# *Assessment of MIDS Performance Goal Alternatives: Runoff Volumes, Runoff Rates, and Pollutant Removal Efficiencies*

***Prepared for***
***Minnesota Pollution Control Agency***

***June 30, 2011***

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## June 30, 2011

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# 1.0 Executive Summary

The Minnesota Pollution Control Agency (MPCA) asked Barr Engineering Company (Barr) to assess various stormwater management performance goals by comparing the runoff rates and volumes of theoretical developed sites conforming to those performance goals to the runoff rates and volumes of the sites under native soils and vegetation conditions. The goal of the assessment was to answer the question, "How well do the identified performance goal alternatives mimic natural hydrology?"

Barr developed long-term continuous simulation XP-SWMM models for the Twin Cities, Southeast Minnesota, and North-Central Minnesota regions that estimated the runoff volume from a 10-acre site with native soils (Hydrologic Soil Group A, B, C, and D) and native vegetation (100% deciduous woods and 100% meadow). Barr also developed long-term continuous XP-SWMM models of the same Minnesota regions to simulate the effectiveness of implementing different commonly used volume control performance goals on development scenarios of varying imperviousness and soil type. The XP-SWMM models also simulated the effectiveness of rate control in controlling runoff rates from six development scenarios for the Twin Cities region. The resulting runoff rates from the six Twin Cities scenarios and volumes from all the developed conditions models were compared to the results of the native vegetation models.

Based on discussion of the results of XP-SWMM modeling of the Twin Cities region and discussion, the MIDS Work Group selected two volume control performance goals for Barr to model in greater detail. The goal of this additional modeling was to determine the retention volume needed to provide the equivalent average annual runoff volume as native conditions for each development scenario, soil type, and state region. Barr also developed a P8 water quality model to compare the estimated total phosphorus and total suspended solids removal efficiencies of the various volume control performance goal alternatives for the Twin Cities region.

Based on these modeling efforts, Barr found the following results:

- Rate and volume control Best Management Practices (BMPs) are needed to mimic native hydrology from developed conditions
- Developed sites without volume control BMPs produce approximately two to four times the average annual runoff volume of native conditions

- All of the volume control performance goals evaluated do well at matching native conditions on an average annual basis
- The performance goals evaluated generally do worse at matching native conditions during non-frozen ground conditions (some yield up to two times more runoff native conditions)
- Volume control BMPs controlled the 1-year, 24-hour SCS Type II peak rates to flows less than or equal to native conditions for most scenarios evaluated
- Volume control performance goals result in significant pollutant loading reduction from developed sites
- All volume control performance goals evaluated have similar removal efficiencies for total phosphorus (TP) and total suspended solids (TSS)
- The BMP size required to match native runoff volumes on an average annual basis varied with soil type, impervious percentage, and region of the state

# 2.0 Introduction, Background, and Acknowledgments

Minnesota Statute 115.03, Subdivision 5c, paragraph c, states, “The agency shall develop performance standards, design standards, or other tools to enable and promote the implementation of low-impact development and other storm water management techniques. For the purposes of this section, "low-impact development" means an approach to storm water management that mimics a site’s natural hydrology as the landscape is developed. Using the low-impact development approach, storm water is managed on-site and the rate and volume of predevelopment storm water reaching receiving waters is unchanged. The calculation of predevelopment hydrology is based on native soil and vegetation.” In the context of this report, post-development runoff is compared to predevelopment runoff, which is also referred to as ‘native’ runoff, to be consistent with the MIDS Legislative charge.

To assist the MPCA in developing a performance standard that mimic’s a site’s natural hydrology, the MPCA asked Barr to assess various commonly used performance goals in comparison with runoff rate and volume from native soil and vegetation conditions. The goal of the assessment was to answer the question, “How well do the performance goal alternatives mimic natural hydrology?”

This report documents Barr’s assessment of the performance goals in regards to how well they mimic natural hydrology. Section 3 of this report describes the performance goals evaluated. Details of the methods used in the evaluation are included in Section 4. The evaluation results are discussed in Section 5. Section 6 includes conclusions.

Throughout Barr’s evaluation process, the MPCA, the MIDS Work Group, and other parties provided input and direction. The Capitol Region Watershed District and the Ramsey-Washington Metro Watershed District funded the portion of the assessment, as discussed in Section 3.

# 3.0 Performance Goals and Regions Analyzed

How well do performance goal alternatives mimic natural hydrology? To answer this question, the MPCA and Barr chose commonly used performance goals which Barr evaluated to determine how closely they match the native soil and native vegetation runoff volumes and rates. The performance goals evaluated included:

1. Runoff Volume Control Only
   a. Retain a runoff volume on site equal to one inch of runoff from the proposed impervious surfaces; hereinafter often referred to as "one inch off of impervious"
   b. Retain the post-construction runoff volume on site for the 95th percentile 24-hour storm (1.4 inches in Minneapolis); hereinafter often referred to as "95th percentile"
   c. Limit the post-construction runoff from the following events to a volume equal to or less than the native soil and native vegetation condition:
      i. 1-year 24-hour design storm; hereinafter often referred to as "1-year match"
      ii. 2-year 24-hour design storm; hereinafter often referred to as "2-year match"
2. Runoff Volume Control and Rate Control Together

   Limit the runoff rate to the 100% meadow native soil and native vegetation condition for the 1-year, 2-year, 10-year, and 100-year 24-hour design storm and the volume control standards listed in (1) above.

Barr developed long-term continuous simulation XP-SWMM models for three regions of Minnesota, Twin Cities, Southeast and North-Central, that estimated the runoff from a 10-acre site[1] with native soils (Hydrologic Soil Group A, B, C, and D) and native vegetation (100% deciduous woods and 100% meadow). Barr also developed long-term continuous XP-SWMM models of the same three Minnesota regions to simulate the effectiveness of implementing different volume control performance goals on development scenarios of varying imperviousness and soil type. Between twenty-six and thirty-five years of measured precipitation data with a time increment of 15 minutes was used in Barr's modeling efforts (see Section 4.1.2). Precipitation in the form of rain and snow

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[1] 10-acre sites were the average area of new development sites of construction permits submitted to the MPCA in 2009, based on personal communication with Michael Findorff

on frozen and unfrozen ground conditions was modeled to determine the effectiveness of common volume control performance goals on annual runoff. While most commonly-used volume control performance goals reference rain events, one of the goals of the continuous modeling was to assess how BMPs sized based on rain event volume performance goals performed on an average annual basis, including snowmelt.

Table 3-1 provides a summary of the developed scenarios analyzed within each of the three Minnesota regions considered. As shown in the table, no volume control performance goals were evaluated on Hydrologic Soil Group (HSG) D soils. This is because volume controls are typically limited or infeasible on these soils. Two of the four volume control performance goals were assessed for the Southeast and North-Central regions. These two performance goals were selected by the MIDS Work Group and the MPCA after discussion of preliminary results of the Twin Cities modeling efforts of all four performance goals. The Twin Cities XP-SWMM model assessed the effectiveness of controlling stormwater runoff rate and volume, while the Southeast and North-Central models assessed the effectiveness of controlling runoff volume alone.

The Capitol Region Watershed District and the Ramsey-Washington Metro Watershed District funded the modeling efforts of the performance goals on the various developed sites on HSG A soils in the Twin Cities region. These two watershed districts also funded the effort to determine the retention volume needed to provide the equivalent average annual runoff volume as native conditions for each development scenario and soil type for the “inches off imperviousness” and “percentile storm” performance goals.

Details of the modeling methods and assumptions as well as the modeling results are presented in later sections of this report. The annual, frozen-ground, and non-frozen ground runoff volumes and rates from the various performance goal alternatives are compared and contrasted to the runoff from native soil and native vegetation conditions.

The MPCA also requested that Barr assess the performance goals based on estimated total phosphorus and total suspended solids removal efficiency on an average annual basis. The portion of average annual runoff volume captured onsite varies depending on the performance goal and resulting BMP volume. While strongly correlated with the amount of runoff captured and infiltrated, the overall pollutant removal efficiency is also dependent on other factors such as the varying concentration of pollutants in runoff (such as the “first flush effect”) and pollutant removal that occurs through sedimentation or other mechanisms.

To evaluate the overall average annual phosphorus and total suspended solids removal efficiencies expected from the four performance goals, Barr  modeled six of the Twin Cities region development scenarios using P8 modeling software (Table 3-1).  Later sections of this report provide details of that modeling effort and a comparison of the treatment efficiencies of the volume control performance goal alternatives.

**Table 3-1 Developed Scenarios and Regions Modeled**

| Hydrologic Soil Group | Native Runoff | Developed Impervious Surface | Developed Runoff With No Volume Control | Volume Control Performance Goals | | | | Modeling to Determine Annual Runoff Match | | Rate Control | Pollutant Modeling with P8 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1 inch off Impervious | 95th Percentile | 1-Year Match | 2-Year Match | Inches off Impervious | Percentile Storm | | |
| *Twin Cities Region* | | | | | | | | | | | |
| A | X | 20, 50, 80% | X | X[1] | X[1] | X[1] | X[1] | X[1] | X[1] | | |
| B | X | 20, 50, 80% | X | X | X | X | X | X[1] | X[1] | X | X |
| C | X | 20, 50, 80% | X | X | X | X | X | X[1] | X[1] | X | X |
| D | X | 20, 50, 80% | X | | | | | | | | |
| *Southeast Region* | | | | | | | | | | | |
| A | X | 20, 80% | X | X | X | | | X | X | | |
| B | X | 20, 80% | X | X | X | | | X | X | | |
| C | X | 20, 80% | X | X | X | | | X | X | | |
| D | X | 20, 80% | X | | | | | | | | |
| *North-Central Region* | | | | | | | | | | | |
| A | X | 20, 80% | X | X | X | | | X | X | | |
| B | X | 20, 80% | X | X | X | | | X | X | | |
| C | X | 20, 80% | X | X | X | | | X | X | | |
| D | X | 20, 80% | X | | | | | | | | |

1 These modeling efforts were financed by the Capitol Region Watershed District and the Ramsey-Washington Metro Watershed District.

# 4.0 Methods

The hydrologic modeling (runoff generation) methods and parameters used in our assessment are discussed in Section 4.1. Section 4.2 provides the hydraulic modeling (runoff routing) methods and parameters. We discuss our water quality treatment modeling methods in Section 4.3. Our limited qualitative sensitivity analysis is summarized in Section 4.4.

## 4.1 Hydrologic Modeling (Runoff Generation)

The U.S. Environmental Protection Agency's Storm Water Management Model (SWMM), with a computerized graphical interface provided by XP Software (XP-SWMM), was used for the stormwater runoff volume and rate analyses for this study. XP-SWMM uses rainfall and watershed information to generate runoff that can be routed simultaneously through complicated pipe and overland flow networks. Simultaneous routing means that flow in the entire system is modeled for each time increment, then the model moves on to the next time increment, and so on (many other models calculate by subwatershed for the entire duration of the storm, before moving to the next subwatershed). Simultaneous routing allows the model to account for detention in ponding areas, backwater conditions, surcharging of culverts, and backflow through culverts. XP-SWMM also has advanced capabilities for conducting long-term continuous simulation.

The 1000-node version of XP-SWMM 2010 (with Service Pack 2 installed) was used in this study. The major types of information required by XP-SWMM for hydrologic modeling include (1) watershed and infiltration data, and (2) climatic data. These data are used by XP-SWMM to generate runoff hydrographs for each watershed, which are then routed hydraulically into each volume control BMP, as discussed in Section 4.2. The following Sections describe each of these data.

### 4.1.1 Watershed Data

#### 4.1.1.1 Statewide Assumptions

##### *4.1.1.1.1 Watershed Size and Impervious Surface Coverage*

The long-term continuous simulation XP-SWMM model was used to estimate the runoff rate and volume from hypothetical 10-acre sites with native soils (HSG A, B, C, and D) and native vegetation (100% deciduous woods and 100% meadow) as well as several hypothetical 10-acre development sites in three Minnesota regions[2]. Developed scenarios ranged in impervious coverage from 20% to 80%, representing a reasonable range of development density from suburban residential (20%) to heavy commercial or industrial (80%). Residential and commercial developments were assumed to be traditionally designed with all impervious surfaces connected to storm sewer with no impervious surface disconnection. For the native soils and vegetation scenarios, the 10-acre sites were assumed to be 100% pervious. Table 3-1 provides a summary of the developed scenarios analyzed within each of the three Minnesota regions considered.

##### *4.1.1.1.2 Infiltration*

Infiltration can be defined as the flow of water from the land surface into the soil. The rate at which the stormwater infiltrates into the soil is dependent on several factors, including the rate and duration of stormwater supply, physical properties of the soil, such as its porosity and hydraulic conductivity, vegetation, slope of the land, and the current moisture content of the soil. The maximum rate at which water can infiltrate into the soil under a given set of conditions is called the infiltration capacity. In general, the rate of infiltration in soils is higher in the beginning of a storm, decreases rapidly, and then slowly decreases over time until it approaches a constant rate (saturated hydraulic conductivity).

For the long-term continuous simulation XP-SWMM modeling, the Green-Ampt infiltration method was used to simulate the variation in infiltration rate with time and soil moisture conditions. The Green-Ampt infiltration input parameters include the saturated hydraulic conductivity (K), initial moisture deficit fraction ($\theta$), and the average capillary suction (psi).

As previously discussed, the modeling analysis included hypothetical watersheds representing all HSG soil types (A, B, C, and D). An approximate estimation of infiltration rates and other properties affecting infiltration can be made based on the HSG. However, there can be significant variation in infiltration rates among soils within each HSG, as the soil groups often include several U.S. Department of Agriculture (USDA) soil textures. For example, sand, loamy sand and sandy loam soil textures are all typically classified as HSG A. However, infiltration rates for a sandy loam can be much lower than that of a sand or loamy sand.

[2] 10-acre sites were the average area of new development sites of construction permits submitted to the MPCA in 2009, based on personal communication with Michael Findorff

To help determine suitable model input parameters for each HSG, a specific soil texture was chosen to represent each HSG. For HSG A, infiltration parameters were selected to reflect a sandy loam soil texture. For groups B, C, and D, infiltration parameters were selected based on loam, sandy clay loam, and silty clay, respectively. The infiltration parameters selected for each of these soil textures are discussed in the following sections.

#### *4.1.1.1.2.1 Saturated Hydraulic Conductivity*

Considerable work has been conducted to characterize infiltration rates based on USDA soil texture. In 1982, Rawls et al presented mean saturated hydraulic conductivity values for eleven USDA soil texture classes, based on a limited survey of literature (Rawls, 1982). Later, Rawls et al assembled a national database of observed saturated hydraulic conductivities (nearly 1,000 values) and summarized the mean and range of saturated hydraulic conductivities for fourteen USDA soil texture classes (Rawls, 1998). The saturated hydraulic conductivities used for the modeling analysis are shown in Table 4-1.

**Table 4-1 Green-Ampt Infiltration Parameters Used In Long-Term Continuous Modeling Analysis**

| Hydrologic Soil Group | Representative Soil Texture | Saturated Hydraulic Conductivity[1] (in/hr) | Initial Moisture Deficit[2] | Average Capillary Suction[3] (in) |
|---|---|---|---|---|
| A | Sandy Loam | 0.90 | 0.20 | 4.33 |
| B | Loam | 0.20 | 0.13 | 8.00 |
| C | Sandy Clay Loam | 0.14 | 0.10 | 8.60 |
| D | Silty Clay | 0.06 | 0.09 | 11.50 |

[1] Rawls, 1998
[2] Rawls, 1998
[3] Maidment, 1993

#### *4.1.1.1.2.2 Initial Moisture Deficit*

The initial moisture deficit of soil, or effective porosity, is a dimensionless parameter that represents the difference between the soil porosity and the soil moisture content. Soil porosity is the void space fraction of total soil volume; void space being composed of air and water volume.

The soil moisture content varies depending on the initial moisture conditions. In the Midwest, "average" soil moisture conditions are appropriate for initial conditions for hydrologic modeling. The soil moisture content fraction in average conditions is approximated by the moisture retained by the soil at -33 kPa. In HSG A soils, for example, the porosity is 0.41 and the water retained at -33 kPa is 0.21, resulting in an initial moisture deficit fraction of 0.20.

The initial moisture deficit parameters set the moisture content for the soils in the native and developed conditions scenarios at the beginning of the continuous simulation. The moisture content of the soil changes throughout the simulation as precipitation and dry periods occur. Over the entire duration of continuous modeling, the impact of the initial moisture deficit parameter is muted significantly. The initial moisture deficit values used for the four soil types are listed in Table 4-1.

###### *4.1.1.1.2.3 Average Capillary Suction*

Average capillary suction represents the suction head at the wetting front within the soil. This parameter is used to determine the total infiltrated volume of water in the soil, which reduces the infiltration rate of the soil as cumulative infiltration increases. The average capillary suction values used in the long-term simulation modeling analysis for the four soil types are listed in Table 4-1.

##### *4.1.1.1.3 Watershed Width Parameter*

The SWMM Runoff Non-linear Reservoir Method was used as the hydrograph generation technique for this modeling analysis. This method computes outflow as the product of velocity, depth and a watershed width factor. Watershed "width" in XP-SWMM is defined as twice the length of the main drainage channel, with adjustments made for watersheds that are skewed (i.e., the areas on both sides of the main drainage channel are not equal). An estimate for the width parameter can also be made by dividing the watershed area by the watershed length. For this analysis, the hypothetical watersheds were idealized as 10-acre square watersheds, with watershed widths of 660 feet.

##### *4.1.1.1.4 Overland Flow Roughness*

Overland flow is the surface runoff that occurs as sheet flow over land surfaces prior to concentrating into defined channels. In order to estimate the overland flow or runoff rate, a modified version of Manning's equation is used by XP-SWMM. A key parameter in Manning's equation is the roughness coefficient. The shallow flows typically associated with overland flow result in substantial increases in surface friction. As a result, the roughness coefficients typically used in open channel flow calculations are not applicable to overland flow estimates. These differences can be accounted for by using an overland roughness coefficient instead of the typical Manning's roughness coefficient for open channel flow.

Typical values for the effective roughness parameter were obtained from National Resources Conservation Service's (NRCS) *Technical Release 55 – Urban Hydrology for Small Watersheds*

(NRCS ,1986) and from the SWMM User Manual (Huber, 1988), for native and developed conditions. Table 4-2 lists the Manning's overland roughness coefficients for the land covers represented in the modeling.

**Table 4-2 Manning's Overland Roughness Coefficients Used In Long-term Continuous Modeling Analysis**

| Land Cover Type | Manning's Overland Roughness Coefficient |
|---|---|
| Forest | 0.40[1] |
| Meadow | 0.15[1] |
| Developed Pervious (turf grass) | 0.24[1] |
| Developed Impervious | 0.014[2] |

[1] TR-55, 1986
[2] Huber, 1988

#### 4.1.1.2 Regional Assumptions

##### *4.1.1.2.1 Depression Storage and Interception*

Depression storage and interception inputs, representing the areas that must be filled with water prior to generating runoff from both pervious and impervious areas, were set within the general range of published values. These represent the initial loss caused by such things as surface ponding, surface wetting, and vegetative interception. The model handles depression storage differently for pervious and impervious areas. The impervious depression storage is replenished during dry simulation periods by evaporation. The water stored as pervious depression storage is subject to both infiltration and evaporation. The values selected for native and developed land covers reflect the suggested values in "MIDS Issue Paper: Abstractions (Interception and Depression Storage)", provided to the MIDS Working Group in final form on December 14, 2010 (Barr, 2010).

A higher value for interception and depression storage was used to model native forests in North-Central region as opposed to Twin Cities and Southeast regions. Interception for coniferous forests is higher than that in deciduous forests by several hundredths of an inch. Historic vegetation maps indicate that while most of the Twin Cities and Southeast regions forests were deciduous, North-Central region forests were about half deciduous and half coniferous, therefore a higher abstraction value was used for North-Central forests.

Table 4-3 lists the depression and interception values (combined) used for the continuous simulation.

**Table 4-3 Depression Storage And Interception Values Used In Long-term Continuous Modeling Analysis**

| Land Cover Type | Depression Storage and Interception Values (Combined)[1] (inches) |
|---|---|
| Forest – Twin Cities and Southeast Regions | 0.40 |
| Forest – North-Central Region | 0.42 |
| Meadow | 0.40 |
| Developed Pervious (turf grass) | 0.25 |
| Developed Impervious | 0.06 |
| [1] MIDS Issue Paper: Abstractions (Barr, 2010) | |

#### *4.1.1.2.2 Slope*

To estimate the overland flow or runoff rate from a watershed, a modified version of Manning's equation is used by XP-SWMM. A key parameter in Manning's equation is the average slope of the watershed. Geospatial analyses were performed with ArcGIS software using the land use data and U.S. Geological Survey 10- meter digital elevation model (DEM) to determine the average slope for each region.

**Table 4-4 Average Slope Used In Long-term Continuous Modeling Analysis**

| Region | Methodology to Determine Slope | Land Use Base Data | Slope |
|---|---|---|---|
| Twin Cities | Average slope of undeveloped parcels that are considered developable (not parkland) | 2006 Met Council Land Use | 3.4% |
| North-Central | Average slope of developed land in Cass County, Minnesota | 2001 USGS National Landcover Dataset | 2.6% |
| Southeast | Average slope of developed and undeveloped land in Olmsted County, Minnesota | Olmsted County Comprehensive Plan | 5.4% |

## 4.1.2 Climatic Data

Climatic input data consists of rainfall, temperature, wind speed, water surface evaporation, and snowmelt parameters. These data are used by the model to generate a snowpack, watershed runoff (due to rainfall and snowmelt), and estimate water surface fluctuations resulting from evaporation.

### 4.1.2.1 Precipitation

Between twenty-six and thirty-five years of measured precipitation data were used for the long-term continuous modeling analyses for each region. The precipitation data used for these analyses have a time interval of 15 minutes. Although hourly precipitation is available from the Twin Cities area for a longer period of record, 15-minute precipitation data was used because it more accurately represents the varying intensity of rainfall. Rainfall intensity is an important factor in determining the rate and volume of stormwater runoff, especially during high intensity rainfall events.

The precipitation datasets were developed using rainfall records from National Weather Service (NWS) gauging stations within each region with 15-minute interval precipitation records.

##### *4.1.2.1.1 Twin Cities Precipitation*

For the Twin Cities region, the primary source of precipitation records was a gauging station located in Golden Valley, Minnesota (NWS Station 213202), in which records were obtained for the time period of 1971-2009. For years where the precipitation dataset from the Golden Valley station was missing data for significant time periods, data from a 15-minute gauging station in Northfield, Minnesota (NWS Station 215987) was used. The City of Northfield is located approximately 40 miles south of Minneapolis/St. Paul and is generally not considered to be part of the Twin Cities metro area. However, this was the closest 15-minute gauging station to the Golden Valley station, and exhibited annual precipitation totals that were similar to observed totals from the NWS station at the Minneapolis-St. Paul International Airport. There were several years within the time period (1971-2009) where the data from both stations was incomplete; these years were removed from the precipitation dataset. In summary, the 35-year dataset includes data from the years 1972-2009, with data from the years 1983, 2001, and 2006 removed due to significant periods of missing data. The precipitation data is from the Golden Valley gauging station for 21 of the 35 years, with the remaining 14 years from the Northfield station.

##### *4.1.2.1.2 North-Central Precipitation*

For the North-Central region, the primary source of precipitation records was a gauging station located in Walker, Minnesota (NWS Station 218621), in which records were obtained from the time period of 1971-2009. For years where the precipitation dataset from the Walker station was missing data for significant time periods, data from a 15-minute gauging station in Frazee, Minnesota (NWS Station 212964) was used. The Frazee station is approximately 60 miles southwest of the Walker station, and is also within the North-Central region. There were several years within the time period (1971-2009) where the data from both stations was incomplete; these years were removed from the precipitation dataset. In summary, the 26-year dataset includes data from the years 1972-2009, with data from the years 1978, 1979, 1982, 1983, 1987, 1995, 1996, 1999, 2000, 2002, 2006, and 2007 removed. The precipitation data is from the Walker station for 21 of the 26 years, with the remaining 5 years from the Frazee station.

##### *4.1.2.1.3 Southeast Precipitation*

For the Southeast region, the primary source of precipitation records was a gauging station located in Spring Valley, Minnesota (NWS Station 217941), in which records were obtained from the time period of 1971-2009. For years where the precipitation dataset from the Spring Valley station was missing data for significant time periods, data from the 15-minute gauging station at Lock and Dam No. 6, near Trempealeau, WI (NWS Station 478589) and from the 15-minute gauging station at Lock and Dam No. 8, near Genoa, WI (NWS Station 473038) were used. The Trempealeau station and the Genoa stations are both located on the border between Minnesota and Wisconsin. The Trempealeau station is approximately 55 miles northeast of the Spring Valley station, while the Genoa station is approximately 60 miles east of the Spring Valley station. There were several years within the time period (1971-2009) where the data from both stations was incomplete; these years were removed from the precipitation dataset. In summary, the 33-year dataset includes data from the years 1972-2009, with data from the years 1975, 1978, 1983, 2002, and 2005 removed. The precipitation data is from the Spring Valley station for 27 of the 33 years, with 3 of the remaining 6 years from the Treampealeau station, and 3 years from the Genoa station.

#### 4.1.2.2 Temperature

Continuous simulations require a complete time series of daily maximum and minimum temperatures. Using these data, XP-SWMM synthesizes hourly temperature by sinusoidal interpolation (see SWMM user’s manual for further explanation of this topic). These hourly temperatures play a critical role in the establishment of a snowpack and ultimately snowmelt runoff.

For the Twin Cities region, the analysis used temperature data from the NWS Station 215435: Minneapolis-St. Paul International Airport. For the Southeast region, the analysis used temperature data from NWS Station 217004: Rochester WSO Airport. For the North-Central region, the analysis used temperature data from the NWS Station 218618: Walker Ah Gwah Ching for the majority of the simulation. For dates where NWS Station 218618 was missing temperature data, data from nearby NWS stations was used. The additional stations were all within a 22-mile radius of NWS Station 218618.

#### 4.1.2.3 Wind Speed

According to the SWMM User's Manual, the wind speeds are only used for snowmelt determination during periods of rainfall. For the Twin Cities region, the 30-year normal monthly wind speeds observed at the Minneapolis - St. Paul International Airport were used for the study. For the North-Central region, the 30-year normal monthly wind speeds observed at the St. Cloud Airport were used for the study. For the Southeast Region, the 30-year normal monthly wind speeds observed at the Rochester Airport were used for the study. These data were obtained from the Climatological Data Annual Summaries for Minnesota published by the National Climatic Data Center (NCDC).

#### 4.1.2.4 Evaporation

Evaporation is important in estimating the amounts of depression storage available prior to a given storm event and therefore ultimately plays a key role in subwatershed runoff estimates. An average monthly evaporation rate is required for all the months in a continuous XP-SWMM model. Evaporation is subtracted from the rainfall and snowmelt intensities at a given time step, and is also used to replenish the depression storage. For the Twin Cities region, monthly average evaporation was calculated using the Meyer model. For the North-Central and Southeast regions, monthly average evaporation was taken from values calculated for Fargo, ND and La Crosse, Wisconsin, respectively, by Dadaser-Celik (2008) using the Meyer formula.

The Meyer Model is a proprietary computer model developed by Barr Engineering Company that can be used to estimate the runoff of a watershed during long-term climatic events. The model is based on work by Adolph Meyer, who presented empirical relationships for evaporation and transpiration in his book, Elements of Hydrology, which was used as a college text from 1916 through the early 1950s. His methods for estimating water surface evaporation were refined and proven during an analysis of 50 years of weather records for the Minnesota Resource Commission in 1942.

The Meyer evaporation formula uses the average monthly water temperature, relative humidity, and wind speed to determine each month's evaporation using the following formula:

$$E = C\ (VW - VA)\ (1 + W/10)$$

Where

| | | |
|---|---|---|
| E | = evaporation, inches per month |
| C | = empirical coefficient |
| VW | = maximum vapor pressure of water at given temperature |
| VA | = vapor pressure of air for given temperature and humidity |
| w | = average wind speed, miles per hour |

#### 4.1.2.5 Snowmelt

Although snowmelt generally produces low flow rates, it may generate a substantial volume of runoff. Rainfall events that occur during periods of snowmelt can result in even higher flow rates and runoff volumes. For the continuous modeling, the precipitation depths from the NWS station were used along with the hourly temperatures determined from the daily minimum and maximum temperatures (See Section 4.1.2.2 for further discussion) to determine if the precipitation is rainfall or snowfall. If the estimated temperature is below a specified dividing temperature (e.g., 34° F was used for this analysis), the precipitation is treated as snowfall and will be stored in the model as a snowpack. This temperature has been shown to be the dividing line between equal probabilities of rain and snow (Huber, 1988).

XP-SWMM utilizes the interpolated hourly temperatures in the snowmelt computations. The snowmelt is generated using a degree-day type equation during dry weather and Anderson's NWS equation during rainfall periods (Huber, 1988). Before any melt can occur the snow must be heated to a base temperature (32° F was used for this study). The computed snowmelt is then handled in a similar manner as rainfall (i.e., the model allows depression storage and infiltration losses prior to generating runoff). During a snowmelt event there is typically less infiltration capacity available in the soil than during a rainfall event due to frozen or partially-frozen ground conditions. In order to model this phenomenon the watersheds were modeled as 100% impervious during periods of frozen soil (see Section 4.1.3)

There are numerous additional input parameters required for snowmelt modeling. The remaining parameters used were set with the range of values published in the SWMM User's Manual (See the SWMM User's Manual for additional information about snowmelt modeling).

### 4.1.3 Frozen Ground Conditions

The cold climate of Minnesota results in time periods during the winter months where the ground is essentially frozen. During these time periods, the infiltration capacity of the soil can be greatly reduced or eliminated due to partially-frozen or frozen soils. In order to model this phenomenon in XP-SWMM, the watersheds were assumed to be 100% impervious during the frozen ground time periods. Depression storage was assumed to be negligible, so all rainfall and snowmelt that occurred during this time period resulted in stormwater runoff.

The duration of the frozen ground period in Minnesota is dependent on several factors, including air temperatures, soil moisture upon initial freeze, snow cover (timing and depth), ground vegetation, and soil type.  The duration of frozen soil conditions can vary every year depending on these and other factors.  However, for the long-term continuous modeling analysis, the frozen ground time period was considered to be consistent every year, as detailed freeze/thaw information was not available on a yearly basis.

For the Twin Cities region, the date of the initial soil freeze was estimated as December 6th, which was the average observed date in St. Paul, Minnesota based on U.S. Army Corp of Engineers frost tube records for the period 1971 – 1988.  The date of soil thaw was estimated as April 7th, based on information from the *Climate of Minnesota Part XVI Incoming and Reflected Solar Radiation at St. Paul* Bulletin (Baker et al, 1987).

For the North-Central region, the date of the initial soil freeze was estimated as November 24th, which was the average observed date in Bemidji, Minnesota based on U.S. Army Corp of Engineers frost tube records for the period 1971 – 1988.  The date of soil thaw was estimated as April 15th, based on information from the *Climate of Minnesota Part XII - The Hydrologic Cycle and Soil Water* Bulletin (Baker et al, 1987).

For the Southeast region, the date of the initial soil freeze was estimated as December 20th, which was the average observed date in Winona, Minnesota based on U.S. Army Corp of Engineers frost tube records for the period 1971 – 1988.  The date of soil thaw was estimated as April 5th, based on information from the *Climate of Minnesota Part XII - The Hydrologic Cycle and Soil Water* Bulletin (Baker et al, 1987).

After discussion with the MIDS Work Group and the MPCA, Barr evaluated the frozen ground period with other assumptions.  See Appendix A for a discussion on the alternative approach evaluated.

## 4.2 Hydraulic Modeling (Runoff Routing)

### 4.2.1 Volume Control BMP Assumptions for Development Scenarios

#### 4.2.1.1 BMP Volume Sizing Methodology

Volume control Best Management Practices (BMPs) were sized for each of the developed conditions based on the selected volume control performance goal discussed in Section 3.  The BMPs were assumed to be bioretention basins (also known as rainwater gardens).  The required volume of each bioretention basin was determined by the applicable volume control performance goal.  The BMP volume varies for each developed scenario based on the performance goal used to size the BMP.  The volume control BMP volumes for each developed scenario and performance goal for the Twin Cities region are listed in Table 4-5.

**Table 4-5 Twin Cities Region Volume Control BMP Size for Four Performance Goals**

| Imperviousness | HSG | Performance Goal BMP Volume (cubic feet) | | | |
|---|---|---|---|---|---|
| | | 1" Off Impervious | 95th Percentile | 1-Year Match | 2-Year Match |
| 20% | A | 7,260 | 8,579 | 8,200 | 9,500 |
| | B | 7,260 | 8,645 | 9,120 | 10,410 |
| | C | 7,260 | 11,933 | 10,000 | 11,100 |
| 50% | A | 18,150 | 21,449 | 20,500 | 23,700 |
| | B | 18,150 | 21,490 | 21,450 | 24,030 |
| | C | 18,150 | 23,544 | 21,220 | 23,210 |
| 80% | A | 29,040 | 34,318 | 33,600 | 39,000 |
| | B | 29,040 | 34,334 | 34,065 | 38,090 |
| | C | 29,040 | 35,156 | 32,350 | 35,375 |

As shown in Table 4-5, the one inch off impervious performance goal resulted in the smallest BMPs for each developed scenario. The 95$^{th}$ percentile storm event or the 2-year match performance goal resulted in the largest BMPs, depending on the soil type and the imperviousness.

The following sections describe how the BMPs were sized for each performance goal.

#### *4.2.1.1.1 Performance Goal: One-Inch off Impervious*

For the one inch off the impervious area volume control performance goal, the volumes of the BMPs were determined by multiplying one inch of depth by the impervious area of each of the developed sites. For example, a 50% impervious developed scenario (regardless of soil type) would require a BMP with a retention volume of 50% x 10 acres x 1 inch = 5 acre-inches, or 18,150 cubic feet.

#### *4.2.1.1.2 Performance Goal: 95$^{th}$ Percentile Storm*

For the 95$^{th}$ percentile storm event performance goal, the BMPs were sized to contain the runoff generated by the 95$^{th}$ percentile storm from the pervious and impervious portions of the developed sites. According to the Minnesota Stormwater Manual, the depth of rainfall for the 95$^{th}$ percentile storm in the Twin Cities and North-Central regions is 1.4 inches, while in Southeast Minnesota the 95$^{th}$ percentile storm is 1.5 inches. The runoff generated by pervious (turf grass) and impervious areas was calculated using the Soil Conservation Service (SCS) Curve Number method, as is standard practice in site development. The developed curve numbers were selected from TR-55

(NRCS, 1986) and are displayed below in Table 4-6. The pervious curve numbers were selected from the published values for lawn, good condition.

**Table 4-6 Curve Numbers For Developed Scenarios**

| Hydrologic Soil Group | Pervious | Impervious |
|---|---|---|
| A | 39 | 98 |
| B | 61 | 98 |
| C | 74 | 98 |

Using distributed curve number methodology, separate runoff volumes for the pervious and impervious portions of the site were calculated and then combined into a total runoff volume that the bioretention basin would be required to contain. The distributed curve number method differs from the composite curve number method in that the distributed method separates pervious and impervious areas, calculating their runoff independently to avoid undesired approximations that occur in composite curve number calculations. Composite curve number methodology aggregates an entire watershed that has multiple curve numbers into one single curve number.

For example, the 50% impervious developed scenario with HSG B soils results in 21,449 cubic feet of runoff from the impervious surfaces and 41 cubic feet of runoff from the pervious surfaces in a 1.4 inch rain event, resulting in a volume control BMP for this performance goal of 21,490 cubic feet.

#### *4.2.1.1.3 Performance Goals: One- and Two-Year Match to Native*

For the Twin Cities region, the one- and two-year storm event match performance goals were considered. The one- and two-year match volume control performance goals require a volume control BMP sized so that the volume of runoff from the developed site matched the volume of runoff that would be created by that site under native conditions. The runoff generated by the site under native conditions was calculated using SCS Curve Number methodology, as is standard practice in site development. While the native conditions for the Twin Cities region were assumed to be meadow for sizing the volume control BMPs, other regions of the state may require a native condition of forest or other land cover. Native conditions curve numbers are listed in Table 4-7. The native curve numbers were selected from TR-55 (NRCS, 1986) from the published values for prairies (no grazing) and woods. Those classifications correspond to the native vegetative conditions used for the modeling analysis (meadow and forest).

**Table 4-7 Curve Numbers for Native Conditions**

| Hydrologic Soil Group | Meadow | Forest[1] |
|---|---|---|
| A | 30 | 25 |
| B | 58 | 55 |
| C | 71 | 70 |

[1]Not used in this analysis

A model of each developed scenario was created using the hydrologic and hydraulic model, XP-SWMM, Version 10. The runoff from each 10-acre site was estimated using SCS Curve Number methodology. The precipitation events analyzed were one- and two-year, 24-hour, SCS Type II rainfall events, with rainfall depths of 2.4 and 2.75 inches, respectively. Volume control BMPs were created using the depth, side slope and infiltration rate assumptions discussed in Section 4.2.1.1. For each of the match performance goals, the volume of the BMP was adjusted until the volume of runoff discharged from the developed conditions was the same as the runoff generated by the native meadow conditions for the corresponding storm event. The native forest conditions were not considered for determining the match volume for this analysis. In all cases, the volume of the volume control BMP was larger for the two-year match performance goal as compared to the one-year match.

For example, for the 50% impervious site with B soils, using the methodology described above for the one- and two-year match of native conditions, these performance goals resulted in bioretention BMPs of 21,450 and 24,030 cubic feet, respectively.

The one- and two-year match performance goals differ from the one-inch off the impervious and 95$^{th}$ percentile performance goals in that the match goals allow infiltration to be modeled during the storm event when determining the required volume of the bioretention BMP, while the other goals typically use the specified standard to develop a BMP volume without consideration of infiltration or storm intensity/duration.

#### 4.2.1.2 BMP Depth and Area Sizing Methodology

Once the BMP volumes were calculated, it was necessary to determine the depths and areas of the bioretention basins for each development scenario. According to the Minnesota Stormwater Manual, the maximum depth of an infiltration basin is determined by the depth of water that can be infiltrated in 48 hours. This design criterion was used for preliminary determination of the basin depths. Infiltration rates were selected from the Minnesota Stormwater Manual for each soil type, with the exception of HSG A soils. Sandy loam was the assumed soil type for HSG A soils used in this analysis. The Minnesota Stormwater Manual suggests an infiltration rate of 0.8 inches per hour for sandy loam; however, since the saturated hydraulic conductivity for sandy loam is 0.9 inches per hour (Table 4-1), a BMP infiltration rate of 0.9 inches per hour was also selected for HSG A soils because the BMP infiltration rate should be at least as high as the infiltration rate of the surrounding terrain. Table 4-8 displays the infiltration rates assumed for the rainwater gardens modeled for this study.

**Table 4-8 Infiltration Rate for Bioretention Basins**

| Hydrologic Soil Group | Infiltration Rate (inches/hour) | Rainwater Garden Depth (inches) |
|---|---|---|
| A | 0.9 | 18 |
| B | 0.6 | 18 |
| C | 0.2 | 9.6 |

Based on the design infiltration rates in the Table 4-8 and the maximum 48-hour drawdown time period, the preliminary basin depths for HSG A, B and C soils were 43.2, 28.8 and 9.6 inches, respectively. As previously discussed, the modeling analysis assumed that the volume control BMPs were in the form of bioretention basins, as this is one of the most common infiltration BMPs. Based on guidance from the Minnesota Stormwater Manual, the depth of bioretention basins should not exceed 18 inches to protect the plantings. With this in mind, the combination of the maximum 48-hour drawdown and the 18 inch maximum depth resulted in the rainwater garden depths reflected in Table 4-8.

For the modeling analysis, the rainwater gardens were assumed to be rectangular in shape with side slopes of four feet horizontal to one foot vertical (4H:1V or 25 percent). The area of each basin was calculated at four equidistant depth intervals. These data were entered into the XP-SWMM modeling software to represent the storage capacity for the continuous hydrologic and hydraulic simulation.

The infiltration rate of the entire basin was calculated as a volumetric flow rate (cubic feet per second, or cfs) by taking the one-dimensional infiltration rate of the BMP (inches per hour) and multiplying by the wetted area of the basin at each depth. Thus, the infiltration volumetric flow rate of the BMP increased as the depth of water in and wetted area within the BMP increased. The infiltration volumetric flow rate (in cfs) was calculated at four equidistant depth intervals; these data were entered into the XP-SWMM modeling software for the continuous hydrologic and hydraulic simulation.

#### 4.2.1.3 Determining BMP Volume to Match Native Conditions

For Twin Cities, North-Central and Southeast regions hydraulic modeling was performed on each developed scenario to determine which BMP volume was required to match native forest and meadow conditions. Each developed scenario referenced in Table 3-1 with varying impervious percentage and soil type (with the exception of HSG D) was modeled with BMPs of varying sizes over the entire continuous modeling time period referenced in Section 4.1.2 for each region.

Multiple volume control BMPs were sized for each developed condition. Most BMPs were sized to treat a certain number of inches off of the impervious surface of the developed conditions, similarly to the sizing methodology described in Section 4.2.1.1.1. One BMP for each developed condition was sized specifically to treat the 95$^{th}$ percentile storm, as discussed in Section 4.2.1.1.2. The BMP volume created by retaining the 95$^{th}$ percentile storm for each developed condition can also be represented by a certain depth off the impervious surfaces. For example, for a 20% impervious site on HSG B soils in the Twin Cities region, a volume control BMP created by retaining the 95$^{th}$ percentile storm is the same size as a BMP created by retaining 1.19 inches from the impervious surfaces. Depending on the developed condition and region, the 95$^{th}$ percentile storm BMP had an equivalent volume to a BMP sized between 1.18 and 1.87 inches off the impervious surfaces.

At least eight BMPs were modeled for each developed condition varying in size from 0.5 to over 3 inches off the impervious surface. For a 10-acre site, this represents a volume between 18,150 and 134,310 cubic feet. Each developed condition with corresponding volume control BMPs was then modeled using continuous simulation to determine the average annual runoff for each BMP size.

### 4.2.2 Rate Control BMP Assumptions for Development Scenarios

As shown in Table 3-1, Barr evaluated rate control for each of the development scenario in the Twin Cities region (HSG B and C soils) for the 1-, 2-, 10-, and 100-year 24-hour, SCS Type II precipitation events, as directed by the MIDS Work Group and MPCA. Rate control BMPs were sized so that the rates discharged from the developed conditions sites did not exceed the rates from the meadow native conditions for the 1-, 2-, 10-, and 100-year frequency, 24-hour storm events.

To achieve controlled flow rates from the developed sites, a rate control BMP was modeled downstream of each volume control BMP. The rate control BMP was modeled as a dry detention basin with a multi-stage outlet. The outlet structure from each BMP was modeled as a four-foot diameter manhole with a beehive overflow for storms in excess of 100-year events. Smaller events were controlled by a combination of low-flow orifices and weirs.

For each of the developed scenarios modeled, the volume control BMP served as the first method of rate control; in fact, for several of the developed scenarios with larger volume control BMPs, the volume control BMP effectively controlled the rate at or below native conditions for the 1- and 2-year events. In these instances, rate control was only necessary for the 10- and 100-year storm events in the single event modeling.

The runoff rates from native and developed conditions were calculated using XP-SWMM. The size of the dry detention basin (rate control BMP) and the configuration of the multi-stage outlets were adjusted until the rate discharged from the rate control BMP did not exceed the flow rate generated by native conditions (meadow, for Twin Cities region) for the 1-, 2-, 10- and 100-year storm events.

## 4.3 Water Quality Treatment Modeling

P8 (Program for Predicting Polluting Particle Passage through Pits, Puddles and Ponds, IEP, Inc., 1990) is a computer model used for predicting the generation and transport of stormwater runoff and pollutants in urban watersheds. P8 is a useful diagnostic tool for designing and evaluating the effectiveness of stormwater BMPs. A variety of treatment devices can be modeled in P8, including detention ponds (wet or dry), infiltration basins, swales and buffers, aquifers, and pipe/manholes.

The P8 model, Version 2.4, was used in this analysis to simulate the stormwater runoff and phosphorus loads generated from hypothetical development sites with varying levels of imperviousness to represent variation in typical development density. The P8 model was also used to compare the pollutant removal effectiveness of BMPs designed to correspond to the four volume control performance goal alternatives and the rate control BMPs discussed in Section 3. The model requires user input for watershed characteristics, BMP design attributes, local precipitation and temperature, and other parameters relating to water quality and BMP pollutant removal performances.

### 4.3.1 Watershed Characteristics

Similar to the XP-SWMM analysis, the P8 analysis evaluated runoff from several hypothetical 10-acre development scenarios with varying levels of imperviousness.

#### 4.3.1.1 Impervious Fraction

Six hypothetical watersheds were included in the P8 modeling analysis, including

1) B soils with 20% imperviousness,

2) B soils with 50% imperviousness,

3) B soils with 80% imperviousness,

4) C soils with 20% imperviousness,

5) C soils with 50% imperviousness, and

6) C soils with 80% imperviousness.

#### 4.3.1.2 Pervious Curve Number

Watershed runoff volumes from pervious areas were computed in P8 using the SCS Curve Number method. Pervious curve numbers were selected for each hypothetical watershed based on soil type and an assumption that the pervious areas within the hypothetical development would be open space areas in fair to good condition. References on SCS curve numbers provide a range of curve numbers that would apply to pervious areas in fair to good condition. The pervious curve numbers were selected such that the P8-generated average annual runoff volumes during the non-frozen ground time period were similar to those estimated using XP-SWMM. The frozen ground time period was excluded from the comparison of XP-SWMM and P8 runoff volume generation, as the two models handle runoff from frozen ground conditions differently. For calculation of runoff volume, the XP-SWMM models allowed no infiltration during the frozen ground time period, whereas the P8 model allows some infiltration during the frozen ground time period (runoff is calculated using the SCS Curve Number method, assuming saturated soil conditions).

A pervious curve number of 65 was used for the watersheds with B soils, resulting in average annual runoff volumes for the non-frozen time period that were within eight, one, and two percent of the volumes generated in XP-SWMM for the 20%, 50%, and 80% impervious development scenarios, respectively. A pervious curve number of 74 was used for the watersheds with C soils, resulting in average annual runoff volumes for the non-frozen time period that were within five, zero, and two percent of the XP-SWMM runoff volumes for the 20%, 50% and 80% impervious developments, respectively.

#### 4.3.1.3 Depression Storage

Depression storage represents the initial loss caused by such things as surface ponding, surface wetting, and interception. As previously discussed, the P8 model utilizes the SCS Curve Number method to estimate runoff from pervious areas. For impervious areas, runoff begins once the cumulative storm rainfall exceeds the specified impervious depression storage, with the runoff rate equal to the rainfall intensity. An impervious depression storage value of 0.06 inches was used for the P8 simulation, which is consistent with the impervious depression storage used in the XP-SWMM continuous modeling analysis.

### 4.3.2 Treatment Device Characteristics

#### 4.3.2.1 Bioretention Basins (Volume Control BMPs)

The volume control treatment devices were modeled as bioretention basins using general devices in P8, where required inputs include an elevation/area relationship and discharge table for up to three outlets, typically infiltration, a normal outlet, and a spillway. The elevation/area relationships for each of the bioretention basins were obtained from the XP-SWMM continuous modeling analysis of the Twin Cities region, as well as the discharge rates representing infiltration and discharge from the stormwater BMPs (see Section 4.2.1).

#### 4.3.2.2 Dry Detention Basins (Rate Control BMPs)

The rate control BMPs were modeled as dry detention basins with multi-stage outlets. A dry detention basin was modeled directly downstream of each volume control bioretention BMP. The rate control BMPs were modeled as general devices in P8, where required inputs include an elevation/area relationship and discharge table for up to three outlets, typically infiltration, a normal outlet, and a spillway. The elevation/area relationships for each of the detention basins were obtained from the XP-SWMM continuous modeling analysis of the Twin Cities region, as well as the discharge rates representing discharge from the stormwater BMPs.

### 4.3.3 Precipitation and Temperature Data

The P8 model requires hourly precipitation and daily temperature data; long-term data was used so that watersheds and BMPs can be evaluated for varying hydrologic conditions. The hourly precipitation and average daily temperature data were obtained from the NWS site at the Minneapolis-St. Paul International Airport. The simulation period used for the P8 analysis was January 1, 1955 through December 31, 2004 (50 years).

The precipitation dataset used for the P8 modeling analysis differs from that used in the XP-SWMM analysis (Section 4.1.2). A 50-year hourly dataset was used for the P8 analysis, which is a longer duration than the 35-year dataset used for the XP-SWMM analyses. For the XP-SWMM analysis, 15-minute precipitation data was used to account for varying precipitation intensity, as this can significantly alter the amount of runoff from a site. The P8 model calculates runoff volume for each model time step, based on the hourly precipitation data (if the time step is less than one hour, the hourly precipitation is divided equally among time steps). P8 does not generate runoff hydrographs; the runoff volumes calculated are independent of rainfall intensity. Given that the XP-SWMM dataset with a 15-minute time step provided no additional benefit to the P8 modeling analysis, was incomplete during some time periods, and provided only approximately 35 years of data, the complete 50-year hourly dataset available from the Minneapolis-St. Paul International Airport was used instead.

For the P8 analysis, the 50-year hourly dataset was modified to exclude the July 23-24, 1987 "super storm" event, in which 10 inches of rainfall fell in 6 hours. This storm event was excluded because of its extreme nature and the resulting skew on the pollutant loading and removal predictions. Excluding the July 23-24, 1987 "super storm", the average annual precipitation throughout the 50-year period used for the P8 modeling was 27.7 inches. This average annual precipitation is similar to that of the 35-year period used for the continuous XP-SWMM modeling analysis (28.1 inches/year). The precipitation dataset used for the XP-SWMM modeling also excluded the 1987 "super storm" event that occurred in the Twin Cities region, as the 1987 precipitation data was obtained from the Northfield 15-minute precipitation gauge.

### 4.3.4 Selection of Other P8 Model Parameters

#### 4.3.4.1 Time Step, Snowmelt, and Runoff Parameters

There are numerous additional input parameters that can be adjusted in the P8 model. Several of the parameters related to simulation of snowmelt and runoff are summarized below:

- Minimum Inter-Event Time (Hours) = 10. P8 summarizes results in a series of discrete events. The minimum inter-event time is equals the minimum number of consecutive dry hours which must occur before a new storm event is initiated. This parameter influences event-based model output, but will not impact overall mass balance or load reductions.

- Snowmelt Factors—Melt Coefficient (Inches/Day-Deg-F) = 0.06. The rate of snowmelt is governed in P8 by the SCS degree-day equation, in which the snowmelt (inches/day) is a product of the melt coefficient and the difference between the observed daily mean temperature and the specified melt temperature (32 degrees F).

- Snowmelt Factors— Scale Factor For Max Abstraction = 1. This factor controls the quantity of snowmelt runoff from pervious areas by adjusting the maximum abstraction used with the

SCS Curve Number method (i.e., controls losses due to infiltration). With a scale factor of 1 (P8 default), the maximum abstraction is unmodified during snowmelt or frozen ground conditions.

- Snowmelt Factors— Soil Freeze Temperature (Deg-F) = 32. This temperature setting can be adjusted to control the rate of runoff from pervious areas when the soil is likely to be frozen. At the start of each precipitation or snowmelt event, if the 5-day-average antecedent air temperature is below the soil freeze temperature, the pervious curve number will be modified to reflect Antecedent Moisture Condition (AMC) III and the Maximum Abstraction scale factor will be applied.

- Runoff Factors- 5-day Antecedent Rainfall and Snowmelt (inches): Growing Season AMC-II = 1.4 and AMC-III = 2.1 (P8 defaults), Non-growing Season AMC-II = 0.5 and AMC-III = 1.1 (P8 defaults). These input parameters allow the model to make curve number adjustments based on antecedent moisture conditions.

#### 4.3.4.2 Particle File Selection

The NURP50.PAR particle file was used for the P8 model. The NURP 50 particle file represents typical concentrations and the distribution of particle settling velocities for a number of stormwater pollutants. The component concentrations in the NURP 50 file were calibrated to the 50$^{th}$ percentile (median) values compiled in the EPA's Nationwide Urban Runoff Program (NURP).

## 4.4 Limited Qualitative Sensitivity Analysis

As part of the modeling effort, several of the watershed and BMP factors discussed in Sections 4.1 and 4.2 were assessed for sensitivity in producing runoff. While a robust sensitivity analysis was not performed, the limited qualitative sensitivity assessment was conducted on the factors that we considered to have the greatest likelihood of influencing the runoff results. The results show that, within a reasonable range of our assumptions, changes to the watershed factors considered would not greatly impact the results of the modeling of annual runoff.

### 4.4.1 Saturated Hydraulic Conductivity

The saturated hydraulic conductivity of soil is dependent upon numerous factors including the grain size distribution of the soil and the density of the soil. As described in Section 4.1.1.1.2.1, the saturated hydraulic conductivities modeled in this analysis were taken from an average compiled by Rawls for each soil type (Rawls, 1998). These assumptions approximate average soil conditions.

Saturated hydraulic conductivity parameters representing denser soils were also considered to simulate compacted soil conditions, based on values from the Rawls paper (Rawls, 1998). For Twin Cities region, developed scenarios of 20, 50 and 80% imperviousness and HSG A, B and C soil types were modeled using the continuous model of 35 years with the average and denser saturated hydraulic conductivities listed in Table 4-9.

**Table 4-9 Saturated Hydraulic Conductivity Range Used in Sensitivity Analysis**

| Hydrologic Soil Group | Representative Soil Texture | Average Saturated Hydraulic Conductivity[1] (in/hr) | Denser Saturated Hydraulic Conductivity[1] (in/hr) |
|---|---|---|---|
| A | Sandy Loam | 0.90 | 0.50 |
| B | Loam | 0.20 | 0.15 |
| C | Sandy Clay Loam | 0.14 | 0.10 |

[1] Rawls, 1998
[2] Rawls, 1998

Two volume control BMPs were modeled for the denser soils, sized for one and 1.5 inches of runoff from the impervious surfaces to determine which size BMP would generate runoff that would match native runoff. When compared to the results of the native match for the average saturated hydraulic conductivity listed in Table 5-10, the compact soils require a BMP that is approximately 0.1 to 0.2 inches off the impervious surface larger, depending on the soil type.

### 4.4.2 Overland Flow Roughness

The only difference in the modeling approach for native conditions forest and meadow in the Twin Cities and Southeast regions was the selection of overland flow roughness, or Manning's n, for overland flow (in North-Central region, native forest had a slightly higher depression storage than native meadow). As discussed in Section 4.1.1.1.4, a literature search concluded that the appropriate Manning's overland roughness coefficients were 0.40 and 0.15 for forest and meadow, respectively.

Modeling the average annual runoff for native forest and meadow scenarios produced eight pairs of results for Twin Cities and Southeast regions and HSG A, B, C and D soils. While measurable differences in average annual runoff between forest and native were observed, those differences are muted when compared to the developed conditions BMPs. Table 5-10 below displays the BMP sizes necessary to match native conditions for both native forest and meadow, with BMP size displayed as inches of runoff from the impervious surfaces. For Twin Cities and Southeast regions, the BMP size required to match forest is always larger than the BMP size required to match meadow, but generally by only 0.1 inches of runoff from the impervious surfaces.

### 4.4.3 Slope

Slope varies significantly across the state, and from site to site within the same region of the state. To assess the potential impact of varying slope on the modeling results, Barr modeled 10-acre sites with HSG A, B, and C soil types, under native conditions and developed 50% impervious. We modeled a range of slopes from 2 to 20%. Because slope affects runoff volume more significantly during larger rainfalls (during small rainfalls of less than one inch there is generally little runoff from any pervious surface), we modeled several large rainfalls ranging from the 1-year to the 100-year, 24-hour, SCS Type II storm events.

We found very little difference in runoff from changing the slopes from 2 to 20%, generally no more than 0.1 inches over the entire storm event, regardless of storm size. More importantly, the increase in native and developed conditions runoff as a result of increasing slope was roughly equivalent; suggesting that any increase or decrease in watershed slope would have approximately the same affect in average annual runoff on both native and developed sites, canceling out any differences in annual runoff.

We then modeled these same 50% impervious sites for the Twin Cities model year 2003 with slopes of 2 and 6%. Again, we found that the annual increase in runoff from increasing slope was similar for native and developed conditions, with native runoff increasing by 0.00 to 0.12 inches and developed runoff increasing by 0.06 to 0.18 inches annually, depending on soil type. The increase in annual runoff for developed conditions was further muted with the introduction of a volume control BMP, which caused the increase in annual runoff generated by increasing slope from 2 to 6% to be reduced to 0.00 to 0.14 inches, depending on soil type.

