BMP Planning to Address Urban Runoff
Plaster Creek Watershed *SUSTAIN* Pilot

December 31, 2012

Prepared for:

U.S. Environmental Protection Agency -- Region 5
Michigan Department of Environmental Quality
Plaster Creek Stewards

Prepared by:

Tetra Tech, Inc.
1468 West Ninth Street, Suite 620
Cleveland, OH 44113

Contents

Figures

Tables

Acronyms

AG	agricultural
BMP	best management practice
COM	commercial
E. coli	Escherichia coli
EMC	event mean concentration
GVMC	Grand Valley Metropolitan Council
HDR	high density residential
HRU	hydrologic response unit
HSG	hydrologic soil group
HSPF	Hydrologic Simulation Program in Fortran
IND	industrial
LID	low impact development
LDR	low density residential
LSPC	Loading Simulation Platform in C++
L-THIA	Long-term Hydrologic Impact Analysis
MPN	most probable number
NLCD	National Land Cover Datasets
NPS	nonpoint source
NPV	Net Present Value
SSURGO	Soil Survey Geographic Database

SUSTAIN	System for Urban Stormwater Treatment and Analysis Integration
TMDL	total maximum daily load
TP	total phosphorus
TSS	total suspended solids
EPA	United States Environmental Protection Agency
USDA	United States Department of Agriculture
WMP	watershed management plan

1. Introduction

A series of projects in several Great Lakes area watersheds have been conducted by U.S. EPA Region 5 to strategically pilot implementation of the System for Urban Stormwater Treatment and Analysis INtegration (*SUSTAIN*). *SUSTAIN* is a decision support system to facilitate selection and placement of best management practices (BMPs) and low impact development (LID) techniques at strategic locations in urban watersheds. It was developed to assist stormwater management professionals in developing implementation plans for flow and pollution control to protect source waters and meet water quality goals.

The Plaster Creek watershed is tributary to the Grand River in west Michigan. Plaster Creek is one of several impaired streams in this area, located in metropolitan Grand Rapids. There are several listed impairments for the Creek including 1) other indigenous aquatic life and wildlife, 2) warm water fishery, and 3) total and partial body contact recreation. Total maximum daily load (TMDL) studies were completed in 2002 for biota and *E. coli* to address the listed impairments. In 2008, a watershed management plan (WMP) was developed which outlines an implementation plan for water quality improvement in the watershed.

Figure 1-1. Plaster Creek at Division Avenue.

This pilot project focuses on the ability of stormwater management practices to reduce pollutant loads, and therefore bacteria are not evaluated in detail. The WMP prioritizes critical areas and provides a framework for implementing restoration practices. It also presents the following goals for sediment and nutrient load reduction:

- 25 percent reduction in sediment, resulting in an in-stream sediment concentration of 30 mg/L (the TMDL suggests a 40 percent reduction in sediment loads to meet the 30 mg/L in-stream concentration)
- 40 percent reduction in total phosphorus loadings
- 20 percent reduction in total nitrogen loadings

There are several entities working to address water quality and stormwater related concerns in Plaster Creek including the Plaster Creek Stewards, West Michigan Environmental Action Council, Michigan Department of Environmental Quality, Kent Conservation District, the Lower Grand River Organization of Watersheds, Friends of Grand Rapids Parks, River Network and municipalities.

A 319 funded project is currently underway that will implement in part the Plaster Creek WMP and reduce pollutant loading in the watershed. This project includes the construction of best management practices (BMPs) at several locations within the watershed, conduct watershed education and outreach, and establish a monitoring program to track BMP effectiveness.

The proposed purpose and goals of the *SUSTAIN* application within Plaster Creek are to provide technical support for local planning and water quality implementation by:

- Providing planning tools to support TMDL implementation and watershed protection
- Simulating existing condition pollutant loadings in the watershed and identifying high priority areas for targeted BMP implementation
- Providing a summary of cost-effective BMPs that will help to address the impaired biota in Plaster Creek resulting from nutrient and sediment loading
- Testing *SUSTAIN's* capacity to address agricultural land uses and associated BMPs

2. Watershed Characteristics

The Plaster Creek watershed is 58 square miles in size, encompassing portions of nine communities including Grand Rapids and Kentwood. There are two approved TMDLs for Plaster Creek including a sediment TMDL which addresses aquatic life use impairments and an *E. coli* TMDL which addresses recreation uses impaired by bacteria. A detailed characterization of the watershed is available in the Plaster Creek WMP, which was published in October 2008. Sources and causes of sediment, *E. coli* bacteria, and nutrient loadings to Plaster Creek are summarized in Table 2-1, as provided in the Plaster Creek WMP (FTC&H 2008).

Table 2-1. Pollutant causes and sources

Prioritized Pollutant	Prioritized pollutant Sources	Potential pollutant causes
Sediment	Streambank erosion	Flashy flows Stormwater outfalls and tile drainage Livestock access Road/stream crossings Log jams Off-road vehicle use
	Urban runoff	Untreated urban runoff
	Agricultural runoff	Rill and gully erosion
	Construction sites	Improper erosion and sediment control measures
E. coli	Animal waste	Livestock access Manure spreading Feedlot runoff Wildlife Pet waste
	Septic system	Improper septic system maintenance
	Sanitary sewer connections	Faulty connections
Nutrients	Lawn inputs	Improper fertilizer management and yard waste disposal
	Animal waste	Livestock access Manure spreading Feedlot runoff Wildlife Pet waste
	Septic systems	Improper septic system maintenance
	Sanitary sewer connections	Faulty connections

Source: FTC&H 2008

2.1 Land Cover Changes

The Plaster Creek watershed exhibits characteristics typical of an urbanizing landscape. Increased impervious surfaces contribute to modified hydrology and pollutant loading to streams. The Lower Grand River WMP indicated that the Plaster Creek watershed was in seriously critical condition regarding flow, sediment, and temperature impairments. This assessment was based upon land classification information from 1992, and the years since have seen the watershed undergo rapid urban expansion (Figure 2-1). Much of the agricultural land (colored orange and yellow) has been converted to developed areas (shades of red), and the density of development has increased as well. As of 2006, 54 percent of the Plaster Creek watershed is developed, with another 19 percent of the land being maintained as developed open space such as lawns, parks, and medians. Agricultural land uses account for 16 percent of the landscape, down from 38 percent in 1992. The remaining 11 percent consists of forests and wetlands.

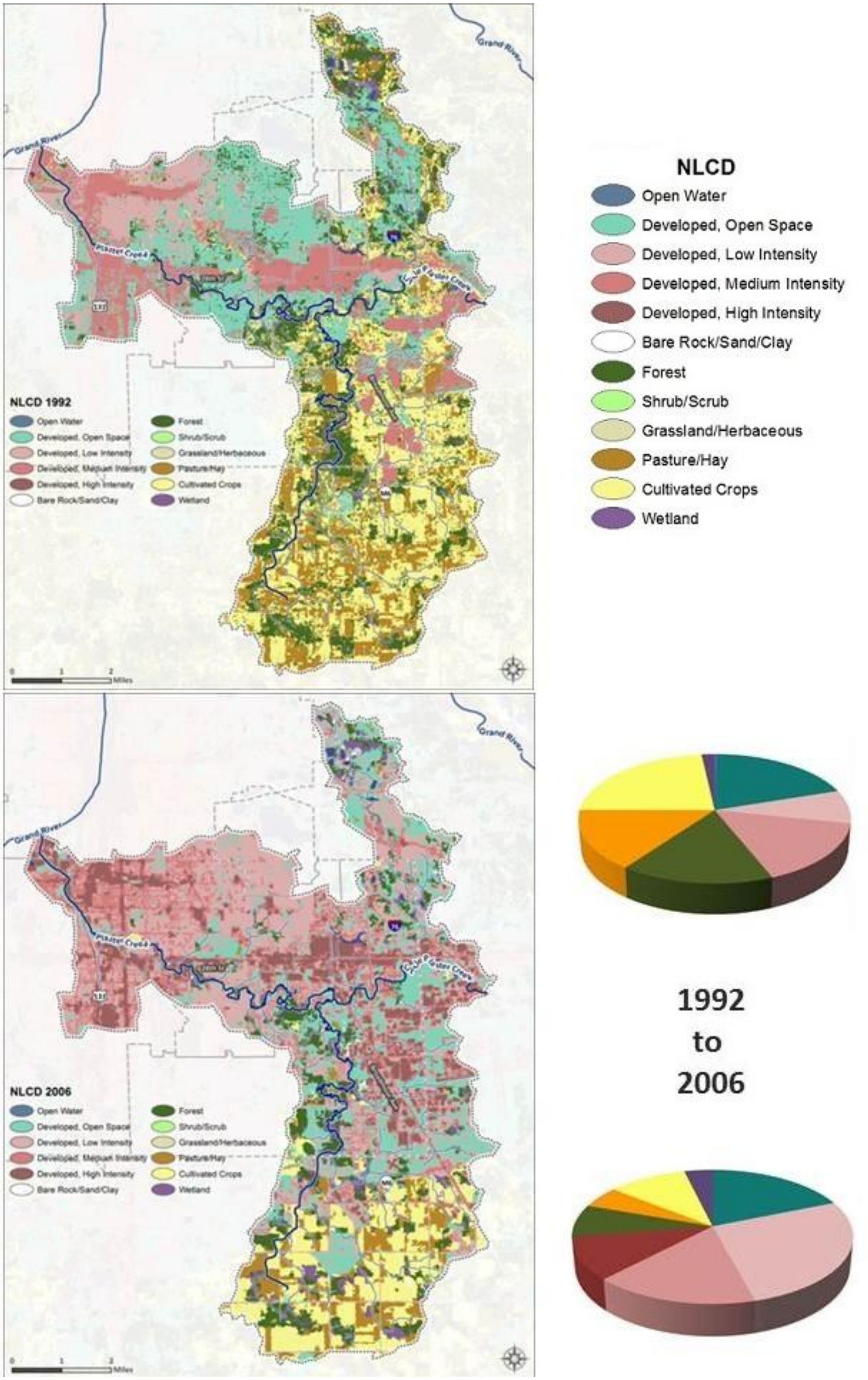

Figure 2-1. Land use in 1992 and 2006.

In addition to land use changes, wetlands have been altered significantly. Figure 2-2 presents the existing and pre-settlement wetlands in the watershed. Pre-settlement wetlands were provided by Michigan DEQ as part of a Landscape Level Wetland Function and Value Assessment. Many wetlands have been altered, drained, or filled over time; however these locations are optimal for wetland restoration projects.

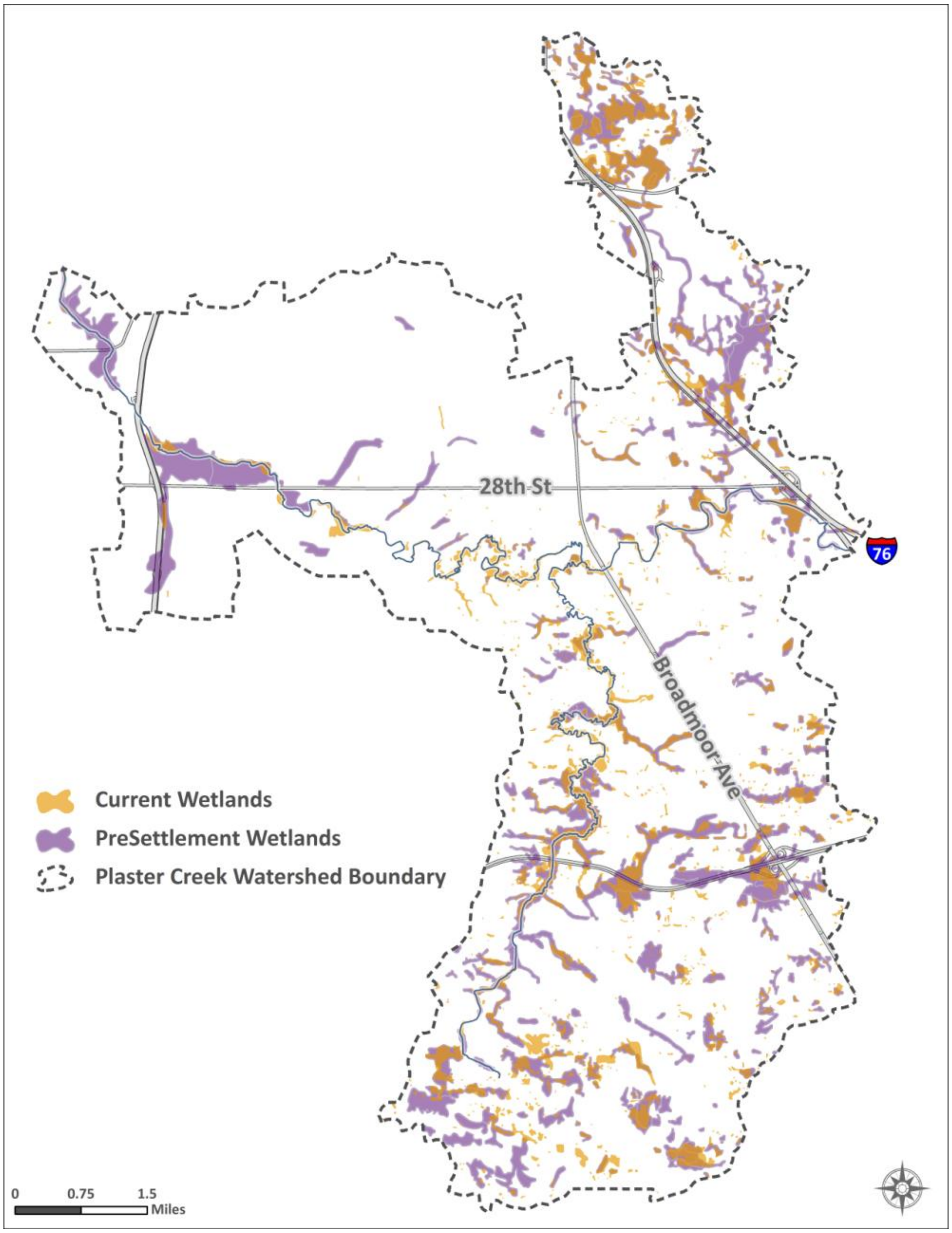

Figure 2-2. Current and pre-settlement wetlands (data provided by DEQ).

2.2 Soils

Hydrologic soil groups (HSG) are based upon a classification system that describes a soils drainage capacity, which is a quality of particular interest in BMP modeling. Soils belonging to HSG A are primarily sandy or loamy and have a high capacity for water infiltration, while HSG D soils have high clay content or are heavily compacted and have a low infiltration capacity. Much of the watershed does not have an associated HSG (Figure 2-3); these areas are typically mapped as urban land in the soil survey. The majority of the mapped watershed contains HSG C soils, although there are areas that have HSG A and B soils, primarily surrounding the main stream channels.

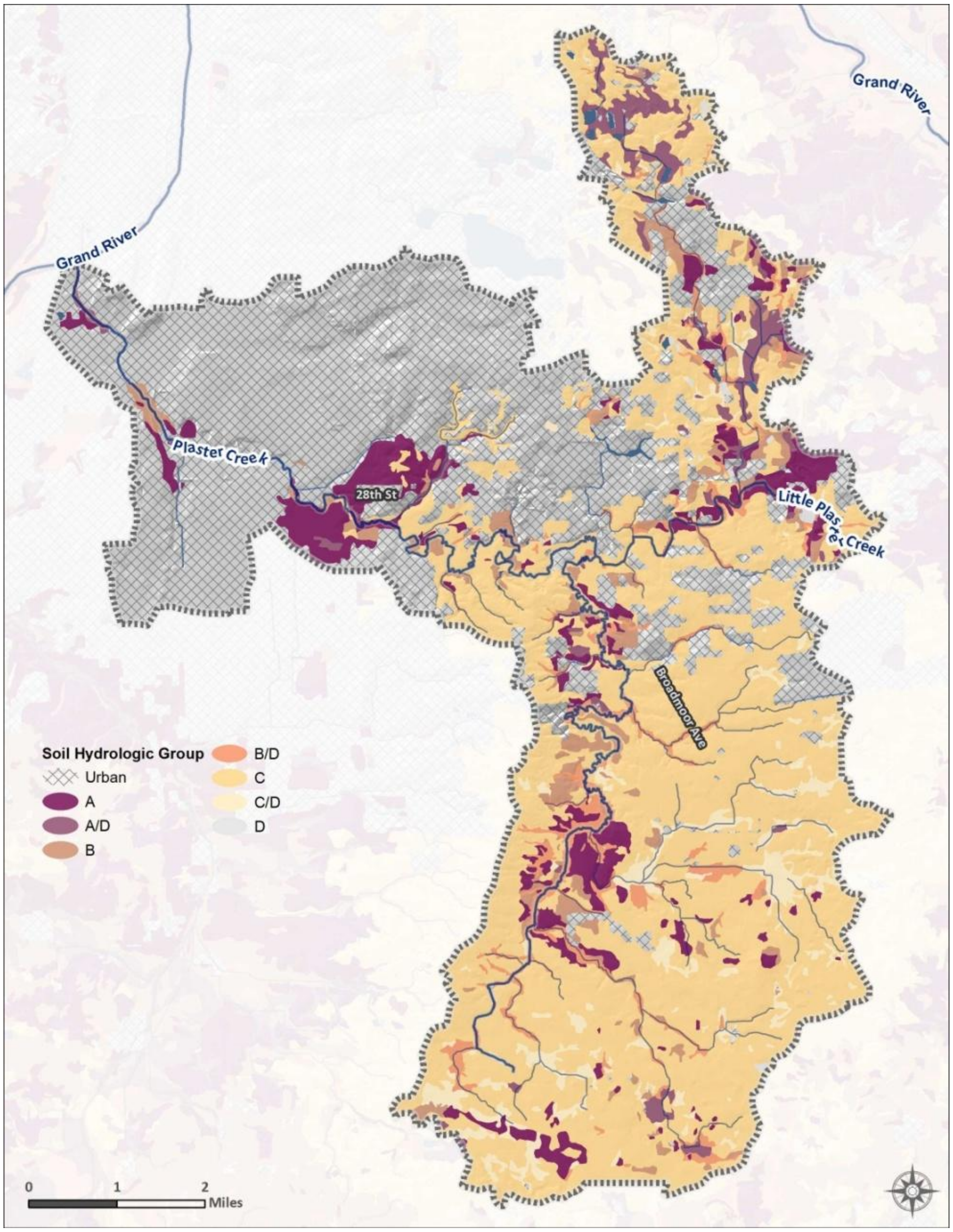

Figure 2-3. Plaster Creek watershed soils.

2.3 *Rainfall-Runoff and Pollutant Loadings*

A watershed model was developed for the entire Plaster Creek watershed, using the Long-Term Hydrologic Impact Analysis (L-THIA; available at https://engineering.purdue.edu/~lthia/) developed by Purdue University, to determine the existing pollutant loads associated with each subwatershed and assist in selecting pilot areas for further analysis. L-THIA is a tool that provides estimates of changes in runoff and nonpoint source pollution resulting from past or proposed land use changes. It produces long-term average annual runoff for a land use configuration, based on long-term climate data. By using many years of climate data in the analysis, L-THIA focuses on the average impact, rather than an extreme year or storm.

2.3.1 Model Inputs

L-THIA was used to model each of the 12 subwatersheds identified in the Plaster Creek WMP. Inputs to the L-THIA model were compiled from the 2006 NLCD, the Soil Survey Geographic Database (SSURGO), and a land use zoning database created by the Grand Valley Metropolitan Council (GVMC). The primary input to the L-THIA model are hydrologic response units (HRUs) that combine basic land use categories with HSGs, which are a classification of soils based upon their capacity to infiltrate water. Available datasets were pre-processed into a format compatible with L-THIA using the following steps:

- The original land classifications in the NLCD dataset were generalized to match L-THIA inputs (Table 2-2).
- The three developed classifications from NLCD were further modified based upon the zoning classes from the GVMC to fit the L-THIA developed land uses (Table 2-3).
- Soils from the SSURGO database that were not assigned a HSG were given values conservative HSG classifications based on their Map Unit Descriptions (Table 2-4).

The resulting land use and soil group datasets were combined to produce the datasets required for input into L-THIA.

Table 2-2. Conversion of NLCD to L-THIA land uses

NLCD land cover categories	L-THIA land uses
Water	Water/Wetlands
Wetland	
Developed, Open Space	Open Spaces
Bare Rock/Sand/Clay	
Developed, Light Intensity	Commercial/Industrial/Residential[a]
Developed, Medium Intensity	
Developed, High Intensity	
Forest	Forest
Shrub	
Cultivated Crops	Agricultural
Grassland	Grass/Pasture
Pasture	

NLCD = National Land Cover Dataset

a. Land uses further subdivided in Table 2-3

Table 2-3. Conversion of GVMC zoning classifications to L-THIA land uses

GVMC zoning classifications	L-THIA land uses
Community Commercial	Commercial
Neighborhood Commercial	
Office	
Regional Commercial	
Right-of-Way	
Residential - 5 to 8 Units per Acre	High Density Residential
Residential - 9 to 12 Units per Acre	
Airport	Industrial
Heavy Industry	
Industry	
Residential - 1 to 4 Units per Acre	Low Density Residential
Residential - 1 to 5 Acres per Residence	
Residential - Greater than 5 Acres per Residence	

Note: GVMC = Grand Valley Metropolitan Council

Table 2-4. Assigned HSG values based upon SSURGO Map Unit Description

HSG	Map unit symbol	Map unit description (excerpt from SSURGO)
D	63 - Urban land-Cohoctah complex	This map unit is a complex of Urban land and Cohoctah soil. The Cohoctah soil is a very poorly drained loamy soil. It is subject to frequent flooding. Permeability is moderately rapid in the upper part and very rapid in the lower part.
B	75 - Udorthents, loamy	These are moderately well drained or well drained areas in which soil material has been so altered that identification of the soil series is not feasible. Texture ranges from sandy loam to clay loam.
B	81B - Urban land-Spinks complex	This is a complex of Urban land and Spinks soils. The Spinks soil is a well-drained sandy soil. Permeability is moderately rapid and the available water capacity is low. Runoff is very slow to medium, depending on slope.
C	82B - Urban land-Perrinton complex	This is a complex of Urban land and Perrinton soils. The Perrinton soil is a well-drained or moderately well drained loamy soil. Permeability is moderately slow and the available water capacity is high.
D	78 - Urban land	No Description.
D	74 - Dumps	No Description.
D	W - Water	No Description.

