What's in This Chapter

Section 3.1 Introduction: Provides an introduction to Treatment Objectives and Performance Goals of stormwater management in West Virginia.

Section 3.2 Stormwater Treatment Capabilities: Introduces the accepted stormwater best management practices (BMPs) and their performance capabilities as documented and implemented using the Runoff Reduction Method.

Section 3.3 BMP Selection: Offers a variety of screening factors that help the designer to select the most appropriate BMP strategy based on the specific site conditions.

Section 3.4 BMP Design: Provides a general overview of the Runoff Reduction BMP design process, including the computational procedures for determining the Target Treatment Volume (Tv).

3.1 Introduction

The selection, location, and design of an appropriate stormwater BMPs for a given development project will be based on factors related to the ability of the BMP to meet the required stormwater Treatment Objectives and Performance Goals of the development project, various site characteristics that influence the applicability and performance of the BMPs, and the designer's best professional judgment in evaluating the most effective implementation strategy.

Stormwater ***Treatment Objectives*** include (but may not be limited to) managing or reducing runoff volume (as required by the MS4 General Permit) and peak rate of discharge, removal pollutants such as nutrients (Total Nitrogen – TN, Total Phosphorus – TP), Total Suspended Solids (TSS), pathogens, metals, polycyclic aromatic hydrocarbons (PAHs), and thermal impacts. These objectives are generally established by state or local permits, watershed strategies related to the presence of sensitive aquatic resources, or as identified by a water body's Total Maximum Daily Loads (TMDLs).

The level to which these treatment objectives are to be managed or reduced is referred to as the ***Performance Goal***. Example performance goals include maintaining the pre-developed peak rate of runoff from the site; limiting the annual load of a particular pollutant (such as TP) that leaves the development site to a pre-determined or pre-developed level, measured in units of pounds per year (lb/ yr), or other measure of performance. In the case of the MS4 General Permit, the Treatment Objective is to manage the volume of runoff from developed areas, and the Performance Goal is to replicate pre-development hydrologic response.

The specific compliance criterion for the applicable Treatment Objectives and Performance Goals are typically spelled out in the local ordinance, state or federal permit, watershed plan (such as a TMDL Watershed Implementation Plan) or other appropriate governing document. The Performance Goal has been further defined by the MS4 General Permit: manage the runoff volume from a one-inch rainfall event – this volume is referred to as the *Treatment Volume (Tv)*. Guidance documents, including this manual, provide structural and non-structural BMPs that have been evaluated and determined to meet the criterion.

BMPs are generally designed to meet a primary design objective. The selected BMP may also be effective to an extent in addressing multiple Treatment Objectives. However, the BMP design must specifically incorporate provisions for those multiple objectives in order to be successful. Therefore, it is important for the designer to understand both the Treatment Objectives and the capabilities of the available BMPs in order to select and design the most effective BMP strategy.

3.2. Stormwater Treatment Capabilities

This section provides the background for designers to understand how the different BMPs perform and the different design adaptations that can improve the BMP's capability to achieve any one or multiple Performance Goals. This includes a description of the Treatment Objectives and the basic pollutant removal pathways of the BMPs.

3.2.1. Overview of the BMPs

West Virginia's approved BMPs are listed here using the **Chapter 4** section designations from the detailed design specifications. **Chapter 1** provides a pictorial introduction and a brief description of each BMP and a basic summary of the design features.

4.2.1 Sheet Flow to Vegetated Filter Strips and Conservation Areas
4.2.2. Impervious Surface Disconnection
- Simple disconnection
- Simple disconnection with soil amendments
- Disconnection with compensatory practices

4.2.3. Bioretention
- Traditional (main chapter)
- Water Quality Swale (Supplement A)
- Urban Bioretention (Supplement B)
- Residential Rain Garden (Supplement C)

4.2.4. Permeable Pavements (permeable interlocking concrete pavers, pervious concrete, porous asphalt, concrete grid pavers)
4.2.5. Grass Swales
4.2.6. Infiltration (dry wells, infiltration trenches, infiltration basins)
4.2.7. Regenerative Stormwater Conveyance System
4.2.8. Rainwater Harvesting (cisterns and rain tanks)
4.2.9. Vegetated Roofs (intensive and extensive)
4.2.10. Filtration (surface sand filters, underground sand filters, perimeter sand filters) – water quality credit only (no runoff reduction performance))
4.2.11. Stormwater Wetlands (subsurface gravel wetlands, wetland basins, multi-cell wetland or pond/wetland combination) – water quality credit only (no runoff reduction performance)

Some Stormwater Ponds Are Not Assigned Runoff Reduction Performance Values

Specifications for Dry Extended Detention Ponds and Wet Ponds are not included in this manual since they are not credited with any Runoff Reduction benefits. However, they can be utilized for other stormwater treatment objectives, such as peak rate control for downstream flood protection.

3.2.2. The Runoff Reduction Method

The Runoff Reduction Method is a three-step design process for implementing structural and nonstructural stormwater BMPs that address the impacts of land development and conversions on the downstream aquatic resources by:

1. Reducing the increase in runoff volumes by minimizing impervious cover and mass grading, and maximizing the retention of forest cover, natural areas, and undisturbed soils (especially those soils that are conducive to landscape infiltration);
2. Applying BMPs individually or in series that have been demonstrated to reduce runoff volumes through infiltration, evapotranspiration, extended filtration, and attenuation; and
3. mplementing additional BMPs to address as needed any remaining volume of runoff, peak rates of discharge, and/or pollutant load reductions.

The use of Better Site Design practices to achieve **Step 1** is covered in detail in **Section 4.1**. The selection of applicable BMPs to achieve **Steps 2** and **3** are discussed in **Section 3.4** of this Chapter.

Runoff Reduction

The MS4 General Permit requires that the increased volume of runoff from urban development be managed on site so as to mimic the natural or pre-developed hydrology. Pre-developed hydrology in the general terms of permit compliance is independent of site specific characteristics and is defined as the natural conditions where runoff from approximately 90% of the annual rainfall is either infiltrated, taken up by plants, or conveyed by shallow subsurface flow (or interflow) to streams and rivers. Nearly all of the remaining rainfall becomes surface runoff conveyed to receiving waters (FISRWG, 1998).

Analysis of precipitation data for West Virginia indicates that 90% of the annual rainfall events are one (1) inch or less. **Therefore, the BMP *Performance Goal* is to manage on-site the runoff from a one-inch rainfall event in order to reasonably mimic natural hydrologic processes**. **Section 3.4** of this chapter provides a description of the calculation procedures for determining the volume of runoff from the one-inch event, referred to as the Treatment Volume (*Tv*).

Since the specific characteristics of the landscape such as soils and slopes, determine the path by which runoff leaves the site in the pre-developed condition, the designer must select an appropriate BMP strategy that is compatible with those characteristics and will therefore mimic those pre-developed pathways. Where pre-developed conditions include permeable soils, BMPs can be designed to effectively mimic infiltration by establishing or preserving adequate ponding (attenuation) volume and surface area of permeable soils in one or multiple locations within the development site. Where the existing soils (Hydrologic Soil Groups C and D) or developed site conditions (such as the extent of earthwork cut and/or fill) preclude the use of Infiltration, other practices can be designed to mimic the attenuation and slow release of runoff by establishing a ponding area, a depth of engineered soil media, and an underdrain. This discharge condition is similar to the shallow subsurface interflow that is common in areas with low soil permeability.

Better Site Design and Runoff Reduction

In almost all cases, BMP performance can be enhanced by providing a vegetative component to improve the evapotranspiration characteristics of the developed site. Section 4.1 discusses the important and effective strategy of minimizing the increase in runoff volume through Better Site Design strategies, thereby reducing the extent to which designers must rely on structural BMPs to achieve the volume reduction Performance Goal.

Pollutant Removal

The MS4 General Permit puts a premium on achieving runoff volume reduction at a development site as a measure of compliance with the goal of protecting downstream resources. This incorporates the beneficial effects of reducing frequency and peak rates of discharge for certain storm events with the additional benefit of reducing pollutant loads. Runoff volume is the first of two important factors in determining the runoff pollutant load; the second being the concentration of the targeted pollutant, usually measured in milligrams per liter (mg/l) or other appropriate units. The computed annual load reported in terms of pounds per year (lbs/yr) is the product of the annual runoff volume multiplied by the typical pollutant concentration. Therefore reducing one or both of these factors will result in a reduced annual load. **Section 3.4** provides a description of the computations used to calculate the pollutant loads associated with the target Tv.

Annual Values for Runoff and Pollutant Concentrations

The runoff volume reduction criteria specifically address the reduction of runoff associated with an "annual" rainfall distribution in order to simplify the computational procedures as well as the variability associated seasonal and daily rainfall patterns. Similarly, the concentration of pollutants can often vary on a seasonal basis or even over the course of a single rain event (based on rainfall intensity, pollutant washoff, etc.) and is therefore measured using a single "event mean concentration" (EMC). The EMC reflects an average pollutant concentration in urban stormwater runoff derived over many storm events and in many different locations. The computed load reduction is therefore considered to be an "annual reduction" and not a single event modeled reduction.

Components of Total Pollutant Load Reduction

The ability of BMPs to reduce the annual runoff volume either through infiltration, evapotranspiration, reuse, or extended filtration is referred to as the ***Runoff Reduction*** capability, and is expressed as a percent removal of the runoff associated with the 90th percentile rain event. The ability of BMPs to reduce annual pollutant loads by reducing the EMC of the particular pollutant(s) is referred to as the ***Pollutant Removal*** capability and is expressed as a percent removal of the annual pollutant load calculated using the Simple Method. The total annual load reduction is referred to as ***Total Pollutant Load Reduction***. **Table 3.4** provides the accepted Runoff Reduction values for the BMPs, and **Table H.2** in **Appendix H** includes the accepted Pollutant Removal and Total Pollutant Load Reduction.

Level 1 and Level 2 BMPs

Each BMP has a different Runoff Reduction capability, as well as a different Pollutant Removal capability. Some BMPs may achieve reductions solely through Pollutant Removal performance and provide no Runoff Reduction, while others may provide only Runoff Reduction and no measureable Pollutant Removal, and finally, some are able to achieve both. To further improve on any given BMP's performance, the designer may choose to improve on the "standard" design features of a Level 1 design by upgrading to the "enhanced" design features of a Level 2 design.