### 4.4.4 BMP Infiltration Rate

According to the Minnesota Stormwater Manual, there are broad ranges of BMP infiltration rates that are applicable to HSG A and B soil types, 0.8 to 1.6 inches per hour for HSG A soils and 0.2 to 0.6 inches per hour for HSG B soils. Sensitivity analysis was performed on Southeast region, A and B soils on 20% and 80% impervious scenarios for the year 1994. The volume control BMP in every case was sized to treat one inch of runoff from the impervious surfaces.

Southeast region year 1994 was selected because the precipitation that year was 32.2 inches, which was close to the average annual precipitation for Southeast region of 34 inches. Additionally, the annual runoff from the developed scenarios for that year was similar to the average annual runoff for the entire Southeast modeling period, suggesting that the modeling year 1994 could reasonably represent the entire dataset.

For HSG A soils, runoff from scenarios with volume control BMPs that infiltrate at 0.9 inches per hour (the infiltration rate used in this modeling effort) and a higher rate of 1.2 inches per hour were compared for both the 20% and 80% impervious developed scenarios. When the infiltration rate of the volume control BMP for HSG A soils was increased from 0.9 to 1.2 inches per hour, the annual runoff discharging from the site decreased by merely 0.05 and 0.20 inches for the 20% and 80% impervious surfaces, respectively. This reduction in annual runoff volume is less than 6% of the annual runoff volume leaving BMP as surface water.

For HSG B soils, runoff from scenarios with volume control BMPs that infiltrate at 0.6 inches per hour (the infiltration rate used in this modeling effort) and a lower rate of 0.45 inches per hour were compared for both the 20% and 80% impervious developed scenarios. When the infiltration rate of the volume-control BMP for HSG B soils was reduced from 0.6 to 0.45 inches per hour, the annual runoff discharging from the site increased by merely 0.08 and 0.14 inches for the 20% and 80% impervious surfaces, respectively. This increase in annual runoff is less than 4% of the annual runoff volume discharging as surface water from the BMP.

### 4.4.5 Frozen Ground Assumptions

As discussed in Section 4.1.3, the assumptions used for frozen ground modeling produced virtually 100 percent runoff from pervious and impervious frozen ground. No infiltration was allowed during the frozen ground period and no depression storage was considered. The infiltration capacity of soil in frozen ground conditions is highly variable and can range from no infiltration to significant infiltration depending on how wet the soils are when the ground freezes.

Additional modeling was performed for the Southeast region using frozen ground assumptions that allowed more infiltration during the frozen ground period. Those results are presented in Appendix A.

# 5.0 Modeling Results

The results of the long-term continuous simulation XP-SWMM and P8 analyses are presented in the following sections.

## 5.1 Runoff Volume

### 5.1.1 Native Conditions

#### 5.1.1.1 Average Annual Runoff Volume

Figures 5-1, 5-2 and 5-3 show the average annual runoff volume from native forest and native meadow for a range of soil types (HSG A through D) based on the modeling analysis for Twin Cities, North-Central and Southeast Regions. The average annual runoff from the forested watersheds ranged from 3.6 inches to 6.0 inches depending on soil types and region of the state, while the average annual runoff from the watersheds vegetated with meadow ranged from 3.6 to 6.4 inches. As would be expected, the least average annual runoff occurs from sites with HSG A soils (sandy soils), as more precipitation infiltrates in sandy soils. The highest average annual runoff occurs from sites with HSG D soils (clay soils), due to the low infiltration rates characteristic of HSG D soils. The annual runoff from the North-Central region is the lowest, while the Southeast and Twin Cities runoff is roughly equivalent. The average annual runoff from native forest conditions is slightly less than runoff from native meadow for all hydrologic soil groups (A, B, C, and D).

##### *5.1.1.1.1 Frozen Ground Time Period*

As discussed in Section 4.1.3, the cold climate of Minnesota results in time periods during the winter months where the ground is essentially frozen, and runoff is typical from snowmelt or rainfall events. To model this phenomenon, the watersheds were assumed to be 100% impervious and depression storage was assumed to be negligible during the frozen ground time period, which differs in beginning and duration by region of the state. All rainfall and snowmelt that occurs during the frozen ground time period results in runoff. The average annual runoff predicted during the frozen ground period does not vary by vegetation cover or soil type, and ranges from 3.4 to 4.0 inches across the three regions modeled (see Figures 5-4, 5-5 and 5-6).

##### *5.1.1.1.2 Non-frozen Ground Time Period*

Figures 5-4, 5-5 and 5-6 show the portion of the average annual runoff volume that occurs during the non-frozen ground time period for each region. Although the proportion of the annual runoff that occurs during the non-frozen ground time period varies from year to year, it is generally lower than the runoff during frozen-ground time period. The average annual runoff from the non-frozen ground time period varies significantly by soil type, ranging from approximately 0.1 - 0.2 inches for HSG A soils to about 1.7 – 2.0 inches for HSG D soils for the Twin Cities region.

#### 5.1.1.2 Variation in Annual Runoff Volumes

The amount of runoff can vary significantly from year to year, depending on variation in climatic conditions and precipitation patterns. Figure 5-7 shows the annual variation in runoff from forested watersheds of HSG A, B, C, and D soil types in the Twin Cities region. The annual runoff depths for HSG A, B and C soils are also summarized in Tables 5-1, 5-2 and 5-3, respectively, for native forest and meadow conditions. Note that most of the tables referenced in Section 5 are compiled at the end of the report in the Tables section. For HSG D soils, the predicted annual runoff ranges from about two and a half inches to nearly 15 inches.

##### *5.1.1.2.1 Frozen Ground Time Period*

The annual runoff depths from watersheds with HSG A, B and C soils for the frozen ground time period are summarized in Tables 5-4, 5-5 and 5-6, respectively. Similar to the annual runoff depths, there is significant variation in the predicted runoff from year to year, ranging from 0.5 inches to 9.7 inches. This variation is a result of several factors, principally the amount of winter precipitation and the timing of snowmelt with regard to the thawing of the soils. The modeling assumptions used to account for frozen ground conditions may overestimate the amount of runoff during this winter time period for some years, as the timing of soil freeze and thaw conditions will vary from year to year and some infiltration and/or surface storage is likely as the snowpack melts and soil begins to thaw. However, it is widely acknowledged that a significant portion of the annual runoff in Minnesota comes from spring snowmelt events and the annual average runoff values predicted are similar to observed values.

##### *5.1.1.2.2 Non-frozen Ground Time Period*

The annual runoff depths from watersheds with HSG A, B and C soils for the non-frozen ground time period are summarized in Tables 5-7, 5-8 and 5-9, respectively. There is significant variation in the non-frozen ground runoff generated from year to year, ranging from zero to over four inches depending on soil type and vegetative conditions. For the modeled years with zero runoff generated, it is likely that there was lower than average precipitation and/or there were no storm events of sufficient rainfall depth and intensity to result in runoff from the sites.

The proportion of annual runoff that occurs during the non-frozen ground time period is generally lower than the runoff during frozen-ground time period. However, in a couple of the modeled years, the runoff during the non-frozen ground time period was similar to or greater than that of the frozen ground time period.

### 5.1.2 Developed Conditions

The long-term continuous simulation XP-SWMM model was used to estimate the runoff rates and volumes from several hypothetical 10-acre development sites with a range of imperviousness (20% and 80% for all regions and also 50% for the Twin Cities region) and a variety of soil types (HSG A, B, C and D). Table 3-1 lists the scenarios modeled for this analysis.

#### 5.1.2.1 Average Annual Runoff Volume Without Volume-Control BMPs

Figures 5-8, 5-9 and 5-10 show the average annual runoff generated from the developed conditions watersheds, in comparison with the runoff from native forest and meadow conditions for a range of soil types (HSG A, B, C, and D soils) for each of the three modeled regions. The average annual runoff from the developed conditions presented in Figures 5-8, 5-9, and 5-10 reflects the runoff when no volume control BMPs were included. As shown in the figure, the runoff from developed conditions is significantly higher than the runoff generated from forested and meadow conditions. Although the amount varies by soil type, the annual runoff from the 20% impervious developed site is approximately twice that of native conditions. The average annual runoff from the 80% impervious developed site is about three to five times that of native conditions.

#### 5.1.2.2 Average Annual Runoff Volume With Volume Control BMPs

Figures 5-11, 5-12, and 5-13 show the average annual runoff from Twin Cities region developed conditions with volume control BMPs in place in comparison with runoff from developed conditions without BMPs and native conditions. The figure summarizes the average annual runoff for each of the performance goal alternatives evaluated for the Twin Cities region. The average annual runoff from developed conditions without BMPs is significantly higher than runoff from native conditions. However, with implementation of the volume control performance goal alternatives, average annual runoff is similar to runoff from native conditions. North-Central and Southeast regions were assessed to determine which size BMP was necessary to match native conditions. Those results are described in Section 5.1.2.4.

Figures 5-11, 5-12, and 5-13 also show the effectiveness of the four evaluated volume control performance goals in reducing the average annual runoff from the sites for Twin Cities HSG A, B, and C soils, respectively, in comparison to native vegetation conditions. Figure 5-14 summarizes the same information, but combines the results from HSG A, B, and C soils. For HSG B and C soils in the Twin Cities region, the one inch off impervious surfaces performance goal produced runoff depths that are slightly greater than native conditions runoff for all impervious scenarios (20%, 50%, and 80%), while for HSG A soils, the runoff generated by the one inch off impervious surface performance goal produced annual runoff depths in between native forest and meadow runoff. For the other three performance goals considered for the Twin Cities, the average annual runoff volumes from the 50% and 80% impervious sites are generally less than native conditions runoff for HSG A, B, and C soils. For the 20% imperviousness development sites, the average annual runoff volumes are generally similar to native conditions runoff, but are slightly higher or lower depending on soil type, performance goal, and the native vegetation scenario being compared against (forest or meadow).

Figures 5-15 and 5-16 show the same information as Figures 5-11, 5-12, and 5-13, but identifies the portions of the average annual runoff volumes that occur during the frozen and non-frozen ground time periods for the Twin Cities modeling.

##### *5.1.2.2.1 Non-frozen Ground Time Period*

Figures 5-17 and 5-18 summarize the average runoff volumes from the non-frozen ground time period for native and developed conditions for HSG A, B, and C soils. During this time period, the average annual runoff from each of the four performance goal scenarios exceeds the runoff from native conditions (meadow and forest). The estimated runoff depths from the 95$^{th}$ percentile and two year match performance goal scenarios most closely match the native conditions runoff during the non-frozen ground time period. The estimated runoff from the one inch off impervious surfaces performance goal scenario is the farthest from matching the native conditions runoff.

As shown on Figures 5-17 through 5-20, an interesting relationship can be observed in the variability of runoff depths amongst the three imperviousness scenarios evaluated. During the non-frozen ground period, the runoff from the one inch off impervious surfaces scenario for HSG C soils varied significantly between the low and high impervious sites (ranging from 1.7 inches to 2.0 inches), with the sites of higher imperviousness discharging more runoff than the sites of lower imperviousness. For HSG C soils, the two year match performance goal scenario varied the least amongst the three imperviousness scenarios (approximately 1.4 inches for all three scenarios).

##### *5.1.2.2.2 Frozen Ground Time Period*

Figures 5-19 and 5-20 summarize the average runoff volumes from the frozen ground time period for native and developed conditions for HSG A, B, and C soils. For the modeling analysis, the soils were assumed to be frozen during the 'Frozen Ground' time period and any snowmelt or precipitation that occurred during this time period would leave the site as runoff. This assumption was consistent for native and developed conditions; therefore, the runoff generated during this time period (from snowmelt or rain on frozen ground) is equal for all scenarios.

Although the modeling allowed no infiltration from the BMPs during this time period, the bioretention basins were allowed to fill up with rainfall and/or snowmelt runoff that occurred. This accounts for the differences in runoff shown amongst the various performance goal scenarios and imperviousness scenarios in Figures 5-19 and 5-20. This is also the reason that all of the developed conditions scenarios have a lower average annual runoff than native conditions during this time period.

#### 5.1.2.3 Variation in Annual Runoff Volumes

As previously discussed, the amount of runoff can vary significantly from year to year. The annual runoff depths for the developed conditions scenarios for HSG A, B and C soils are summarized in Tables 5-1, 5-2 and 5-3, respectively. The effectiveness of the four volume control performance goal alternatives in matching native conditions runoff volumes varies by year, depending on variations in climatic conditions and precipitation patterns. With the information presented in Tables 5-1, 5-2 and 5-3, the annual runoff depths from developed conditions can be compared and contrasted with native conditions. Figure 5-21 shows the percentage of years for the Twin Cities region (based on the 35-year simulation) where the annual runoff from developed conditions exceeds the runoff from native meadow conditions for the four performance goal alternatives for HSG B and C soils. In general, runoff from the one inch off impervious surfaces performance goal scenarios exceeds native runoff most frequently (in comparison with the other performance goal alternatives). As shown in Figure 5-21, the frequency of exceeding native runoff depths is greater for the sites with less imperviousness. When designing BMPs for the one inch off impervious performance goal, those sites with more impervious surface require larger stormwater treatment facilities which in turn, lower the frequency of exceeding native runoff volumes.

The annual runoff depths during the frozen ground time period for the developed conditions scenarios are summarized in Tables 5-4, 5-5 and 5-6 for HSG A, B and C soils, respectively. For the frozen ground period, the annual runoff depths for developed conditions are always less than the runoff from native conditions. This is because the runoff from frozen ground conditions is the same for all modeled scenarios (native and developed), but the BMPs are allowed to fill with snowmelt and/or rainfall runoff.

The annual runoff depths during the non-frozen ground time period for the developed conditions scenarios are summarized in Tables 5-7, 5-8 and 5-9 for HSG A, B and C soils, respectively. For the non-frozen ground period, the annual runoff depths for developed conditions are greater than the runoff from native conditions for most years and performance goal alternatives.

#### 5.1.2.4 Determining BMP Volume to Match Native Conditions

As discussed in Section 4.2.1.1.4, a range of BMP sizes was modeled for each region and each developed scenario for HSG A, B, and C in order to determine the BMP volume necessary to match average annual runoff for native conditions (forest and meadow). Developed scenarios were modeled with volume control BMP sizes ranging from non-existent to a BMP sized for over 3 inches of runoff from the impervious surfaces (approximately the 5-year, 24-hour rainfall depth).

The average annual runoff for each developed condition was plotted on the Y-axis, and the BMP size as a function of a volume control performance standard was plotted on the X-axis. A line was fitted to the points representing the runoff generated by developed sites with BMPs of varying size. Then the native conditions meadow and forest average annual runoff for the corresponding hydrologic soil group and region was plotted on the graph. Where the fitted line for each developed condition crossed the average annual runoff for native conditions line, that point along the X-axis represented the size of the volume control BMP necessary to match native conditions. Figures 5-22 through 5-39 display these graphs for the three regions and HSG A, B, and C.

Two types of volume control performance goals were considered: (1) BMP volume determined by a specific depth of runoff from the impervious surfaces (such as the one inch off the impervious surfaces standard) and (2) BMP volume determined by the runoff generated by a specific return frequency storm event (such as the 95$^{th}$ percentile storm). The modeled BMPs were sized for a range of depths of runoff from the impervious surfaces and percentile storm events and the results were plotted (Figures 5-22 – 5-30 for the depth performance goal scenarios and Figures 5-31 – 5-39 for the percentile storm event scenarios). To determine the corresponding percentile storm for each region, we used Issue Paper B: Precipitation Frequency Analysis of the Minnesota Stormwater Manual:

- Twin Cities Region – Minneapolis-St. Paul Airport
- North-Central Region – Itasca State Park
- Southeast Region - Rochester

Table 5-10 displays the BMP size required to match native conditions for each developed condition and region considered. The table summarizes each region by soil type and provides an overall statewide average BMP size required to match native conditions for each soil type.

**Table 5-10 Summary of BMP Volumes Required to Match Native Conditions**

| Minnesota Region | Natural Vegetation | Developed Site Impervious-ness | X needed for "X times the impervious area" to not exceed the Natural Average Annual Runoff Volume (inches) | | | Retainage from Percentile Storm needed to not exceed the Natural Average Annual Runoff Volume (Precipitation Amount, inches) | | |
|---|---|---|---|---|---|---|---|---|
| | | | Hydrologic Soil Group | | | Hydrologic Soil Group | | |
| | | | A | B | C | A | B | C |
| Twin Cities | Meadow | 20% | 1.2 | 1.2 | 1.3 | 95.5% | 95.0% | 93.0% |
| | | | | | | (1.475) | (1.4) | (1.25) |
| | | 50% | 1.2 | 1.1 | 1.1 | 95.0% | 93.0% | 92.0% |
| | | | | | | (1.4) | (1.25) | (1.2) |
| | | 80% | 1.2 | 1.0 | 1.0 | 94.0% | 93.5% | 92.0% |
| | | | | | | (1.35) | (1.3) | (1.2) |
| | | *Average* | *1.2* | *1.1* | *1.13* | *94.8%* | *93.8%* | *92.3%* |
| | | | | | | *(1.41)* | *(1.32)* | *(1.22)* |
| | Forest | 20% | 1.3 | 1.5 | 1.6 | 96.0% | 97.0% | 95.0% |
| | | | | | | (1.55) | (1.6) | (1.4) |
| | | 50% | 1.2 | 1.1 | 1.2 | 95.0% | 94.0% | 93.5% |
| | | | | | | (1.4) | (1.35) | (1.3) |
| | | 80% | 1.2 | 1.1 | 1.1 | 95.0% | 93.5% | 93.0% |
| | | | | | | (1.4) | (1.3) | (1.25) |
| | | *Average* | *1.23* | *1.23* | *1.3* | *95.3%* | *94.8%* | *93.8%* |
| | | | | | | *(1.45)* | *(1.42)* | *(1.32)* |
| | **Average** | ***Average*** | ***1.225*** | ***1.165*** | ***1.215*** | ***95.1% (1.44)*** | ***94.3% (1.37)*** | ***93.1% (1.27)*** |

**Table 5-10 (continued) Summary of BMP Volumes Required to Match Native Conditions**

| Minnesota Region | Natural Vegetation | Developed Site Imperviousness | X needed for "X times the impervious area" to not exceed the Natural Average Annual Runoff Volume (inches) | | | Retainage from Percentile Storm needed to not exceed the Natural Average Annual Runoff Volume (Precipitation Amount, inches) | | |
|---|---|---|---|---|---|---|---|---|
| | | | Hydrologic Soil Group | | | Hydrologic Soil Group | | |
| | | | A | B | C | A | B | C |
| North-Central | Meadow | 20% | 1.0 | 0.8 | 0.8 | 92.0% | 89.5% | 87.5% |
| | | | | | | (1.15) | (1.025) | (0.975) |
| | | 80% | 1.0 | 0.9 | 0.9 | 92.0% | 91.0% | 91.0% |
| | | | | | | (1.15) | (1.1) | (1.1) |
| | | *Average* | *1.0* | *0.85* | *0.85* | *92.0%* | *90.3%* | *89.3%* |
| | | | | | | *(1.15)* | *(1.063)* | *(1.038)* |
| | Forest | 20% | 1.0 | 1.0 | 1.0 | 92.0% | 92.0% | 90.0% |
| | | | | | | (1.15) | (1.15) | (1.05) |
| | | 80% | 1.0 | 1.0 | 1.0 | 92.0% | 92.0% | 92.0% |
| | | | | | | (1.15) | (1.15) | (1.15) |
| | | *Average* | *1.0* | *1.0* | *1.0* | *92.0%* | *92.0%* | *91.0%* |
| | | | | | | *(1.15)* | *(1.15)* | *(1.1)* |
| | **Average** | ***Average*** | ***1.0*** | ***0.925*** | ***0.925*** | ***92.0%*** | ***91.1%*** | ***90.1%*** |
| | | | | | | ***(1.15)*** | ***(1.106)*** | ***(1.069)*** |

**Table 5-10 (continued) Summary of BMP Volumes Required to Match Native Conditions**

| Minnesota Region | Natural Vegetation | Developed Site Impervious-ness | X needed for "X times the impervious area" to not exceed the Natural Average Annual Runoff Volume (inches) | | | Retainage from Percentile Storm needed to not exceed the Natural Average Annual Runoff Volume (Precipitation Amount, inches) | | |
|---|---|---|---|---|---|---|---|---|
| | | | Hydrologic Soil Group | | | Hydrologic Soil Group | | |
| | | | A | B | C | A | B | C |
| Southeast | Meadow | 20% | 1.2 | 1.2 | 1.2 | 94.0% | 92.5% | 91.0% |
| | | | | | | (1.45) | (1.275) | (1.2) |
| | | 80% | 1.2 | 1.1 | 1.1 | 94.0% | 92.5% | 92.5% |
| | | | | | | (1.45) | (1.275) | (1.275) |
| | | *Average* | *1.2* | *1.15* | *1.15* | *94.0%* | *92.5%* | *91.8%* |
| | | | | | | *(1.45)* | *(1.275)* | *(1.238)* |
| | Forest | 20% | 1.3 | 1.4 | 1.4 | 95.0% | 95.0% | 92.5% |
| | | | | | | (1.5) | (1.5) | (1.275) |
| | | 80% | 1.2 | 1.2 | 1.2 | 94.0% | 93.5% | 93.0% |
| | | | | | | (1.45) | (1.375) | (1.3) |
| | | *Average* | *1.25* | *1.3* | *1.3* | *94.5%* | *94.3%* | *92.8%* |
| | | | | | | *(1.475)* | *(1.438)* | *(1.2885)* |
| | **Average** | ***Average*** | ***1.225*** | ***1.225*** | ***1.225*** | ***94.3%*** | ***93.4%*** | ***92.3%*** |
| | | | | | | ***(1.463)*** | ***(1.356)*** | ***(1.263)*** |
| **Overall Average of Three Regions** | **Average of Natural Vegetation** | ***Average of Impervious-ness*** | ***1.15*** | ***1.105*** | ***1.12*** | ***93.9%*** | ***93.2%*** | ***91.8%*** |

## 5.2 Runoff Rates

### 5.2.1 Flow Frequency Curves

To summarize the runoff rate results of the continuous modeling, a flow frequency curve was developed for each of the Twin Cities native and developed conditions scenarios for HSG B and C (with and without rate control) based on the methodology described in Bulletin 17B of the Interagency Committee on Water Data "Guidelines for Determining Flood Flow Frequency." The maximum runoff flow rate from every year was selected from the continuous simulation. The compiled data series is referred to as the annual maxima series. Weibull plotting position methods were implemented to assign an exceedance probability (the probability of the annual maximum runoff flow rate being greater than or equal to a value) to every runoff flow rate in the annual maxima series. The probabilities were then plotted on a semi-log axis to fit a trend line to the data.

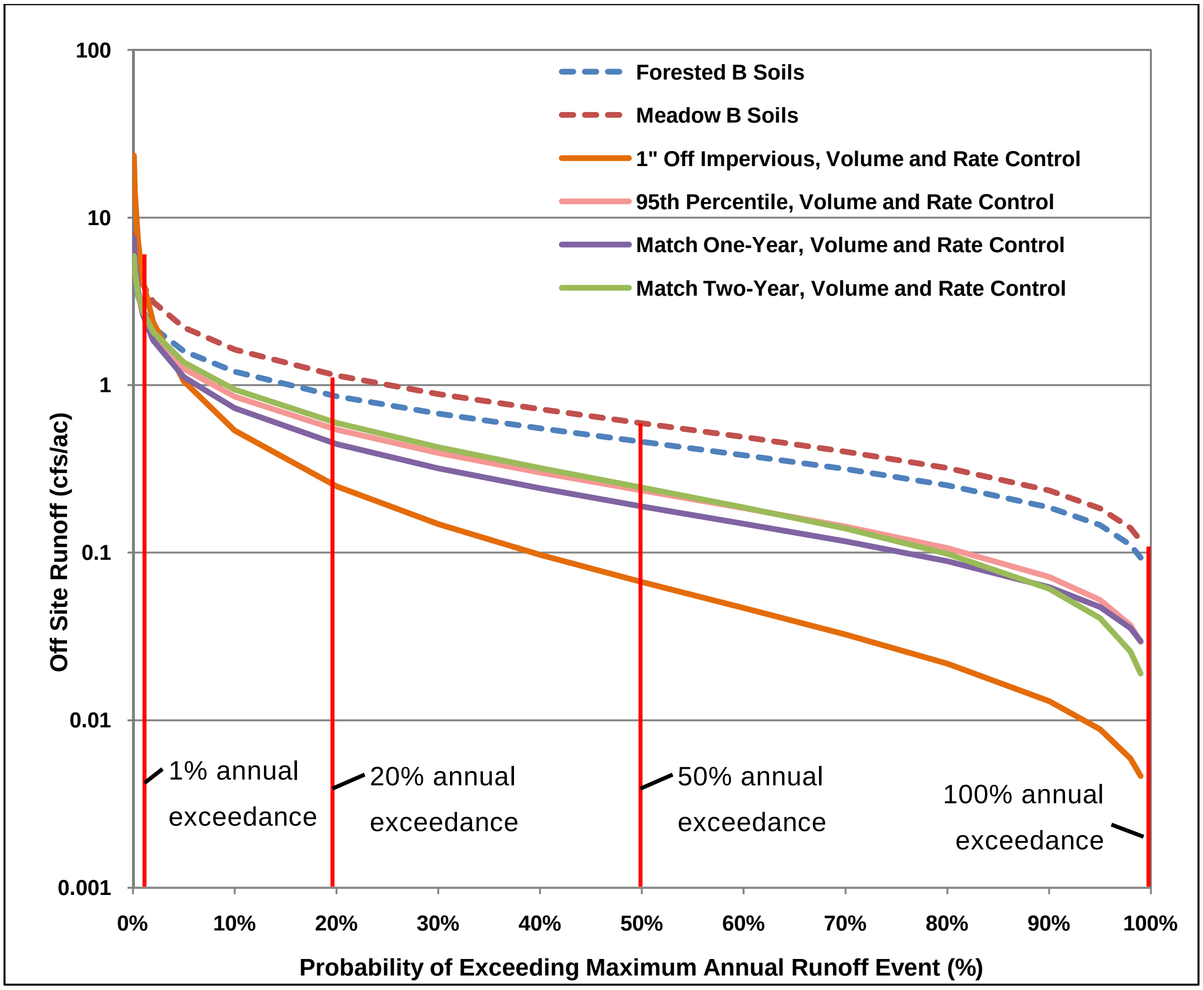
Curves from the native and developed scenarios were normalized based on drainage area to provide a flow rate per acre. The flow frequency curves are included in Figures 5-40 through 5-45. The flow frequency curve for the HSG B soils, 80% impervious development scenario is included below as Graphs 1 and 2, and as Figure 5-44. Each figure contains plots of the native conditions (forest and meadow) and each of the four volume control performance goals considered. Probability plots from each volume performance goal, with and without rate control, were plotted, for a total of eight developed conditions plots per figure.

A flow frequency curve plots the probability that the annual maximum runoff event will exceed a given flow rate. For example, the flow frequency curves for the native meadow conditions in Graphs 1 and 2 and Figure 5-44 indicate that for any given year, there is a 28% probability that the maximum runoff from the site will be equal to or greater than 1 cubic feet per second per acre (cfs/acre).

#### 5.2.1.1 Volume and Rate Control BMPs

The objective of the rate control performance goal for the continuous modeling is to control the runoff stormwater runoff rate from developed conditions to a rate equal to or less than the runoff rate generated from native meadow conditions for the 1-, 2-, 10-, and 100-year 24-hour SCS Type II precipitation events. The continuous modeling confirms that this performance goal achieves the stated objective. The information shown in Graph 1 depicts this outcome, showing that for a given exceedance probability, the runoff rates from the developed conditions with volume and rate control BMPs (solid lines) are lower than the runoff rates from native meadow conditions (heavy dashed red line), up to approximately one percent annual exceedance probability.

As shown in Graph 1, the flow frequency curves for the four performance goal alternatives with volume and rate control are similar, with the exception of the curve for the one-inch off impervious surfaces performance goal. Generally, the differences in the probabilities between the four volume control performance goals can be explained by the slightly different approaches to rate control that were required for each BMP. Some rate control BMPs, required a very small low flow orifice to control flows from smaller storms (such as the one-year frequency event). Modeling results indicated that use of this outlet configuration over-restricted flow in some cases and resulted in flow frequency curves that were significantly lower than those of native conditions and the other performance goal alternatives. This is shown in Graph 1, where the flow frequency curve for the one inch off impervious surfaces performance goal is significantly lower than the curves for the other performance goals, reflecting that in this development scenario the one-inch off the impervious performance goals used a low flow orifice for rate control, while the other three goals used multi-stage weir control structures.



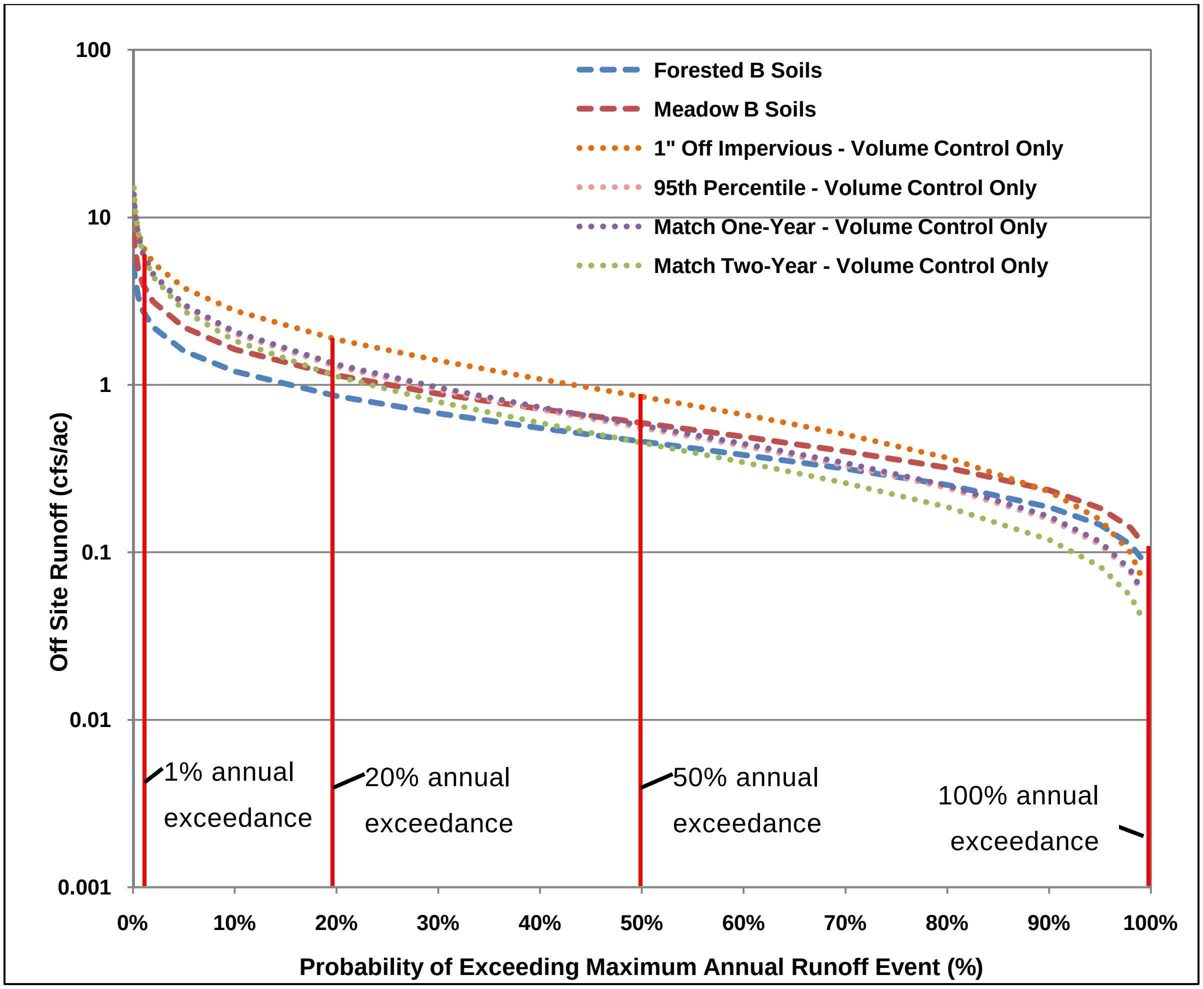

**Graph 1 Flow Frequency Curve: Twin Cities Native B Soils and Developed B soils, 80% Impervious for Volume and Rate Control**

#### 5.2.1.2 Volume Control BMPs Alone

The flow frequency curves from the Twin Cities developed conditions with only volume control BMPs (no rate control) demonstrate that the volume control BMPs provide some rate control benefit. The rate control benefit of a volume control BMP (rainwater garden) is dependent on the volume of the BMP; the larger the BMP volume, the more frequently runoff rate is restricted to levels below native conditions. The frequency curves demonstrate that the volume control performance goals that create the largest BMPs control runoff rate more effectively than performance goals that create a smaller BMP.

Graph 2 shows the performance curves for developed conditions (HSG B soils, 80% impervious) with volume control BMPs alone (no rate control BMPs) in comparison to the native conditions curves. The smallest volume control BMP (the one-inch off impervious performance goal) controlled rate to less than the native meadow conditions runoff rate up an annual maximum flow rate exceedance probability of 90%. For this specific developed scenario, the one year match and 95$^{th}$ percentile performance goal BMPs controlled runoff rate to less than the meadow runoff rate to an annual maximum flow rate exceedance probability of 50%. The two year match performance goal controlled rate to meadow conditions to an annual maximum flow rate exceedance probability of 20%. For flow rates higher and with a lower probability than those listed above, the volume control BMPs did not control runoff rate to or below the runoff rate from native meadow conditions.

Figures 5-40 through 5-45 display the flow frequency curves for all of the six developed conditions scenarios analyzed. These plots suggest that while volume control BMPs can control rate for the more frequent rain events, rate control BMPs are still required for the larger rainfall events.



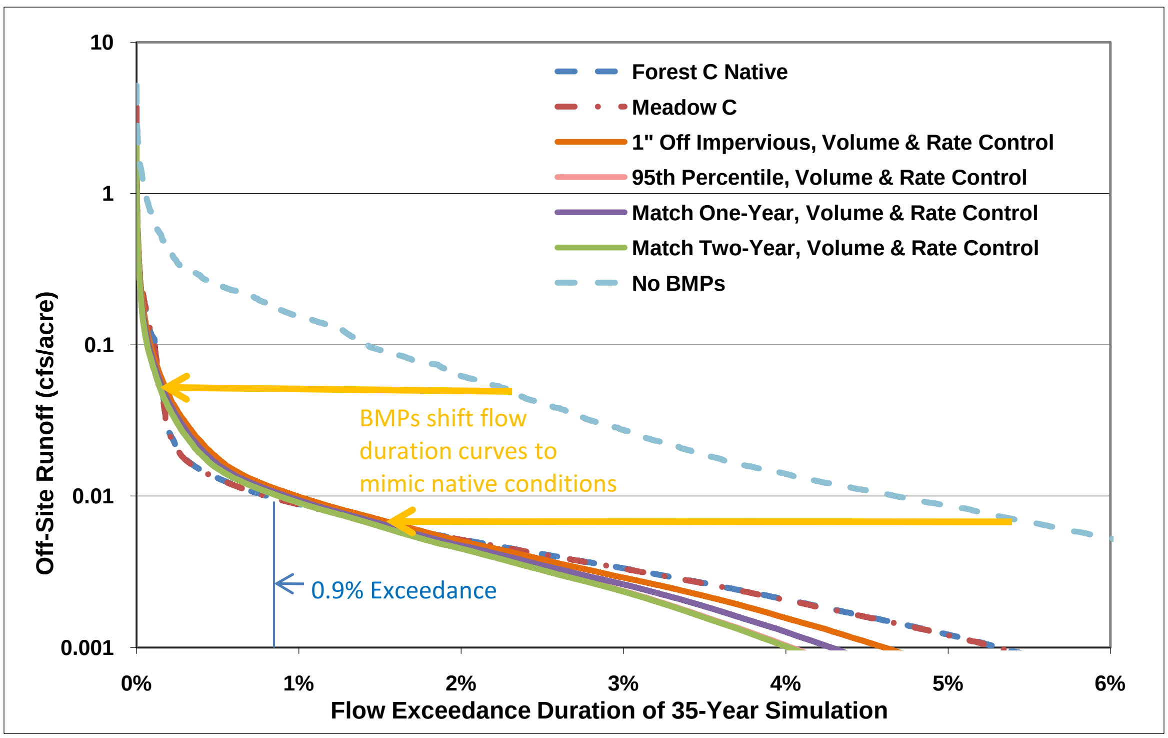

**Graph 2 Flow Frequency Curve: Twin Cities Native B Soils and Developed B soils, 80% Impervious for Volume Control Only**

### 5.2.2 Flow Duration Curves

A flow duration curve was developed for each of the Twin Cities native and developed conditions for HSG B and C scenarios (with and without rate control), with model results normalized based on drainage area. Flow duration curves plot the percentage of time over the entire period of interest (35 years modeled for the Twin Cities region) that runoff leaving the site exceeds a given flow rate. Figures 5-46 through 5-51 display the curves for each of the six development scenarios. Each figure contains the curves for the two native conditions (forest and meadow) and each of the four volume control performance goals, with and without rate control, for a total of eight developed conditions flow duration curves.

Graph 3 (similar to Figure 5-51) displays the flow duration curves for the native and developed conditions scenario representing C soils and 80% imperviousness, with volume and rate control BMPs. As previously mentioned, the flow duration curves plot the percentage of time over the entire modeling period that runoff from the sites exceeds a given flow rate. For example, as shown in Graph 3, the runoff from native meadow conditions is equal to or greater than 0.01 cfs/acre 0.9% of the 35 years modeled.

Graph 3 also shows the flow duration curve for the developed conditions scenario without any rate or volume control BMPs. The graph shows that for a given flow rate, a developed site without any BMPs will exceed that flow rate more frequently than native conditions For example, the runoff from the developed conditions site without any BMPs is equal to or greater than 0.01 cfs/acre approximately 4.6% of the 35 years modeled, while the runoff from native conditions is equal to or greater than 0.01 cfs/acre approximately 0.9% of the time.




**Graph 3 Flow Duration Curve: Twin Cities Native C Soils and Developed C Soils, 80% Impervious**

Comparison of the flow duration curves in Graph 3 indicates that implementation of volume and rate control BMPs results in a significant shift of the developed conditions flow duration curves toward the curves representing native conditions. Overall, the duration of runoff leaving the site from developed conditions with volume and rate control BMPs compares closely to the durations from native conditions for most flow rates above 0.005 cfs/acre. For lower flow rates (less than 0.005 cfs/acre), the runoff durations from developed conditions with volume and rate control BMPs were somewhat less than native conditions.

The modeling results indicate that the runoff from developed conditions with implementation of volume and rate control BMPs closely mimics runoff from native conditions.

## 5.3 Pollutant Removal Efficiencies

As discussed in Section 4.3, a P8 model was developed to assess the performance goals based on estimated total phosphorus and total suspended solids removal efficiency. The portion of average annual runoff volume captured onsite varies depending on the performance goal and resulting BMP volume. While strongly correlated with the amount of runoff captured and infiltrated, the overall pollutant removal efficiency is also dependent on other factors such as the varying concentration of pollutants in runoff (such as the "first flush effect") and pollutant removal that occurs through sedimentation or other mechanisms. All of these factors were considered in the long-term P8 analysis.

In addition to evaluating the effectiveness of the volume control BMPs, the cumulative pollutant removal efficiencies of volume control and rate control BMPs were also evaluated. As the P8 modeling results are considered, it is important to note that the model is more accurate in making relative predictions than in determining absolute values. Runoff water quality can be highly variable with time and location, dependent on numerous factors including land use and soil conditions. Without site-specific data on pollutant wash-off rates, concentrations and sediment characteristics, model inputs related to pollutant generation and washoff were determined based on national average values.

### 5.3.1 Volume Control BMPs

The P8 modeling results indicate that implementation of the four volume control performance goals significantly reduces the loading of total phosphorus and suspended sediment from the development sites. Figures 5-52 and 5-53 compare the average annual loadings from the hypothetical development sites with and without volume control BMPs for total phosphorus and total suspended solids, respectively.

The effectiveness of the volume control BMPs in reducing the pollutant load from the development sites was evaluated for the four performance goal alternatives. The results are summarized in

Table 5-11. Figures 5-54 and 5-55 show the percent phosphorus and total suspended solids removal predicted for the four performance goals based on the 50 years of continuous simulation. The percent removals reflect the differences between the pollutant loading generated from the site and the loading leaving the sites in terms of mass. For calculation of phosphorus removal efficiencies, it was assumed that the phosphorus leaving the site via infiltration from the volume control BMP (commonly in dissolved form) is completely removed. The predicted phosphorus removals range from 89 percent to 98 percent for sites with HSG B soils and from 81 percent to 97 percent for sites with HSG C soils, depending on imperviousness and performance goal. The estimated pollutant removal efficiencies are lower for the sites with lower imperviousness (20% impervious) and higher for the sites with higher imperviousness (80% impervious), which is a reflection of the larger BMP storage volumes for the sites of higher imperviousness. The predicted total suspended solids removal efficiencies range from 95 percent to 99 percent for sites on HSG B soils and from 91 percent to 99 percent for sites on HSG C soils, depending on imperviousness and performance goal.

The variation in pollutant removal efficiency amongst the four volume control performance standards is shown in Figures 5-56 and 5-57 for total phosphorus and total suspended solids, respectively. The small differentiation in treatment effectiveness amongst the performance goals suggests that the pollutant removal effectiveness is not a significant factor in determining which performance goal is optimal.

### 5.3.2 Rate Control BMPs

As described in Section 4.3.2, rate control BMPs were modeled directly downstream of the volume control BMPS as dry detention basins with multi-stage outlets. Dry detention basins, which do not have a permanent pool (volume below the basin outlet), are typically designed with a primary objective of controlling discharge rates, and do not provide significant pollutant removal. However, some level of pollutant removal occurs through the sedimentation process, depending on design parameters such as basin configuration and outlet.

The cumulative effectiveness of the volume control and rate control BMPs in removing total phosphorus and total suspended solids load from the site runoff was evaluated for the four performance goal alternatives. The results are summarized in Table 5-11.

The predicted cumulative phosphorus removals range from 90 percent to 98 percent for sites with HSG B soils and from 83 percent to 97 percent for sites with HSG C soils, depending on imperviousness and performance goal. The cumulative removal efficiencies are not significantly greater than those achieved through just the volume control BMPs. The volume control BMPs, modeled first in the treatment chain, remove most of the phosphorus load through infiltration. A large portion of the particulate phosphorus that is not infiltrated will be removed in the volume control BMP through sedimentation, with the remaining particulate and dissolved phosphorus discharged to the downstream rate control BMP. The rate control BMPs remove some of the remaining particulate phosphorus through sedimentation, but remove very little of the dissolved phosphorus.

Estimated pollutant removal efficiencies are lower for the sites with lower imperviousness (20% impervious) and higher for the sites with higher imperviousness (80% impervious), which is a reflection of the larger BMP storage volumes for the sites of higher imperviousness. The predicted total suspended solids removal efficiencies range from 95 percent to 99 percent for sites on HSG B soils and from 91 percent to 99 percent for sites on HSG C soils, depending on imperviousness and performance goal.

The predicted cumulative total suspended solids removals range from 97 percent to 99 percent for sites with HSG B soils and from 93 percent to 97 percent for sites with HSG C soils, depending on imperviousness and performance goal. Similar to phosphorus, the cumulative removal efficiencies from the volume and rate control BMPs combined are not significantly greater than those achieved through just the volume control BMPs.

# 6.0 Conclusions

Based on the XP-SWMM and P8 modeling efforts, Barr found the following results:

- Rate and volume control Best Management Practices (BMPs) are needed to mimic native hydrology from developed conditions
- Developed sites without volume control BMPs produce approximately two to four times the average annual runoff volume of native conditions
- All of the volume control performance goals evaluated do well at matching native conditions on an average annual basis
- All of the performance goals evaluated do worse at matching native conditions during non-frozen ground conditions (some yield up to two times more runoff than runoff form native conditions)
- Volume control BMPs controlled the 1-year, 24-hour peak rates to flows less than or equal to native conditions for most scenarios evaluated
- Volume control performance goals result in significant pollutant loading reduction from developed sites
- All volume control performance goals evaluated have similar removal efficiencies for TP and TSS
- The BMP size required to match native runoff volumes on an average annual basis varied with soil type, impervious percentage, and region of the state

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# Tables

Table 5-1. Annual Runoff Depth from A Soils (inches)

| Year* | Native 10 Acre Site | | Developed 10 Acre Site | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Forest | Meadow | No Volume Control BMP | | | BMP that retains a runoff volume equal to one inch times the proposed impervious surfaces | | | BMP that retains the post-construction runoff volume on site for the 95th percentile storm | | | BMP sized to match the native runoff volume for the one-year 24-hour design storm | | | BMP sized to match the native runoff volume for the two-year 24-hour design storm | | |
| | | | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious |
| 1972 | 1.7 | 1.7 | 5.2 | 10.3 | 15.3 | 1.6 | 1.5 | 1.6 | 1.5 | 1.6 | 1.4 | 1.5 | 1.3 | 1.6 | 1.3 | 1.3 | 1.0 |
| 1973 | 4.4 | 4.4 | 7.1 | 11.3 | 15.4 | 4.1 | 4.1 | 4.1 | 4.0 | 3.9 | 3.7 | 3.7 | 3.7 | 3.6 | 3.4 | 3.4 | 3.2 |
| 1974 | 3.8 | 3.8 | 6.1 | 9.5 | 12.9 | 3.4 | 3.4 | 3.4 | 3.3 | 3.1 | 3.0 | 3.0 | 2.9 | 2.8 | 2.6 | 2.7 | 2.5 |
| 1975 | 0.5 | 0.5 | 6.6 | 15.4 | 24.1 | 1.1 | 0.7 | 0.9 | 0.6 | 1.7 | 0.8 | 1.1 | 0.4 | 2.4 | 1.1 | 1.3 | 0.4 |
| 1976 | 4.2 | 4.2 | 6.0 | 8.7 | 11.3 | 4.0 | 3.9 | 3.9 | 3.8 | 3.6 | 3.5 | 3.5 | 3.4 | 3.4 | 3.1 | 3.2 | 3.0 |
| 1977 | 6.1 | 6.1 | 9.5 | 14.8 | 20.0 | 5.6 | 5.5 | 5.5 | 5.2 | 5.2 | 4.7 | 4.9 | 4.6 | 4.8 | 4.5 | 4.5 | 4.2 |
| 1978 | 1.7 | 1.7 | 5.0 | 9.8 | 14.5 | 2.3 | 1.9 | 1.9 | 1.9 | 2.6 | 2.1 | 2.4 | 2.0 | 2.8 | 2.1 | 2.2 | 1.6 |
| 1979 | 4.8 | 4.9 | 9.5 | 16.1 | 22.6 | 5.2 | 5.0 | 5.1 | 5.0 | 5.2 | 5.1 | 5.2 | 4.6 | 5.7 | 5.0 | 5.2 | 4.8 |
| 1980 | 2.9 | 2.9 | 6.1 | 10.6 | 15.1 | 3.0 | 2.9 | 2.9 | 2.8 | 3.1 | 2.7 | 2.8 | 2.6 | 3.0 | 2.6 | 2.6 | 2.3 |
| 1981 | 4.0 | 4.0 | 8.2 | 14.3 | 20.2 | 4.0 | 4.1 | 4.1 | 3.7 | 3.8 | 3.7 | 3.8 | 3.6 | 3.9 | 3.6 | 3.7 | 3.3 |
| 1982 | 4.9 | 4.9 | 8.6 | 14.1 | 19.4 | 4.7 | 4.5 | 4.5 | 4.4 | 4.1 | 3.8 | 3.8 | 3.6 | 3.6 | 3.2 | 3.2 | 2.8 |
| 1984 | 4.3 | 4.3 | 9.3 | 16.7 | 23.9 | 4.4 | 4.2 | 4.3 | 4.2 | 4.6 | 4.3 | 4.4 | 4.3 | 5.0 | 4.7 | 4.8 | 4.5 |
| 1985 | 5.2 | 5.2 | 9.3 | 15.2 | 21.0 | 5.3 | 5.2 | 5.2 | 5.1 | 5.5 | 5.1 | 5.2 | 5.0 | 5.4 | 4.8 | 4.9 | 4.6 |
| 1986 | 5.7 | 5.8 | 9.9 | 16.0 | 22.0 | 6.2 | 6.0 | 6.0 | 6.0 | 6.3 | 6.2 | 6.3 | 6.3 | 7.0 | 6.6 | 6.6 | 6.4 |
| 1987 | 3.9 | 4.3 | 7.2 | 11.6 | 15.8 | 4.6 | 4.3 | 4.5 | 4.0 | 4.3 | 3.9 | 4.1 | 3.7 | 4.5 | 3.9 | 4.0 | 3.5 |
| 1988 | 3.3 | 3.3 | 6.0 | 9.8 | 13.6 | 3.5 | 3.4 | 3.4 | 3.4 | 3.6 | 3.4 | 3.4 | 3.3 | 3.6 | 3.2 | 3.3 | 3.0 |
| 1989 | 3.5 | 3.5 | 6.2 | 10.2 | 14.1 | 3.4 | 3.3 | 3.4 | 3.3 | 3.3 | 3.0 | 3.1 | 2.9 | 3.1 | 2.7 | 2.8 | 2.4 |
| 1990 | 5.3 | 5.3 | 9.7 | 16.1 | 22.4 | 5.4 | 5.3 | 5.3 | 5.1 | 5.5 | 5.1 | 5.2 | 4.9 | 5.6 | 5.0 | 5.1 | 4.6 |
| 1991 | 4.7 | 4.9 | 10.9 | 19.7 | 28.3 | 5.8 | 5.3 | 5.3 | 5.2 | 6.4 | 6.4 | 6.0 | 5.7 | 7.2 | 6.6 | 6.7 | 5.5 |
| 1992 | 5.8 | 6.1 | 10.8 | 17.6 | 24.3 | 6.9 | 6.6 | 6.6 | 6.2 | 7.2 | 6.8 | 7.1 | 6.6 | 8.4 | 7.3 | 7.2 | 6.6 |
| 1993 | 4.0 | 4.0 | 8.9 | 15.9 | 22.8 | 4.0 | 3.9 | 3.9 | 3.7 | 4.0 | 3.7 | 3.8 | 3.7 | 4.2 | 3.8 | 3.8 | 3.6 |
| 1994 | 2.9 | 2.9 | 7.0 | 12.8 | 18.6 | 2.9 | 2.9 | 2.9 | 2.9 | 2.8 | 2.7 | 2.7 | 2.6 | 2.6 | 2.4 | 2.4 | 2.2 |
| 1995 | 4.7 | 4.7 | 8.9 | 14.8 | 20.7 | 4.8 | 4.6 | 4.6 | 4.5 | 4.4 | 4.3 | 4.4 | 4.1 | 4.3 | 4.0 | 4.0 | 3.7 |
| 1996 | 2.7 | 2.8 | 6.5 | 12.0 | 17.4 | 2.7 | 2.6 | 2.6 | 2.5 | 2.6 | 2.3 | 2.4 | 2.1 | 2.5 | 2.0 | 2.0 | 1.6 |
| 1997 | 5.1 | 5.4 | 10.5 | 18.1 | 25.5 | 6.0 | 6.0 | 5.9 | 5.8 | 7.1 | 6.6 | 6.9 | 6.1 | 8.2 | 7.1 | 7.3 | 6.5 |
| 1998 | 9.9 | 10.0 | 15.2 | 22.8 | 30.1 | 11.0 | 11.1 | 10.9 | 10.6 | 11.7 | 11.4 | 11.4 | 11.0 | 12.7 | 12.0 | 11.7 | 11.1 |
| 1999 | 4.6 | 4.7 | 9.1 | 15.6 | 22.0 | 4.6 | 4.5 | 4.6 | 4.3 | 4.3 | 4.2 | 4.2 | 4.0 | 4.2 | 3.8 | 3.9 | 3.6 |
| 2000 | 3.1 | 3.2 | 7.7 | 14.2 | 20.5 | 3.9 | 3.7 | 3.7 | 3.6 | 4.6 | 4.4 | 4.4 | 4.2 | 5.6 | 5.0 | 4.9 | 4.4 |
| 2002 | 2.5 | 2.5 | 6.9 | 13.4 | 19.8 | 2.5 | 2.3 | 2.3 | 2.2 | 2.7 | 2.3 | 2.4 | 2.1 | 2.9 | 2.2 | 2.4 | 1.8 |
| 2003 | 2.1 | 2.2 | 5.9 | 11.1 | 16.3 | 3.0 | 3.3 | 3.1 | 3.0 | 3.7 | 3.5 | 3.5 | 3.4 | 4.4 | 4.1 | 4.1 | 4.1 |
| 2004 | 3.2 | 3.2 | 6.7 | 11.8 | 16.8 | 3.0 | 2.8 | 2.9 | 2.8 | 2.9 | 2.6 | 2.7 | 2.4 | 2.9 | 2.3 | 2.3 | 2.0 |
| 2005 | 4.9 | 4.9 | 9.0 | 15.1 | 21.1 | 5.5 | 5.3 | 5.3 | 5.2 | 5.8 | 5.6 | 5.6 | 5.4 | 6.5 | 6.0 | 6.0 | 5.6 |
| 2007 | 6.3 | 6.3 | 10.7 | 17.2 | 23.5 | 6.7 | 6.5 | 6.6 | 6.5 | 7.0 | 6.6 | 6.7 | 6.4 | 7.2 | 6.7 | 6.8 | 6.2 |
| 2008 | 4.5 | 4.5 | 7.1 | 10.8 | 14.5 | 4.5 | 4.4 | 4.5 | 4.3 | 4.3 | 4.1 | 4.1 | 3.9 | 4.0 | 3.7 | 3.8 | 3.5 |
| 2009 | 3.4 | 3.4 | 7.1 | 12.4 | 17.7 | 3.5 | 3.5 | 3.5 | 3.4 | 3.7 | 3.4 | 3.5 | 3.4 | 4.0 | 3.4 | 3.5 | 3.4 |
| Average | 4.1 | 4.2 | 8.1 | 13.9 | 19.5 | 4.4 | 4.2 | 4.3 | 4.1 | 4.5 | 4.2 | 4.3 | 4.0 | 4.7 | 4.2 | 4.2 | 3.8 |

*Precipitation records were incomplete for years 1983, 2001, and 2006. Therefore these years were not modeled and do not appear in this series.