2.3.2 Model Results

The L-THIA Basic model was used to determine average annual runoff and pollutant loadings from each of the 12 delineated subwatersheds. The following results present the average annual runoff volume, fecal coliform load, nitrogen load, phosphorus load, and suspended solids load. The model results are weighted by area and ranked from lowest (1) to highest (12) pollutant load.

Average Annual Runoff Volume

The average annual runoff volume is the amount of rainfall that is converted to runoff during the year. Figure 2-4 shows the ranking and distribution of runoff volume in the Plaster Creek watershed. Runoff volumes increased as development intensified. The highest runoff volumes occur in the lower reaches of the watershed. While the L-THIA model did not simulate high runoff volumes in the headwaters area (i.e., subwatersheds 0 and 1), the presence of tiling in this area is likely contributing runoff volumes and peak flow rates that are causing downstream bank erosion.

Subwatershed ID	Subwatershed area (acres)	Runoff volume (acre-feet/year)	Normalized runoff (acre-feet/year/acre)	Rank
11	2,802	1,351	0.48	12
8	2,040	979	0.48	11
10	4,101	1,866	0.46	10
9	2,507	1,081	0.43	9
4	2,963	1,272	0.43	8
6	8,204	3,378	0.41	7
7	163	58	0.35	6
2	5,350	1,643	0.31	5
5	996	251	0.25	4
0	2,825	594	0.21	3
1	3,713	746	0.20	2
3	784	153	0.20	1

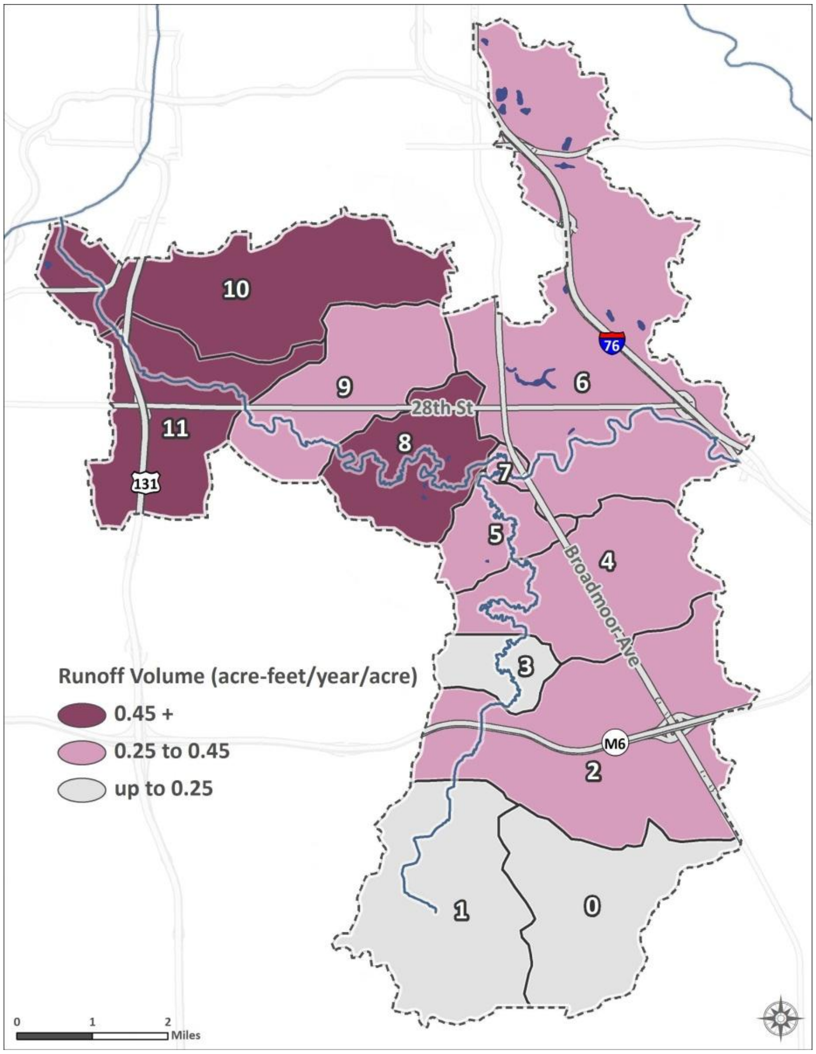

Figure 2-4. Average annual runoff volume yields and ranking in the Plaster Creek watershed.

Nitrogen

The L-THIA model simulated a total of 60,872 pounds of nitrogen per year in the watershed. Most of this load originates from high density residential properties, followed by agriculture and a nearly equal contribution from commercial and industrial lands (Figure 2-5). Nitrogen loading shows a similar spatial distribution to runoff volume shown in Figure 2-4, with the highest pollutant yields concentrated downstream (Figure 2-6).

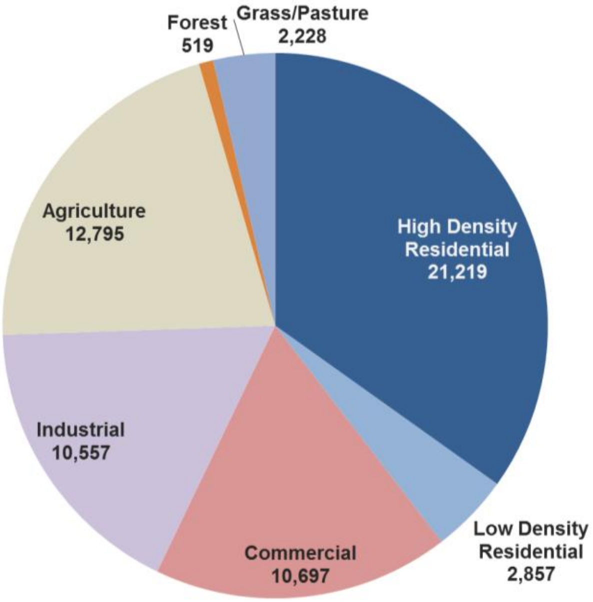

Figure 2-5. Contributions of each land use to nitrogen loading (in pounds per year).

Subwatershed ID	Subwatershed area (acres)	Nitrogen (pounds/year)	Normalized N load (pounds/acre/year)	Rank
8	2,040	4,179	2.05	12
11	2,802	5,632	2.01	11
10	4,101	8,242	2.01	10
9	2,507	4,881	1.95	9
0	2,825	4,880	1.73	8
6	8,204	12,931	1.58	7
1	3,713	5,845	1.57	6
2	5,350	8,025	1.50	5
4	2,963	4,367	1.47	4
7	163	196	1.20	3
5	996	939	0.94	2
3	784	660	0.84	1

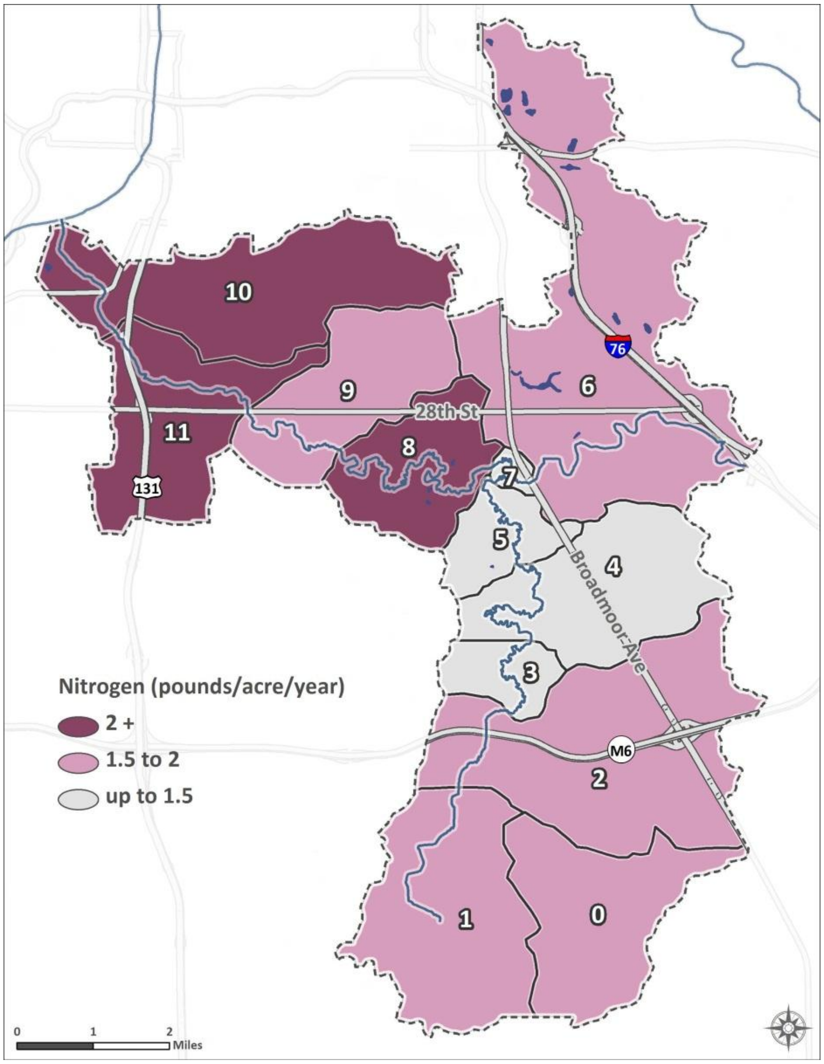

Figure 2-6. Nitrogen yield and ranking in the Plaster Creek watershed.

Phosphorus

The L-THIA model simulated a total of 16,252 pounds of phosphorus per year in the watershed. Most of this load originates from high density residential properties, followed by agriculture and a nearly equal contribution from commercial and industrial lands (Figure 2-7). Higher phosphorus yields are concentrated near the mouth where development is intense and in the headwaters where agricultural activities are prevalent (Figure 2-8).

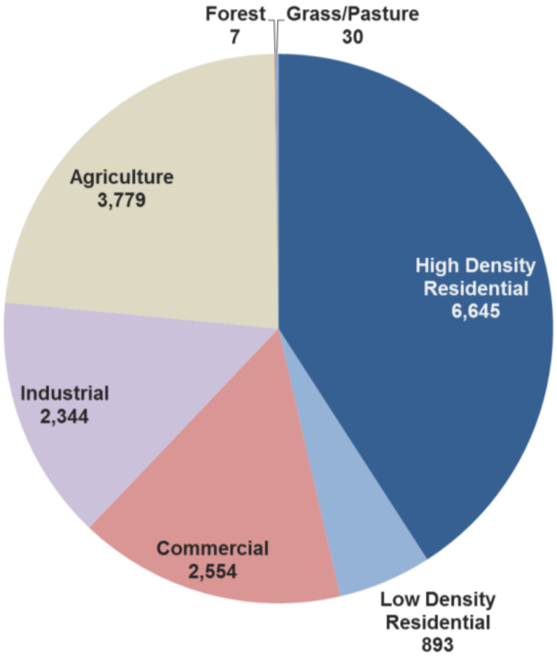

Figure 2-7. Contributions of each land use to phosphorus loading (in pounds per year).

Subwatershed ID	Subwatershed area (acres)	Phosphorus (pounds/year)	Normalized P load (pounds/acre/year)	Rank
10	4,101	2,375	0.58	12
9	2,507	1,431	0.57	11
8	2,040	1,164	0.57	10
11	2,802	1,540	0.55	9
0	2,825	1,352	0.48	8
1	3,713	1,600	0.43	7
6	8,204	3,276	0.40	6
2	5,350	2,039	0.38	5
4	2,963	967	0.33	4
7	163	43	0.26	3
5	996	235	0.24	2
3	784	174	0.22	1

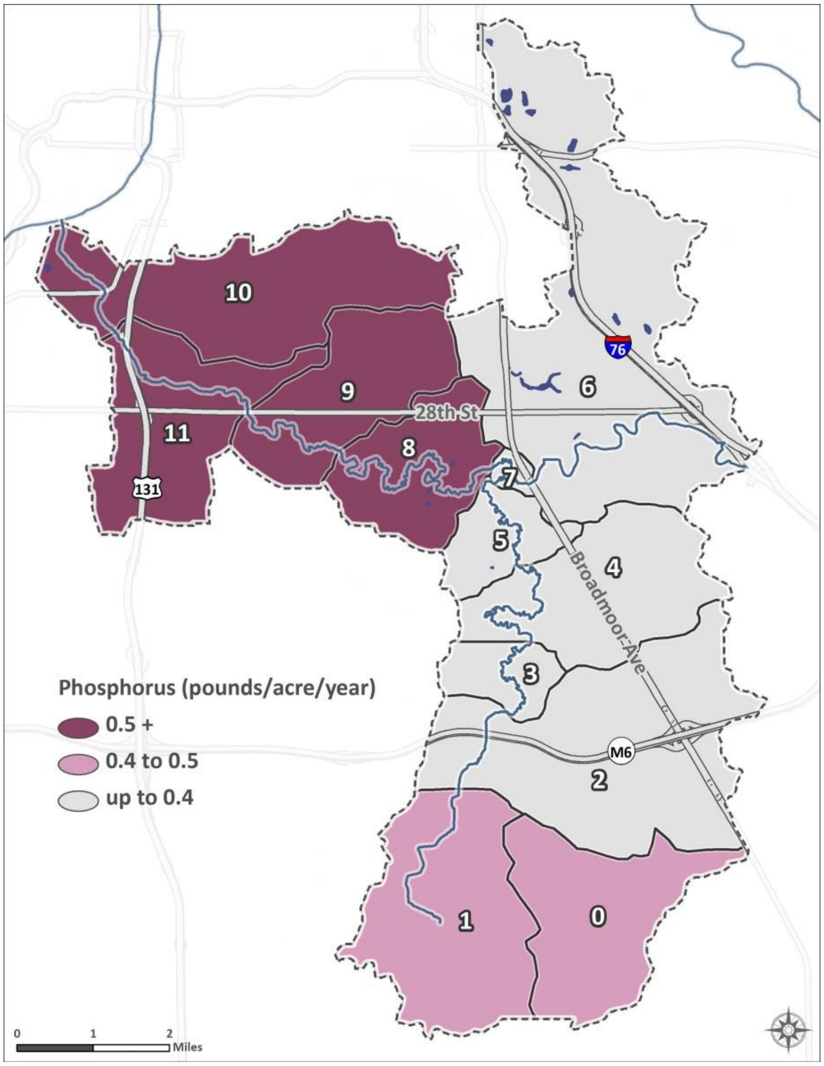

Figure 2-8. Phosphorus yield and ranking in the Plaster Creek watershed.

Suspended Solids

Suspended solid loading is a result of stormwater carrying particulate material into waterways. These particles do not settle out immediately and become suspended in the water, degrading habitats by limiting light penetration and clogging the gills of fish and other aquatic organisms. The L-THIA model simulated a total of 1,807,773 pounds of sediment per year in the watershed (Figure 2-9). Most of this load originates from developed properties (industrial, commercial, and high density residential). Agriculture contributes 17 percent of the watershed load. Figure 2-10 presents the suspended solids loading results by subwatershed.

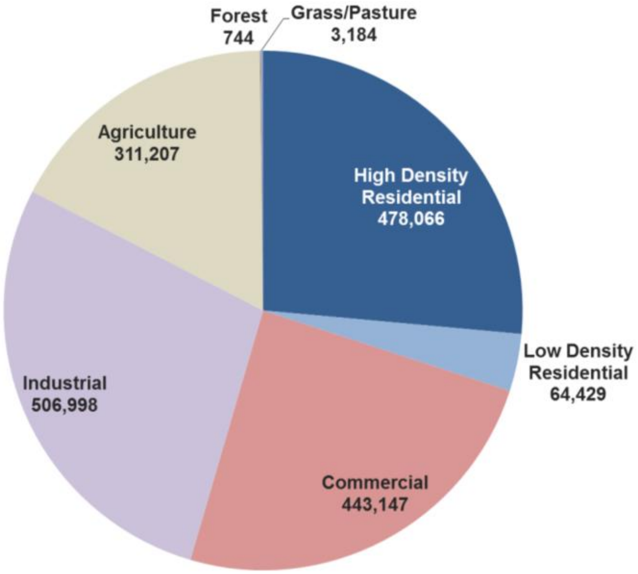

Figure 2-9. Contributions of each land use to suspended solid loading (in pounds per year).

Subwatershed ID	Subwatershed area (acres)	Suspended solids (pounds/year)	Normalized SS load (pounds/acre/year)	Rank
11	2,802	182,571	65.17	12
4	2,963	183,990	62.09	11
8	2,040	119,818	58.73	10
10	4,101	237,599	57.94	9
6	8,204	418,018	50.96	8
9	2,507	127,376	50.80	7
2	5,350	240,550	44.96	6
7	163	7,245	44.37	5
0	2,825	114,210	40.42	4
1	3,713	136,317	36.71	3
5	996	26,765	26.87	2
3	784	13,216	16.87	1

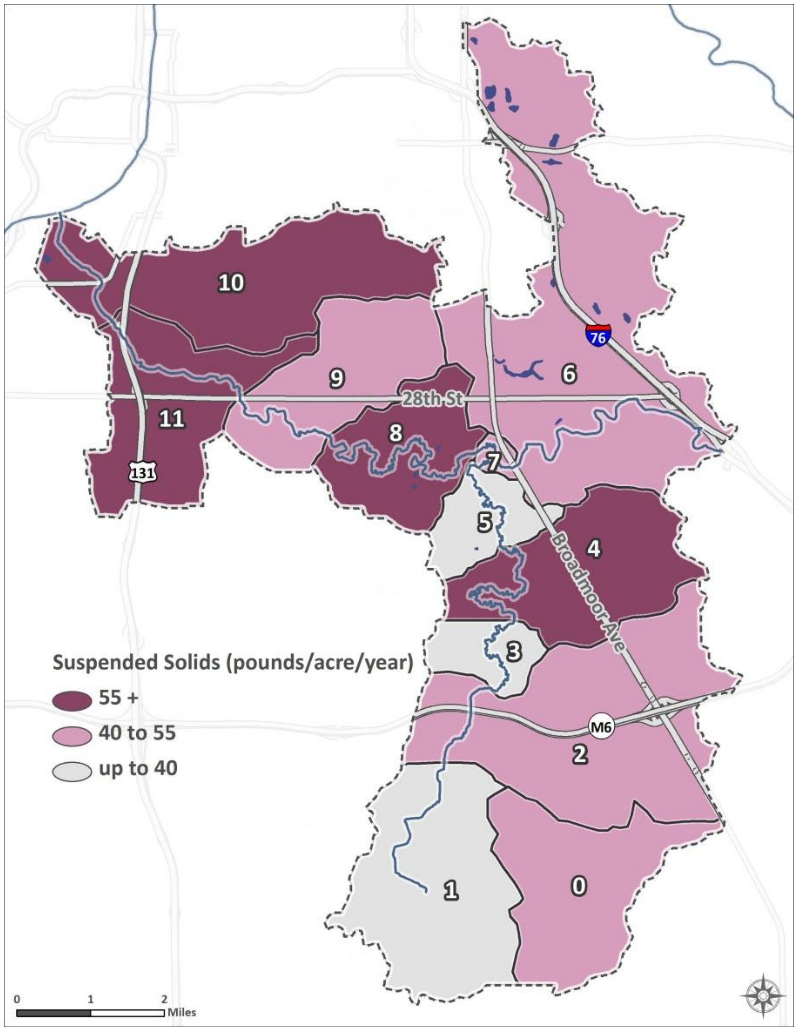

Figure 2-10. Suspended solid load and ranking in the Plaster Creek watershed.

Pathogens

Sources of pathogens, specifically fecal coliform as modeled in L-THIA, predominately include animal and human waste. Wastewater discharges from wastewater treatment facilities; septic systems; pet, livestock, and wildlife waste; and manure are all probably sources within the watershed. Bacteria are also present in the soils and can persist in stream sediments over time. High levels of bacteria can cause unsafe conditions in waterways and impair recreational uses.

High levels of bacteria correspond to the most developed areas in the watershed. Nearly half of the modeled pathogen load originates from high density residential areas, followed by industrial, agricultural, and commercial land uses (Figure 2-11). Loading is highest in the heavily developed areas (refer to Figure 2-12 for the fecal coliform loading by subwatershed).

Specific practices in agricultural areas were not inventoried in the watershed; it is likely that animal agricultural activities in the headwaters are contributing additional bacteria to the stream that are not reflected in the model results.

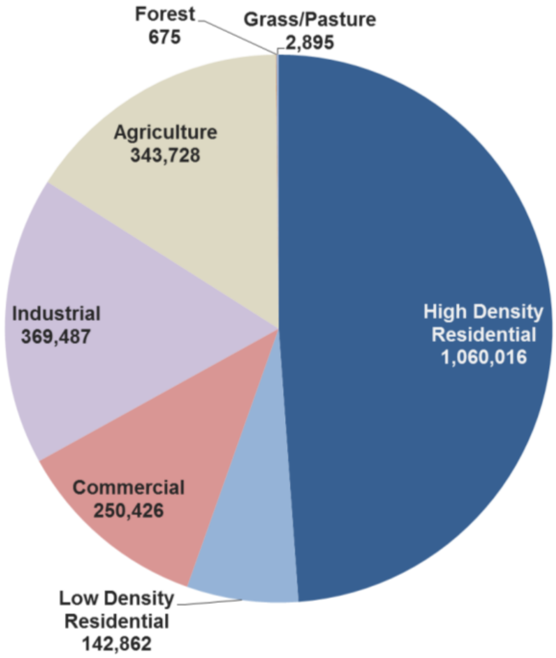

Figure 2-11. Contributions of each land use to fecal coliform loading (in millions of coliform per year).

