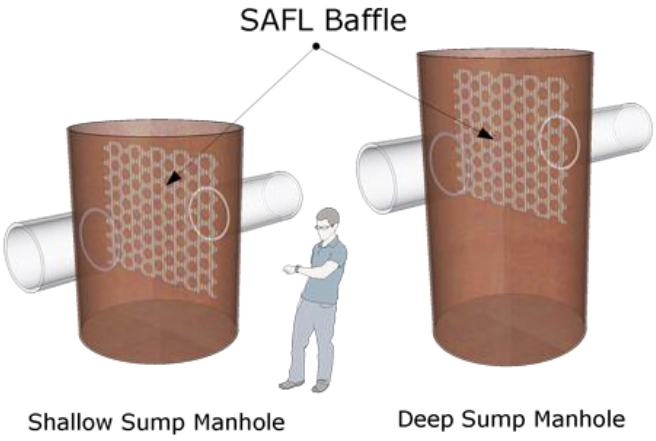

Figure 2.4.1a: A schematic of two standard sump manholes retrofitted with SAFL Baffles. Left - A 6-ft diameter and 3-ft deep "shallow" sump; Right - A 6-ft diameter and 6-ft deep "deep" sump. (Upstream Technologies, Inc., http://www.revolutionarybaffle.com)

2.4.2 – SHSAM Modeling

SHSAM is a computer program written by Barr engineering Company to predict the amount of suspended sediments removed from stormwater runoff by a given hydrodynamic separator (e.g. sump) over a period of time. SHSAM is comprised of a simple continuous runoff model, a generic sediment removal response function and a washout function. In this project SHSAM 6.6 has been utilized to assess the performance of standard manholes in removing suspended solids form stormwater runoff and to show the effect of SAFL Baffle on increasing this removal efficiency. Subwatershed 266 that is discharged to Windsor Lake is considered as a representative subwatershed for modeling by SHSAM. The area of the subwatershed is 41.7 acres. Other characteristics of this subwatershed have been extracted from GIS layers or relevant references and listed below.

The curve number (CN) used in SHSAM should represent the average CN of the pervious areas and the disconnected impervious areas of the drainage basin. Considering the land use of the subwatershed and lot sizes (0.5 acre) the average CN is assumed as 70 (NRCS, 1986). The percent imperviousness should represent the connected impervious areas of the drainage basin. Assuming that all the streets and parking lots in the subwatershed 266 are directly connected to storm sewers, the connected impervious area will be approximately 27 percent. As the topographic data are not available, watershed is assumed to have a squared shape and the water travels through its diagonal. Therefore, the hydraulic length of the subwatershed can be found as: Hydraulic length= Length of the diagonal of watershed = $\sqrt{2A} = 1906\,ft$

The average slope of the subwatershed is assumed equal to 0.5%. The input precipitation data should be based on the NCDC 15-minute precipitation data. In this study, precipitation data from Golden Valley, MN weather station for years 1995-2007 have been used. SHSAM either uses a 68 ˚F (20 ˚C) for calculating the settling velocities of the particles or the daily water temperature data at that location. Since stormwater temperature is relatively similar to daily air temperature, daily air temperature data for St. Paul, MN in the period of 1991-2007 have been used in this study. SHSAM uses a constant influent concentration for all storms and throughout each storm. So the influent concentration of suspended sediments for the study area is considered equal to 184 mg/L (Gulliver and Anderson, 2008).

In this project the effect of particle size distribution on TSS removal efficiency of sumps has been assessed by using three different distributions for particle sizes: (1)National Urban Runoff Program- NURP (U.S. EPA 1986), (2) The New Jersey Corporation for Advanced Technology (NJCAT), and (3) The particle size distribution reported by Sansalone et al. (1998). The three distributions are shown in Figure 2.4.2a. All of the particles have been considered to be inorganic with a specific gravity of 2.65.