Table 5-2. Annual Runoff Depth from B Soils (inches)

| Year* | Native 10 Acre Site | | Developed 10 Acre Site | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Forest | Meadow | No Volume Control BMP | | | BMP that retains a runoff volume equal to one inch times the proposed impervious surfaces | | | BMP that retains the post-construction runoff volume on site for the 95th percentile storm | | | BMP sized to match the native runoff volume for the one-year 24-hour design storm | | | BMP sized to match the native runoff volume for the two-year 24-hour design storm | | |
| | | | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious |
| 1972 | 2.3 | 2.4 | 5.9 | 10.8 | 15.5 | 2.2 | 1.9 | 1.6 | 2.0 | 1.7 | 1.3 | 2.0 | 1.7 | 1.3 | 1.9 | 1.5 | 1.0 |
| 1973 | 4.4 | 4.4 | 7.1 | 11.3 | 15.4 | 4.1 | 3.8 | 3.5 | 4.0 | 3.6 | 3.2 | 4.0 | 3.6 | 3.2 | 4.0 | 3.5 | 3.1 |
| 1974 | 3.8 | 3.8 | 6.1 | 9.5 | 12.9 | 3.4 | 3.0 | 2.6 | 3.3 | 2.9 | 2.5 | 3.3 | 2.9 | 2.5 | 3.2 | 2.8 | 2.3 |
| 1975 | 0.6 | 0.7 | 7.0 | 15.7 | 24.3 | 2.0 | 2.4 | 3.1 | 1.3 | 1.3 | 1.5 | 1.3 | 1.3 | 1.5 | 1.0 | 0.7 | 0.7 |
| 1976 | 4.2 | 4.2 | 6.0 | 8.7 | 11.3 | 4.0 | 3.7 | 3.2 | 4.0 | 3.4 | 3.0 | 3.9 | 3.4 | 3.0 | 3.8 | 3.3 | 2.8 |
| 1977 | 6.3 | 6.4 | 9.8 | 15.0 | 20.1 | 5.7 | 5.2 | 4.9 | 5.5 | 4.8 | 4.5 | 5.5 | 5.1 | 4.5 | 5.6 | 4.8 | 4.1 |
| 1978 | 2.3 | 2.6 | 5.9 | 10.4 | 14.7 | 2.9 | 3.6 | 3.6 | 2.7 | 3.0 | 2.9 | 2.5 | 3.0 | 2.9 | 2.7 | 2.7 | 2.1 |
| 1979 | 5.7 | 6.0 | 10.5 | 16.8 | 22.9 | 7.3 | 6.8 | 6.0 | 6.5 | 5.9 | 5.2 | 6.0 | 5.9 | 5.2 | 6.6 | 5.6 | 4.8 |
| 1980 | 3.2 | 3.3 | 6.5 | 10.9 | 15.2 | 3.8 | 3.6 | 3.2 | 3.4 | 3.1 | 2.6 | 3.5 | 3.1 | 2.6 | 3.4 | 3.0 | 2.3 |
| 1981 | 4.1 | 4.1 | 8.4 | 14.5 | 20.3 | 4.4 | 4.3 | 4.2 | 4.1 | 3.8 | 3.4 | 4.0 | 3.8 | 3.5 | 3.9 | 3.6 | 3.2 |
| 1982 | 4.9 | 5.0 | 8.8 | 14.2 | 19.5 | 4.7 | 4.1 | 3.4 | 4.6 | 3.8 | 2.9 | 4.5 | 3.7 | 3.0 | 4.5 | 3.4 | 2.7 |
| 1984 | 4.6 | 4.9 | 10.0 | 17.2 | 24.2 | 5.1 | 5.1 | 5.4 | 4.9 | 4.8 | 4.8 | 4.8 | 5.0 | 4.9 | 4.6 | 4.5 | 4.4 |
| 1985 | 5.2 | 5.2 | 9.3 | 15.2 | 21.0 | 5.3 | 5.5 | 5.3 | 5.2 | 5.1 | 4.7 | 5.2 | 5.0 | 4.7 | 5.2 | 4.9 | 4.4 |
| 1986 | 6.2 | 6.4 | 10.3 | 16.3 | 22.1 | 6.5 | 6.8 | 7.1 | 6.5 | 6.8 | 6.9 | 6.5 | 6.7 | 6.9 | 6.5 | 6.6 | 6.6 |
| 1987 | 5.4 | 5.9 | 8.6 | 12.4 | 16.1 | 5.2 | 4.9 | 4.6 | 5.2 | 4.4 | 4.0 | 4.9 | 4.4 | 4.0 | 4.8 | 4.1 | 3.6 |
| 1988 | 3.4 | 3.4 | 6.1 | 10.0 | 13.7 | 3.6 | 3.8 | 3.6 | 3.8 | 3.7 | 3.2 | 3.7 | 3.7 | 3.2 | 3.7 | 3.5 | 2.9 |
| 1989 | 3.9 | 4.1 | 6.4 | 10.3 | 14.2 | 4.0 | 3.7 | 3.1 | 3.7 | 3.2 | 2.6 | 3.8 | 3.3 | 2.6 | 3.8 | 3.0 | 2.3 |
| 1990 | 5.3 | 5.3 | 9.8 | 16.2 | 22.4 | 5.8 | 5.8 | 5.8 | 5.6 | 5.3 | 5.0 | 5.5 | 5.4 | 5.0 | 5.3 | 5.1 | 4.6 |
| 1991 | 6.7 | 7.4 | 13.2 | 21.3 | 29.0 | 7.6 | 7.8 | 8.0 | 7.3 | 7.5 | 7.3 | 7.3 | 7.5 | 7.4 | 7.4 | 7.2 | 6.7 |
| 1992 | 8.0 | 8.5 | 12.9 | 18.9 | 24.8 | 9.0 | 9.5 | 9.2 | 8.9 | 8.6 | 7.9 | 8.8 | 8.5 | 7.7 | 8.6 | 8.1 | 7.1 |
| 1993 | 4.0 | 4.1 | 9.1 | 16.1 | 22.9 | 4.4 | 4.5 | 4.6 | 4.3 | 4.0 | 4.0 | 4.2 | 4.0 | 4.0 | 3.9 | 3.8 | 3.7 |
| 1994 | 2.9 | 2.9 | 7.0 | 12.9 | 18.6 | 3.0 | 2.8 | 2.5 | 2.9 | 2.6 | 2.2 | 2.9 | 2.6 | 2.2 | 2.9 | 2.5 | 2.1 |
| 1995 | 4.8 | 4.8 | 9.0 | 15.0 | 20.8 | 4.6 | 4.4 | 4.2 | 4.6 | 4.2 | 3.8 | 4.5 | 4.2 | 3.8 | 4.4 | 4.0 | 3.6 |
| 1996 | 3.0 | 3.2 | 7.0 | 12.3 | 17.5 | 3.1 | 3.0 | 2.5 | 3.1 | 2.5 | 1.9 | 3.1 | 2.5 | 1.9 | 3.0 | 2.3 | 1.5 |
| 1997 | 6.8 | 7.4 | 12.3 | 19.3 | 26.0 | 7.9 | 8.1 | 8.4 | 8.0 | 7.3 | 7.3 | 7.4 | 7.3 | 7.4 | 7.3 | 7.3 | 6.3 |
| 1998 | 12.3 | 13.1 | 17.7 | 24.5 | 30.9 | 14.5 | 13.8 | 13.0 | 14.2 | 13.4 | 12.6 | 13.7 | 13.2 | 12.7 | 13.4 | 12.9 | 12.0 |
| 1999 | 4.8 | 4.9 | 9.4 | 15.8 | 22.1 | 4.9 | 4.7 | 4.1 | 4.8 | 4.2 | 3.7 | 4.7 | 4.2 | 3.7 | 4.4 | 4.0 | 3.4 |
| 2000 | 4.7 | 5.3 | 9.5 | 15.3 | 21.0 | 5.0 | 5.4 | 6.4 | 6.1 | 5.9 | 5.6 | 5.9 | 5.7 | 5.6 | 5.5 | 5.5 | 5.2 |
| 2002 | 3.2 | 3.5 | 8.0 | 14.1 | 20.1 | 3.2 | 3.3 | 3.4 | 3.1 | 3.0 | 2.4 | 3.0 | 3.1 | 2.5 | 3.0 | 2.5 | 2.0 |
| 2003 | 4.1 | 4.4 | 7.6 | 12.2 | 16.7 | 4.8 | 4.9 | 4.9 | 4.6 | 4.7 | 4.5 | 4.6 | 4.7 | 4.5 | 4.6 | 4.6 | 4.2 |
| 2004 | 3.2 | 3.2 | 6.8 | 11.8 | 16.8 | 3.1 | 3.0 | 2.9 | 2.8 | 2.5 | 2.2 | 2.8 | 2.6 | 2.3 | 2.7 | 2.3 | 1.9 |
| 2005 | 5.6 | 5.9 | 10.0 | 15.8 | 21.4 | 6.5 | 6.7 | 6.7 | 6.3 | 6.2 | 6.2 | 6.3 | 6.2 | 6.2 | 6.2 | 6.0 | 5.9 |
| 2007 | 6.9 | 7.3 | 11.9 | 18.0 | 23.9 | 7.8 | 7.8 | 7.8 | 7.9 | 7.3 | 7.2 | 7.7 | 7.5 | 7.2 | 7.2 | 7.1 | 6.5 |
| 2008 | 4.6 | 4.6 | 7.2 | 10.9 | 14.5 | 4.6 | 4.4 | 4.1 | 4.7 | 4.1 | 3.6 | 4.6 | 4.1 | 3.6 | 4.5 | 4.0 | 3.4 |
| 2009 | 3.7 | 3.9 | 7.6 | 12.8 | 17.9 | 3.9 | 4.3 | 4.4 | 4.0 | 3.8 | 3.6 | 3.9 | 3.9 | 3.7 | 3.8 | 3.6 | 3.4 |
| Average | 4.7 | 4.9 | 8.8 | 14.4 | 19.7 | 5.1 | 5.0 | 4.9 | 5.0 | 4.6 | 4.3 | 4.9 | 4.6 | 4.3 | 4.8 | 4.4 | 3.9 |

*Precipitation records were incomplete for years 1983, 2001, and 2006. Therefore these years were not modeled and do not appear in this series.

Table 5-3. Annual Runoff Depth from C Soils (inches)

| Year* | Native 10 Acre Site | | Developed 10 Acre Site | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Forest | Meadow | No Volume Control BMP | | | BMP that retains a runoff volume equal to one inch times the proposed impervious surfaces | | | BMP that retains the post-construction runoff volume on site for the 95th percentile storm | | | BMP sized to match the native runoff volume for the one-year 24-hour design storm | | | BMP sized to match the native runoff volume for the two-year 24-hour design storm | | |
| | | | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious |
| 1972 | 2.5 | 2.7 | 6.1 | 10.9 | 15.6 | 2.2 | 2.0 | 1.7 | 2.0 | 1.6 | 1.3 | 2.1 | 1.8 | 1.5 | 2.1 | 1.7 | 1.2 |
| 1973 | 4.4 | 4.4 | 7.2 | 11.3 | 15.4 | 4.2 | 4.0 | 3.7 | 3.9 | 3.5 | 3.2 | 4.0 | 3.7 | 3.5 | 4.0 | 3.6 | 3.2 |
| 1974 | 3.8 | 3.8 | 6.1 | 9.5 | 12.9 | 3.3 | 3.0 | 2.6 | 3.2 | 2.8 | 2.4 | 3.2 | 2.9 | 2.5 | 3.2 | 2.8 | 2.4 |
| 1975 | 0.8 | 0.9 | 7.3 | 16.0 | 24.5 | 2.6 | 3.5 | 4.2 | 1.2 | 1.7 | 2.5 | 1.7 | 2.3 | 3.1 | 1.5 | 1.8 | 2.4 |
| 1976 | 4.2 | 4.2 | 6.0 | 8.7 | 11.3 | 4.1 | 3.7 | 3.3 | 3.8 | 3.3 | 2.9 | 3.9 | 3.5 | 3.0 | 3.8 | 3.4 | 2.9 |
| 1977 | 6.4 | 6.5 | 9.9 | 15.1 | 20.1 | 5.9 | 5.4 | 5.0 | 5.4 | 4.8 | 4.4 | 5.7 | 5.1 | 4.7 | 5.4 | 5.0 | 4.4 |
| 1978 | 2.7 | 3.0 | 6.4 | 10.7 | 14.8 | 3.6 | 4.2 | 4.4 | 3.1 | 3.4 | 3.6 | 3.4 | 3.7 | 3.8 | 3.4 | 3.4 | 3.4 |
| 1979 | 5.9 | 6.3 | 10.8 | 17.0 | 23.0 | 6.8 | 6.4 | 5.7 | 6.0 | 5.6 | 5.0 | 6.2 | 6.0 | 5.3 | 6.1 | 5.6 | 5.1 |
| 1980 | 3.4 | 3.6 | 6.8 | 11.2 | 15.4 | 4.1 | 4.0 | 3.9 | 3.4 | 3.3 | 2.9 | 3.9 | 3.5 | 3.3 | 3.8 | 3.3 | 2.9 |
| 1981 | 4.2 | 4.4 | 8.8 | 14.7 | 20.5 | 4.8 | 4.7 | 4.4 | 4.2 | 3.8 | 3.5 | 4.4 | 4.2 | 3.9 | 4.2 | 3.9 | 3.4 |
| 1982 | 5.0 | 5.1 | 8.9 | 14.3 | 19.5 | 4.9 | 4.1 | 3.4 | 4.4 | 3.6 | 2.9 | 4.6 | 3.8 | 3.2 | 4.4 | 3.7 | 2.9 |
| 1984 | 5.0 | 5.3 | 10.5 | 17.5 | 24.3 | 5.5 | 5.7 | 5.9 | 4.8 | 4.8 | 4.8 | 5.3 | 5.1 | 5.1 | 4.9 | 4.9 | 4.8 |
| 1985 | 5.2 | 5.2 | 9.3 | 15.2 | 21.0 | 5.5 | 5.6 | 5.6 | 5.2 | 5.0 | 4.9 | 5.2 | 5.3 | 5.2 | 5.1 | 5.0 | 4.8 |
| 1986 | 6.6 | 6.7 | 10.5 | 16.4 | 22.1 | 7.0 | 7.2 | 7.4 | 6.8 | 7.0 | 7.2 | 7.1 | 7.0 | 7.4 | 6.8 | 7.0 | 7.2 |
| 1987 | 5.9 | 6.3 | 9.0 | 12.7 | 16.2 | 5.5 | 5.1 | 4.6 | 5.0 | 4.4 | 4.0 | 5.2 | 4.6 | 4.3 | 5.0 | 4.4 | 4.0 |
| 1988 | 3.4 | 3.5 | 6.3 | 10.0 | 13.7 | 3.8 | 4.0 | 3.6 | 3.7 | 3.6 | 3.1 | 3.9 | 3.8 | 3.4 | 3.7 | 3.6 | 3.1 |
| 1989 | 4.0 | 4.3 | 6.5 | 10.4 | 14.2 | 4.2 | 3.8 | 3.1 | 3.7 | 3.1 | 2.5 | 4.1 | 3.4 | 2.8 | 3.8 | 3.2 | 2.5 |
| 1990 | 5.4 | 5.5 | 10.1 | 16.4 | 22.5 | 5.9 | 6.0 | 6.0 | 5.5 | 5.3 | 5.2 | 5.7 | 5.6 | 5.6 | 5.6 | 5.4 | 5.1 |
| 1991 | 7.4 | 8.1 | 13.9 | 21.7 | 29.2 | 8.5 | 8.6 | 8.4 | 7.8 | 7.8 | 7.6 | 8.1 | 8.0 | 7.9 | 8.1 | 7.9 | 7.6 |
| 1992 | 8.5 | 9.0 | 13.4 | 19.3 | 25.0 | 10.1 | 10.0 | 10.0 | 9.0 | 8.7 | 8.2 | 9.5 | 9.1 | 8.9 | 9.2 | 8.7 | 8.1 |
| 1993 | 4.2 | 4.3 | 9.4 | 16.3 | 23.1 | 5.1 | 5.0 | 5.1 | 4.2 | 4.2 | 4.3 | 4.5 | 4.5 | 4.7 | 4.3 | 4.3 | 4.3 |
| 1994 | 2.9 | 2.9 | 7.0 | 12.9 | 18.7 | 3.1 | 3.0 | 2.9 | 2.9 | 2.5 | 2.3 | 2.9 | 2.7 | 2.5 | 2.9 | 2.6 | 2.2 |
| 1995 | 4.8 | 4.9 | 9.2 | 15.1 | 20.8 | 5.0 | 4.6 | 4.5 | 4.5 | 4.1 | 3.8 | 4.6 | 4.3 | 4.0 | 4.5 | 4.1 | 3.8 |
| 1996 | 3.2 | 3.4 | 7.2 | 12.5 | 17.6 | 3.8 | 3.3 | 2.7 | 2.9 | 2.5 | 1.9 | 3.1 | 2.7 | 2.2 | 3.0 | 2.5 | 1.9 |
| 1997 | 7.3 | 7.9 | 12.9 | 19.6 | 26.2 | 9.0 | 9.6 | 9.5 | 8.1 | 8.0 | 7.5 | 8.6 | 8.6 | 8.4 | 8.5 | 8.0 | 7.5 |
| 1998 | 13.1 | 14.1 | 18.6 | 25.0 | 31.1 | 15.2 | 14.9 | 14.2 | 14.2 | 13.6 | 12.9 | 14.4 | 13.9 | 13.5 | 14.5 | 13.6 | 12.7 |
| 1999 | 4.9 | 5.0 | 9.6 | 15.9 | 22.2 | 5.1 | 4.9 | 4.5 | 4.4 | 4.1 | 3.8 | 4.7 | 4.4 | 4.1 | 4.5 | 4.1 | 3.8 |
| 2000 | 5.2 | 5.8 | 9.9 | 15.6 | 21.1 | 5.9 | 6.3 | 6.2 | 5.9 | 5.8 | 5.9 | 5.8 | 6.1 | 6.2 | 5.8 | 5.8 | 5.8 |
| 2002 | 3.6 | 3.9 | 8.4 | 14.4 | 20.3 | 4.1 | 4.0 | 3.6 | 3.2 | 2.7 | 2.5 | 3.4 | 3.2 | 2.9 | 3.3 | 2.9 | 2.4 |
| 2003 | 4.5 | 4.8 | 8.0 | 12.5 | 16.8 | 5.3 | 5.4 | 5.3 | 5.0 | 4.7 | 4.5 | 4.9 | 4.8 | 4.8 | 4.9 | 4.7 | 4.5 |
| 2004 | 3.2 | 3.3 | 7.0 | 12.0 | 16.9 | 3.6 | 3.4 | 3.2 | 2.8 | 2.6 | 2.4 | 3.0 | 2.9 | 2.7 | 2.9 | 2.6 | 2.3 |
| 2005 | 6.3 | 6.6 | 10.5 | 16.1 | 21.6 | 7.5 | 7.1 | 6.9 | 6.4 | 6.3 | 6.3 | 6.7 | 6.5 | 6.4 | 6.5 | 6.3 | 6.2 |
| 2007 | 7.3 | 7.9 | 12.5 | 18.4 | 24.1 | 8.5 | 8.5 | 8.4 | 7.8 | 7.5 | 7.5 | 8.3 | 8.0 | 8.0 | 8.0 | 7.6 | 7.4 |
| 2008 | 4.7 | 4.8 | 7.4 | 11.0 | 14.6 | 4.9 | 4.3 | 4.0 | 4.6 | 4.1 | 3.5 | 4.5 | 4.2 | 3.8 | 4.5 | 4.1 | 3.6 |
| 2009 | 3.9 | 4.2 | 8.0 | 13.1 | 18.0 | 4.5 | 4.4 | 4.5 | 3.8 | 3.8 | 3.7 | 4.1 | 4.0 | 4.0 | 3.9 | 3.8 | 3.7 |
| Average | 5.0 | 5.2 | 9.1 | 14.6 | 19.8 | 5.5 | 5.4 | 5.2 | 4.9 | 4.7 | 4.4 | 5.2 | 4.9 | 4.7 | 5.0 | 4.7 | 4.4 |

*Precipitation records were incomplete for years 1983, 2001, and 2006. Therefore these years were not modeled and do not appear in this series.

Table 5-4. Frozen Ground Time Period Runoff Depth from A Soils (inches)

| Year* | Native 10 Acre Site | | Developed 10 Acre Site | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Forest | Meadow | No Volume Control BMP | | | BMP that retains a runoff volume equal to one inch times the proposed impervious surfaces | | | BMP that retains the post-construction runoff volume on site for the 95th percentile storm | | | BMP sized to match the native runoff volume for the one-year 24-hour design storm | | | BMP sized to match the native runoff volume for the two-year 24-hour design storm | | |
| | | | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious |
| 1972 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.4 | 1.4 | 1.4 | 1.4 | 1.1 | 1.0 | 1.1 | 1.0 | 0.8 | 0.7 | 0.7 | 0.5 |
| 1973 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.1 | 4.1 | 4.1 | 4.0 | 3.8 | 3.7 | 3.7 | 3.7 | 3.5 | 3.4 | 3.4 | 3.2 |
| 1974 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.4 | 3.4 | 3.4 | 3.3 | 3.1 | 3.0 | 3.0 | 2.9 | 2.8 | 2.6 | 2.7 | 2.5 |
| 1975 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.4 | 0.4 | 0.4 | 0.4 | 0.1 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 1976 | 4.2 | 4.2 | 4.2 | 4.2 | 4.2 | 4.0 | 3.9 | 3.9 | 3.8 | 3.6 | 3.5 | 3.5 | 3.4 | 3.3 | 3.1 | 3.2 | 3.0 |
| 1977 | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 | 5.5 | 5.4 | 5.4 | 5.2 | 4.7 | 4.7 | 4.7 | 4.6 | 4.5 | 4.4 | 4.4 | 4.2 |
| 1978 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.5 | 1.5 | 1.5 | 1.3 | 1.2 | 1.2 | 1.0 |
| 1979 | 4.7 | 4.7 | 4.7 | 4.7 | 4.7 | 4.5 | 4.5 | 4.5 | 4.4 | 4.2 | 4.1 | 4.1 | 4.0 | 3.9 | 3.7 | 3.7 | 3.6 |
| 1980 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.7 | 2.7 | 2.7 | 2.7 | 2.4 | 2.3 | 2.4 | 2.3 | 2.1 | 2.0 | 2.0 | 1.9 |
| 1981 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 3.9 | 3.9 | 4.0 | 3.6 | 3.5 | 3.4 | 3.4 | 3.4 | 3.2 | 3.1 | 3.1 | 3.0 |
| 1982 | 4.9 | 4.9 | 4.9 | 4.9 | 4.9 | 4.5 | 4.4 | 4.4 | 4.4 | 3.9 | 3.7 | 3.7 | 3.6 | 3.3 | 3.0 | 3.0 | 2.8 |
| 1984 | 4.3 | 4.3 | 4.3 | 4.3 | 4.3 | 4.1 | 4.1 | 4.1 | 4.0 | 3.8 | 3.7 | 3.8 | 3.8 | 3.7 | 3.8 | 3.8 | 3.7 |
| 1985 | 5.2 | 5.2 | 5.2 | 5.2 | 5.2 | 5.2 | 5.1 | 5.1 | 5.1 | 5.2 | 5.0 | 5.1 | 5.0 | 4.8 | 4.7 | 4.7 | 4.6 |
| 1986 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.6 | 5.6 | 5.6 | 5.7 |
| 1987 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.3 | 2.2 | 2.3 | 1.9 | 1.5 | 1.3 | 1.4 | 1.2 | 1.0 | 0.9 | 0.9 | 0.7 |
| 1988 | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 | 3.4 | 3.4 | 3.4 | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 | 3.2 | 3.1 | 3.1 | 3.0 |
| 1989 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 | 3.3 | 3.3 | 3.3 | 3.2 | 3.0 | 2.9 | 2.9 | 2.8 | 2.7 | 2.6 | 2.6 | 2.4 |
| 1990 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.1 | 5.1 | 5.1 | 5.0 | 4.8 | 4.7 | 4.7 | 4.6 | 4.5 | 4.3 | 4.3 | 4.2 |
| 1991 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.2 | 4.2 | 4.2 | 4.1 | 3.9 | 3.8 | 3.8 | 3.7 | 3.6 | 3.4 | 3.5 | 3.3 |
| 1992 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.2 | 5.1 | 5.1 | 5.0 | 4.8 | 4.7 | 4.7 | 4.6 | 4.5 | 4.3 | 4.4 | 4.2 |
| 1993 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 3.8 | 3.8 | 3.8 | 3.7 | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 |
| 1994 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.8 | 2.7 | 2.7 | 2.6 | 2.5 | 2.4 | 2.4 | 2.2 |
| 1995 | 4.7 | 4.7 | 4.7 | 4.7 | 4.7 | 4.6 | 4.5 | 4.6 | 4.5 | 4.2 | 4.1 | 4.2 | 4.1 | 3.9 | 3.8 | 3.8 | 3.6 |
| 1996 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.5 | 2.5 | 2.5 | 2.4 | 2.2 | 2.1 | 2.1 | 2.0 | 1.9 | 1.7 | 1.8 | 1.6 |
| 1997 | 4.6 | 4.6 | 4.6 | 4.6 | 4.6 | 4.4 | 4.3 | 4.3 | 4.3 | 4.0 | 4.0 | 4.0 | 3.9 | 3.7 | 3.6 | 3.6 | 3.5 |
| 1998 | 9.7 | 9.7 | 9.7 | 9.7 | 9.7 | 9.7 | 9.7 | 9.7 | 9.6 | 9.2 | 9.1 | 9.1 | 9.1 | 8.9 | 8.7 | 8.8 | 8.6 |
| 1999 | 4.6 | 4.6 | 4.6 | 4.6 | 4.6 | 4.5 | 4.5 | 4.5 | 4.3 | 4.1 | 4.0 | 4.0 | 4.0 | 3.8 | 3.7 | 3.7 | 3.6 |
| 2000 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 3.0 | 2.9 | 3.0 | 2.8 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 |
| 2002 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.1 | 2.0 | 2.0 | 2.0 | 1.8 | 1.7 | 1.7 | 1.6 | 1.5 | 1.3 | 1.3 | 1.2 |
| 2003 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 2.0 | 1.9 | 2.0 | 1.8 | 1.6 | 1.5 | 1.6 | 1.5 | 1.3 | 1.2 | 1.2 | 1.1 |
| 2004 | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 | 2.8 | 2.8 | 2.8 | 2.8 | 2.5 | 2.4 | 2.5 | 2.4 | 2.2 | 2.1 | 2.1 | 2.0 |
| 2005 | 4.9 | 4.9 | 4.9 | 4.9 | 4.9 | 4.8 | 4.8 | 4.8 | 4.7 | 4.4 | 4.4 | 4.4 | 4.3 | 4.1 | 4.0 | 4.0 | 3.9 |
| 2007 | 6.3 | 6.3 | 6.3 | 6.3 | 6.3 | 6.2 | 6.1 | 6.1 | 6.0 | 5.8 | 5.7 | 5.7 | 5.7 | 5.5 | 5.4 | 5.4 | 5.2 |
| 2008 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.4 | 4.3 | 4.4 | 4.3 | 4.1 | 4.0 | 4.0 | 3.9 | 3.8 | 3.6 | 3.7 | 3.5 |
| 2009 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.5 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 |
| Average | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 3.9 | 3.8 | 3.9 | 3.8 | 3.6 | 3.5 | 3.5 | 3.4 | 3.3 | 3.2 | 3.2 | 3.1 |

*Precipitation records were incomplete for years 1983, 2001, and 2006. Therefore these years were not modeled and do not appear in this series.

Table 5-5. Frozen Ground Time Period Runoff Depth from B Soils (inches)

| Year* | Native 10 Acre Site | | Developed 10 Acre Site | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Forest | Meadow | No Volume Control BMP | | | BMP that retains a runoff volume equal to one inch times the proposed impervious surfaces | | | BMP that retains the post-construction runoff volume on site for the 95th percentile storm | | | BMP sized to match the native runoff volume for the one-year 24-hour design storm | | | BMP sized to match the native runoff volume for the two-year 24-hour design storm | | |
| | | | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious |
| 1972 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.4 | 1.0 | 0.7 | 1.3 | 0.9 | 0.5 | 1.3 | 0.9 | 0.5 | 1.3 | 0.8 | 0.4 |
| 1973 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.0 | 3.7 | 3.4 | 4.0 | 3.6 | 3.2 | 4.0 | 3.6 | 3.2 | 4.0 | 3.5 | 3.1 |
| 1974 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.4 | 3.0 | 2.6 | 3.3 | 2.9 | 2.5 | 3.3 | 2.9 | 2.5 | 3.2 | 2.8 | 2.3 |
| 1975 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.4 | 0.1 | 0.0 | 0.4 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 |
| 1976 | 4.2 | 4.2 | 4.2 | 4.2 | 4.2 | 3.9 | 3.5 | 3.1 | 3.8 | 3.4 | 3.0 | 3.8 | 3.4 | 3.0 | 3.7 | 3.3 | 2.8 |
| 1977 | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 | 5.3 | 4.7 | 4.3 | 5.2 | 4.6 | 4.2 | 5.1 | 4.6 | 4.2 | 5.1 | 4.5 | 4.0 |
| 1978 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.5 | 1.2 | 1.6 | 1.4 | 1.0 | 1.6 | 1.4 | 1.0 | 1.6 | 1.3 | 0.9 |
| 1979 | 4.7 | 4.7 | 4.7 | 4.7 | 4.7 | 4.4 | 4.1 | 3.7 | 4.5 | 4.0 | 3.5 | 4.4 | 4.0 | 3.6 | 4.4 | 3.9 | 3.4 |
| 1980 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.7 | 2.3 | 2.0 | 2.6 | 2.2 | 1.8 | 2.7 | 2.2 | 1.8 | 2.6 | 2.1 | 1.7 |
| 1981 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 3.8 | 3.5 | 3.1 | 3.7 | 3.4 | 2.9 | 3.6 | 3.4 | 2.9 | 3.6 | 3.3 | 2.8 |
| 1982 | 4.9 | 4.9 | 4.9 | 4.9 | 4.9 | 4.4 | 3.7 | 3.0 | 4.3 | 3.4 | 2.7 | 4.2 | 3.4 | 2.7 | 4.2 | 3.3 | 2.6 |
| 1984 | 4.3 | 4.3 | 4.3 | 4.3 | 4.3 | 4.1 | 3.8 | 3.8 | 4.0 | 3.8 | 3.6 | 4.0 | 3.8 | 3.7 | 3.9 | 3.8 | 3.5 |
| 1985 | 5.2 | 5.2 | 5.2 | 5.2 | 5.2 | 5.2 | 5.1 | 4.7 | 5.2 | 4.9 | 4.5 | 5.2 | 4.9 | 4.5 | 5.2 | 4.9 | 4.4 |
| 1986 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 |
| 1987 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.1 | 1.3 | 0.9 | 1.9 | 1.1 | 0.7 | 1.7 | 1.1 | 0.7 | 1.7 | 1.0 | 0.6 |
| 1988 | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 | 3.1 | 3.4 | 3.3 | 2.9 | 3.3 | 3.3 | 2.9 | 3.3 | 3.2 | 2.8 |
| 1989 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 | 3.3 | 2.9 | 2.6 | 3.2 | 2.8 | 2.4 | 3.2 | 2.8 | 2.4 | 3.2 | 2.7 | 2.3 |
| 1990 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.0 | 4.7 | 4.3 | 5.0 | 4.6 | 4.1 | 5.0 | 4.6 | 4.1 | 4.9 | 4.5 | 4.0 |
| 1991 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.2 | 3.8 | 3.4 | 4.1 | 3.7 | 3.3 | 4.1 | 3.7 | 3.3 | 4.1 | 3.6 | 3.1 |
| 1992 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.1 | 4.7 | 4.4 | 5.0 | 4.6 | 4.2 | 5.0 | 4.6 | 4.2 | 5.0 | 4.5 | 4.1 |
| 1993 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 3.8 | 3.6 | 3.6 | 3.7 | 3.6 | 3.6 | 3.7 | 3.6 | 3.6 | 3.7 | 3.6 | 3.6 |
| 1994 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.7 | 2.4 | 2.9 | 2.6 | 2.2 | 2.9 | 2.6 | 2.2 | 2.9 | 2.5 | 2.1 |
| 1995 | 4.7 | 4.7 | 4.7 | 4.7 | 4.7 | 4.5 | 4.1 | 3.8 | 4.4 | 4.0 | 3.6 | 4.4 | 4.0 | 3.6 | 4.4 | 3.9 | 3.5 |
| 1996 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.5 | 2.1 | 1.8 | 2.4 | 2.0 | 1.6 | 2.4 | 2.0 | 1.6 | 2.4 | 1.9 | 1.5 |
| 1997 | 4.6 | 4.6 | 4.6 | 4.6 | 4.6 | 4.3 | 3.9 | 3.6 | 4.3 | 3.8 | 3.4 | 4.3 | 3.8 | 3.4 | 4.2 | 3.8 | 3.3 |
| 1998 | 9.7 | 9.7 | 9.7 | 9.7 | 9.7 | 9.6 | 9.1 | 8.6 | 9.5 | 9.0 | 8.5 | 9.5 | 9.0 | 8.5 | 9.4 | 8.9 | 8.4 |
| 1999 | 4.6 | 4.6 | 4.6 | 4.6 | 4.6 | 4.4 | 4.0 | 3.7 | 4.3 | 3.9 | 3.5 | 4.3 | 3.9 | 3.5 | 4.3 | 3.9 | 3.4 |
| 2000 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.8 | 2.9 | 2.9 | 2.8 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 |
| 2002 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.0 | 1.7 | 1.3 | 2.0 | 1.5 | 1.1 | 2.0 | 1.5 | 1.1 | 1.9 | 1.5 | 1.0 |
| 2003 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.6 | 1.2 | 1.8 | 1.5 | 1.0 | 1.8 | 1.5 | 1.0 | 1.8 | 1.4 | 0.9 |
| 2004 | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 | 2.8 | 2.4 | 2.1 | 2.7 | 2.3 | 1.9 | 2.7 | 2.3 | 1.9 | 2.7 | 2.2 | 1.8 |
| 2005 | 4.9 | 4.9 | 4.9 | 4.9 | 4.9 | 4.6 | 4.4 | 4.0 | 4.7 | 4.2 | 3.8 | 4.7 | 4.2 | 3.8 | 4.7 | 4.2 | 3.7 |
| 2007 | 6.3 | 6.3 | 6.3 | 6.3 | 6.3 | 6.1 | 5.7 | 5.4 | 6.0 | 5.6 | 5.2 | 6.0 | 5.6 | 5.2 | 6.0 | 5.5 | 5.1 |
| 2008 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.4 | 4.0 | 3.6 | 4.3 | 3.9 | 3.5 | 4.3 | 3.9 | 3.5 | 4.2 | 3.8 | 3.3 |
| 2009 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.5 | 3.4 | 3.4 | 3.5 | 3.4 | 3.4 |
| Average | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 3.8 | 3.5 | 3.2 | 3.8 | 3.4 | 3.0 | 3.7 | 3.4 | 3.0 | 3.7 | 3.3 | 2.9 |

*Precipitation records were incomplete for years 1983, 2001, and 2006. Therefore these years were not modeled and do not appear in this series.

Table 5-6. Frozen Ground Time Period Runoff Depth from C Soils (inches)

| Year* | Native 10 Acre Site | | Developed 10 Acre Site | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Forest | Meadow | No Volume Control BMP | | | BMP that retains a runoff volume equal to one inch times the proposed impervious surfaces | | | BMP that retains the post-construction runoff volume on site for the 95th percentile storm | | | BMP sized to match the native runoff volume for the one-year 24-hour design storm | | | BMP sized to match the native runoff volume for the two-year 24-hour design storm | | |
| | | | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious |
| 1972 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.4 | 1.0 | 0.7 | 1.2 | 0.9 | 0.5 | 1.3 | 0.9 | 0.6 | 1.3 | 0.9 | 0.5 |
| 1973 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.1 | 3.7 | 3.4 | 3.9 | 3.5 | 3.2 | 4.0 | 3.6 | 3.3 | 4.0 | 3.6 | 3.2 |
| 1974 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.3 | 3.0 | 2.6 | 3.2 | 2.8 | 2.4 | 3.2 | 2.9 | 2.5 | 3.2 | 2.8 | 2.4 |
| 1975 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.4 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 |
| 1976 | 4.2 | 4.2 | 4.2 | 4.2 | 4.2 | 3.8 | 3.5 | 3.1 | 3.7 | 3.3 | 2.9 | 3.8 | 3.4 | 3.0 | 3.7 | 3.3 | 2.9 |
| 1977 | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 | 5.3 | 4.7 | 4.3 | 5.0 | 4.5 | 4.1 | 5.1 | 4.6 | 4.2 | 5.0 | 4.5 | 4.1 |
| 1978 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.5 | 1.2 | 1.6 | 1.3 | 1.0 | 1.6 | 1.4 | 1.1 | 1.6 | 1.4 | 1.0 |
| 1979 | 4.7 | 4.7 | 4.7 | 4.7 | 4.7 | 4.5 | 4.1 | 3.7 | 4.3 | 3.9 | 3.5 | 4.3 | 4.0 | 3.6 | 4.3 | 3.9 | 3.5 |
| 1980 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.7 | 2.3 | 2.0 | 2.5 | 2.2 | 1.8 | 2.6 | 2.2 | 1.9 | 2.6 | 2.2 | 1.8 |
| 1981 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 3.8 | 3.5 | 3.1 | 3.7 | 3.3 | 2.8 | 3.7 | 3.4 | 3.0 | 3.7 | 3.3 | 2.8 |
| 1982 | 4.9 | 4.9 | 4.9 | 4.9 | 4.9 | 4.4 | 3.7 | 3.0 | 4.1 | 3.3 | 2.7 | 4.2 | 3.5 | 2.8 | 4.1 | 3.3 | 2.7 |
| 1984 | 4.3 | 4.3 | 4.3 | 4.3 | 4.3 | 4.0 | 3.8 | 3.8 | 3.9 | 3.8 | 3.6 | 3.9 | 3.8 | 3.7 | 3.9 | 3.8 | 3.6 |
| 1985 | 5.2 | 5.2 | 5.2 | 5.2 | 5.2 | 5.2 | 5.1 | 4.7 | 5.2 | 4.9 | 4.5 | 5.1 | 5.0 | 4.6 | 5.1 | 4.9 | 4.5 |
| 1986 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 |
| 1987 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.0 | 1.3 | 0.8 | 1.7 | 1.0 | 0.6 | 1.8 | 1.1 | 0.7 | 1.7 | 1.0 | 0.6 |
| 1988 | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 | 3.1 | 3.3 | 3.3 | 2.9 | 3.3 | 3.3 | 3.0 | 3.3 | 3.3 | 2.9 |
| 1989 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 | 3.3 | 2.9 | 2.5 | 3.1 | 2.7 | 2.3 | 3.2 | 2.8 | 2.4 | 3.1 | 2.7 | 2.3 |
| 1990 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.0 | 4.7 | 4.3 | 4.9 | 4.4 | 4.0 | 4.9 | 4.6 | 4.2 | 4.9 | 4.5 | 4.0 |
| 1991 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.1 | 3.8 | 3.4 | 4.0 | 3.6 | 3.2 | 4.1 | 3.7 | 3.3 | 4.0 | 3.6 | 3.2 |
| 1992 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.1 | 4.7 | 4.3 | 4.9 | 4.5 | 4.1 | 5.0 | 4.6 | 4.2 | 4.9 | 4.5 | 4.1 |
| 1993 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 3.8 | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 | 3.7 | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 |
| 1994 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.7 | 2.4 | 2.9 | 2.5 | 2.2 | 2.9 | 2.6 | 2.3 | 2.9 | 2.6 | 2.2 |
| 1995 | 4.7 | 4.7 | 4.7 | 4.7 | 4.7 | 4.5 | 4.1 | 3.8 | 4.3 | 4.0 | 3.6 | 4.4 | 4.0 | 3.7 | 4.4 | 4.0 | 3.6 |
| 1996 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.5 | 2.1 | 1.8 | 2.3 | 1.9 | 1.6 | 2.4 | 2.0 | 1.6 | 2.4 | 1.9 | 1.5 |
| 1997 | 4.6 | 4.6 | 4.6 | 4.6 | 4.6 | 4.3 | 3.9 | 3.6 | 4.1 | 3.8 | 3.4 | 4.2 | 3.8 | 3.5 | 4.2 | 3.8 | 3.4 |
| 1998 | 9.7 | 9.7 | 9.7 | 9.7 | 9.7 | 9.5 | 9.0 | 8.7 | 9.3 | 8.8 | 8.5 | 9.4 | 8.9 | 8.6 | 9.3 | 8.8 | 8.5 |
| 1999 | 4.6 | 4.6 | 4.6 | 4.6 | 4.6 | 4.4 | 4.0 | 3.7 | 4.3 | 3.9 | 3.5 | 4.3 | 3.9 | 3.6 | 4.3 | 3.9 | 3.5 |
| 2000 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 |
| 2002 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.0 | 1.6 | 1.3 | 1.9 | 1.5 | 1.1 | 1.9 | 1.5 | 1.1 | 1.9 | 1.5 | 1.0 |
| 2003 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.6 | 1.2 | 1.8 | 1.4 | 1.0 | 1.8 | 1.5 | 1.1 | 1.8 | 1.4 | 1.0 |
| 2004 | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 | 2.8 | 2.4 | 2.1 | 2.6 | 2.3 | 1.9 | 2.7 | 2.3 | 2.0 | 2.7 | 2.3 | 1.9 |
| 2005 | 4.9 | 4.9 | 4.9 | 4.9 | 4.9 | 4.7 | 4.4 | 4.0 | 4.5 | 4.2 | 3.8 | 4.6 | 4.3 | 3.9 | 4.6 | 4.2 | 3.8 |
| 2007 | 6.3 | 6.3 | 6.3 | 6.3 | 6.3 | 6.1 | 5.7 | 5.4 | 5.9 | 5.5 | 5.2 | 6.0 | 5.6 | 5.2 | 5.9 | 5.5 | 5.1 |
| 2008 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.3 | 4.0 | 3.6 | 4.2 | 3.8 | 3.4 | 4.2 | 3.9 | 3.5 | 4.2 | 3.8 | 3.4 |
| 2009 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 |
| Average | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 3.8 | 3.5 | 3.2 | 3.7 | 3.3 | 3.0 | 3.7 | 3.4 | 3.1 | 3.7 | 3.3 | 3.0 |

*Precipitation records were incomplete for years 1983, 2001, and 2006. Therefore these years were not modeled and do not appear in this series.

Table 5-7. Non-frozen Ground Time Period Runoff Depth from A Soils (inches)

| Year* | Native 10 Acre Site | | Developed 10 Acre Site | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Forest | Meadow | No Volume Control BMP | | | BMP that retains a runoff volume equal to one inch times the proposed impervious surfaces | | | BMP that retains the post-construction runoff volume on site for the 95th percentile storm | | | BMP sized to match the native runoff volume for the one-year 24-hour design storm | | | BMP sized to match the native runoff volume for the two-year 24-hour design storm | | |
| | | | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious |
| 1972 | 0.0 | 0.0 | 3.3 | 8.3 | 13.6 | 0.2 | 0.2 | 0.2 | 0.1 | 0.5 | 0.4 | 0.4 | 0.3 | 0.8 | 0.6 | 0.6 | 0.5 |
| 1973 | 0.0 | 0.0 | 2.9 | 7.0 | 11.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 |
| 1974 | 0.0 | 0.0 | 2.4 | 5.8 | 9.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 1975 | 0.0 | 0.0 | 5.6 | 14.2 | 23.6 | 0.6 | 0.3 | 0.5 | 0.2 | 1.6 | 0.8 | 1.0 | 0.4 | 2.4 | 1.1 | 1.3 | 0.4 |
| 1976 | 0.0 | 0.0 | 1.7 | 4.3 | 7.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 |
| 1977 | 0.0 | 0.0 | 3.6 | 8.9 | 14.2 | 0.1 | 0.1 | 0.1 | 0.0 | 0.5 | 0.1 | 0.2 | 0.0 | 0.4 | 0.1 | 0.1 | 0.0 |
| 1978 | 0.0 | 0.1 | 3.1 | 7.6 | 12.8 | 0.7 | 0.3 | 0.3 | 0.3 | 1.0 | 0.6 | 0.9 | 0.5 | 1.5 | 0.9 | 1.0 | 0.6 |
| 1979 | 0.1 | 0.2 | 4.8 | 11.4 | 17.9 | 0.7 | 0.6 | 0.6 | 0.6 | 1.0 | 1.0 | 1.1 | 0.6 | 1.8 | 1.3 | 1.4 | 1.2 |
| 1980 | 0.0 | 0.0 | 3.1 | 7.7 | 12.1 | 0.3 | 0.2 | 0.2 | 0.1 | 0.7 | 0.4 | 0.4 | 0.4 | 0.9 | 0.6 | 0.6 | 0.4 |
| 1981 | 0.0 | 0.0 | 4.2 | 10.2 | 16.2 | 0.1 | 0.2 | 0.1 | 0.1 | 0.3 | 0.3 | 0.3 | 0.3 | 0.6 | 0.5 | 0.5 | 0.3 |
| 1982 | 0.0 | 0.0 | 3.8 | 9.2 | 14.5 | 0.1 | 0.0 | 0.0 | 0.0 | 0.2 | 0.1 | 0.1 | 0.0 | 0.4 | 0.2 | 0.2 | 0.0 |
| 1984 | 0.0 | 0.0 | 5.0 | 12.4 | 19.6 | 0.3 | 0.2 | 0.2 | 0.2 | 0.9 | 0.5 | 0.7 | 0.5 | 1.3 | 0.9 | 1.0 | 0.8 |
| 1985 | 0.0 | 0.0 | 4.1 | 10.0 | 15.9 | 0.1 | 0.0 | 0.1 | 0.0 | 0.4 | 0.1 | 0.2 | 0.0 | 0.6 | 0.1 | 0.2 | 0.0 |
| 1986 | 0.1 | 0.1 | 4.2 | 10.3 | 16.3 | 0.5 | 0.3 | 0.3 | 0.4 | 0.6 | 0.6 | 0.7 | 0.7 | 1.3 | 0.9 | 1.0 | 0.7 |
| 1987 | 1.4 | 1.8 | 4.7 | 9.1 | 13.2 | 2.3 | 2.1 | 2.2 | 2.1 | 2.9 | 2.6 | 2.7 | 2.5 | 3.5 | 3.1 | 3.1 | 2.8 |
| 1988 | 0.0 | 0.0 | 2.7 | 6.5 | 10.3 | 0.1 | 0.1 | 0.1 | 0.0 | 0.3 | 0.1 | 0.2 | 0.0 | 0.3 | 0.2 | 0.2 | 0.0 |
| 1989 | 0.0 | 0.0 | 2.7 | 6.7 | 10.6 | 0.1 | 0.1 | 0.1 | 0.0 | 0.3 | 0.1 | 0.2 | 0.0 | 0.4 | 0.1 | 0.2 | 0.0 |
| 1990 | 0.0 | 0.0 | 4.4 | 10.8 | 17.1 | 0.3 | 0.2 | 0.2 | 0.1 | 0.7 | 0.4 | 0.5 | 0.3 | 1.1 | 0.7 | 0.8 | 0.3 |
| 1991 | 0.3 | 0.5 | 6.5 | 15.3 | 23.9 | 1.6 | 1.2 | 1.1 | 1.0 | 2.5 | 2.6 | 2.2 | 1.9 | 3.6 | 3.1 | 3.2 | 2.2 |
| 1992 | 0.5 | 0.8 | 5.5 | 12.3 | 19.0 | 1.7 | 1.5 | 1.5 | 1.1 | 2.5 | 2.1 | 2.4 | 1.9 | 3.9 | 3.0 | 2.8 | 2.4 |
| 1993 | 0.0 | 0.0 | 4.8 | 11.9 | 18.8 | 0.1 | 0.1 | 0.1 | 0.0 | 0.4 | 0.1 | 0.2 | 0.1 | 0.6 | 0.2 | 0.3 | 0.1 |
| 1994 | 0.0 | 0.0 | 4.0 | 9.9 | 15.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 |
| 1995 | 0.0 | 0.0 | 4.1 | 10.1 | 16.0 | 0.2 | 0.1 | 0.1 | 0.0 | 0.2 | 0.1 | 0.2 | 0.1 | 0.4 | 0.2 | 0.2 | 0.1 |
| 1996 | 0.0 | 0.1 | 3.8 | 9.3 | 14.7 | 0.2 | 0.1 | 0.2 | 0.0 | 0.4 | 0.2 | 0.3 | 0.1 | 0.6 | 0.2 | 0.2 | 0.0 |
| 1997 | 0.5 | 0.8 | 5.9 | 13.5 | 20.9 | 1.7 | 1.7 | 1.6 | 1.5 | 3.1 | 2.6 | 2.9 | 2.2 | 4.5 | 3.5 | 3.7 | 3.0 |
| 1998 | 0.2 | 0.4 | 5.5 | 13.1 | 20.5 | 1.3 | 1.4 | 1.2 | 1.0 | 2.5 | 2.2 | 2.3 | 1.9 | 3.8 | 3.2 | 2.9 | 2.5 |
| 1999 | 0.0 | 0.0 | 4.5 | 10.9 | 17.3 | 0.1 | 0.0 | 0.1 | 0.0 | 0.2 | 0.1 | 0.2 | 0.1 | 0.4 | 0.2 | 0.2 | 0.0 |
| 2000 | 0.2 | 0.3 | 4.8 | 11.2 | 17.6 | 0.9 | 0.8 | 0.8 | 0.8 | 1.7 | 1.5 | 1.5 | 1.3 | 2.7 | 2.0 | 2.0 | 1.5 |
| 2002 | 0.0 | 0.0 | 4.5 | 10.9 | 17.3 | 0.4 | 0.3 | 0.3 | 0.2 | 1.0 | 0.6 | 0.7 | 0.5 | 1.4 | 0.9 | 1.0 | 0.6 |
| 2003 | 0.2 | 0.3 | 3.9 | 9.2 | 14.3 | 1.0 | 1.3 | 1.2 | 1.2 | 2.1 | 2.0 | 2.0 | 1.9 | 3.1 | 2.9 | 2.9 | 3.0 |
| 2004 | 0.0 | 0.0 | 3.5 | 8.6 | 13.6 | 0.2 | 0.1 | 0.1 | 0.0 | 0.4 | 0.1 | 0.2 | 0.0 | 0.7 | 0.2 | 0.3 | 0.0 |
| 2005 | 0.0 | 0.0 | 4.2 | 10.2 | 16.2 | 0.7 | 0.5 | 0.5 | 0.5 | 1.4 | 1.2 | 1.2 | 1.1 | 2.4 | 2.0 | 2.0 | 1.8 |
| 2007 | 0.0 | 0.0 | 4.4 | 10.9 | 17.2 | 0.5 | 0.4 | 0.4 | 0.5 | 1.2 | 0.9 | 0.9 | 0.8 | 1.7 | 1.4 | 1.4 | 1.0 |
| 2008 | 0.0 | 0.0 | 2.6 | 6.3 | 10.0 | 0.0 | 0.1 | 0.1 | 0.0 | 0.2 | 0.1 | 0.1 | 0.0 | 0.2 | 0.1 | 0.2 | 0.0 |
| 2009 | 0.0 | 0.0 | 3.6 | 9.0 | 14.2 | 0.1 | 0.0 | 0.1 | 0.0 | 0.3 | 0.0 | 0.1 | 0.0 | 0.6 | 0.0 | 0.1 | 0.0 |
| Average | 0.1 | 0.2 | 4.1 | 9.8 | 15.5 | 0.5 | 0.4 | 0.4 | 0.4 | 0.9 | 0.7 | 0.8 | 0.6 | 1.4 | 1.0 | 1.0 | 0.7 |

*Precipitation records were incomplete for years 1983, 2001, and 2006. Therefore these years were not modeled and do not appear in this series.

Table 5-8. Non-frozen Ground Time Period Runoff Depth from B Soils (inches)

| Year* | Native 10 Acre Site | | Developed 10 Acre Site | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Forest | Meadow | No Volume Control BMP | | | BMP that retains a runoff volume equal to one inch times the proposed impervious surfaces | | | BMP that retains the post-construction runoff volume on site for the 95th percentile storm | | | BMP sized to match the native runoff volume for the one-year 24-hour design storm | | | BMP sized to match the native runoff volume for the two-year 24-hour design storm | | |
| | | | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious |
| 1972 | 0.5 | 0.7 | 4.2 | 9.0 | 13.8 | 0.8 | 0.9 | 1.0 | 0.7 | 0.8 | 0.8 | 0.7 | 0.8 | 0.8 | 0.6 | 0.7 | 0.6 |
| 1973 | 0.0 | 0.0 | 2.9 | 7.1 | 11.1 | 0.0 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 1974 | 0.0 | 0.0 | 2.4 | 5.8 | 9.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 1975 | 0.1 | 0.2 | 6.4 | 15.2 | 23.8 | 1.6 | 2.3 | 3.1 | 1.0 | 1.3 | 1.5 | 1.0 | 1.3 | 1.5 | 0.7 | 0.7 | 0.7 |
| 1976 | 0.0 | 0.0 | 1.9 | 4.6 | 7.2 | 0.2 | 0.1 | 0.1 | 0.2 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 |
| 1977 | 0.2 | 0.3 | 4.0 | 9.2 | 14.3 | 0.4 | 0.5 | 0.6 | 0.4 | 0.2 | 0.3 | 0.4 | 0.5 | 0.4 | 0.6 | 0.3 | 0.1 |
| 1978 | 0.7 | 0.9 | 4.3 | 8.8 | 13.1 | 1.3 | 2.1 | 2.5 | 1.1 | 1.6 | 1.9 | 0.9 | 1.6 | 1.9 | 1.0 | 1.4 | 1.3 |
| 1979 | 1.0 | 1.3 | 5.8 | 12.1 | 18.2 | 2.8 | 2.7 | 2.2 | 2.0 | 1.9 | 1.6 | 1.6 | 2.0 | 1.7 | 2.2 | 1.7 | 1.4 |
| 1980 | 0.2 | 0.4 | 3.6 | 8.0 | 12.3 | 1.1 | 1.3 | 1.3 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.6 |
| 1981 | 0.0 | 0.1 | 4.4 | 10.4 | 16.3 | 0.6 | 0.8 | 1.0 | 0.4 | 0.5 | 0.5 | 0.4 | 0.4 | 0.6 | 0.2 | 0.4 | 0.4 |
| 1982 | 0.1 | 0.1 | 3.9 | 9.3 | 14.6 | 0.3 | 0.4 | 0.4 | 0.3 | 0.3 | 0.2 | 0.3 | 0.3 | 0.3 | 0.3 | 0.2 | 0.1 |
| 1984 | 0.4 | 0.6 | 5.7 | 12.9 | 19.9 | 1.1 | 1.4 | 1.6 | 0.9 | 1.1 | 1.2 | 0.8 | 1.2 | 1.2 | 0.6 | 0.7 | 0.9 |
| 1985 | 0.0 | 0.0 | 4.1 | 10.0 | 15.9 | 0.2 | 0.4 | 0.6 | 0.0 | 0.1 | 0.2 | 0.0 | 0.1 | 0.2 | 0.0 | 0.0 | 0.0 |
| 1986 | 0.6 | 0.7 | 4.6 | 10.6 | 16.4 | 0.8 | 1.1 | 1.5 | 0.7 | 1.1 | 1.2 | 0.8 | 1.1 | 1.2 | 0.8 | 0.9 | 1.0 |
| 1987 | 2.9 | 3.3 | 6.1 | 9.9 | 13.6 | 3.1 | 3.6 | 3.7 | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 | 3.1 | 3.1 | 3.1 |
| 1988 | 0.1 | 0.1 | 2.8 | 6.6 | 10.4 | 0.3 | 0.5 | 0.5 | 0.4 | 0.4 | 0.3 | 0.4 | 0.4 | 0.3 | 0.4 | 0.3 | 0.1 |
| 1989 | 0.4 | 0.6 | 2.9 | 6.8 | 10.7 | 0.7 | 0.7 | 0.5 | 0.5 | 0.4 | 0.2 | 0.5 | 0.5 | 0.2 | 0.6 | 0.2 | 0.1 |
| 1990 | 0.0 | 0.0 | 4.5 | 10.9 | 17.2 | 0.7 | 1.1 | 1.4 | 0.6 | 0.8 | 0.9 | 0.5 | 0.8 | 0.9 | 0.4 | 0.6 | 0.6 |
| 1991 | 2.3 | 3.0 | 8.8 | 16.9 | 24.6 | 3.5 | 4.0 | 4.6 | 3.2 | 3.8 | 4.0 | 3.2 | 3.8 | 4.1 | 3.4 | 3.5 | 3.6 |
| 1992 | 2.7 | 3.2 | 7.5 | 13.6 | 19.5 | 4.0 | 4.8 | 4.8 | 3.9 | 4.0 | 3.7 | 3.8 | 3.9 | 3.5 | 3.7 | 3.6 | 3.0 |
| 1993 | 0.0 | 0.1 | 5.0 | 12.1 | 18.9 | 0.6 | 0.9 | 1.0 | 0.6 | 0.4 | 0.4 | 0.5 | 0.4 | 0.5 | 0.3 | 0.2 | 0.1 |
| 1994 | 0.0 | 0.0 | 4.1 | 9.9 | 15.7 | 0.0 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 1995 | 0.0 | 0.1 | 4.3 | 10.2 | 16.1 | 0.1 | 0.3 | 0.4 | 0.1 | 0.2 | 0.2 | 0.1 | 0.2 | 0.2 | 0.1 | 0.1 | 0.1 |
| 1996 | 0.3 | 0.5 | 4.3 | 9.6 | 14.8 | 0.6 | 0.9 | 0.7 | 0.7 | 0.5 | 0.3 | 0.7 | 0.5 | 0.3 | 0.6 | 0.3 | 0.1 |
| 1997 | 2.2 | 2.8 | 7.8 | 14.7 | 21.4 | 3.6 | 4.2 | 4.8 | 3.7 | 3.5 | 3.9 | 3.1 | 3.5 | 3.9 | 3.0 | 3.5 | 3.0 |
| 1998 | 2.6 | 3.4 | 8.0 | 14.8 | 21.2 | 4.9 | 4.7 | 4.4 | 4.7 | 4.4 | 4.1 | 4.2 | 4.2 | 4.2 | 3.9 | 4.0 | 3.6 |
| 1999 | 0.2 | 0.3 | 4.7 | 11.1 | 17.4 | 0.5 | 0.7 | 0.4 | 0.4 | 0.2 | 0.2 | 0.4 | 0.2 | 0.2 | 0.1 | 0.1 | 0.0 |
| 2000 | 1.8 | 2.4 | 6.6 | 12.4 | 18.1 | 2.1 | 2.5 | 3.5 | 3.3 | 3.0 | 2.7 | 3.1 | 2.7 | 2.7 | 2.6 | 2.6 | 2.3 |
| 2002 | 0.8 | 1.0 | 5.5 | 11.6 | 17.6 | 1.1 | 1.7 | 2.1 | 1.2 | 1.5 | 1.3 | 1.1 | 1.5 | 1.4 | 1.1 | 1.0 | 1.0 |
| 2003 | 2.2 | 2.5 | 5.6 | 10.3 | 14.7 | 2.9 | 3.3 | 3.7 | 2.8 | 3.3 | 3.4 | 2.8 | 3.3 | 3.5 | 2.9 | 3.2 | 3.3 |
| 2004 | 0.0 | 0.0 | 3.5 | 8.6 | 13.6 | 0.3 | 0.5 | 0.8 | 0.1 | 0.2 | 0.3 | 0.1 | 0.3 | 0.4 | 0.0 | 0.1 | 0.1 |
| 2005 | 0.7 | 1.0 | 5.1 | 10.9 | 16.6 | 1.9 | 2.3 | 2.7 | 1.6 | 2.0 | 2.4 | 1.6 | 2.0 | 2.4 | 1.5 | 1.8 | 2.2 |
| 2007 | 0.6 | 1.0 | 5.6 | 11.7 | 17.6 | 1.7 | 2.1 | 2.4 | 1.8 | 1.7 | 2.0 | 1.7 | 1.9 | 2.0 | 1.3 | 1.6 | 1.5 |
| 2008 | 0.1 | 0.1 | 2.7 | 6.4 | 10.0 | 0.3 | 0.4 | 0.4 | 0.4 | 0.2 | 0.2 | 0.4 | 0.2 | 0.2 | 0.3 | 0.2 | 0.1 |
| 2009 | 0.2 | 0.4 | 4.2 | 9.4 | 14.5 | 0.6 | 0.8 | 0.9 | 0.5 | 0.4 | 0.2 | 0.4 | 0.4 | 0.2 | 0.3 | 0.2 | 0.0 |
| Average | 0.7 | 0.9 | 4.8 | 10.3 | 15.7 | 1.3 | 1.6 | 1.7 | 1.2 | 1.3 | 1.3 | 1.1 | 1.3 | 1.3 | 1.1 | 1.1 | 1.0 |

*Precipitation records were incomplete for years 1983, 2001, and 2006. Therefore these years were not modeled and do not appear in this series.