Subwatershed ID	Subwatershed area (acres)	Bacteria (millions of coliform/year)	Normalized bacteria load (millions of coliform/acre/year)	Rank
10	4,101	370,522	90.4	12
9	2,507	217,698	86.8	11
8	2,040	171,975	84.3	10
11	2,802	225,882	80.6	9
6	8,204	447,792	54.6	8
4	2,963	150,327	50.7	7
0	2,825	128,725	45.6	6
2	5,350	234,859	43.9	5
7	163	7,150	43.8	4
1	3,713	151,941	40.9	3
5	996	36,774	36.9	2
3	784	26,339	33.6	1

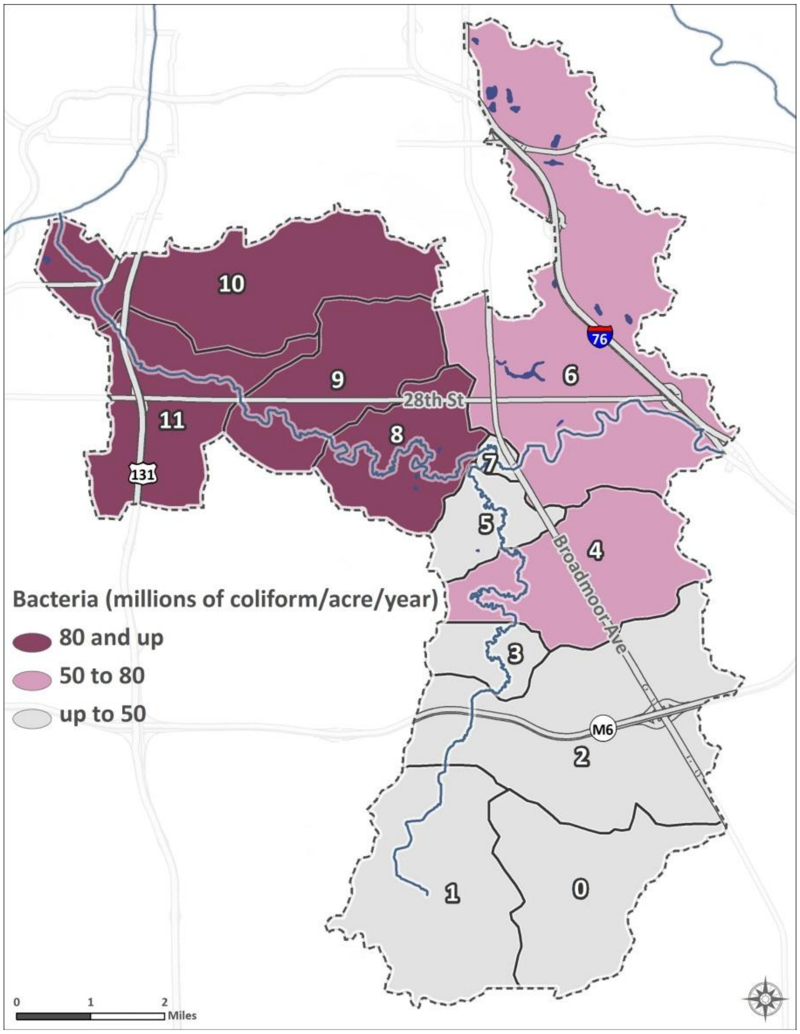

Figure 2-12. Bacteria load and ranking in the Plaster Creek watershed.

2.4 Priority Watersheds

Subwatersheds have been ranked to determine priority watersheds based on the model results. Implementation of BMPs within the highest priority watersheds will potentially provide the most significant effect on water quality improvement.

Each subwatershed was given a score between 1 and 12 for each of the water quality parameters, with 12 being the highest loading subwatersheds (Table 2-5). These scores were then summed across all categories, and the cumulative score was used to determine which subwatersheds are contributing the most to stream impairments. Figure 2-13 summarizes the overall ranking and shows that subwatershed loading increases from the headwaters to the lower subwatersheds of Plaster Creek. The Plaster Creek WMP also ranked the subwatersheds by level of impairment, but used a different set of criteria. In addition to nitrogen, phosphorus, and sediment loading, the Plaster Creek WMP considered septic systems, miles of section 303(d)-listed stream channel, and *E. coli* concentration. Table 2-5 includes these rankings for comparison. The *Plaster Creek WMP NPS rank* refers to the ranking based upon nitrogen, phosphorus, and sediment loading, while the final rank includes the aforementioned additional criteria. Subwatersheds 8, 10, and 11 have the highest ranking and are priority watershed for BMP implementation. Although subwatersheds 0, 1 and 2, which are predominately agricultural, have fairly low rankings compared to the heavily urbanized watersheds, the L-THIA model is not likely representing the full effects of tile drainage on agricultural lands. Tile drainage can lead to flashy flows and increased pollutant loading, similar to those found in urbanized areas.

Table 2-5. Subwatershed priority ranking

Subwatershed ID	Subwatershed area (acres)	Annual runoff volume (acre-feet/year)	Nitrogen load (pounds/year)	Phosphorus load (pounds/year)	Suspended solids load (pounds/year)	Pathogen load (millions of coliform/year)	Runoff volume rank	Nitrogen rank	Phosphorus rank	Suspended solids rank	Pathogen rank	Cumulative score	Cumulative rank	Plaster Creek WMP NPS rank	Plaster Creek WMP final rank
11	2,802	1,351	5,632	1,540	182,571	225,882	12	11	9	12	9	**53**	**12**	11	10
8	2,040	979	4,179	1,164	119,818	171,975	11	12	10	10	10	**53**	**11**	5	7
10	4,101	1,866	8,242	2,375	237,599	370,522	10	10	12	9	12	**53**	**10**	9	3
9	2,507	1,081	4,881	1,431	127,376	217,698	9	9	11	7	11	**47**	**9**	6	4
6	8,204	3,378	12,931	3,276	418,018	447,792	7	7	6	8	8	**36**	**8**	12	6
4	2,963	1,272	4,367	967	150,327	183,990	8	4	4	11	7	**34**	**7**	7	8
0	2,825	594	4,880	1,352	114,210	128,725	3	8	8	4	6	**29**	**6**	3	2
2	5,350	1,643	8,025	2,039	240,550	234,859	5	5	5	6	5	**26**	**5**	10	12
1	3,713	746	5,845	1,600	136,317	151,941	2	6	7	3	3	**21**	**4**	8	11
7	163	58	196	43	7,245	7,150	6	3	3	5	4	**21**	**3**	2	9
5	996	251	939	235	26,765	36,774	4	2	2	2	2	**12**	**2**	4	5
3	784	153	660	174	13,216	26,339	1	1	1	1	1	**5**	**1**	1	1

NPS = nonpoint source; WMP = watershed management plan

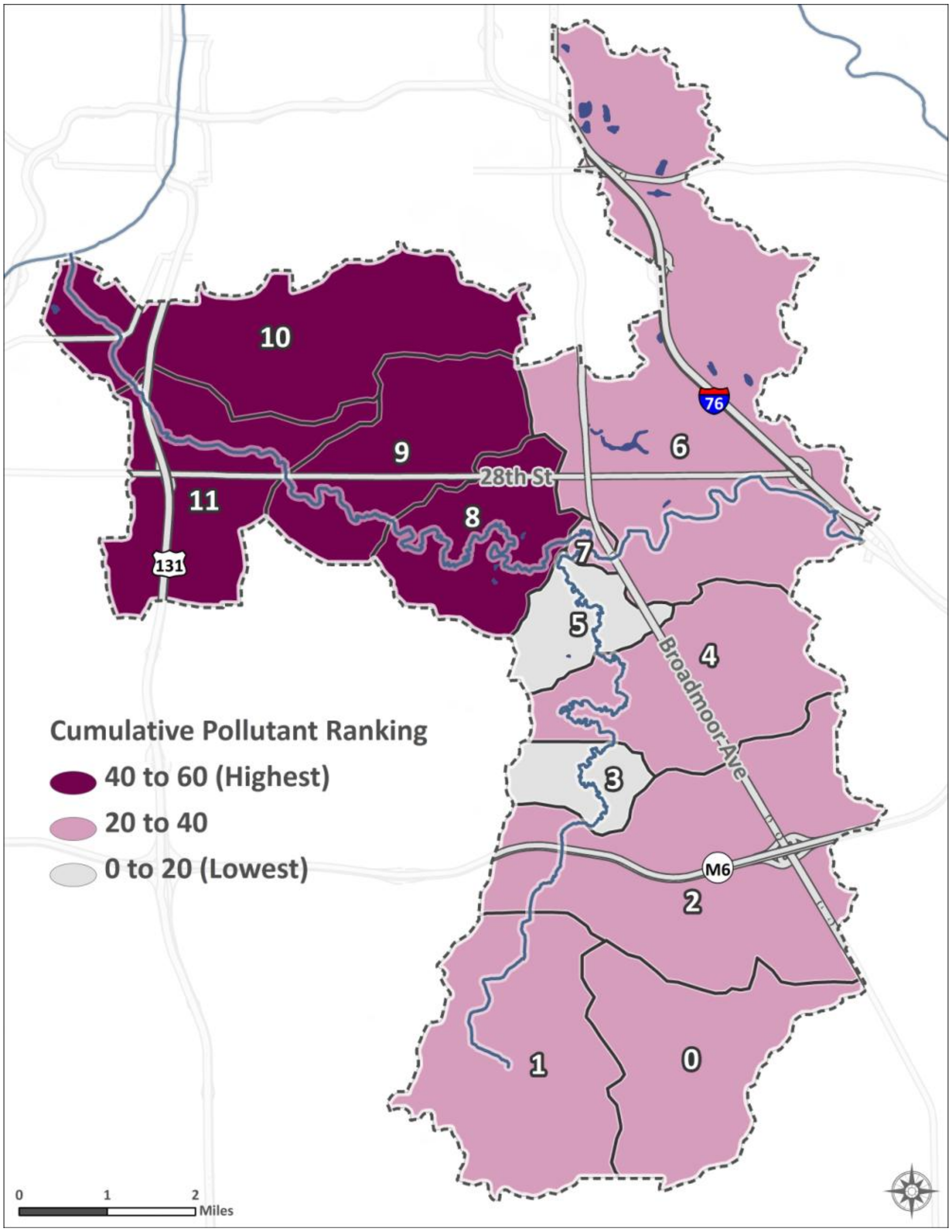

Figure 2-13. Priority ranking of subwatersheds in the Plaster Creek watershed.

2.5 Pilot Area Selection

A series of pilot areas were identified (Figure 2-14 and Figure 2-15) within the watershed representing the most common land uses for further analysis. These include-high density residential (HDR), low-density residential (LDR), commercial (COM), industrial (IND), and agricultural (AG) land uses that overlay various soil hydrologic groups (Table 2-6). Analysis includes an evaluation of BMPs and determining the most cost-effective combination of BMPs that meet watershed goals for each land use. Results are then extrapolated to the entire watershed to identify an implementation scenario that would achieve watershed goals.

Table 2-6. Descriptions of the pilot areas

Site label	Area (acres)	Nearby road intersection
HDR-B	27	Burton St. & Towner Ave.
HDR-C	54	Boston St. & Conlon Ave.
LDR-C	124	Forest Hill Ave. & Braeburn St.
COM-X	46	Paris Ave. & 28th St.
IND-C	44	44th St. & Patterson Ave.
AG-X	126	76th St. & Brenton Ave.

AG = agricultural; B = hydrologic soil group B; C = hydrologic soil group C; COM = commercial; HDR = high-density residential; IND = industrial; LDR = low-density residential; X = multiple hydrologic soil groups.

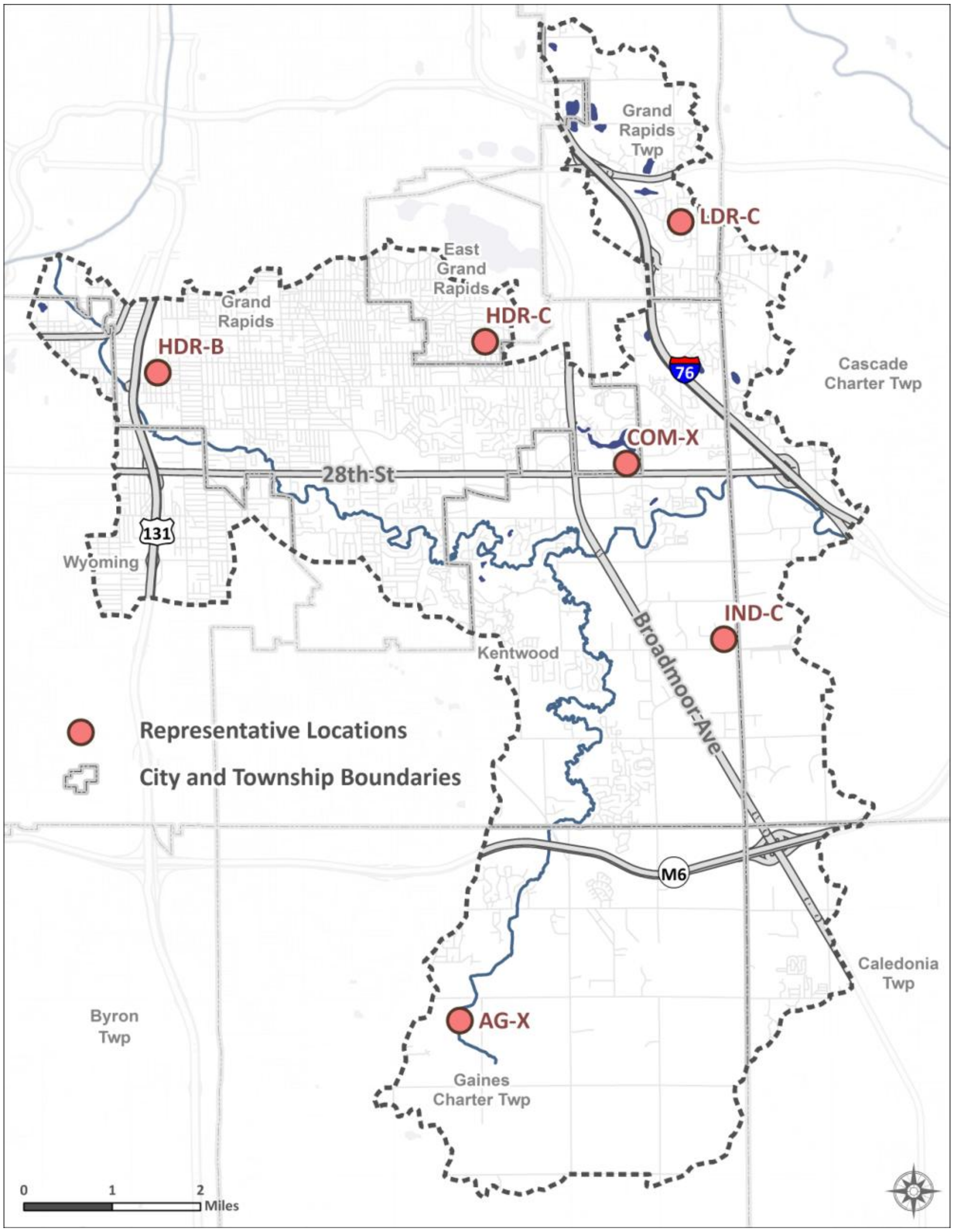

Figure 2-14. Pilot areas (mapped locations).

Figure 2-15. Pilot areas (aerial photographs).

3. BMP Optimization Approach

Development of effective stormwater management strategies is an important part of the transition from water quality program planning to implementation. The goal of this project is to provide technical support for local planning and water quality implementation by analyzing and selecting the most appropriate suite of BMPs to achieve pollutant load reductions.

Five general steps were used in this pilot effort to evaluate stormwater management opportunities:

Step 1 - Establish baseline conditions
Step 2 - Identify potential BMPs
Step 3 - Determine BMP configurations and performance
Step 4 - Identify BMP costs
Step 5 - Perform BMP optimization analysis

Figure 3-1 presents a general flow diagram of the process and identifies considerations and inputs. Information on BMP effectiveness coupled with cost information was used to identify the most economical alternatives through an optimization step. The goal is to target specific implementation activities that address water quality problems related to stormwater. The remainder of this section presents summaries of each of the five analysis steps presented in Figure 3-1.

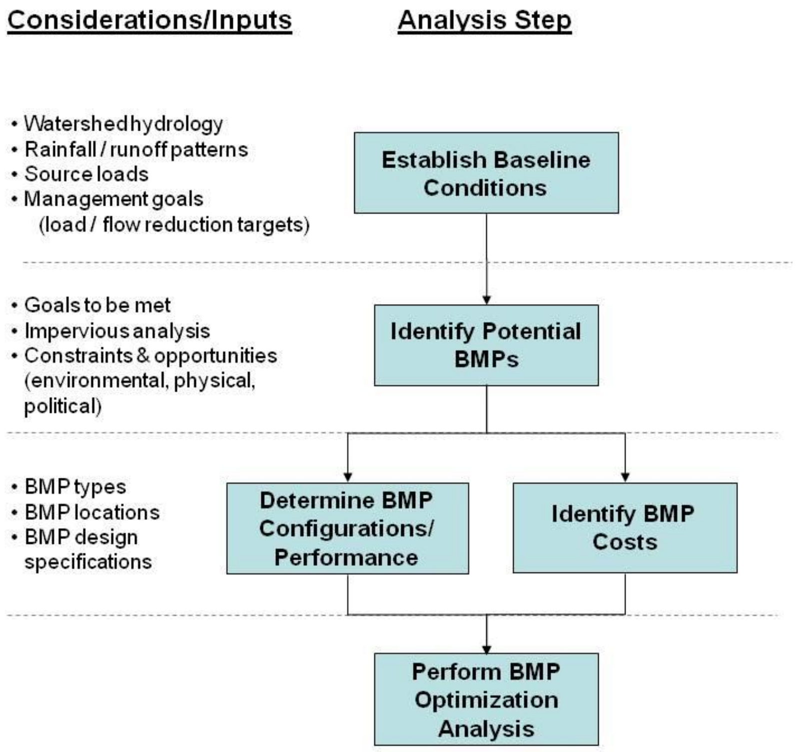

Figure 3-1. Process for BMP targeting and optimization.

Step 1 – Establish Baseline Conditions. The initial step in evaluating and selecting BMPs to achieve stormwater management program goals is to establish baseline conditions. Baseline conditions reflect the existing flow conditions and pollutant loading from a stormwater source. Identifying and understanding baseline conditions provides a starting point from which improvements are made and progress is measured (i.e., BMP effectiveness is measured against the established baseline conditions).

Step 2 – Identify Potential BMPs. In the second step, baseline condition information is coupled with local factors to generate a list of potential BMPs. Information about baseline conditions provides a benchmark that helps stormwater planners identify potential BMPs, or combinations of BMPs, to achieve overall program goals. In its simplest form, for example, the runoff volume produced by a certain design storm can be used to estimate detention needs. While identifying and selecting potential BMPs, it is important to understand other factors that might affect successful BMP implementation. These factors include environmental, physical, social, and political considerations.

Step 3 – Determine BMP Configurations and Performance. The goal of this step is to evaluate the list of potential BMPs and determine their overall performance at the watershed-scale. The intent is to identify options prior to selecting final BMP strategies. Assessing configuration opportunities, stormwater planners can examine the expected performance of potential BMPs to help select those that will meet the goals identified in Step 1. Although challenging, this activity is essential to selecting BMPs with the most potential for making progress toward management objectives. For purposes of describing the overall process, this is discussed as a separate step after compiling the list of possible BMPs. However, stormwater planners can make assumptions and determinations about BMP applicability, configuration and performance while generating the list.

Step 4 – Identify BMP Costs. Identifying BMP costs is an important undertaking for stormwater planners. Resource constraints can affect the number and type of BMPs that can be used to achieve progress toward program goals. At a minimum, stormwater planners should compare costs and expected pollutant reductions to ensure the final suite of BMPs will provide the most reductions for the least amount of money. For stormwater planners engaged in a more rigorous BMP optimization analysis, cost information on potential BMPs is essential for developing cost-effectiveness ratios (i.e., cost per unit of pollutant removed) to compare different BMPs for one type of land use or across several types of land uses.

Step 5 – Perform BMP Optimization Analysis. At this stage, stormwater planners have identified the suite of feasible BMPs based on site-specific needs, goals, opportunities and constraints. Depending on the size of the planning area, the implementation goals and the resources available, there could be any number of combinations of BMP types and locations to meet goals. A goal of targeting and optimization is to examine management strategies based on opportunities consistent with site suitability considerations. For example, slope and soil infiltration rates are key factors that affect successful performance of structural BMPs.

To select the final BMP strategy, stormwater planners generally evaluate, prioritize or rank the potential BMPs based on relevant decision criteria, either qualitatively or quantitatively. Decision criteria may include short-term and long-term costs, BMP performance, expected progress toward watershed goals, and compatibility with other planning priorities and objectives. Depending on the area and number of BMPs needed, a stormwater planner might use a qualitative evaluation of potential BMPs and targeted locations based on professional and local knowledge. Simple spreadsheet analysis could also be employed to identify the most appropriate and cost-effective scenario. While adaptive management can support the short-term implementation of priority BMPs with subsequent evaluation and modification, a stormwater planner tries to identify the most effective scenario first to minimize the need for additional BMPs and associated implementation costs. Therefore, the level of detail for the evaluation to select final BMPs can be driven by the benefit of the additional analyses compared to the potential costs to correct ineffective implementation.

4. Establish Baseline Conditions

Effective implementation planning starts with a review of baseline conditions and watershed-scale factors that contribute to documented water quality problems. An understanding of the basic hydrology of the watershed is necessary to establish baseline conditions. The water cycle is a natural, continuous process that can be generalized as the movement of rainfall from the atmosphere to the land, then back to the atmosphere. The balanced water cycle of precipitation, evapotranspiration, infiltration, groundwater recharge, and stream base flow is a key part of sustaining water resources (Figure 4-1). When identifying and establishing baseline conditions, a critical part of the analysis involves an assessment of watershed characteristics that affect the resultant runoff. Source areas and delivery mechanisms that will be the focus of targeted BMPs are driven by watershed response to precipitation.

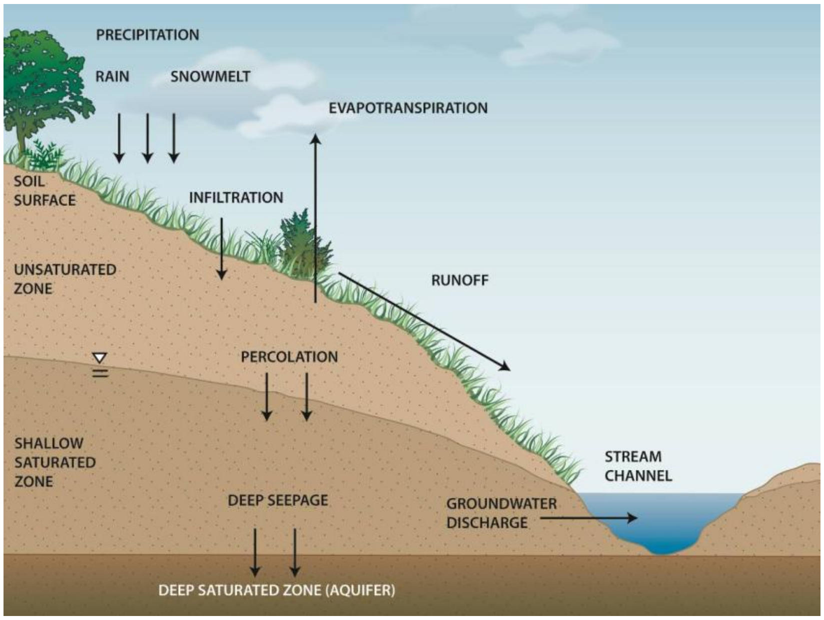

Figure 4-1. Simplified representation of the elements in the water cycle.

