Source Area and Regional Storm Water Treatment Practices: Options for Achieving Phase II Retrofit Requirements in Wisconsin

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Abstract

A recently calibrated urban runoff model, the Source Loading and Management Model (SLAMM), is used to compare the cost-effectiveness of using source area and regional stormwater treatment practices. The demonstration is done for the totally urbanized Lake Wingra watershed in Madison, Wisconsin. The goal is to retrofit practices that are able to reduce the annual total suspended solids load by 40%. Model results indicate the parking lots and streets are the most important sources of total suspended solids. Practices evaluated for the parking lots include the Delaware Perimeter Sand Filter, Stormceptor, Multi-Chamber Treatment Tank, bioretention, porous pavement, and infiltration trenches. Individually they reduced the solids load to Lake Wingra by 7 to 19%. High efficiency street sweeping is projected to reduce the annual solids load by 17%.

Nine combinations of the source area practices are able to achieve the 40% reduction goal. For example, a 42% reduction in solids load to Lake Wingra is estimated for the combination of high efficiency street sweeping on all the streets and Delaware Perimeter Sand Filters on all the parking lots. Alternatively, the 40% reduction is achieved by using regional detention ponds with a total of 20 acres of permanent pool area. Many of the combinations of source area practices are more cost-effective than the regional practice. Assuming a lifespan of 20 years the annual cost of the source area practices ranges from abut $573,000 to $1,504,000, while the range for the detention ponds is $963,000 to $1,840,000. The least expensive combination of source area practices would only increase the annual stormwater utility bill for the Madison taxpayers by about $6, while the most likely detention pond alternative will increase the utility bills by about $18. Cities should consider retrofitting source area practices as a cost-effective way to meet reduction goals for total suspended solids.

Introduction

A new rule (NR151) to be administrated by the Wisconsin Department of Natural Resources (Department) contains performance standards to reduce the impacts of stormwater for both developing and established urban areas. Over 200 Wisconsin cities will be affected by the rules, because the performance standards will be in their EPA Phase II permits. Standards for the developing areas address problems of construction erosion, post-development suspended solids loads, and sustaining the natural hydrology of the watersheds. These developing areas standards should reduce the risk of any future degradation to our lakes and streams. The Department also hopes to enhance the quality of our degraded urban lakes and streams by requiring some sediment reduction in established urban areas.

Performance standards for the established areas will require the cities to reduce the annual total suspended solids (TSS) loads by 40%. The standard must be achieved by the year 2013. Since the Phase II permits will be issued in 2003, the cities will have two permit cycles to achieve the standard. Ten years seems like a long time, but the cities will need the time to implement the practices. It might take more than two years just for cities to develop their management strategies

The 40% reduction assumes no stormwater treatment practices (STPs) exist in the established urban areas. A city will receive credit for any existing STPs. Since most cities rely on street sweeping and catch basin cleaning for reducing solids loads in older neighborhoods, they will have to add more practices or completely replace their old ones to achieve the 40%. Older style broom street sweepers and catch basin cleaning is not expected to achieve more than a 20% reduction in annual suspended solids loads.

Cites will have the challenge of both determining the benefits of their existing STPs and deciding what additional practices they will need to achieve the goal. At the same time they need to select STPs that have the lowest possible capital and maintenance cost. To meet the challenge the cities will have to use urban runoff models and the latest information available on the effectiveness and cost of STPs.

Our purpose is to demonstrate the types and cost of STPs that will achieve the 40% reduction in the Lake Wingra watershed, which is an established urban area in Madison, Wisconsin. Of special interest to us is to compare the benefits of using source area STPs, such as street sweeping and filtration devices, with regional practices, such as detention ponds. An urban runoff model called Source Loading and Management Model (SLAMM) is used along with literature values for practice effectiveness and cost.

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A Description of the Lake Wingra Watershed

A lot of the information needed to complete a stormwater plan is already available for the Lake Wingra watershed. Not only has there been a lot of research completed on the lake itself, but the watershed has also been the object of two planning efforts (Univ. of WI., 1999; Dane County, 1992). Both of the plans identify sedimentation as an important issue for the lake. Both plans say that stormwater is an important source of the suspended solids load to the lake. The priority watershed plan suggests a 30 to 50% reduction in the annual suspended solids load. Neither plan did a comprehensive analysis of the alternative stormwater practices, which means they did not do a detailed comparison of source area and regional practices.

Lake Wingra is a small (325 acres), shallow, highly eutrophic lake, but its location in a highly populated urban area makes it the focus of many recreational activities. Sedimentation problems are bad enough around sewer outfalls to restrict access by boats – even canoes. Heavy weed growth in the lake also reduces the area of the lake used by canoes, sailboats, and sail boarders. Water quality problems contribute to a decline in attendance at the swimming beach, but there is still a lot of use of the beach.

The most recent landuse information is available from the City of Madison. The city has divided the watershed into eight sub-watersheds (Figure 1). Five of the sub-watersheds are highly urbanized, while two of the sub-watersheds (WI-05 and WI-08) are mostly in the University of Wisconsin arboretum. Most of this land is forest and prairie preserve managed by the university. There is almost no new construction in the watershed.

The watershed is about 3947 acres (6.2 square miles) in size (Table 1). This value does not include the area of the lake, the 210 acres of wetlands and 48 acres of ponds in the watershed. Residential is the largest landuse category in the watershed and most of it is medium density residential. Open space is the next largest landuse category at 29%, which includes the University Arboretum, golf courses, city parks, and cemeteries. About 62% of the open space is in the University Arboretum. Together the residential, open space and commercial landuses account for 92% of all the land in the watershed. Most of the commercial landuse is divided equally between shopping centers and office parks. The watershed also includes a freeway, five schools, and some light industrial sites.

Table 1. Landuse areas for the eight subwatershed in the Lake Wingra Watershed[1]

Landuse	Acres of landuse by subwatershed[2]								Watershed Total	
	WI-01	WI-02	WI-03	WI-04	WI-05	WI-06	WI-07	WI-08	Ac	%
Residential	418	829	229	31	37	43	371	11	1968	50
Institutional	0	18	63	0	0	0	0	0	81	2
Commercial	256	7	9	0	0	0	256	0	528	13
Industrial	0	0	0	0	14	0	40	0	54	1
Open	88	170	188	0	104	13	41	539	1144	29
Freeway	53	27	0	0	0	0	92	0	172	5
Total	815	1051	489	31	155	56	800	550	3947	100

1. Lake Wingra (325 ac), wetlands (210 ac) and ponds (48) are not included in landuse areas.
2. Most of WI-05 and WI-08 are in the University of Wisconsin Arboretum.