Table 5-9. Non-frozen Ground Time Period Runoff Depth from C Soils (inches)

| Year* | Native 10 Acre Site | | Developed 10 Acre Site | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Forest | Meadow | No Volume Control BMP | | | BMP that retains a runoff volume equal to one inch times the proposed impervious surfaces | | | BMP that retains the post-construction runoff volume on site for the 95th percentile storm | | | BMP sized to match the native runoff volume for the one-year 24-hour design storm | | | BMP sized to match the native runoff volume for the two-year 24-hour design storm | | |
| | | | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious | 20% Impervious | 50% Impervious | 80% Impervious |
| 1972 | 0.8 | 0.9 | 4.3 | 9.2 | 13.8 | 0.9 | 1.0 | 1.0 | 0.8 | 0.8 | 0.8 | 0.8 | 0.9 | 0.9 | 0.8 | 0.8 | 0.8 |
| 1973 | 0.0 | 0.0 | 2.9 | 7.1 | 11.2 | 0.1 | 0.2 | 0.4 | 0.0 | 0.0 | 0.1 | 0.0 | 0.1 | 0.2 | 0.0 | 0.0 | 0.1 |
| 1974 | 0.0 | 0.0 | 2.4 | 5.8 | 9.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 1975 | 0.2 | 0.4 | 6.8 | 15.4 | 23.9 | 2.2 | 3.5 | 4.2 | 0.9 | 1.7 | 2.5 | 1.4 | 2.3 | 3.1 | 1.2 | 1.8 | 2.4 |
| 1976 | 0.0 | 0.0 | 1.9 | 4.6 | 7.2 | 0.3 | 0.2 | 0.1 | 0.1 | 0.0 | 0.0 | 0.2 | 0.1 | 0.0 | 0.1 | 0.0 | 0.0 |
| 1977 | 0.3 | 0.4 | 4.1 | 9.3 | 14.3 | 0.6 | 0.7 | 0.6 | 0.4 | 0.3 | 0.3 | 0.6 | 0.5 | 0.5 | 0.4 | 0.4 | 0.3 |
| 1978 | 1.1 | 1.4 | 4.7 | 9.1 | 13.2 | 2.0 | 2.6 | 3.3 | 1.5 | 2.1 | 2.6 | 1.8 | 2.3 | 2.8 | 1.8 | 2.1 | 2.5 |
| 1979 | 1.2 | 1.6 | 6.1 | 12.3 | 18.3 | 2.3 | 2.3 | 2.0 | 1.8 | 1.7 | 1.5 | 1.9 | 2.0 | 1.7 | 1.8 | 1.7 | 1.6 |
| 1980 | 0.4 | 0.6 | 3.9 | 8.2 | 12.4 | 1.4 | 1.7 | 1.9 | 0.9 | 1.1 | 1.2 | 1.3 | 1.3 | 1.4 | 1.2 | 1.2 | 1.1 |
| 1981 | 0.2 | 0.3 | 4.8 | 10.7 | 16.4 | 1.0 | 1.2 | 1.3 | 0.5 | 0.5 | 0.6 | 0.7 | 0.9 | 0.9 | 0.5 | 0.6 | 0.6 |
| 1982 | 0.2 | 0.3 | 4.0 | 9.4 | 14.6 | 0.5 | 0.5 | 0.4 | 0.3 | 0.3 | 0.2 | 0.4 | 0.4 | 0.4 | 0.3 | 0.3 | 0.2 |
| 1984 | 0.7 | 1.0 | 6.2 | 13.2 | 20.0 | 1.4 | 1.9 | 2.1 | 0.9 | 1.1 | 1.2 | 1.4 | 1.3 | 1.4 | 1.0 | 1.1 | 1.2 |
| 1985 | 0.0 | 0.0 | 4.1 | 10.0 | 15.9 | 0.3 | 0.6 | 0.9 | 0.0 | 0.1 | 0.4 | 0.0 | 0.3 | 0.6 | 0.0 | 0.2 | 0.3 |
| 1986 | 0.9 | 1.0 | 4.8 | 10.7 | 16.4 | 1.3 | 1.6 | 1.8 | 1.2 | 1.4 | 1.5 | 1.4 | 1.4 | 1.7 | 1.1 | 1.4 | 1.5 |
| 1987 | 3.3 | 3.8 | 6.5 | 10.2 | 13.7 | 3.5 | 3.8 | 3.8 | 3.3 | 3.4 | 3.4 | 3.4 | 3.5 | 3.6 | 3.3 | 3.4 | 3.4 |
| 1988 | 0.1 | 0.2 | 2.9 | 6.7 | 10.4 | 0.5 | 0.6 | 0.5 | 0.4 | 0.4 | 0.3 | 0.6 | 0.4 | 0.4 | 0.4 | 0.4 | 0.3 |
| 1989 | 0.5 | 0.7 | 3.0 | 6.9 | 10.7 | 0.9 | 0.9 | 0.6 | 0.6 | 0.4 | 0.2 | 0.9 | 0.6 | 0.4 | 0.7 | 0.4 | 0.2 |
| 1990 | 0.1 | 0.2 | 4.8 | 11.1 | 17.2 | 0.9 | 1.4 | 1.7 | 0.6 | 0.9 | 1.1 | 0.7 | 1.1 | 1.4 | 0.7 | 0.9 | 1.1 |
| 1991 | 3.1 | 3.7 | 9.5 | 17.3 | 24.8 | 4.4 | 4.8 | 5.0 | 3.8 | 4.1 | 4.3 | 4.0 | 4.3 | 4.5 | 4.1 | 4.3 | 4.3 |
| 1992 | 3.2 | 3.7 | 8.0 | 13.9 | 19.6 | 5.0 | 5.3 | 5.6 | 4.1 | 4.2 | 4.1 | 4.5 | 4.5 | 4.6 | 4.2 | 4.2 | 3.9 |
| 1993 | 0.2 | 0.3 | 5.4 | 12.3 | 19.0 | 1.4 | 1.4 | 1.5 | 0.6 | 0.6 | 0.8 | 0.8 | 0.9 | 1.1 | 0.7 | 0.7 | 0.8 |
| 1994 | 0.0 | 0.0 | 4.1 | 10.0 | 15.7 | 0.1 | 0.3 | 0.6 | 0.0 | 0.0 | 0.1 | 0.0 | 0.1 | 0.2 | 0.0 | 0.0 | 0.1 |
| 1995 | 0.1 | 0.2 | 4.4 | 10.3 | 16.1 | 0.5 | 0.5 | 0.7 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 | 0.1 | 0.2 | 0.2 |
| 1996 | 0.5 | 0.7 | 4.5 | 9.8 | 14.9 | 1.3 | 1.2 | 0.9 | 0.6 | 0.5 | 0.4 | 0.8 | 0.7 | 0.6 | 0.7 | 0.6 | 0.4 |
| 1997 | 2.7 | 3.4 | 8.3 | 15.1 | 21.6 | 4.7 | 5.7 | 5.9 | 4.0 | 4.2 | 4.2 | 4.4 | 4.8 | 4.9 | 4.3 | 4.2 | 4.1 |
| 1998 | 3.4 | 4.4 | 9.0 | 15.4 | 21.5 | 5.7 | 5.9 | 5.6 | 4.9 | 4.7 | 4.4 | 5.0 | 5.0 | 5.0 | 5.2 | 4.7 | 4.3 |
| 1999 | 0.2 | 0.4 | 4.9 | 11.3 | 17.5 | 0.8 | 0.8 | 0.8 | 0.2 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.2 | 0.2 | 0.3 |
| 2000 | 2.3 | 2.9 | 7.0 | 12.7 | 18.2 | 3.1 | 3.4 | 3.4 | 3.0 | 2.9 | 3.0 | 2.9 | 3.2 | 3.3 | 2.9 | 3.0 | 2.9 |
| 2002 | 1.1 | 1.5 | 5.9 | 12.0 | 17.8 | 2.0 | 2.3 | 2.4 | 1.3 | 1.3 | 1.4 | 1.5 | 1.7 | 1.7 | 1.5 | 1.4 | 1.4 |
| 2003 | 2.6 | 2.9 | 6.1 | 10.5 | 14.9 | 3.5 | 3.8 | 4.1 | 3.2 | 3.3 | 3.5 | 3.1 | 3.4 | 3.7 | 3.1 | 3.3 | 3.5 |
| 2004 | 0.0 | 0.1 | 3.8 | 8.8 | 13.7 | 0.8 | 0.9 | 1.1 | 0.2 | 0.4 | 0.5 | 0.3 | 0.5 | 0.7 | 0.2 | 0.3 | 0.5 |
| 2005 | 1.4 | 1.7 | 5.6 | 11.3 | 16.7 | 2.7 | 2.7 | 2.9 | 1.9 | 2.1 | 2.5 | 2.1 | 2.2 | 2.5 | 1.9 | 2.1 | 2.4 |
| 2007 | 1.0 | 1.6 | 6.2 | 12.1 | 17.8 | 2.4 | 2.8 | 3.0 | 1.9 | 2.0 | 2.3 | 2.3 | 2.4 | 2.7 | 2.0 | 2.1 | 2.3 |
| 2008 | 0.2 | 0.3 | 2.9 | 6.5 | 10.1 | 0.6 | 0.3 | 0.3 | 0.4 | 0.3 | 0.1 | 0.3 | 0.4 | 0.2 | 0.3 | 0.3 | 0.2 |
| 2009 | 0.5 | 0.8 | 4.5 | 9.6 | 14.6 | 1.0 | 1.0 | 1.0 | 0.4 | 0.4 | 0.3 | 0.6 | 0.6 | 0.6 | 0.5 | 0.4 | 0.3 |
| Average | 0.9 | 1.2 | 5.1 | 10.5 | 15.8 | 1.7 | 1.9 | 2.0 | 1.3 | 1.4 | 1.4 | 1.5 | 1.6 | 1.7 | 1.4 | 1.4 | 1.4 |

*Precipitation records were incomplete for years 1983, 2001, and 2006. Therefore these years were not modeled and do not appear in this series.

Table 5-11. Summary of total phoshorus and total suspended sediment removal efficiencies from volume control and rate control BMPs for four performance goal alternatives

| **Performance Goal used to Size Bioretention BMP** | Pollutant Removal Efficiency from Volume Control BMPs[1] | | | | Cumulative Pollutant Removal Efficiency (Volume Control BMPs[1]+ Rate Control BMPs[2]) | | | |
|---|---|---|---|---|---|---|---|---|
| | **B Soils** | | **C Soils** | | **B Soils** | | **C Soils** | |
| | **TP Removal[3] (%)** | **TSS Removal[3] (%)** | **TP Removal[3] (%)** | **TSS Removal[3] (%)** | **TP Removal[3] (%)** | **TSS Removal[3] (%)** | **TP Removal[3] (%)** | **TSS Removal[3] (%)** |
| **1-inch Off Impervious Surfaces** | | | | | | | | |
| 20% Impervious Site | 89 | 95 | 81 | 91 | 90 | 97 | 83 | 93 |
| 50% Impervious Site | 95 | 98 | 92 | 97 | 96 | 99 | 93 | 98 |
| 80% Impervious Site | 96 | 99 | 95 | 99 | 97 | 99 | 95 | 99 |
| **95th Percentile Storm** | | | | | | | | |
| 20% Impervious Site | 91 | 96 | 88 | 94 | 92 | 97 | 88 | 95 |
| 50% Impervious Site | 97 | 99 | 95 | 98 | 97 | 99 | 95 | 98 |
| 80% Impervious Site | 97 | 99 | 97 | 99 | 98 | 99 | 97 | 99 |
| **Match One Year Storm** | | | | | | | | |
| 20% Impervious Site | 91 | 96 | 86 | 93 | 92 | 97 | 86 | 94 |
| 50% Impervious Site | 97 | 99 | 94 | 98 | 97 | 99 | 94 | 98 |
| 80% Impervious Site | 97 | 99 | 96 | 99 | 98 | 99 | 96 | 99 |
| **Match Two Year Storm** | | | | | | | | |
| 20% Impervious Site | 93 | 96 | 87 | 93 | 93 | 97 | 87 | 94 |
| 50% Impervious Site | 97 | 99 | 95 | 98 | 97 | 99 | 95 | 98 |
| 80% Impervious Site | 98 | 99 | 97 | 99 | 98 | 100 | 97 | 99 |

[1] Volume control BMPs modeled as bioretention basins

# Figures

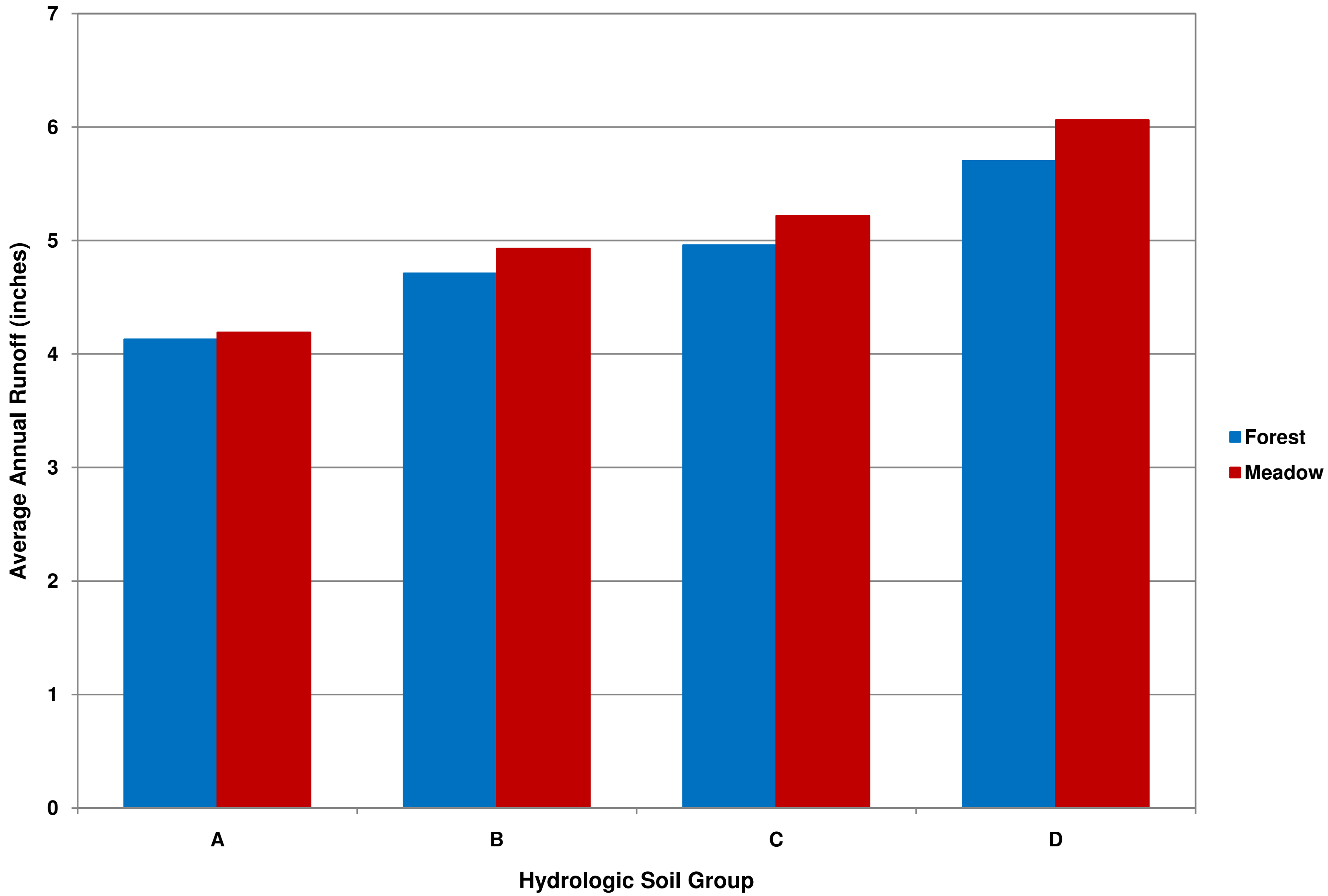


**Figure 5-1**
**Native Conditions - Twin Cities Region**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**

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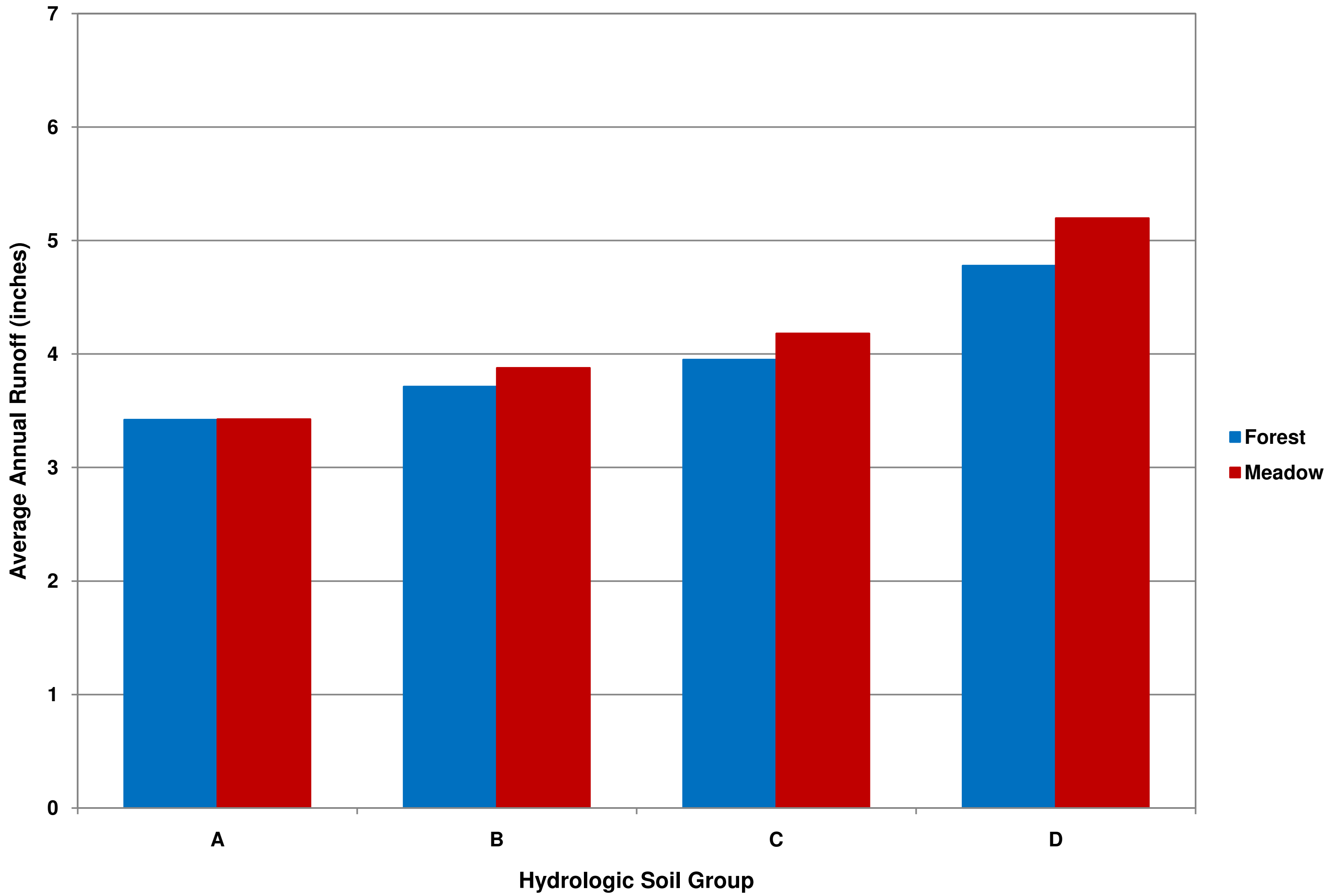


**Figure 5-2**
**Native Conditions - North Central Region**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**

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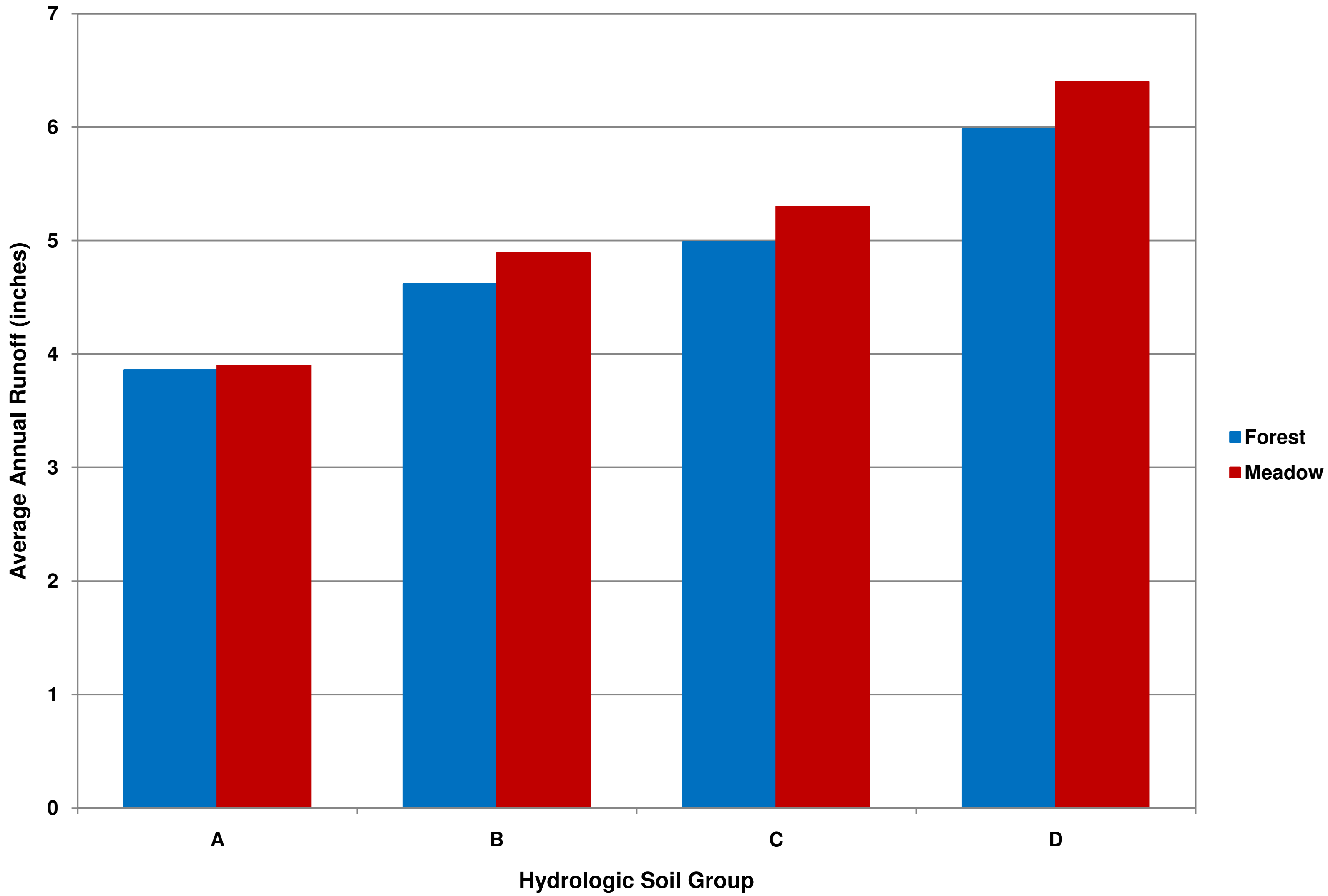


**Figure 5-3**
**Native Conditions - Southeast Region**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**

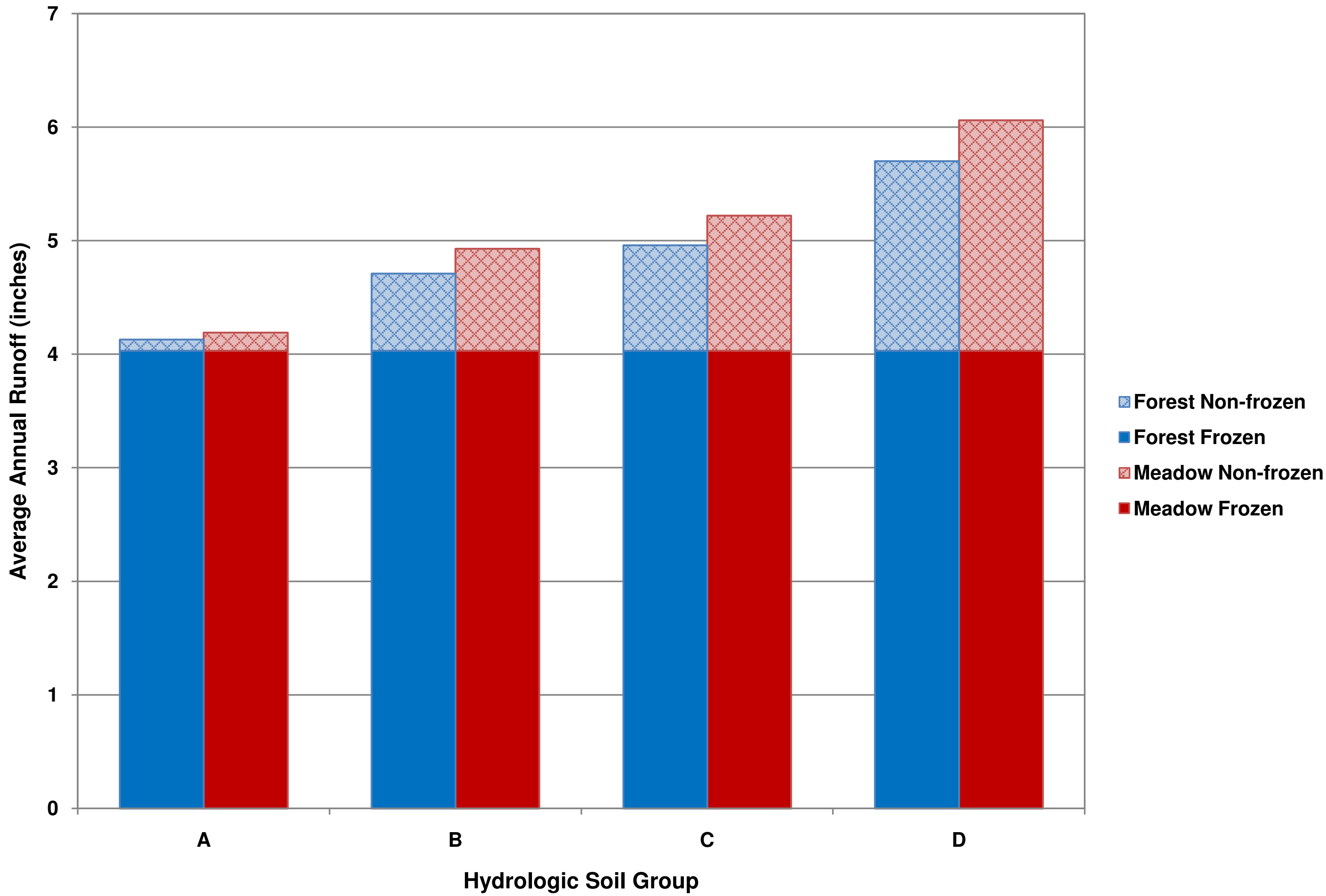


**Figure 5-4**
**Native Conditions - Twin Cities Region**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site During Frozen and**
**Non-frozen Ground Time Periods**

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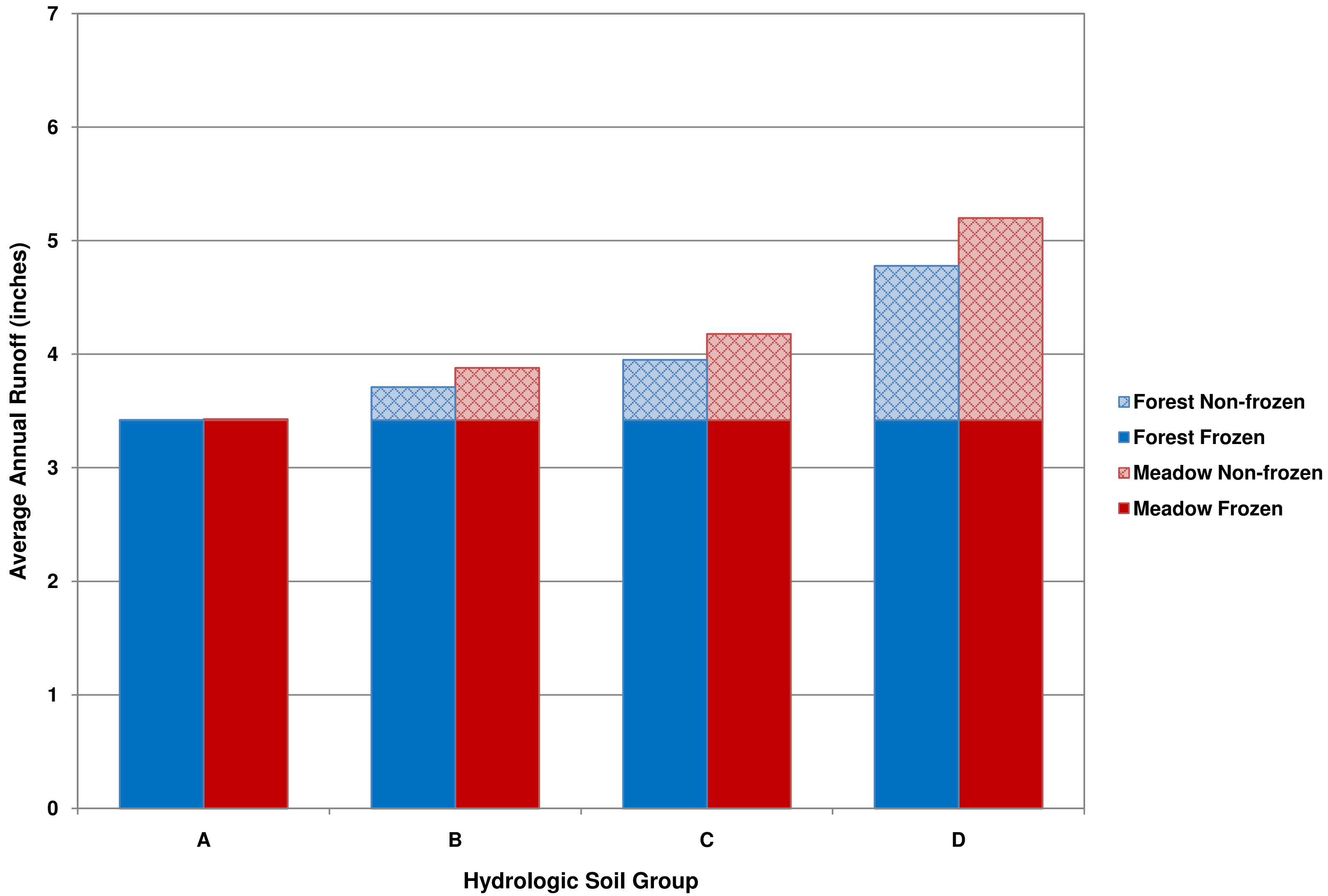


**Figure 5-5**
**Native Conditions - North Central Region**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site During Frozen and**
**Non-frozen Ground Time Periods**

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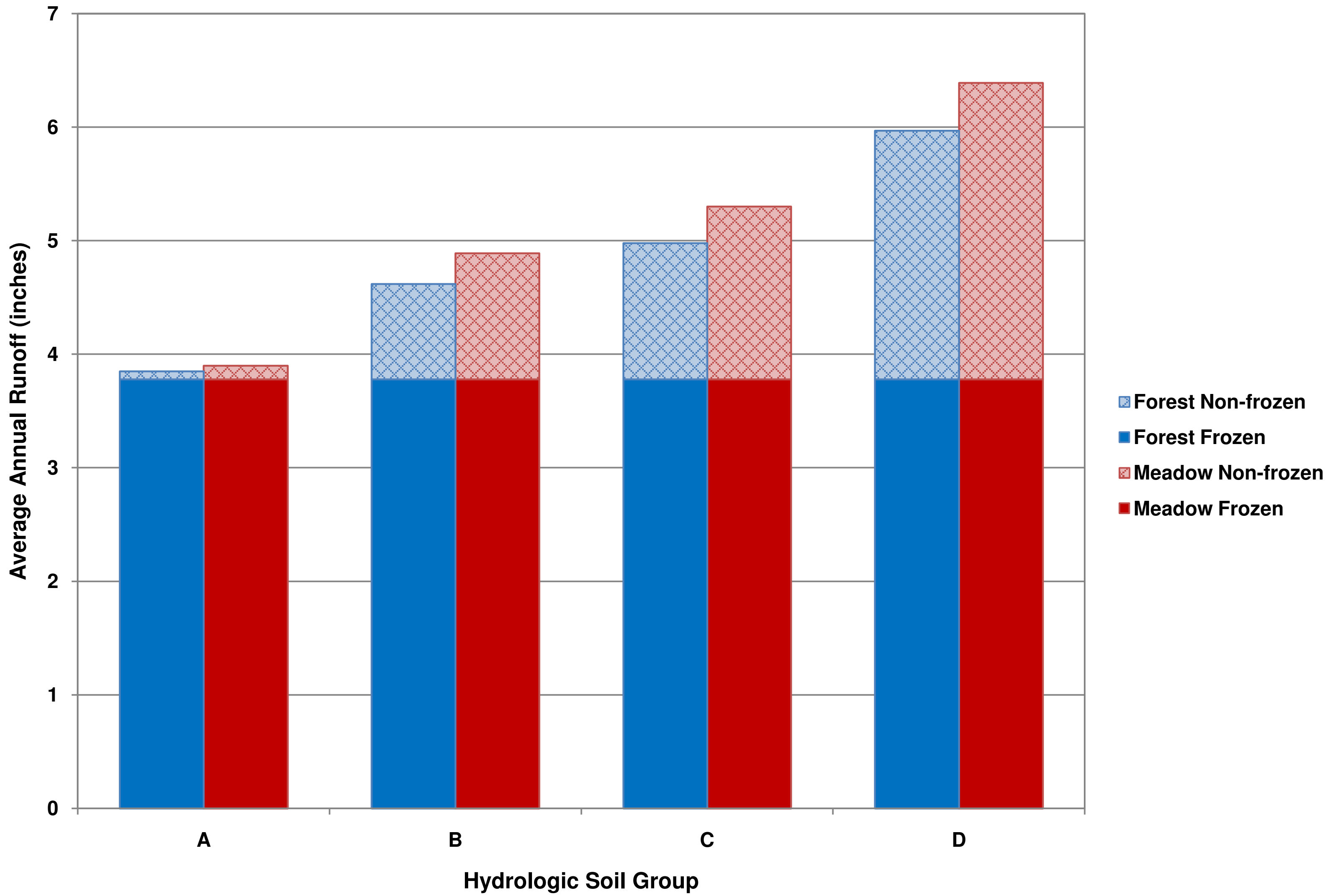
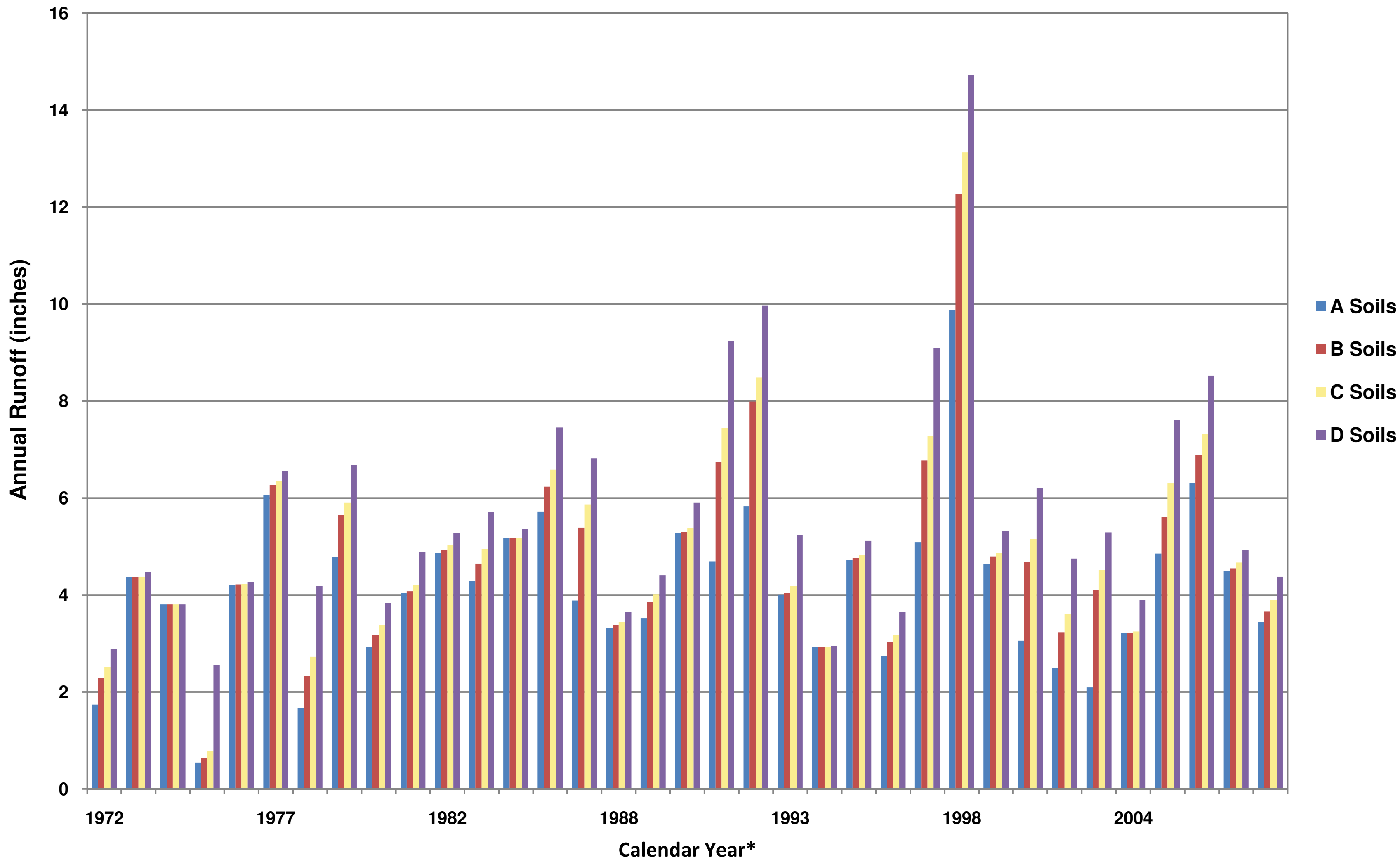



**Figure 5-6**
**Native Conditions - Southeast Region**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site During Frozen and**
**Non-frozen Ground Time Periods**




*Precipitation records were incomplete for years 1983, 2001, and 2006.
Therefore, these years were not modeled and do not appear in this series.

**Figure 5-7**
**Native Conditions (Forest) - Twin Cities Region**
**Annual Stormwater Runoff Depth**
**Over 10-Acre Site**

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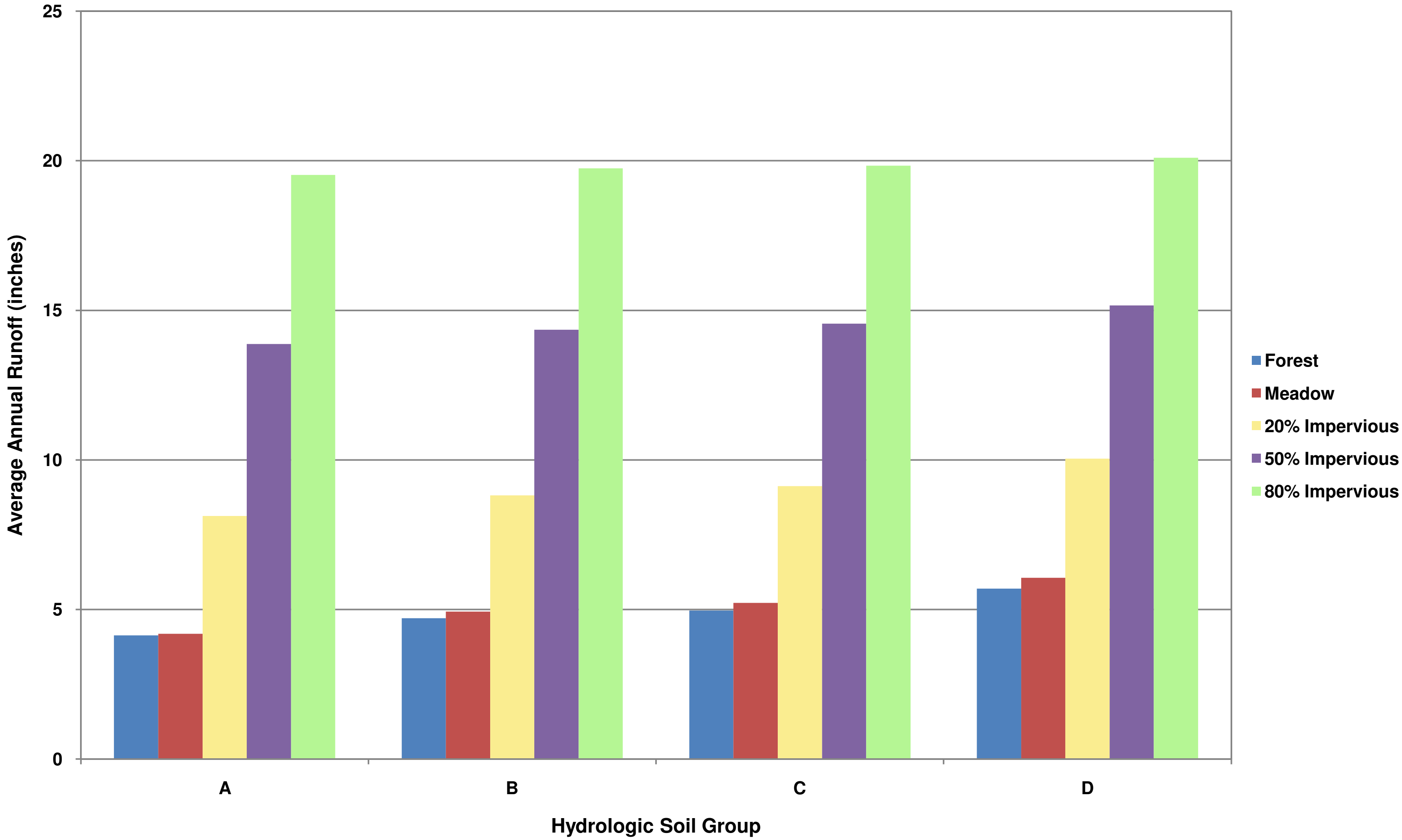


**Figure 5-8**
**Native Conditions and**
**Developed Conditions with No BMPs**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**Twin Cities Region**

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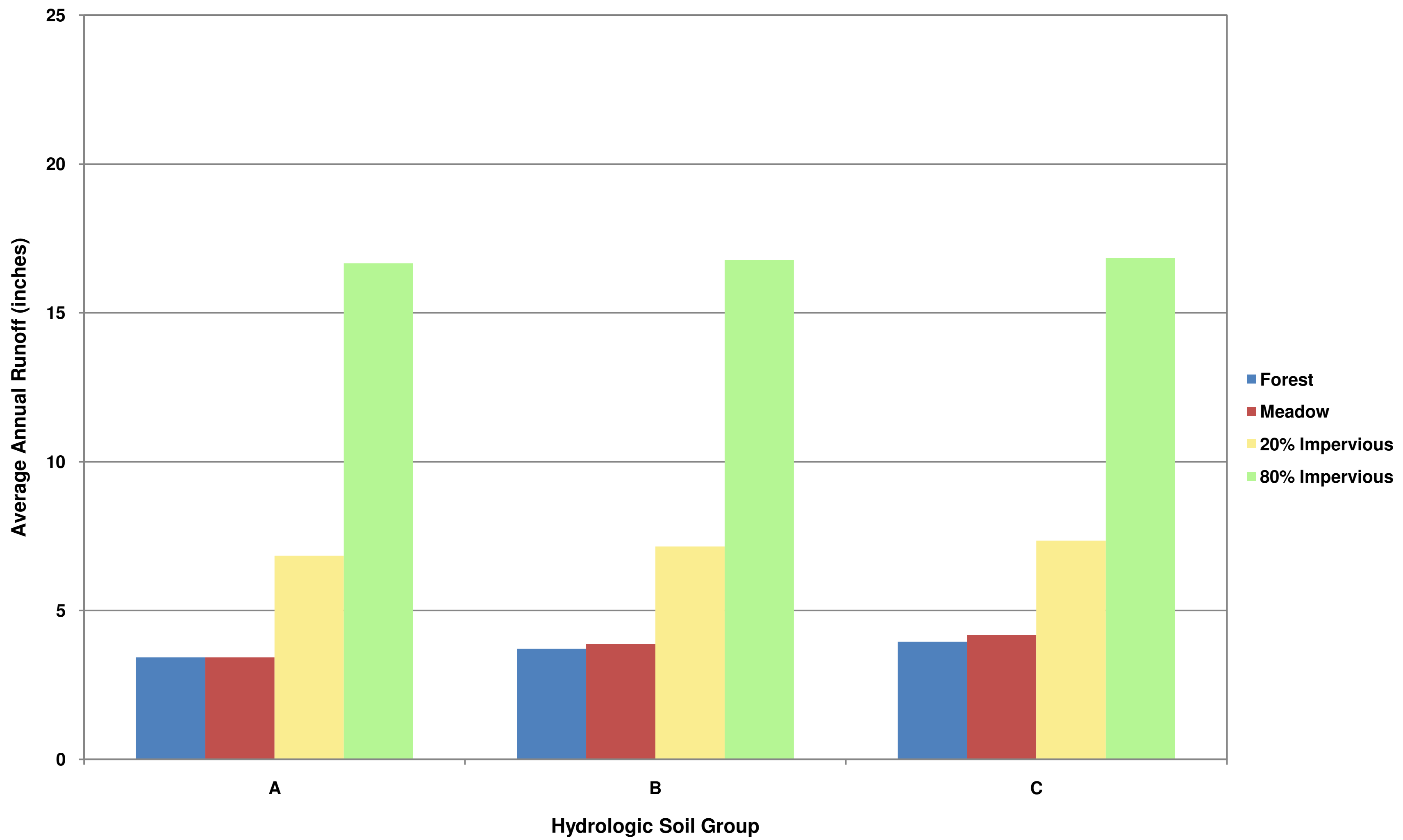


**Figure 5-9**
**Native Conditions and**
**Developed Conditions with No BMPs**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**North Central Region**

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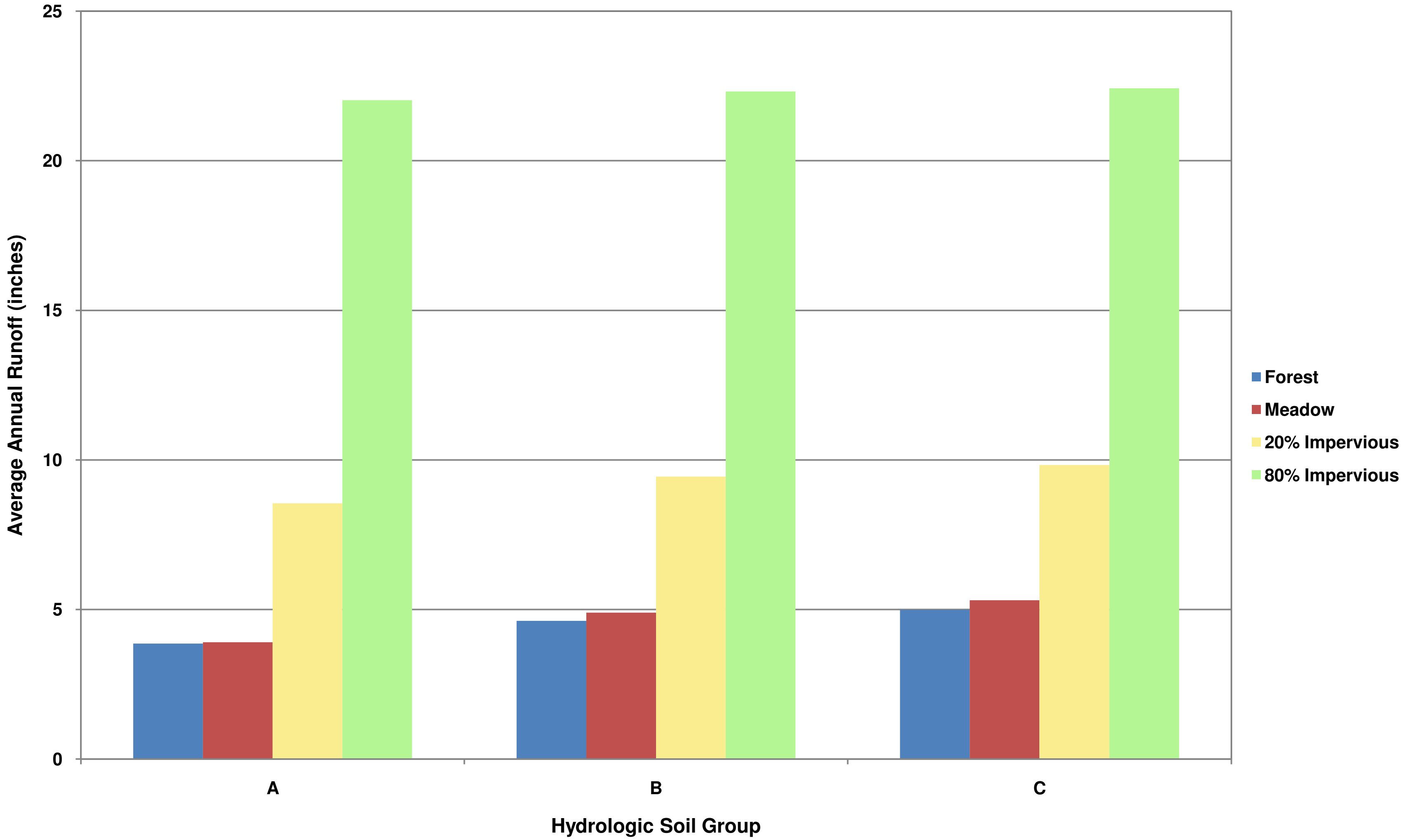


**Figure 5-10**
**Native Conditions and**
**Developed Conditions with No BMPs**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**Southeast Region**

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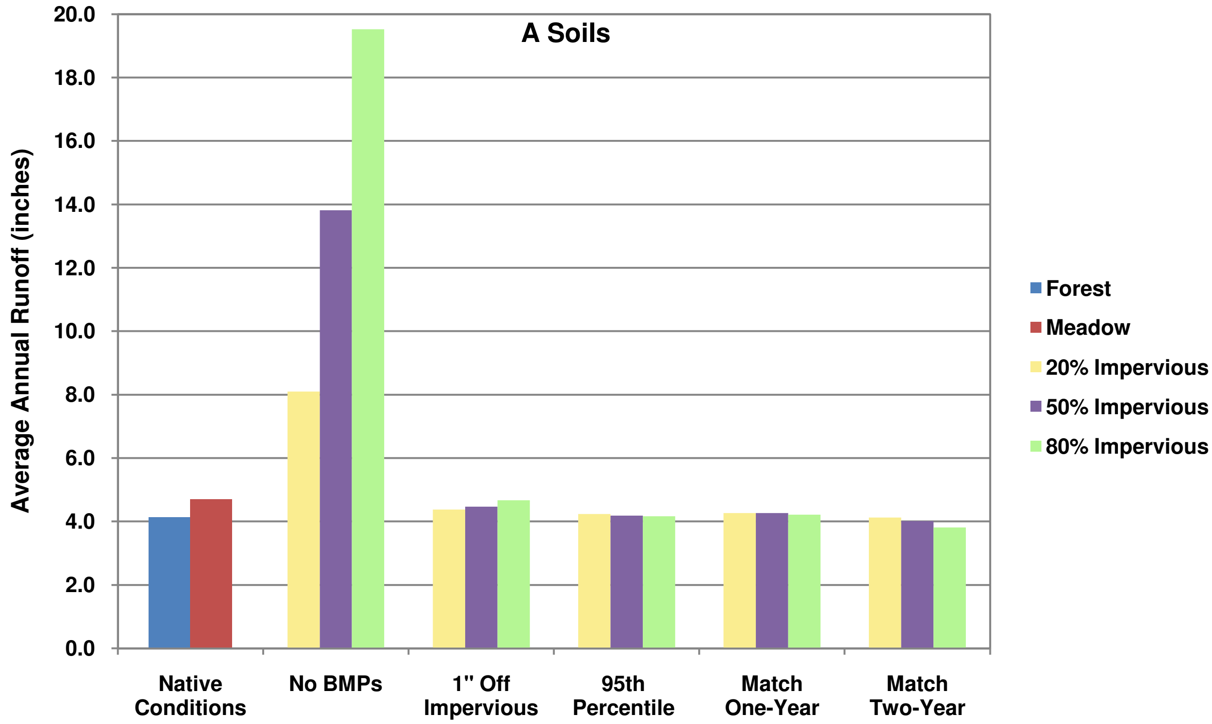


