Technical Memorandum:

The Runoff Reduction Method

Developed for the Following Projects:

Extreme BMP Makeover – Enhancing Nutrient Removal Performance for the Next Generation of Urban Stormwater BMPs in the James River Basin

Virginia Stormwater Regulations & Handbook Technical Assistance

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List Of Acronyms

BMP	best management practice
CDA	contributing drainage area
CSN	Chesapeake Stormwater Network
CWP	Center for Watershed Protection, Inc.
DCR	Virginia Department of Conservation & Recreation
ED	extended detention
EMC	event mean concentration
ESD	environmental site design
IC	impervious cover
HSG	hydrologic soil group
LID	low impact development
NPRPD	National Pollutant Removal Performance Database
NSQD	National Stormwater Quality Database
P-index	phosphorus index for soils
PR	pollutant removal
Q3	75th percentile value – or third quartile
RR	runoff reduction
SA	surface area
SNDS	stormwater nutrient design supplement
TN	total nitrogen
TP	total phosphorus
TR	total (mass) removal
Tv	treatment volume

1. INTRODUCTION & BACKGROUND

Through the convergence of various projects, the Center for Watershed Protection, Inc. (CWP) and the Chesapeake Stormwater Network (CSN) have been working to articulate the next generation of stormwater best management practices (BMPs) in the Chesapeake Bay Watershed. These practices must have the following characteristics:

- Achieve superior pollutant removal performance compared to current practices, particularly for the removal of nutrients.
- Support nutrient reduction targets outlined in Tributary Strategies.
- Be accessible and understandable to design professionals who prepare plans and local government staff who review them.
- Offer a broader menu of BMPs, including both conventional and innovative practices.
- Be based on sound science and the most up-to-date research on BMP design and performance.
- Address, through design features, long-term maintenance obligations.

CWP and CSN are collaborating on this work through the following projects:

> Extreme BMP Makeover: Enhancing the Nutrient Removal Performance of the Next Generation of Urban Stormwater BMPs in the James River Watershed
> This multi-year effort is supported by a grant from the National Fish and Wildlife Foundation (NFWF). The project aims to collect the best stormwater BMP science and apply to the creation of a Stormwater Nutrient Design Supplement (SNDS). Several “Early Adopter” communities within the James River Basin will apply various components of the SNDS and provide feedback to improve BMP design and implementation. The project also includes training for design professionals and local government staff, and dissemination of the SNDS to communities in the James River Basin and Chesapeake Bay Watershed.
>
> Besides CWP and CSN, project partners include the James River Association and the Hampton Roads Planning District Commission. The project will continue through 2010
>
> Technical Assistance for Virginia Stormwater Management Regulations & Handbook
> As a related project, CWP and CSN are working with the Virginia Department of Conservation & Recreation (DCR) on the development of technical support material for the updated stormwater regulations and handbook. The technical part of this work focuses on the creation of a “Runoff Reduction Method” for compliance with proposed regulations for new development and redevelopment. CWP and CSN are also participating in several site design charettes around the State to introduce the method and apply it on a trial basis to various real-world site plans. These charettes are sponsored by DCR and the Virginia Chapter of the American Society of Civil Engineers.

National Pollutant Removal Performance Database, Version 3
Over the years, CWP has been active in compiling and analyzing BMP pollutant removal performance data from research across the nation. CWP's National Pollutant Removal Performance Database was one of the first efforts in the country to systematically compile this type of data. Version 2 of the database (Winer, 2000) consisted of 139 individual BMP performance studies published through 2000. The database was recently updated to include an additional 27 studies published through 2006 (CWP, 2007).

These three projects will be instrumental in bringing research, field experience, and stakeholder involvement together to define key elements for future BMP design and implementation. This technical memorandum is the first step in the process. The memorandum outlines the results of BMP research and distills this information into a framework that can be used by design professionals and plan reviewers to verify compliance with proposed stormwater regulations in Virginia. The resulting "Runoff Reduction Method" is a system that incorporates site design, stormwater management planning, and BMP selection to develop the most effective stormwater approach for a given site.

Following the release of this memorandum, work will continue on both the Extreme BMP Makeover and Virginia DCR projects. This work will involve continued vetting the method with various stakeholder groups and technical advisory committees, conducting a field study of BMPs, developing the SNDS, conducting trainings on BMP design, installation, and maintenance, and disseminating the results within the James River and Chesapeake Bay watersheds. DCR will also continue with its process to update the stormwater regulations and handbook, with the assistance of various technical advisory committees.

One particular emphasis for future work will be to define how water quality and quantity criteria can be integrated in the BMP computation and design process. The current version of this technical memorandum outlines a method to account for water quality (nutrient) reductions. However, "full" stormwater compliance at a site includes other components, such as channel protection and flood control. CWP will be working with DCR and other stakeholders to help better define the relationship between quality and quantity, and future versions of this memorandum will include proposed methods.