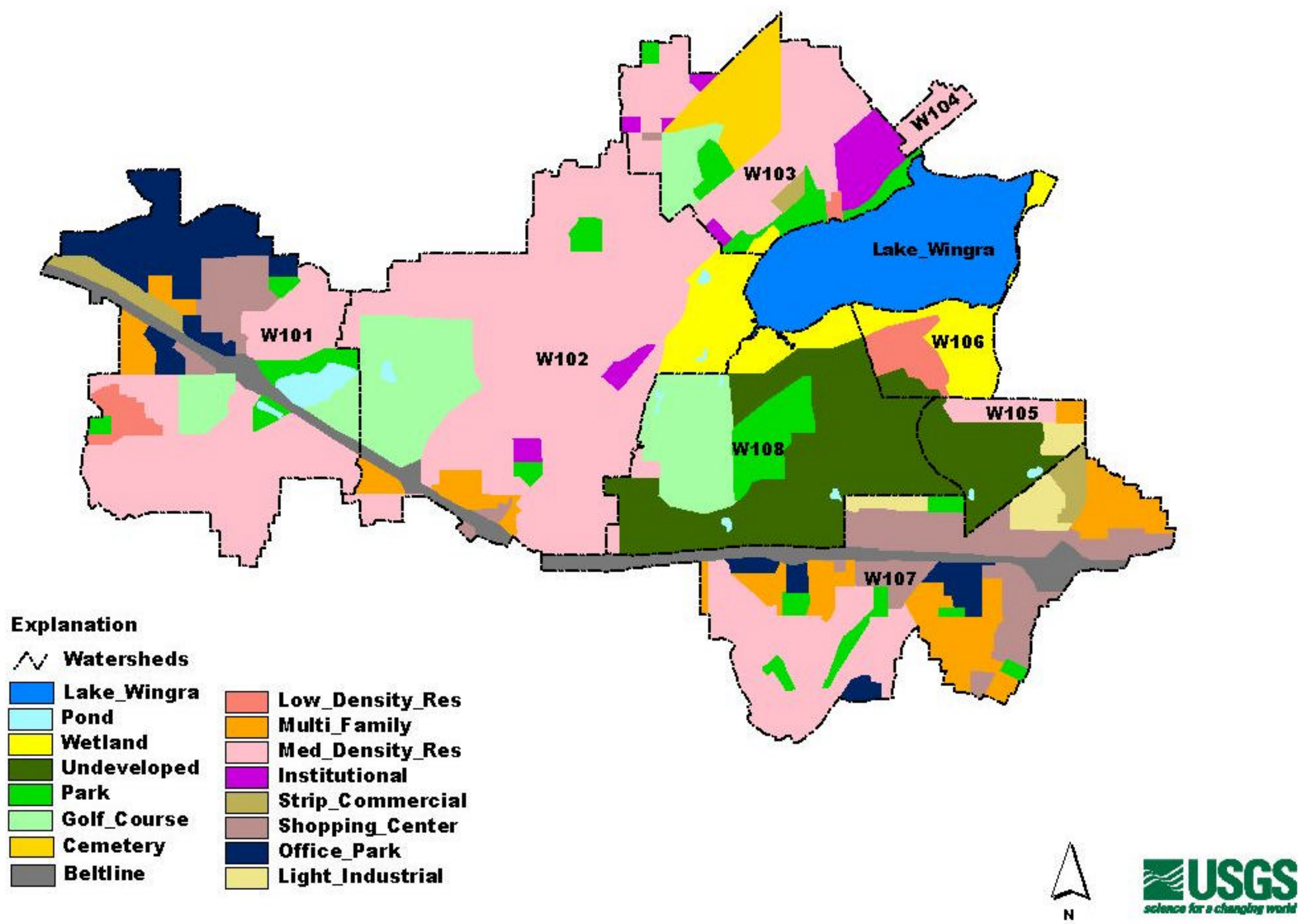

Figure 1. Distribution of landuses in the Lake Wingra watershed.

For the purpose of the demonstration, we assumed no pre-exiting practices in the Lake Wingra watershed. Consequently, our model runs do not include any pre-existing practices. In fact, the city does street sweeping and there are seven detention ponds in the watershed. Six of the detention ponds are located on the University Arboretum property. These are seen as small blue dots in Figure 1. The remaining detention pond is on the golf course in WI-01 [Figure 1]. The arboretum built the detention ponds to reduce the erosive effects of the runoff and to protect their wetlands from sedimentation. These practices are helping to reduce the suspended solid load to Lake Wingra. Otherwise much of the runoff from four of the more urbanized sub-watersheds (WI-01, WI-02, WI-05, and WI-07) would flow unchecked down open channels to Lake Wingra.

Also, we do not include sediment loads from bank erosion in our estimate of total sediment loads to Lake Wingra. Severe bank erosion is occurring in several streams tributary to the lake. Bank stabilization projects are necessary to control this source of sediment.

Six Steps to Finding the 40% Solution

Developing a stormwater plan that considers both source area and regional STPs will require more steps than a plan that just considers regional practices. To include the source area practices, more work is needed to identify the sources of the pollutants of concern, more types of STPs need to be evaluated, and more sites in the drainage area must be identified. Although it takes more work to include source area practices, we think a retrofit plan has a better chance of being implemented if it is not limited to regional practices. Source area practices can be incorporated into places that regional practices will simply not fit and they are usually less disruptive to the neighborhood. Previous experience in Wisconsin has demonstrated how unreceptive people can be to being displaced from their parks and homes by regional stormwater treatment practices.

We think the following six steps should be part of any stormwater management plan that includes source area practices. We used these steps to demonstrate the validity of using source area practices in the Lake Wingra watershed. Since we are only trying to demonstrate the relative cost-effectiveness of source area and regional practices, the steps do not include all the activities needed to actually install STPs in the Lake Wingra watershed. For example, a more comprehensive stormwater plan should include collection of site information, such as soil types and location of utilities, sizing of the STPs in each location, and the actual cost of installation at each site.