Modeling was used to help establish baseline conditions. Watershed models use site-specific spatial and temporal elements to characterize the rainfall runoff response. The watershed model time series represent the existing condition (or baseline conditions), which serves as the reference point from which stormwater improvement will be measured.

4.1 Model Setup

The pilot areas identified in Section 2.4 were modeled using the Loading Simulation Platform in C++ (LSPC). LSPC is a re-coded version of the Hydrologic Simulation Program in Fortran (HSPF) watershed model. LSPC provides a comprehensive watershed and receiving water quality modeling framework that is generally considered one of the most advanced available. The current version of LSPC is version 3.1 and is available for download at http://www.epa.gov/athens/wwqtsc/html/lspc.html.

Each pilot area was modeled as a single subwatershed (Table 4-1). Each subwatershed was simulated individually with no routing from one to the other, therefore the runoff and associated loads being simulated should not be used to compare directly with in-stream concentrations. There are a total of 11 land uses in the model configuration with agriculture being represented as a single land use and the remaining land uses being represented by both impervious and pervious classes. The model was run continuously on an hourly timestep between 1/1/1980 and 1/31/2012.

Table 4-1. Plaster Creek baseline model setup

Land use	Hydrologic soil group	Acres	Percent pervious	Percent impervious
Agricultural	C	126.0	100%	0%
Commercial	C	40.6	33%	67%
Industrial	C	40.2	37%	63%
Low Density Residential	C	127.3	73%	27%
High Density Residential	C	55.4	57%	43%
High Density Residential	B	32.8	53%	47%

The snow and hydrology modules were parameterized by using default assumptions based on Technical Note 6 (EPA 2000) and best professional judgment. Infiltration rate was the only parameter differentiated between hydrologic soil groups B and C and was parameterized with the mean of the range stated in Technical Note 6. Additionally, parameter differentiation was developed for only impervious and pervious land units, i.e. pervious urban C and pervious agriculture C utilized the same set of parameters.

Water quality was simulated for the following parameters: TSS, TN, TP, and *E. coli*. Event mean concentrations (EMCs) were used to define the concentration of the constituent in runoff for developed land uses and for runoff and shallow lateral flows (interflow) for agricultural areas (Table 4-2) based on the EMCs used in the L-THIA model. Loading from agricultural interflow was included to represent contributions from tile drainage typically used to reduce waterlogging of agricultural fields.

Table 4-2. EMC by constituent and land use

Constituent	Residential	Commercial	Industrial	Agricultural
TSS (mg/L)	41.0	55.5	60.5	107
TP (mg/L)	0.57	0.32	0.28	1.3
TN (mg/L)	1.82	1.34	1.26	4.4
E. coli (MPN/100mL)	10,931	5,373	1,281	21,813

MPN – Most probable number

4.2 Hydrologic Response

The goal of hydrologic setup and parameterization was to ensure the individual land uses responded similarly to theoretical hydrologic regimes as presented in Figure 4-2. Figure 4-3 presents a summary of the hydrologic response showing an average annual water budget and Figure 4-4 presents the modeled annual average runoff by land use. Agricultural land use has the highest evapotranspiration and lowest runoff due to a lack of impervious area. Developed areas with high levels of imperviousness have higher runoff and lower evapotranspiration. Low intensity development falls in between the response of agriculture and land uses with higher levels of imperviousness.

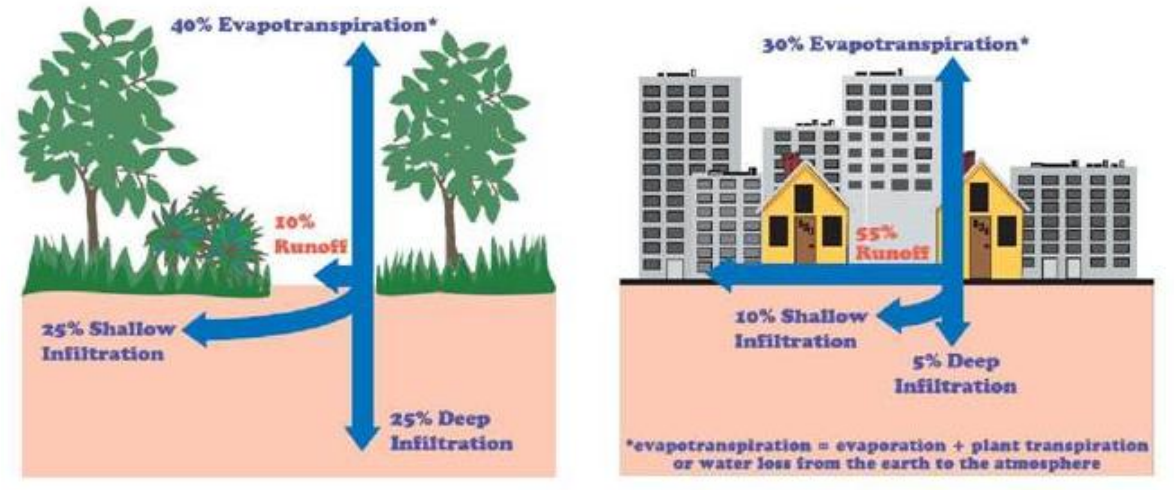

Figure 4-2. Effect of land use change on hydrologic regime (American Rivers 2010).

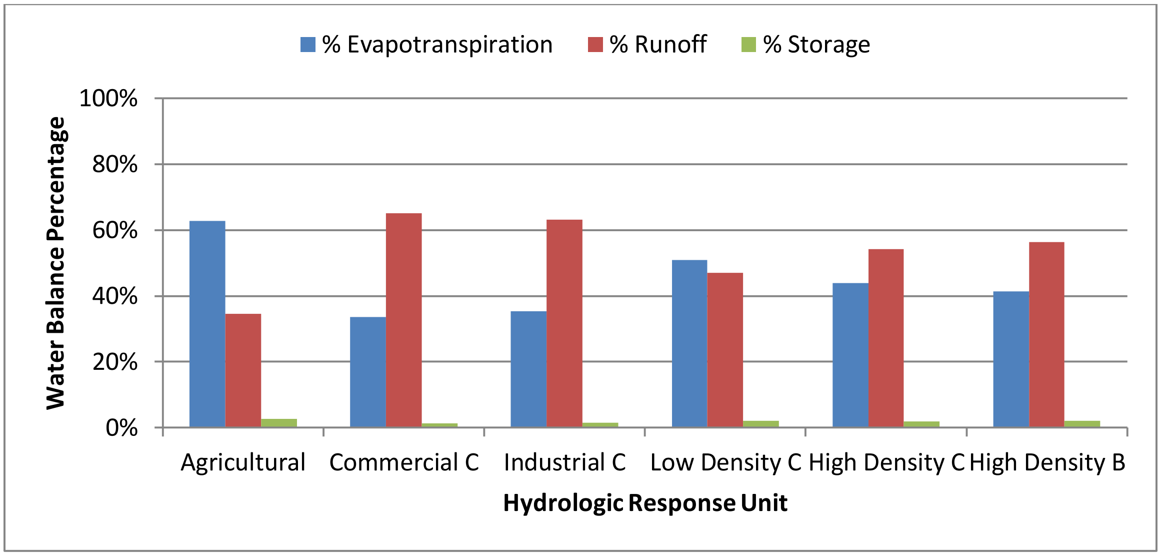

Figure 4-3. Average annual water budget by land use.

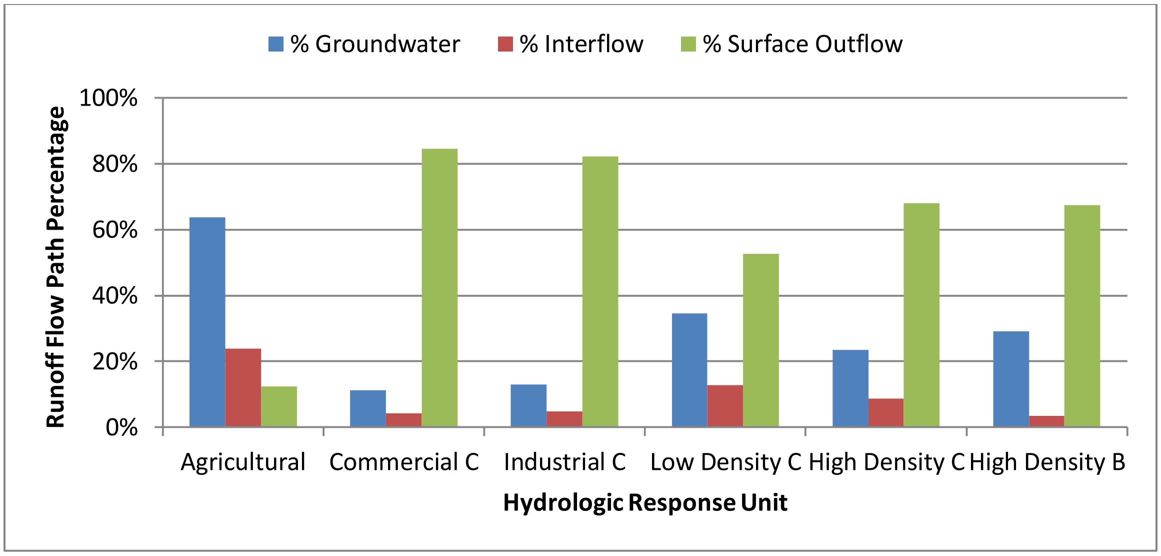

Figure 4-4. Average annual runoff by land use.

4.3 Water Quality Response

The water quality model was parameterized with surface flow concentrations for all land uses and, additionally, interflows for agricultural areas. This means that pollutant concentrations in outflows only differ by land use; therefore load by land use is entirely dependent on the volume of water in the surface flow path for developed land uses and surface flow and interflow for agriculture. Figure 4-5 through Figure 4-8 present the annual average yield for each water quality parameter. Figure 4-9 through Figure 4-12 present the annual yield over time for each water quality parameter.

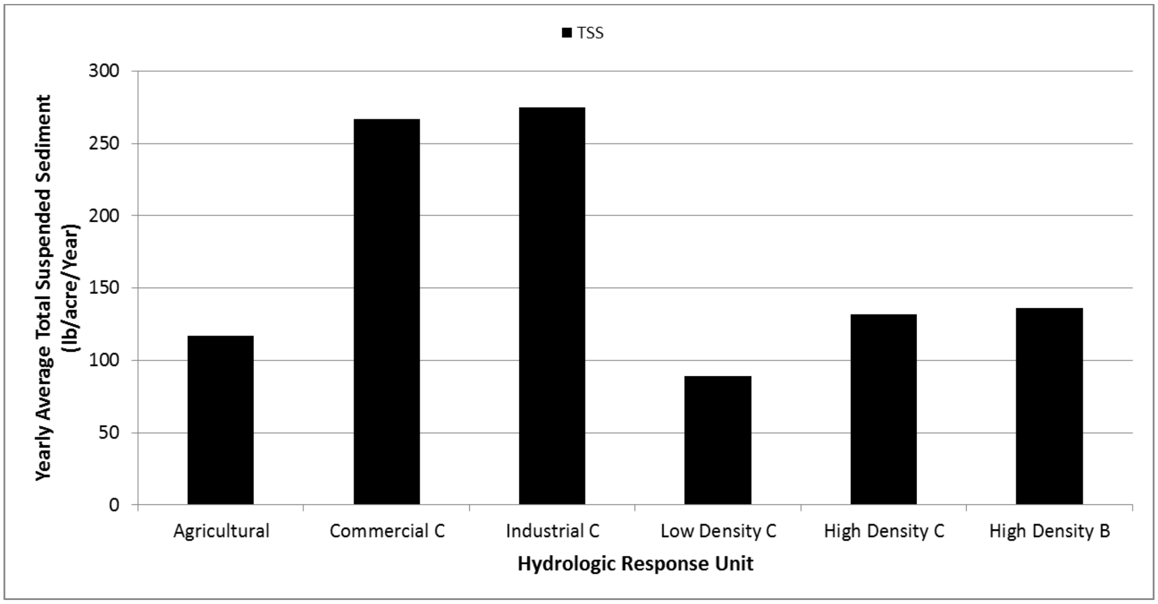

Figure 4-5. Yearly average total suspended sediment load.

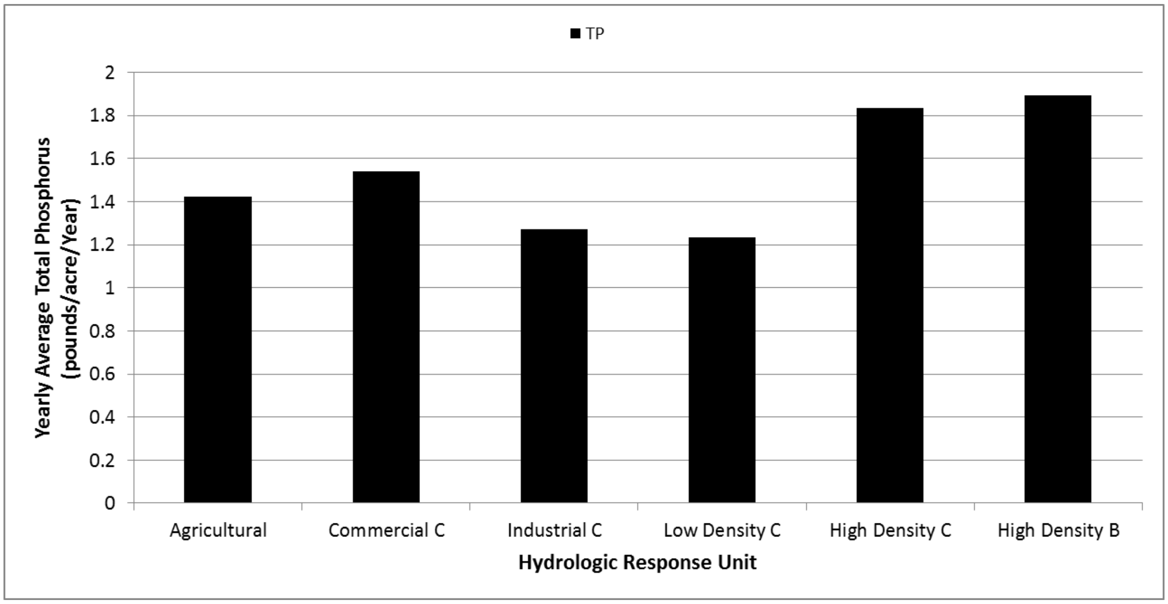

Figure 4-6. Yearly average total phosphorus load.

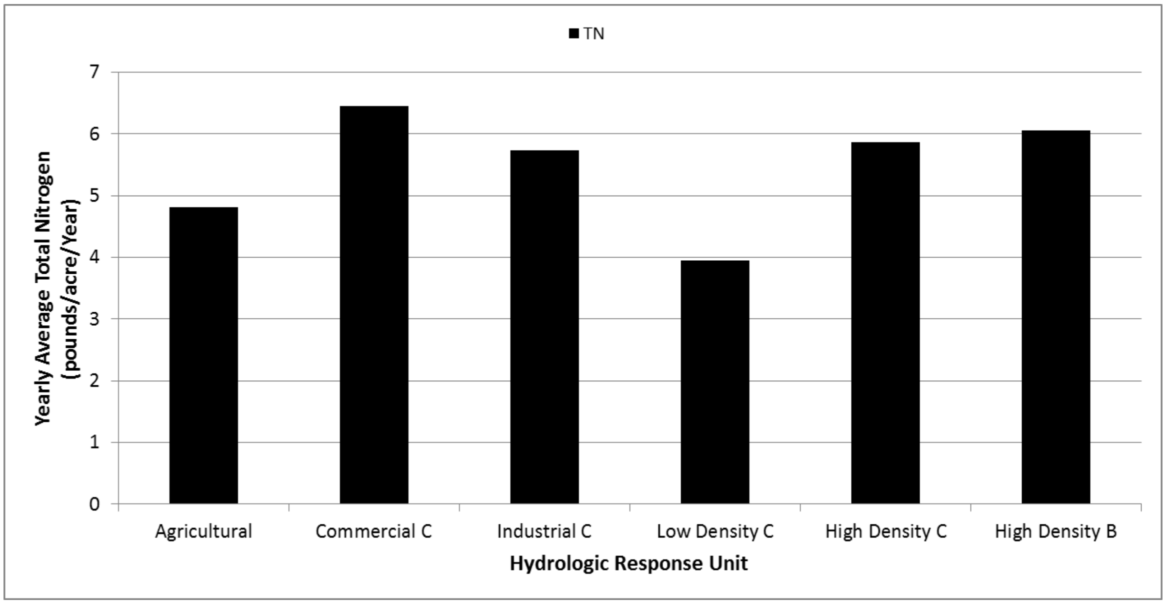

Figure 4-7. Yearly average total nitrogen load.

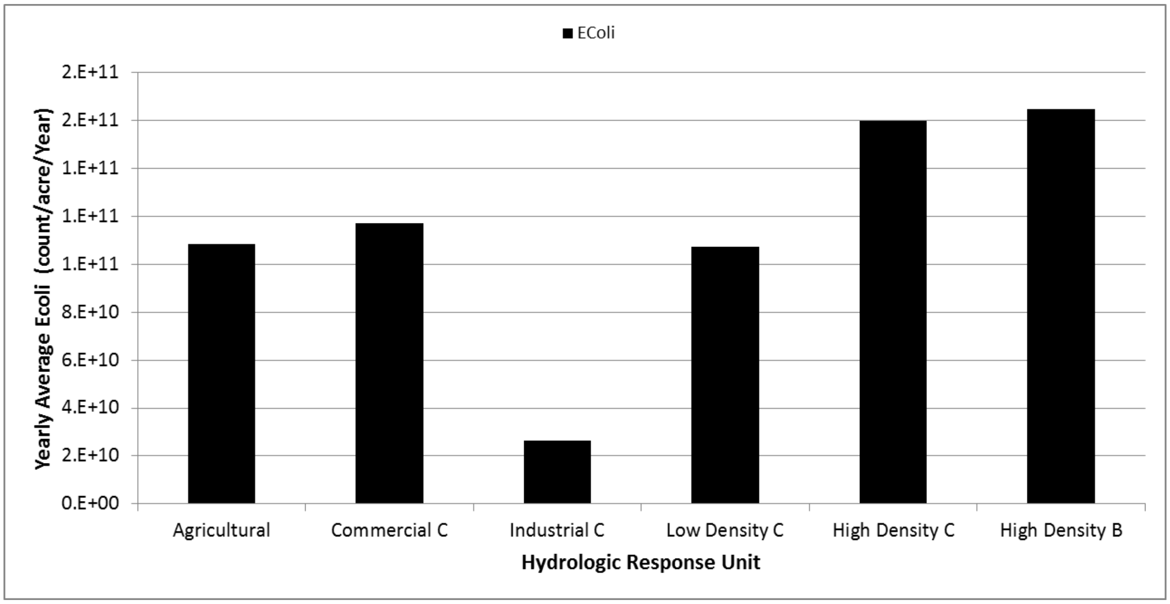

Figure 4-8. Yearly average *E. coli* load.

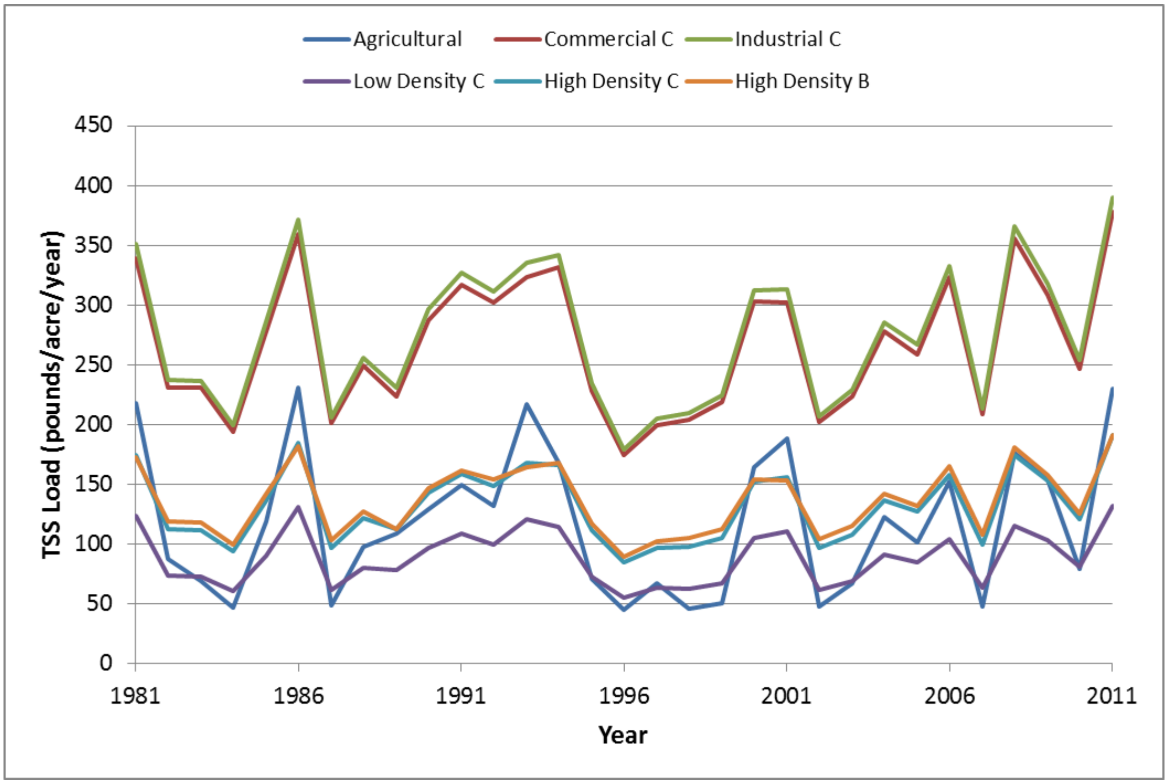

Figure 4-9. Yearly total suspended sediment load by land use.