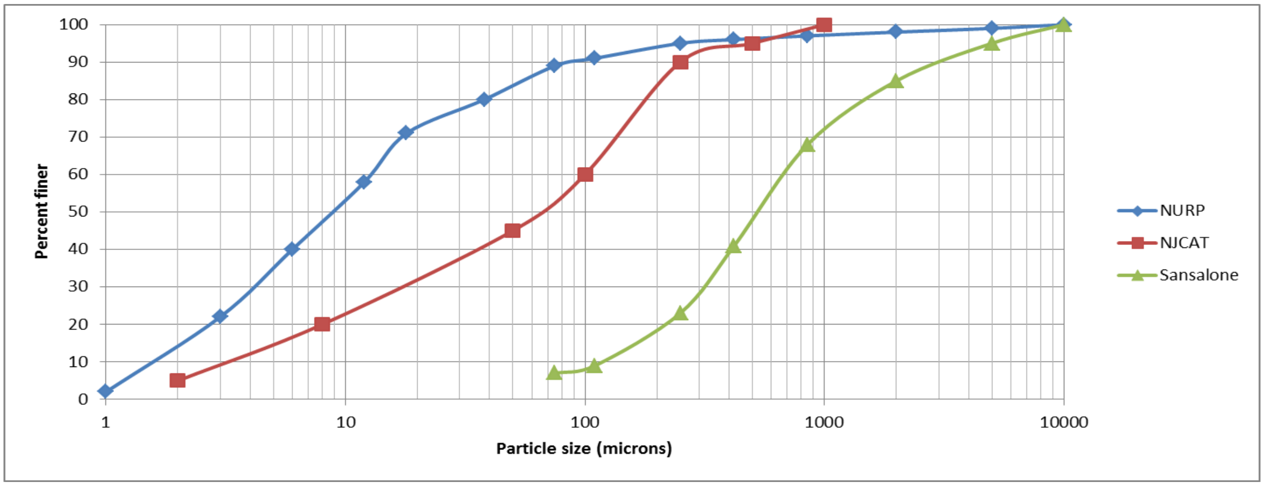

Figure 2.4.2a: Comparison of particle size distributions- NURP (U.S. EPA 1986) and Sansalone et al. (1998)

Modeling has been performed for standard sumps (with and without SAFL Baffle) and with different assumptions of particle size distribution and sump cleaning frequency in 9 cases as following:

Case a: Standard sumps, NURP particle size distribution, sump cleaning frequency of once a year

Case b: Standard sumps, NURP particle size distribution, sump cleaning frequency will be determined by the program

Case c: Standard sumps, Sansalone particle size distribution, sump cleaning frequency of once a year

Case d: Standard sumps, Sansalone particle size distribution, sump cleaning frequency will be determined by the program

Case e: Standard sumps with SAFLE Baffle, NURP particle size distribution, sump cleaning frequency of once a year

Case f: Standard sumps with SAFLE Baffle, NURP particle size distribution, sump cleaning frequency will be determined by the program

Case g: Standard sumps with SAFLE Baffle, Sansalone particle size distribution, sump cleaning frequency of once a year

Case h: Standard sumps with SAFLE Baffle, Sansalone particle size distribution, sump cleaning frequency will be determined by the program

Case i: Standard sumps with SAFLE Baffle, NJCAT particle size distribution, sump cleaning frequency of once a year

In cases a, c, e, g, and i, it is assumed that the sumps will be cleaned once a year. In the other cases, the program will keep track of number of sump cleanings per year.

3 – Results

3.1 – Traditional BMPs

3.1.1 - Average Cost-Effectiveness of BMPs

Using the data calculated in section 2.1, we were able to take the average 20 year cost of each practice and divide it by the average 20 year removal load to come up with a quantitative metric to compare the BMPs. This was necessary not only to compare the BMPs covered in this section, but also to relate it to the other BMPs included in this paper.