1. Select and calibrate an urban runoff model.
2. Determine the annual suspended solids loads for each sub-watershed, landuse, and source area in the watershed.
3. Select source area and regional practices to be evaluated for watershed.
4. Determine ability of each practice and combinations of practices to achieve pollutant reduction goal.
5. Identify unit capital and maintenance cost of each practice.
6. Determine cost of each management alternative that achieves pollutant reduction goal.

We think enough information is available now to complete all six steps for any watershed. Cost information about each STP is the hardest to find. Fortunately we could find some conceptual cost data for each practice. Information about the effectiveness of each practice is also very limited (Winer, 2000), but ongoing monitoring efforts, such as the EPA's Environmental Technology Verification effort, should greatly increase our database over the next few years. New monitoring sites are being added to the National Stormwater Best Management Practices (BMP) Database all the time (EPA,1999). We relied on an urban runoff model to help identify the most important sources of the TSS.

We selected the Source Loading and Management Model (SLAMM) to demonstrate the relative benefits of regional and source area practices (Pitt, 2002). We considered other models, such as P8 and SIMTPM, but only SLAMM is designed to easily produce a TSS load for each source area, such as streets and parking lots (Sutherland, 1999 and Walker, 1990). All three models are capable of testing regional practices, but only SLAMM is designed to specifically evaluate the effectiveness of practices on all the source areas.

Source areas are the building blocks for calculating runoff volumes and pollutant loads for the six landuses addressed by SLAMM – residential, commercial, industrial, institutional, open space, and transportation landuses. Examples of the source areas characteristic of each landuse are roofs, parking lots, driveways, sidewalks, streets, small landscaping (lawns), large landscaping, playgrounds, isolated areas, undeveloped areas, and unpaved parking lots. Pollutant loads and runoff volumes calculated for each source area are added together to produce the estimates for each landuse.

Stormwater treatment practices can be applied to each source area, the conveyance system, and/or the end-of-the-pipe. Some of the practices are only applied to source areas, such as street sweeping and porous pavement. Others, such as catch basin cleaning and grass swales, are reserved for the conveyance system. Many of the available practices in SLAMM, such as detention ponds and infiltration devices, are applied to both source area and end-of-the-pipe solutions. A user may select multiple sites and practices or just decide to apply one practice at one location. The model output summarizes the benefits of the practices by source area and landuse.

To make the source area loads as valid as possible, we think it is very important to calibrate SLAMM for all parts of the country. A minimum calibration requires the collection of event related flow and TSS concentration data at the end of a stormsewer pipe. Although most people preparing stormwater plans will not have enough data to calibrate a model, our efforts to calibrate SLAMM should make the model a reasonable choice for preparing stormwater plans in the upper Midwest.

SLAMM Calibration

To help people prepare stormwater management plans in Wisconsin, we calibrated SLAMM using data collected by the U.S. Geological Survey office in Madison, Wisconsin. Fortunately, they have recently collected source area runoff volumes and TSS concentrations, rain depths for monitored storms, and runoff volumes and TSS concentrations at the stormsewer outfall at six sewersheds in Wisconsin and one in Michigan (Table 2).

Table 2. Comparison of measured and predicted TSS loads and runoff volume at eight stormwater study sites.

Site	Landuse Type	TSS		Runoff Volume	
		Number of Events for Calibration	Percent Difference	Number of Storms for Calibration	Percent Difference
Harper[1]	Residential	23	11	55	-27
Monroe[1]	Res/com	32	-52	75	7
Canterbury[1]	Res/com	14	12	55	10
Marquette	Res/com	71	-29	64	19
Superior	Commercial	21	-66	91	-4
West Towne[1]	Commercial	-	N/A	66	31
Syene[1]	Light Industrial	82	19	108	-8
Badger Road[1]	Light Industrial	18	-40	40	-4

1. Sites are near or in Lake Wingra Watershed.

The mostly residential Monroe study site is in the Lake Wingra watershed and four of the study sites are located very near the Wingra watershed (Bannerman and others, 1990 and Waschbusch and others, 1999). These are the Harper, Canterbury, Syene, and Badger Road study sites. The Marquette site is in Michigan (Steur and others, 1997) and the Superior site is northern Wisconsin (Steur and others, 1997). The median number of storms collected for flow is 64, while the median value for the number of water quality storms is 23.

The following is a list of the files we calibrated in SLAMM and the name of the file we use in Wisconsin. These and other files for the model are on the U.S. Geological web page with the URL of http://wi.water.usgs.gov/slamm/index.html. Copies of SLAMM are available at WINSLAMM.com.

1. Runoff coefficient: .rsv (WISI01.rsv)
2. Particulate Solids Concentration: psc (WIAVG01)
3. Pollutant Probability Distribution: .ppd (WIGEO01)
4. Particulate Residue Reduction: .ppr (WIPLV01)
5. Street Delivery Parameter: .std (WISTR01)

SLAMM did a good job of matching the total runoff volumes and TSS loads measured at the end of the stormsewer pipe for each study site. The median difference between the predicted and measured runoff volume is 8% and the median difference for the total suspended solids loads is about 29% (Table 2). We are concerned about the differences of around 50% for suspended solids at Monroe, Superior, and Badger Road sites. It appears the model is not accounting for some of the sediment collected by the automatic samplers at these three sites during the largest rainfall events. Over half the difference between the measured and estimated sediment load at the Superior site are caused by the model underestimating the load for the largest rainfall. Estimated sediment loads would be ten percent higher without the effect of the largest rainfall at the Badger Road site. Piles of soil observed at both sites could be the source of sediments the model does not account for during larger events. Estimated and measured runoff volumes are very close for those larger events, so the difference in loads is due to the difference in concentrations.

A 52% difference at Monroe seems to be explained by the unusual amount of deposited sediment observed in the flat part of the storm sewer pipe. Six high intensity storms accounted for most of the error at Monroe Street. The model is not designed to account for the re-suspension of sediment deposited at the bottom of a storm sewer pipe.