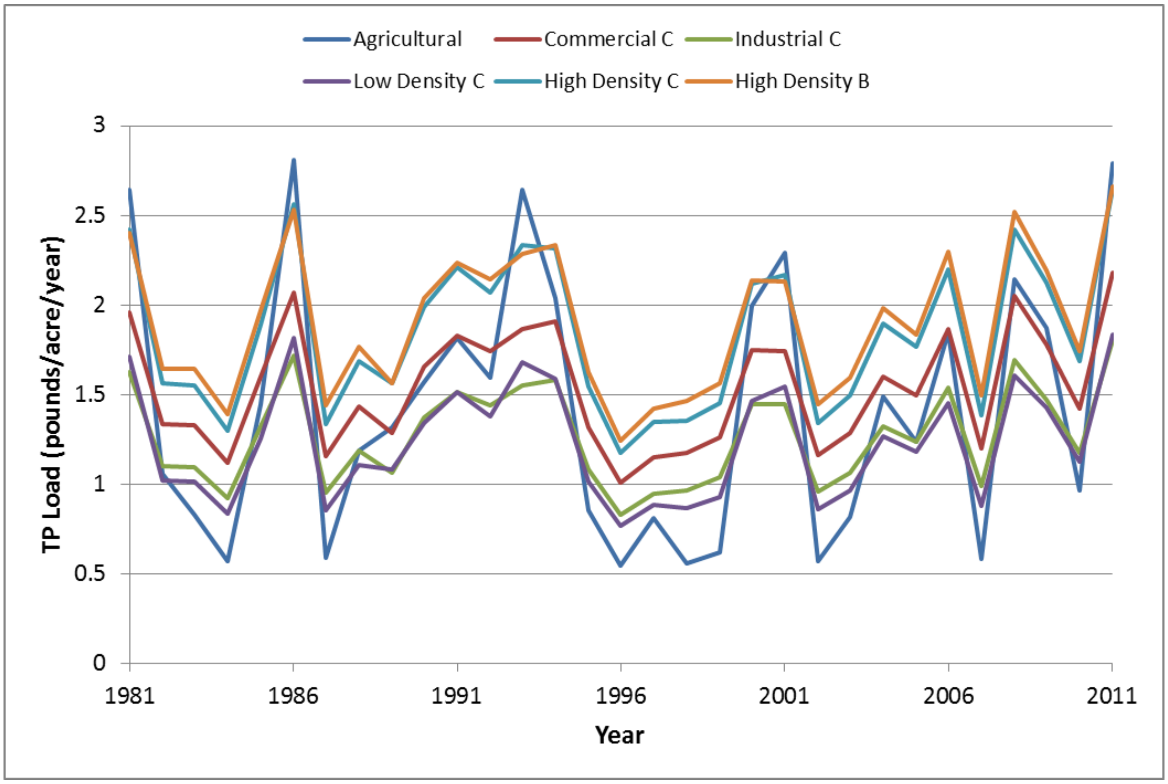

Figure 4-10. Yearly total phosphorus load by land use.

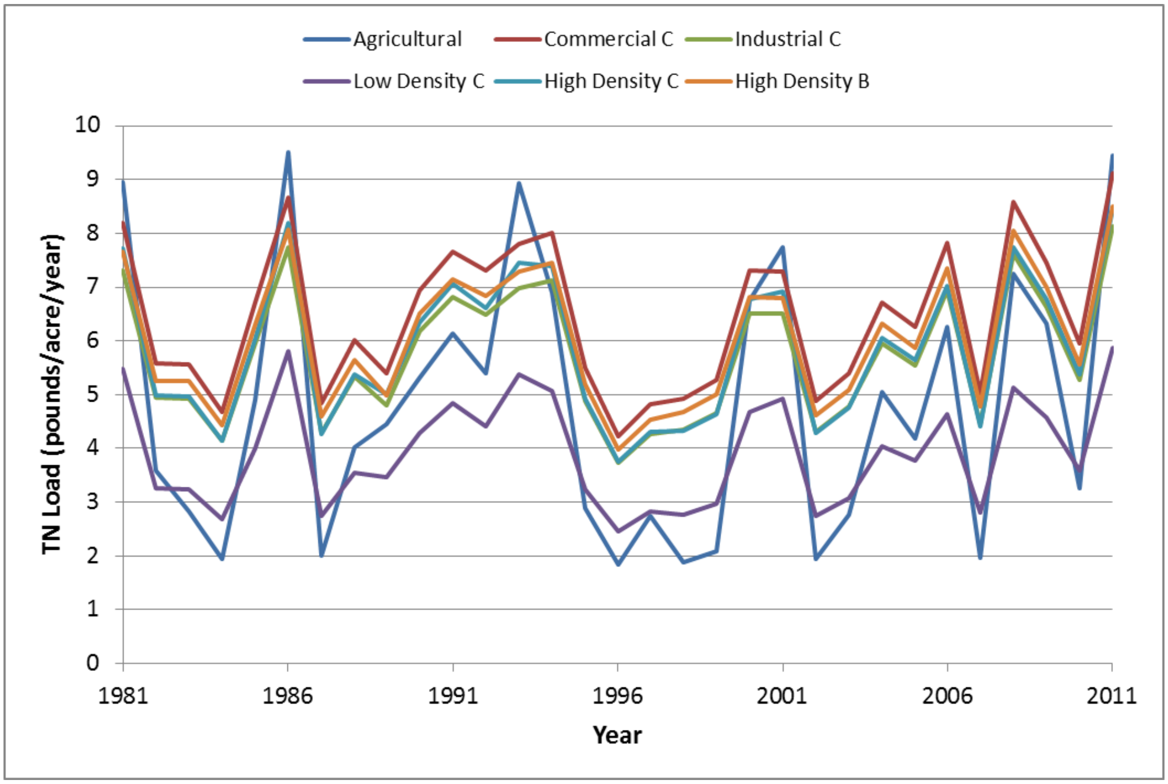

Figure 4-11. Yearly total nitrogen load by land use.

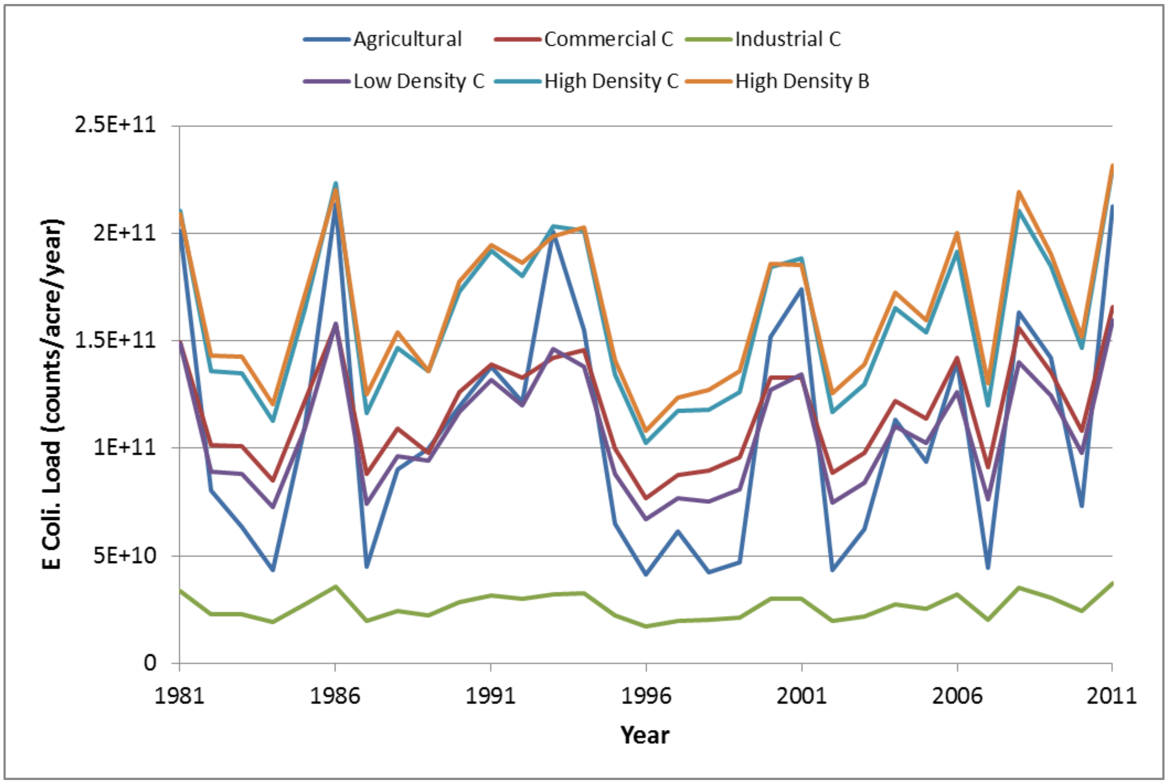

Figure 4-12. Yearly *E. coli* load by land use.

5. Identify Potential BMPs

Identifying the appropriate suite of BMPs for analysis in *SUSTAIN* requires an understanding of the watershed, pollutant sources, available treatment area, and feasibility of BMP construction. BMPs for the Plaster Creek pilot areas were selected based upon the characteristics of each land use and soil conditions. The selection of BMPs is dependent upon the suitability of the BMPs for each area based upon site conditions and performance goals. *SUSTAIN* is able to model most BMPs including both conventional (i.e. ponds) and LID practices (i.e. rain gardens, porous pavement). Specific agricultural BMPs are not explicitly included in the *SUSTAIN* model, however, many of those BMPs can be represented as a change in the watershed model boundary conditions. The following BMPs have been selected for consideration:

- Bioretention
- Rain garden
- Porous pavement
- Rain barrels
- Green roofs
- Regional ponding
- Conservation tillage
- Agricultural buffers
- Wetland restoration

Each of the BMPs was evaluated for applicability in the pilot areas on the basis of a review of aerial imagery and field reconnaissance. The assessment of BMP opportunities also involved analyzing various combinations of practices (i.e., treatment trains). Using a treatment train approach, stormwater management begins with simple methods that minimize the amount of runoff that occurs from a site. Typically those practices involve either on-site interception (e.g., rain barrels) or on-site treatment (e.g., bioswale, porous pavement). The following sections provide a description of each BMP and the considerations made during the applicability analysis. Design assumptions for the urban BMPs are compiled from the Michigan Low Impact Design Manual and based on local project information and best professional judgment.

5.1 Bioretention

Bioretention facilities are designed to capture and retain runoff from local paved roads, driveways, and the front half of parcels. Bioretention facilities can be linear features constructed adjacent to roadways, small ponding areas in the form of curb bump outs, or larger ponding areas. Bioretention is modeled in *SUSTAIN* as an aggregate practice, which means that specific locations are not identified. However, within each discrete drainage area, a template was designed and applied to treat the relevant land sources upstream. With that approach, the fraction of area treated or untreated was also defined. BMP sizing and treatment distribution are the optimization variables of concern.

Potential locations for bioretention were identified through aerial imagery analysis. Of the residential areas, only the high density residential B pilot had sufficient space between the sidewalk and street to install bioretention swales. The area modeled includes up to 50 percent of the linear area adjacent to the streets, with an


Figure 5-1. Linear bioretention example.

average width of ten feet. Opportunities for bioretention exist in the commercial and industrial areas as well, which were sized to make use of all available open space. The type of soils in which the bioretention treatments take place affect the design considerations. As such, bioretention facilities within the high density residential B area are designed for one foot of ponded depth and one and one-half feet of plant and soil media. Bioretention facilities placed in the commercial and industrial areas, which contain C type soils, are designed for one half foot of ponded depth, three feet of plant and soil media, and include free-flowing underdrains set three feet below the bottom of the basin.

Figure 5-2. Bioretention example in parking lot.

5.2 Rain Garden

Rain garden areas are assumed to be located in front yards of residential areas and are designed to serve the overflow from rain barrels and runoff from the surrounding area throughout low density residential C and high density residential C areas. The high density residential B area did not contain sufficient front yard area to accommodate rain gardens. One-half of the roof and one-half of the front yard are assumed to be routed to each rain garden. Driveways are also routed to rain gardens through a trench drain at the bottom of the driveway, thereby capturing this impervious area prior to discharging into the road.

Rain gardens are assumed to be constructed and maintained by the homeowner with little costs associated with design. A two foot soil amendment is assumed with no underdrain. Front yard size was considered when setting the size of the rain garden (200-300 square feet). As such, high density residential B does not have sufficient yard space for rain gardens. In high density residential C and low density residential C, it is assumed that a maximum of 30 percent of homes could be served by rain gardens in combination with rain barrels.

5.3 Porous Pavement

Porous pavement was assumed to be applicable throughout the pilot area for both roads in the residential areas and parking lots in commercial and industrial areas. The modeled porous pavement design for streets includes two strips of porous pavement, each four feet wide and located along both sides of the curb (Figure 5-3). An underdrain is included two feet below the pavement. The contributing drainage area includes the pavement itself, driveways, and contributing roof and urban lawn areas. Roads are delineated using GIS, and driveway, roof, and front yard areas are estimated using a representative number of homes.

Figure 5-3. Porous pavement example.

Porous pavement can also be used effectively in parking lots. Sixty percent of each paved parking lot in commercial areas, and forty percent in industrial areas, were considered for porous pavement installation, which assumes that driving lanes remain asphalt or concrete and the parking spots are made permeable. All parking lots are assumed to have underdrain systems. The drainage area is represented by the entire parking lot area.

5.4 Rain Barrel

Rain barrels provide for storage of runoff in the residential areas. Following rainfall events, the water stored in rain barrels and cisterns can be used for irrigating vegetation. Rain barrels are typically applied in residential areas while cisterns are used in commercial or institutional areas. It was assumed that up to 30 percent of homes in all of the residential areas could be retrofitted with up to two rain barrels. The sequence assumes that the entire rain barrel volume is released by opening a bottom orifice two days after the end of a storm. The stored water is used to irrigate bioretention vegetation. The rain barrel capacity at any point during the simulation is a function of the amount of water released after a previous event. If rain barrels are filled to capacity, back-to-back precipitation events can show bypass, with no rain barrel benefit. During cold-weather conditions, the rain barrels are assumed to be disconnected from rooftop downspouts. The standard size of rain barrels used for this pilot was 55 gallons, with a maximum of two units per home. The drainage area to each rain barrel is assumed to be equal to one-quarter of the roof area.

5.5 Green Roof

Green roofs can typically be placed on any flat roof surface in the commercial and industrial areas, assuming the roof can support the additional weight. Potential green roof locations were identified within the commercial and industrial land uses using aerial photography. It was assumed that flat roofs would have the structural support necessary to carry a green roof, which results in an overestimation of the maximum potential area suitable for green roofs. The drainage area to green roofs is assumed to include the entire roof surface. An extensive green roof was assumed.

Figure 5-4. Green roof example.

5.6 Regional Ponding

The potential for regional ponding was identified in the commercial and industrial land uses based on available green space. Regional ponds are assumed to be wet ponds with four foot depth of ponding, serving as the last BMP in a treatment train within both commercial and industrial areas. The contributing drainage area includes all area upstream of the regional pond. Regional ponds are modeled as area BMPs in *SUSTAIN*.

5.7 Conservation Tillage

Conservation tillage practices and residue management are commonly used to control erosion and surface transport of pollutants from fields used for crop production. The residuals not only provide erosion control, but also provide a nutrient source to growing plants, and continued use of conservation tillage results in a more productive soil with higher organic and nutrient content. Several practices are commonly used to maintain surface residues:

- No-till systems disturb only a small row of soil during planting, and typically use a drill or knife to plant seeds below the soil surface.
- Strip till operations leave the areas between rows undisturbed, but remove residual cover above the seed to allow for proper moisture and temperature conditions for seed germination.
- Ridge till systems leave the soil undisturbed between harvest and planting: cultivation during the growing season is used to form ridges around growing plants. During or prior to the next planting, the top half to two inches of soil, residuals, and weed seeds are removed, leaving a relatively moist seed bed.

- Mulch till systems are any practice that results in at least 30 percent residual surface cover, excluding no-till and ridge till systems.

Conservation tillage is modeled as a change in boundary conditions, assuming that all row crop agricultural fields are converted from traditional plowing methods (e.g. chisel plow) to a strip till operation. This conversion results in a 68 percent reduction in phosphorus loads (Czapar et al. 2006). In addition to phosphorus reduction, EPA (2003) reports that a reduction of 50 percent can be achieved for sediment when plowing methods provide 20 to 30 percent residual cover. USDA (1999) reports a 30 percent reduction in evaporative loss with 30 percent residual cover.

5.8 Agricultural Buffers

Preserving the natural vegetation along a stream corridor can mitigate pollutant loading associated with human disturbances. The root structure of the vegetation in a filter strip of buffer enhances infiltration and subsequent trapping of pollutants. Buffers can also prevent cattle access to streams, reducing streambank trampling and defecation in the stream.

A 50 foot buffer is modeled in *SUSTAIN* at the edge of field adjacent to the waterway. The drainage area being served by the filter strip is 300 feet of adjacent land. Vegetation is assumed to consist of be native, deep rooted plants, trees, and shrubs with dense groundcover.

5.9 Wetland Restoration

As development has occurred in this watershed, many wetlands were drained. Wetland restoration opportunities were identified based on the Michigan Department of Environmental Quality’s pre-settlement wetland coverage, corrected for the presence of existing wetlands. Figure 5-5 identifies the wetland restoration opportunities within the existing agricultural areas, representing approximately 15 percent of the area. A wetland restoration opportunity was assumed to be equal to 15 percent of the agricultural pilot area. This results in the agricultural pilot being modeled as a theoretical site, rather than an actual pilot site, which allows for a more realistic extrapolation of results to other areas.

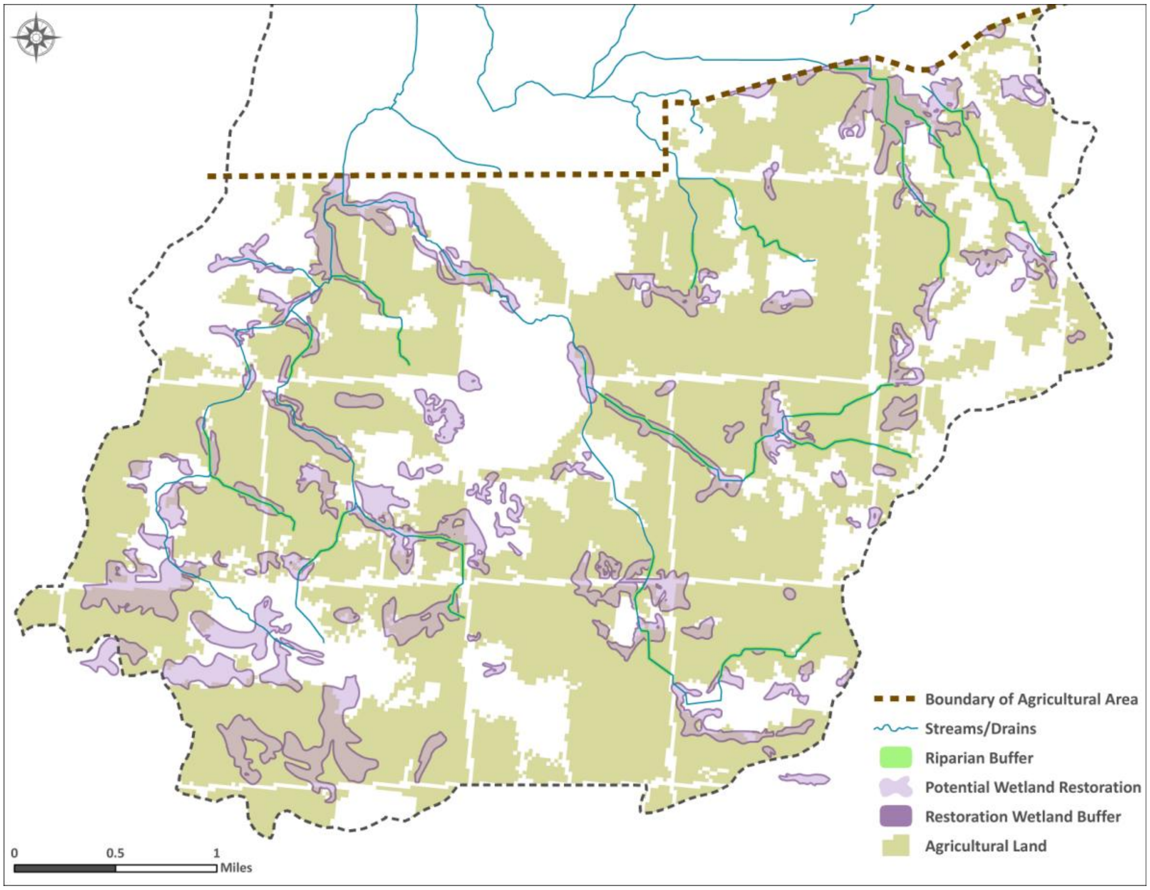

Figure 5-5. Potential wetland restoration sites.

6. Determine BMP Configuration and Performance

BMPs are simulated in *SUSTAIN* according to design specifications, with the performance modeled using a unit-process parameter-based approach. That contrasts with and has many advantages over most other techniques that simply assign a single percent effectiveness value to each type of practice. *SUSTAIN* predicts BMP performance as a function of its physical configuration, storm size and associated runoff intensity and volume, and moisture conditions in the BMP.

Many of the BMPs were simulated in aggregate, recognizing the scale and model resolution of the watershed model. The aggregate approach is a computationally efficient and analytically robust approach that *SUSTAIN* provides for evaluating relative management practice selection and performance at a small subwatershed scale. Additionally, BMP performance was reduced in winter months by reducing the load reaching the BMPs.

An aggregate BMP consists of a series of process-based optional components, including on-site interception, on-site treatment, routing attenuation, and regional storage/treatment. Each aggregate BMP component evaluates storage and infiltration characteristics from multiple practices simultaneously without explicit recognition of their spatial distribution and routing characteristics in the selected watershed. For example, certain rain barrels in the aggregate BMP network are modeled in series with rain gardens and serve residential rooftop runoff area.

In lieu of modeling each individual BMP, such as a rain barrel or bioretention area, the aggregate approach allows the user to define generalized application rules on the basis of BMP opportunity and typical practice. The role of optimization is to determine the relative size (or number) of each BMP component that achieves the defined management objective at the lowest cost. For this application, an aggregate practice is developed for each of the pilot areas, illustrated in Figure 6-1. For example, the high density residential B (HDR-B) land use aggregate practice includes three component practices—rain barrel, bioretention, and porous pavement.