This section determined the cost per lb. of pollutant removed using a method borrowed from Weiss et al. (2007). As shown by the confidence intervals for both the pollutant removals and BMP prices, there is a high variability involved when estimating these values. This variability is inherent and must be considered when comparing the effectiveness of each BMP, but we found that this was the most appropriate method available to compare the effectiveness of each BMP. Table 3.1.1a offers a comparison of each BMP considered in this section of the report, but it will also be used to compare the effectiveness of each BMP to street sweeping and SAFL Baffles.

Table 3.1.1a: Average Cost per Pound of Pollutant Removed

BMP	Average Cost per lb. TSS Removed	Average Cost per lb. Phosphorus Removed
Dry Basin	$2.33	$2,218
Wet Basin	$2.10	$1,081
Sand Filters	$4.02	$4,088
Bio-Infiltration Basins	$3.93	$1,567
Wetland	$1.29	$959
Infiltration Trenches	$6.57	$4,465

3.2 – Small Scale Infiltration Basins

Calculation of the infiltration basin drainage area and thereby the infiltration basin sizes was completed using Microsoft Excel and can be found below in Table 3.2a:

Table 3.2a – Watershed and Basin Attributes

SWS Name	Area (ac)	Lot Size (ac)	Imp. Area (ac.)	IB Drainage Area (ac)	Inf Basin Size (ac)
WS 1					
263	8.18	0.3	2.868	0.408	0.02
264.b	8.06	0.5	3.3	0.391	0.02
264a	2.63	0.5	0.658	0.199	0.01
266	41.7	0.5	20.685	0.237	0.012
265	6.69	0.5	1.883	0.304	0.015
				Total	0.077
WS 2					
268	2.67	0.3	0.936	0.111	0.006
269-2	6.72	0.3	1.831	0.42	0.021
269-1	3.89	0.3	1.486	0.034	0.002
267	9.79	0.3	3.54	0.539	0.027
269	24.31	0.3	11.165	0.913	0.046
				Total	0.101
WS 3					
270c	7.14	0.3	2.494	0.306	0.015
270a	14.29	0.3	4.864	0.745	0.037
270b	2.99	0.3	1.315	0.03	0.001
272-1	9.16	0.5	3.213	0.269	0.013
272-2	4.56	0.3	1.521	0.27	0.013
				Total	0.081
WS 4					
272a	31.81	0.3	20.705	1.694	0.085
272b	13.62	0.3	4.733	0.608	0.03
				Total	0.115

After modeling the infiltration basins in P8, the overall pollutant removal efficiencies were found. The results are represented in table 3.2b.

Table 3.2b – Removal Efficiencies of Infiltration Basins

Variable	OVERALL (%)	Inf_basin_1 (%)	Inf_basin_2 (%)	Inf_basin_3 (%)	Inf_basin_4 (%)	Direct_runoff (%)
P0%	6.6	51.8	89.1	51.8	61.3	
P10%	10.1	59.3	99.6	59.2	71.6	0
P30%	11.8	78.5	99.9	78.5	86.6	0
P50%	13.1	93.1	100	93.1	96.4	0
P80%	13.6	99.4	100	99.4	99.7	0
TSS	12.4	85.9	99.9	85.9	90.8	0
TP	10	70.1	96.9	70.1	78.4	0
TKN	9.5	67.7	95.9	67.7	76.2	0
CU	10.6	77.1	97.1	77.1	83.1	0
PB	11.8	82.9	98.9	82.9	88.2	0
ZN	7.2	55.5	90.6	55.5	64.7	0

(TSS= Total Suspended Solids, TP= Total Phosphorus, TKN= Total Kjeldahl Nitrogen, CU=Copper, PB=Lead, ZN=Zinc)

The water mass balance for this same data above is represented below in table 3.2c.