Sources of Total Suspended Solids in the Lake Wingra Watershed

After we completed the calibration, we thought SLAMM was ready to help us identify the important sources of TSS in the Wingra watershed. We first ran SLAMM on the eight sub-watersheds with the hope of eliminating some of the sub-watersheds from the rest of the analysis. The city of Madison provided the acres of each landuse in the subwatersheds and the development characteristics we needed for each landuse were obtained from the average development characteristic files on the U.S. Geological Survey web page (http://wi.water.usgs.gov/slamm/index.html). Examples of the development characteristics are the acres of each source area, amount of connected imperviousness, and street texture.

We used the average rainfall year file for the Madison area (MSN1981.ran) to run SLAMM for the eight subwatersheds. Four of the sub-watersheds contribute about 92% of the annual suspended solids load for the watershed (Table 3). In an average rainfall year sub-watersheds WI-01, WI-02, WI-03, WI-07 contribute about 457 tons of suspended solids to Lake Wingra. This is about the same as the average load

(401 tons) estimated for the watershed when the principle landuse was agricultural (Corsi and others, 1997). It is not a surprise that these four watersheds contribute most of the sediment, since they contain about 95% of all the built-up landuses in the Wingra watershed.

Table 3. Annual TSS loads and runoff volume for each subwatershed in the Lake Wingra Watershed

Subwatershed	% of Total Area	TSS (lbs)	TSS, %	Annual runoff volume (ft^3)	Percent runoff volume
WI-01	21	269,000	27	30,519,000	28
WI-02	27	253,000	26	23,886,000	22
WI-03	12	108,000	11	11,149,000	10
WI-04	1	8,000	1	724,000	1
WI-05	4	19,000	2	2,376,000	2
WI-06	1	8,000	1	663,000	1
WI-07	20	284,000	28	37,314,000	33
WI-08	14	44,000	4	3,114,000	3
Total	100	993,000	100	109,745,000	100

Regional or source area STPs should be implemented in these four critical subwatersheds. If regional STPs were to be installed at the ends of the critical subwatersheds, they would need to have at least a 50% removal efficiency in order to achieve the 40% reduction goal. The output from the model runs used to identify the critical subwatershed can also be summarized to determine landuses with the highest TSS loads. This is the next step in the identification of the most important source areas to control.

Commercial and residential landuses in the critical subwatersheds contribute about 82% of the annual TSS loads (Figure 2). Residential loads are proportionate to the percent of the area they occupy, while percent of the load contributed by the commercial is almost twice as high as the percent of the area it occupies. This makes the commercial landuse an important target for our management efforts. On the other hand it is less cost effective to treat the open space landuses, since 16% of the area produces only 5% of the load. We did not add industrial landuse to our targeted landuse list, because they represent only 2% of the load. If we assume the institutional and commercial landuses have similar source areas, we can add the 4% TSS load from the institutional landuses to the commercial load for a total of 35%. Source areas within the commercial, institutional, and residential landuses were expected to yield the highest percent of the annual TSS load.

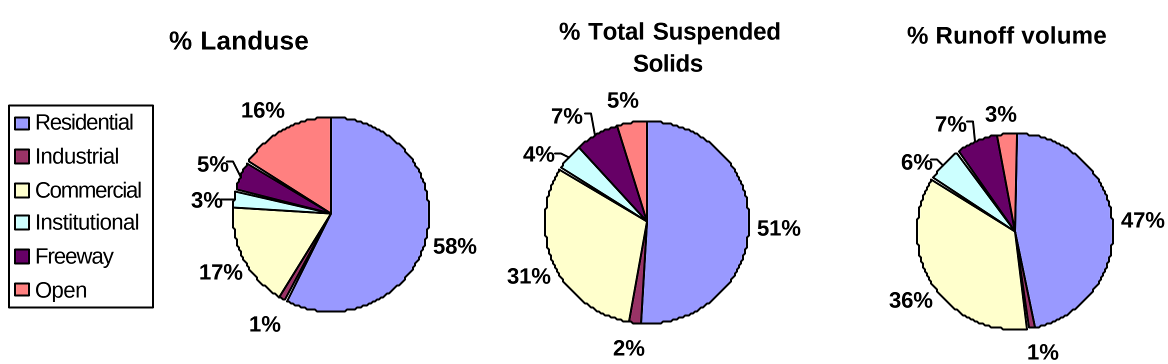

Figure 2. Percent area, TSS load, and runoff volume for landuses in four Lake Wingra sub-watersheds.

Parking lots and streets in the four sub-watersheds represent only 26% of the area, but contribute about 66% of the annual suspended solids load (Figure 3). These two source areas are mostly in the commercial, institutional, and residential landuses. Roofs and lawns are a less critical source of suspended solids, because they represent 47% of the area and only produce about 12% of the load. The same is true for large landscaped areas, which includes city parks and golf courses. To be cost-effective our practice selection has to target the streets and parking lots as much as possible.

If we want to evaluate source area STPs that have a removal effectiveness for TSS of less than about 70%, we have to include some of the other source areas in our analysis.

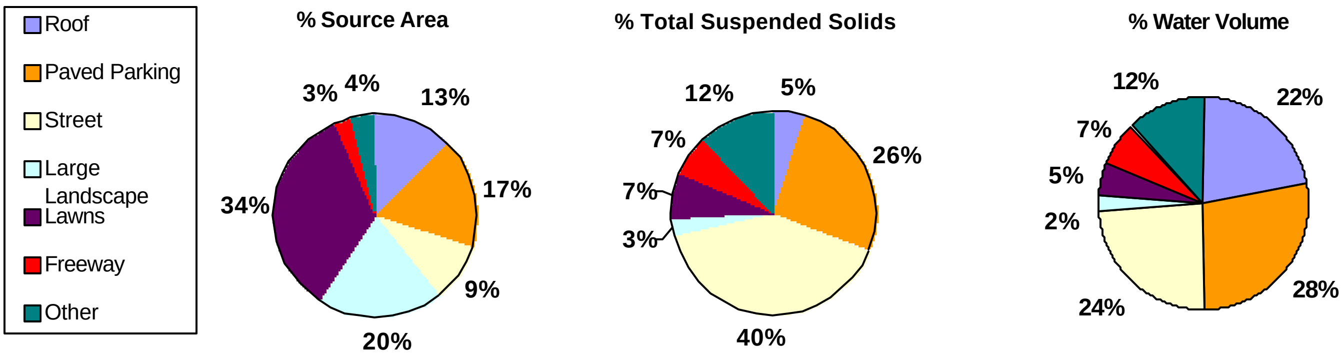

Figure 3. Percent area, TSS load, and runoff volume for source areas in four Lake Wingra sub-watersheds.