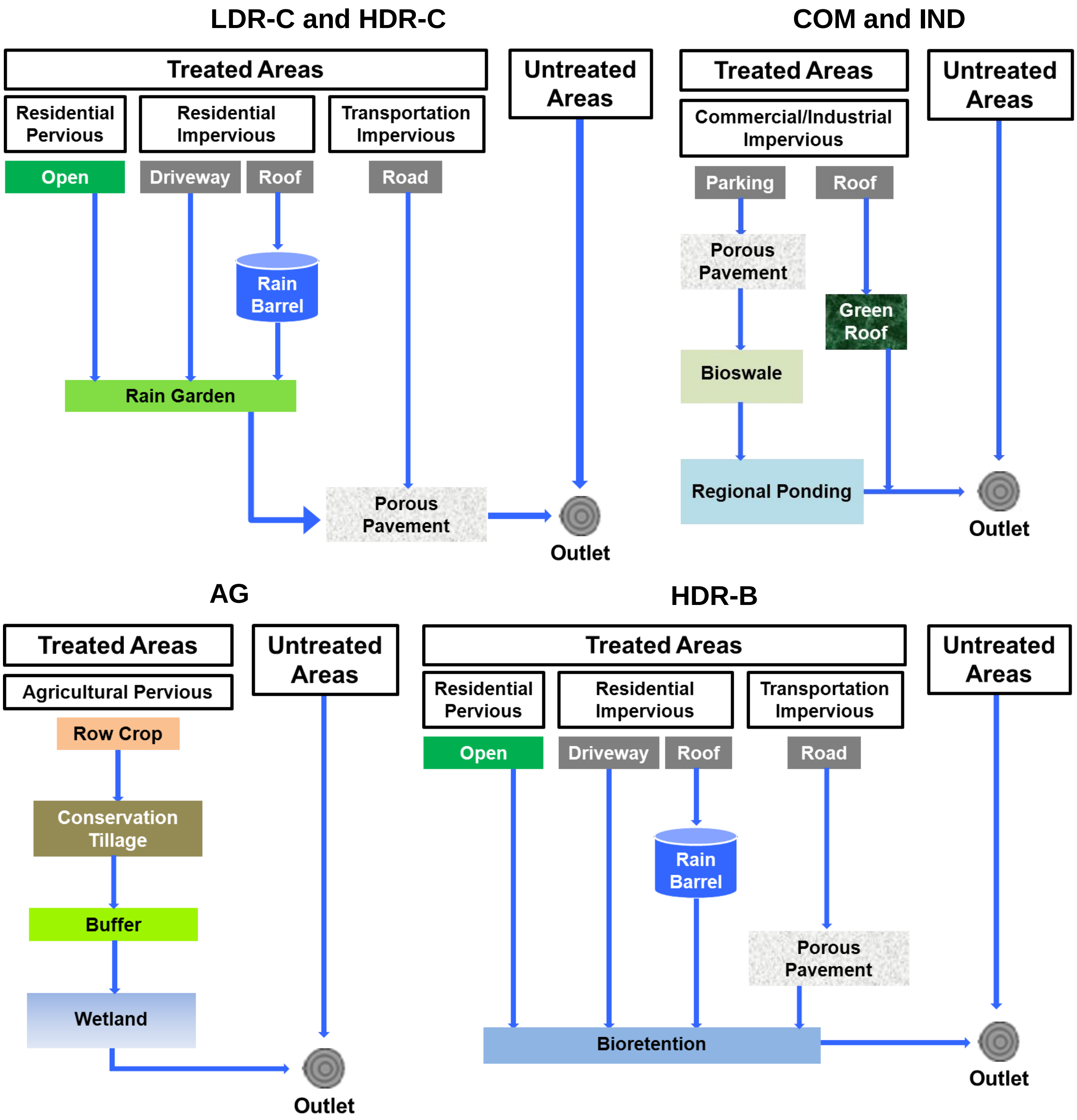

Figure 6-1. Aggregate BMP schematics identifying treatment train options.
LDR-C – low density residential C; HDR-B – high density residential B; HDR-C – high density residential C; COM – commercial; IND – industrial; AG - agricultural

Outflows from the most downstream BMP and runoff from any type of land use that is not subject to treatment by aggregate practice components are routed directly to the outlet. This is in recognition of the fact that grading and/or other physical land features may preclude portions of the drainage areas for smaller distributed practices from receiving runoff for treatment. Note that the aggregate BMP setup is a tool to determine which BMP(s) are most efficient at achieving an environmental outcome without representing each individual BMP explicitly (e.g., representing rain barrels for each roof in the study area). The configuration of BMP routing in the aggregate setup are meant to represent a treatment train that makes sense based upon the BMP design characteristics and assumed topographic conditions of the most likely drainage network. The aggregate BMP network represents the maximum potential sizing and routing for BMPs in a study area. Just because a type of BMP is included in the aggregate, does not mean that it will be favored when optimization analysis is performed.

The objective of this effort was to identify combinations of practices that maximize phosphorus reductions while minimizing the lifecycle cost of the associated group of BMPs. To run the optimization analysis, a set of decision variables was identified to explore the best possible combinations of the various BMP practices. For this analysis, the decision variables consisted of the following:

- Number of fixed-size rain barrel and rain gardens
- Surface area of regional ponds, bioretention, porous pavement, green roof, wetland restoration, and buffer

Because the decision variable values can range anywhere between zero to a maximum number or size, it is possible for one component in the treatment train to never be selected if it is not cost-effective toward achieving the objective. For example, even though an aggregate BMP setup includes rain barrels, if rain gardens are found to be a more cost-effective solution under all conditions, all roof runoff will be directly routed to available rain gardens. In other words, the aggregate BMP provides a menu of options that might or might not be selected, depending on cost-effectiveness. Table 6-1 summarizes the maximum extent of each practice determined through aerial photography analysis, field reconnaissance and on the basis of best professional judgment as described in Section 4.3. Those values define the upper boundary of the optimization search space. The physical configuration data and infiltration parameters for each BMP component are listed in Table 6-2.

Table 6-1. Maximum extent of BMPs

	Maximum BMP extent					
BMP	**LDR-C**	**HDR-B**	**HDR-C**	**COM**	**IND**	**AG**
Rain Garden (unit)	68.0	28.0		--	--	--
Rain Barrel (unit)	136.0	112.0	132.0	--	--	--
Bioretention (acres)	--	--	0.9	2.6	2.8	--
Porous Pavement Roads (acres)	3.5	1.1	1.8	--	--	--
Porous Pavement Parking Lots (acres)	--	--	--	10.8	5.2	--
Green Roof (acres)	--	--	--	6.1	10.2	--
Regional Pond (acres)	--	--	--	2.7	1.3	--
Conservation Tillage (acres)	--	--	--	--	--	126
Buffers (linear feet)	--	--	--	--	--	2,000
Wetland Restoration (acres)						19.0

LDR-C – low density residential C; HDR-B – high density residential B; HDR-C – high density residential C; COM – commercial; IND – industrial; AG - agricultural

Table 6-2. BMP configuration parameters

Parameter	Rain barrel	Rain garden	Bio-retention	Regional pond	Porous pavement	Green roof	Wetland	Buffer
Physical Configuration								
Unit size	55 gal	LDR-C - 300 sq ft HDR-C - 200 sq ft	N/A	N/A	N/A	N/A	N/A	50 feet wide
Substrate depth (ft)	N/A	2	B- 1.5 C, D - 3	N/A	2	0.67	1	N/A
Underdrain storage depth (ft)	N/A	N/A	B - NA C, D - 1	N/A	1	0.1	N/A	N/A
Ponding depth (ft)	N/A	0.5	B - 1 C, D - 0.5	4	0.1	0.1	3	0.1
Infiltration								
Substrate layer porosity	N/A	0.4	0.4	N/A	0.45	0.4	0.3	0.4
Substrate layer field capacity	N/A	0.25	0.25	N/A	N/A	0.4	0.25	0.25
Substrate layer wilting point	N/A	0.1	0.1	N/A	N/A	0.1	0.1	0.1
Underdrain gravel layer porosity	N/A	N/A	0.5	N/A	0.5	0.5	N/A	N/A
Vegetative parameter, A	N/A	1	1	N/A	N/A	0.6	1	1
Background infiltration rate for each hydrologic soil group (in/hr)	N/A	B – 0.5 C – 0.3 D – 0.1	B – 0.5 C – 0.3 D – 0.1	N/A	B – 0.5 C – 0.3 D – 0.1	N/A	0.5	0.3
Media final constant infiltration rate (in/hr)	N/A	0.5	0.5	N/A	1	1	N/A	N/A

LDR-C – low density residential C; HDR-C – high density residential C

Infiltration parameters were determined on the basis of the assumed soil substrate. The background infiltration rate refers to the infiltration rate of the native soils below the engineered media and varies dependent upon the predominant hydrologic soil group within each subwatershed. The vegetative parameter, or the percent vegetative cover, and wilting point values were provided by Tetra Tech, Inc. (2001). Wilting point is defined as the minimal soil moisture required to prevent vegetation wilting.

7. BMP Costs

Identifying BMP costs in an important step in the BMP Optimization Approach because resource constraints may limit the type and number of BMPs that can be used to achieve program goals. BMP costs are typically evaluated with estimated pollutant reductions to select the final set of BMPs that are most cost-effective. There are three types of BMP costs to consider over the life cycle of a BMP:

- Probable Construction Costs – The initial cost to construct the BMP.
- Annual Operation and Maintenance – The annual costs to maintain the BMP.
- Repair and Replacement Costs – The additional costs to repair or replace the BMP.

A standard unit cost was defined for each BMP category, since the range of BMPs was unknown and expected to vary significantly. Each unit cost was converted to 2012 dollars by applying a three percent inflation rate by the number of years from the published year of the cost data to 2012. A discount rate of 3 percent was used for converting annual operation and maintenance and repair and renewal costs to present value.

The lifecycle period was defined as 20-years to take into account costs for replacing some BMPs. Several of the published sources used to derive costs data for structural practices to be input into *SUSTAIN* defined engineering and design or contingency factors based upon a percent of the base construction cost, while other published sources intentionally omitted them. A default 15 percent engineering and design cost factor and 25 percent contingency cost factor were assigned to probable construction costs when no values were provided for all structural practices without available cost data. No land, capital, administration, demolition, or legal cost factors were defined for any of the probable construction costs. Table 7-1 presents the lifecycle costs for each of the BMPs.

The following sources were reviewed when defining the lifecycle costs:

- BMP and Low Impact Development Whole Life Cost Models Version 2.0. Water Environment Research Foundation (WERF 2009).
- BMP cost data provided by City of Grand Rapids
- Long-Term Hydrologic Impact Analysis Low Impact Development Version - 2.0.
- National Green Values Calculator, Center for Neighborhood Technology (Center for Neighborhood Technology 2009).
- The Cost and Effectiveness of Stormwater Management Practices, University of Minnesota (Weiss et al. 2005).
- Low Impact Development for Big Box Retailers. Prepared for U.S. Environmental Protection Agency (Low Impact Development Center 2005).
- Low Impact Development Manual for Michigan, Southeast Michigan Council of Governments.
- National Management Measures to Control Nonpoint Source Pollution from Agriculture (EPA 2003).

Additional Tetra Tech projects and best professional judgment were also considered when defining the range of lifecycle unit costs. Literature indicates that the cost of conversion between conventional tillage practices and conversation tillage practices can be negligible.

Table 7-1. BMP lifecycle costs

Parameter	**Rain barrel**	**Rain garden**	**Regional pond/ wetland**	**Bio-retention**	**Porous pavement**	**Green roof**	**Buffer**
Life Cycle Cost Data							
Lifecycle Unit Cost [A+B+C] (NPV)	$165 ea.	$1,500 ea.	$5/ft^2	$36/ft^2	$11/ft^2	$39/ft^2	$0.12/ ft^2
A) Probable Unit Cost	$95.00 ea.	$750 ea.	$4/ ft^2	$28/ ft^2	$7	$25/ ft^2	$0.11/ ft^2
B) Annual O&M (NPV)	$0	$0	$1/ ft^2	$7/ ft^2	$4/ ft^2	$13/ ft^2	$0.01/ ft^2
C) Repair & Replacement (NPV)	$70 ea.	$750 ea.	$0	$0	$0	$1/ ft^2	$0
BMP Lifecycle Period	10-yrs	10-yrs	--	--	--	--	--

NPV – Net Present Value

8. BMP Optimization Analysis

The final step in the BMP Optimization approach is to evaluate and prioritize the potential BMPs based upon costs, BMP performance, and other goals of the stormwater management planning. The objective of optimization modeling for the Plaster Creek pilot areas was to evaluate pollutant loading reductions on six different land uses using the previously described suite of practices, and then extrapolate those projected benefits for larger-scale management planning. In assessment of the study objective, this analysis:

- Develops a cost-effectiveness curve for each of six land use/soil combinations that shows the tradeoffs between cost and load reduction for increasing management targets
- Prioritizes BMP selection for selected management levels of interest for each land use
- Evaluates a 40 percent total phosphorus reduction solution for each land use and evaluates the impact on other modeled pollutants and flow volumes
- Performs a watershed wide optimization to identify a cost-effective solution that achieves the 40 percent TP reduction goal and evaluate the reduction of other pollutants
- Establishes rules for extrapolating individual land use results to the watershed scale
    - Summarize cost, modeled load reduction, and modeled flow volume reduction for select points along each cost-effectiveness curve
    - Summarize costs and benefits for agricultural management areas
- Configures watershed-wide optimization to integrate urban and non-urban management opportunities
- Provides an example extrapolation of the results to an area within the City of Grand Rapids

8.1 Optimization Results

The goal of optimization within the Plaster Creek pilot watersheds was to maximize TP reduction while minimizing costs. Optimization was based on the annual average TP load reduction since this pollutant required the largest reduction in comparison to total nitrogen and suspended sediment (FTC&H 2008). The *SUSTAIN* model was run for the time period 10/1/1992–9/30/1996 (water years 1993–1996). These water years capture high, low, and average annual precipitation totals in the watershed as shown in Figure 8-1.

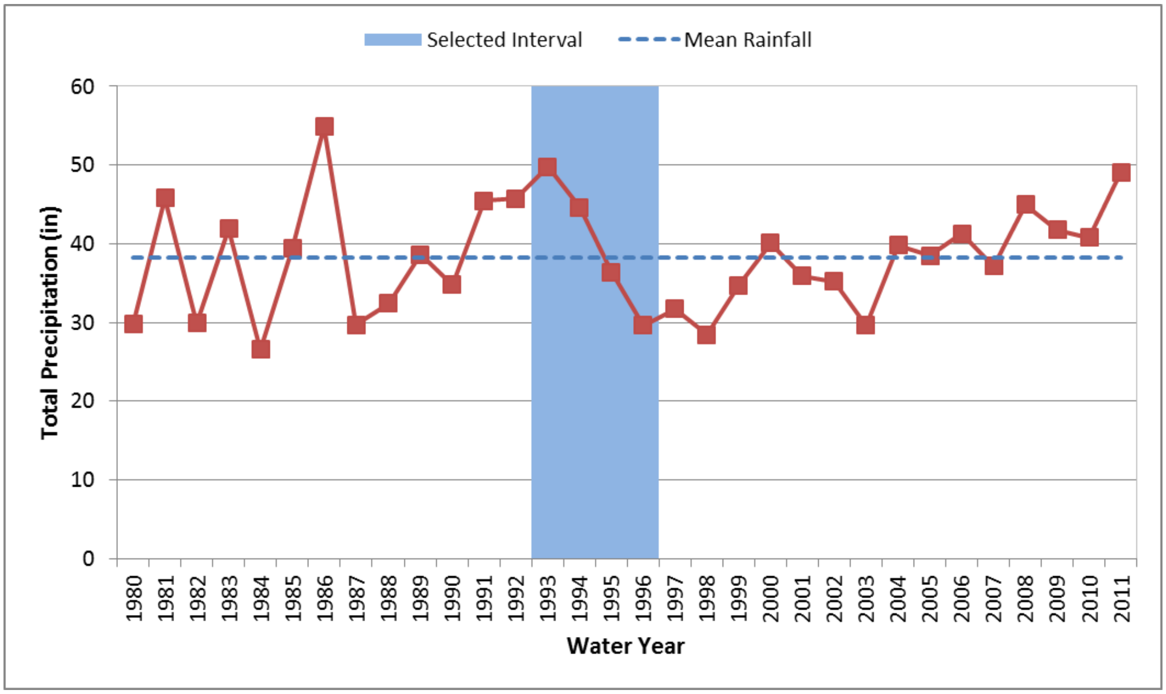

Figure 8-1. Total rainfall (inches) by water year at Grand Rapids, MI International Airport.

Cost-effectiveness curves for the residential, commercial and industrial, and agricultural pilot watersheds are presented in Figure 8-2, Figure 8-3, and Figure 8-4, respectively. In these figures, the small blue and red points represent “all reduction solutions” that were evaluated during optimization, in terms of pounds-per-acre and percent reduction, respectively. The larger green points along the left-and-upper-most perimeter of the curve represent the lowest cost options at selected reduction target intervals. The solutions are called “Best Solutions” simply because they are the lowest cost values associated with the selected reduction target. They are “best” relative to other solutions that achieved the same reduction.

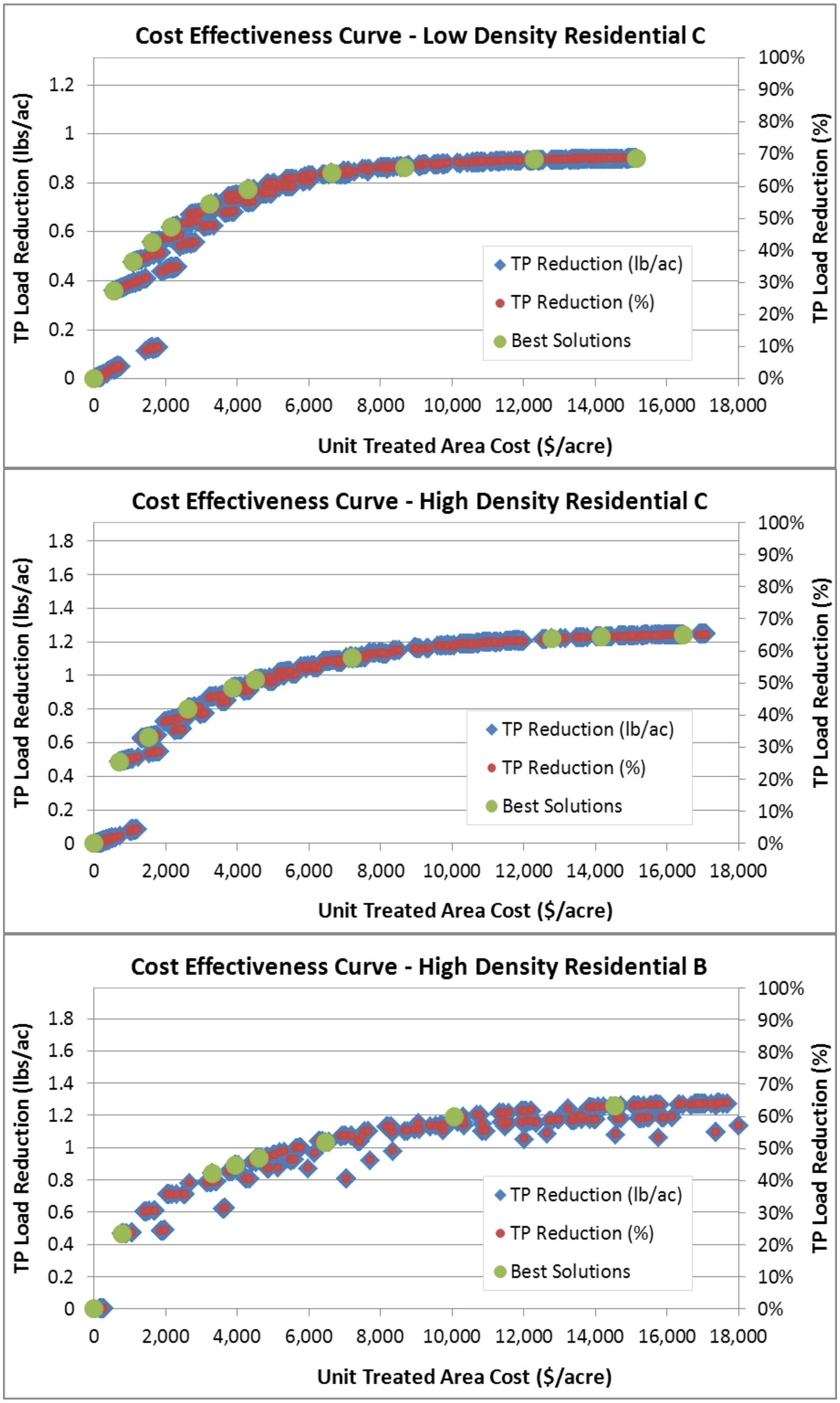

Figure 8-2. Total phosphorus load control cost-effectiveness curve for Plaster Creek residential pilot watersheds.