The basis of the Level 1 and Level 2 design format is a thorough evaluation of BMP performance literature. BMP design factors that enhance nutrient pollutant removal and runoff reduction were isolated. Standard design features that should be included in all designs (i.e., not directly related to differential nutrient removal or runoff reduction rates) were identified. These include any features needed to maintain proper and safe function of the BMP.

Next, prior research into BMP adaptations for the purposes of urban retrofitting was utilized to identify and isolate additional design features and their influence on performance. These combined efforts helped to accurately identify critical design features that could be enhanced to improve performance in terms of both Pollutant Removal and Runoff Reduction, as well as the expected relative improvement in performance that could be expected. The result is the Level 1 and Level 2 design criteria and performance credits.

The standard Level 1 design features typically include the following:

- Key safety features;
- Aesthetics;
- Safe conveyance of larger storms;
- Operational longevity (design with maintenance in mind); and
- Standard site feasibility constraints.

The Level 2 enhanced features typically include:

- Providing a larger storage component within the BMP;
- Improving design geometry and hydraulics to increase the length of the flow path and residence time within the BMP;
- ncreasing the surface area and variety of vegetative cover within the BMP to improve evapotranspiration and pollutant uptake; and
- Providing additional runoff reduction and/or pollutant removal pathways to the BMP, such as adding soil amendments to a grass swale (thereby adding enhanced features for infiltration and attenuation to the standard feature of settling).

Table 3.1 describes the Bioretention design Levels as an example of the different criteria typically associated with Level 1 and Level 2. These Level 1 and Level 2 design features are outlined in detail within the design specifications in **Chapter 4**. It is important to note that some BMPs in **Chapter 4** have only one design level (e.g., Infiltration, Rainwater Harvesting). This is because the sizing and design guidance and the resulting runoff reduction performance are more straight-forward and not conducive to the design level approach.

Table 3.1. Bioretention Design Levels: Descriptions & Performance

Design Level	Description	Applications	Performance Achieved Towards Reducing 1" of Rainfall
Level 1	Basic Design -- Underdrain At least 1.5 feet of soil media depth, but less than 2.0 feet No infiltration sump below underdrain pipe(s)	Sites with vertical constraints such as high bedrock or water table OR confirmed karst, stormwater hotspot, or other applications that require an impermeable liner.	60% volume reduction for the Design Volume of the practice[1]
Level 2	Infiltration Design – No underdrain, water infiltrates into the underlying soil within 48 hours. OR Extended Filtration Design – • Underdrain • At least 2.0 feet of soil media depth, OR • At least 1.5 feet of soil media depth with stone sump below underdrain designed to drain design volume within 48 hours on suitable soils (e.g., limited on fill).	Generally most sites that have good to marginal infiltration rates -- Hydrologic Soil Groups (HSGs) A, B, and C and do not require an impermeable liner. Use the Infiltration Design for tested infiltration rates > 0.5 inches per hour, and the Extended Filtration Design for other sites.	100% volume reduction for the Design Volume of the practice1

[1] *Design Volume includes storage on the surface, within the soil media, and in the infiltration sump. The Design Volume can be 100% of that needed to meet the 1-inch performance standard OR some proportion of it when used in conjunction with other practices.*

Peak Rate Control

Designers may also be required to design stormwater practices to provide peak rate control for larger storms for downstream channel protection and/or flood control. In West Virginia, this is likely to be a local stormwater standard or requirement. The Runoff Reduction Method allows for the annual Runoff Reduction credit to be applied to the large storm computations to possibly reduce the detention storage volume required to control the larger design storm events. This is achieved through a curve number adjustment for the contributing drainage area (CDA): the annual Runoff Reduction credit is converted from cubic feet or acre-feet to watershed-inches of retention storage and used to "back calculate" an adjusted (reduced) curve number using the TR-55 Runoff Equations (USDA, 1986). This new curve number can then used when computing the large storm peak discharge and storage volume needed to meet downstream channel or flood protection requirements. This computational procedure is discussed in more detail in **Section 3.4.4** of this Chapter.

Adjusted Curve Numbers Vary by Storm Event

An adjusted curve number must be computed for each storm event (e.g., 2-year, 10-year, etc.) due to the diminishing effect of the retention storage on increasing rainfall depths.

If the BMP has a storage component that can be expanded in order to provide a greater volume of storage than required by the Level 1 or Level 2 criteria, the designer may increase those components (as allowed by the BMP design specifications) and increase the large storm benefits. The designer may also choose to route the design storm through the available storage (taking into account the retention and slow drawdown characteristics of the Runoff Reduction BMP) using a storage-indication method routing model rather than compute an adjusted curve number.

It is very important for designers to understand the difference between the "annual" runoff volume credit and a single event modeled peak rate of discharge. The reduced curve number may not be appropriate for the sizing of downstream drainage infrastructure. In all cases, the designer should evaluate the stormwater management requirements and verify the appropriate hydrologic design methods.

Table 3.2 provides a general comparative summary of the basic Treatment Objective capabilities of the different BMPs.

The combined performance of Runoff Reduction and Pollutant Removal, in conjunction with the Level 1 and Level 2 design, is the foundation of the Runoff Reduction Method. The technical support for the credited performance of the BMPs can be found in Hirschman et al. (2008), and consists of extensive reviews of BMP performance monitoring studies incorporated into the National Pollutant Removal Performance Database (CWP, 2007). Estimates for some BMPs should be considered provisional (e.g., filter strips) due to limited data. Estimates for new practices as well as updates to existing practices will be provided as supported by ongoing research. (Refer to **Section 3.2.4** for the process of developing and approving new performance credits, design criteria, and BMPs.)

Table 3.2. Comparative Overall Performance Capability of BMPs

BMP		Runoff Reduction[1]	Pollutant Removal[1]	Total Pollutant Load Reduction	Peak Rate Control
Sheet Flow to Vegetated Filter Strips		YES	NO	PARTIAL[2]	PARTIAL[5]
Simple Disconnection		YES	NO	PARTIAL[2]	PARTIAL[5]
Simple Disconnection with Compensatory Practices	Micro-Infiltration	YES	YES	YES	PARTIAL to FULL[6]
	Residential Rain Garden	YES	YES	YES	PARTIAL to FULL[6]
	Rainwater Harvesting	YES	YES	YES	PARTIAL[6]
	Urban Bioretention	YES	YES	YES	PARTIAL[6]
Bioretention		YES	YES	YES[3]	PARTIAL to FULL[6]
Permeable Pavement		YES	YES	YES[3]	PARTIAL to FULL[6]
Grass Swales		YES	YES	YES[3]	PARTIAL[5]
Infiltration		YES	YES	YES[3]	PARTIAL to FULL[6]
Regenerative Stormwater Conveyance System		YES	YES	YES	PARTIAL to FULL[6]
Rainwater Harvesting		YES	NO	PARTIAL[2]	PARTIAL[6]
Vegetative Roofs		YES	NO	PARTIAL[2]	PARTIAL[5]
Filtration		NO	YES	PARTIAL[4]	NONE
Stormwater Wetlands		NO	YES	PARTIAL[4]	PARTIAL[7]

[1] *The* Runoff Reduction *and/or* Pollutant Removal *can be improved by upgrading the design from Level 1 to Level 2. Refer to* Section 3.2.2.

[2] *Total Pollutant Load Reduction is a function of* Runoff Reduction *only.*

[3] **Total** *Pollutant Load Reduction is a function of* Runoff Reduction *and* Pollutant Removal.

[4] *Total Pollutant Load Reduction is a function of* Pollutant Removal *only.*

[5] *Adjustment to CDA curve number & time of concentration.*

[6] *Adjustment to CDA curve number & time of concentration, and additional storage volume.*

[7] *Limited ponding depth allowed above the wetland normal pool.*

Pollutant Removal Processes

At most sites, designers may need to employ several practices in a "roof to stream" sequence in order to meet the criteria of managing the Tv runoff reduction targets (e.g., rooftop disconnection drains to front yard bioretention, which then drains to a dry swale, and then to a constructed wetland). These "treatment trains" are effective in sequentially reducing runoff volumes through each BMP. Pollutant Removal, on the other hand, is limited since the available pollutant load, i.e. the fraction of the targeted pollutant that is physically able to be removed by the particular pollutant removal processes or pathways in the BMP, is finite. Therefore, there is an upper limit to the pollutant removal performance of any given BMP or series of BMPs.

This upper limit on Pollutant Removal highlights a significant benefit of utilizing and accounting for the Runoff Reduction component of the BMPs. Runoff Reduction is a function of combining flow attenuation with i) infiltration into existing soils, ii) evapotranspiration through the soil and vegetation interface, iii) alternative uses such as irrigation or internal non-potable water demand, and iv) extended filtration to mimic the flow path of runoff in areas with tight or low-permeable soils. The cumulative Runoff Reduction benefit of these design features is not limited by a removal process or the form of a targeted pollutant, allowing multiple Runoff Reduction BMPs in series to achieve a very high performance goal through Runoff Reduction rather than Pollutant Removal.

It should be noted that extended filtration in an undeveloped watershed also incorporates the natural processes of infiltration and evapotranspiration; however, concentrating runoff from a developed drainage area to a small footprint (relative to the drainage area) limits the capability of these natural processes, especially when also confronted with less than favorable soil conditions. Extended filtration BMPs provide an engineered soil media to overcome the limitations common on development sites (disturbed soil profiles, limited space for dispersing runoff, etc.).

Becoming familiar with the performance characteristics of the BMPs will help the designer meet the challenges of typical and atypical development sites. **Table 3.3** provides a brief overview of the more common physical, chemical, and biological processes by which the BMPs remove pollutants.

Table 3.3. Stormwater Pollutant Removal Processes

Removal Process	Description and Pollutants Affected	BMPs
Gravitational Separation (also settling or sedimentation)	**Definition**: Downward removal of solids denser than water, and floatation removal of those lighter than water. **Pollutants**: sediment, solids (particulates associated with other pollutants such as nutrients and metals), oil (hydrocarbons), BOD, particulate COD	Cisterns, Permeable Pavement, Grass Swale, BMPs with ponding component, Bioretention, Regenerative Stormwater Conveyance System, Filtration, Stormwater Wetlands, and Wet and Dry Extended Detention Ponds
Filtering	**Definition:** Straining of pollutants by passing stormwater through a media finer than the target pollutants. **Pollutants**: solids, pathogens, particulate nutrients, particulate metals, BOD, particulate COD	Filtration, Vegetated Filter Strips, Bioretention, Permeable Pavement, Grass Swale, Regenerative Stormwater Conveyance System, Vegetated Roof, Stormwater Wetlands.