Table 3.2c- Water Mass Balance

Term	Overall (ac-ft)	Inf_basin_1 (ac-ft)	Inf_basin_2 (ac-ft)	Inf_basin_3 (ac-ft)	Inf_basin_4 (ac-ft)	Direct_runoff (ac-ft)
watershed inflows	281.8	6.4	8.3	6.7	7.3	253.1
infiltrate	20.7	3.7	8.2	3.9	4.9	0
exfiltrate	20.7	3.7	8.2	3.9	4.9	0
filtered	0	0	0	0	0	0
spillway outlet	261	2.7	0.1	2.9	2.3	253.1
sedimen + decay	0	0	0	0	0	0
total inflow	281.8	6.4	8.3	6.7	7.3	253.1
surface outflow	261	2.7	0.1	2.9	2.3	253.1
groundw outflow	20.7	3.7	8.2	3.9	4.9	0
total outflow	281.8	6.4	8.3	6.7	7.3	253.1
total trapped	0	0	0	0	0	0
storage increase	0	0	0	0	0	0
mass balance check	0	0	0	0	0	0
Load Reduction %	0	0	0	0	0	0
Mass Balance Error %	0	0	0	0	0	0

When looking through this data, it is apparent that infiltration basins can be quite effective at reducing overall pollutants in stormwater. In the tested application above, 13.6% of all the runoff was infiltrated. Not only this, but an overall 12.4% reduction of TSS was achieved in the model. One of the impressive notions of this practice is that of the small need for land. A total of 0.374 acres was all that was utilized as space for infiltration basins. If it is assumed that all the infiltration basins are residential rain gardens averaging 100 ft^2, only approximately 200 of them would be necessary across the watershed.

It is of note that the infiltration drainage areas for the sub-subwatersheds 272a and 269 are quite large. Because these two areas contain large water bodies, there is most likely an overestimation of the rooftop area that is able to contribute to the infiltration basins. As a result, the results for total infiltration and for removal of pollutants will be higher than what reality may allow. However, if some of the runoff from streets or parking lots were diverted into infiltration basins as well, the difference could be easily made up.

The results of this analysis show that if a total of 7.5 acres of impervious surface were directly connected to infiltration basins totaling a surface area of approximately 0.37 acres, a sizeable reduction in TSS, phosphorus, and total hydraulic loading on the lake could be achieved.

One of the main advantages of rain gardens is that often, they are welcomed onto the properties of residents. The residents often see them as amenities to their current properties often assist in the maintenance of the implements. This may help bring down their cost and improve the public perception of them.

3.3 – Street Sweeping

After conducting a site visit, the Lake Windsor watershed was determined to have a medium canopy cover with mostly flat streets and very few hills. Using GIS data and Google Maps, the total curb-length of the water shed is equal to just about 10 miles.

From the study conducted in San Diego, the vacuum sweeper proved to be the most effective in the amount of debris captured. In phase 1 of the study the vacuum sweeper on average collected around 40 more pounds per curb-mile than the mechanical sweeper (Brown, 2012). Phase 2 concluded that on relatively flat surfaces the vacuum sweeper out preforms both the mechanical and regenerative-air sweepers, but on streets with a steep incline the mechanical sweeper performed the best (Brown, 2012). Phase 3 results showed that the amount of debris collected while sweeping the median were very similar to the amount collected while sweeping the curbside of the street (Brown, 2012). Finally phase 4 suggest that the operating speed of the machines does not change the amount of debris collected from 3 to 12 miles per hour (Brown, 2012).

The Prior Lake study results show that 15% of the total dry weight collected was organic material and contained 36% of the total phosphorous and 71% of the total nitrogen collected in the study (Kalinosky, 2013). However, during the fall organic material accounted for 36% of the total dry weight collected and contained 60% of the total phosphorous and 80% of the total nitrogen collected during that time (Kalinosky, 2013). Applying these capture percentages to the operating cost of street sweeping the study concluded that the most cost effective times for phosphorous collection are during the spring and fall seasons.

The results from the Ramsey-Washington Metro Watershed District are included in table 3.3a. As seen in the table, mechanical sweepers are cheaper to purchase but are not as cost effective and have a shorter lifespan in comparison to vacuum sweepers. Table 3.3a has been adjusted to be specific for the Lake Windsor watershed.