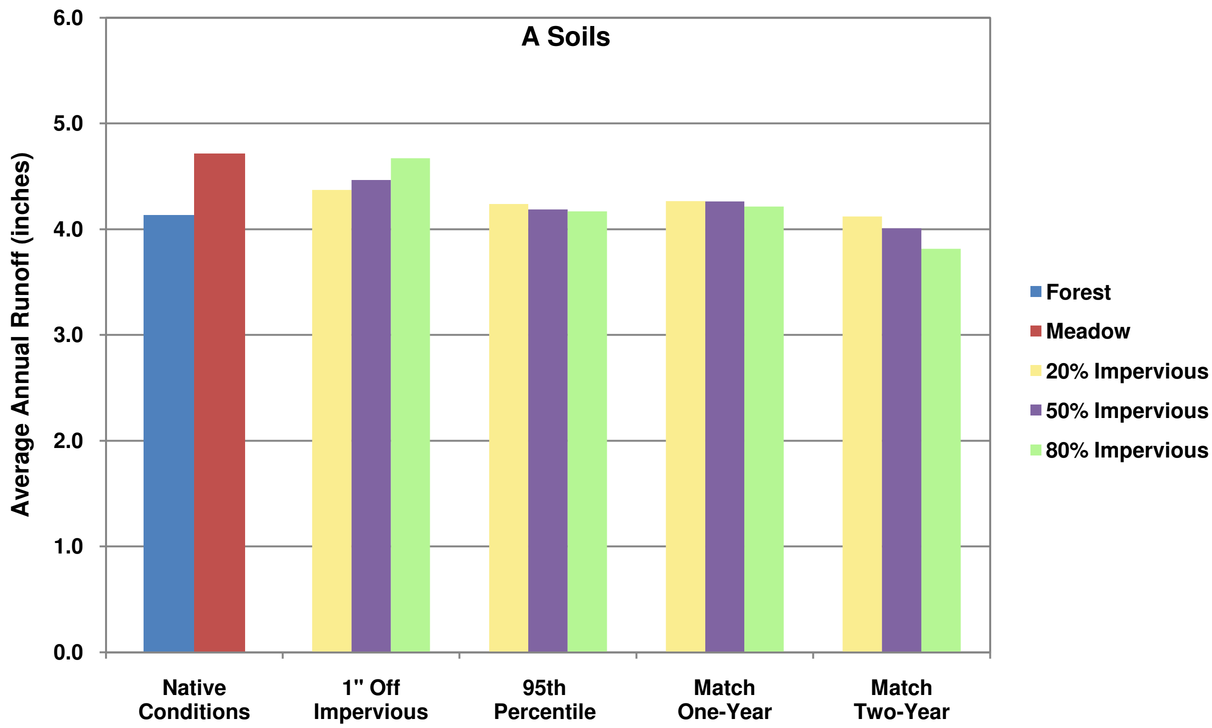
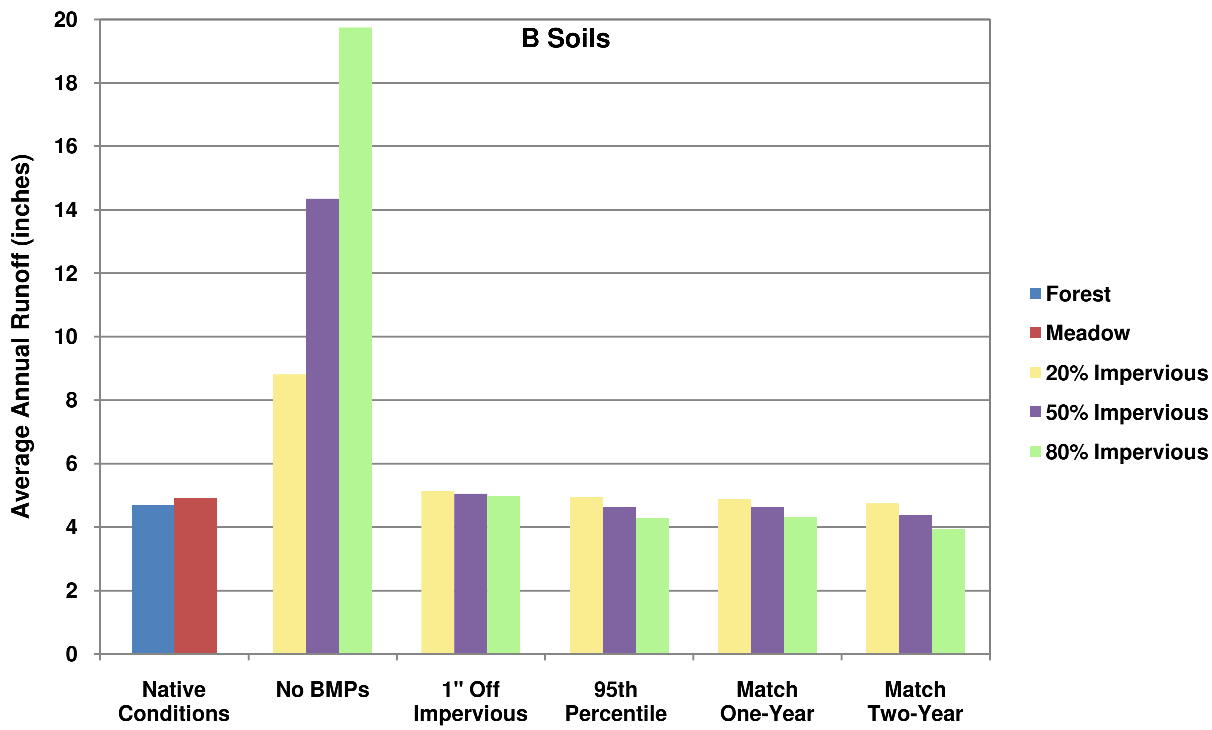




**Figure 5-11**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site from**
**Native Conditions and**
**Developed Conditions with and without BMPs**
**A Soils - Twin Cities Region**



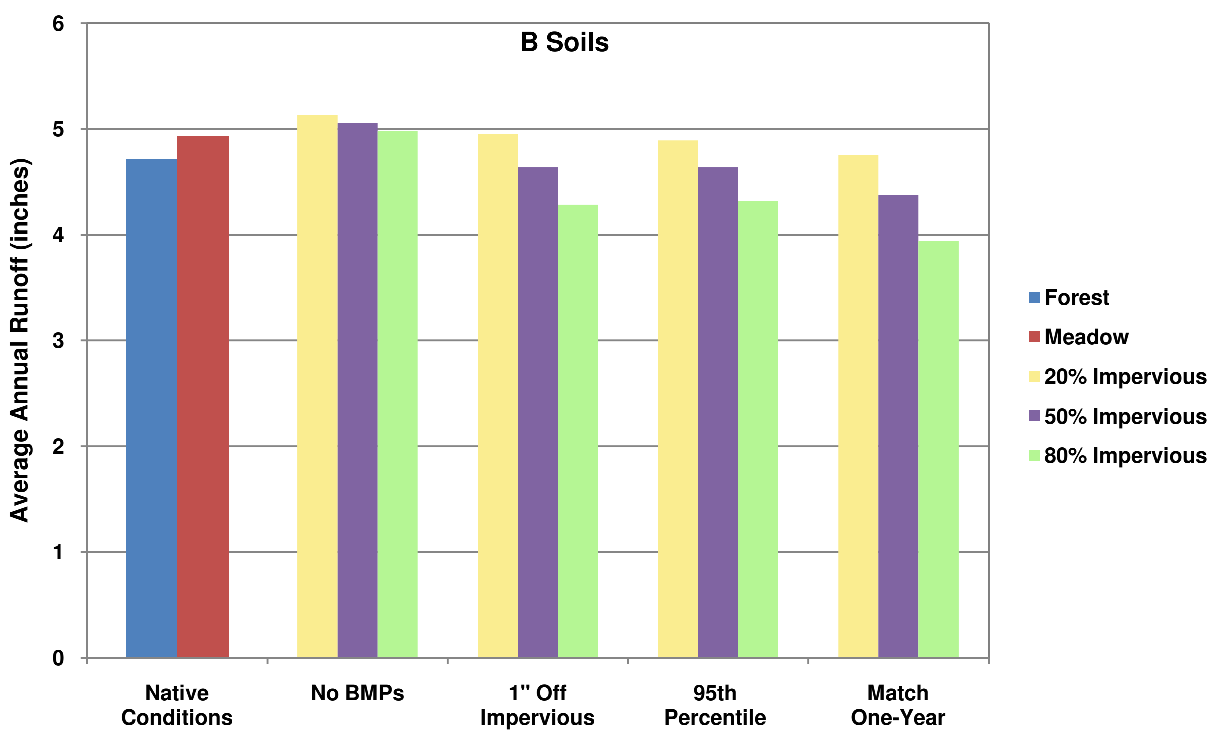




**Figure 5-12**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site from**
**Native Conditions and**
**Developed Conditions with and without BMPs**
**B Soils - Twin Cities Region**

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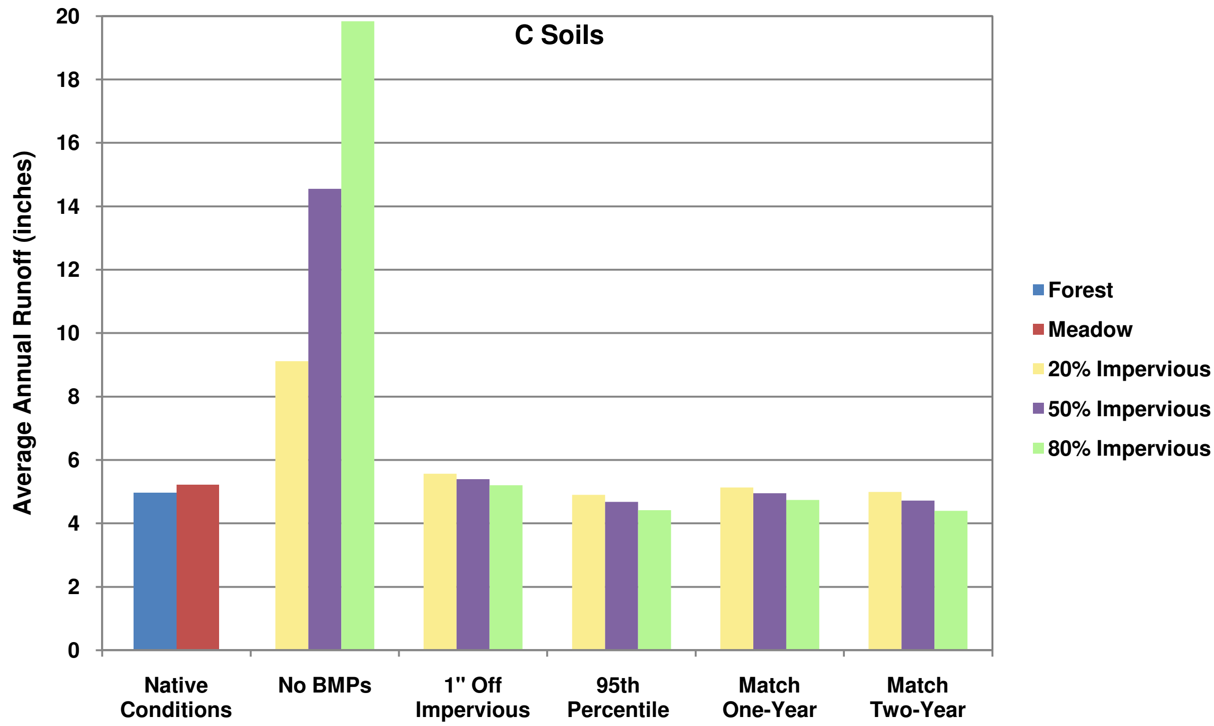


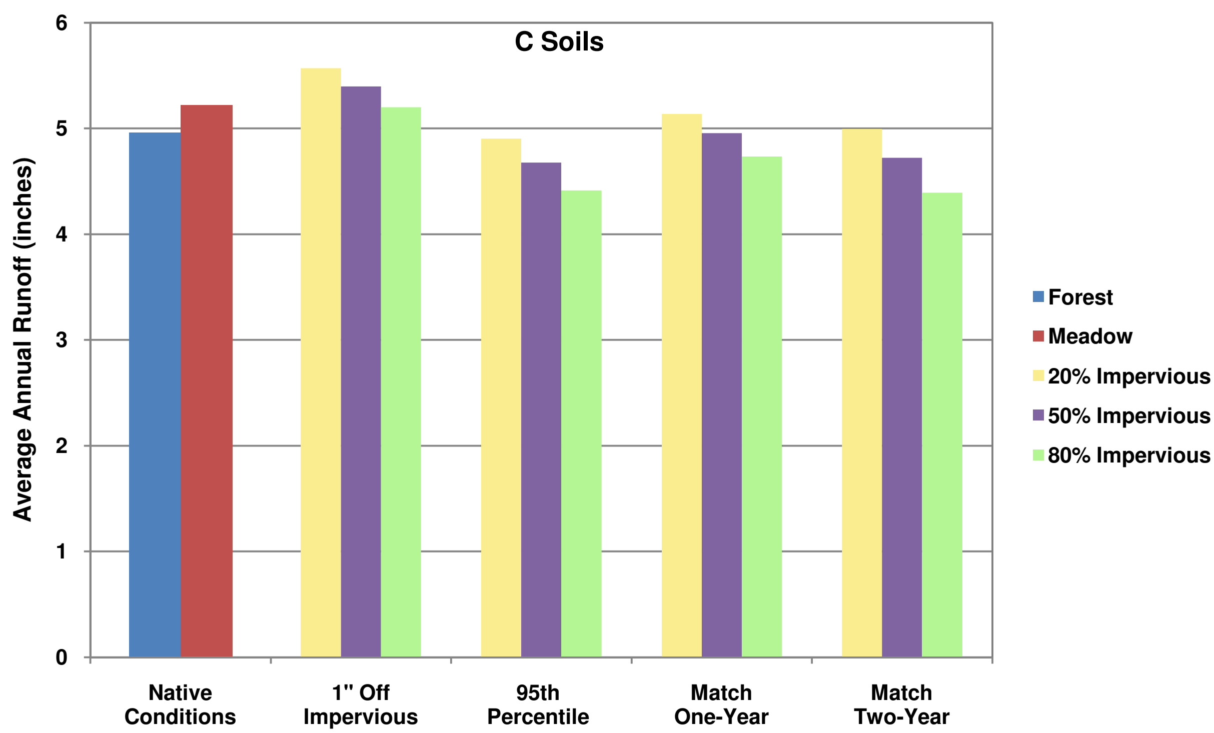


**Figure 5-13**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site from**
**Native Conditions and**
**Developed Conditions with and without BMPs**
**C Soils - Twin Cities Region**

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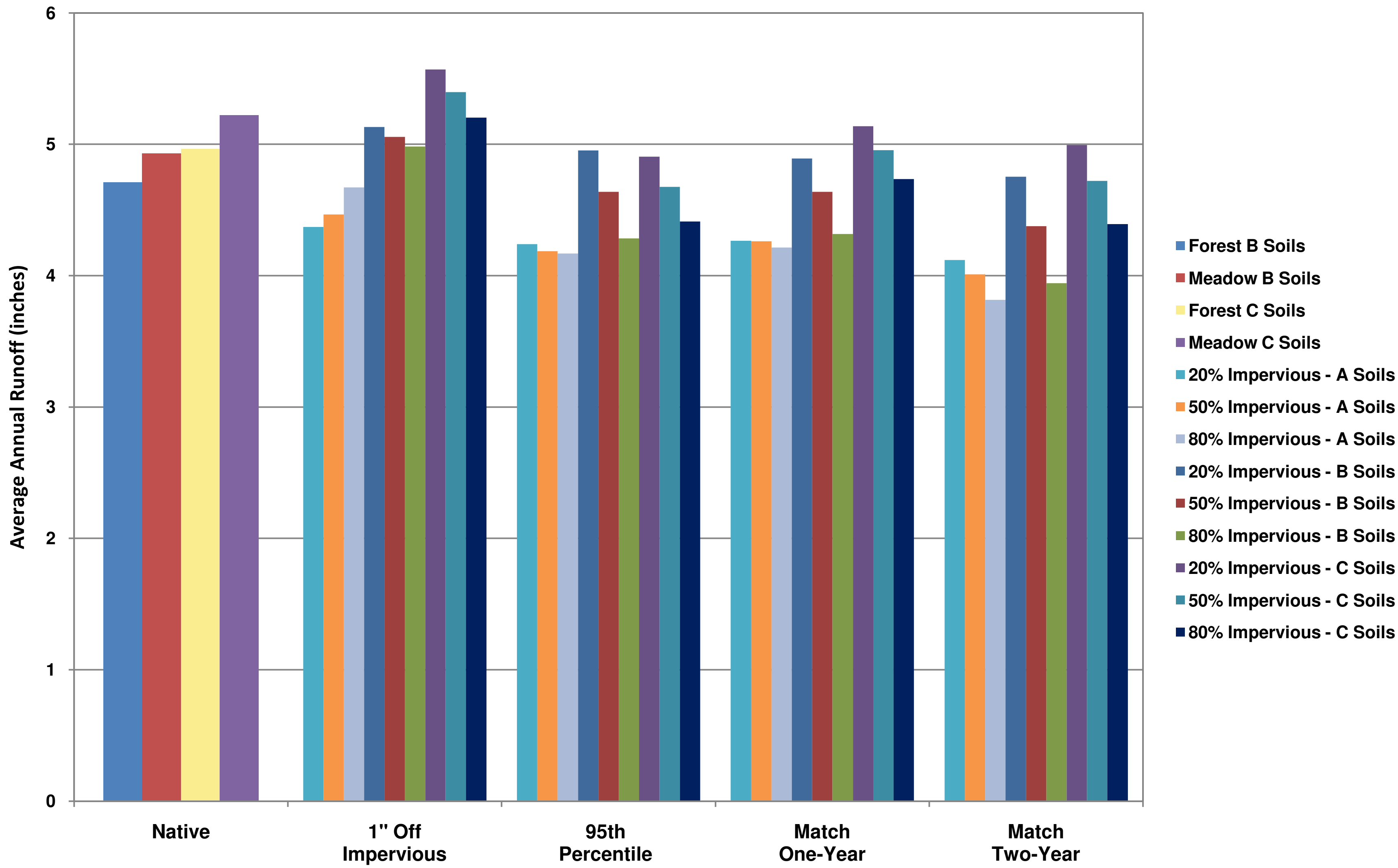


**Figure 5-14**
**Comparison of All Volume Controls**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**Twin Cities Region**

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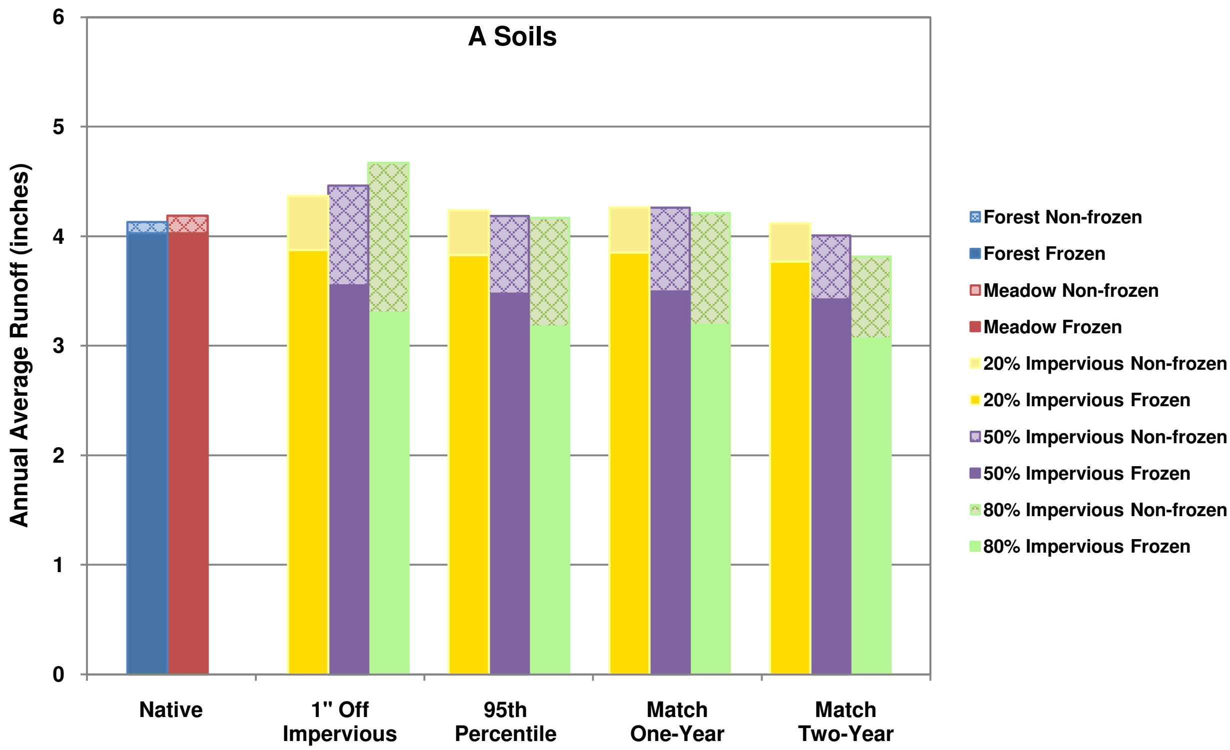
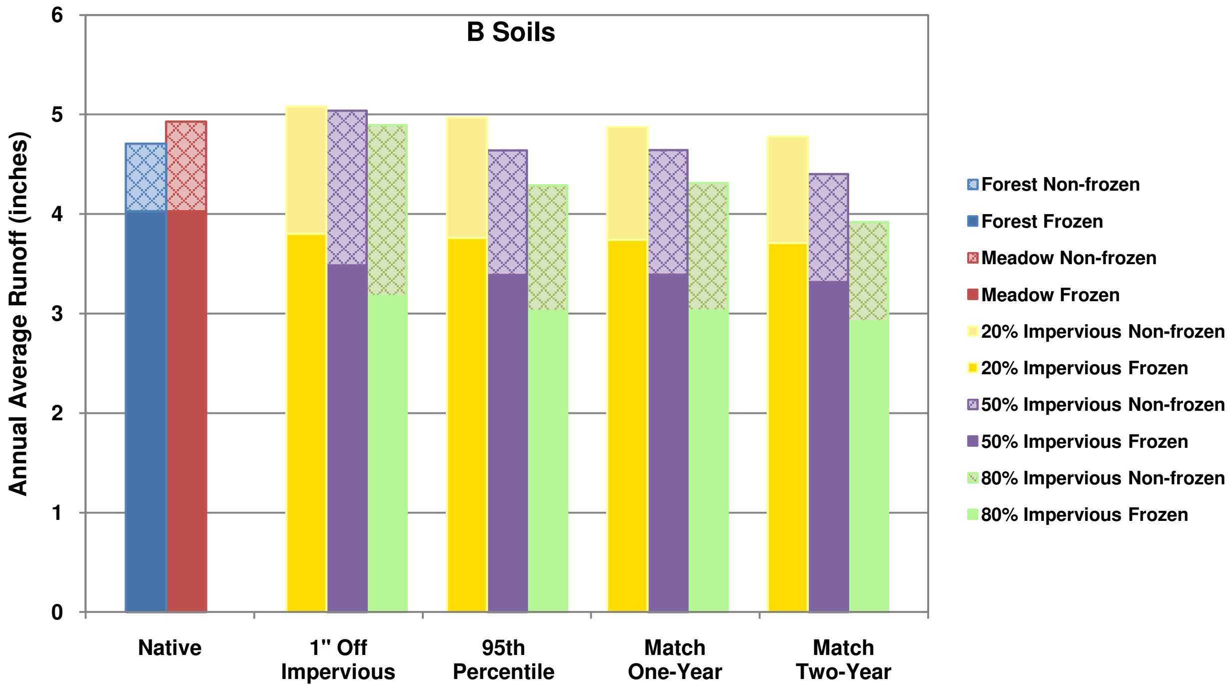



**Figure 5-15**
**Comparison of Volume Control BMPs**
**Twin Cities Region**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**During Frozen and Non-frozen Ground**
**Time Periods**



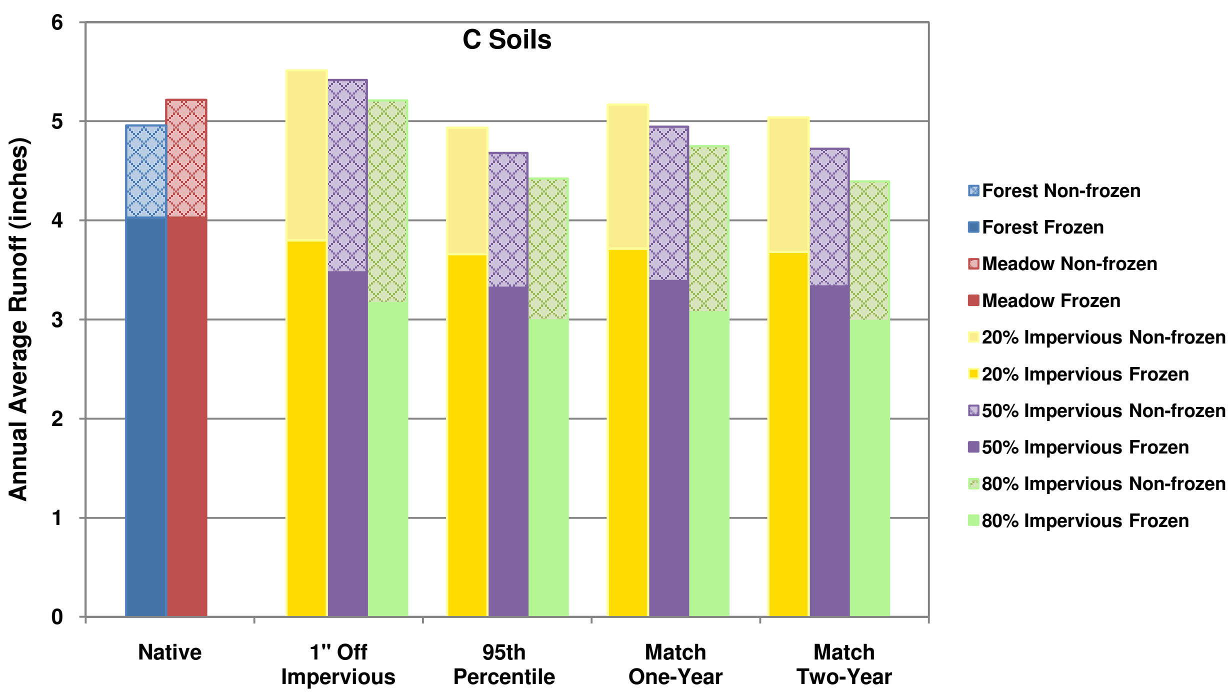




**Figure 5-16**
**Comparison of Volume Control BMPs**
**Twin Cities Region**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**During Frozen and Non-frozen Ground**
**Time Periods**

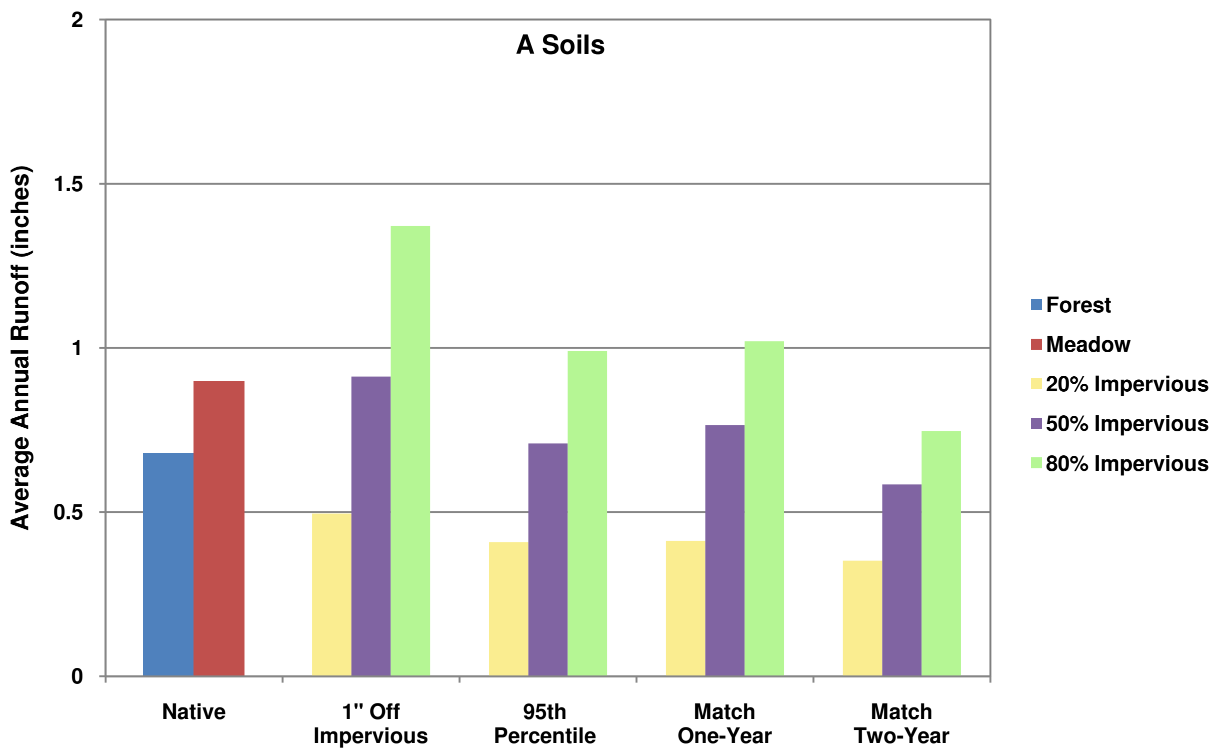



**Figure 5-17**
**Comparison of Volume Control BMPs**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**During Non-frozen Ground Time Period**
**Twin Cities Region - A Soils**

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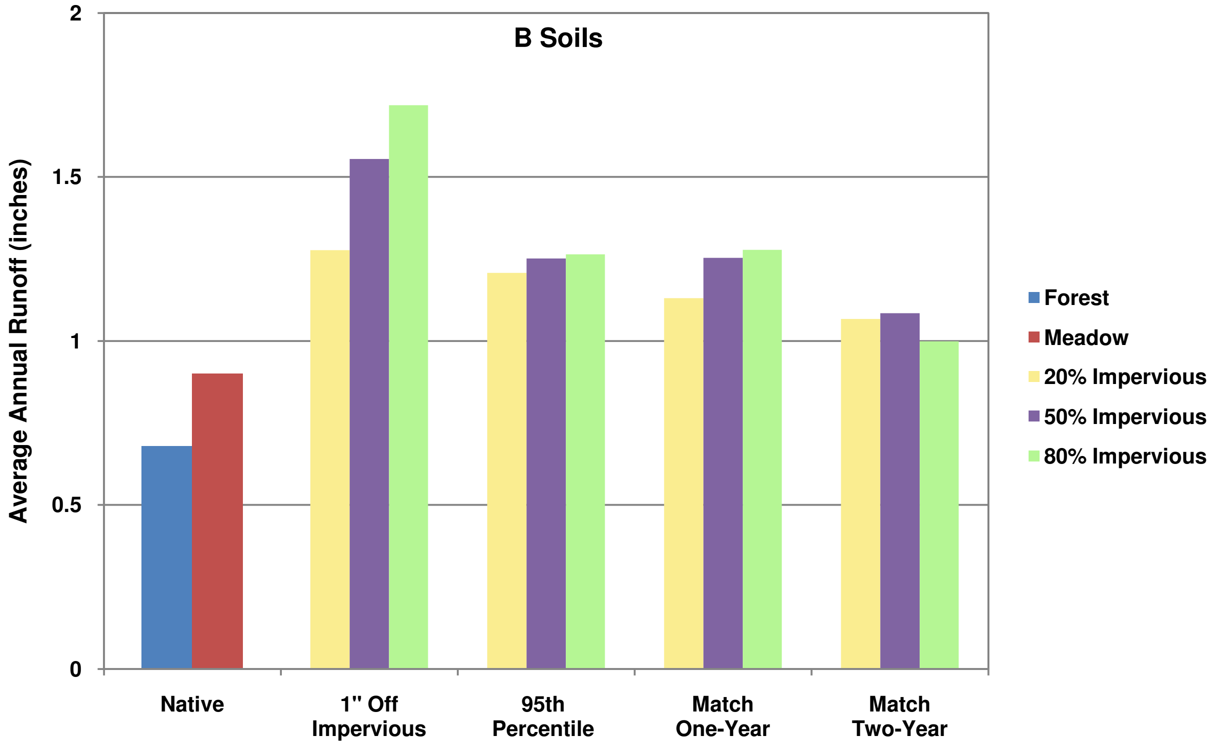


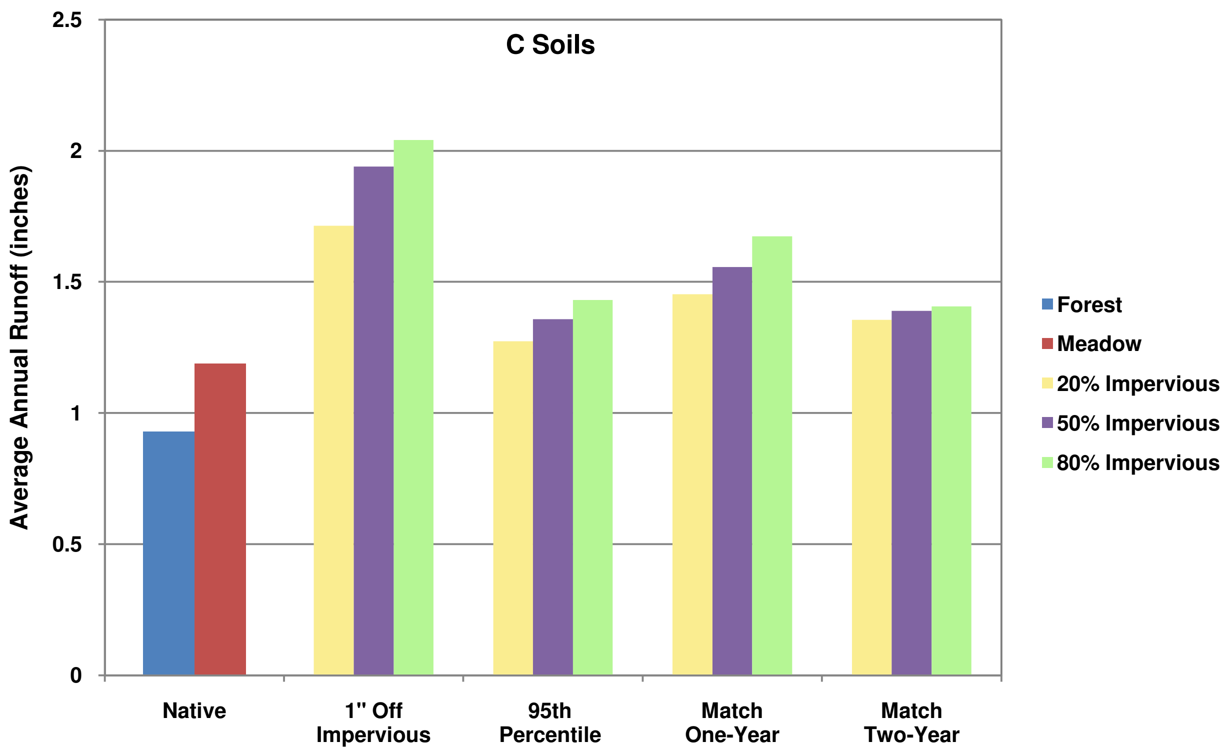


**Figure 5-18**
**Comparison of Volume Control BMPs**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**During Non-frozen Ground Time Period**
**Twin Cities Region - B and C Soils**

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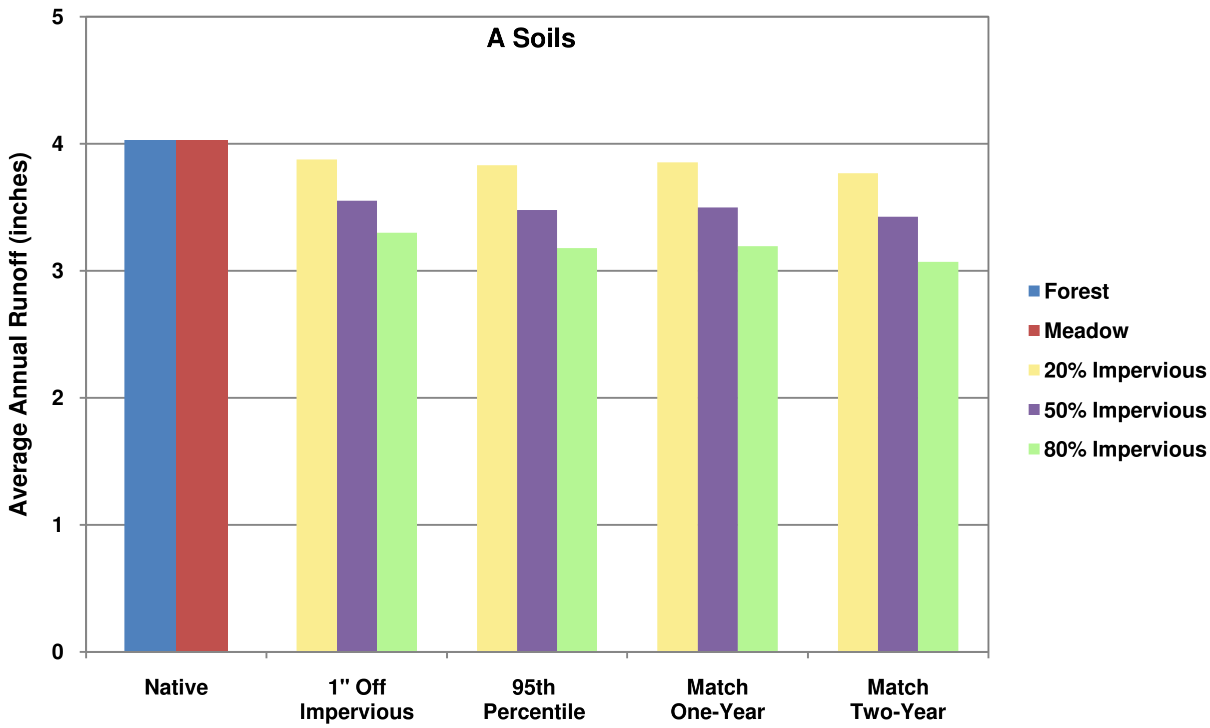
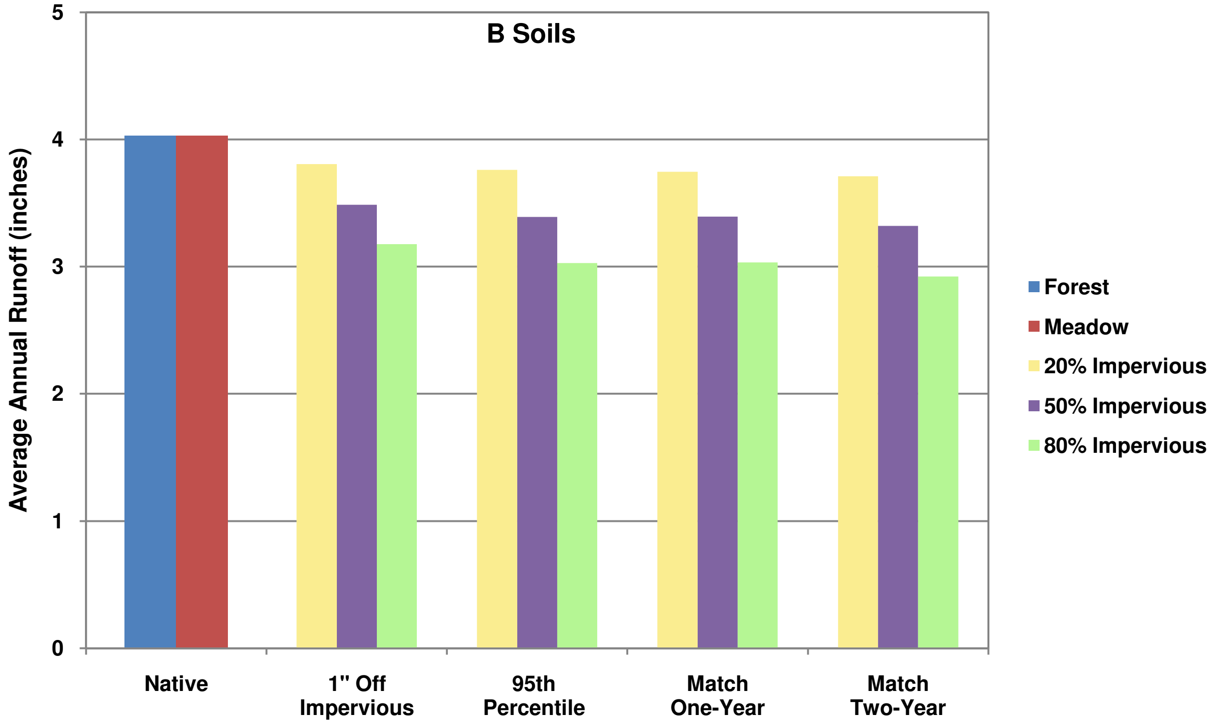



**Figure 5-19**
**Comparison of Volume Control BMPs**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**During Frozen Ground Time Period**
**Twin Cities Region - A Soils**



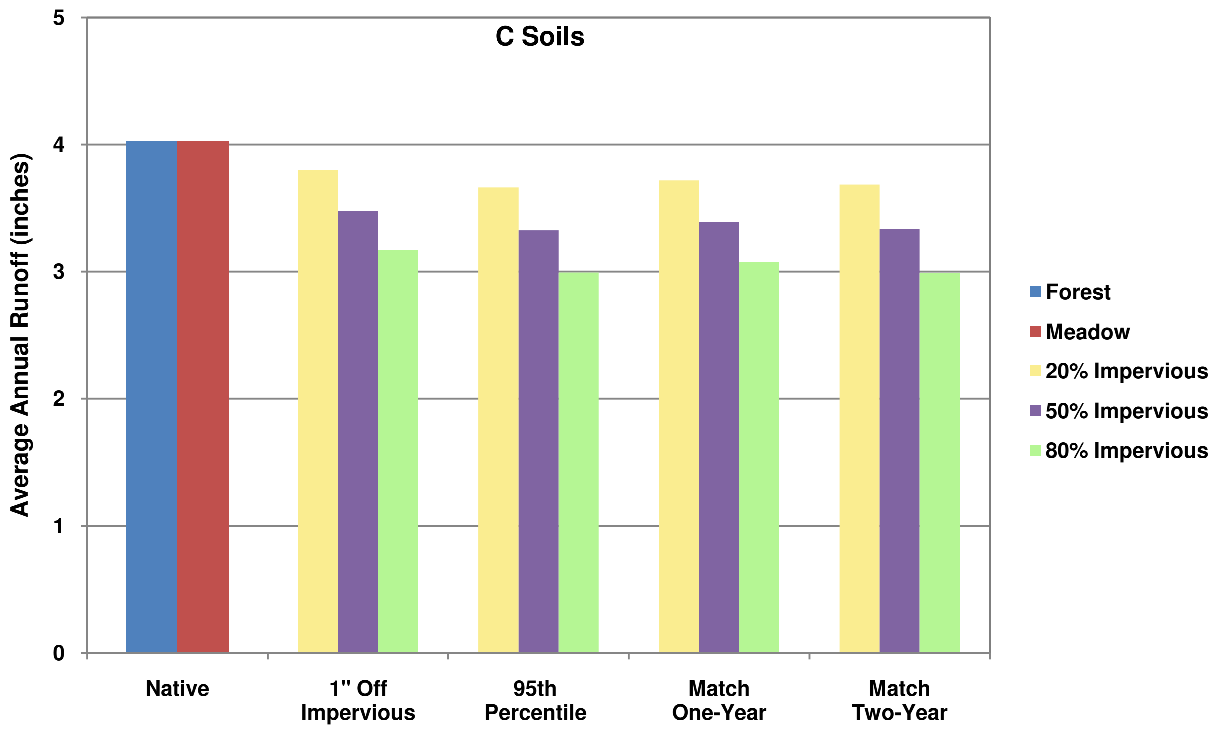




**Figure 5-20**
**Comparison of Volume Control BMPs**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**During Frozen Ground Time Period**
**Twin Cities Region - B and C Soils**

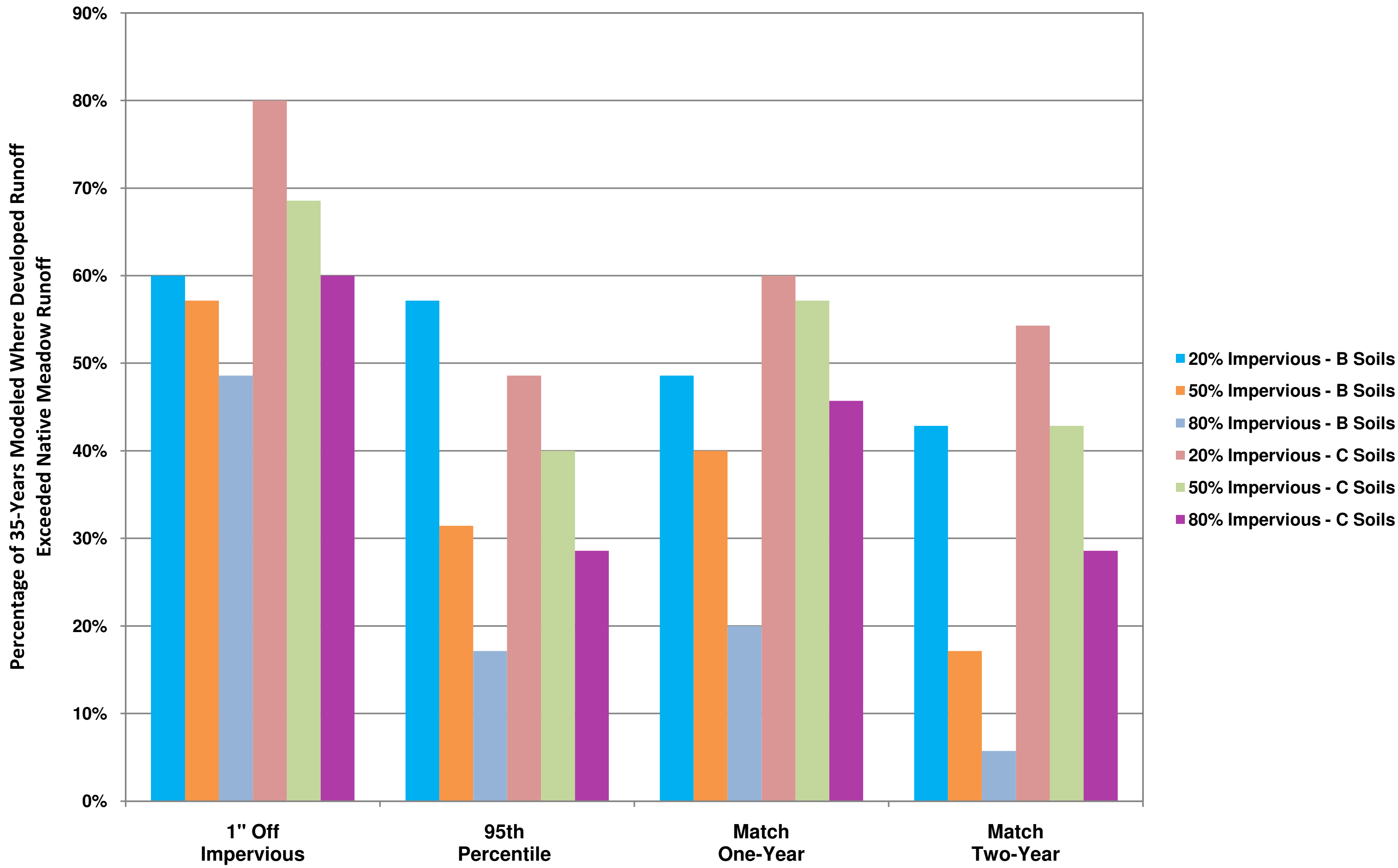



**Figure 5-21**
**Annual Variability**
**of Performance Goals**
**Twin Cities Region**

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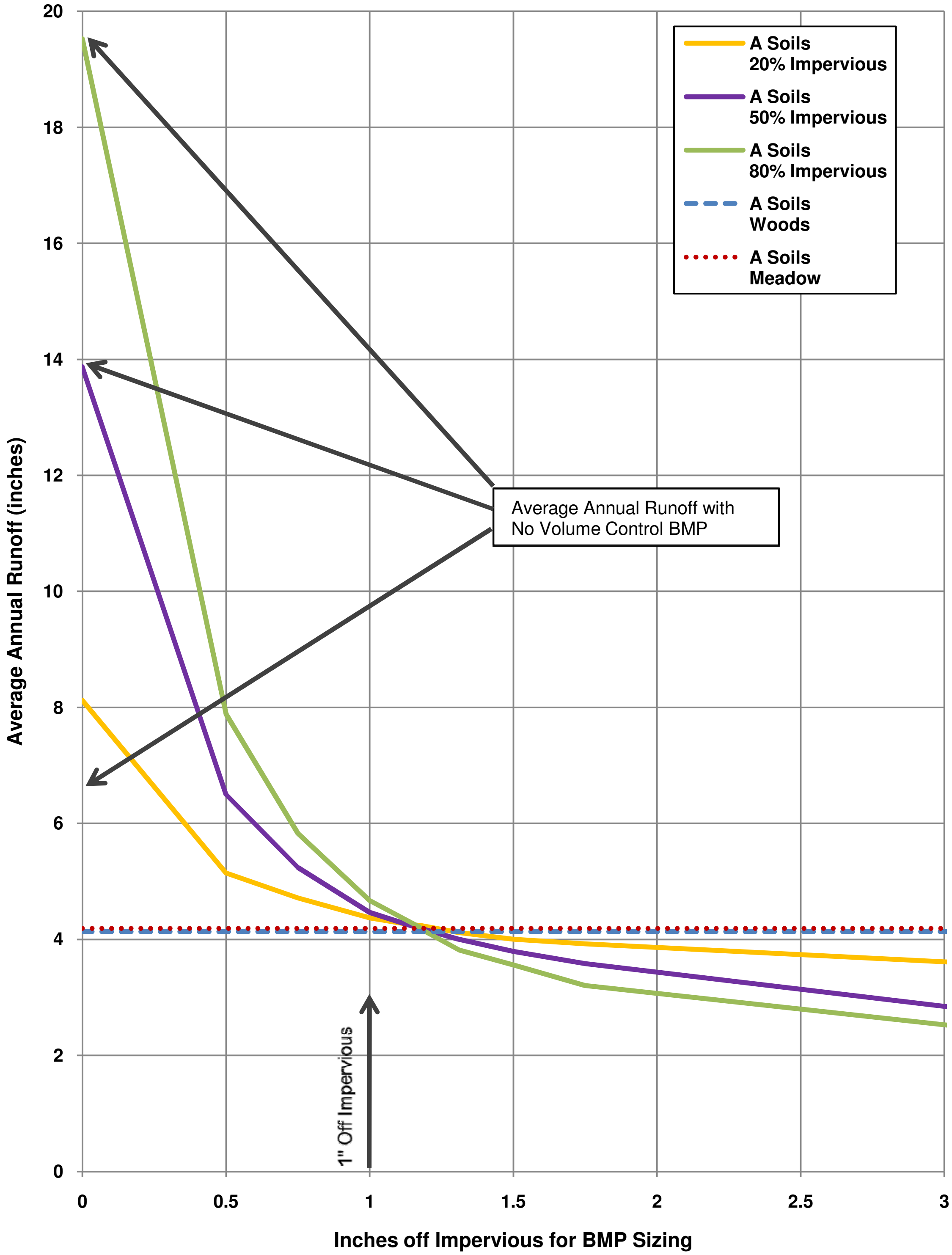


**Figure 5-22**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**A Soils - Twin Cities Region**
**BMPs Sized Using**
**Inches Off Impervious Performance Goal**

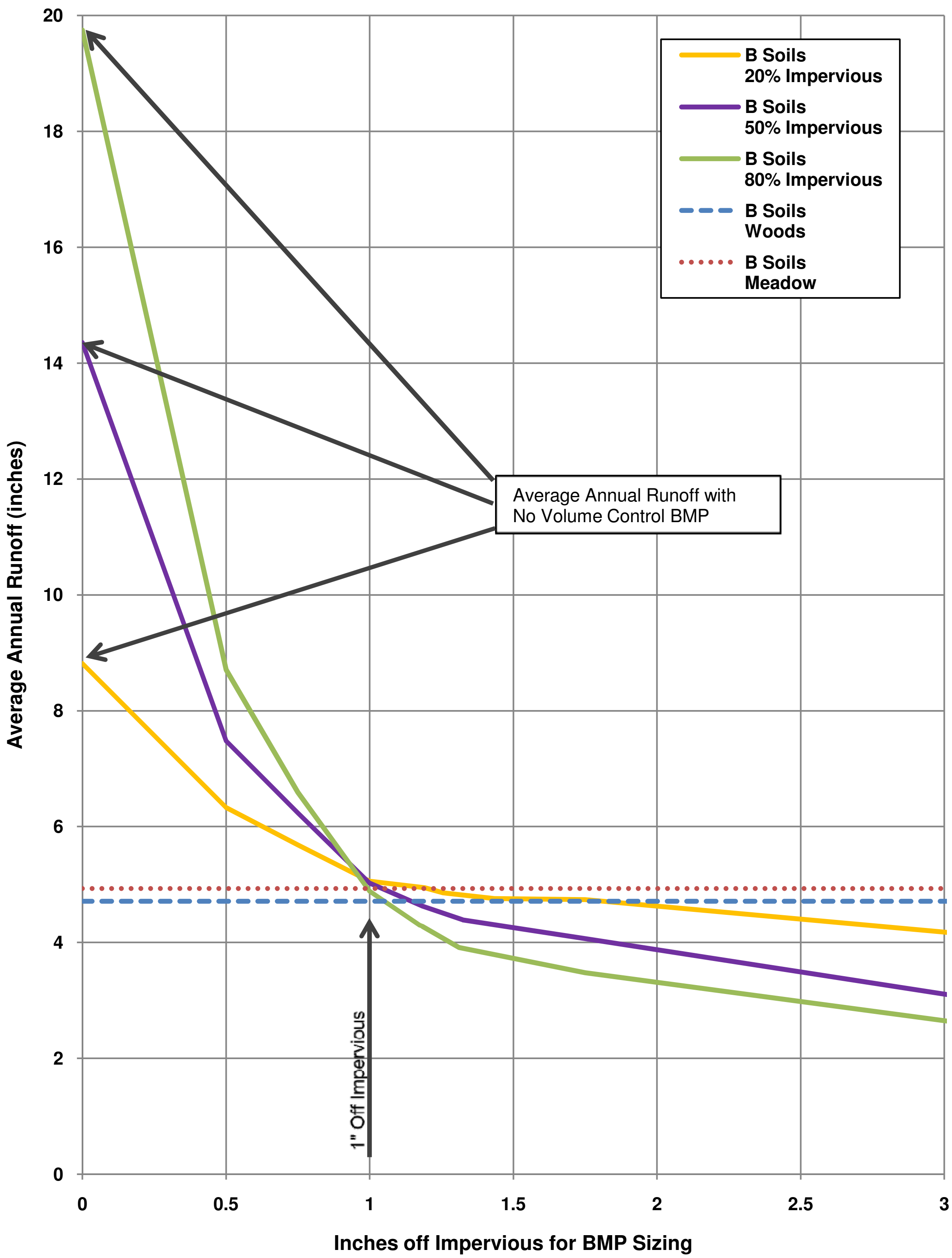


**Figure 5-23**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**B Soils - Twin Cities Region**
**BMPs Sized Using**
**Inches Off Impervious Performance Goal**