Removal Process	Description and Pollutants Affected	BMPs
Infiltration	**Definition:** passing stormwater downward through existing soils below the surface grade **Pollutants**: volume, solids, pathogens, nutrients, metals, organics, BOD, particulate COD	Infiltration, Vegetated Filter Strips, Bioretention, Permeable Pavement, Grass Swale, Regenerative Stormwater Conveyance System,
Sorption	**Definition**: Includes Adsorption and Absorption – the physical molecular level attraction of a pollutant to media or soil particles. No chemical change (such as ion exchange occurs). **Pollutants**: dissolved phosphorus, metals, and organics.	Filtration, Vegetated Filter Strips, Bioretention, Permeable Pavement, Grass Swale, Regenerative Stormwater Conveyance System, Vegetated Roof, Stormwater Wetlands.
Biological Uptake	**Definition**: Broadly termed transfer of substances from runoff to plants; can include evapotranspiration. **Pollutants**: volume, hydrocarbons, nutrients, metals, organics, BOD, particulate COD	Vegetated Filter Strips, Bioretention, Grass Swale, Vegetated Roof, Stormwater Wetlands
Ion Exchange	**Definition**: Molecular exchange of one ion from the soil or filter media with an ion in the stormwater to remove pollutants; the ion from the media passes harmlessly through with the stormwater, while the pollutant remains sequestered in the media. **Pollutants**: metals	Filtration (depending on the media)
Chemical Transformation	**Definition:** Process by which pollutants react with other compounds to change structure and are either harmlessly removed or sequestered. **Pollutants:** nitrogen (ammonia, nitrate, nitrite), organics, hydrocarbons	Filtration, Vegetated Filter Strips, Bioretention, Permeable Pavement, Grass Swale, Regenerative Stormwater Conveyance System, Vegetated Roof, Stormwater Wetlands.

3.2.3. BMP Runoff Reduction Credits

Table 3.4 provides the comparative runoff reduction credits of the BMPs covered in this manual. These BMPs also have corresponding pollutant removal credits for TN, TP, and TSS for compliance with requirements in the Chesapeake Bay watershed, as well as other parameters that may be required in watersheds designated as impaired. **Appendix H** provides an expanded version of **Table 3.4** to include these other credits.

Table 3.4. Comparative Runoff Reduction Credit of BMPs

Best Management Practice		Runoff Reduction Credit[1,2] (%)
Sheet Flow to Vegetated Filter Strips[2]	A/B Soils	50 (.06ft^3/ft^2)
	C/D Soils	25 (.03ft^3/ft^2)
	C/D Soils w/ compost amended soils (CA) (See Appendix D)	50 (.06ft^3/ft^2)
Sheet Flow to Conservation Area[2]	A/B Soils	75 (.09ft^3/ft^2)
	C/D Soils	50 (.04ft^3/ft^2)
Simple Disconnection[2]	A/B Soils	50 (.04ft^3/ft^2)
	C/D Soils	25 (.02ft^3/ft^2)
	C/D Soils w/ CA (Appendix D)	50 (.04ft^3/ft^2)
Simple Disconnection with Compensatory Practices	Micro Infiltration	Refer to Infiltration
	Residential Rain Garden	Refer to Bioretention Level 1 and Level 2
	Rainwater Harvesting	Refer to Rainwater Harvesting
	Urban Bioretention	40
Bioretention	Level 1	60
	Level 2	100
Permeable Pavement	Level 1	45
	Level 2	100

Best Management Practice		**Runoff Reduction Credit[1,2] (%)**
Grass Swale	A/B Soils	20
	C/D Soils	10
	C/D w/ CA	20
Infiltration		100
Regenerative Stormwater Conveyance System[3]	A/B Soils	100
	C/D/Soils	60
Rainwater Harvesting		90[4]
Vegetative Roof		100
Filtration	Level 1	0
	Level 2	0
Stormwater Wetlands	Level 1	0
	Level 2	0
Dry Extended Detention	Level 1	0
	Level 2	15
Wet Pond	Level 1	0
	Level 2	0

[1]Runoff Reduction expressed as a percent reduction in the annual volume of runoff from rain events up to 1" (Hirschman et al., 2008) based on the BMP design as prescribed in Chapter 4 of this manual

[2] Runoff Reduction values for sheet flow and simple disconnection practices are based on a ft^3 credit per ft^2 of BMP surface area (refer to Section 3.4 for details).

[3] New practice – performance credits comparable to bioretention/amended media filter. Credit is 100% of provided storage in step pools.

[4]Runoff Reduction credit is variable up to 90% - based upon storage and water usage budget.

3.2.4. New BMPs and Updated Design Criteria

Over the last 10 years, as new stormwater programs have been adopted by state and local governments, numerous products have been developed to help designers and regulators easily address requirements on new and redevelopment sites. The process of introducing new proprietary and public domain stormwater treatment technologies has been very inconsistent nationwide.

The rapid pace of new stormwater treatment product development by manufacturers has created a complex regulatory hurdle for accepting and assigning an appropriate performance credit (e.g., pollutant removal) to new technologies. Some states implement a performance review process while others simply accept the professional responsibility of the licensed engineer as having evaluated the accuracy of the various performance claims. As more products are placed in service, it becomes very evident whether a particular product actually works, and will work for the desired operational life cycle (usually assumed to be at least one year of typical rainfall). The result has been for many jurisdictions to arbitrarily disallow or limit the number of proprietary products, both good and bad.

The introduction of new public domain practices, including design changes, has been much more paced since they have typically been introduced concurrent with a two or three-year research project with unofficial preliminary results setting the stage for gradual acceptance and further research. In recent years, several studies on stormwater BMPs have been completed in NC, MD, PA, NH, and other states. Research in New Hampshire at the University of New Hampshire Stormwater Center is especially relevant to West Virginia given the cold weather testing being conducted.

The intent of this guidance manual is to capture the latest research and design guidelines. However, even as this manual is written, experts are researching more improvements that may boost the performance or decrease the costs, or both, of stormwater BMPs. Therefore, the West Virginia Department of Environmental Protection (WVDEP) will implement official updates to this guidance manual as necessary.

In West Virginia, new products will be reviewed on a case by case basis until such time that a more formal performance evaluation protocol is established and adopted at WVDEP, perhaps in conjunction with or based upon similar protocols in other states (e.g., Virginia, New Jersey).

Chapter 3. Best Management Practice Selection and Design Methodology

3.3. BMP Selection

The selection of appropriate BMPs for any given development project is based on a review of the available BMPs, the different performance and design characteristics, and most importantly, best professional judgment. The process outlined here is a suggested chronology of selecting, locating, and designing BMPs for new and redevelopment projects and builds upon the three-step Runoff Reduction Method design process introduced in **Section 3.2.2**.

This Runoff Reduction Method design process is based on the presumption that the designer has already identified the specific Treatment Objectives and Performance Goals for the project. This is important because it will provide the foundation on which to evaluate the relative benefits of different Runoff Reduction Method strategies such as Better Site Design and/ or structural Runoff Reduction BMPs.

The process of identifying the specific Treatment Objectives and Performance Goals for the project should have also included an assessment of whether any Incentive Standards can apply to the particular project. Incentive Standards include a reduced volume reduction Performance Goal for any of the following development types:

a) Redevelopment;
b) Brownfield redevelopment;
c) High density (>7 units per acre);
d) Vertical density, (floor to area ratio of 2 or >18 units per acre);
e) Mixed use and transit oriented development (within ½ mile of transit)

Runoff Reduction Method Step 1: Reduce the increase in runoff volumes by minimizing impervious cover and mass grading, and maximizing the retention of existing vegetation, forest cover, natural areas, and undisturbed soils (especially those soils that are conducive to landscape infiltration).

The design strategies for this step, generally referred to as Better Site Design, are presented in **Chapter 4.1**. The process of evaluating and maximizing the implementation of these site design strategies as a first step is critical in selecting appropriate BMPs since it has the potential to dramatically reduce the target Tv; the designer may be able to select BMPs with a smaller footprint or lower Runoff Reduction credit.

First Step: Better Site Design

The evaluation and implementation of Better Site Design strategies as outlined in Chapter 4.1 should be the first step of this process as it will likely reduce the Tv required and therefore influence the selection of the most effective BMP(s).

Runoff Reduction Method Step 2: Apply BMPs individually or in series that have been demonstrated to reduce runoff volumes through infiltration, evapotranspiration, extended filtration, and attenuation.

The Runoff Reduction Method Step 2 involves the process of screening the different BMPs based on their performance capabilities and the feasibility factors associated with the project site. This includes assessing the Treatment Objectives and Performance Goals of the project (**Tables 3.2** and **3.4**), land use factors (**Table 3.5**), site characteristics and feasibility (**Table 3.6**), water resource settings (**Table 3.7**), and community acceptance (**Table 3.8**).

The first screening is a review of potential BMPs in terms of the Treatment Objectives and Performance Goals and is presented in **Table 3.2** and **Table 3.4**. The designer should assess the ability of the BMP to meet any of the following Treatment Objectives as may be required:

Treatment Objectives:
- Runoff Reduction (MS4 General Permit compliance)
- Pollutant Removal (Chesapeake Bay or local TMDLs)
  - o Nutrients (TP, TN)
  - o Sediment (TSS)
- Peak Rate Control (most likely local stormwater requirements)
  - o Channel Protection
  - o Flood Protection
- Other watershed specific objectives:
  - o Temperature
  - o Pathogens
  - o Metals

Once the designer has established the "short list" of BMPs that will adequately address the Treatment Objectives, the next step is to ensure the applicability to the given site characteristics and future land uses. The tables provided in **Sections 3.3.1** through **3.3.4** provide a general level of screening for each BMP. Designers will gradually gain experience in the performance capabilities of the practices and how they fit into the different site conditions so as to select the most appropriate BMP or combinations of BMPs.