Table 3.3a: Street Sweeping Cost Results

Sweeper Type			Frequency ($/year)					
	Lifespan	Purchase Price	Weekly	Bi-weekly	Monthly	Quarterly	Semi-annual	Annual
Mechanical	5 years	$100,000	$22,350	$11,200	$5,200	$1,700	$900	$450
Vacuum	8 years	$200,000	$12,600	$6,300	$2,900	$1,000	$500	$250

(Schilling, 2005)

Combining the results from the Prior Lake Study and the RWMWD study, tables 3.3b and 3.3c were generated to find the cost efficiencies of mechanical and vacuum sweepers. When the initial cost of the sweeper is not considered, the vacuum sweeper is seen to be much more efficient. With the initial cost of the sweeper included it is observed that over the expected lifetime of the machine the efficiencies of the two types of sweepers produce similar results.

Table 3.3b: Cost Efficiency for Mechanical Sweeper

	Without Purchase Cost of Machine		With Purchase Cost of Machine/Expected Lifetime	
Frequency	**Cost/lbs. Dry Material/Year**	**Cost/lbs Phosphorus/Year**	**Cost/lbs. Dry Material/Year**	**Cost/lbs Phosphorus/Year**
Weekly	$0.31	$399.11	$0.58	$756.25
Bi-weekly	$0.27	$320.00	$0.74	$891.43
Monthly	$0.24	$346.67	$1.16	$1,680.00

Table 3.3c: Cost Efficiency for Vacuum Sweeper

	Without Purchase Cost of Machine		With Purchase Cost of Machine/Expected Lifetime	
Frequency	**Cost/lbs. Dry Material/Year**	**Cost/lbs Phosphorus/Year**	**Cost/lbs. Dry Material/Year**	**Cost/lbs Phosphorus/Year**
Weekly	$0.18	$225.00	$0.52	$671.43
Bi-weekly	$0.15	$180.00	$0.74	$894.29
Monthly	$0.14	$193.34	$1.28	$1,860.00

3.4 – Sump Retrofits

A summary of the results is presented in Table 3.4a. The TSS removal efficiency in sumps varies with sump model (i.e. sump dimensions). The larger dimensions, the greater removal efficiency. The results show the role of SAFL baffle in increasing the TSS removal efficiency of standard sumps. While the maximum removal efficiency of standard sump and standard sump with SAFL Baffle for NURP particle size distribution is 2.8% and 7%, respectively, this amount for Sansalone particle size distribution is 60.4% and 73.6%, respectively. NURP introduces much finer particles in comparison to Sansalone distribution. So, it is concluded that neither standard sumps nor standard sumps with SAFL baffle has a good performance in removing fine suspended sediments from runoff in the study area. However, both of them has notable removal efficiency for coarser particles and are recommended in this regard. So the result corresponding to NJCAT distribution (that is in between of NURP and Sansalone distributions) is used as an average size of sediments for final recommendations in this study. Also, the results show that sump cleaning frequency of once a year is a reasonable recommendation for the study area.

Table 3.4a: SAFL Baffle Performance Results

Modeling case	Description	TSS Removal Efficiency (%)	
		Min	Max
a	Sump , NURP , fr=1	0	2.8
b	Sump , NURP	0	2.8
c	Sump , Sansalone , fr=1	4.7	60.3
d	Sump , Sansalone	4.7	60.4
e	Sump+SAFL Baffle, NURP, fr=1	0.2	7
f	Sump+SAFL Baffle, NURP	0.2	7
g	Sump+SAFL Baffle, Sansalone, fr=1	10.6	73.4
h	Sump+SAFL Baffle, Sansalone	12.1	73.6
i	Sump+SAFL Baffle, NJCAT, fr=1	1.6	32.2

4-Conclusions and Recommendations

It is apparent looking at the water quality conditions of Windsor Lake that action needs to be taken. With the lake below standards for its Level III status, the lake becomes more of a problem to the areas residents instead of an amenity. It is therefore recommended that a mix of solutions be implemented in order to achieve maximum water quality improvements.