A 70% control of parking lots and streets would just achieve the 40% (46% control TSS) reduction goal for the Wingra watershed. This is partially because a 100% control of the two source areas results in TSS reduction of 66% for the entire watershed. To give us more choices in our practice selection, we needed to boost the total% of the TSS load we could control. We did this by including other source areas in our analysis, especially freeways, lawns, and roofs.

Selection of Stormwater Treatment Practices

To achieve the goal of the demonstration, it was only necessary to select one regional practice. Several types of source area practices are needed, however, to cover all the types of source areas. Selection of a number of source area practices would allow us to include proprietary and non-proprietary practices with a range of TSS removal values. These could represent a number of treatment processes, such as settling, filtration, and infiltration. Our criteria for selecting regional and source area practices included the availability of good data to verify their effectiveness, some cost information, and hopefully some experience with the practice in Wisconsin.

Regional Practice

Detention ponds met all our criteria, so they were selected as the regional practice to compare to source area practices. Settling is the main treatment process for the detention ponds. Many studies including one in Wisconsin indicate detention pond can achieve an 80% reduction in annual suspended solids loads (House and others, 1993, Winer, 2000). The regional practice had to have a TSS removal capability of at least 50%

to achieve the 40% reduction goal for the watershed. By using a practice with a TSS removal of 80% the regional practice could be located to serve less the whole drainage area and still achieve the 40% goal (Table 4).

Table 4. TSS removal values reported for selected stormwater treatment practices.

Stormwater Treatment Practices	Description of Stormwater Treatment Practices	Abbreviation of Stormwater Treatment Practices	Reported TSS removal, % (1)
Multi Chamber Treatment Tank	Three chambers – grit chamber, settling chamber, and sand/peat filter media chamber with by-pass	MCTT	80
Stormceptor	Vertical single cylindrical chamber using swirl action and settling with built in by-pass	Stormceptor	33
Delaware Perimeter Sand Filter	Underground sand filter using settling chamber followed by sand filter chamber	Delaware Filter	83
High Efficiency Street Sweeping (city street)	Vacuum action pick-up assisted by brooms and/or jets of air	High Sweep	60[2]
High Efficiency Street Sweeping (freeway)	Vacuum action pick-up assisted by brooms and/or jets of air	High Sweep	45[3]
Detention Ponds	Holes in the ground with permanent pools designed to settle particles	Ponds	80
Bioretention	Shallow depressed planted area underlain by a layer of formulated soil (mostly sand) over a layer of gravel. Treatment includes sedimentation, filtration, adsorption, microbial decay, and plant uptake.	Bioretention	75
Broom Street Sweeper	Broom action pick-up assisted by conveyor belt	Broom Sweep	20[2]
Porous Pavement	Porous asphalt or interlocking paving blocks providing infiltration	Pavement	95
Infiltration Trench	A lined excavated trench backfilled with gravel. Infiltration followed by filtration in native soils	Trench	NA[4]
Rain Gardens	Shallow depression that's planted with a variety of perennials.	Gardens	75[5]

1. Percent assumes all devices working at maximum efficiency.
2. Removal efficiency for city streets with sweeping once per week for 30 weeks.
3. Removal efficiency for freeways with sweeping once per week for 30 weeks.
4. TSS removal is probably very high, because reportedTP removal is 100%.
5. Assume same as reported bioretention.

Of course, many detention ponds have been installed in Wisconsin. With so many being installed in new development sites, Wisconsin cities have accepted them as a good way to meet their goals for flood control and reduce TSS loads. Very few of them, however, have been retrofitted into existing urban areas. Refrofiting a detention pond in an existing urban area has the potential to cause a lot of disruption to people living in the neighborhood. In most cases, this alternative will not be politically feasible, except when a there is a lot of open land, such as the presence of the arboretum in the Lake Wingra watershed. A stormwater plan prepared for the Lincoln Creek Watershed in the City Milwaukee was promptly rejected when the groups involved realized the only alternative being offered was to put detention ponds in many of the public parks – 60 ponds altogether.

In estimating costs for ponds, it was assumed that either the land is available and must be purchased at a fair market price or the land is available but the purchase price included the cost of existing buildings (Table 5). Both alternatives assumed a cost for repositioning the existing storm sewer system (Southeastern Regional, 1991). Since the retrofit cost calculations are over ten years old, we applied an annual inflation factor of 3% to building and maintenance of the ponds and we increased the land cost by 10% each year. Retrofit cost of about one to two million dollars for each acre of permanent pool is prohibitive compared to the approximate cost of $100,000 for each acre pond in a new development.

Table 5. Conceptual unit capital and maintenance cost for selected stormwater treatment practices.

Stormwater treatment practice	Unit capital cost, $	Annual maintenance cost, $
Source area practices		
MCTT	38,000 / acre of imper.[1]	2,200/practice
Stormceptor	15,000 / acre of imper.[1]	500/practice
Delaware Filter	17,500 / acre of imper.[1]	1,700/practice
Bioretention	20/ft^2 of practice or 44,000/acre of imper.[1]	2/ft
Trench	18/ft^2 of practice or 88/ft of trench	6/ft
Pavement	85,500/acre of practice	290/ac of practice
Broom Sweep	39/curb mile	Included in capital
High Sweep	41/curb mile	Included in capital
Gardens	6/ft^2 of practice	0
Regional Practices		
Ponds (with no land cost)	383,000/acre of pond	3,500/acre of pond
Ponds (with land cost)	980,000/acre of pond	3,500/acre of pond
Ponds (with land cost & buildings)	1,935,000/acre of pond	3,500/acre of pond

1. Imper. = connected imperviousness.

Source Area Practices

Nine source area practices were selected that best met our criteria (Table 4). The TSS reduction capabilities of the practices have been verified by at least one monitoring study (Winer, 2000, Shoemaker and others, 2000; Bell and others, undated; Young, 1996; National Stormwater, 1999). The TSS removal values include the losses of pollutant load if the practice has a bypass mechanism. Although most of the practices do not have many test results, the available results indicate most of the practices can achieve a high level of suspended solids reduction. All the proprietary and nonproprietary practices that are available should have an efficiency that falls somewhere in the range of efficiencies we used in the demonstration.