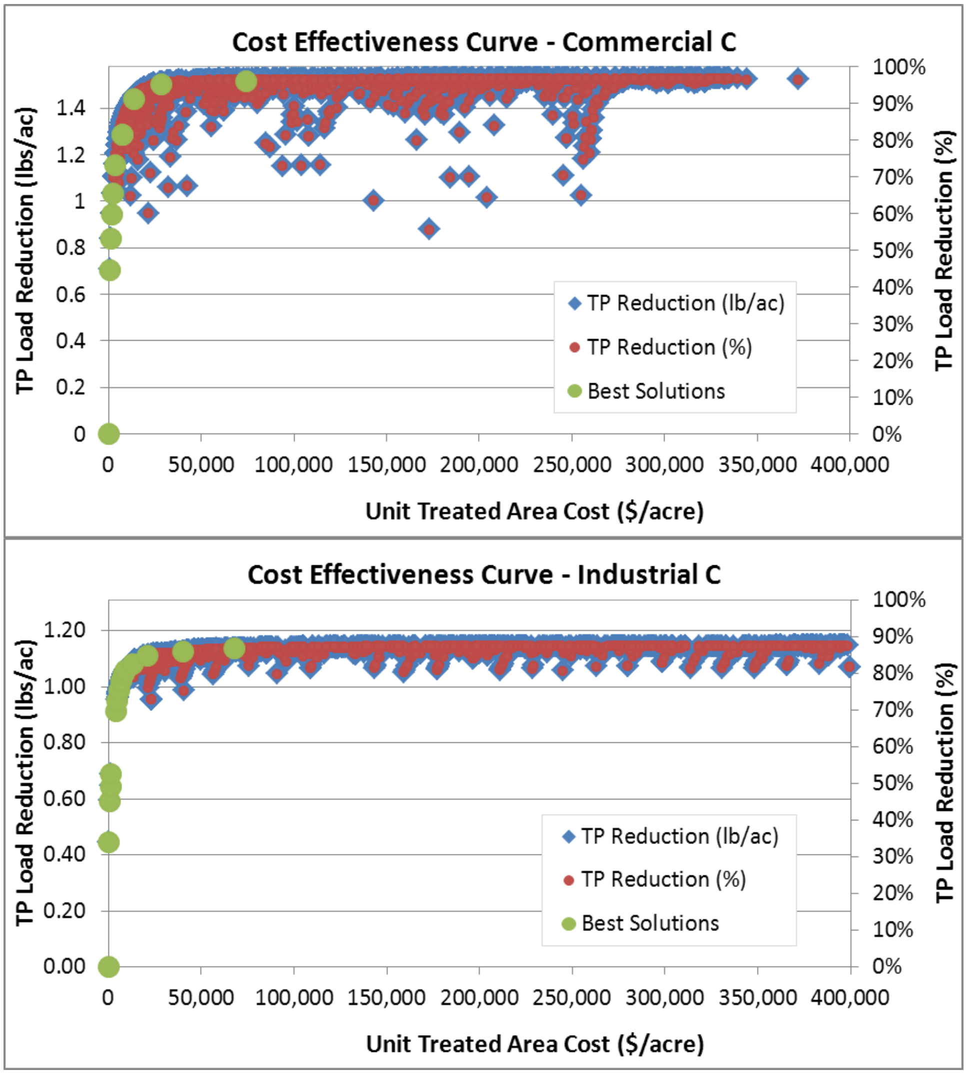

Figure 8-3. Total phosphorus load control cost-effectiveness curve for Plaster Creek commercial and industrial pilot watersheds.

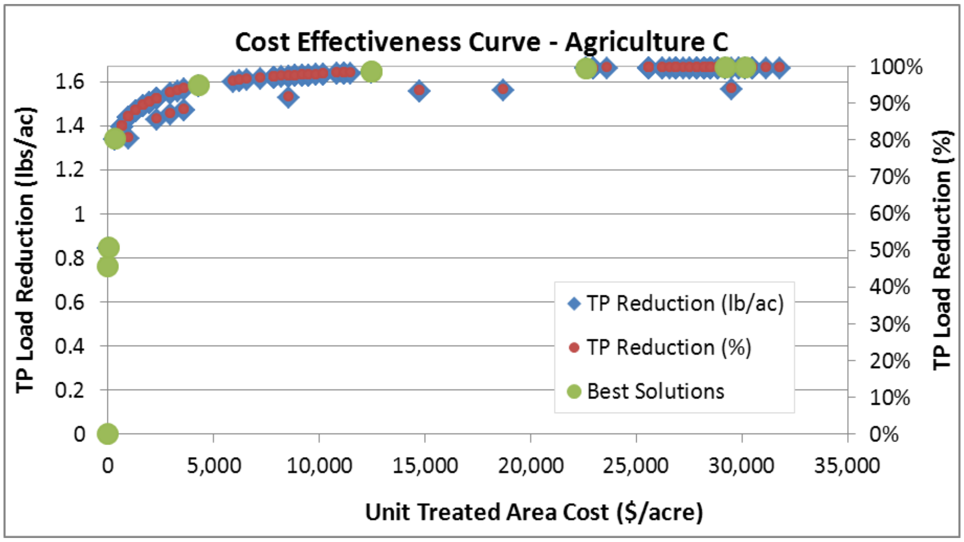

Figure 8-4. Total phosphorus load control cost-effectiveness curve for Plaster Creek agricultural pilot watershed.

To illustrate the breadth of BMP implantation strategies, a series of solutions were selected at 20 percent reduction intervals. These solutions are presented in Table 8-1. In general, the highest levels of treatment are attainable for the commercial, industrial, and agricultural areas due to the BMP opportunities in these areas which include regional ponds for commercial and industrial areas and conservation tillage for agricultural areas. Regional ponds are capable of treating runoff from large areas and conservation tillage is assumed to treat the entire agricultural area. Table 8-1 shows that as the level of treatment increases, the marginal return on cost, or the treatment gained by spending an additional dollar, decreases.

Table 8-1. Total phosphorus load target solutions for Plaster Creek pilot watersheds

Pilot watershed	Area (acres)	Cost effectiveness metric	Approximate reduction				
			20%	40%	60%	80%	100%
High Density Residential B	33.6	TP Reduction (lbs)	16	28	40	--	--
		Cost ($)	26,450	110,930	338,438	--	--
High Density Residential C	55.4	TP Reduction (lbs)	27	44	61	--	--
		Cost ($)	38,530	144,130	399,130	--	--
Low Density Residential C	127.3	TP Reduction (lbs)	45	71	98	--	--
		Cost ($)	70,266	206,138	545,818	--	--
Commercial C	40.6	TP Reduction (lbs)	--	29	38	52	62
		Cost ($)	--	23,700	71,100	301,820	3,012,052
Industrial C	40.2	TP Reduction (lbs)	--	24	28	42	--
		Cost ($)	--	32,940	54,900	329,756	--
Agriculture C	126.2	TP Reduction (lbs)	--	95	106	169	209
		Cost ($)	--	0	344	41,726	2,855,702

TP – total phosphorus

8.1.1 Selected BMP Solutions

Cost effectiveness curve solutions were selected on the basis of the 40 percent total phosphorus reduction goal identified for the Plaster Creek watershed. For each pilot watershed, the load reduction closest to forty percent was selected. Figure 8-5 presents the cost-effectiveness curves for each pilot watershed and selected solutions.

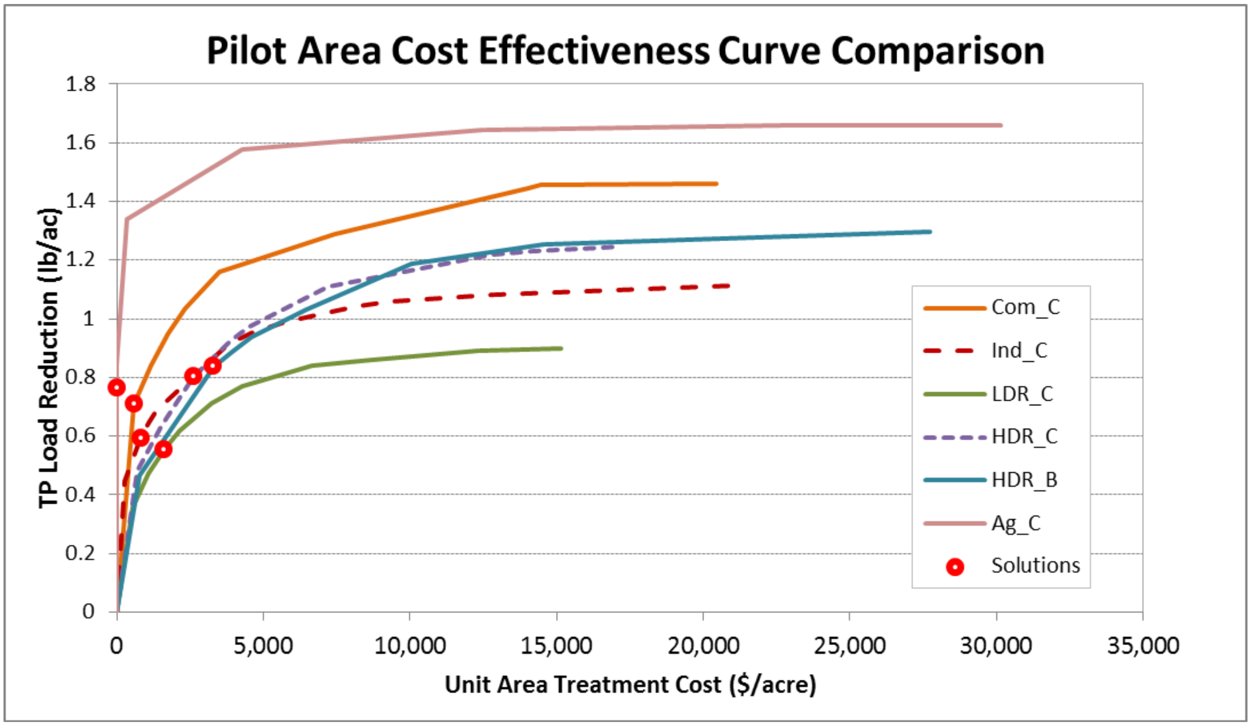

Figure 8-5. Total phosphorus load control cost-effectiveness curve and solutions for Plaster Creek pilot watersheds.

The percent utilization of BMPs for the six pilot watersheds for the selected solutions is shown in Table 8-2. Percent utilization for each solution is the area or number of BMPs in the selected solution divided by the maximum potential area or number of BMPs in the model.

Table 8-2 shows that a single BMP is implemented to reach the load reduction target for each pilot watershed. For residential pilot watersheds the BMP is porous pavement, for the commercial and industrial pilot watersheds the BMP is a regional pond, and for the agricultural pilot watershed the BMP is conservation tillage. The reason a single BMP was selected for each area is suggested by the unit cost of each and the composition and size of the contributing drainage area. In the commercial and industrial areas, the cost of the regional pond on a per square foot basis is significantly less than the other BMPs. In the case of the residential areas, although porous pavement has a similar per square foot cost to rain gardens, porous pavement provides additional treatment using under drains and serves a larger drainage area and therefore is a more effective BMP. As load reductions increase above the 40 percent target, however, other BMP opportunities in the pilot watersheds are utilized.

Table 8-2. Best management practice percent utilization for Plaster Creek pilot watersheds

Pilot land use	Selected BMP	Modeled BMP extents (acres)	BMP utilization (%)
High Density Residential B	Porous Pavement	0.22	20
High Density Residential C	Porous Pavement	0.288	16
Low Density Residential C	Porous Pavement	0.42	12
Commercial C	Regional Pond	0.108	4
Industrial C	Regional Pond	0.156	12
Agriculture C	Conservation Tillage	126	100

The pollutant load and volume reductions for the selected solution are presented in Table 8-3 and Figure 8-6. Attainment of the forty percent target total phosphorus reduction results in the pollutant reduction goals for total suspended solids (25 percent) and total nitrogen (20 percent) being met. TMDL pollutant load reductions for sediment (40 percent) are also met. Significant flow volume reductions are also simulated for the residential pilot watersheds with the highest seen for high density residential B (38 percent reduction) followed by high density residential C (26 percent reduction) and low density residential C (25 percent reduction).

The flow volume reduction simulated in the commercial and industrial pilot watersheds are below one percent and the implementation of conservation tillage in the agriculture pilot watershed did not provide any flow volume reduction. Regional ponds, the selected BMP in commercial and industrial pilot areas, provides significant pollutant reduction, but very little volume reduction as infiltration from the ponds is assumed to be negligible (Table 6-2). If it were determined that flow volume reduction was the primary concern to be addressed in the Plaster Creek watershed, optimization simulations would select different BMPs for the industrial, commercial, and agricultural pilot watersheds, and would also likely modify the selected BMPs for the other pilot watersheds.

Table 8-3. Selected solution pollutant load and flow volume reductions for Plaster Creek pilot watersheds

Pilot land use	Solution cost ($)	Average annual reductions							
		Flow volume		TP		TSS		TN	
		%	Qnty. (ac-ft)	%	Qnty. (lbs)	%	Qnty. (lbs)	%	Qnty. (lbs)
High Density Residential B	110,930	37.9	16.3	42.1	28	42.1	2,026	39.8	85
High Density Residential C	144,130	25.5	17.4	41.9	44	42.4	3,237	36.7	124
Low Density Residential C	206,138	24.5	26.2	42.5	71	43.0	5,146	36.6	194
Commercial C	23,700	0.6	0.4	44.7	29	44.7	5,000	36.4	98
Industrial C	32,940	0.8	0.6	45.3	24	45.3	5,170	37.7	90
Agriculture C	0	0.0	0.0	45.0	95	75.0	12,976	55.0	391

TP – total phosphorus; TSS – total suspended solids; TN – total nitrogen

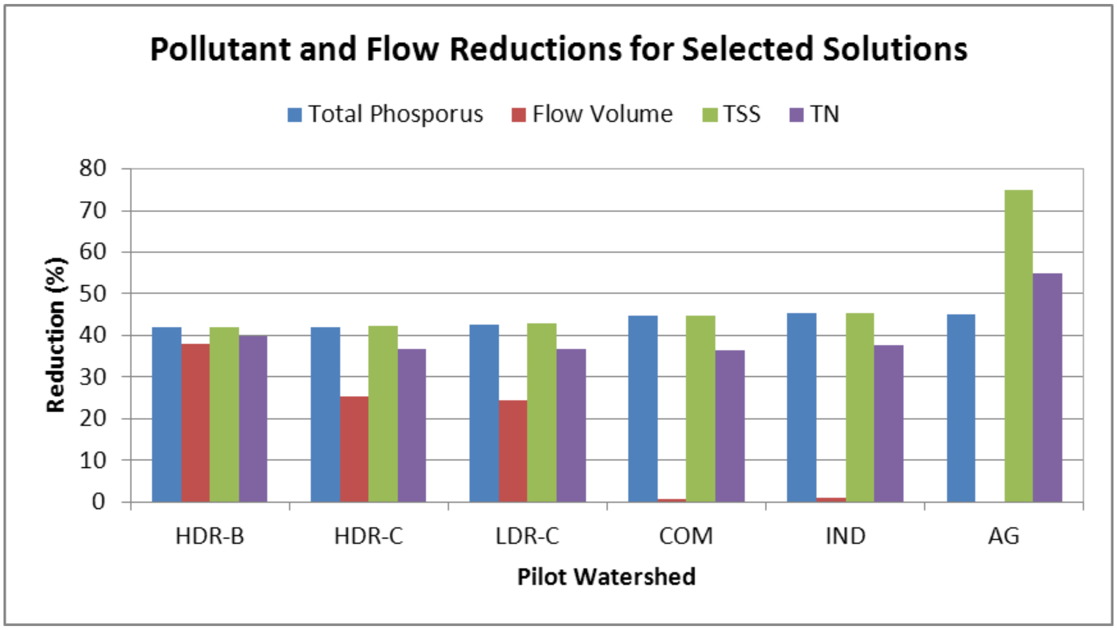

Figure 8-6. Pollutant and flow reduction for the selected BMP solutions.

8.2 *Watershed-Wide Extrapolation*

A watershed-wide extrapolation of the pilot watershed optimization was performed to analyze the potential cost of attaining the 40 percent total phosphorus reduction goal throughout the entire watershed. Two methods were used to evaluate BMP implementation. The first was a uniform reduction done on the basis of the pilot watershed optimization results where costs were linearly associated with land use area and areas were set to the watershed totals. The second method performed a second targeted optimization for the entire watershed where total BMP opportunity was scaled-up from the pilot watershed scale assuming a linear relationship between opportunity and the treated area. The results of the two methods of analysis are discussed in the following sections.

8.2.1 Uniform Reduction

A watershed-wide evaluation was performed to identify cost-effective BMP solutions in the entire Plaster Creek watershed. Pilot area results were extrapolated to the entire watershed, assuming a linear relationship between effectiveness, cost, and area (Table 8-4). Watershed-wide results achieve an area weighted 43.6 percent reduction in TP at a cost of approximately $37 million. Further evaluation of the cost per pound of TP removed identifies the commercial, industrial, and agricultural areas as the most cost-effective land uses to treat. Table 8-5 summarizes the BMPs that could be used to achieve these reductions.

Table 8-4. Summary of watershed extrapolation results

	TP reduction (%)	Pilot area			Watershed-wide			
		Area (acres)	**Cost**	**TP load reduction (lbs /yr)**	**Area (acres)**	**Cost ($)**	**TP load reduction (lbs /yr)**	**$/pound of TP reduced**
High Density Residential B	42.1	32.8	$110,930	28	4,701	$15,898,839	4,013	**$3,961.79**
High Density Residential C	41.9	55.4	$144,130	44	4,224	$10,989,262	3,355	**$3,275.68**
Low Density Residential C	42.5	127.3	$206,138	71	2,683	$4,344,605	1,496	**$2,903.35**
Commercial C	44.7	40.6	$23,700	29	3,291	$1,921,101	2,351	**$817.24**
Industrial C	45.3	40.2	$32,940	24	4,683	$3,837,264	2,796	**$1,372.50**
Agriculture C	45.0	126	$0	95	3,853	$0	2,905	**$0.00**

Table 8-5. Extrapolated BMP results

Land Use	BMP	BMP extent (acres)
Residential[a]	Porous Pavement	62.3
Commercial	Regional Pond	8.8
Industrial	Regional Pond	18.2
Agricultural	Conservation Tillage	3,853

a. All residential areas combined

8.2.2 Targeted Reduction

A watershed-wide targeted reduction scenario was developed to estimate the cost of implementing BMPs in the Plaster Creek watershed to achieve the 40 percent total phosphorus reduction goal. The watershed was represented as six parallel land uses, as illustrated in Figure 8-7 for the watershed wide optimization. The assessment point, depicted as a star in the figure, is a virtual outlet that receives runoff from all land uses. The BMP configurations of each of the six land uses are the same as described previously for the pilot watersheds. The decision variables that underlie the optimization are the number of units and sizes of all BMP types.

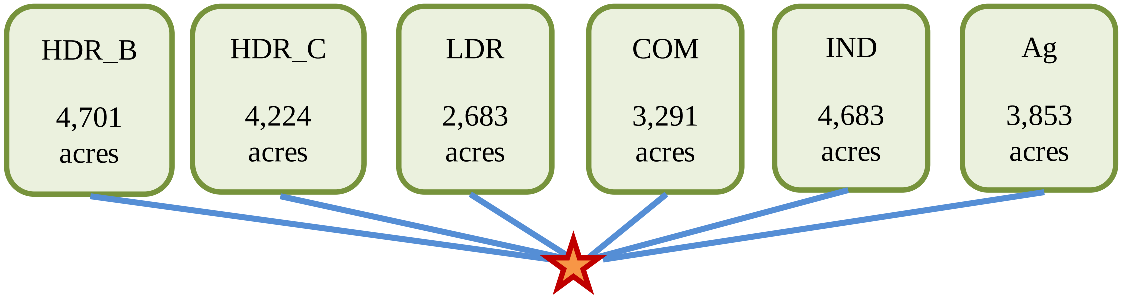

Figure 8-7. Schematic of watershed wide optimization representation.

The targeted watershed wide optimization cost-effectiveness curve is presented in Figure 8-8. Because conservation tillage has zero cost it is always selected during optimization and is shown as the approximately ten percent total phosphorus reduction achieved at no cost. The stream buffer strip is also very cost-effective because of its marginal cost and is also called out in the figure. The selected solution, marked as a green diamond, achieves a 43.9 percent total phosphorus load reduction throughout the watershed at a total cost of $14 million.

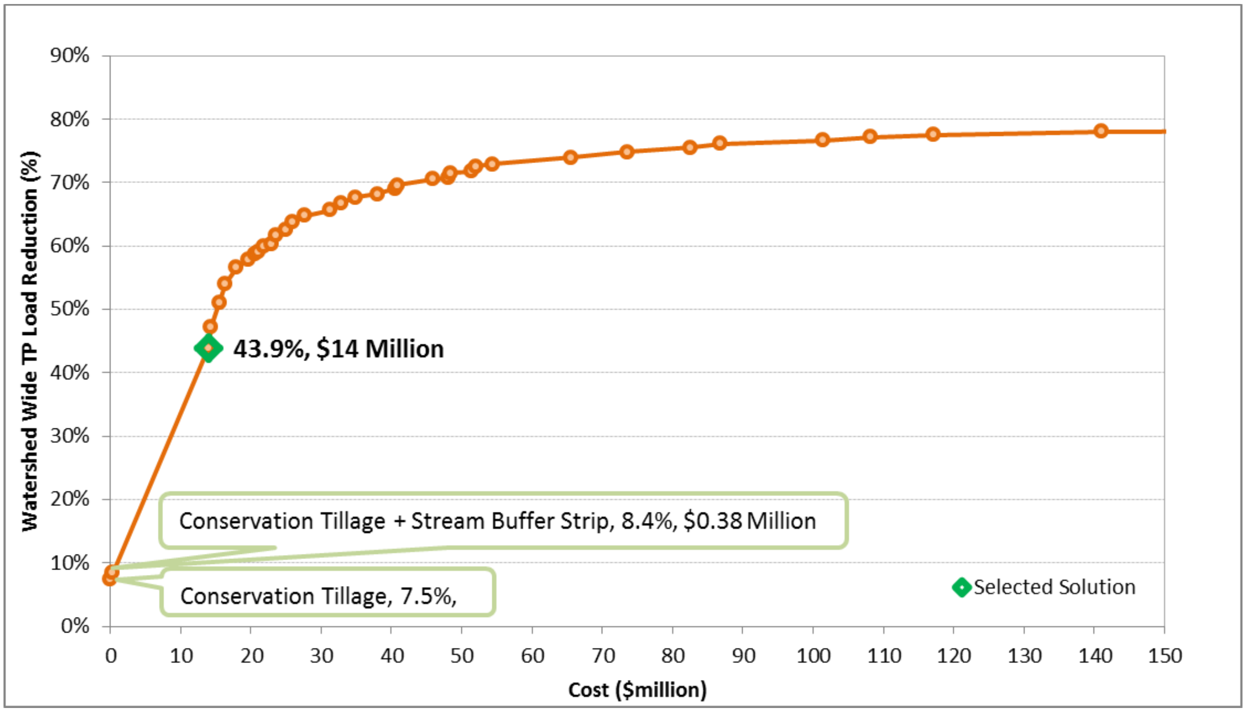

Figure 8-8. Watershed wide optimization cost-effectiveness curve.

The percent utilization of BMPs for the targeted watershed-wide optimization is shown in Table 8-4. Percent utilization for each solution is the area or number of BMPs in the selected solution divided by the maximum potential area or number of BMPs in the model. Table 8-4 shows that, unlike for the assessment of individual land uses, a suite of BMPs have been selected to reach the 43.9 percent load reduction target.