After the BMPs have been screened and the most appropriate BMPs have been selected, the designer will move to Step 3 of the Runoff Reduction Method:

Runoff Reduction Method Step 3: Evaluate the overall performance of the selected BMPs in reducing the target Tv and pollutant loads, and apply additional Runoff Reduction or Pollutant Removal BMPs as needed.

Step 3 is covered in detail along with the computations for the Tv and annual pollutant loads in **Section 3.4**.

3.3.1. Land Use

The first and most basic screening factor is the proposed land use which is to be served by the BMP. Definitions and explanations of the land use categories in **Table 3.5** are as follows:

Rural: Impervious cover within rural land use (generally considered residential lots > 1/3 acre) is generally widely dispersed. And while the acreage of managed turf can be significant, there is usually adequate space to implement any number of low cost, low maintenance BMPs.

Rural lands are especially suited for minimization and avoidance strategies, as well as vegetated BMPs such as filter strips, conservation areas, etc.

Residential: This includes medium to high density residential developments (< 1/3 acre lot sizes) that generally have limited space compared to rural land. Also, depending on house size and roadway widths, BMPs are likely to be located in close proximity to residences where public safety, nuisance insects, and maintenance are common concerns related to stormwater control measures.

Roads and Highways: Roads and highways typically generate high stormwater pollutant loads due to vehicle traffic and winter deicing activities. Project specific limitations on placement of BMPs related to traffic safety, large storm conveyance, and available space for adequate pre-treatment will typically limit application.

Commercial Development: Commercial development is the most varied land use in terms of project drainage area size, land use, pollutant loads, and other factors. Since commercial development can potentially have available space and is generally a large drainage area under one management, most practices can be recommended. Limitations are based on the potential for drainage areas that are too large, or practices specifically intended for residential areas.

Industrial Development: Industrial development is also highly variable in terms of size and land use. Many industrial facilities are completely covered and do not expose materials or processes to stormwater, thus being more similar to office or business settings. Restrictions on BMPs are generally based on the potential for stormwater "Hotspots," covered in detail in **Chapter 5.**

Table 3.5. BMP Screening: Land Use

BMP	Rural	Residential	Roads & Highways	Commercial	Industrial
Vegetated Filter Strips[1]	Preferred	Preferred	Preferred	Preferred	Limited[2]
Simple Disconnection	Preferred	Preferred	Restricted	Limited[3]	Restricted[3]
Simple Disconnection with Compensatory Practices	Limited[4]	Limited[4]	Restricted	Limited[3]	Restricted[3]
Bioretention	Preferred	Preferred	Preferred	Preferred	Restricted[5]
Permeable Pavement	Limited[6]	Limited[6]	Limited[6]	Preferred	Restricted[5]
Grass Swale	Preferred	Preferred	Preferred	Limited[7]	Limited[7]
Infiltration	Preferred	Preferred	Preferred	Preferred	Restricted[5]
Regenerative Stormwater Conveyance System	Limited	Preferred	Preferred	Preferred	Preferred
Rainwater Harvesting	Preferred	Preferred	NA	Preferred	Preferred
Vegetative Roof	Restricted[8]	Restricted[8]	NA	Preferred	Preferred

BMP	Rural	Residential	Roads & Highways	Commercial	Industrial
Filtration	Limited[9]	Limited[9]	Preferred	Preferred	Preferred
Stormwater Wetlands	Preferred	Preferred	Preferred	Preferred	Preferred

Preferred	– Good application
Limited	– Probably not the best choice due to one of the screening factors, but can be accepted
Restricted	– specific design restrictions based on one of the screening factors

[1] Vegetated Filter Strips include Sheet Flow to Conservation Areas.
[2] May require pretreatment depending on land use and pollutant loading.
[3] Intended for residential or other small impervious areas.
[4] Alternative practices add a maintenance component – should be adequate room for Simple Disconnection
[5] Depending on specific land use – may limit infiltration and require additional maintenance
[6] Maintenance requirements
[7] Drainage area and large storm conveyance. Adjustment to CDA, curve number & time of concentration, and additional storage volume.
[8] Typical residential roof geometry restricts application
[9] Excessive maintenance burden of underground systems in residential areas

3.3.2. Site Characteristics and Feasibility

This screening factor begins the process of correlating the site conditions to the practical design factors for the different BMPs. The designer must identify any physical constraints at the project site that may restrict or preclude the use of a particular BMP. This includes the existing site conditions such as soil types (and depth to limiting layers such as bedrock), as well as the proposed site conditions such as earthwork, available space, and grades (see **Table 3.6**). More detailed site investigations may be required to adequately address some constraints.

The primary factors are as follows:

Soils: The key evaluation factors are based on an initial investigation of the Natural Resources Conservation Service (NRCS) Hydrologic Soil Groups (HSGs) at the site. Knowledge of the soil groups present on the site is also needed for runoff calculations. Note that more detailed geotechnical tests are typically required for infiltration feasibility and during design to confirm other engineering characteristics; however the presence of HSG A or HSG D soils is most likely enough to screen the choice of certain BMPs. Additional information on soils and soil testing is provided in **Appendix B**.

Depth to Water Table: The separation of the BMP and the seasonally high water table is a safety factor intended to protect the water table and the BMP.The debate over the need for greater than one-foot of separation is often based on the presumed margin of error in predicting the actual water table elevation.This distance, measured from the bottom or floor of the BMP can be modified based on the reliability of the investigation.

Depth to Bedrock: Similar to the depth to water table, this factor includes a constructability element that is best predicted before construction. A relatively shallow depth to bedrock may limit practices that require a deep footprint or outlet structure.

Minimum Hydraulic Head:This factor reflects the estimate of the required elevation difference needed to pass runoff through the BMP (from the inflow to the outflow) to allow for gravity operation.

Slope: This reflects the potential effect of slope on the practice. Specifically, the slope guidance refers to how flat the area must be where the practice is installed, and/or the grades of the interior components. In addition, similar considerations can be made for the contributing drainage area; however, steep drainage areas can be addressed with adequate energy dissipation as the flow approaches the practice.

Contributing Drainage Area (CDA): This factor reflects the recommended minimum or maximum drainage area that is considered optimal for a practice. If the CDA present at a site is slightly greater or smaller than that which is recommended, some leeway may be warranted if design considerations address the potential issue and more importantly, the practice meets other management objectives.

Space: This is a very general estimate of the area of BMP footprint as a function of the CDA.

Table 3.6. BMP Screening: Site Characteristics and Feasibility

BMP	Soils[1]		Other Site Constraints[2]					
	HSG A/B	HSG C/D	Depth WT[3]	Depth BR[3]	Min Hyd Head[4]	Max Slope[5]	CDA	Space[6]
Vegetated Filter Strips[7]	Yes	Yes w/ CA[8]	1 to 2ft.	1 to 2 ft.	NA	6%/8%[9]	3 ac.	15to25%
Simple Disconnection	Yes	Yes w/ CA[8]	1 ft.	1 ft.	NA	5%; 1%to2% is best	Max 1,000 sq.ft.	Nominal
Simple Disconnection with Compensatory Practices	Refer to each practice: Bioretention, Infiltration, Rainwater Harvesting, Urban Bioretention.							

BMP	Soils[1]		Other Site Constraints[2]					
	HSG A/B	HSG C/D	Depth WT[3]	Depth BR[3]	Min Hyd Head[4]	Max Slope[5]	CDA	Space[6]
Bioretention	Yes	Yes w/ UD[10]	2 ft.	1 ft.	3to5ft.	1% to 5%	2.5 ac.[11]	4%to6%
Urban Bioretention	NA	NA	NA	NA	3to4ft.	NA	2,500 sq.ft.[12]	Nominal
Permeable Pavement	Yes w/ IR[13]	Yes w/ UD[10]	2 ft.	1 to 2 ft.	2 ft.	1%-3%[14]	2:1 ratio[15]	Nominal
Grass Swale	Yes	Yes w/ CA[16]	1 ft.	1 ft.	2 ft.	4%[17]	5 ac.	3%to5%
Infiltration	Yes w/ IR[13]	NO	2 ft.	2 ft.	2to4ft.	0to5%	2.5ac[18]	1%to4%
Regenerative Stormwater Conveyance System	Yes	Yes	Below pond level	1 to 2 ft.	Varies	10%[21]	10 to 30 ac.	4%to6%
Rainwater Harvesting	NA	NA	NA	NA	Varies	NA	roof only	Nominal
Vegetative Roof	NA	NA	NA	NA	NA	NA	roof only	NA
Filtration	NA	NA	1 ft.	1 ft.	2to8ft.	NA	2to5 ac.[19]	0to3%
Stormwater Wetlands	Yes w/ liner	Yes	Below	2 ft.	2to4ft.	NA	10 to 25[20]	3%

Abbreviations: WT = water table; BR = bedrock; Min Hyd Head = minimum hydraulic head; CDA = contributing drainage area

[1]NRCS HSGs. [2] These are general ranges only. [3] Vertical distance from bottom invert of practice to water table (WT) or bedrock (BR); may be different in karst. [4] Vertical distance from inflow to practice and its bottom invert. [5] Maximum internal slope of the practice. [6] Typical footprint of practice as percent of drainage area. [7]Vegetated Filter Strips include Sheet Flow to Conservation Areas. [8]with compost Soil Amendments. [9] 6% forested, 8% grass. [10]With underdrain. [11] Can be larger in some cases. [12]Upper limit is typically based on practical size of planter box. [13]With adequate measured infiltration rate. [14]Slopes can be broken up with terracing. [15]Ratio of area of "run on" pavement to permeable pavement. [16]Some credit with C/D soils, however Compost Amendments provide a boost. [17]Slopes can be broken up with check dams. [18]Critical design factor is limiting the CDA to Infiltration surface area ratio. [19] 100% impervious. [20] 10 ac. may be feasible if groundwater is intercepted and adequate water balance provided. [21] Steeper systems can be designed by increasing the number and size of cobbles and boulders.