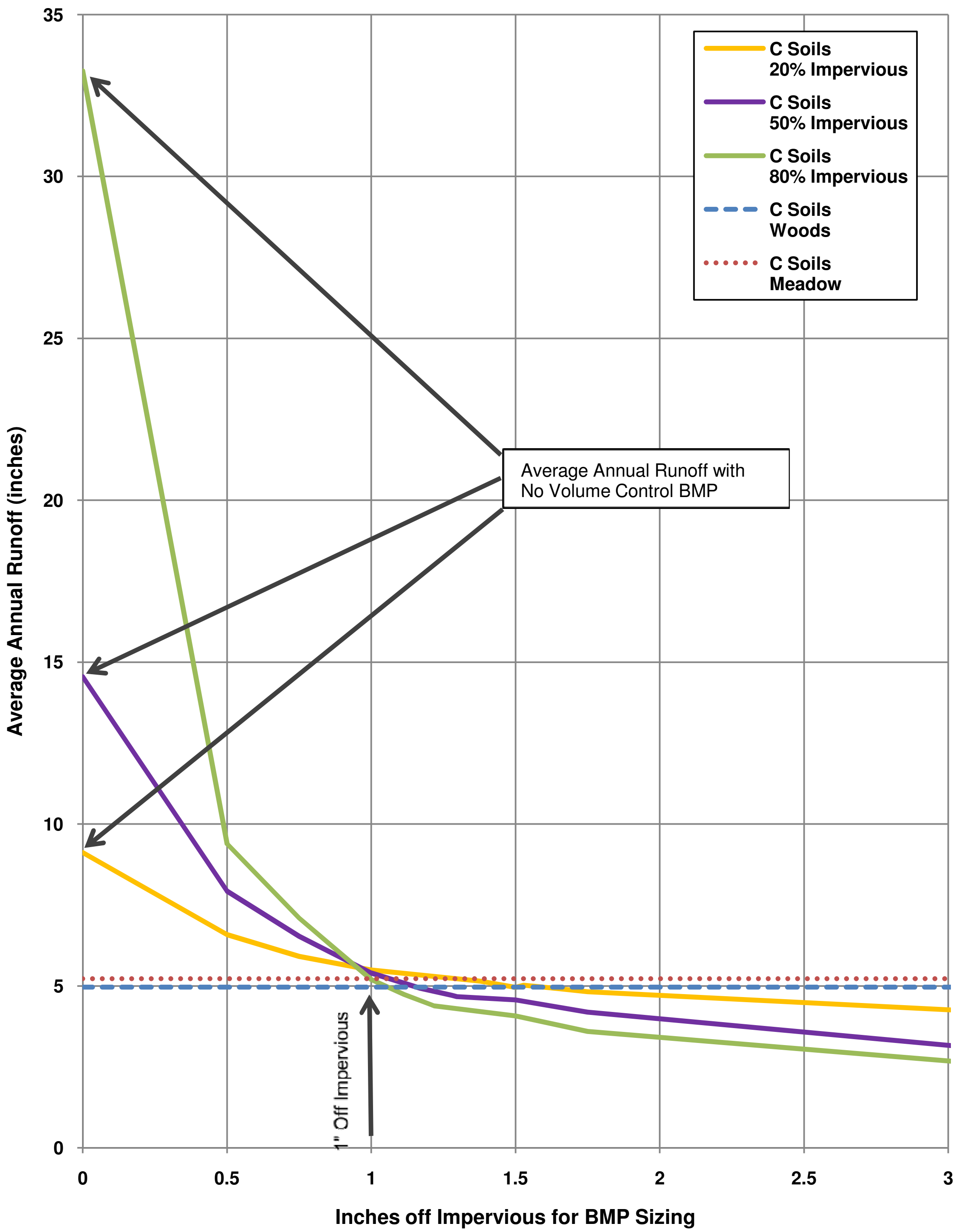


**Figure 5-24**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**C Soils - Twin Cities Region**
**BMPs Sized Using**
**Inches Off Impervious Performance Goal**

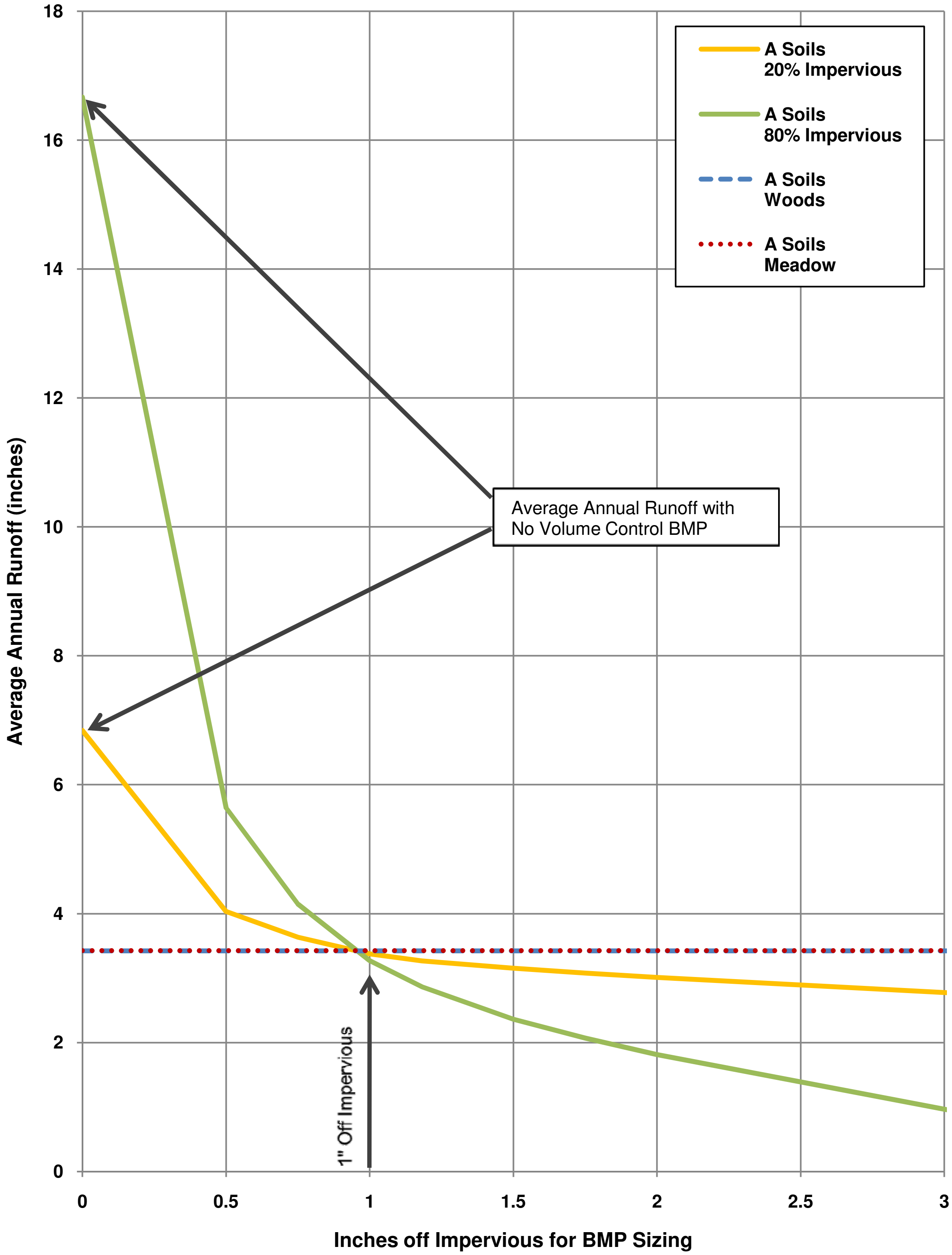


**Figure 5-25**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**A Soils - North Central Region**
**BMPs Sized Using**
**Inches Off Impervious Performance Goal**

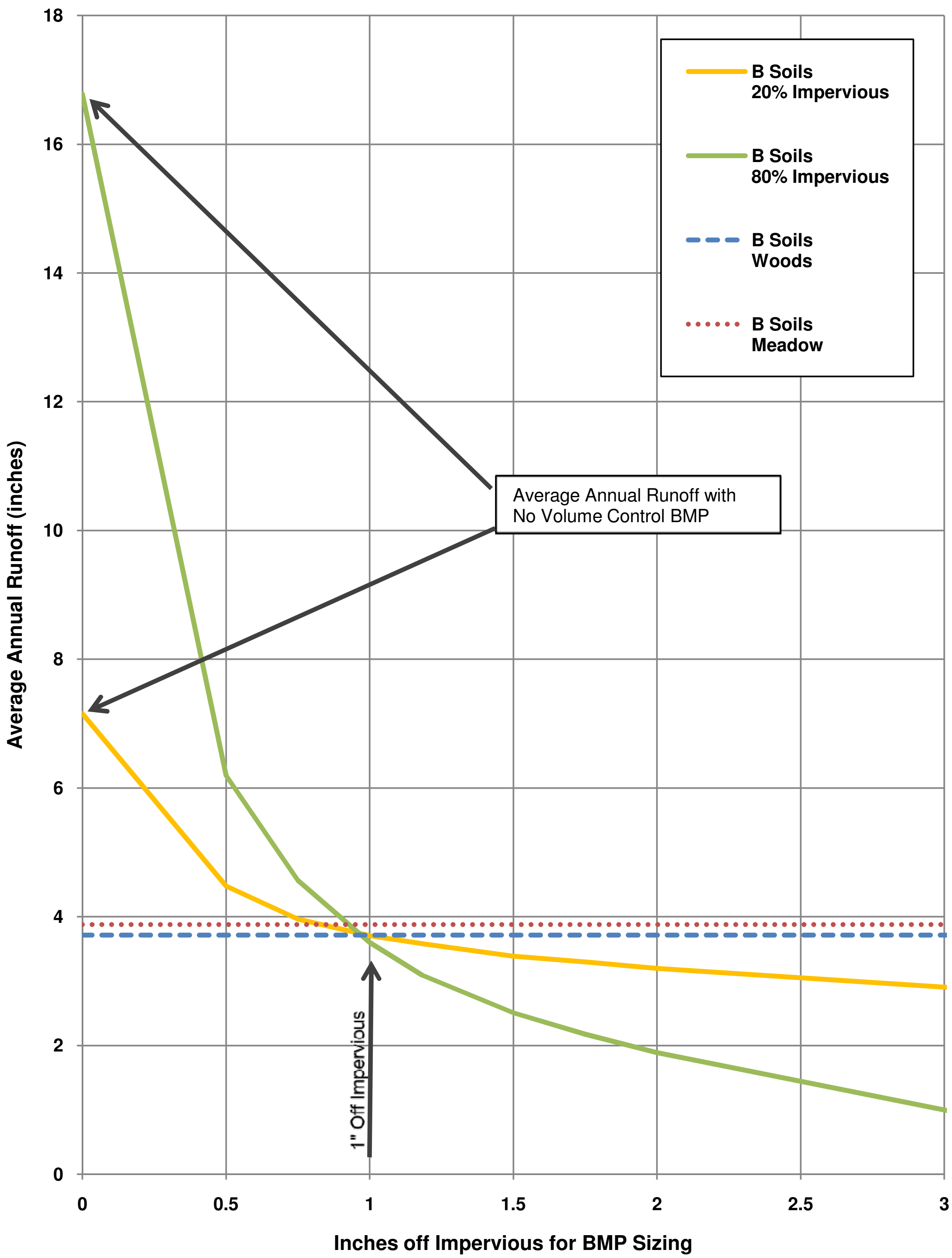


**Figure 5-26**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**B Soils - North Central Region**
**BMPs Sized Using**
**Inches Off Impervious Performance Goal**

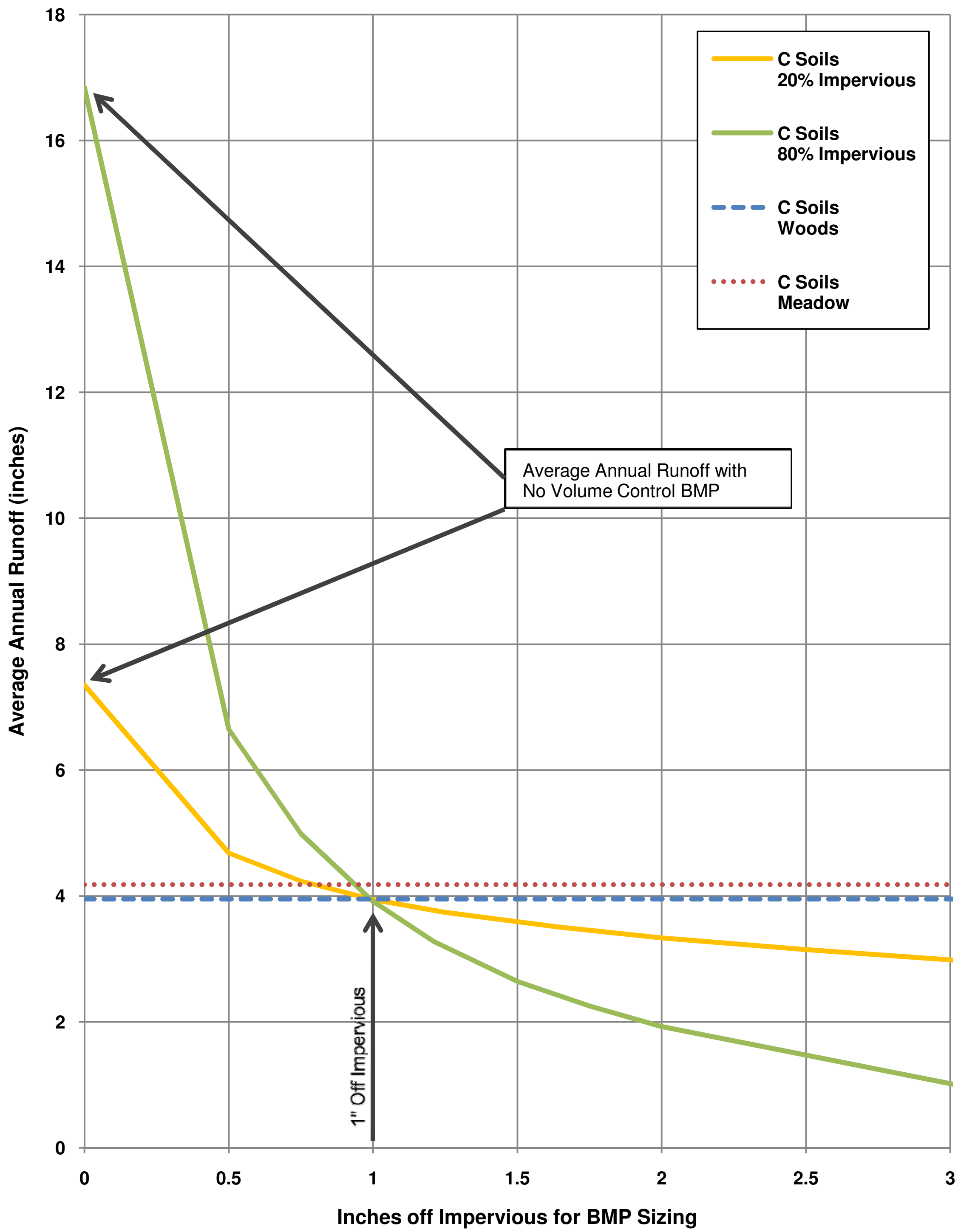


**Figure 5-27**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**C Soils - North Central Region**
**BMPs Sized Using**
**Inches Off Impervious Performance Goal**

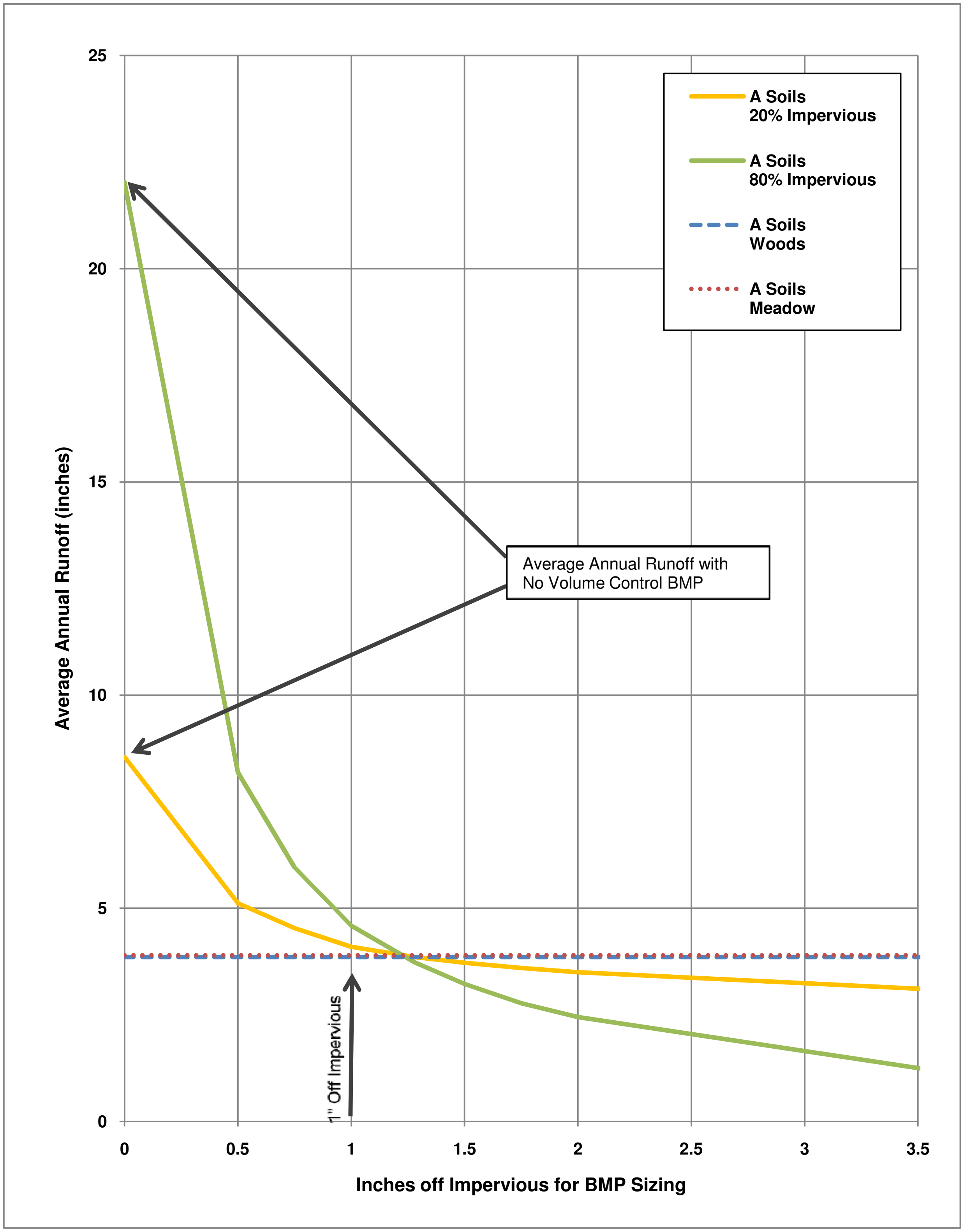


**Figure 5-28**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**A Soils - Southeast Region**
**BMPs Sized Using**
**Inches Off Impervious Performance Goal**

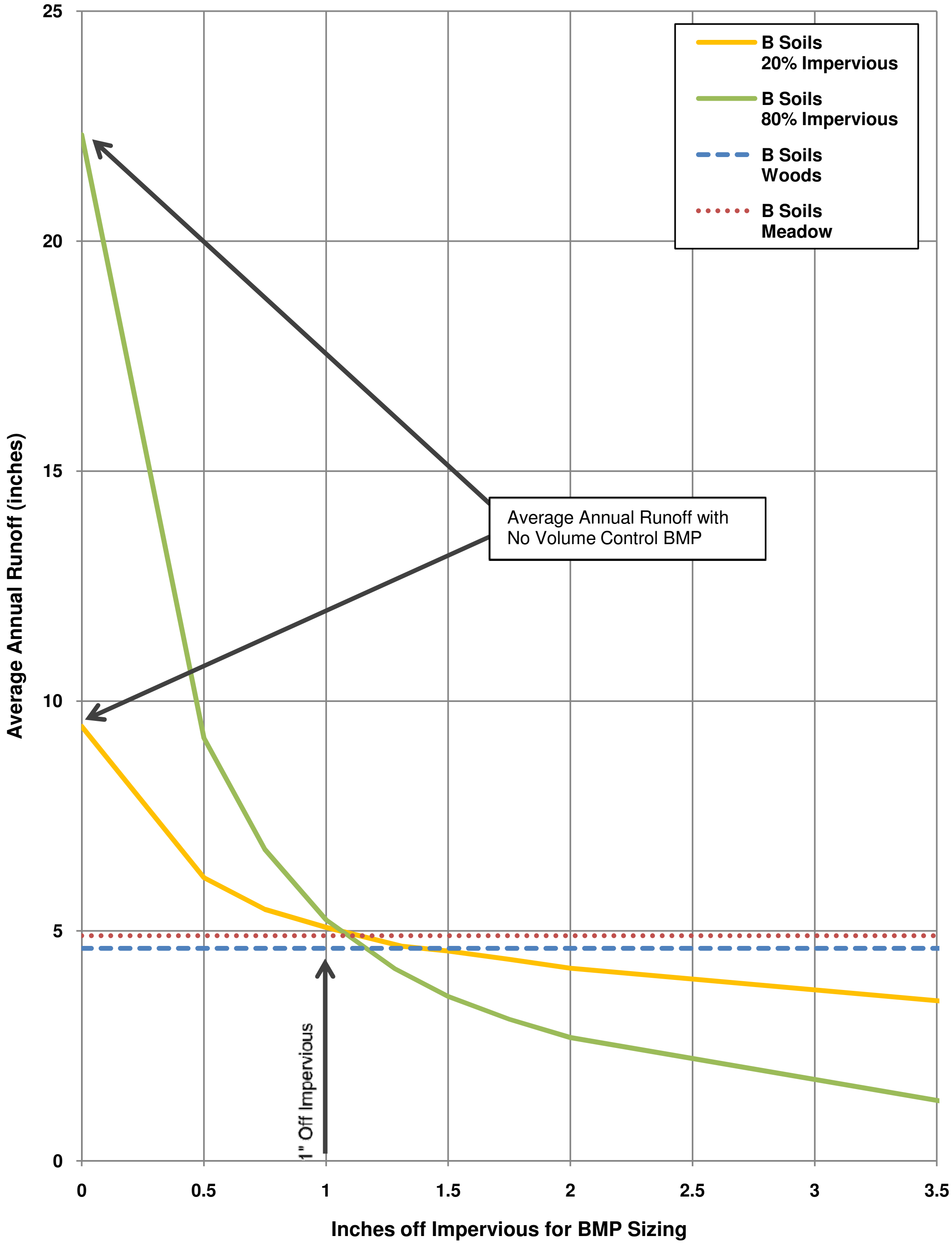


**Figure 5-29**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**B Soils - Southeast Region**
**BMPs Sized Using**
**Inches Off Impervious Performance Goal**

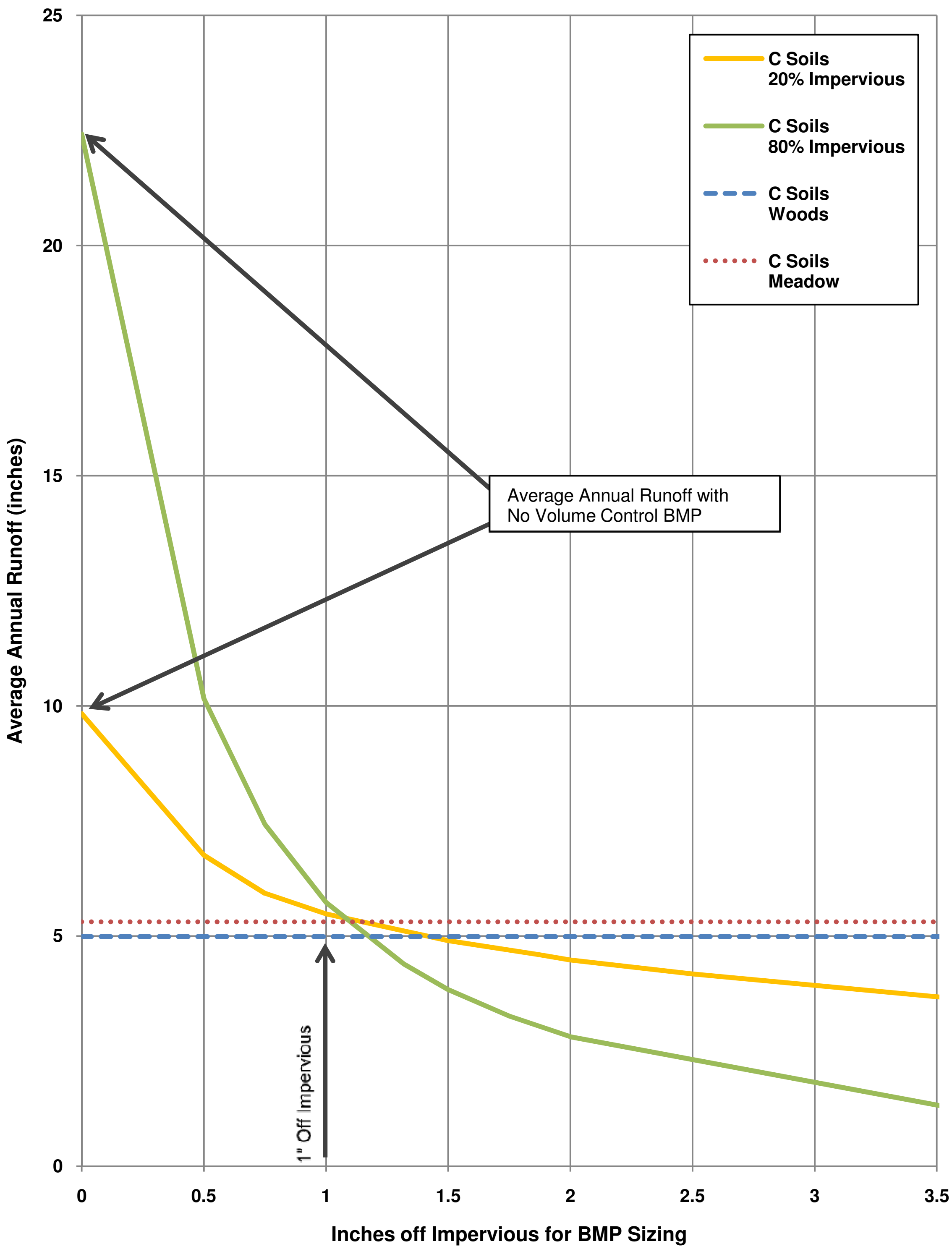


**Figure 5-30**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**C Soils - Southeast Region**
**BMPs Sized Using**
**Inches Off Impervious Performance Goal**

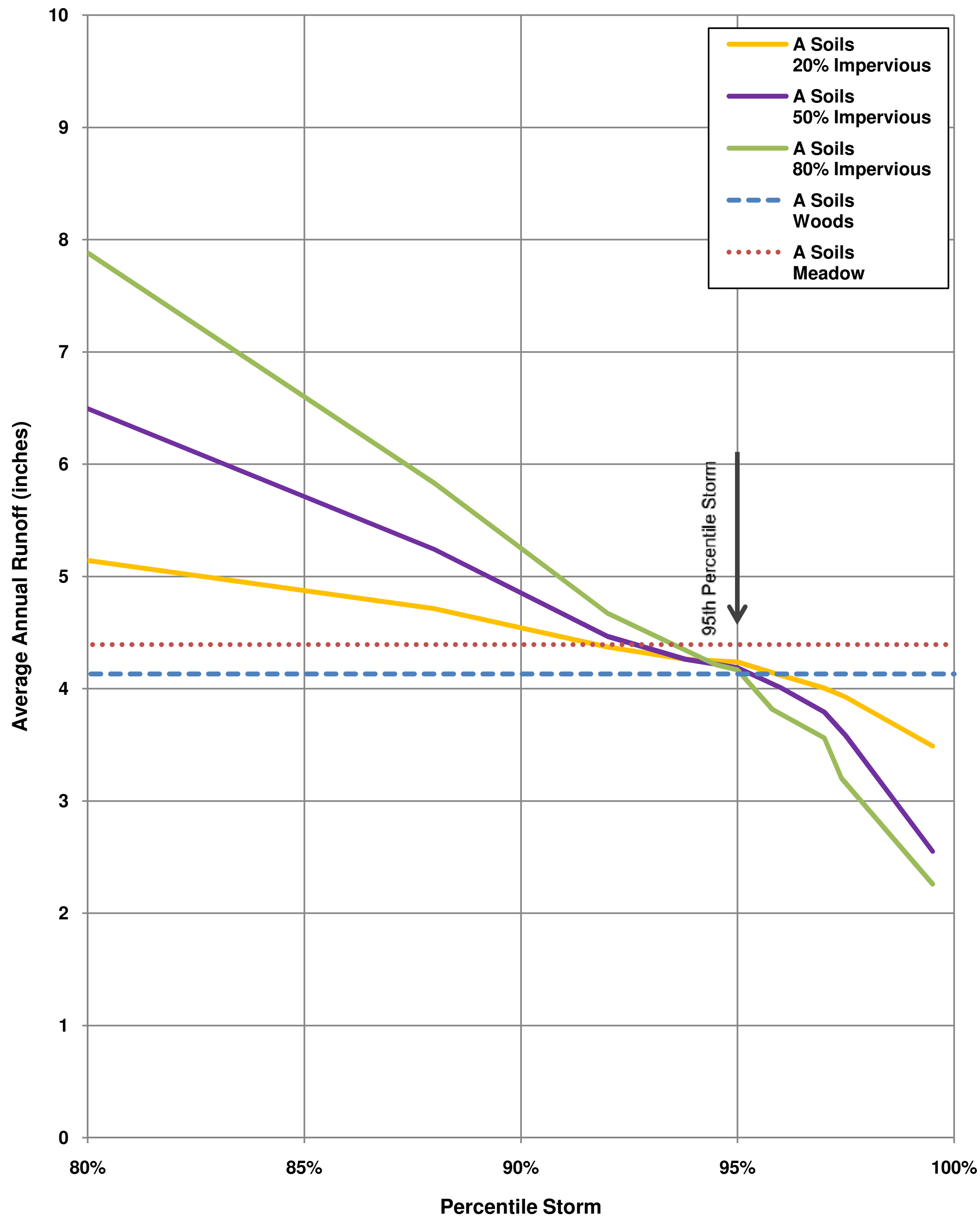


**Figure 5-31**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**A Soils - Twin Cities Region**
**BMPs Sized Using**
**Percentile Storm Performance Goal**

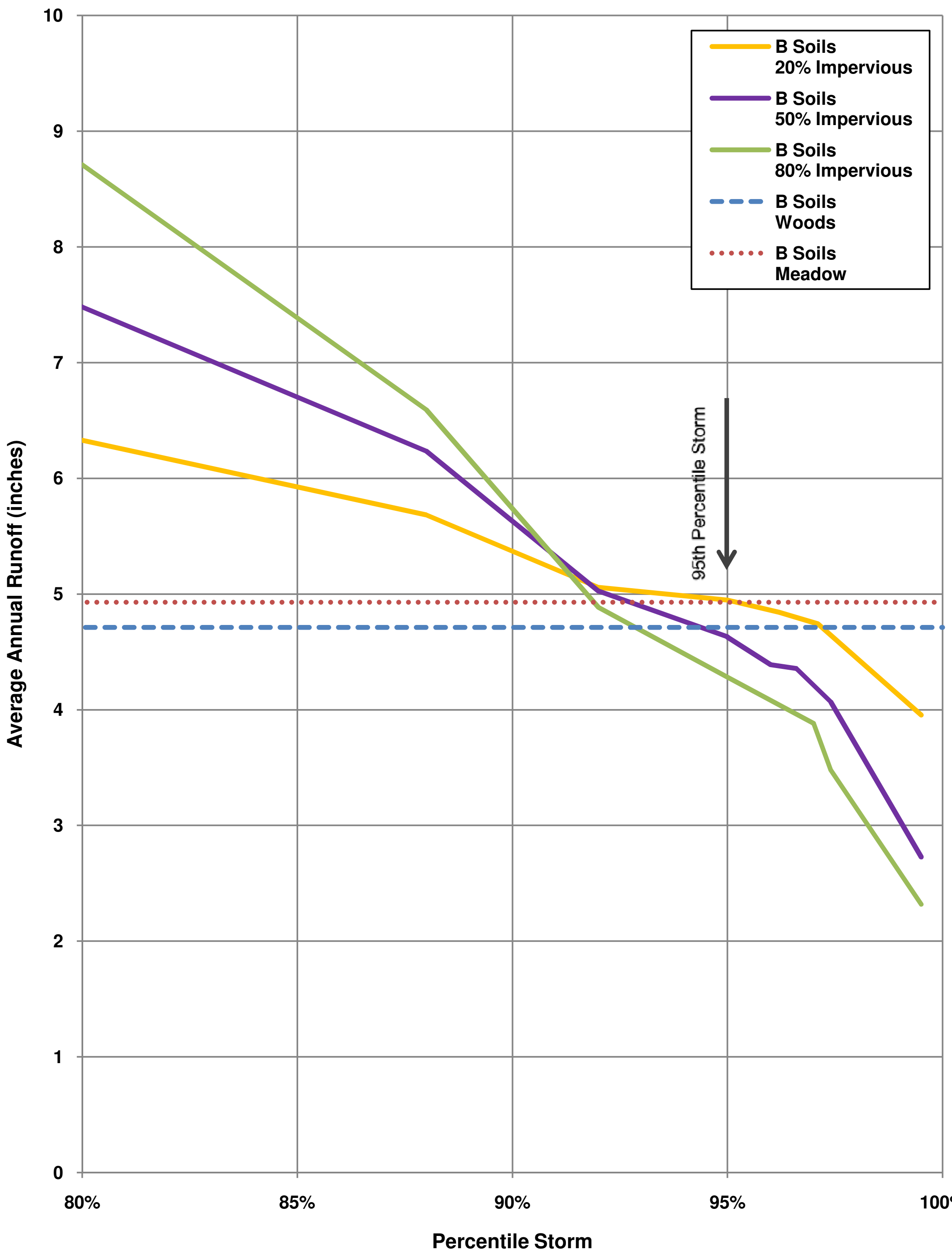


**Figure 5-32**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**B Soils - Twin Cities Region**
**BMPs Sized Using**
**Percentile Storm Performance Goal**

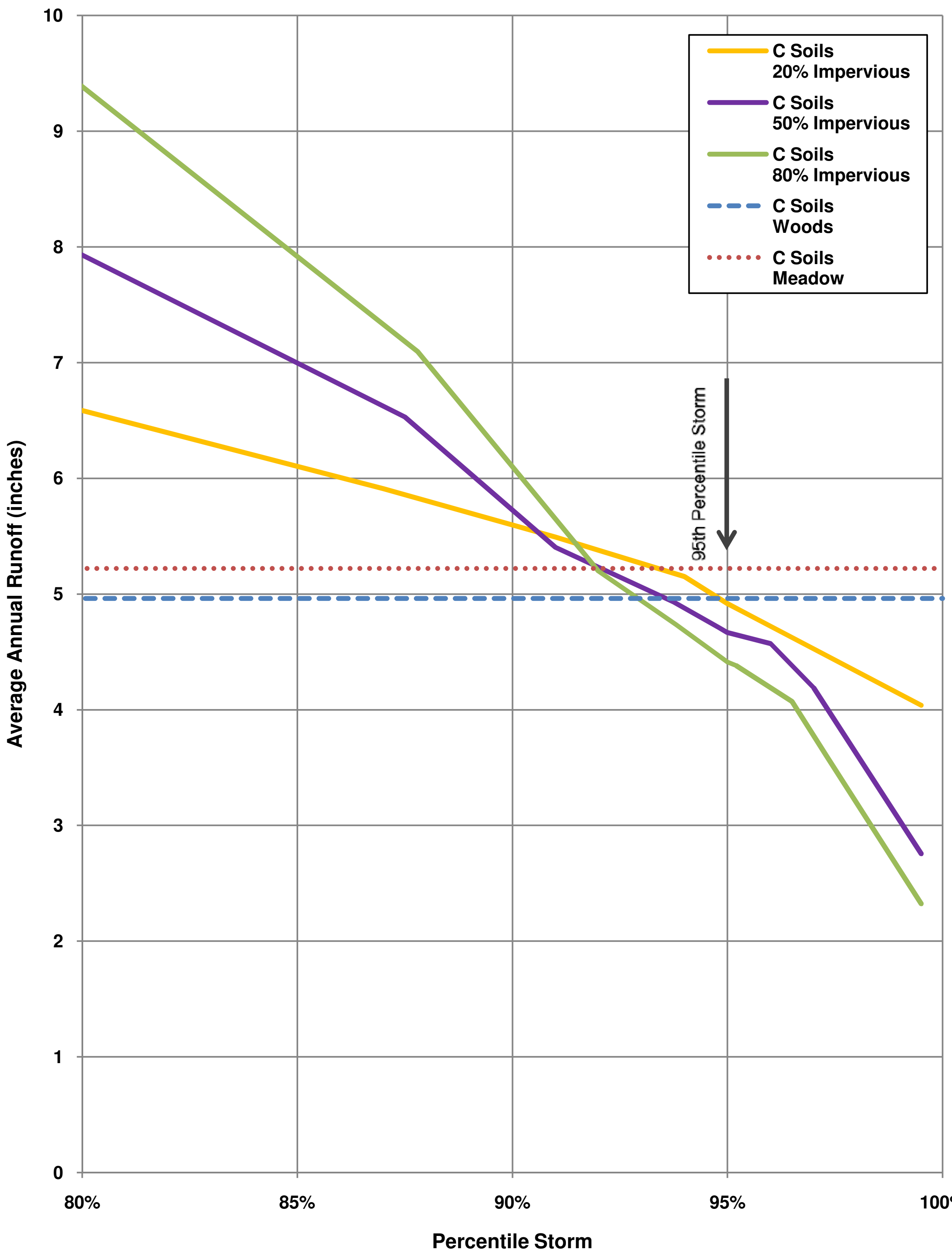


**Figure 5-33**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**C Soils - Twin Cities Region**
**BMPs Sized Using**
**Percentile Storm Performance Goal**

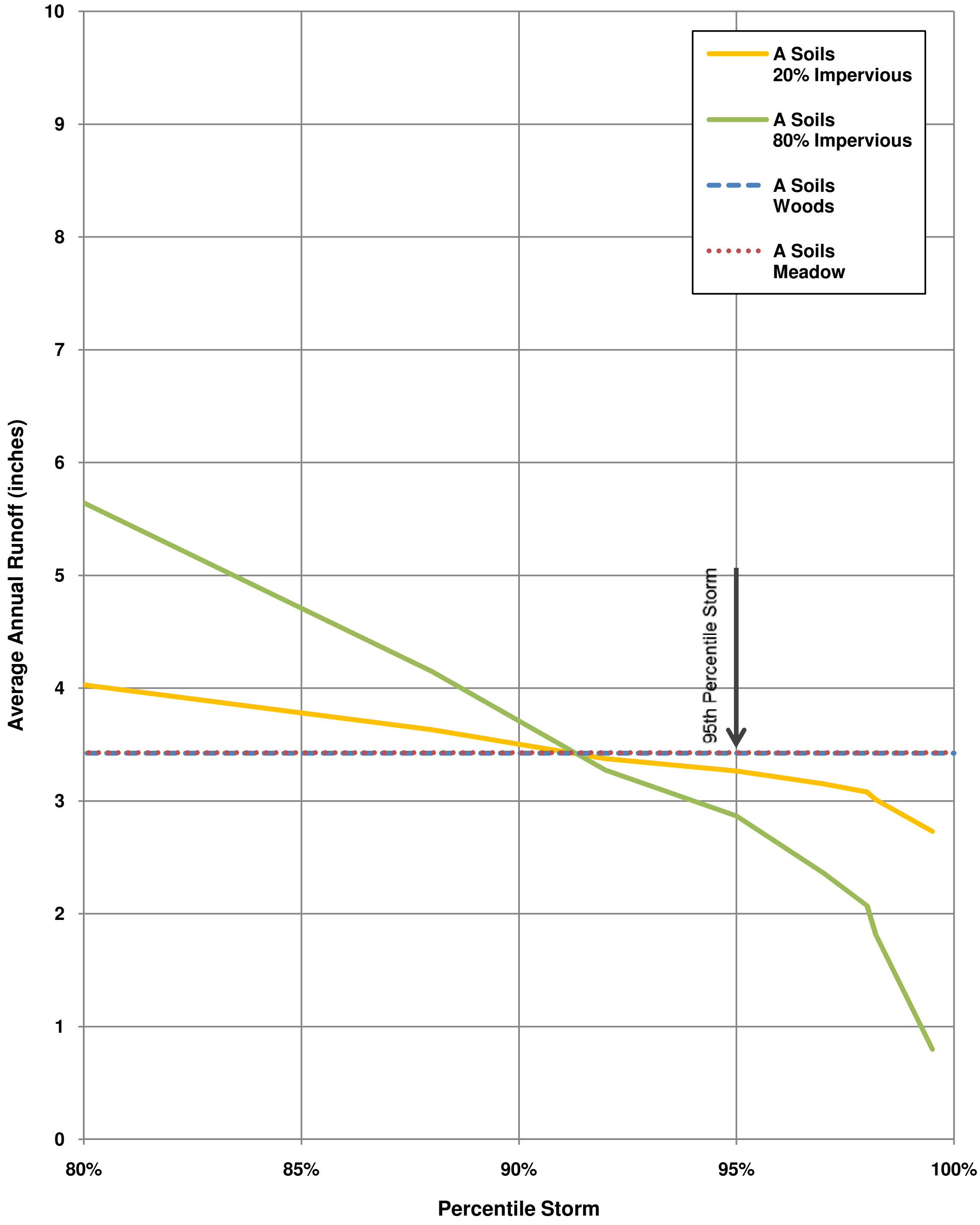


**Figure 5-34**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**A Soils - North Central Region**
**BMPs Sized Using**
**Percentile Storm Performance Goal**

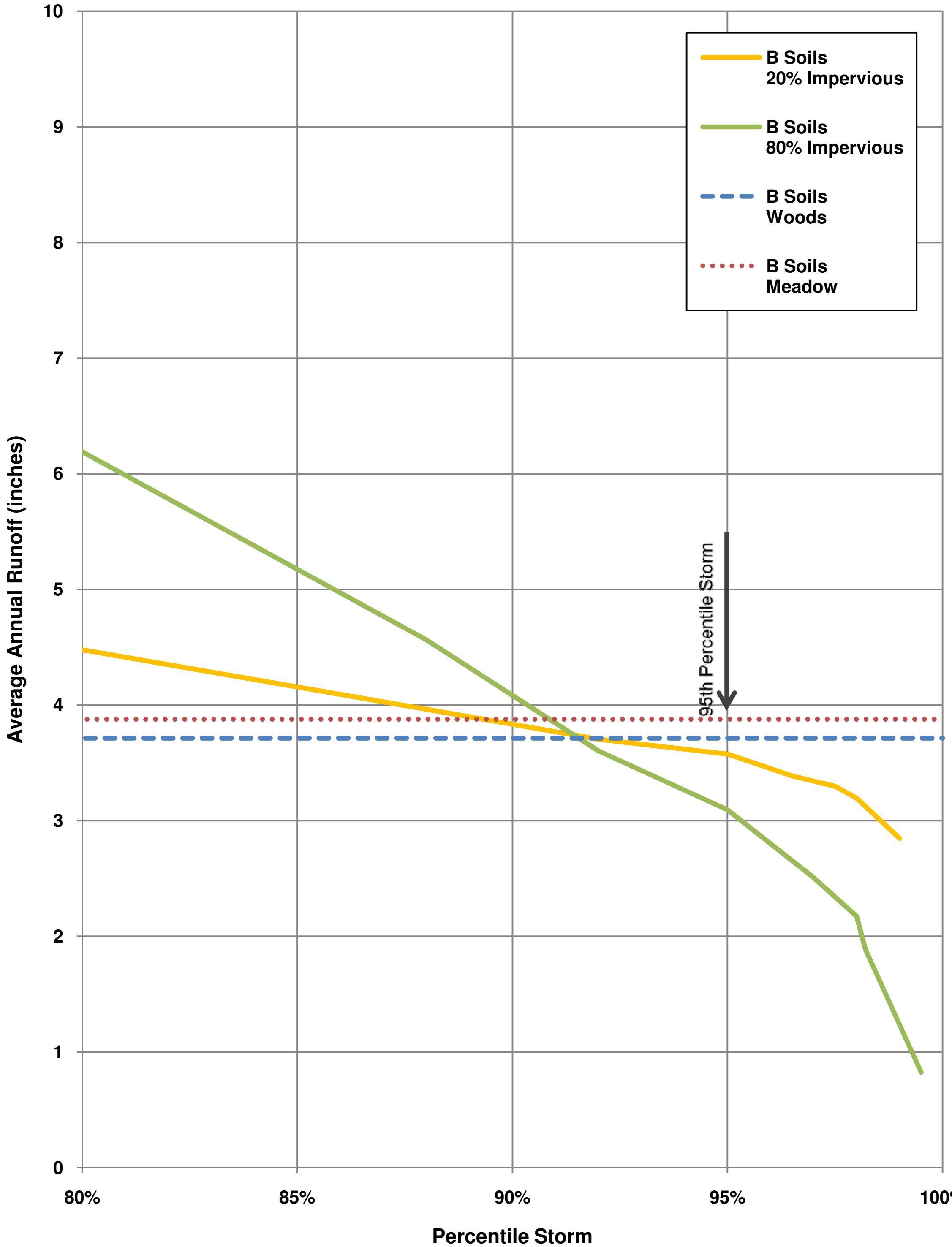


**Figure 5-35**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**B Soils - North Central Region**
**BMPs Sized Using**
**Percentile Storm Performance Goal**

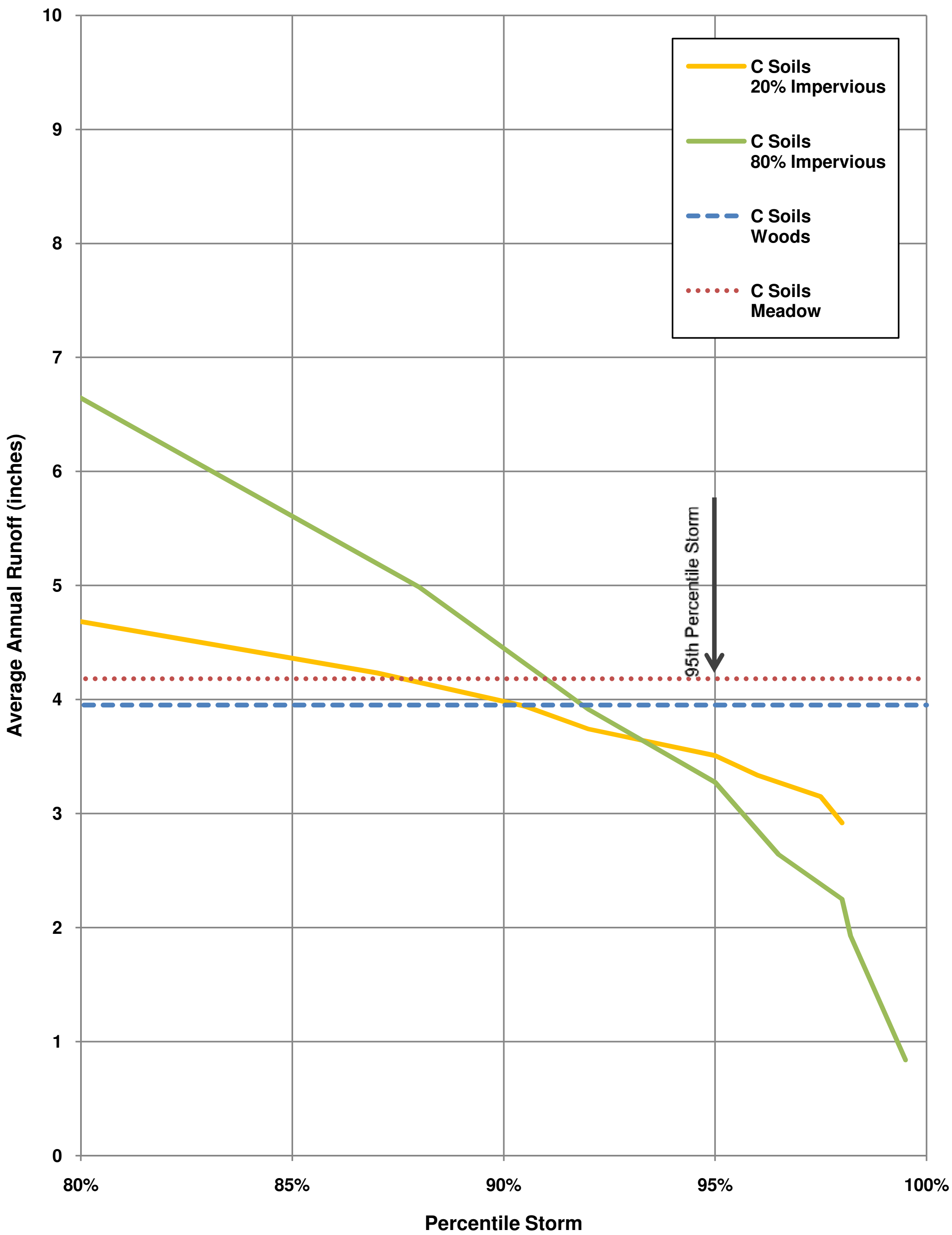


**Figure 5-36**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**C Soils - North Central Region**
**BMPs Sized Using**
**Percentile Storm Performance Goal**

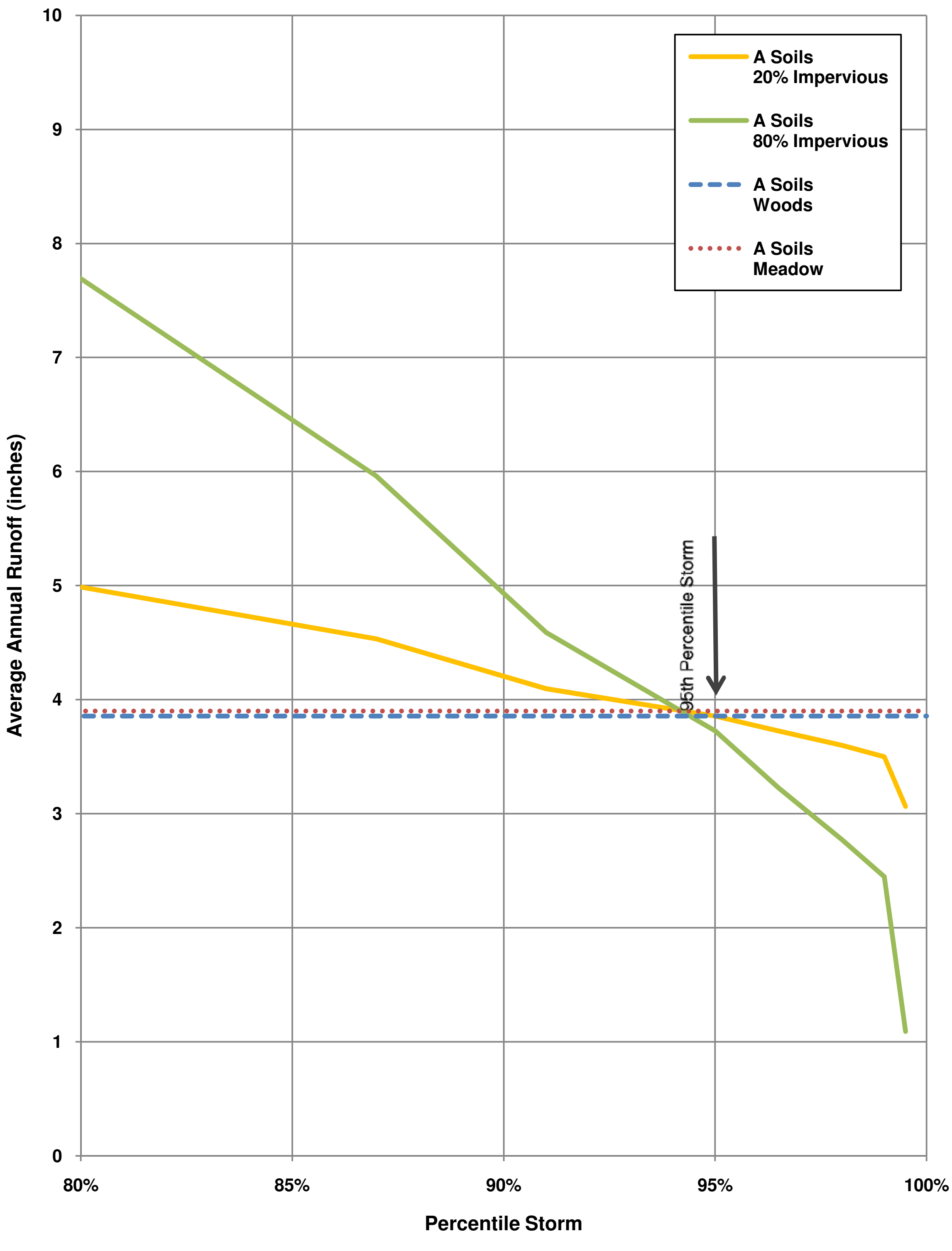


**Figure 5-37**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**A Soils - Southeast Region**
**BMPs Sized Using**
**Percentile Storm Performance Goal**

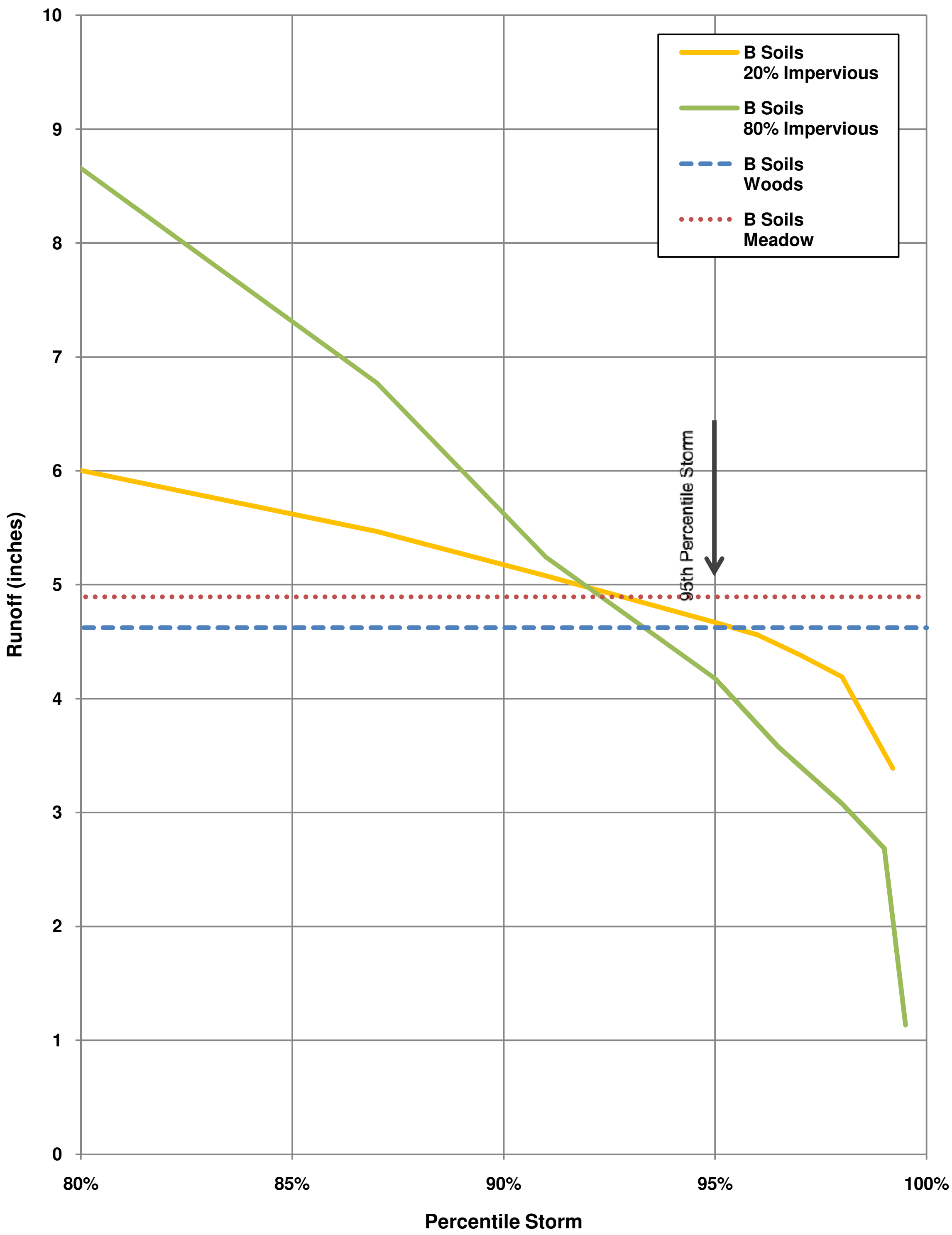


**Figure 5-38**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**B Soils - Southeast Region**
**BMPs Sized Using**
**Percentile Storm Performance Goal**