Table 8-6. . Best management practice percent utilization for the Plaster Creek watershed

BMP	Unit	Max extent (unit)	Extent utilized (unit)	Utilization (%)
Bioretention	acres	668	0	0.0
Buffer Strip	acres	70	70	100.0
Conservation Tillage	acres	3,046	3,046	100.0
Green Roof	acres	1,673	0	0.0
Porous Pavement	acres	1,245	6	0.5
Rain Barrel	units	29,864	4,866	16.3
Rain Garden	unit	3,569	543	15.2
Regional Pond	acres	968	29	3.0
Wetland	acres	581	12	2.0

As discussed earlier, buffer strips and conservation tillage for agricultural areas are both 100 percent utilized because of their low cost. Twelve acres (2 percent utilization) of wetland restoration is also selected for implementation on agriculture land. For residential areas, unlike the individual pilots, three BMPs were selected, which include rain barrels, rain gardens, and porous pavement. Of these, rain gardens and rain barrels have similar utilization of 16.3 and 15.2 percent, respectively. Porous pavement has a very low utilization of approximately 0.5 percent. Comparing the pilot watershed and watershed-wide results, it appears that rain gardens have generally supplanted the utilization of porous pavement in residential areas. This is an indicator that the marginal cost of treatment provided by these two BMPs is similar. Though rain gardens are less expensive on a unit area basis ($5 - $7.50 versus $11.00) porous pavement provides additional treatment using under drains and an additional media layer. The utilization of rain barrels increases the runoff storage capacity in residential areas, and therefore increases the efficacy of the rain gardens, which are located directly downstream in the treatment train.

The BMP utilization for commercial and industrial areas is similar between the pilot and watershed-wide optimizations, where only regional ponds are selected to provide treatment. The unit area costs are lowest for regional ponds as compared to all other BMPs. That they are consistently selected for both the watershed-wide and pilot watershed optimizations suggest that the level of treatment provided is high with respect to cost. The utilization of regional ponds on commercial and industrial areas is lower for the watershed-wide analysis, however, which is related to the land use distribution in the Plaster Creek watershed. Residential areas account for most of the developed area, therefore, in order to meet the total phosphorus reduction goal BMP utilization was shifted to those land uses.

The pollutant load and volume reductions for the selected watershed-wide solution are presented in Table 8-7 and Figure 8-6. Attainment of a 43.9 percent reduction in TP results in a 52.6 percent reduction in TSS and a 40.5 percent reduction in TN. Reductions in TSS and TN are much higher under this scenario when compared with the uniform reduction scenario, due to focused implementation on agricultural land uses. Flow volume and *E. coli* load reductions are also simulated.

Table 8-7. Selected solution pollutant load and flow volume reductions for Plaster Creek watershed

Constituent	Unit	BMP reduction	
		%	Quantity (unit)
Total Phosphorus	tons/yr	43.9	9
Flow Volume	acre-feet/yr	3.5	1,040
TSS	tons/yr	52.6	1,124
Total Nitrogen	tons/yr	40.5	28
Ecoli	# x 10^9/yr	32.7	927,579

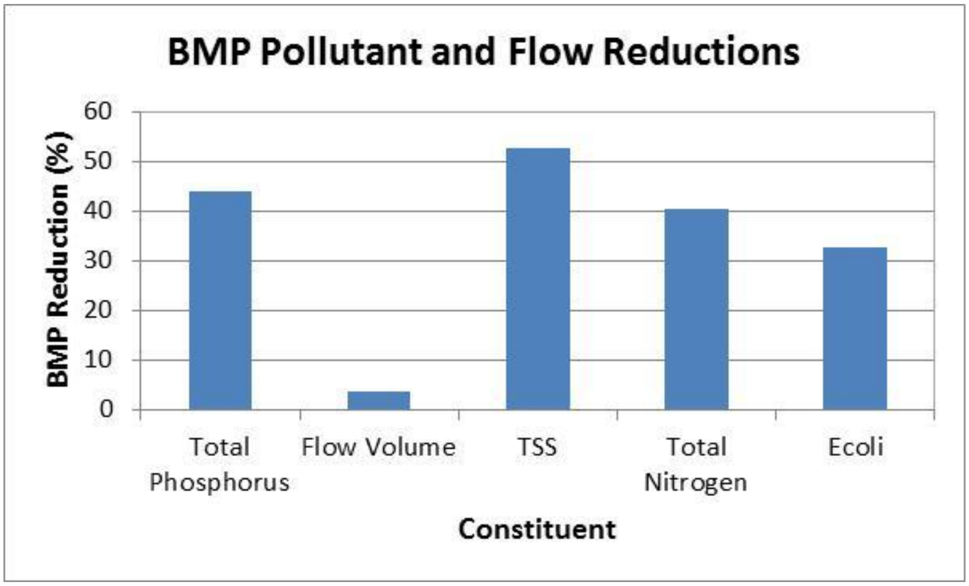

Figure 8-9. Pollutant and flow reduction for the watershed-wide BMP solution

As identified in the pilot watershed analysis, the implementation of conservation tillage provides no flow volume reduction and regional pond BMPs provide very little volume reduction as infiltration from the ponds is assumed to be negligible. If it were determined that flow volume reduction was the primary concern to be addressed in the Plaster Creek watershed, optimization simulations would prioritize BMP utilization that promoted large infiltration volumes and long term detention and evaporation.

8.2.3 Comparison of Uniform and Targeted Reductions

A comparison of the cost of phosphorus load reductions between addressing the pilot watersheds individually (uniform reduction) and addressing the watershed as a whole (targeted reduction) is shown in Figure 8-10. Addressing each pilot watershed separately limits the suite of BMPs that may be implemented to reach the 40 percent phosphorus load reduction goal. To meet that goal, the BMPs utilized are restricted to those that are included in the treatment train designed specifically for each land use. This removes the assessment of possibly lower cost solutions that can be achieved for other land uses that when taken in aggregate still achieve the load reduction target.

On average the phosphorus load percent reduction for the uniform reduction scenarios is 44.4 percent. This is approximately equal to the 43.9 percent load reduction realized with the targeted approach, which has a $22.6 million lower cost. The 62 percent reduction in cost for the targeted reduction is achievable because the lowest cost BMP options are optimized across all land uses and the entire suite of BMPs is evaluated together.

The results of the targeted reduction show that phosphorus load reductions are more cost effectively achieved on agriculture, commercial, and industrial land uses. This is reflected in the load reductions by land use where the highest reductions are achieved on agriculture (88 percent) followed by commercial (77 percent) and industrial (59 percent). This result is reflective of the low cost of implementing conservation tillage and buffer strips on agriculture and regional ponds on commercial and industrial land uses as discussed previously. Because the cost of implementing these BMPs is generally lower than for the suite of BMPs available for residential land uses, load reductions are prioritized for these areas reflected in the shift of load reduction away from residential land uses, which is optimized at 18 percent.

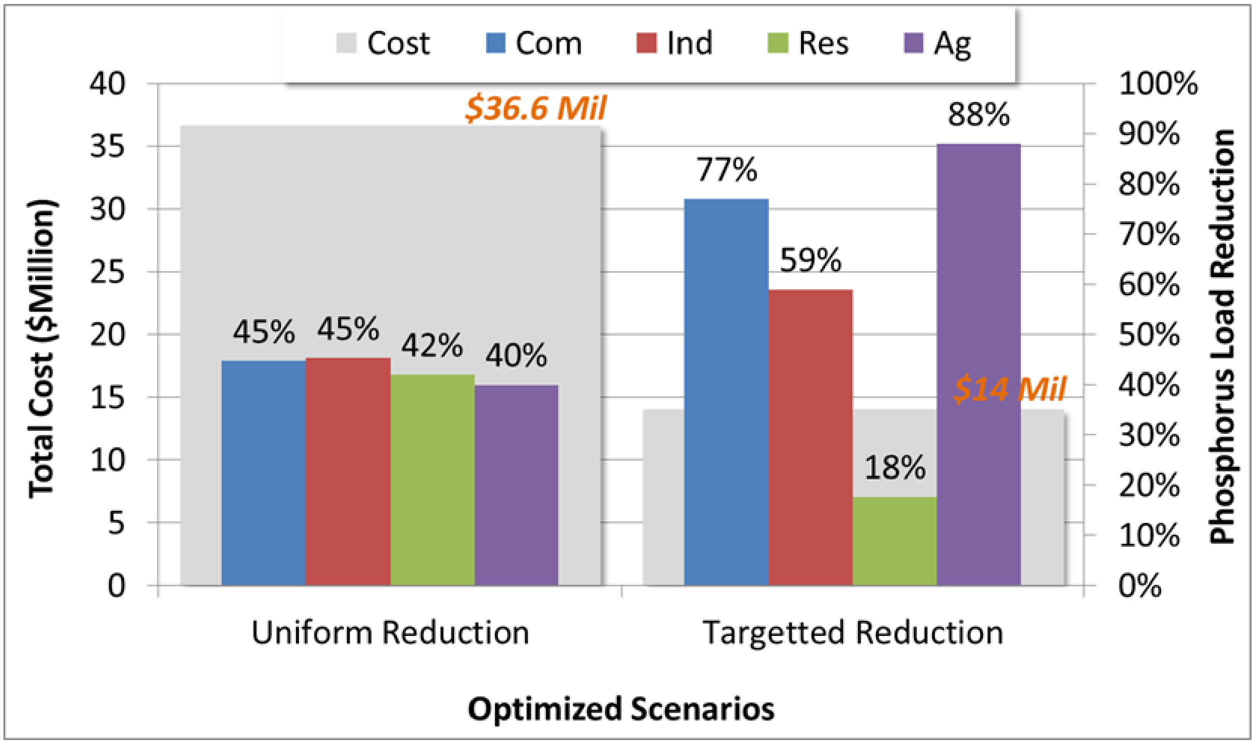

Figure 8-10. Uniform and targeted reductions.

8.3 Grand Rapids CSO 21 and 22 Watershed Extrapolation

Two sewersheds in Grand Rapids were further evaluated by applying the *SUSTAIN* results to determine the combination of BMPs that could be used to reduce phosphorus loading (Figure 8-11). The sewersheds are located in the City's combined sewer area and are being evaluated by the City to determine the potential effect of green infrastructure on CSO controls. The sewersheds are 158 acres in size consisting of residential, commercial, and open spaces. The *SUSTAIN* results were extrapolated for the developed portions of the watershed (residential and commercial areas). A uniform reduction was assumed for this extrapolation. It is important to note that the *SUSTAIN* model was optimized for phosphorus reduction, and therefore volume reduction was not considered when determining the most cost-effective BMPs. Table 8-8 provides the extrapolated results for the CSO 21 and 22 watersheds. Both porous pavement and regional ponds are recommended for a cost of $374,237. BMPs achieve a reduction in approximately 119 pounds of phosphorus and 18.5 acre-feet of runoff volume reduction per year.

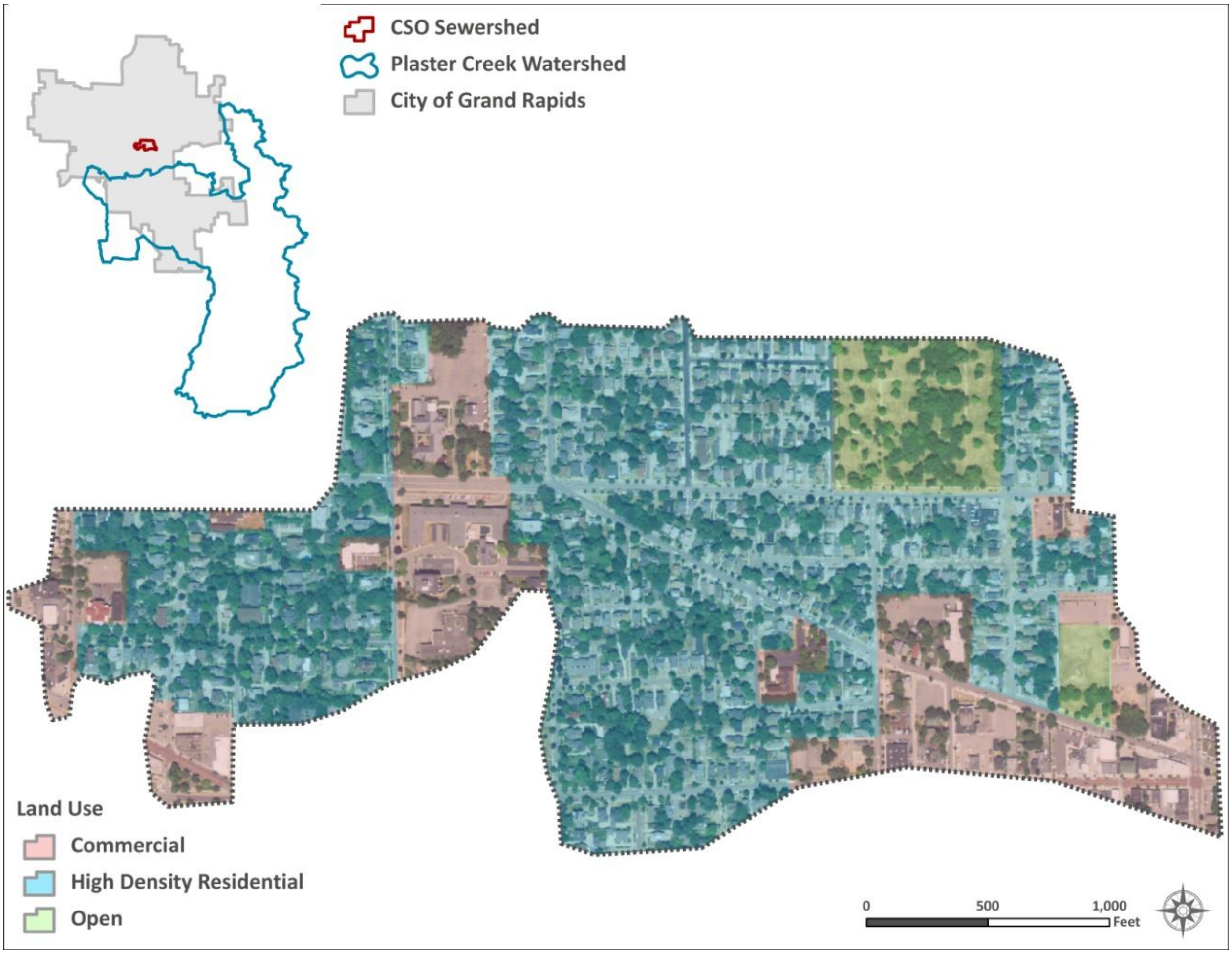

Figure 8-11. CSO 21 and 22 watersheds.

Table 8-8. CSO 21 and 22 BMP results

Land use	Area (acres)	BMP type	BMP extent	Pollutant removal (lbs/year)			Flow volume reduction (acre-feet/year)	Cost
				Nitrogen	Phosphorus	TSS		
Commercial	43	Regional pond	0.1	103.7	30.7	5,291.1	17.2	$ 25,080
High density residential B	103.2	Porous pavement	0.7	267.5	88.1	6,376.9	1.3	$349,157
			Total	**371.2**	**118.8**	**11,668.0**	**18.5**	**$374,237**

9. Finding and Recommendations

Overall findings indicate that a moderate level of BMP implementation is needed to achieve the water quality goals specified in the Plaster Creek WMP. Focusing implementation activities in high priority watersheds will be important to achieve cost-effective solutions. Key findings as relate to priority watersheds include:

- Priority watersheds, identified by the highest pollutant yield, for BMP implementation include those watersheds with the greatest amount of impervious surfaces.
- An evaluation of BMP cost-effectiveness identifies agricultural areas as the best land use to focus implementation activities. Agricultural BMPs have the highest level of effectiveness compared to the cost.
- While agricultural watersheds were not identified as high priority areas, the L-THIA model does not appear to accurately represent the activities that are causing flashy flows and bank erosion such as tile drainage. The LSPC model could be used to further evaluate the flow conditions that result from agricultural areas, although in-stream flow data would be needed for calibration.

The types of BMPs used to implement water quality improvement projects should reflect the most cost-effective solutions. The following findings relate to optimization of BMPs in the Plaster Creek watershed:

- BMP optimization analysis on a pilot watershed basis with total phosphorus as the target utilizes a single BMP for each land use type—porous pavement for residential, regional pond for commercial and industrial, and conservation tillage for agriculture.
- Uniform extrapolation based on the individual pilot area results for the entire Plaster Creek watershed results in meeting the water quality goals for pollutant load reductions at a cost of $37 million.
- Targeted watershed reduction resulting from a watershed-wide optimization strategy results in higher pollutant load reductions for a cost of $14 million. Pollutant load reductions are higher using this scenario achieving a 43.9 percent reduction in TP, 52.6 percent reduction in TSS, and 40.5 percent reduction in TN.
- Optimization on a watershed-wide basis results in a larger suite of BMPs being selected to meet the reduction goal including conservation tillage, agricultural buffers, rain gardens, rain barrels, porous pavement, regional ponds, and wetland restoration.
- Watershed-wide implementation of BMPs is most cost-effective on agricultural, commercial, and industrial land uses compared to retrofitting residential areas.
- Simulated runoff volume reductions are significantly lower than pollutant loads on a percentage basis. Regional ponds have the potential to reduce peak flows significantly, and could therefore address other sources of sediment in the watershed that result from stream flashiness.

Key recommendations include:

- A focused effort should take place to work with agricultural producers in the watershed to implement conservation tillage and other agricultural BMPs. Funding is available for these activities through federal programs in conjunction with the Natural Resources Conservation Service.

- The *SUSTAIN* results can be applied to sites in and near the watershed, assuming the weather data obtained from the airport and land use/soil combinations are representative. It is important to note that application of the results is also dependent on achieving the same water quality goals used to generate the model results which was total phosphorus reduction.
- In addition to retrofitting developed land uses, a stormwater and water quality ordinance that requires pollutant loads under a developed condition to meet the requirements of the TMDL and watershed plan should be adopted.
- Further analysis is needed to understand the effect of watershed BMPs on stream flow energy and channel and bank erosion. The LSPC model could be expanded to represent the entire watershed and stream routing could be incorporated to represent stream conditions.

10. References

Al-Kaisi, M., M. Hanna, and M. Tidman. 2000. Survey: Iowa No-Till Holds Steady. Integrated Crop Management, IC-484(23), October 23, 2000.

American Rivers. 2010. Low Impact Development Manual for the Lower Maumee and Ottawa River Watersheds. Prepared by Tetra Tech and the Low Impact Development Center. Funded by the Joyce Foundation. Toledo, OH.

Center for Neighborhood Technology, 2009. National Green Values Calculator. June 30, 2009.

Czapar, G., J. Laflen, G. McIsaac, D. McKenna. 2006. Effects of Erosion Control Practices on Nutrient Loss, University of Illinois.

Dillaha, T., R. Renear, S. Mostaghimi, and D. Lee. 1989. Vegetative filter strips for agricultural nonpoint source pollution control. Transactions of the American Society of Agricultural Engineers, 32(2):513-519.

EPA (U.S. Environmental Protection Agency). 2000. BASINS Technical Note 6. Estimating Hydrology and Hydraulic Parameters for HSPF. Office of Water, U.S. Environmental Protection Agency. Washington, DC.

EPA (U.S. Environmental Protection Agency). 2003. National Management Measures to Control Nonpoint Source Pollution from Agriculture. EPA 841-B-03-004, July 2003.

EPA (U.S. Environmental Protection Agency). 2009. SUSTAIN—A Framework for Placement of Best Management Practices in Urban Watersheds to Protect Water Quality. EPA/600/R-09/095. U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC.

FTC&H (Fishbeck, Thompson, Carr & Huber. 2008. Plaster Creek Watershed Management Plan. Prepared for the Grand Valley Metropolitan Council.

Harman, W., T. Gerik, H. Torbert III, K. Potter. 2003. Agronomic and Economic Implications of Conservation Tillage and Ultra-Narrow Row Cropping Systems. National Conservation Tillage Cotton and Rice Conference Proceedings. Jan. 23-24, Houston, TX. p. 11-13.

Kohler, M., T. Nordenso, and W. Fox. 1955. Evaporation from Pans and Lakes. U.S. Dept. Com., Weather Bur. Res. Paper 38. 21 pp.

Low Impact Development Center, Inc., 2005. Low Impact Development for Big Box Retailers. Prepared for U.S. Environmental Protection Agency.

NCSU (North Carolina State University). 2002. Riparian Buffers and Controlled Drainage to Reduce Agricultural Nonpoint Source Pollution. Departments of Soil Science and Biological and Agricultural Engineering, North Carolina Agricultural Research Service, North Carolina State University, Raleigh, North Carolina. Technical Bulletin 318, September 2002.

Penman, H. 1948. Natural Evaporation from Open Water, Bare Soil, and Grass. Proceedings of Roy. Soc. London A193:120-146.

Schueler, T., D. Hirschman, M. Novotney, and J. Zielinkski. 2007. Urban Stormwater Retrofit Practices V 1.0, Appendices. Prepared for U.S. Environmental Protection Agency, Office of Wastewater Management, Washington, DC, by Center for Watershed Protection, Ellicott City, MD.

Tetra Tech, Inc. 2001. Low–Impact Development Management Practices Evaluation Computer Module User's Guide. Prepared for Prince George's County, Department of Environmental Resources, by Tetra Tech, Inc., Fairfax, VA.

Tetra Tech, Inc. 2009. Green Best Management Practice (BMP) Operation and Maintenance Study. Prepared for the City of Columbus, Ohio, Public Utilities Department, Columbus, OH, by Tetra Tech, Inc., Fairfax, VA.

Tetra Tech, Inc. 2012. Connecting TMDL Implementation to Stormwater Management – Swan Creek Watershed Pilot. Prepared by Tetra Tech in support of the U.S. Environmental Protection Agency Region 5. Chicago, IL. EPA Contract Number EP075000170.

USDA (United States Department of Agriculture). 1999. CORE4 Conservation Practices Training Guide The Common Sense Approach to Natural Resource Conservation. United States Department of Agriculture, Natural Resources Conservation Service.

Weiss, P., J. Gulliver, and A. Erickson, 2005. The Cost and Effectiveness of Stormwater Management Practices. University of Minnesota. Prepared for the Minnesota Department of Transportation.

Wenger, S. 1999. A Review of the Scientific Literature on Riparian Buffer Width, Extent, and Vegetation. for the Office of Public Service & Outreach Institute of Ecology, University of Georgia, Revised Version March 5, 1999.

WERF (Water Environment Research Foundation). 2009. BMP and Low Impact Development Whole Life Cost Models Version 2.0.