3.3.3. Water Resource Settings

Karst Geology: Karst can be a challenging condition in which to apply stormwater management practices. Karst is a dynamic landscape composed of soluble bedrock that is associated with sinkholes, springs, caves, and a highly irregular soil-rock interface. Active karst is defined as karst features within 50 feet of the surface of the site and poses many challenges to BMP design. BMPs that store runoff can actually promote sinkhole formation that may threaten the integrity of the practice as well as structures on the site. In addition, Karst geology provides rapid pathways for water to travel from the surface to deep groundwater and aquifers, so it is safe to assume that any treated or untreated runoff that is infiltrated can reach a drinking water supply in karst areas. Specific site and BMP design considerations are required in areas of karst geology.

Trout Waters: Trout can serve as an indicator for many aquatic organisms that are affected by water temperature. Many aquatic organisms, such as fish and insects, are *ectotherms*, meaning their body temperatures are regulated by their surroundings. Increased water temperatures can lead to behavioral changes, such as increased feeding or aggressiveness, as well as physiological changes, such as increased metabolism or loss of motor function. Fish, especially trout, possess some of the most stringent temperature requirements. Most trout prefer water temperatures between 40 to 70°F, with increased temperatures leading to injury or death.

Especially during the summer months, pavement and rooftop materials capture solar radiation, reaching temperatures much higher than those of natural surfaces. During a storm event, heat is transferred from pavement and rooftops to stormwater runoff, with runoff temperatures at times exceeding 110°F. Runoff at the beginning of a storm often exhibits a temperature spike with temperatures decreasing as rainfall continues and surfaces cool.

Stormwater Hotspots: The ability of BMPs to effectively treat runoff from designated stormwater hotspots varies with the specific land uses and related pollutants and pollutant loads. Generally, hotspots are considered to generate pollutants or concentrations of pollutants that are beyond the performance capacity of traditional stormwater BMPs. Therefore, BMPs that receive hotspot runoff may have design restrictions. Proprietary products, such as oil/water coalescing chambers for fuel handling areas, may be available that can serve to reduce the potential impact. In addition, the entire site may not necessarily be a hotspot; individual activities on the site may be identified as *stormwater hotspot sources areas* and isolated with BMPs that target the particular pollutant. **Chapter 5** contains more detailed information on stormwater hotspots.

Ultra-Urban Sites: This screening factor includes multiple design considerations: high density of people, limited space, high value land, impacted or disturbed soil profiles, pre-set drainage infrastructure, and a wide range of potential urban pollutants. BMPs appropriate for ultra-urban sites are also frequently used at redevelopment and infill sites and to retrofit existing urban development.

See Table 3.7 for a summary of BMPs and water resources settings.

Table 3.7. BMP Screening: Water Resource Settings

BMP	Karst Terrain[1]	Trout Waters[2]	Ultra Urban[3]	Hotspots[4]	Cold Climate
Vegetated Filter Strips[5]	Preferred	Preferred	Restricted	Restricted	Preferred
Simple Disconnection	Preferred	Preferred	Restricted	Accepted[6]	Accepted
Simple Disconnection with Compensatory Practices	Refer to Individual Practices: Bioretention, infiltration, Rainwater Harvesting, Urban Planter.				
Bioretention	SS: Acc LS: Rest.	Preferred	Preferred	Accepted	Preferred
Urban Bioretention	Preferred	Preferred	Preferred	Accepted	Preferred
Permeable Pavement	Preferred	Preferred	Preferred	Prohibited	Preferred
Grass Swale	Accepted	Accepted	Restricted	Restricted	Accepted
Infiltration	SS: Acc LS: Pro	Preferred	Restricted	Prohibited	Accepted
Regenerative Stormwater Conveyance System					
Rainwater Harvesting	Preferred	Preferred	Preferred	Accepted	Accepted
Vegetative Roof	Preferred	Preferred	Preferred	Preferred	Accepted
Filtration	Preferred	Accepted	Preferred	Preferred	Accepted
Stormwater Wetlands	Accepted	Accepted	Restricted	Restricted	Accepted

Preferred	– Widely feasible and recommended
Accepted	--Can work depending on site conditions
Restricted	– Extremely limited feasibility
Prohibited	– Do not use due to limited feasibility and environmental risk

[1] CSN (2009); [2] NCSU (2007); [3] CSN 2011; [4] CWP (2005); **[5]** *Vegetated Filter Strips include Sheet Flow to Conservation Areas.*
[6]Impervious Surface Disconnection.
SS: Small scale application
LS: Large scale application

3.4 BMP Design Methods

The design of stormwater BMPs to manage a volume of runoff can be grouped into two categories: those that utilize a designed storage volume component as the primary mechanism for managing the Tv; and those that utilize the designated treatment surface area of the practice to manage the Tv. Many BMPs depend on both these features for performance; however, the primary sizing and design process typically focuses on one or the other.

Therefore, in order for the designer to select the most effective BMP(s) (**Runoff Reduction Method Step 2**), and evaluate the BMP selection's performance in terms of managing the runoff volume from the 1-inch rainfall event and, when necessary, reducing the targeted pollutant load (**Runoff Reduction Method Step 3**), the designer must first establish the *Tv*.

3.4.1. Target Treatment Volume and Design Volume

The Tv is established by the MS4 General Permit as the volume of runoff from the one inch rainfall event based on the size and land cover of the CDA as determined by the Design Compliance Spreadsheet (and **Equation 3.1**). The basis for this design standard is to provide a simple implementation standard for protecting the physical, chemical, and biological characteristics of receiving waters. Historic rainfall data supports the characterization that approximately 90% of the rainfall events in West Virginia are one inch or less, and that under natural conditions approximately 10% of the volume of precipitation falling to earth runs off to surface waters via surface/overland flow (FISRWG, 1998). Therefore managing the runoff from this design rain event will reasonably mimic the natural hydrologic process.

The calculation procedure for computing this volume of runoff is as follows:

Equation 3.1

$$Tv = \frac{P \times [(Rv_I \times \%I) + (Rv_T \times \%T) + (Rv_F \times \%F)] \times SA}{12}$$

Where:

- Tv = Target Treatment Volume, in acre-feet (ac.-ft.)
- P = Depth of target rainfall event = one inch
- Rv_I = Volumetric Runoff Coefficient for impervious cover (unit-less)[1]
- $\%I$ = Percent of site in impervious cover (fraction)
- Rv_T = Volumetric Runoff Coefficient for turf cover or disturbed soils (unit-less)[1]
- $\%T$ = Percent of site in turf cover (fraction)
- Rv_F = Volumetric Runoff Coefficient for forest cover (unit-less)[1]
- $\%F$ = Percent of site in forest cover (fraction)
- SA = Total site area, in acres

[1]The Rv coefficients are provided in **Table 3.8** and the land cover definitions are provided in **Table 3.9.**

The Individual BMP Design Volume (Dv) is the volume designed into a particular practice based on sizing criteria as prescribed in each individual BMP specification. The Dv can equal the Tv if there is only one BMP in the CDA. Where multiple BMPs are used as part of a treatment train, the Dv of each individual practice will be part of the overall Tv for the drainage area, with the sum of each BMP's Dv equaling or exceeding the Tv.

Hydrologic Methods

There are numerous methods of modeling the volume and peak flow of stormwater runoff. The NRCS Technical Release 55 (TR55) is the most common for developing runoff hydrographs in order to calculate runoff volume and peak rate of flow. TR55, sometimes referred to as the Curve Number Method, incorporates drainage area characteristics of land cover condition, soil types, and the drainage area time of concentration to predict the rate and volume of runoff resulting from a standard 24-hour rainfall distribution. However, TR55 has been documented to underestimate the runoff from small storm events (VADCR, 1999).

Another common modeling tool is the Rational Method. The Rational Method utilizes a unit-less runoff coefficient and the rainfall intensity, measured in inches per hour, to predict an instantaneous peak rate of runoff. The method was developed specifically for sizing drainage culverts and stormwater conveyance systems to carry the maximum peak rate of runoff from a homogeneous and highly impervious drainage area. The Rational Method does not generate a runoff volume, and while there have been attempts to expand the method's utility by generating a theoretical discharge hydrograph to serve as a BMP design tool, the method is not appropriate for calculating the target Tv.

The Rational Method and the NRCS TR55 are considered single-event design storm methodologies. Another method that is commonly referenced when modeling stormwater runoff is continuous simulation. Continuous simulation models utilize a chronological record of rainfall as input to a rainfall-runoff model (such as NRCS Curve Number methods) to determine the maximum runoff peak rate and total volume. The method will predict the rainfall depth and runoff characteristics for a specific frequency return interval (such as the 90th percentile rainfall event) based on the specific time period of record being evaluated.

These methods all have their strengths and weaknesses. They all require site specific design parameters in order to compute the runoff characteristics. The Runoff Reduction Method calculation for the target Tv as noted above is not necessarily the most accurate; it is independent of the rainfall distribution patterns (rainfall intensity and duration) and the shape of the discharge hydrograph. This means that the entire design Tv may reach the BMP in the first few minutes of an intense storm; or the Tv may slowly enter the BMP over the course of several hours during a steady light rainfall.

As such, the Tv calculation is intended to be a simple and straightforward method for sizing BMPs independent of the obvious variability of rainfall patterns. For this reason, many BMPs have conservative sizing standards for capturing the Tv regardless of storm intensity or peak rate of inflow. These standards include energy dissipation, forebays, and in the case of Bioretention in particular, a minimum requirement for the surface ponding volume.

Volumetric Runoff Coefficient - Rv

The calculation of the Tv is dependent upon knowing the proposed land covers for the site. The Tv calculation provided in **Section 3.4.1** and included in the Design Compliance Spreadsheet contains three general land cover categories: (1) **Impervious Cover**, (2) **Managed Turf** or **Disturbed Soils**, and (3) **Forest/Open Space**.

The negative impact of impervious cover on receiving water bodies has been well documented (CWP 2003, Walsh 2004; Shuster et al. 2005; Bilkovic et al. 2006). More recent research indicates that other land covers, such as disturbed soils and managed turf, also impact stormwater runoff quality and quantity (Law et al, 2008). Numerous studies have documented the impact of grading and construction on the compaction of soils, as measured by increase in bulk density, declines in soil permeability, and increases in the runoff coefficient (OCSCD et al, 2001; Pitt et al, 2002; Schueler, 2000a). As a result, these compacted "pervious" areas have a much greater hydrologic response than is typically predicted in urban runoff models.