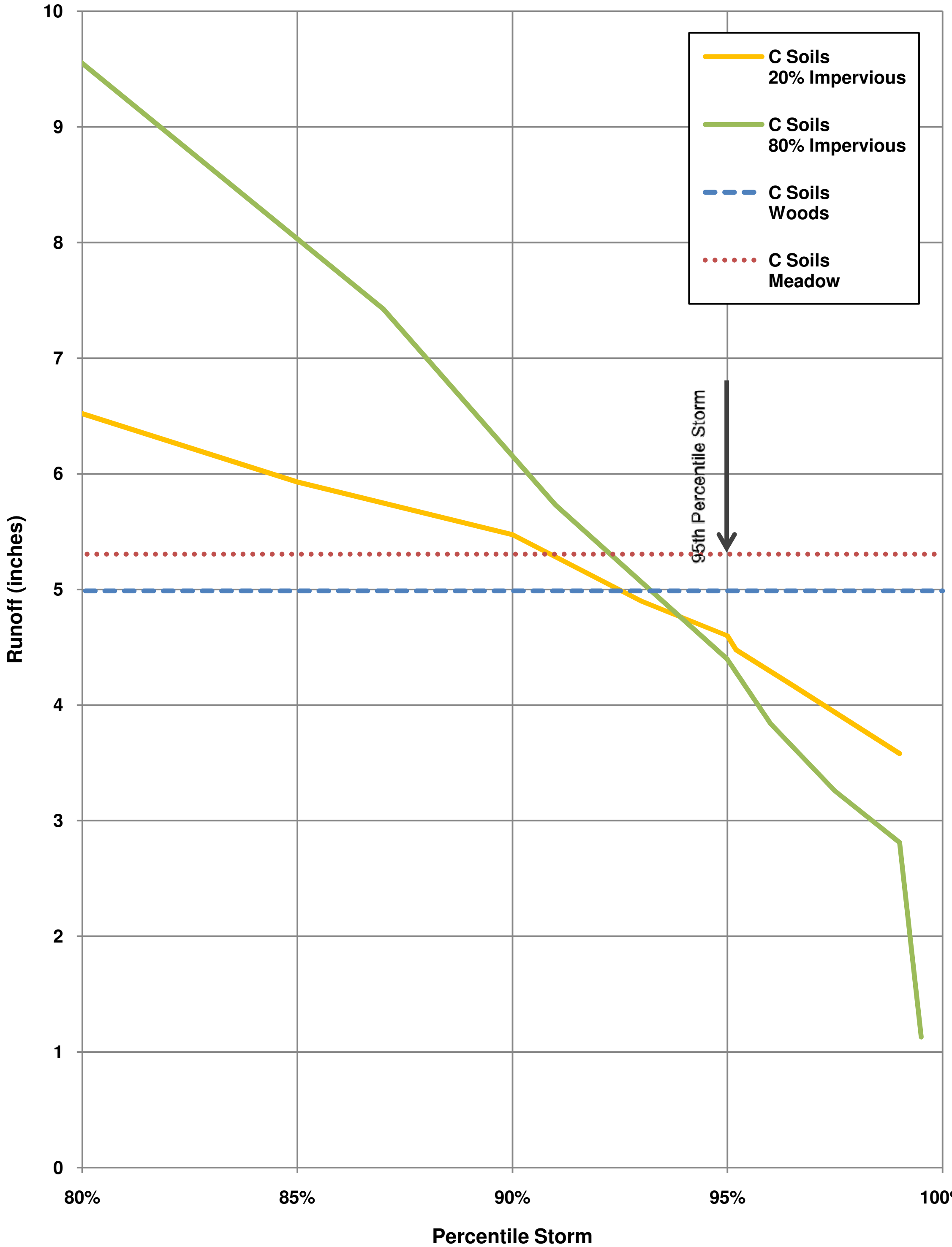


**Figure 5-39**
**Average Annual Stormwater Runoff Depth**
**Over 10-Acre Site**
**C Soils - Southeast Region**
**BMPs Sized Using**
**Percentile Storm Performance Goal**

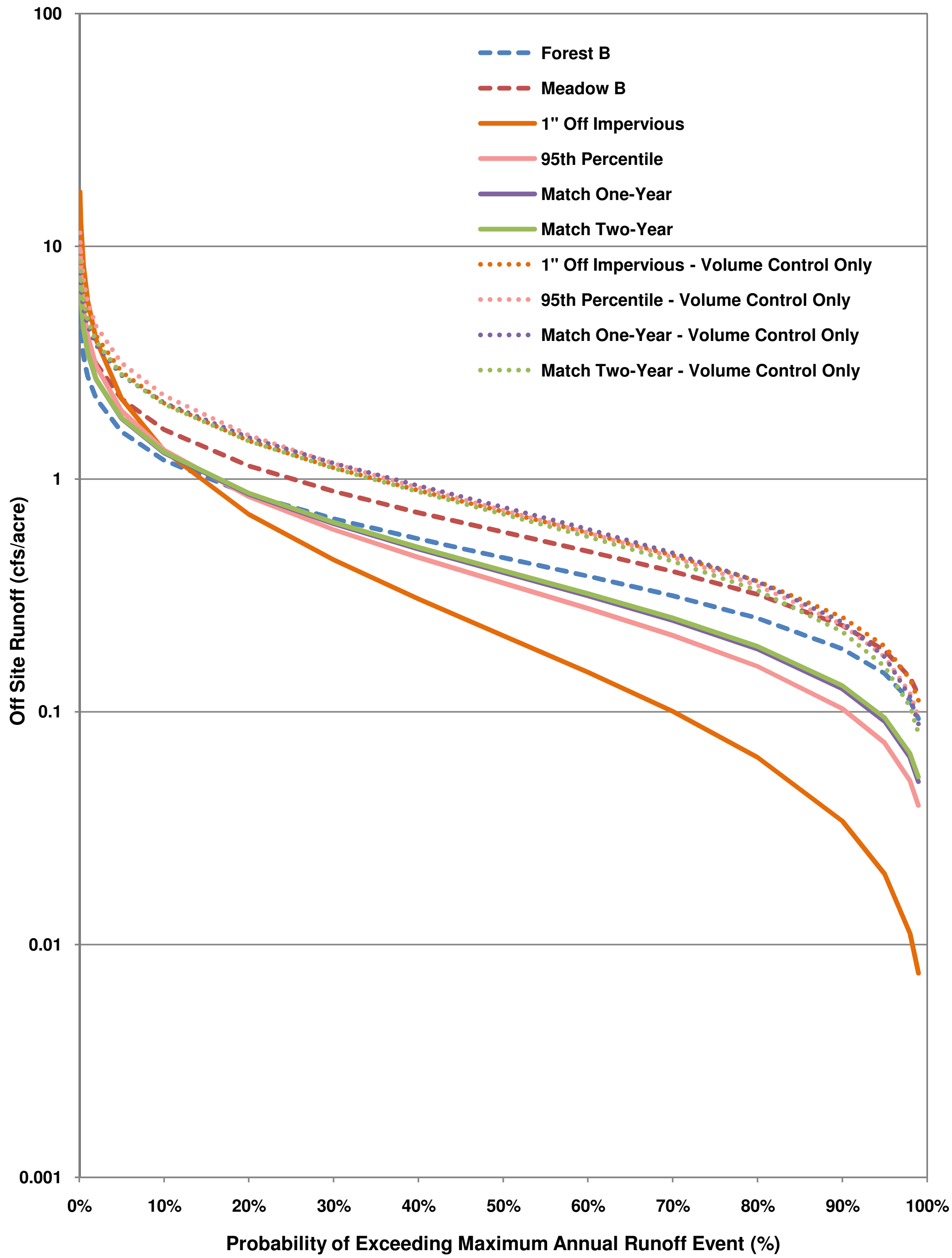


**Figure 5-40**
**Flow Frequency Curve**
**Native B Soils and**
**Developed, 20% Impervious**
**Twin Cities Region**

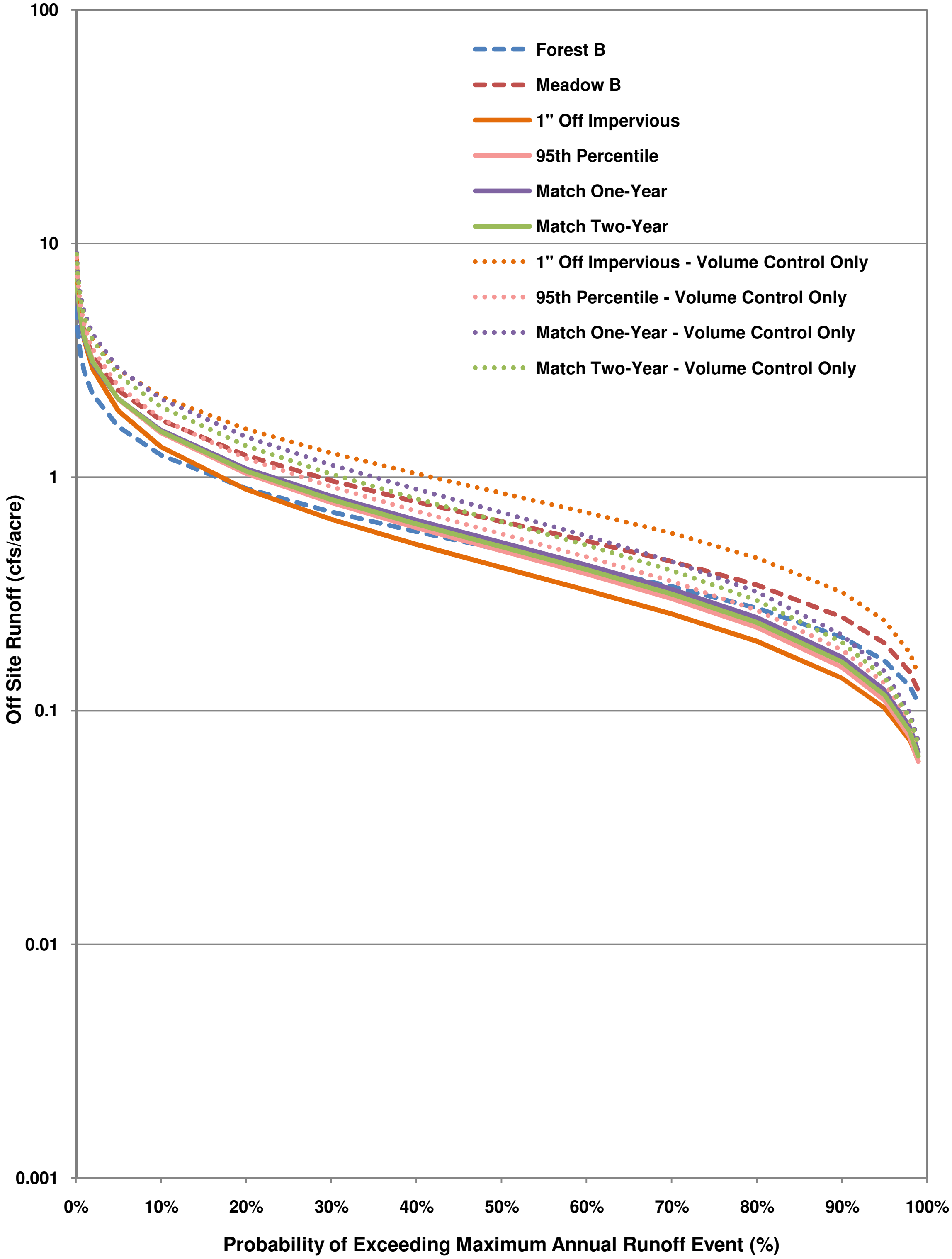


**Figure 5-41**
**Flow Frequency Curve**
**Native C Soils and**
**Developed, 20% Impervious**
**Twin Cities Region**

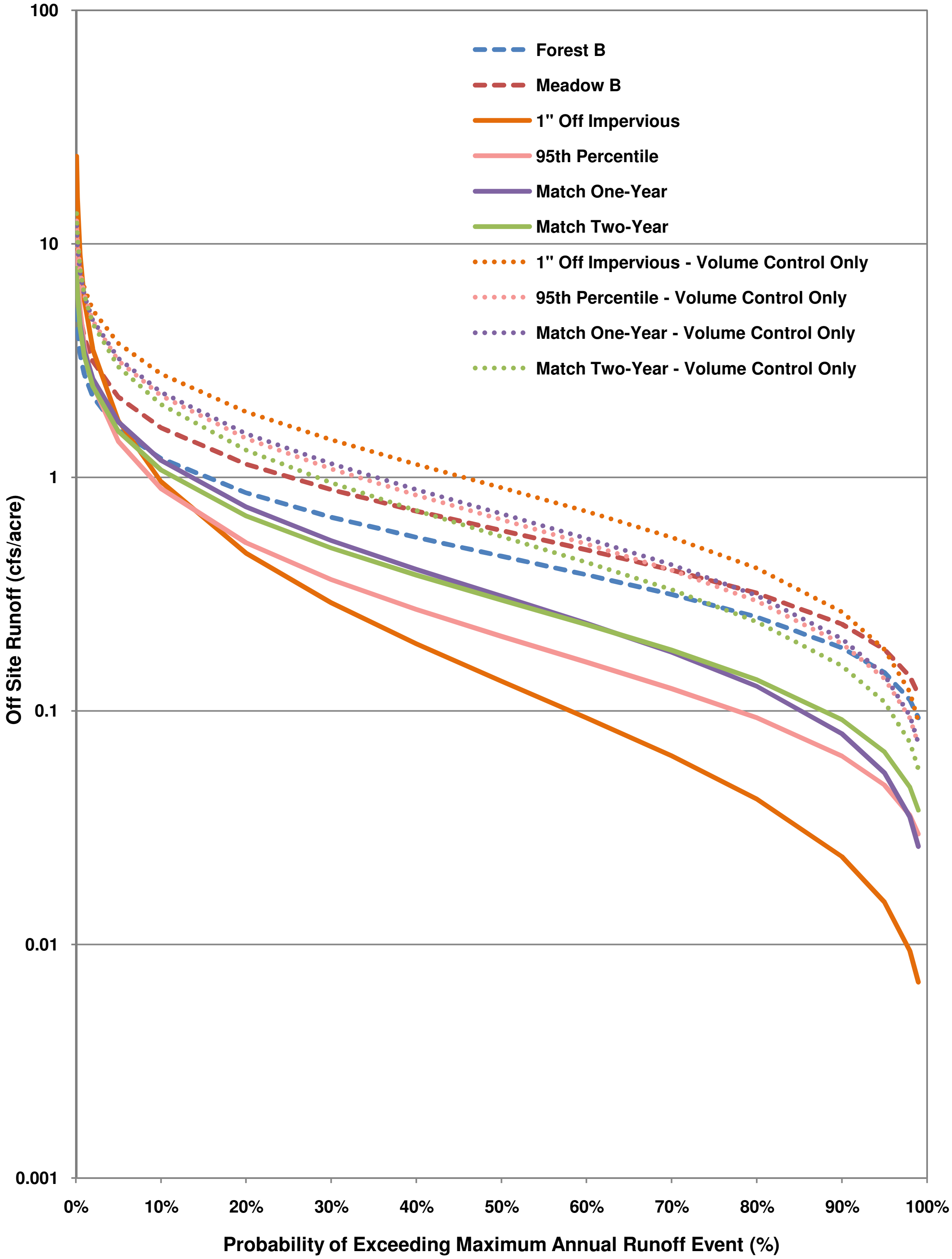


**Figure 5-42**
**Flow Frequency Curve**
**Native B Soils and**
**Developed, 50% Impervious**
**Twin Cities Region**

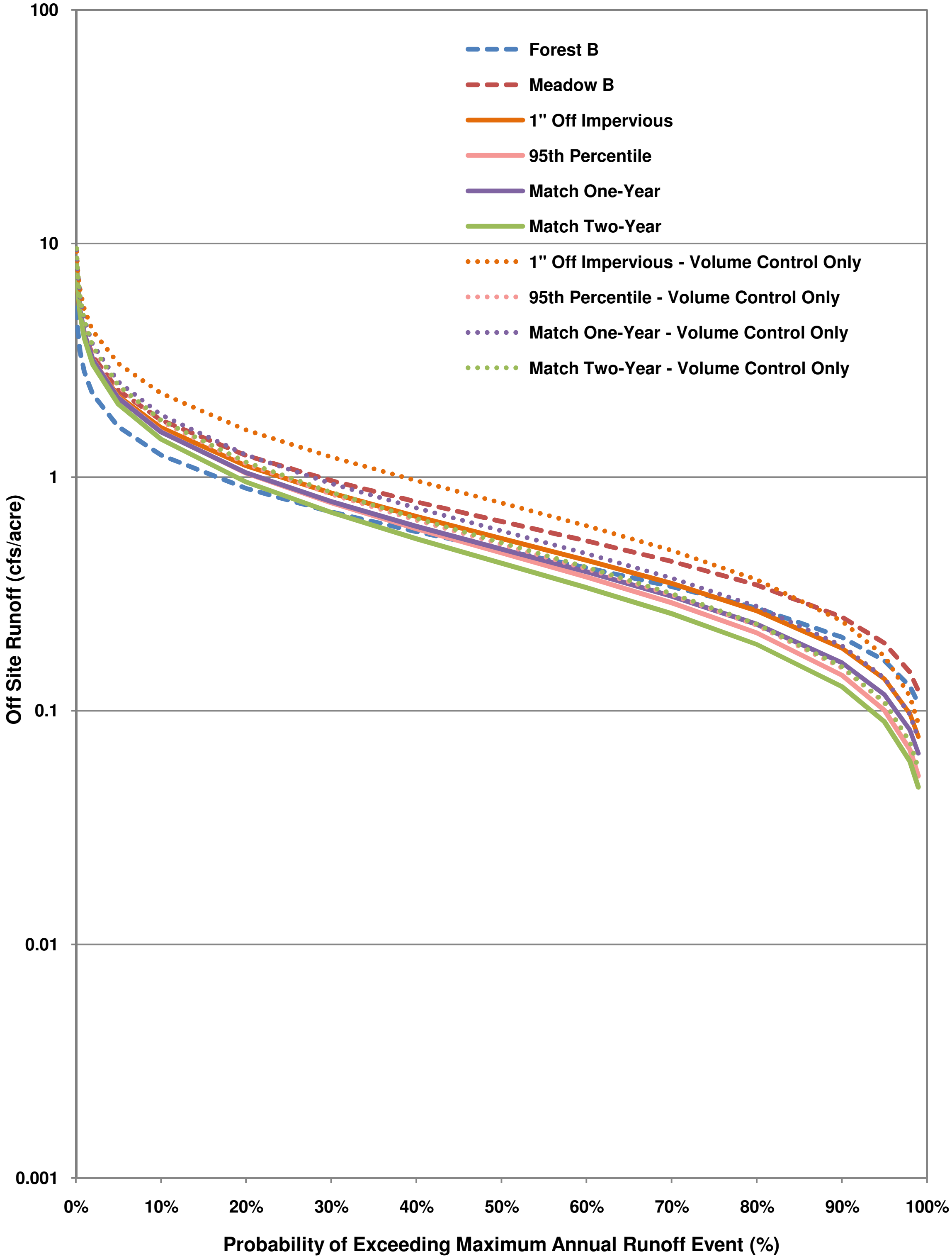


**Figure 5-43**
**Flow Frequency Curve**
**Native C Soils and**
**Developed, 50% Impervious**
**Twin Cities Region**

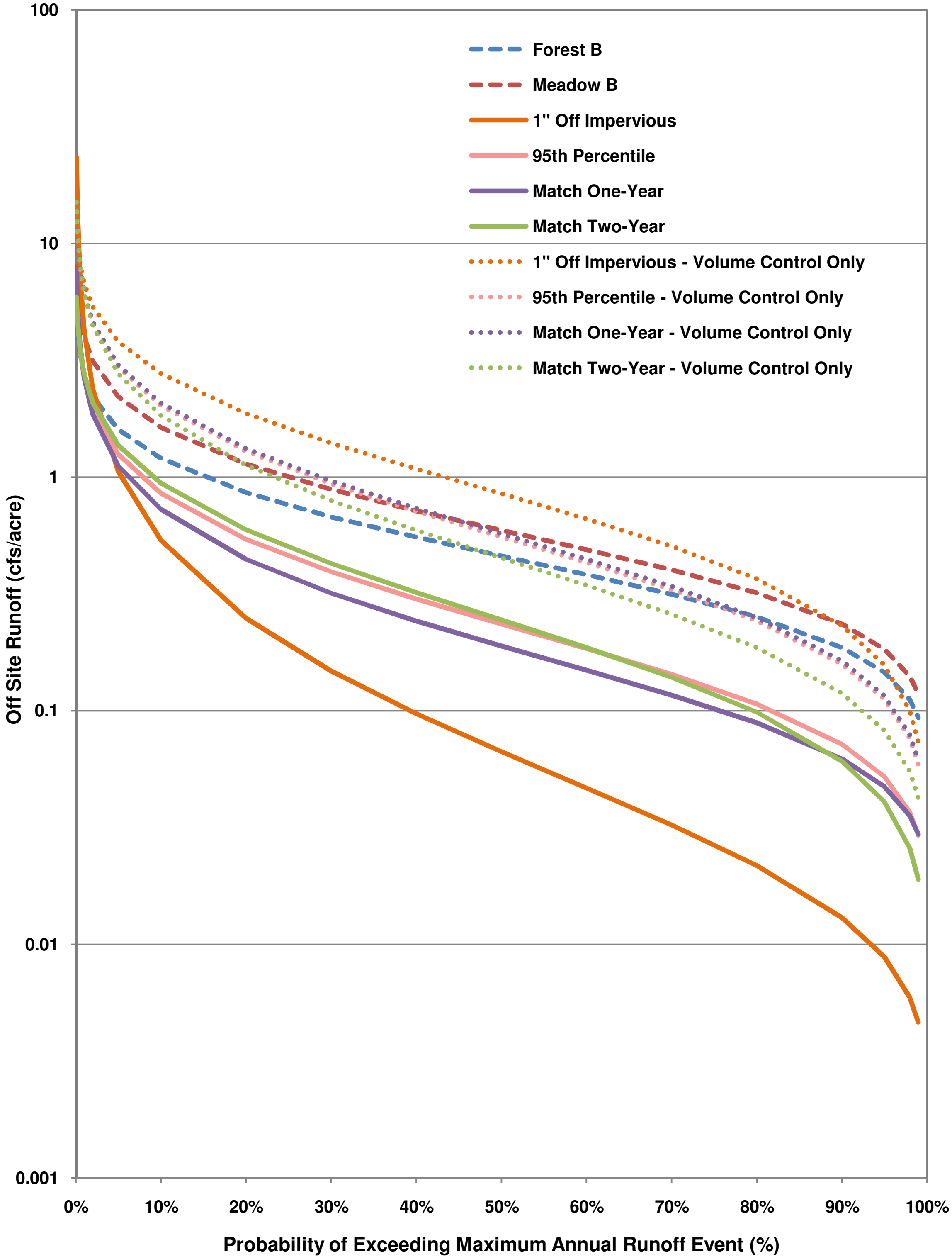


**Figure 5-44**
**Flow Frequency Curve**
**Native B Soils and**
**Developed, 80% Impervious**
**Twin Cities Region**

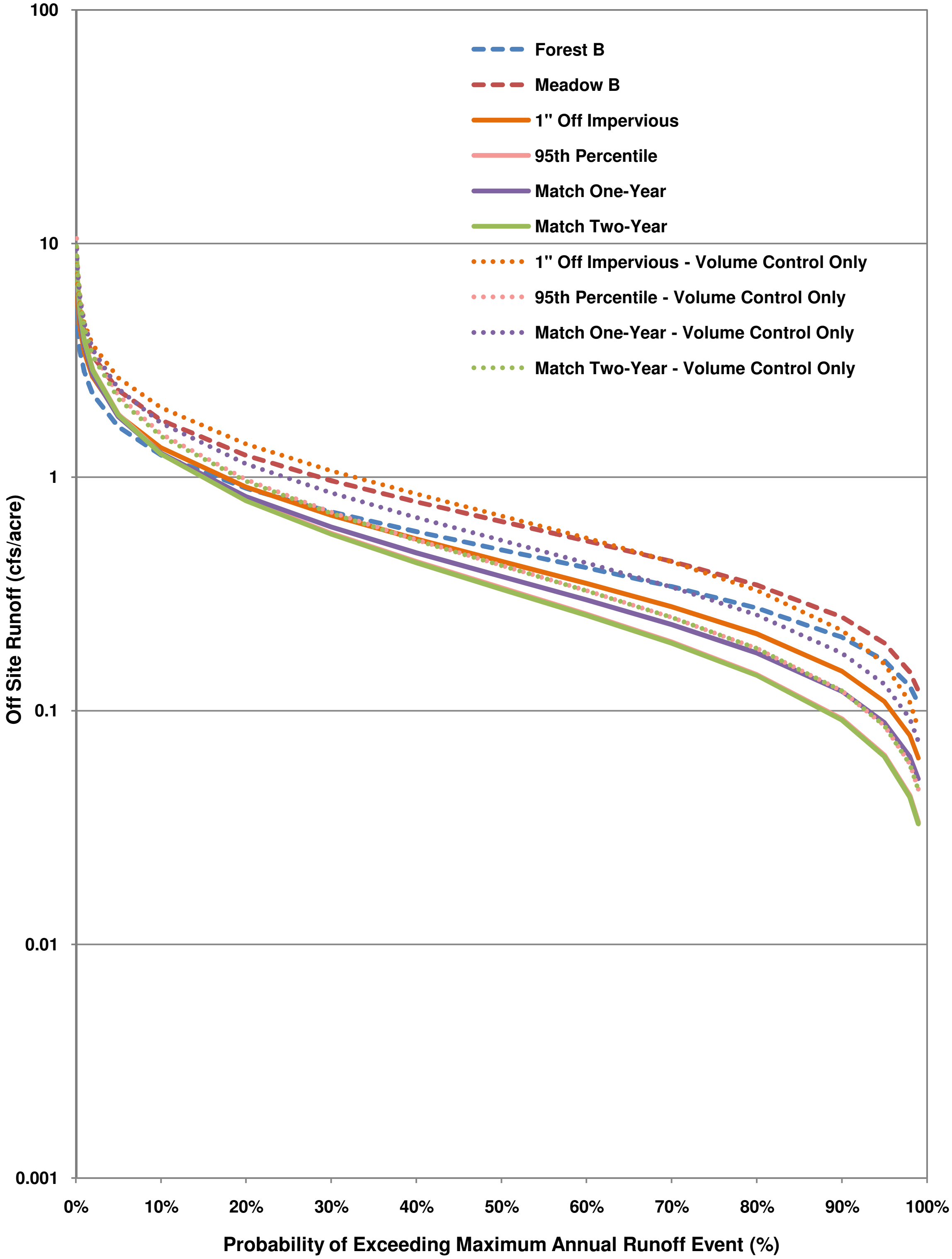


**Figure 5-45**
**Flow Frequency Curve**
**Native C Soils and**
**Developed, 80% Impervious**
**Twin Cities Region**

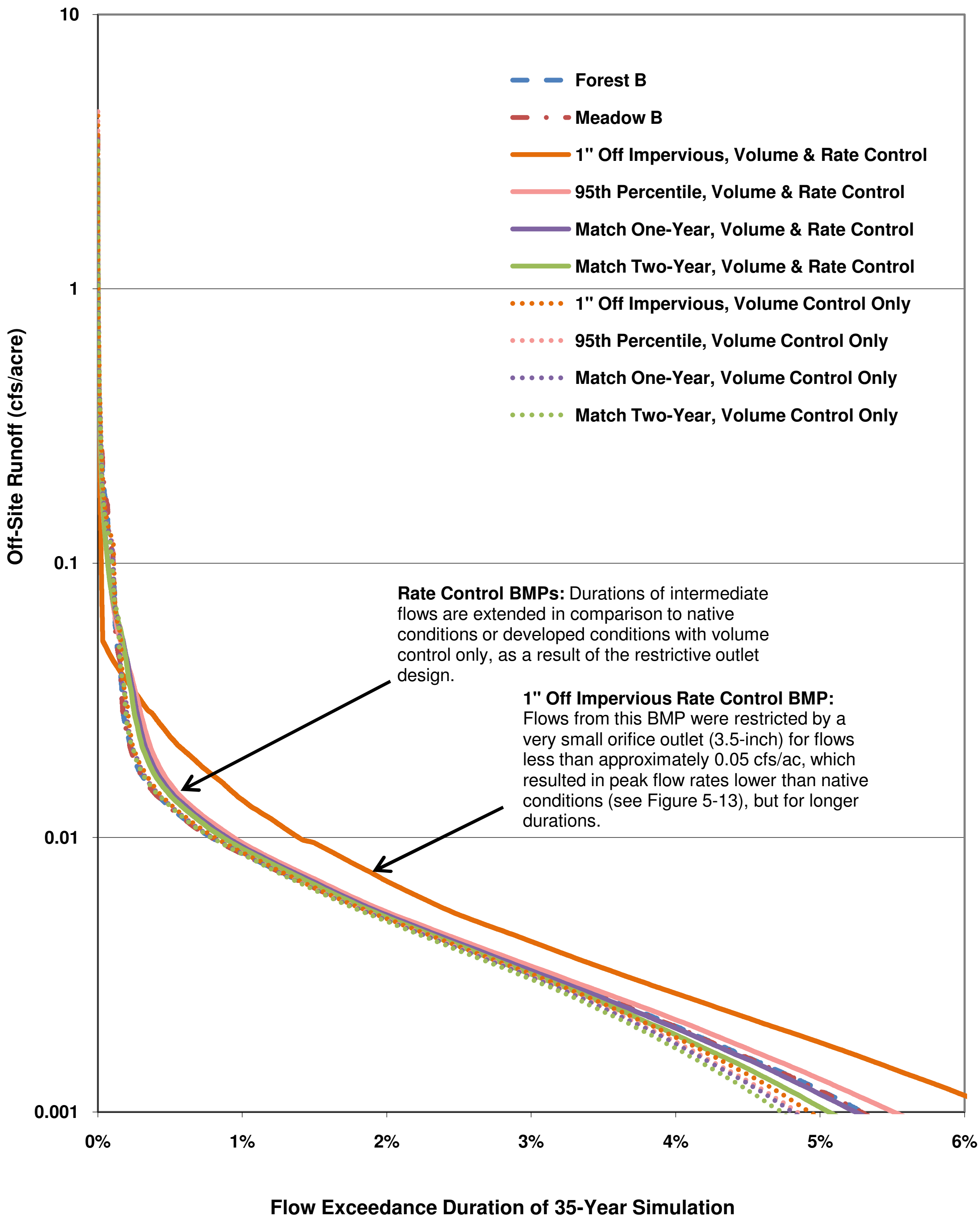


**Figure 5-46**
**Flow Duration Curve**
**Native B Soils and**
**Developed, 20% Impervious**
**Twin Cities Region**

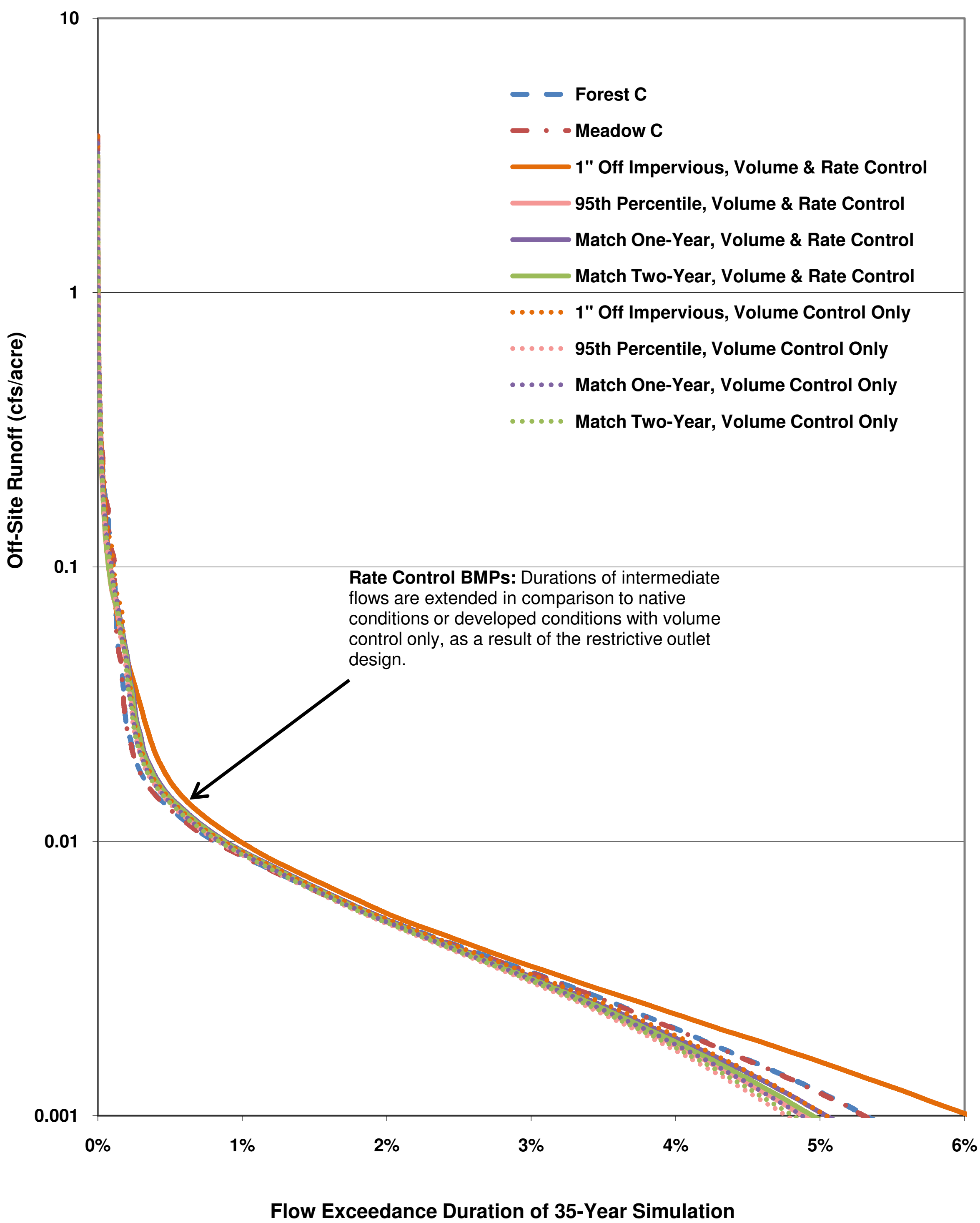


**Figure 5-47**
**Flow Duration Curve**
**Native C Soils and**
**Developed, 20% Impervious**
**Twin Cities Region**

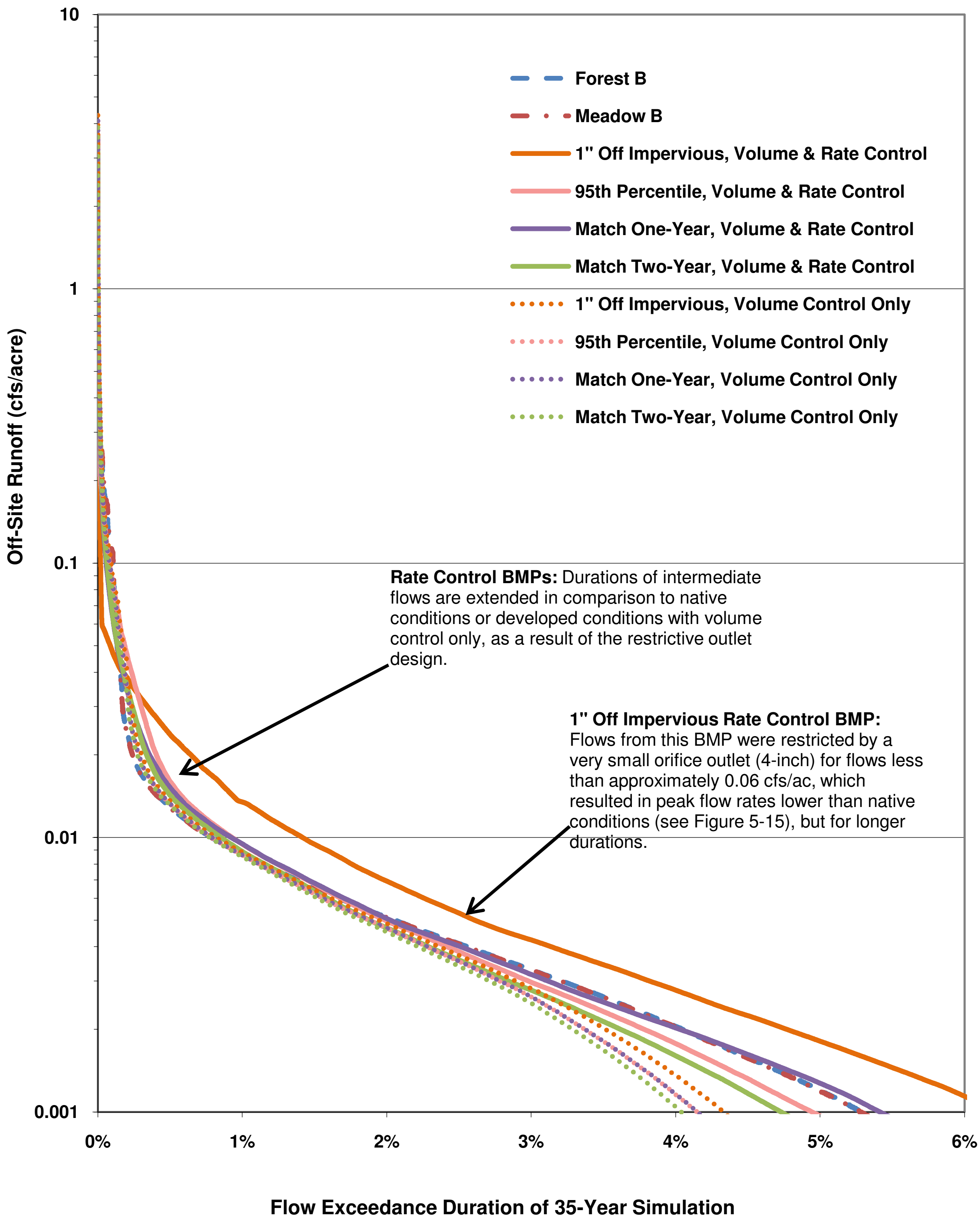


**Figure 5-48**
**Flow Duration Curve**
**Native B Soils and**
**Developed, 50% Impervious**
**Twin Cities Region**

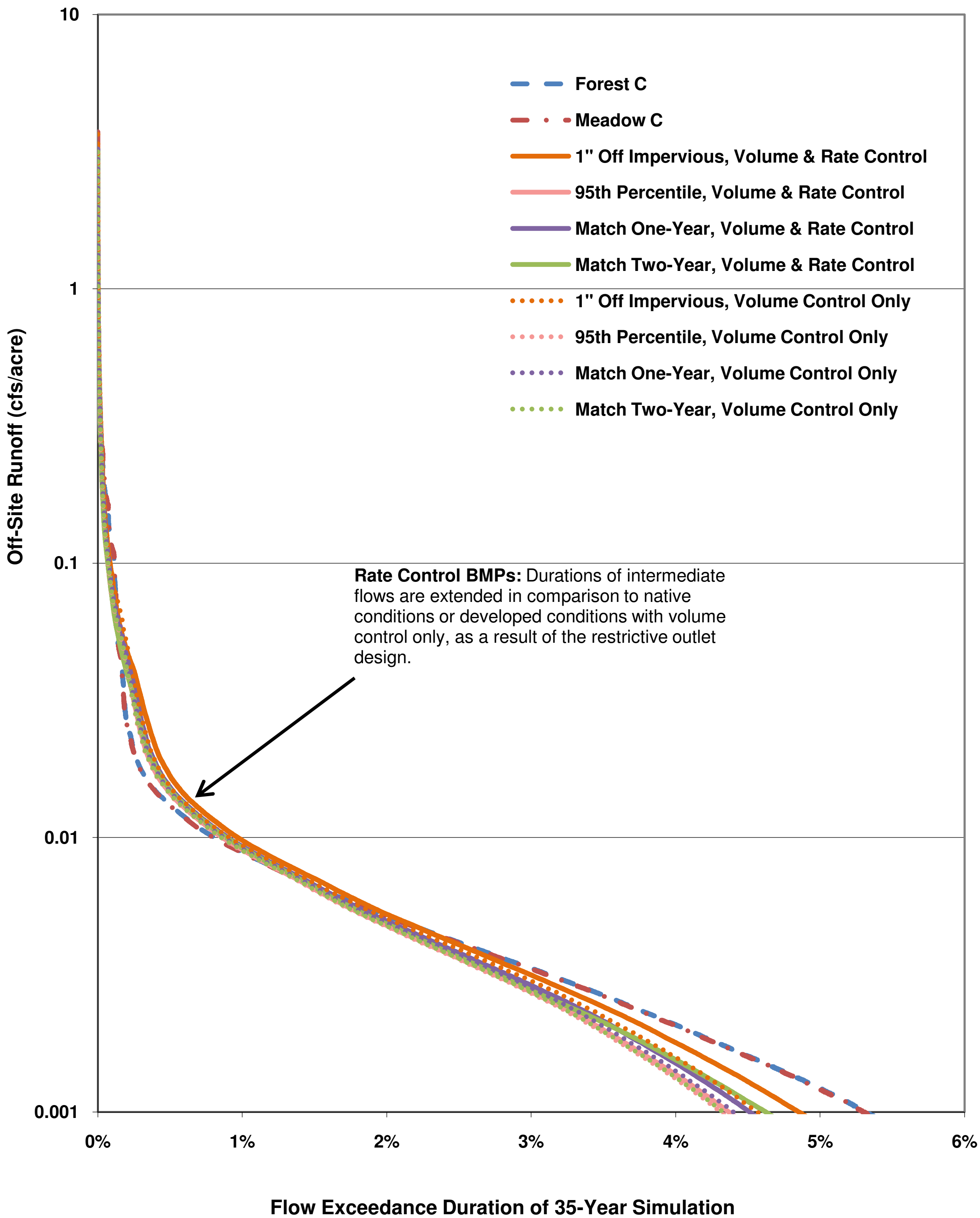


**Figure 5-49**
**Flow Duration Curve**
**Native C Soils and**
**Developed, 50% Impervious**
**Twin Cities Region**

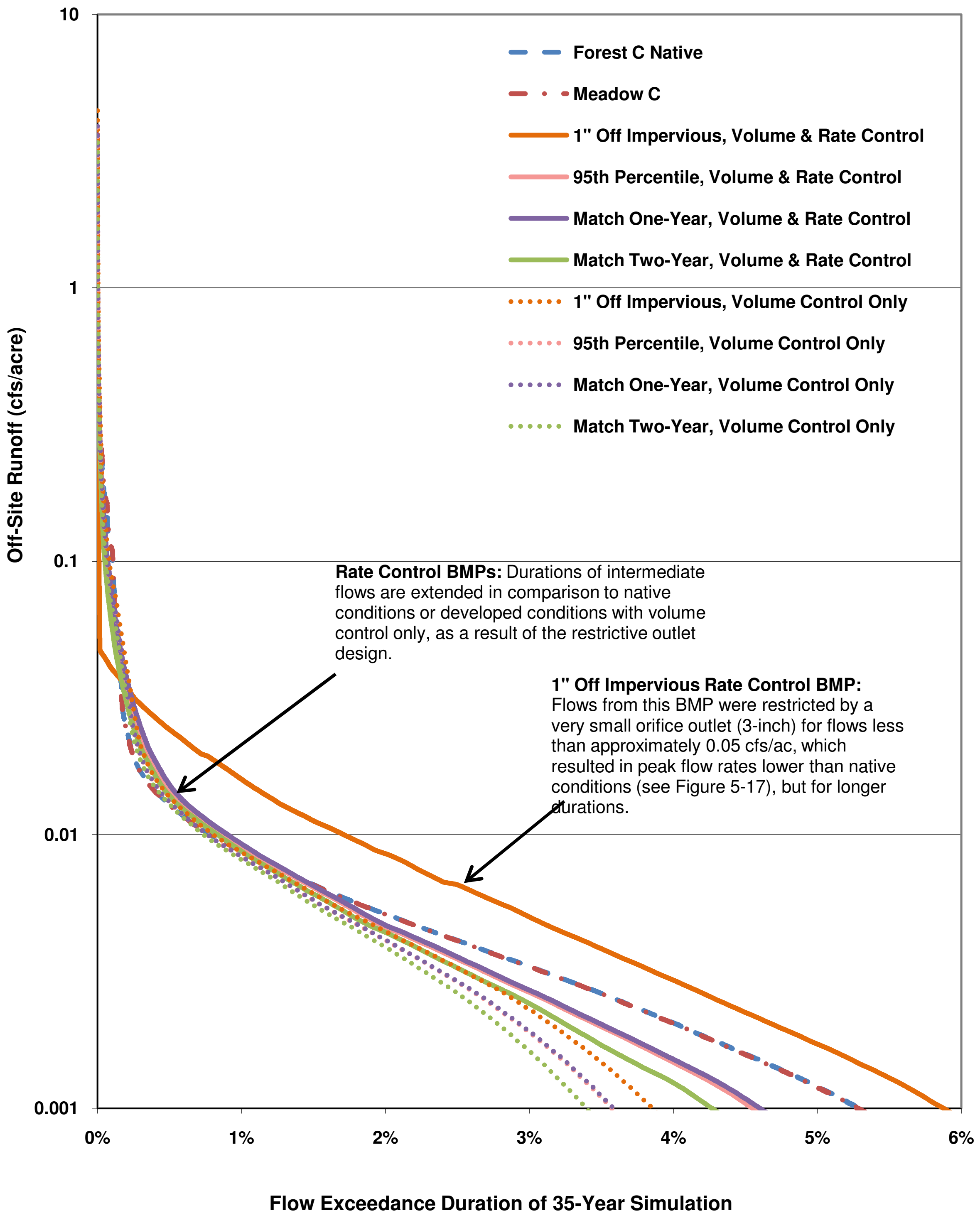


**Figure 5-50**
**Flow Duration Curve**
**Native B Soils and**
**Developed, 80% Impervious**
**Twin Cities Region**

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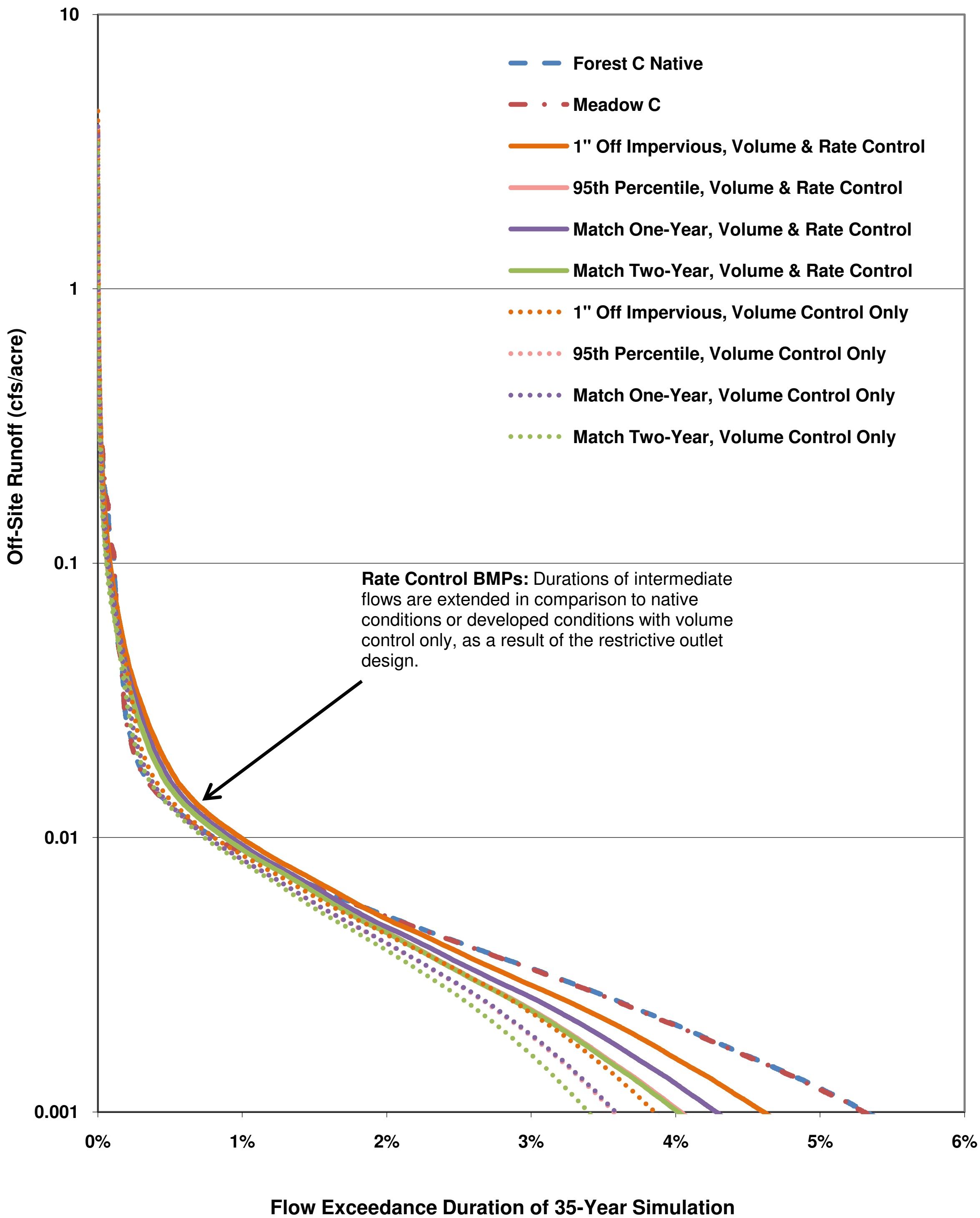
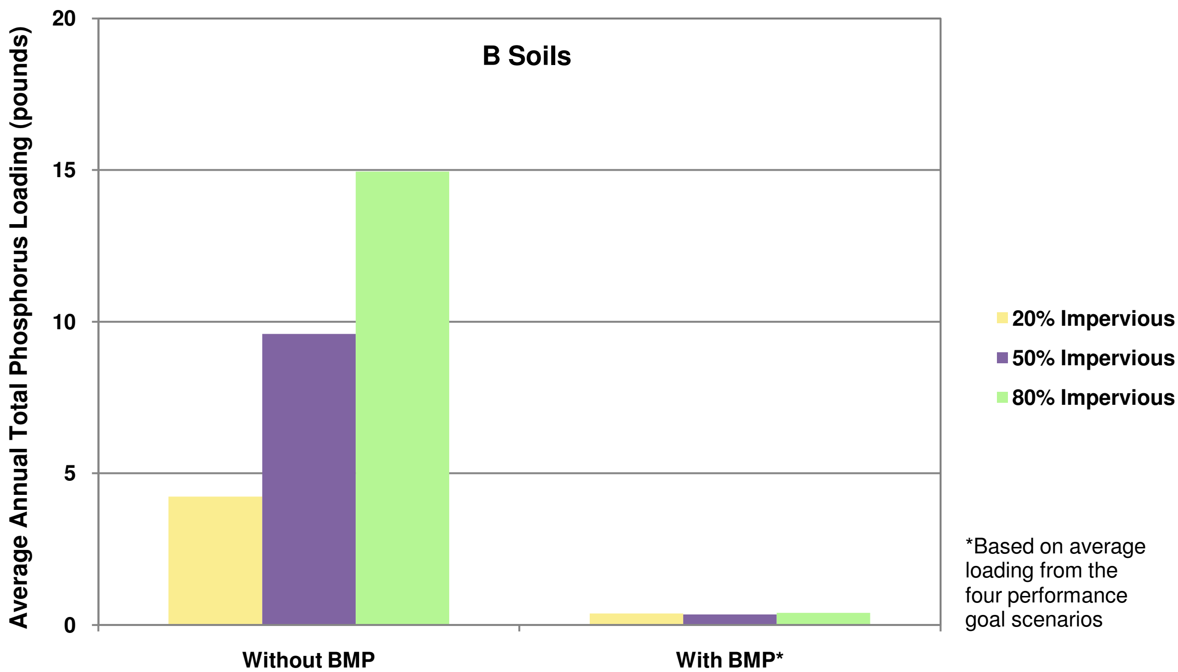



**Figure 5-51**
**Flow Duration Curve**
**Native C Soils and**
**Developed, 80% Impervious**
**Twin Cities Region**



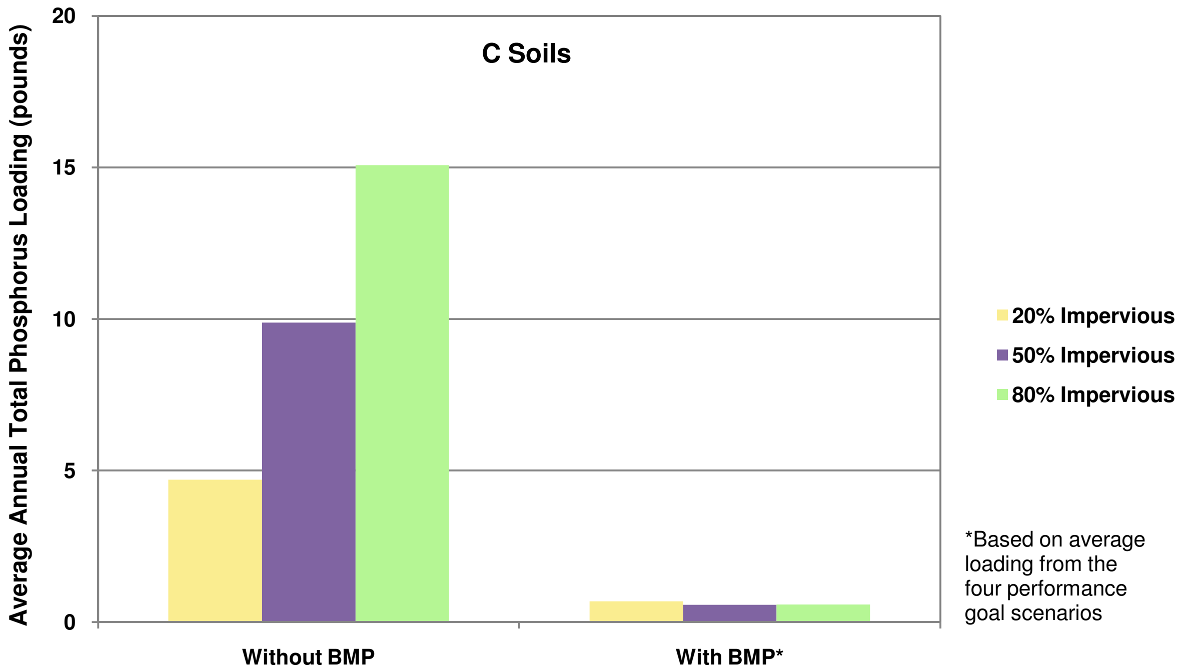
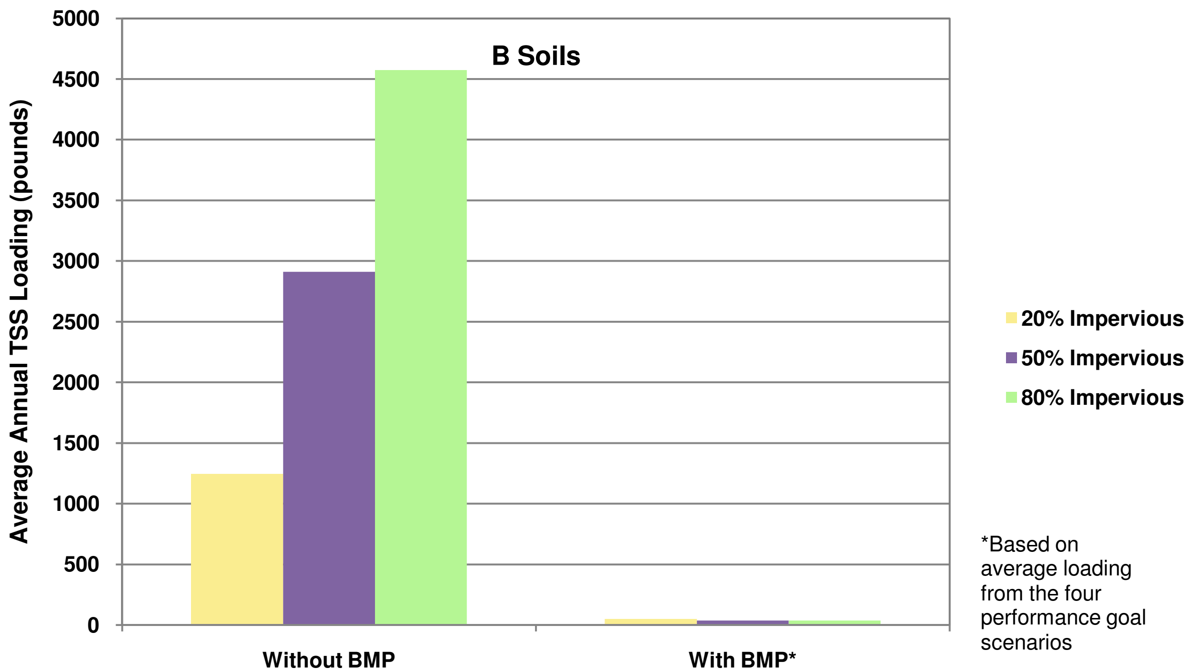