The Stormceptor™ represents many of source area practices with a moderate level of suspended solids reduction, while the multi-chamber treatment tank (MCTT) represents the practices with a high level of suspended solids reduction. Test results indicate the Stormceptor™ should reduce the annual suspended solids load by about 30% (Waschbusch, 1999). Many single chamber practices relying on settling will probably achieve similar levels of reduction. Many multi-chamber practices that include filtration have a better chance of achieving the 80% reduction in annual suspended solids loads observed for the MCTT (Corsi and others, 1999). Eighty percent is probably near the maximum annual load reduction we can expect for a source area treatment practice, because the practices that have 98% removal efficiencies, such as the MCTT, usually bypass some of the higher flows. It is assumed most devices are designed to bypass some flows for rainfalls greater than about 1.25 inches in 24 hours.

Reported TSS reduction for the old style broom street sweeper is low at 20% (Bannerman, 1983, Sutherland, 1999). Street sweeping has the potential to be a very effective practice, because the source areas that can be swept (parking lots and streets) are the most important sources of TSS. Changes to sweeping schedules and types of machines would be much less disruptive to the public than any other source area practice. New types of street sweepers appear to be more effective (Sutherland, 1999). High efficiency street sweepers should be able to reduce TSS loads from residential streets by at least 60%. These numbers are based on estimates from a calibrated version of the SIMTPM model. The same type of high efficiency street sweepers should be able to reduce the TSS loads from freeways by about 45% (Martinelli, 2002).

The selected source area practices cover a range of treatment processes. Bioretention, MCTT, infiltration trenches (trench), rain gardens (gardens), and the Delaware perimeter sand filter (Delaware filter) all use settling and filtration to remove solids from stormwater. Infiltration also lowers loads by reducing runoff volumes. Infiltration is a key element of trenches, bioretention, gardens, and porous pavement (pavement).

We have experience in Wisconsin with all of the selected source area practices except for bioretention and Delaware sand filters. Personnel communications with cities supporting the source area practices indicate they are mostly happy with their performance. Public works people in Osceola, Wisconsin are telling us they are happy with the performance of their high efficiency street sweeper. Two MCTTs installed in different cites seem to performing well. We are not aware of any complaints about the several Stormceptors that are installed around Wisconsin. Most of the porous pavement installations seem to be in the form of paver blocks. Some people have observed failures of infiltration trenches. These failures appear to have been caused by clogging during the construction process. Homeowners have reported they are very satisfied with the operation of their rain gardens.

At best, the available cost information can only be used for conceptual purposes (Shoemaker, 2000; Southeastern Regional, 1991) (Table 5). Obviously, the cost will vary with each site depending on factors such as obstacles to installing the practice, cost of the land, and how difficult it is to connect the practice to existing conveyance systems. Existing utilities have already increased the cost of some of our retrofit efforts in Milwaukee. A need to support truck traffic and the presence of underground pipes increased the cost of installing a MCTT in a city maintenance facility. The cost of connecting the existing plumbing to the practices was the major part of the construction cost of installing two source area controls at a freeway site. Conceptual is good enough, though, for a demonstration.

Unit capital and maintenance cost calculation varies from practice to practice (Table 5). Some of the literature provides the cost in terms of the amount of drainage area to the practice, while other cost are determined from the size of the practice. When more than one cost value was available we always selected the higher value. For older cost values we assumed an inflation of 3% each year. Some of the practices share similar costs. For example, the MCTT and bioretention cost about $40,000 for each acre of imperviousness in the drainage area. Surprisingly, the Delaware filter achieves about the same solids reduction as the MCTT and bioretention, but only costs about $17,500 for each acre of imperviousness. This is one reason we included the Delaware filter in our demonstration.

Location and Sizing of the Practices

Before we could use SLAMM to determine the benefits of installing each type of source area STP, we had to match each practice to the appropriate source area(s). Street sweeping is an obvious match for streets in the three landuses contributing the largest amount of TSS (Table 6). All of the source area practices except street sweeping and rain gardens are applied to parking lots in the commercial and institutional areas. Practices like the MCTT and bioretention are recommended for relatively small drainage areas such as a parking lot. Not enough information is available about treatment levels and cost to include street sweeping

Table 6. Sizing information for selected stormwater treatment practices.

Stormwater Treatment Practice	Source area treated	Dimensions each site (ft)	Total area of practice or area of connected impervious draining to practice (ac)	Estimated number of treatment sites
		Residential		
Rain Gardens	Lawn & roof	10 x 17 x 0.33	47.6	12,200
Bioretention	All	15 x 30 x 4	27.5	2,666
MCTT	All	1 site/2 ac. of imper.	563[1]	281
Stormceptor	All	1 site/2 ac. of imper	563[1]	281
Delaware Filter	Driveway	1 site/driveway	92[1]	6,100
Broom Sweep	Streets	1/week for 30 weeks	-	4110[2]
High Sweep	Streets	1/week for 30 weeks	-	4110[2]
		Commercial/Institutional		
Infiltration Trench	Parking lots	5 x 200 x 4	6.2	270
Infiltration Trench	Roofs	5 x 200 x 4	2.2	96
Bioretention	Parking lots	15 x 30 x 4	15.6	1,500
Porous Pavement	Parking lots	-	306	20
MCTT	Parking lot	1 site/ 2 ac imper.	310[1]	155
Stormceptor	Parking lot	1site/2 ac imper.	310[1]	155
Delaware Filter	Parking lot	-	310[1]	55
MCTT	All	1 site /2ac imper.	530[1]	265
Stormceptor	All	1 site / 2 ac imper.	530[1]	265
High sweep	Streets	1/week for 30 weeks	-	990[2]
Broom Sweep	Streets	1/week for 30 weeks	-	990[2]
		Freeway		
Infiltration Trench	All	5 x 200 x 4	1.74	75
MCTT	All	1 site / 2ac. imper.	91	45
Stormceptor	All	1 site / 2 ac. imper.	91	45
High sweep	Freeway	1/week for 30 weeks	-	141[2]
		Regional		
Ponds	All	8.5 ac.	34	4

1. Acres of connected imperviousness.
2. Total curb miles each year.

as a parking lot practice. Together lawns and roofs produce enough of the TSS load (12%) to include them in the analysis of source practices. Residential lawns and roofs are treated with rain gardens and commercial roofs are treated with infiltration trenches.