Further, highly managed turf can contribute to elevated nutrient loads. Typical turf management activities include mowing, active recreational use, and fertilizer and pesticide applications (Robbins and Birkenholtz, 2003). Research indicates that relatively low impervious cover residential land uses contained significantly higher nutrient concentrations than sites with higher impervious cover (CWP, 2008). This suggests that residential areas with relatively low impervious cover can have disturbed and intensively managed pervious areas that contribute to elevated nutrient levels.

The Runoff Reduction Method Tv computation takes into account impervious cover as well as the other land cover types that have been identified as generating more runoff from the developed site. In addition, this Tv value is utilized in the pollutant load computations (discussed in **Section 3.2.2**).

The runoff coefficients provided in **Table 3.8** were derived from research as outlined in the Runoff Reduction Technical Memorandum (Hirschman et al., 2008).

Table 3.8. Site Cover Volumetric Runoff Coefficients (Rv)

Land Cover	Hydrologic Soil Group			
	A	B	C	D
Forest Cover	.02	.03	.04	.05
Disturbed Soil/ Managed Turf	.15	.20	.22	.25
Impervious Cover	.95	.95	.95	.95

References: Pitt et al (2005), Lichter and Lindsey (1994), Schueler (2000a), Schueler, (2000b), Legg et al (1996), Pitt et al (1999), Schueler (1987) and Cappiella et al (2005).

There can be many points of interpretation about which land covers fall into each of the three categories for any particular site. **Table 3.9** provides guidance on how to assign land covers for each of the categories.

Table 3.9. Land Cover Guidance for Calculating the Design Volume

Impervious Cover
• Roadways, driveways, rooftops, parking lots, sidewalks, and other areas of impervious cover. • Gravel roadways, parking lots, and other gravel surfaces on top of a compacted sub-base. • This category also includes the surface area of stormwater BMPs that: (1) are wet ponds, OR (2) replace an otherwise impervious surface (e.g., Vegetated Roof, Permeable Pavement).[1]
Managed Turf
Managed turf is grassed soil that no longer functions in its natural hydrological state due to disturbance, compaction, or excessive management. Land disturbed and/or graded for eventual use as managed turf includes: • Portions of residential yards that are graded or disturbed, including yard areas, septic fields, residential utility connections • Roadway rights-of-way that will be mowed and maintained as turf • Turf areas intended to be mowed and maintained as turf within residential, commercial, industrial, and institutional settings

Forest/Preserved Open Space

Land that will remain undisturbed OR that will be restored to a hydrologically functional state:

- Portions of residential yards that will NOT be disturbed during construction
- Portions of roadway rights-of-way that, following construction, will be used as filter strips, grass channels, or stormwater treatment areas; MUST include soil restoration or placement of engineered soil mix as per the design specifications
- Community open space areas that will not be mowed routinely, but left in a natural vegetated state (can include areas that will be bush hogged no more than four times per year)
- Utility rights-of-way that will be left in a natural vegetated state (can include areas that will be bush hogged no more than four times per year)
- Surface area of stormwater BMPs that are NOT wet ponds, have some type of vegetative cover, and that do not replace an otherwise impervious surface. BMPs in this category include bioretention, water quality swale, grass swales, detention pond (used for local flood control requirements) that is not mowed routinely, stormwater wetland, soil amended areas that are vegetated, and infiltration practices that have a vegetated cover.
- Other areas of existing forest and/or open space that will be protected during construction and that will remain undisturbed. These include wetlands.

Operational & Management Conditions for Land Cover in Forest & Open Space Category:

- Undisturbed portions of yards, community open space, and other areas that will be considered as forest/open space must be shown outside the limits of disturbance on approved erosion and sediment control plans AND demarcated in the field (e.g., fencing) prior to commencement of construction.
- Portions of roadway rights-of-way that will count as forest/open space are assumed to be disturbed during construction, and must follow the most recent design specifications for soil restoration and, if applicable, site reforestation, as well as other relevant specifications if the area will be used as a filter strip, grass channel, bioretention, or other BMP
- All areas that will be considered forest/open space for stormwater purposes must have documentation that prescribes that the area will remain in a natural, vegetated state. Appropriate documentation includes: subdivision covenants and restrictions, deeded operation and maintenance agreements and plans, parcel of common ownership with maintenance plan, third-party protective easement, within public right-of-way or easement with maintenance plan, or other documentation approved by the local program authority
- While the goal is to have forest/open space areas remain undisturbed, some activities may be prescribed in the appropriate documentation, as approved by the local program authority: forest management, control of invasive species, replanting and re-vegetation, passive recreation (e.g., trails), limited bush hogging to maintain desired vegetative community, etc.

[1] *Certain stormwater BMPs are considered impervious with regard to the land cover computations. These BMPs are still assigned Runoff Reduction rates within the spreadsheet, so their "values" for stormwater management are still accounted for. The reason they are considered impervious is that they either do not reduce runoff volumes (e.g., wet ponds) or their Runoff Reduction rates are based on comparison to a more conventional land cover type (e.g., vegetated roofs, permeable pavement). In other words, the spreadsheet considers them to be impervious, and then the assigned Runoff Reduction rate reduces the resulting Treatment Volume.*

3.4.2. BMP Design Volume and Credit

Once the Target Tv has been calculated, the designer must select the best BMP or combination of BMPs for the particular development site. As noted previously, the BMP design elements of volume and surface area are determined as a function of the CDA Tv. **Table 3.10** provides a quick reference to those practices that reflect a sizing and design standard for volume (cubic feet) and surface area (square feet). Only two practices, Sheet Flow to Vegetated Filter Strips and Conservation Areas (**Design Specification 4.2.1**), and Impervious Surface Disconnection (**Design Specification 4.2.2**) stand out as the only practices that are sized solely based on surface area and do not have a combined volume and surface area design standard. As expected, these practices are also credited solely based on the surface area provided. It is important to recognize that most BMPs incorporate a surface area design feature that, while not the primary sizing factor, is a critical design feature for ensuring BMP performance and longevity. This combined design element is identified in column 3 of **Table 3.10**.

An example of combined design elements is that of Bioretention (**Design Specification 4.2.3**, includes Residential Rain Gardens, Urban Bioretention and Water Quality Swales) where the design is focused on providing an adequate total storage volume and surface area within the practice. This includes the storage volume elements of surface ponding volume within the soil media and gravel layers, and the additional requirement of establishing a minimum surface area in order to effectively manage the incoming volume and peak rate of runoff.

The Design Compliance Spreadsheet computes the compliance of the BMP implementation strategy by tabulating volume. Even Impervious Surface Disconnection and Sheet Flow practices that are designed to provide a minimum surface area are tabulated in the spreadsheet with a corresponding treatment volume. (A credit of cubic feet is awarded for every square foot of surface area.)

Storage Volume is Just One Critical Design Element

It is important to recognize that most practices will include critical design features in addition to the required storage volume, such as surface area requirements, vegetation, geometry, and other features that are essential for effective management of the Tv.

Table 3.10. Primary BMP Design and Compliance Feature

BMP		Volume Based Load Reduction Credit[1]	Surface Area Based Load Reduction Credit[2]	Combined Volume & Surface Area Design Criteria[3]
Sheet Flow to Conservation Areas			✓	
Sheet Flow to Vegetated Filter Strips			✓	
Simple Disconnection			✓	
Simple Disconnection with Compensatory Practices	Micro-Infiltration	✓		✓
	Residential Rain Garden	✓		✓
	Rainwater Harvesting	✓		
	Urban Planter	✓		✓
Bioretention		✓		✓
Permeable Pavement		✓		✓
Grass Swale		✓		✓
Infiltration		✓		✓
Regenerative Stormwater Conveyance System		✓		✓
Rainwater Harvesting		✓		
Vegetative Roof		✓		✓
Filtration		✓		✓
Stormwater Wetlands			✓	✓

[1]Compliance with permit criteria measured in terms of storage volume provided.
[2] Compliance with permit measured in terms of surface area of the practice.
[3] Minimum design criteria that includes volume and surface area design features.

It is important to note that where Runoff Reduction is credited as a percentage of the incoming runoff volume, it is numerically impossible to achieve compliance with the goal of 100% reduction unless the practice is credited with 100% reduction. For example, a Level 1 Bioretention is credited with removing 60% of the incoming runoff volume when sized for a one-inch rainfall event. Continuing to apply a 60% reduction to the incoming runoff volume will continue to reduce volume and approach the 100% goal, but not reach it. The primary solution for achieving compliance in these cases is to oversize the volume component of the Level 1 BMP to achieve the required volume credit. Using Bioretention as an example, over sizing the storage volume (or Dv) of a Level 1 Bioretention by 167% will achieve the 100% compliance for the specific drainage area being managed.

There are some important limitations and caveats on how these sizing (or oversizing) and crediting rules can be applied. Some are general rules in the application of the Runoff Reduction Method, and others are specific to particular BMPs. **Table 3.11** provides an overview of these key limitations and caveats.

Table 3.11. Sizing Limitations and Caveats for Selected BMPs

1. Runoff Reduction credits cannot be greater than 100% in order to compensate for another drainage area (e.g., 125% Runoff Reduction credit in sub-area 1 to compensate for only achieving 75% Runoff Reduction credit in sub-area 2).
2. **Bioretention**: Design criteria govern the relative size of the surface and subsurface (media) storage volume is specified for Level 1 and Level 2 designs. These criteria are to prevent the extreme cases of creating large surface ponding areas with minimal filter media. Continuing the Dv over sizing example of the Level 1 Bioretention described above, both the design surface area and storage volume must reflect the increased Dv in order to achieve runoff reduction performance values.
3. **Impervious Surface Disconnection**: The previously noted method of crediting Impervious Surface Disconnection and Sheet Flow to Vegetated Filter Strips and Conservation Areas is limited in that there is a maximum size or surface area as a function of the CDA that will limit the "oversizing" of disconnection areas. (These design sizing rules are detailed in the individual design specifications in **Chapter 4**).
4. **Permeable Pavement**: The minimum Permeable Pavement stone reservoir depth required to manage the Tv or Dv will often be less than the stone bedding typically provided under pavement sections as required by the pavement structural design, or the minimum stone depth provided to allow for construction tolerances (i.e. grading for the installation of pavement gravel bedding is typically a "rough grade" depth that will include tolerances of a few inches, whereas the minimum depth of a stone reservoir to manage a 1" rainfall depth may be as little as 2.5 inches). Therefore, most Permeable Pavement installations may be oversized for reasons other than stormwater treatment. The annual volume reduction performance value for Level 1 Permeable Pavement (RR=45%) will not increase with additional volume in the stone reservoir layer because the water does not have a high residence time in the stone (as compared to, say, bioretention soil mix). The Level 1 performance value is capped at 45% (or 0.45 watershed inches), and the Level 2 value at 100% (or one watershed-inch).
5. **Grass Swale**: Grass Swales are designed based on a peak rate of discharge of the Dv (as computed in accordance with **Appendix F**). When a Grass Swale is the downstream BMP in a treatment train, the design and runoff reduction credit can be:
   i. Based on the Dv peak rate of discharge from the upstream BMP and credited with a 10% or 20% runoff reduction credit (depending on soils) applied to the incoming volume; or
   ii. Based on the entire drainage area Tv peak rate of discharge and credited with a 0.1 or 0.2 watershed-inch runoff reduction credit applied to the incoming volume.