**Figure 5-52**
**Average Annual Total Phosphorus Loading from Developed Conditions with and without Volume Control BMPs**



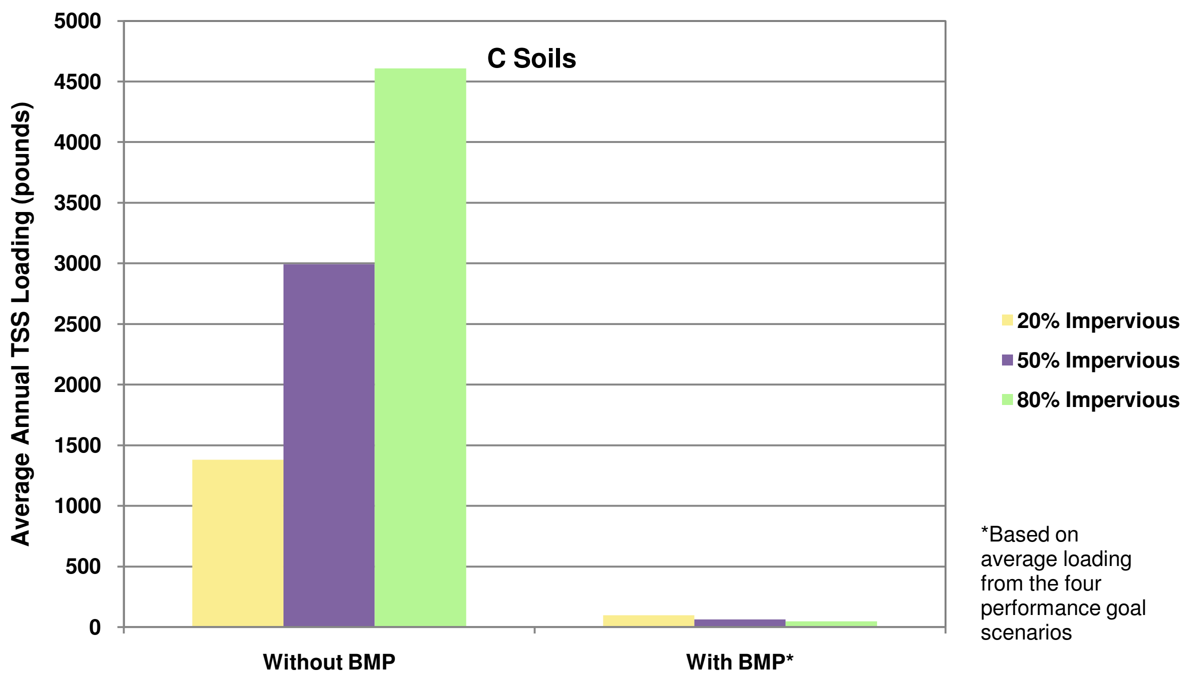
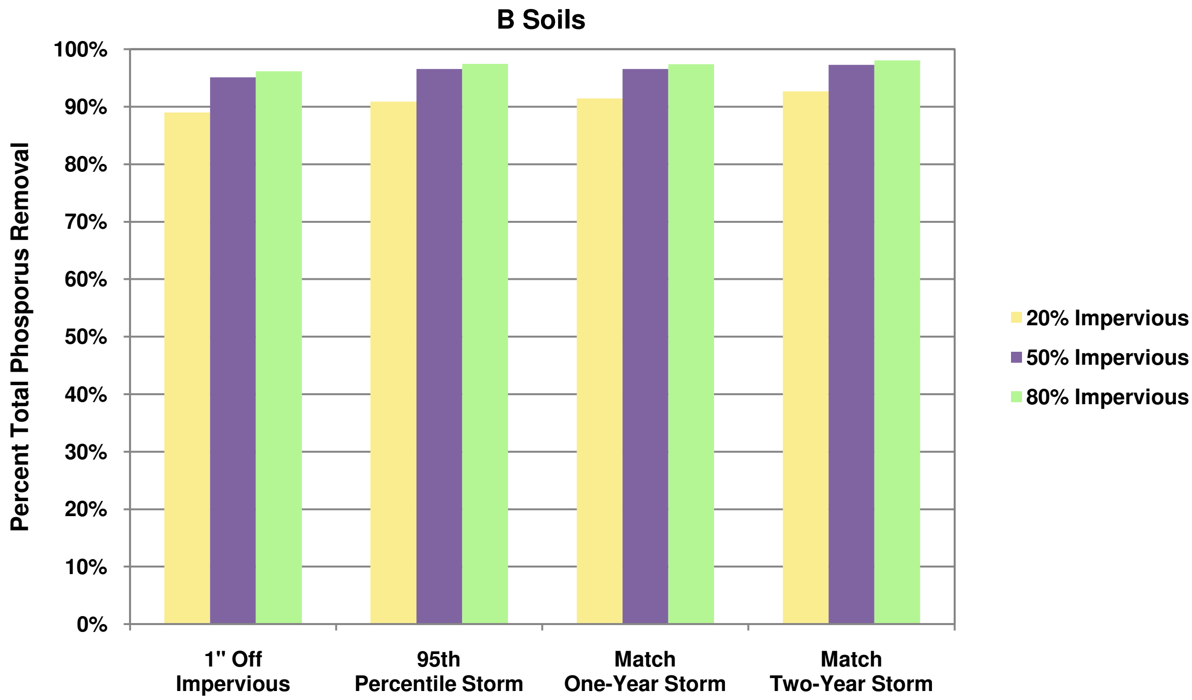




**Figure 5-53**
**Average Annual Total Suspended Solids Loading from Developed Conditions with and without Volume Control BMPs**



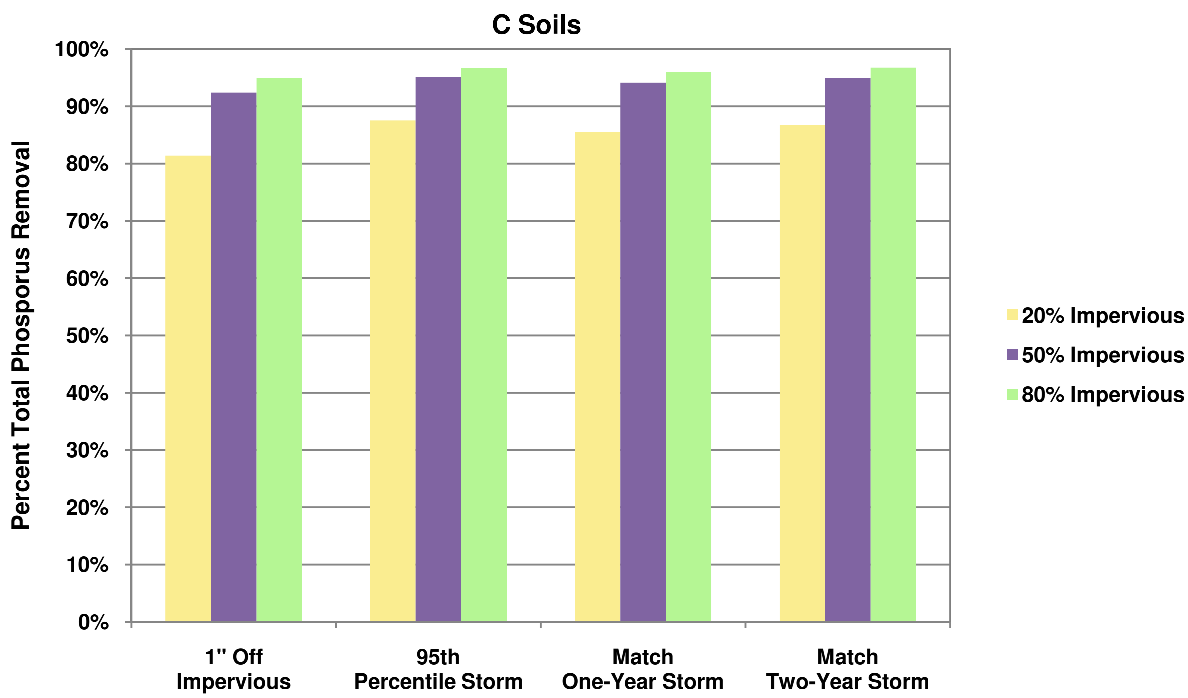




**Figure 5-54**
**Phosphorus Removal from Four Performance Goal Alternatives**

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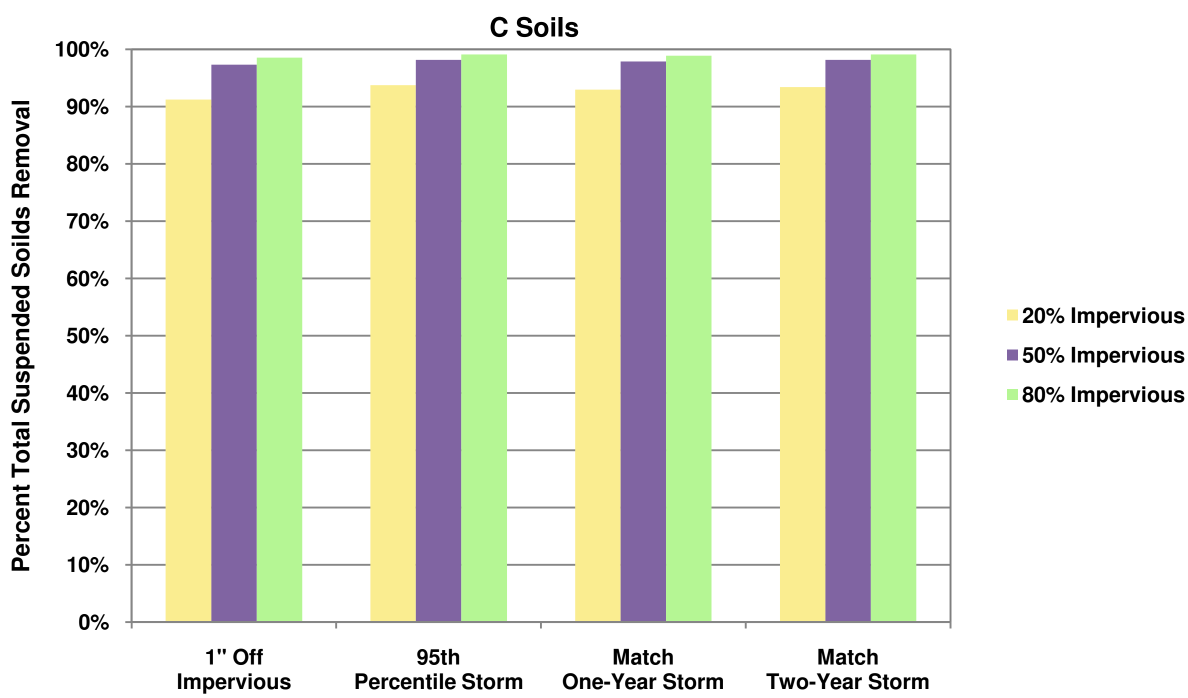


**Figure 5-55**
**Total Suspended Solids Removal from Four Performance Goal Alternatives**

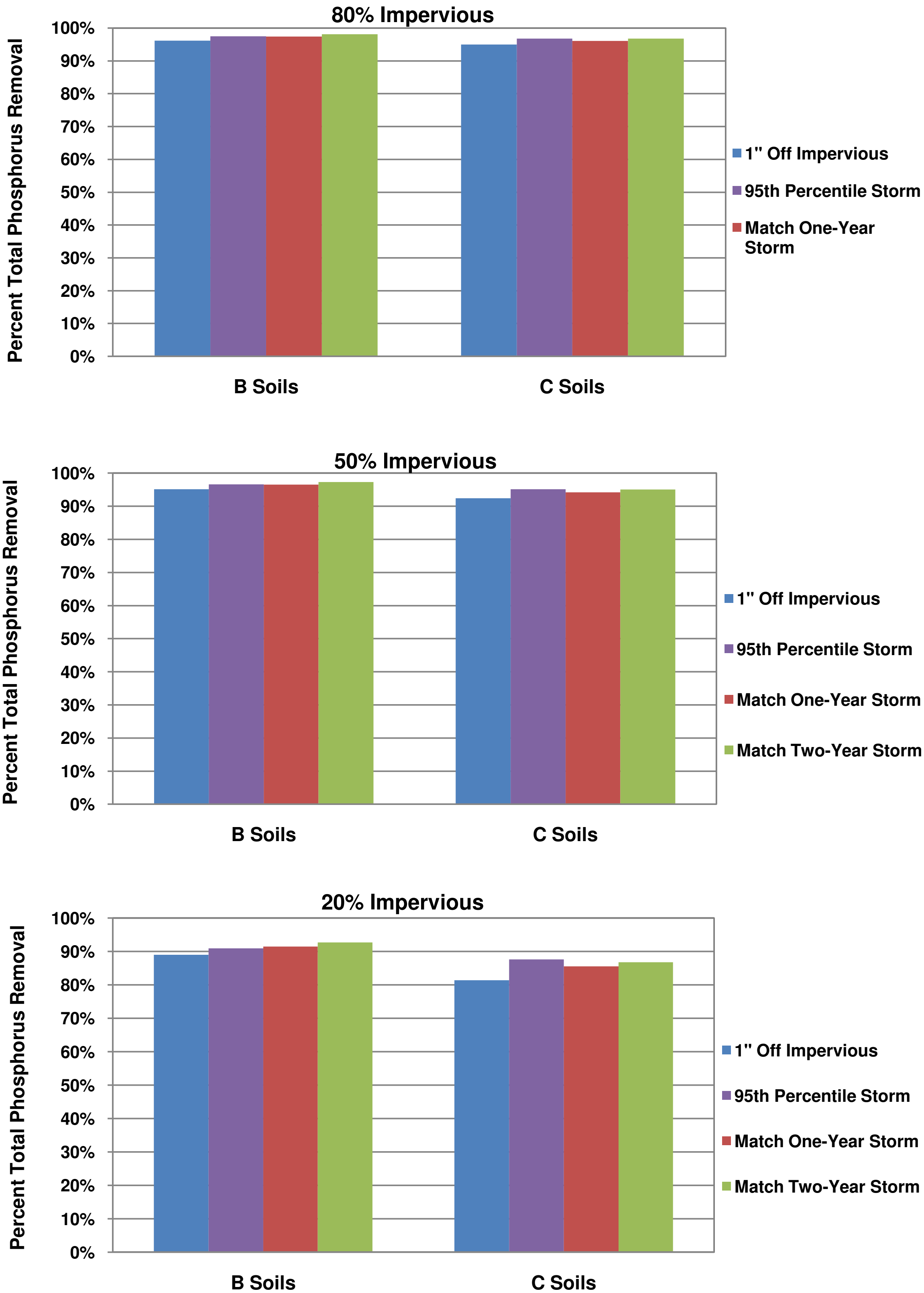


**Figure 5-56**
**Comparison of Total Phosphorus Removal from Four Performance Goal Alternatives**

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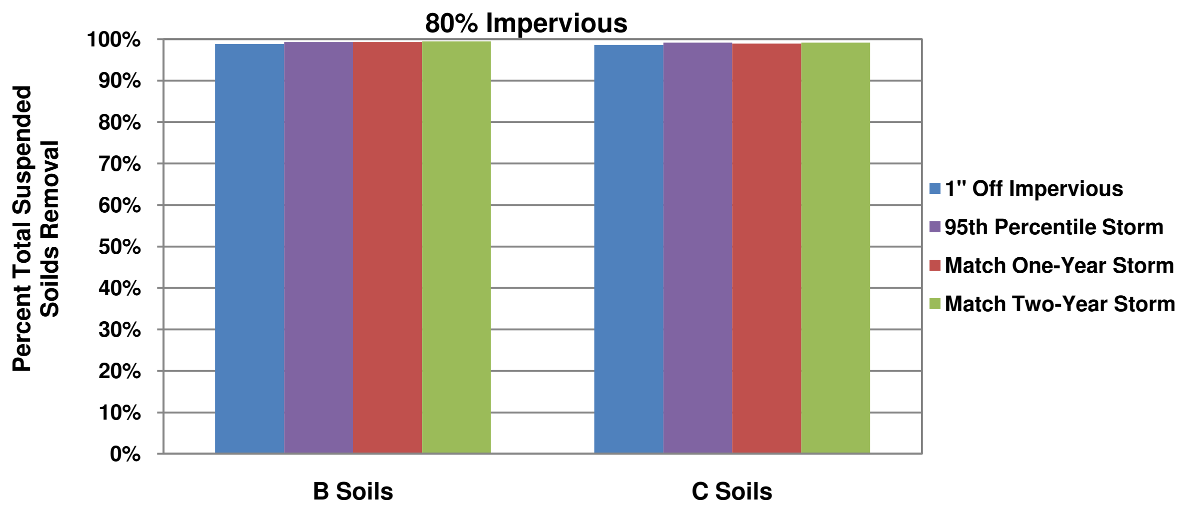


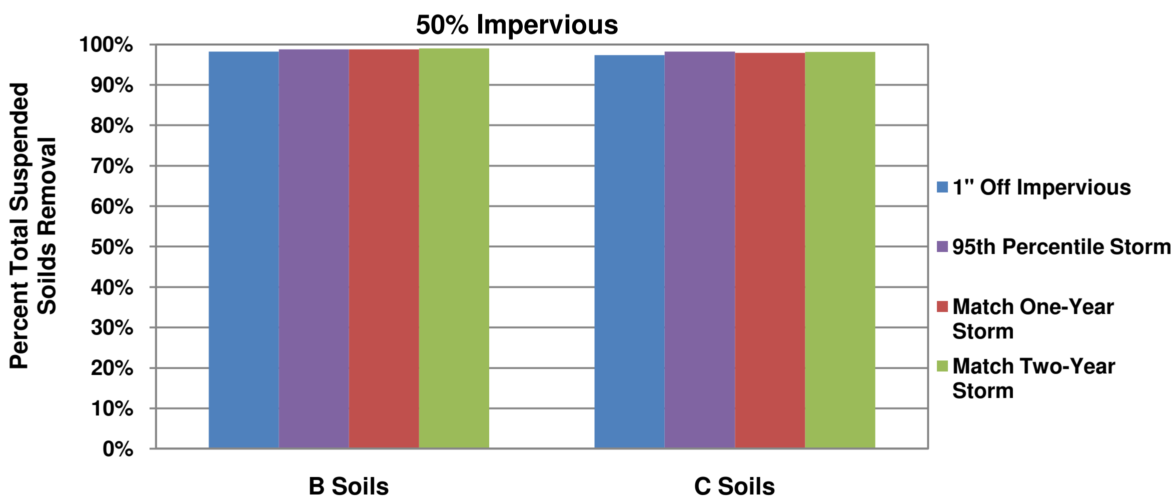


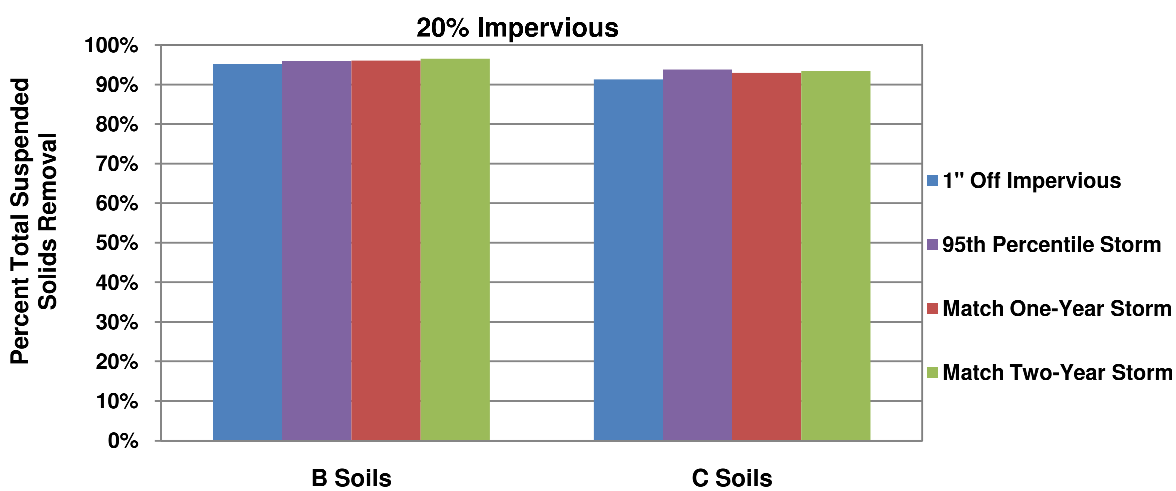


**Figure 5-57**
**Comparison of Total Suspended Solids Removal from Four Performance Goal Alternatives**

# Appendices

## Appendix A

# *Alternative Modeling Method of Frozen Ground Conditions*

## A.1 Background

As discussed in Section 4.1.3, Frozen Ground Conditions, for the MIDS continuous simulation, pervious surfaces were modeled to produce the maximum runoff during frozen ground conditions. During the period of frozen ground, native and developed watersheds were considered 100% impervious with no depression storage. Any snowmelt that occurred during this period would runoff from the site, with only minor evaporation losses.

Snowmelt on frozen ground conditions is highly variable from year to year depending on the depth of the frozen ground and the moisture content of the soil when the ground initially froze. Ground that had a high water content in the fall can act as impervious during the spring snowmelt, while ground that freezes without moisture content may allow infiltration at close to summer rates.

MPCA directed Barr to model frozen ground conditions using assumptions that would generate less runoff during snowmelt and compare those results to the high runoff frozen ground assumptions. For this comparison, Southeast region was chosen. Native conditions and 20 and 80% impervious developed conditions were modeled for HSG A, B and C soils over the entire 33-year continuous simulation. A range of BMPs were modeled, similar to the original analysis, in order to determine the size BMP necessary to match native forest and meadow conditions.

## A.2 Frozen Ground Assumptions Considered

### A.2.1 Native Conditions

The overland roughness coefficient was assumed to be near zero (0.014) in the original frozen ground modeling (high runoff method), to be consistent with the assumption that the ground would act as an impervious surface. In the alternative frozen ground modeling (low runoff method), the overland roughness coefficient was made consistent with the non-frozen runoff modeling. For native forest and meadow, the overland roughness coefficients were modeled as 0.4 and 0.14, respectively.

Interception and depression storage in the original frozen ground modeling was assumed to be zero as it was assumed that the storage would fill with water and freeze, removing much of the depression storage capacity. In the alternative frozen ground modeling, the depression storage for native was placed at 0.3 inches. This is slightly lower than the 0.4 inches of depression storage used in the non-frozen ground modeling due to the loss of some vegetative interception. Research by Xiao indicates that leaf interception in forests will intercept approximately 0.1 inches of precipitation. Since during the frozen ground period this interception is not available, a lower interception value of 0.3 inches was used.

The interception and depression storage were modeled in the hydraulics layer in the XP-SWMM model as a 4.5-inch deep basin, 2/3 of an acre in area, creating depression storage volume equivalent to 0.3 inches over the entire 10-acre site. This assumption acknowledges that snowmelt will find deeper depressions, or intermediate low points, where runoff can pool several inches. Depression storage was modeled in the hydraulics layer, as opposed to the hydrologic layer, due to the limitations of XP-SWMM in simulating runoff and infiltration in frozen ground conditions.

To simulate infiltration during frozen ground conditions, the interception and depression storage basins were allowed to infiltrate at half the rate of summer BMP infiltration rates referenced in Table 4-6. The basins infiltrated at rates of 0.45, 0.3 and 0.1 inches per hour for HSG A, B and C, respectively. Any runoff generated by snowmelt or rainfall during frozen ground conditions that did not infiltrate through the interception/depression storage basins ran off the site and was reported as runoff. These runoff results (low runoff) are compared to the original frozen ground modeling results (high runoff) below in Table A-1.

Using the low runoff method, the runoff is much lower and varies significantly based on the soil type, with HSG C soils generating over three times as much runoff as HSG A soils. Using the original high runoff method, all soils and vegetation types produce the same runoff.

**Table A-1 Average Annual Runoff from Native Conditions, Southeast Region, Using High and Low Runoff Frozen Ground Methodologies**

| Hydrologic Soil Group | Native Vegetation | Frozen Ground Modeling Method | |
|---|---|---|---|
| | | High Runoff | Low Runoff |
| | | Average Annual Runoff Depth (inches) | Average Annual Runoff Depth (inches) |
| A | Meadow | 3.78 | 0.36 |
| | Forest | 3.78 | 0.42 |
| B | Meadow | 3.78 | 0.57 |
| | Forest | 3.78 | 0.63 |
| C | Meadow | 3.78 | 1.38 |
| | Forest | 3.78 | 1.46 |

### A.2.2 Developed Conditions

For developed pervious surfaces, the overland roughness coefficient was assumed to be near zero (0.014) in the original frozen ground modeling (high runoff method), to be consistent with the assumption that the ground would act as an impervious surface. In the alternative frozen ground modeling (low runoff method), the overland roughness coefficient was made consistent with the non-frozen runoff modeling. For pervious developed turf grass, the overland roughness coefficient was modeled as 0.24.

Depression storage in the original frozen ground modeling was assumed to be zero as it was assumed that the storage would fill with water and freeze, removing much of the depression storage capacity. In the alternative frozen ground modeling, the depression storage for pervious turf grass was placed at 0.25 inches, the same assumption as non-frozen ground modeling.

Pervious depression storage was modeled in the hydraulics layer in the XP-SWMM model as a six-inch deep basin, sized to accommodate 0.25 inches over the pervious portion of the developed 10-acre site. This assumption acknowledges that snowmelt will find deeper depressions, or intermediate low points, where runoff can pool several inches. Pervious depression storage was modeled in the hydraulics layer, as opposed to the hydrologic layer, due to the limitations of XP-SWMM in simulating runoff and infiltration in frozen ground conditions.

For the alternative frozen ground modeling, impervious depression storage was assumed to be the same as the non-frozen modeling, or 0.06 inches. This depression storage was modeled in the hydrologic layer.

To simulate infiltration on the turf grass, or pervious surfaces, during frozen ground conditions, the pervious depression storage basins were allowed to infiltrate at one quarter the rate of summer BMP infiltration rates referenced in Table 4-6, due to the more compacted nature and shallow roots of developed pervious surfaces. The basins infiltrated at rates of 0.225, 0.15 and 0.05 inches per hour for HSG A, B and C, respectively. Any runoff generated by snowmelt or rainfall during frozen ground conditions that did not infiltrate through the pervious depression storage basins then ran into the volume control BMP, or rainwater garden.

Runoff that overtopped the pervious depression storage basins and runoff from the impervious surfaces was routed into volume control BMPs, or rainwater gardens, where infiltration could occur. The original, high runoff methodology assumed that the volume control BMPs did not infiltrate during the frozen ground period. The BMPs were allowed to fill with snowmelt or rain one time, and then infiltrate after the ground thawed. The alternative, low runoff methodology allows infiltration in the BMP during the frozen ground period. The BMP was allowed to infiltrate at half the rate of summer BMP infiltration rates referenced in Table 4-6. The basins infiltrated at rates of 0.45, 0.3 and 0.1 inches per hour for HSG A, B and C, respectively. Any runoff generated by snowmelt or rainfall during frozen ground conditions that did not infiltrate through in the volume control BMP ran off the site and was reported as runoff. These runoff results (low runoff) are compared to the original frozen ground modeling results (high runoff) below in Table A-2 for a volume control BMP sized for one inch of runoff from the impervious surfaces.

Using the low runoff method, the runoff is much lower and varies significantly based on the soil type, with HSG C soils generating several times as much runoff as HSG A soils. The sites with more impervious, and thus a larger BMP, had significantly less runoff; larger BMPs were able to keep up with the rate of snowmelt easier and infiltrate more snowmelt during the frozen ground period.

**Table A-2 Average Annual Runoff from a Developed Site in Southeast Region with BMP Sized to Retain One Inch Times the Impervious Surface Area, Using High and Low Runoff Frozen Ground Methodologies**

| Hydrologic Soil Group | Developed Site Imperviousness | Frozen Ground Modeling Method: High Runoff – Average Annual Runoff Depth (inches) | Frozen Ground Modeling Method: Low Runoff – Average Annual Runoff Depth (inches) |
|---|---|---|---|
| A | 20% | 3.59 | 0.36 |
| | 80% | 2.96 | 0.03 |
| B | 20% | 3.59 | 0.59 |
| | 80% | 2.96 | 0.08 |
| C | 20% | 3.56 | 1.23 |
| | 80% | 2.95 | 0.26 |

## A.3 Matching Native Runoff

For each developed condition in Southeast region, BMPs of varying sizes were modeled in order to determine which size BMP is required to match native runoff for meadow and forest under the alternative frozen ground runoff method. Sections 4.2.1.3 and 5.1.2.4 describe the methodology used for determine the matching runoff volume. The BMP size required using the performance goals of a certain depth off of the impervious area and retainage of a percentile storm using the original, high runoff frozen ground methodology are summarized in Figures 5-28, 5-29, 5-30, 5-37, 5-38 and 5-39 and Table 5-10.

Using the alternative, low runoff frozen ground methodology for Southeast region, larger volume control BMPs are required to match native conditions. Figures A-1 through A-6 show the results of the modeling of developed and native conditions and indicate how the matching BMP volume was determined. The results of that analysis are presented in Table A-3.

Using the low runoff, alternative frozen ground methodology, results in BMP sizes that are more sensitive to the soil type. As Table 5-10 indicates, the BMP volume required by the high runoff method ranges from 1.1 to 1.4 inches off the impervious surfaces, with an average of 1.225 for each of the hydrologic soil groups. The BMP size required by the low runoff method ranges from 1.0 to 1.7 inches off the impervious surfaces, with the average BMP size varying by soil type from 1.15 inches for HSG C to 1.6 inches for HSG A.

**Table A-3 Summary of BMP Volumes Required to Match Native Conditions Using Alternative Frozen Ground Methodology**

| Minnesota Region | Natural Vegetation | Developed Site Imperviousness | X needed for "X times the impervious area" to not exceed the Natural Average Annual Runoff Volume (inches) | | | Retainage from Percentile Storm needed to not exceed the Natural Average Annual Runoff Volume (Precipitation Amount, inches) | | |
|---|---|---|---|---|---|---|---|---|
| | | | Hydrologic Soil Group | | | Hydrologic Soil Group | | |
| | | | A | B | C | A | B | C |
| Southeast | Meadow | 20% | 1.5 | 1.2 | 1.0 | 96.0% | 94.0% | 91.0% |
| | | | | | | (1.6) | (1.45) | (1.2) |
| | | 80% | 1.6 | 1.2 | 1.1 | 97.5% | 94.0% | 91.0% |
| | | | | | | (1.8) | (1.45) | (1.2) |
| | | *Average* | *1.55* | *1.2* | *1.05* | *96.75%* | *94.0%* | *91.0%* |
| | | | | | | *(1.7)* | *(1.45)* | *(1.2)* |
| | Forest | 20% | 1.6 | 1.6 | 1.4 | 97.5% | 97.0% | 92.5% |
| | | | | | | (1.8) | (1.7) | (1.275) |
| | | 80% | 1.7 | 1.3 | 1.1 | 98.0% | 95.0% | 92.5% |
| | | | | | | (2.0) | (1.5) | (1.275) |
| | | *Average* | *1.65* | *1.45* | *1.25* | *97.75%* | *96.0%* | *92.5%* |
| | | | | | | *(1.9)* | *(1.6)* | *(1.275)* |
| | **Average** | ***Average*** | ***1.6*** | ***1.325*** | ***1.15*** | ***97.25%*** | ***95.0%*** | ***91.75%*** |
| | | | | | | ***(1.8)*** | ***(1.53)*** | ***(1.24)*** |

## A.4 Discussion

The average annual runoff generated by the low runoff frozen ground methodology appears to be too low, while the runoff from the original high runoff methodology is intuitively too high; clearly, some infiltration would occur in some years. Research into frozen ground infiltration and runoff yields runoff depths that range from the low to the high assumptions. One long-term study in northern Minnesota showed that over a nearly 20-year record approximately 75% of the annual runoff occurred in the spring (Nichols, 2001).

## References

Nichols, D. S. and Verry, E. S., 2001. “Stream flow and ground water recharge from small forested watersheds in north central Minnesota”, Journal of Hydrology. Accepted January 31, 2001.

Xiao, Q. and McPherson, E. G., 2003. “Rainfall Interception by Santa Monica’s municipal urban forest”, Urban Ecosystems. Accepted September 30, 2003.

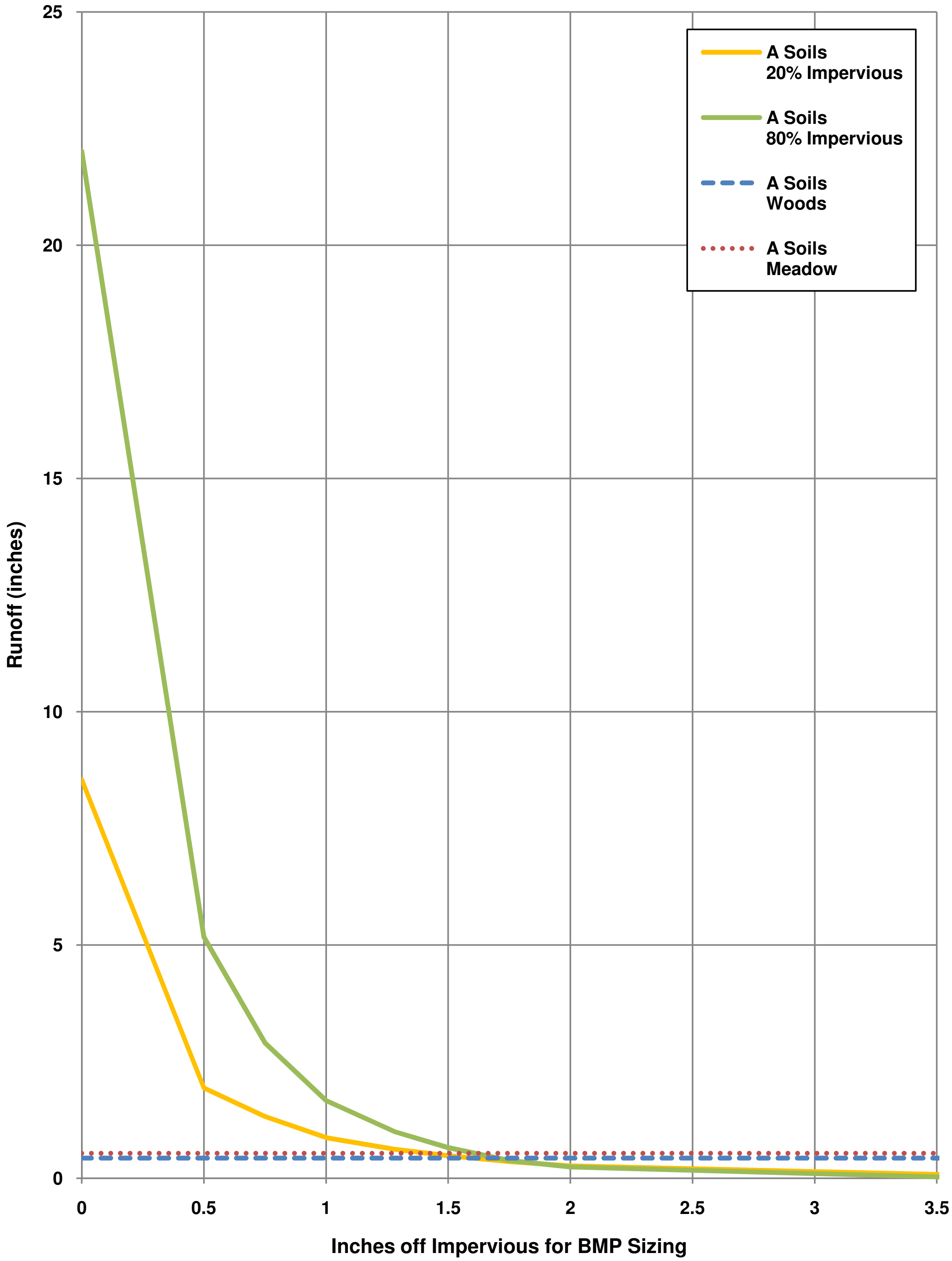


**Figure A-1**
**Annual Runoff Depth**
**A Soils, Southeast Region**
**Alternative Frozen Ground Assumptions**
**Inches Off Impervious Performance Goal**

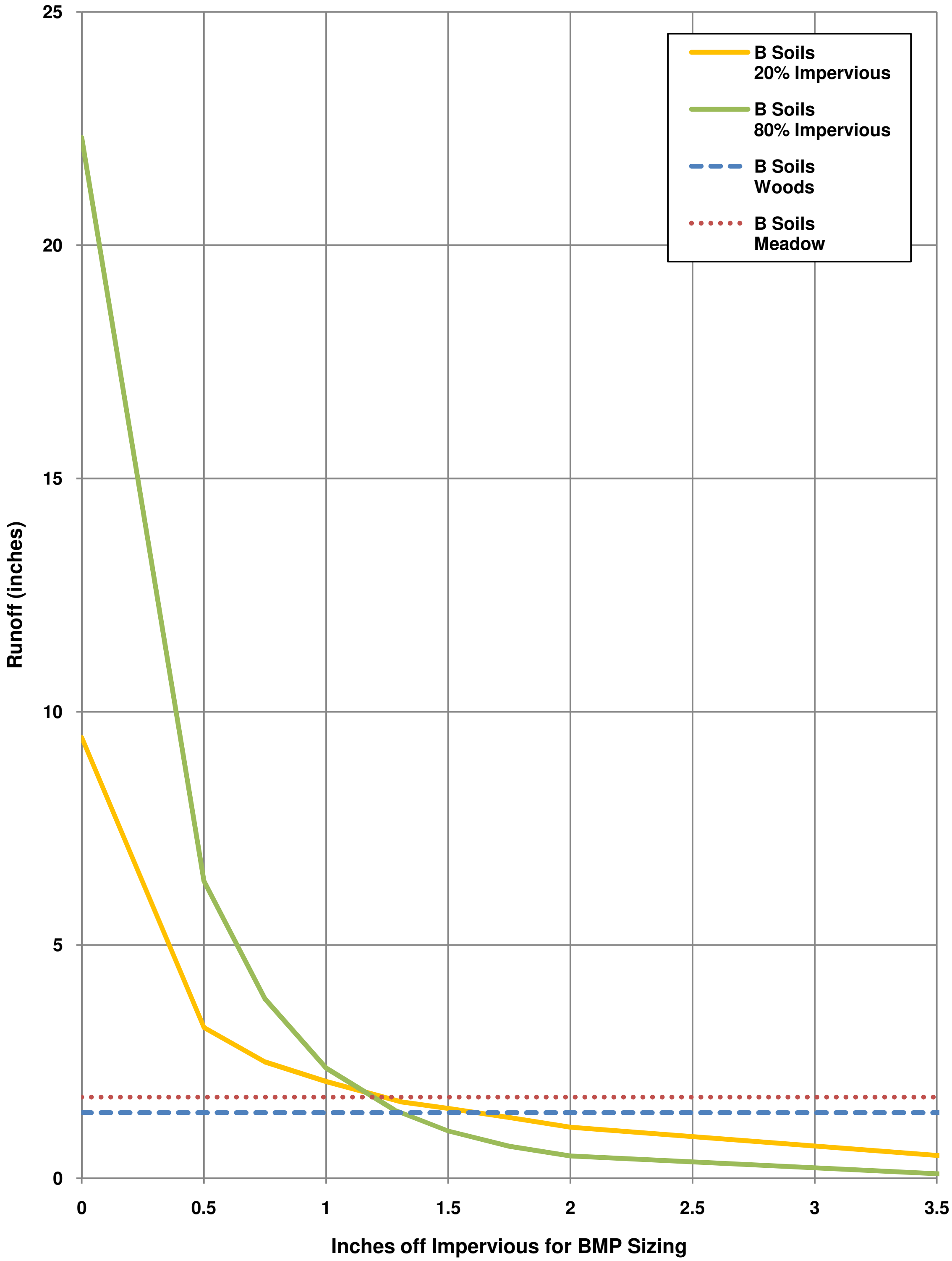


**Figure A-2**
**Annual Runoff Depth**
**B Soils, Southeast Region**
**Alternative Frozen Ground Assumptions**
**Inches Off Impervious Performance Goal**

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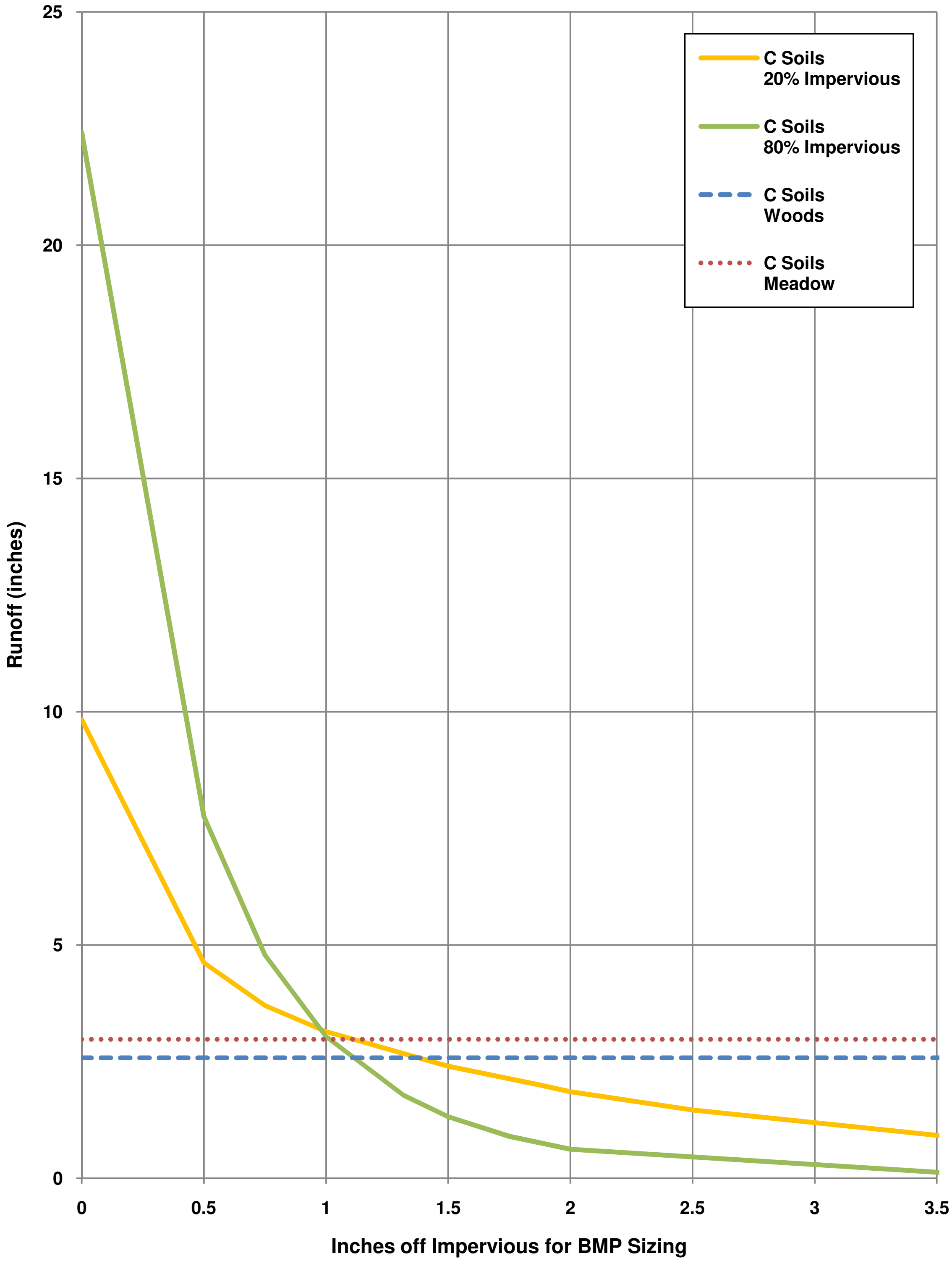


**Figure A-3**
**Annual Average Runoff Depth**
**C Soils, Southeast Region**
**Alternative Frozen Ground Assumptions**
**Inches Off Impervious Performance Goal**

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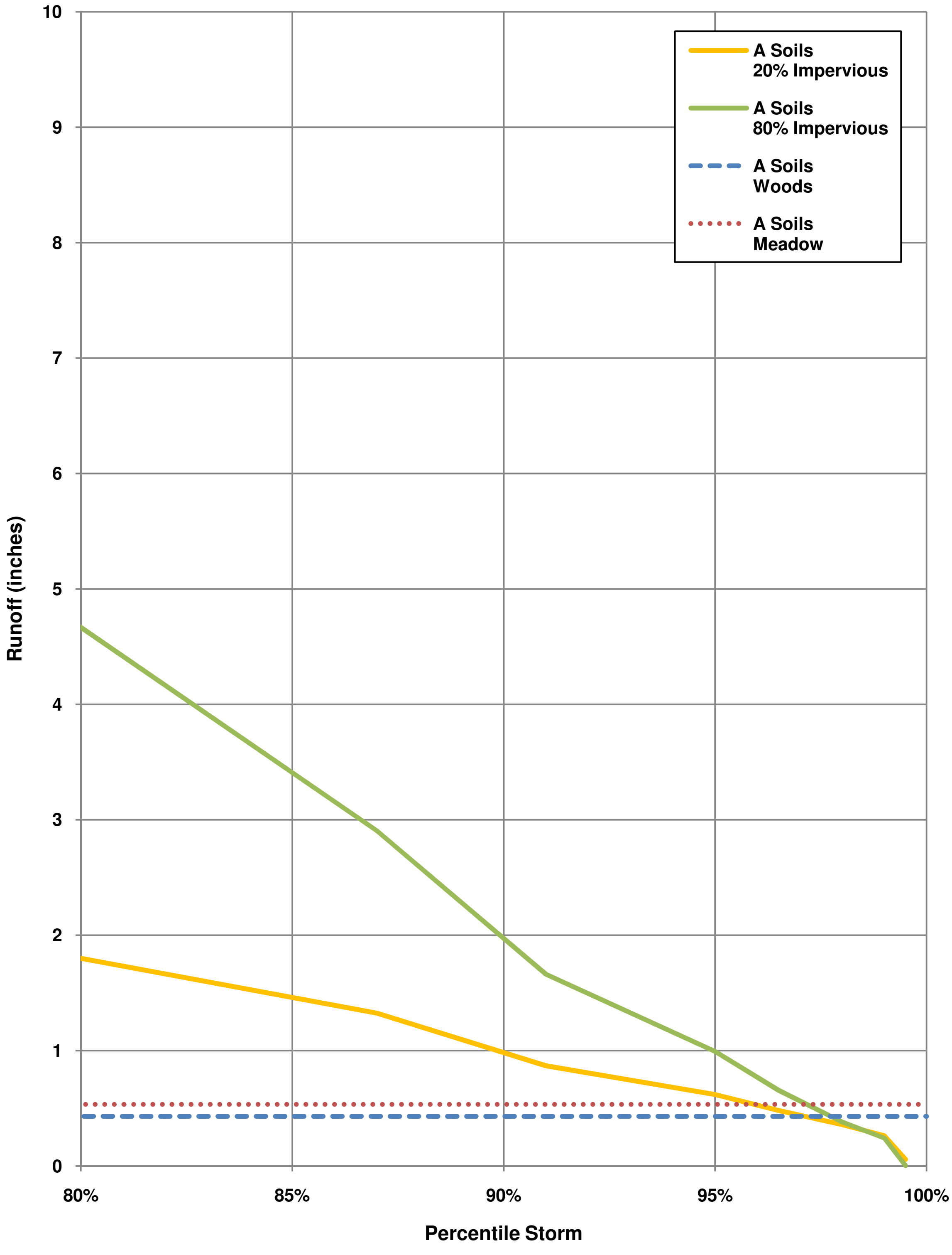


**Figure A-4**
**Annual Average Runoff Depth**
**A Soils, Southeast Region**
**Alternative Frozen Ground Assumptions**
**Percentile Storm Performance Goal**

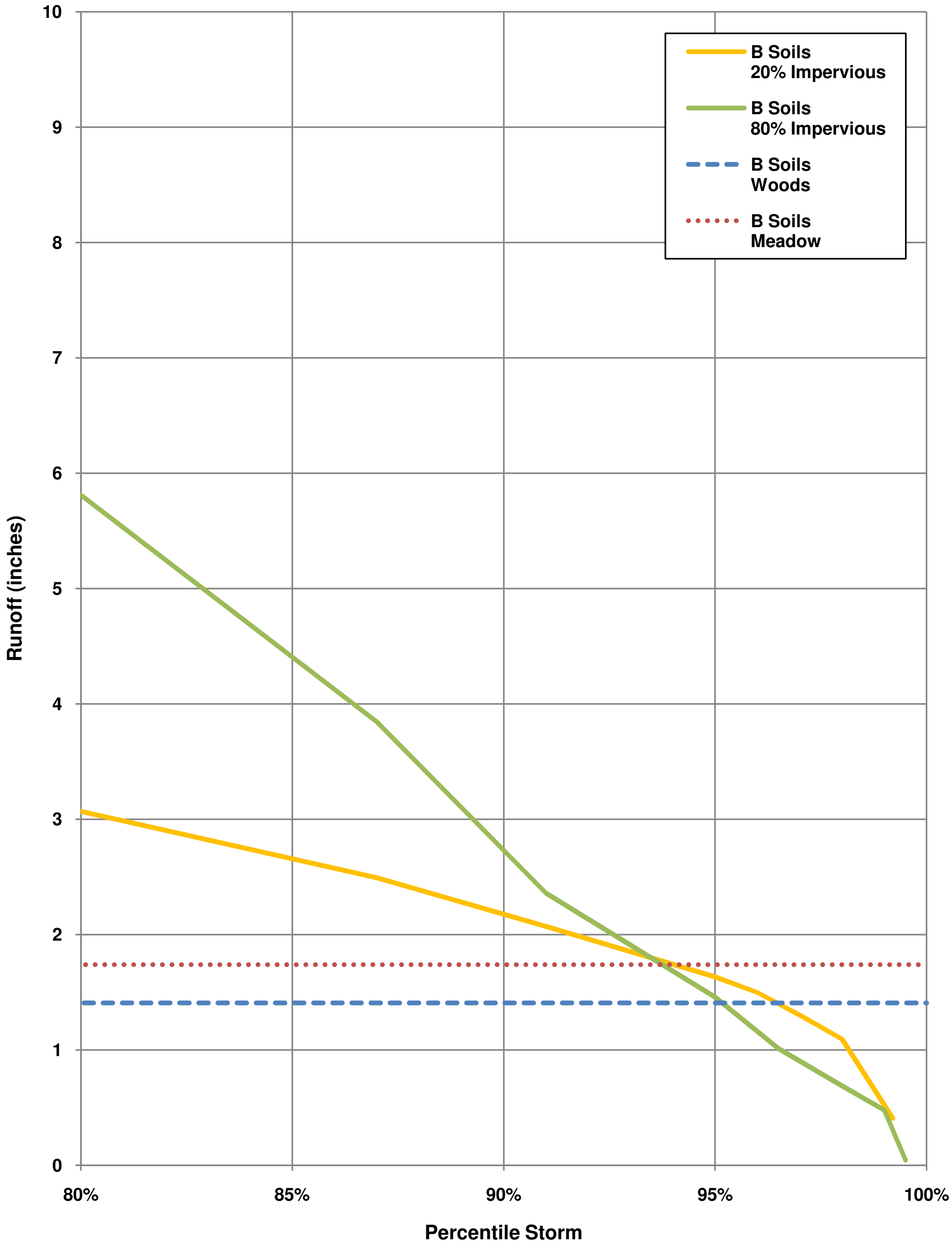


**Figure A-5**
**Annual Average Runoff Depth**
**B Soils, Southeast Region**
**Alternative Frozen Ground Assumptions**
**Percentile Storm Performance Goal**

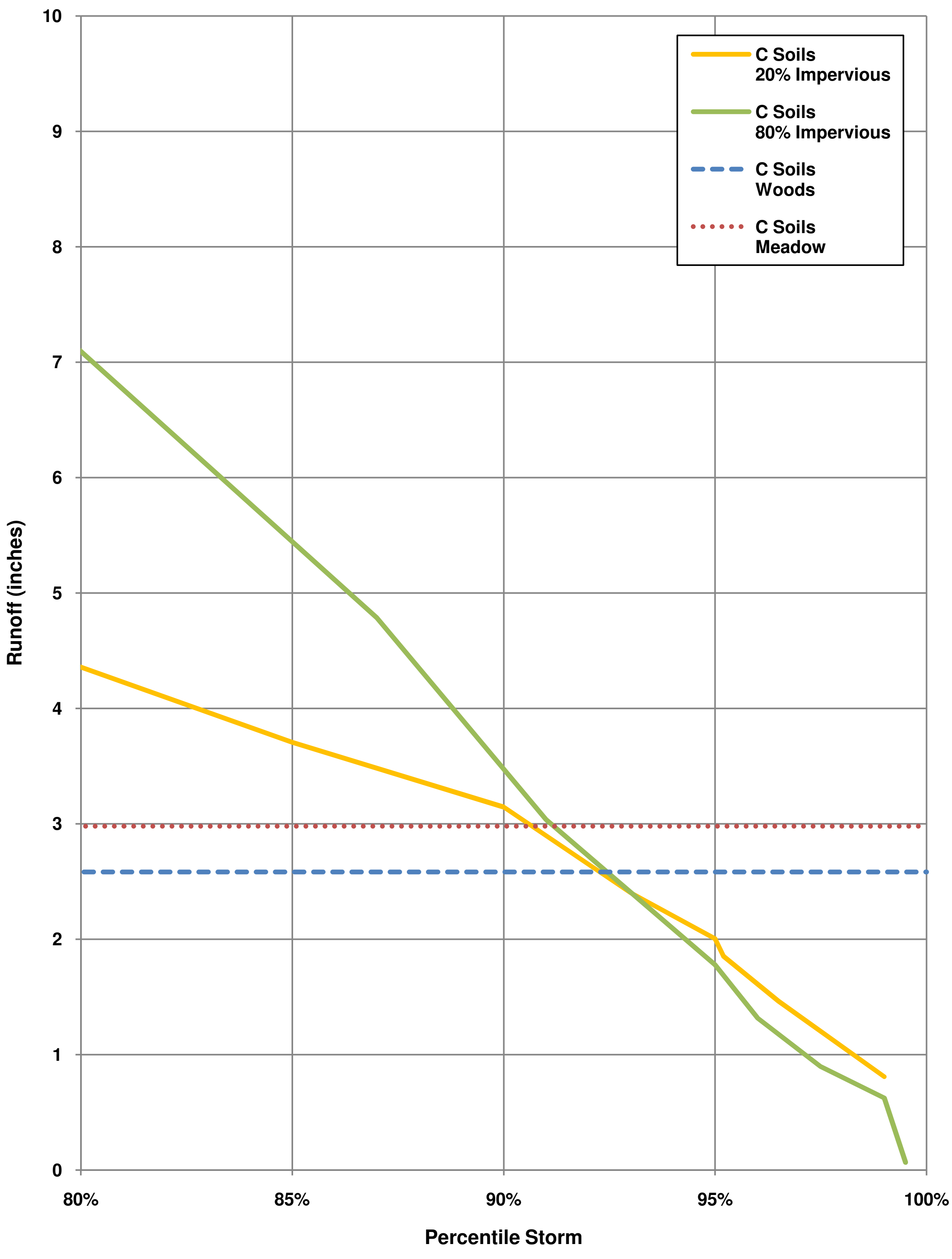


**Figure A-6**
**Annual Average Runoff Depth**
**C Soils, Southeast Region**
**Alternative Frozen Ground Assumptions**
**Percentile Storm Performance Goal**