To understand the maximum possible benefit of using an STP in the three landuses, some of the source area practices are applied to all the source areas in each landuse. By installing MCTTs, Stormceptors, and bioretention systems near or under the streets they should be in a position to treat the runoff coming from all the source areas. It is assumed that some of the water is bypassed for these source area practices.
For example, we assumed 2,666 bioretention systems or 27.5 acres of treatment surface area is required to treat all the source areas in residential landuses (Table 6). Each bioretention site would cover a surface area of at least 15 feet wide and 40 feet long and the practice would be installed next to the street in the right of way. It is assumed the people living on the street are responsible for the maintenance of the bioretention plants.

In most cases it seems impractical to assume enough source area practices would be installed in a subwatershed to act as a regional practice. But some examples already exist in this country where cities have installed source area practices in the public right-of-way to control the amount and quality of runoff from all the source areas. Rain gardens are already being installed along residential streets in the Maplewood, Minnesota (Cavett, 2002). They are also being installed as part of street drainage system during street reconstruction projects. Bioretention swales have been installed along a street in Seattle, Washington (http://www.ci.seattle.wa.us/util/urbancreeks/SEAstreets/history.htm) to treat the runoff from the two year return interval storm. They project that the addition of bioretention swales will not significantly increase the cost of street reconstruction projects.

For the regional practice we assumed that there is one detention pond for each of the four subwatersheds. Since this is a demonstration effort, it is not necessary to match the number of ponds to the number of available sites. It is very likely the total number of ponds would exceed four, if a number of ponds is needed in each subwatershed to overcome the constraints of each site.

Among the selected practices, SLAMM is able to predict the TSS reduction of street sweeping, porous pavement, rain gardens, bioretention systems, infiltration trenches, and detention ponds. Iterations of the model are used to determine the optimum size of rain gardens, porous pavement, bioretention systems and infiltration trenches (Table 6). Reported TSS removal values for the other practices are inserted directly into the model. The model accepts the reported values in the "other" option for source areas, the conveyance system, and the outfall controls.

Total Suspended Solids Reductions Estimated for Individual Practices

Evaluation of the individual source area practices produced only two examples of a practice achieving about a 40% reduction in annual TSS loads to Lake Wingra (Table 7). Bioretention systems and MCTTs located to control all the residential source areas are those two practices. They worked because the residential landuse represents about 50% of the TSS load to Lake Wingra and they have a TSS removal capability of 80%. The other applications of the source area practices are usually treating landuses or source areas that start with less than 40% of the annual TSS load. One exception is streets with 40% of the annual TSS load, but a practice applied to streets would need almost a 100% removal of TSS to achieve the goal. Source area practices will have to be combined to offer more ways for source area practices to achieve a 40% reduction.

Since the ponds are designed to achieve an 80% reduction it is not surprising that the regional practice achieved the TSS reduction goal (Table 7).

Table 7. Reduction in annual TSS loads to Lake Wingra for stormwater treatment practices applied to four subwatersheds

Practice	Source area treated	Annual TSS reduction, %[1]
	Residential	
Broom Sweep	Streets	4
Delaware Filter	Driveways	7
Gardens	Lawn & roof	9
Stormceptor	All	16
High Sweep	Streets	17
MCTT	All	38
Bioretention	All	41
	Commercial/Institutional	
Broom Sweep	Streets	1
Trench	Roofs	2
High Sweep	Streets	5
Stormceptor	Parking lot	7
Stormceptor	All	11
Trench	Parking lot	12
Bioretention	Parking lot	13
MCTT	Parking lot	17
Delaware Filter	Parking lot	19
Pavement	Parking lot	19
MCTT	All	27
	Freeways	
Stormceptor	All	1
High Sweep	Freeway	4
MCTT	All	5
Trench	All	6
	Regional	
Ponds (with land cost)	All	74

1. Percent of load for all eight subwatersheds, i.e. entire load to Lake Wingra.

Their actual reduction is 74% because we divided the total suspended solids load reductions by the solids loads for the entire watershed, not just the four sub-watersheds where they were applied. Detention ponds could, therefore, be located to serve less of each subwatershed and still meet the TSS reduction goal for the entire watershed.

Cost Comparisons Between Source Area and Regional Practices

To make a valid comparison between source area practices and regional practices it was important to select configurations of the practices that achieved about a 40% reduction in annual TSS loads. From the analysis of the individual source area practices we discovered it is necessary to try combinations of them to have more than a couple of alternatives that achieve the 40%. These alternatives could also be more reasonable than applying a source area practice to all the source areas in a landuse, which is needed to achieve a 40% reduction with the MCTT and bioretention. Since detention ponds were determined to achieve a 74% in annual TSS loads to Lake Wingra, it is possible to achieve the 40% reduction by assuming less of each subwatershed drains to each pond. This not only has the effect of reducing the TSS removal by the ponds, but also reduces their costs.

Combinations of Source Area Practices Determined to Achieve 40% Reduction

To evaluate the benefits of combining the source area practices, the practices were arranged into about 80 combinations. One important consideration is to avoid redundant practices, such as using street sweeping and the MCTT under the street in the same area. After eliminating all the combinations that were lower than 40% or higher than a 45% reduction, we were left with a set of about 15 combinations. We dropped about six more combinations for different reasons. For example, we eliminated all those combinations with trenches on the parking lots because we thought this practice would be hard to implement due to the potentially high cost of pretreatment. Porous pavement is not included because of the potential disruption and cost associated with removing the existing pavement. Nine combinations of source area practices met our criteria for percent TSS reduction and reasonableness (Table 8).

All of the combinations included at least one source area practice in the residential area. To make them more reasonable, MCTTs and bioretention systems were applied to one-half the area. By treating one-half the area the number of bioretention systems required drops from 2,666 to 1333. Rain gardens were designed to treat one-half of the roof and lawn area. High efficiency sweeping is an important part of all the combinations except one. The 40% could not be achieved for the combinations without some kind of source area practice on the parking lots. In every case one of three source area practices (bioretention systems, MCTTs, and Delaware Perimeter Sand Filter) was designed to treat the entire area for each parking lot. Infiltration trenches along the freeway are the most effective freeway practice at a 6% TSS reduction, so they are included in three of the combinations.