   The site designer has the discretion to investigate which approach best suits the site and stormwater design.

Additional BMP specific design criteria in **Chapter 4** will further refine how the BMP storage volume must be configured: geometry, surface storage, media storage, and other factors. Other BMP criteria are less prescriptive and allow the designer to manipulate the practice as needed to fit the site conditions. The design examples in **Chapter 6** illustrate further the application of design criteria.

3.4.3. Large Storm Conveyance

The BMPs in West Virginia will typically be designed to manage the runoff from the one-inch rainfall event. In some cases, designers may be required to manage or detain a larger storm event for purposes of downstream channel protection or flood control. In all cases, the designer must account for the conveyance of these larger storms *through* the BMP (the BMP is said to be **On-Line**) or *around* the BMP (thus making the BMP **Off-Line**). In either case, a bypass control is necessary to manage the large flow so the runoff in excess of the one-inch rain event will not damage the BMP (excessive velocity or ponding depth) or re-suspend and export previously trapped pollutants.

An ***Off-Line*** BMP includes a low-flow diversion structure that channels the small storm flow volume into the BMP, while allowing the larger flows to bypass the BMP. **Figure 3.1** illustrates a simple offline design that diverts the runoff past the Bioretention basin once it has filled up to the maximum design volume depth. **Figure 3.2** illustrates a similar concept using a bypass structure to divert flows past a level spreader. In both cases, larger flows by-pass around the BMP and therefore do not impact the design of the BMP. Bypass structures can be external – thereby diverting the flow before it gets to the BMP, or it can be part of the BMP inlet structure such as a forebay or level spreader.

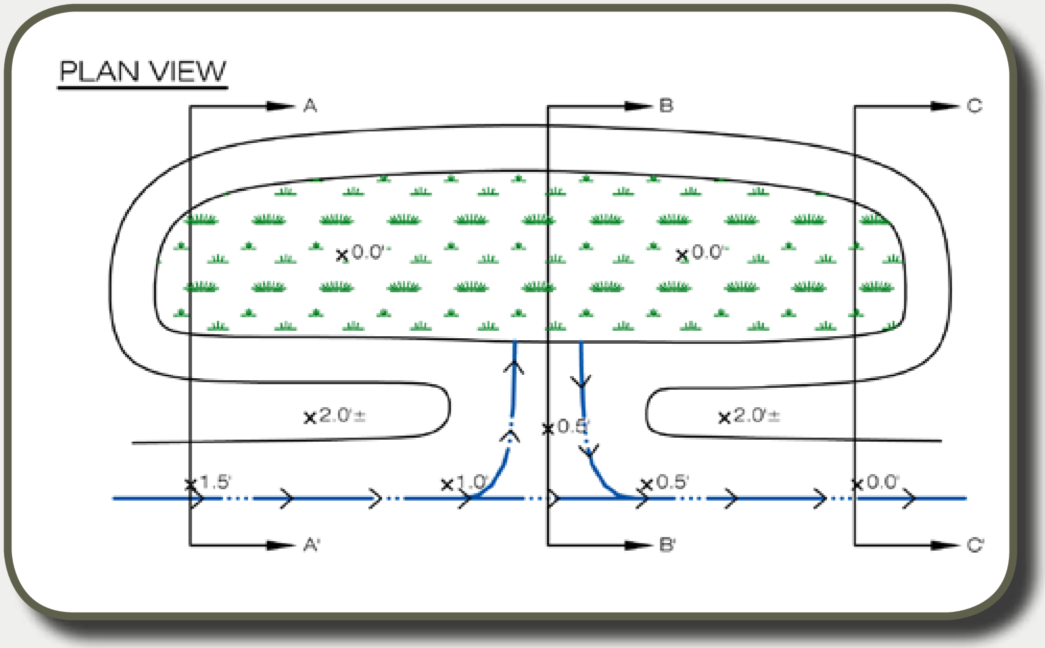

Figure 3.1. Simple Off-Line BMP Design

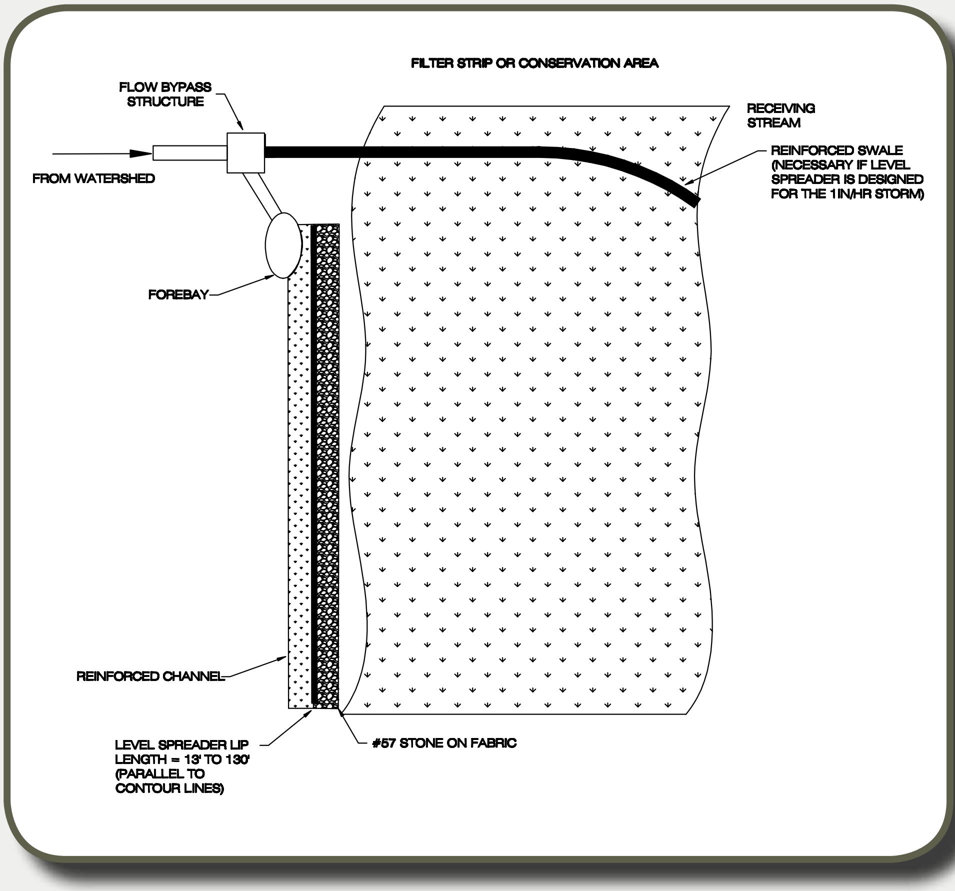

Figure 3.2. External Bypass Structure for Level Spreader

An ***On-Line*** BMP accepts all the runoff from the CDA. Flows that exceed the design capacity exit the practice via an overflow structure or weir within the BMP. On-line BMPs must be carefully designed to accommodate the large storm design peak flow rate in terms of inflow velocity and energy, as well as an adequately sized overflow to allow the runoff to safely exit the BMP.

Off-line designs are usually the preferred option for volume reduction BMPs, especially where larger drainage areas (e.g., greater than 0.5 to 1 acre) are conveyed by a pipe or armored drainage system. On-line systems in these cases will require careful design and construction to ensure adequate conveyance of the large storm inflow.

On-line systems should include the following:

- Inflow points should be protected from erosive velocity;
- An overflow structure must be provided within the practice to pass storms greater than the design storm storage to a stabilized conveyance or storm sewer system;
- Discharge from the overflow structure should be controlled so that velocities are non-erosive at the outlet point;
- The overflow structure type and design should be scaled to the application – this may be a landscape grate or yard inlet for small practices or a commercial-type structure for larger installations.

It should be noted that both types of design approaches require attention to safe conveyance of larger flows in adequate conveyances and with adequate freeboard to a receiving waterbody. Drainage design (pipes, culverts, etc.) should be based on expected peak discharges assuming that upstream volume reduction practices are full.

3.4.4. Large Storm Runoff Reduction Credit

The menu of runoff reduction BMPs available for use includes the Better Site Design strategies described in **Chapter 4, Specification 4.1** (*Watershed Protection Elements*) and the runoff reduction stormwater BMPs outlined in remaining specifications of **Chapter 4** (*Site and Neighborhood Design Elements*). The Watershed Protection Elements include site design strategies that are self crediting; that is, strategies that reduce impervious cover will in turn result in a lower developed condition annual runoff volume as well as the single-event modeled peak rate of runoff by virtue of a lower developed condition runoff Curve Number for all storms. The Runoff Reduction BMPs, as discussed in this chapter, also reduce the annual runoff volume leaving the site. However, additional computations are required in order to incorporate those reductions into single-event hydrologic models.

Peak flow rate reduction for single-event runoff and hydraulic routing models is accomplished by accounting for BMP stage-storage-discharge relationships. Many of the volume based BMPs used in the Runoff Reduction Method provide some amount of storage volume, and designers could apply hydraulic routing relationships. However, the response characteristics of many runoff reduction practices may not follow the traditional detention/retention design parameters. Routing of runoff reduction BMPs can be a difficult and complex task given all the hydrologic and hydraulic variables associated with volume reduction, such as evapotranspiration, storage within the soil media, infiltration, and extended filtration.