Currently, the City is only sweeping the streets of the watershed once a year, in the spring. It is clear from the research completed in Section 3 that *much* greater removals of phosphorus and TSS are possible with increased sweeping. It is also of note that in terms of cost per pound of pollutant removed, they are among the most cost effective. It can be seen in *Table 4.1* that in terms of TSS, street sweeping is by far the least expensive. It is also among the cheaper options in terms of cost per pound of phosphorus removed. It is therefore recommended that the City sweep all the streets of the contributing watershed bi-weekly. It can be seen in *Table 4.2* that this is the most cost effective frequency in terms of phosphorus removal. It is of note that this level of frequency is *not* the most cost effective means of sweeping for TSS. However, because phosphorus is such a concern in this particular watershed, it was given the priority. While the vacuum sweeper costs more up front than the mechanical sweeper it has numerous benefits. These benefits include a longer lifespan, reduced operating costs, and increased efficiency.

An extremely effective method of increasing TSS removal would be to introduce retrofits to the existing stormwater infrastructure. As mentioned in Section 2.4, the SAFL Baffle is capable of doubling the minimum TSS removal efficiency of existing sump manholes. The costs associated with them are also remarkably low compared to the other practices. However, there is no data on phosphorus removal improvements. Also, they have very poor removal efficiency values during high flow events. For these reasons, in order to supplement TSS removal, it is recommended that several SAFL Baffles are installed in sumps near stormwater outlets to the Lake.

As a result of the lake's poor water quality, street sweeping may not be enough to bring the pollutant levels in the lake up to an acceptable level. As can be seen in *Table 4.1*, at maximum, street sweeping would only be able to remove approximately 56 lbs of phosphorus per year. In contrast, infiltration basins have the potential to remove the *most* phosphorus. The analysis in Section 4 made note of the fact that even with a conservative implementation of infiltration basins (12.8% of total impervious draining to practices), a total phosphorus reduction of ~10% is possible. The more liberal estimate of treating all impervious areas (as talked about in Section 2), would allow for a much greater removal percentage. However, this assumption is not practical. It is therefore recommended that small scale infiltration basins such as rain gardens be implemented in residential areas across the watershed. The area of land utilized for these practices would be determined based upon how great a reduction in TSS, phosphorus, and water runoff volume was desired.

Table 4.1 – Practice Cost Effectiveness

BMP	Average ($/lb) TSS Removed	Average ($/lb) P Removed	Average TSS Removed (lb/yr)***	Average P Removed (lb/yr)***
Dry Basin	$2.33	$2,218	22,376	42
Wet Basin	$2.10	$1,081	27,406	85
Sand Filters	$4.02	$4,088	34,512	74
Bioretention Filters	$3.93	$1,567	35,969	146
Wetland	$1.29	$959	28,709	65
Infiltration Trenches	$6.57	$4,465	40,202	106
Street Sweeping*	$0.52 - $1.28	$671 - $1,860	21,790 – 72,920	15 - 56
Sump + SAFL Baffle	$0.40	NA	1,670**	NA

*Includes the cost of purchasing a street sweeper

** Per Device

***Assumes Treatment of 100% Impervious Surface

Table 4.2 – Estimated Practice Cost to Treat

BMP	Cost/Year for Lifespan	Lifespan
Dry Basin	$37,000*	20 Years**
Wet Basin	$51,000*	20 Years**
Sand Filters	$132,000*	20 Years**
Bioretention Filters	$130,000*	20 Years**
Wetland	$26,000*	20 Years**
Infiltration Trench	$257,000*	20 Years**
Street Sweeping	$35,000 – 42,000*	5 – 8 Years
Sump + SAFL Baffle (per device)	$700	20 Years

*Cost to treat 100% of impervious surface across watershed

**Costs observed over this time period

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