Selection of the Most Cost-effective Practices

The most cost-effective practices will achieve the 40% goal for the least amount of cost. To calculate the cost the capitol cost is added to the maintenance cost assuming the practices have a useful lifespan of 20 years. The twenty year cost for the source area practice combinations ranges from $11,000,000 to $30,000,000 (Table 8). The next cheapest combination of source area practices is almost twice the cost of the cheapest one. Five of the combinations have a very similar cost. Making a choice between the combinations with similar cost is more a judgment of which ones are easiest to install.

All of the combinations of source area practices cost less than retrofitting detention ponds if you have to buy the land and the buildings on the land. To create 40 acres (20 acres of permanent pool and 20 acres of space around the pool) of open space in a developed area will probably mean buying some of the land that has buildings on it. In a medium density residential area this is equivalent to about 136 homes. Even if the cost of retrofitting the detention ponds is cheaper than the source area practices, it is unlikely the people living in the neighborhoods would tolerate the condemning of 136 homes to build the detention ponds.

If the conceptual costs for the street sweeping and the Delaware filter are realistic than combining these two practices is the most cost effective approach to reducing the TSS load to Lake Wingra by 40%. Improving the street sweeping program for all the streets and installing Delaware Perimeter Sand Filters on all the parking lots seems like a reasonable goal for the city. To maximize the benefit of the enhanced sweeping programs the city should also implement alternate side parking restrictions. The city should be able to meet this goal by 2013 as required by NR 151. It will probably be more difficult to meet this time frame for combinations using MCTT, rain gardens, and bioretention systems in the residential areas.

Table 8. Cost of combining stormwater treatment practices to achieve a 40 to 45% reduction in annual TSS loads to Lake Wingra.[1]

Practice combinations	Total cost for twenty years[1] ($)	Annual cost ($)	Additional utility fee for households in Madison, $/household/year.[2]
High sweep (All)[3] + Delaware Filter (Lots)	11,460,000	573,000	6
Bioretention (1/2 Res) + Delaware Filter (Lots) + High sweep (Com/Inst)	20,420,000	1,021,000	10
High sweep (Res) + MCTT (Lots) + Trench (Freeway)	19,860,000	993,000	10
MCTT (1/2 Res) + Delaware Filter (Lots) + High sweep (Com/Inst)	21,540,000	1,077,000	10
Gardens (1/2 Res) + High sweep (Res) + Bioretention (Lots) + Trench (Freeway)	25,240,000	1,262,000	12
Gardens (1/2 Res) + High sweep (All) + MCTT (Lots)	26,020,000	1,301,000	13
Bioretention (1/2 Res) + MCTT (Lots) + High sweep (Com/Inst)	27,940,000	1,397,000	14
MCTT (1/2 Res+ Com Lots) + High sweep (Com/Inst)	29,060,000	1,453,000	14
Bioretention (1/2 Res) + Trench (Com/Inst roof) + Bioretention (Lots) + Trench (Freeway)[4]	30,080,000	1,504,000	14
Detention Pond (treat 1/2 of area)[4]	19,260,000	963,000	9
Detention Pond (treat 1/2 of area)[5]	36,800,000	1,840,000	18

[1] Capital and maintenance cost included.
[2] Annual cost divided by 46,553 household paying stormwater utility fee in City of Madison and multiplied by 45% to adjust for percent of total utility revenues paid by homeowners.
[3] Does not include freeways.
[4] Includes cost of land.
[5] Includes cost of land and buildings.

Although the annual cost of the cheapest combination of practices is only about $600,000, the impact of this cost can only be measured in terms of how much it will cost each tax payer. We are able to do this for the City of Madison because the city has created a stormwater utility district. Each household pays a utility fee of about $36 a year. If we assume the utility district would use any additional fees to pay a bond back over twenty years, we can calculate the amount of increase to this fee by dividing the annual cost of the practice by the 46,553 households in the city and multiplying the result by 45%. In the City of Madison the households are paying about 45% of the utility fee, while the commercial and institutional property owners are paying the rest. To pay back the cost of the least expensive combination practice combinations would raise the annual fee to each household by $6 (Table 8). If the cost of the practices is assessed to just the people living in the Lake Wingra watershed the annual cost of the practices for each household would be approximately 6 times higher than the values in table 8.

The most expensive fee increase would be only $14 each year. All the source area fees are in the range of the values for the regional practices. Only the taxpayers can answer the question if this too much money to significantly reduce the pollutant load to Lake Wingra, but it seems like a reasonable fee to pay.

Conclusions

A six step process can be used to determine the most cost effective practices for achieving an annual TSS load reduction of 40% in an established urban area. An important element of the process is the use of an urban runoff model to determine the most important sources of the TSS and the levels of TSS reduction achieved by each management alternative. The steps are valuable for demonstrating the most cost effective management approach, but do not include the steps for selecting the sites, making final design decisions, and determining the actual cost for installing the practices at each site.

The goal of reducing the annual suspended loads by 40% to Lake Wingra can be achieved at what seems to be a reasonable cost to the Madison city taxpayers. A combination of source area practices, such as street sweeping and Delaware Perimeter Sand Filters on parking lots, are the most cost effective practices. Given the potentially high amount of disruption caused by the implementation of regional structural practices, a combination of source area practices also appears to be a more feasible way to achieve the reduction goal. Not only is a combination of source controls possibly more acceptable to the people living in the watershed, but also the annual cost to each household could be as little as six dollars. This is much less than retrofitting detention ponds at eighteen dollars for sites that include the cost of the buildings.

Although the retrofit performance standard in NR 151 is only for TSS, people in Wisconsin recognize there are other problem pollutants in storm water. Levels of heavy metals, polycyclic aromatic hydrocarbons (PAHs), and bacteria in storm water frequently exceed water quality standards (Bannerman and others, 1996). Some of these pollutants will be reduced if the TSS performance standard is achieved. Since SLAMM is designed to estimate loads for metals and PAHs, future reports will evaluate the sources and levels of control possible for other problem pollutants.

Both source area and regional practices will take at least ten years to implement. The source area practices because so many sites need to be installed and the regional practices because so much land must be secured. Combinations of practices that include street sweeping and source area practices on the parking lots have the best chance of meeting the retrofit deadline of 2013.

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