The Runoff Reduction Method provides a simpler method for crediting specific runoff reduction values toward peak flow reduction. The method converts the total annual Runoff Reduction credit from all the BMPs in the drainage area from cubic feet (or acre-feet) to watershed-inches of retention storage, and then utilizes the NRCS TR55 runoff e**quations 2-1 through 2-4** to derive a reduced curve number that reflects the reduced runoff volume. This new curve number can then be used for computing the large storm peak discharge from the drainage area for determining the storage volume needed for downstream channel or flood protection requirements.

Adjusted Curve Number and Larger Storm Events

It is unlikely that the reduced curve number will be sufficient to fully comply with any locally-required 2-year or 10-year or larger frequency storm event detention or peak flow standards. However, it may allow for a reduction of the overall size and footprint of structural detention practices, thereby providing an economic incentive to optimize the runoff reduction practices to the maximum extent practicable.

A simplified derivation of the computational procedure starts with the combined NRCS Runoff Equations in order to express the runoff depth in terms of rainfall and potential maximum retention, TR-55 **Equations 2-1 through 2-3.** In addition, the potential maximum retention, S, is related to soil and cover conditions of the watershed through the curve number as described by TR-55 **Equation 2-4**.

(Eq. 2-1, TR-55)
$$Q = \frac{(P - I_a)^2}{(P - I_a) + S}$$

(Eq. 2-2, TR-55)
$$I_a = 0.2S$$

(Eq. 2-3, TR-55)
$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

(Eq. 2-4, TR-55)
$$S = \frac{1000}{CN} - 10$$

(Modified Eq. 2-3)
$$Q - R = \frac{(P - 0.2\,S)^2}{(P + 0.8\,S)}$$

where:

Q = runoff depth (in),
P = rainfall depth (in),
I_a = Initial abstraction (in),
S = potential maximum retention after runoff begins (in),
CN = Runoff Curve Number, and
R = Retention storage provided by Runoff Reduction practices (in).

The retention storage depth equivalent to the Runoff Reduction values assigned by the Runoff Reduction Method, and any additional retention storage provided on the site (expressed in terms of retention storage R) is subtracted from the total runoff depth associated with the developed condition curve number, which then will provide for a new value of S (**Modified Equation 2-3**). A new curve number is then back-calculated from the new value of S using **Equation 2-4** (Koch, 2005).

While it is not easy to predict the absolute runoff hydrograph modification provided by reducing stormwater runoff volumes, it is clear that reducing runoff volumes will have an impact on the runoff hydrograph of a development site. Simple routing exercises have indicated that this curve number adjustment approach represents a conservative estimate of peak reduction.

This procedure is simplified for designers in the Design Compliance Spreadsheet. It is important to note that the curve number reduction associated with the retention of one watershed-inch of runoff volume will decrease as the rainfall depth increases (meaning one-inch of volume reduction has less of an impact on a five-inch rain event than it will on a two-inch rain event). Therefore, the curve number adjustment must be computed for each design storm depth.

3.4.5. Evaluating BMP Compliance – The Design Compliance Spreadsheet

The Design Compliance Spreadsheet is a tool that integrates the runoff volume reduction methods and stormwater BMP performance values discussed in this chapter. The spreadsheet is primarily a tool to be used by site designers and local program plan reviewers to evaluate compliance with the 1-inch capture performance goal in the MS4 General Permit. While its primary function is as a compliance tool, the spreadsheet can also be used by site designers as a stormwater BMP planning tool. The spreadsheet allows the designer to develop and test various BMP scenarios and preliminary sizing guidelines in a relatively quick and efficient manner.

The following is a quick overview of the tabs and capabilities of the Design Compliance Spreadsheet:

- A **Site Data** tab allows the user to input proposed land covers by drainage area. The tab uses the Runoff Reduction Method calculations outlined in this chapter to derive the post-development Treatment Volume for each drainage area. This tab also applies the volume "credits" associated with any Incentive Standards that apply to the site (e.g., redevelopment, brownfields, high density, etc.).
- Individual **Drainage Area** tabs allows the user the run various BMP scenarios, using different combinations of BMPs and BMP storage volume/surface area scenarios to accomplish the Treatment Volume objectives. These tabs include all the BMPs in this manual that are assigned a runoff volume reduction performance value.
- A **Runoff Reduction Summary** tab tracks cumulative volume reductions from the BMPs in the Drainage Area tabs, and compares this value to the required Treatment Volume. This is essentially a quick compliance check.
- A **Channel and Flood Protection** tab utilized the Curve Number adjustment method outlined in **Section 3.4.4**, yielding adjusted Curve Numbers for each drainage area, depending on the cumulative runoff reduction volume achieved. These adjusted Curve Numbers can be used, at the discretion of the local plan approving authority, to model compliance with local stormwater detention and/or channel and flood protection requirements.

REFERENCES

Bilkovic, D.M., Roggero, M., Hershner, C. H., and Havens, K. H. 2006. "Influence of Land Use on Macrobenthic Communities in Nearshore Estuarine Habitats." Estuaries and Coasts, 29(6B), 1185-1195.

Cappiella, K., T. Schueler, and T. Wright. 2005. Urban Watershed Forestry Manual. Part 2: Conserving and Planting Trees at Development Sites. USDA Forest Service, Newtown Square, PA.

Center for Watershed Protection (CWP). 2003. Impacts of IC on Aquatic Systems. CWP, Ellicott City, MD.

Center for Watershed Protection (CWP). 2005. Urban Subwatershed Restoration Manual Series, Manual 8, Pollution Source Control Practices, Version 2.0. CWP, Ellicott City, MD.

Center for Watershed Protection (CWP). 2007. National Pollutant Removal Performance Database Version 3.0. CWP, Ellicott City, MD.

Center for Watershed Protection (CWP). 2008. Draft Virginia Stormwater Management Nutrient Design System. Prepared for Technical Advisory Committee and Virginia DCR. CWP, Ellicott City, MD.

Chesapeake Stormwater Network (CSN). 2009. Technical Bulletin No. 1: Stormwater Design Guidelines For Karst Terrain In The Chesapeake Bay Watershed, Version 2.0. CSN, Baltimore, MD.

Chesapeake Stormwater Network (CSN). 2011. Technical Bulletin No. 5: Stormwater Design for High Intensity Redevelopment Projects in the Chesapeake Bay Watershed Version 3.0. CSN, Baltimore, MD.

FISRWG 1998. Federal Interagency Stream Restoration Working Group. Stream Corridor Restoration: Principles, Processes and Practices. PB98-158348LUW.)

Hirschman, D., Collins, K., and T. Schueler. 2008. Technical Memorandum: The Runoff Reduction Method. Center for Watershed Protection and Chesapeake Stormwater Network. Ellicott City, MD.

Koch, Paul R. 2005. "A Milwaukee Model for LID Hydrologic Analysis." Proceedings from Managing Watersheds for Human and Natural Impacts: Engineering, Ecological, and Economic Challenges, American Society of Civil Engineers, Reston, VA.

Law N.L., Cappiella, K., Novotney, M.E. 2008. The need to address both impervious and pervious surfaces in urban watershed and stormwater management. Journal of Hydrologic Engineering (accepted).

Legg, A. R. Bannerman and J. Panuska. 1996. Variation in the relation of runoff from residential lawns in Madison, Wisconsin. USGS Water Resources Investigations Report 96-4194.

Lichter J. and P. Lindsey. 1994. Soil compaction and site construction: assessment and case studies. The Landscape Below Ground. International Society of Arboriculture

North Carolina State University (NCSU). 2007. Stormwater BMPs for Trout Waters. Matthew P. Jones, E.I., William F. Hunt, Ph.D., P.E. Biological and Agricultural Engineering, North Carolina State University, Raleigh, NC.

Ocean County Soil Conservation District (OCSCD), Schnabel Engineering Associates, Inc. and U.S. Department of Agriculture (USDA) Natural Resources Conservation Service. (2001). Impact of Soil Disturbance During Construction on Bulk Density and Infiltration in Ocean County, New Jersey. OCSCD, Forked River, NJ.

REFERENCES

Pitt, R. J. Lantrip and R. Harrison. 1999. Infiltration through disturbed urban soils and compost-amended soil effects on runoff quality and quantity. Research Report EPA/600/R-00/016. Office of Research and Development. U.S. EPA. Washington, D.C.

Pitt, R., Chen, S., and Clark, S. (2002). "Compacted Urban Soils Effects on Infiltration and Bioretention Stormwater Control Designs." Proceedings of the Ninth International

Conference on Urban Drainage: Global Solutions for Urban Drainage, American Society of Civil Engineers, Reston, VA.

Pitt, R. S. Chen, S. Clark and J. Lantrip. 2005. Soil structure effects associated with urbanization and the benefits of soil amendments. World Water and Environmental Resources Congress. Conference Proceedings. American Society of Civil Engineers. Anchorage, AK.

Robbins, P., and Birkenholtz, T. 2003. "Turfgrass revolution: measuring the expansion of the American lawn." Land Use Policy, 20, 181-194.

Schueler, T. 1987. Controlling urban runoff: a practical manual for planning and designing urban best management practices. Metropolitan Washington Council of Governments. Washington, DC.

Schueler, T. 2000a. The compaction of urban soils. Pgs 210-214 in The Practice of

Watershed Protection, edited by T.R. Schueler and H.K Holland. Center for Watershed Protection, Ellicott City, MD.

Schueler, T. 2000b. Can urban soil compaction be reversed? Pgs 215-218 in The Practice of Watershed Protection, edited by T.R. Schueler and H.K Holland. Center for Watershed Protection, Ellicott City, MD.

Shuster, W.D., Bonta, J., Thurston, H., Warnemuende, E., and Smith, D. R. 2005. "Impacts of impervious surface on watershed hydrology: A review." Urban Water Journal, 2(4), 263-275.

U.S. Department of Agriculture (USDA) Natural Resource Conservation Service. (1986). Urban Hydrology for Small Watersheds

VADCR 1999. Virginia Stormwater Management Handbook, Volumes 1 & 2. Virginia Department of Conservation and Recreation.

Walsh, C.J. 2004. "Protection of In-Stream Biota from Urban Impacts: Minimize Catchment Imperviousness or Improve Drainage Design?" Marine and Freshwater Research, 55(3), 317-326.

This page blank