The technical memorandum includes the following sections:

1. Introduction & Background: A brief review of the project background and framework.

2. The Runoff Reduction Method – A Three-Step Process for Better Stormwater Design: An overview of the rational and process outlined in the Runoff Reduction Method.

3. Documenting Runoff Reduction (RR) and Pollutant Removal (PR) Capabilities of BMPs: Key definitions and data tables to assign RR and PR values to BMPs.

4. Site-Based Nutrient Load Limits: A brief description of Virginia's proposed approach to stormwater compliance based on Tributary Strategy goals.

5. Runoff Coefficients – Moving Beyond Impervious Cover: An introduction to new runoff coefficients to better reflect land cover conditions that affect water quality.

6. Treatment Volume – The Common Currency for Site Compliance: An introduction to the Treatment Volume computation and rational.

7. Runoff Reduction Practices: A brief explanation of the research basis for assigning runoff reduction rates to BMPs.

8. Pollutant Removal Practices: Similar to Section 7, a brief explanation of the research basis for assigning pollutant removal rates to BMPs.

9. Level 1 and 2 Design Factors – Accountability for Better BMP Design: The resources and reasoning for identifying design factors that lead to better BMP performance.

2. THE RUNOFF REDUCTION METHOD: A THREE-STEP PROCESS FOR BETTER STORMWATER DESIGN

The Runoff Reduction Method ("RR Method") was developed in order to promote better stormwater design and as a tool for compliance with Virginia's proposed regulations. There several shortcomings to existing stormwater design practices that the method seeks to overcome:

- Levelling the BMP Playing Field: The suite of BMPs that can be used to comply with the existing regulations is limited to those listed in the *Virginia Stormwater Management Handbook*. For many site designers, this leaves out many innovative practices that have proven effective at reducing runoff volumes and pollutant loads. In particular, good site design practices, that reduce stormwater impacts through design techniques, are not "credited" in the existing system. The RR Method puts conventional and innovative BMPs on a level playing field in terms of BMP selection and site compliance.
- Meeting the Big-Picture Goals: The existing stormwater compliance system does not meet Tributary Strategy goals for urban land. As sites are developed, the total urban land load increases at a rate that exceeds urban land targets. The RR Method uses better science and BMP specifications to help with the job of incrementally attaining the Tributary Strategy goals for phosphorus and nitrogen.
- Beyond Impervious Cover: Existing computation procedures use impervious cover as the sole indicator of a site's water quality impacts. More recent research indicates that a broad range of land covers – including forest, disturbed soils, and managed turf – are significant indicators of water quality and the health of receiving streams. The RR Method accounts for these land covers and provides built-in incentives to protect or restore forest cover and reduce impervious cover and disturbed soils.
- Towards Total BMP Performance: The current system for measuring BMP effectiveness is based solely on the pollutant removal functions of the BMP, but does not account for a BMP's ability to reduce the overall volume of runoff. Recent research has shown that BMPs are quite variable in terms of runoff reduction, and that some are quite promising. Runoff reduction has benefits beyond pollutant load reductions. BMPs that reduce runoff volumes can do a better job of replicating pre-development hydrologic conditions, protecting downstream channels, recharging groundwater, and, in some cases, reducing overbank (or "nuisance") flooding conditions. The RR Method uses recent research on runoff reduction to better gage total BMP performance.
- Accountability for Design: Currently, it can be difficult for site designers and plan reviewers to verify BMP design features – such as sizing, pretreatment, and vegetation – that should be included on stormwater plans in order to achieve a target level of pollutant removal. Clearly, certain BMP design features either enhance or diminish overall pollutant removal performance. The RR Method provides clear guidance that links design features with performance by distinguishing between "Level 1" and "Level 2" designs.

The RR Method relies on a three-step compliance procedure, as described below.

> Step 1: Apply Site Design Practices to Minimize Impervious Cover, Grading and Loss of Forest Cover. This step focuses on implementing Environmental Site Design (ESD) practices during the early phases of site layout. The goal is to minimize impervious cover and mass grading, and maximize retention of forest cover, natural areas and undisturbed soils (especially those most conducive to landscape-scale infiltration). The RR Method uses a spreadsheet to compute runoff coefficients for forest, disturbed soils, and impervious cover and to calculate a site-specific target treatment volume and phosphorus load reduction target.
>
> Step 2: Apply Runoff Reduction (RR) Practices. In this step, the designer experiments with combinations of nine Runoff Reduction practices on the site. In each case, the designer estimates the area to be treated by each Runoff Reduction practice to incrementally reduce the required treatment volume for the site. The designer is encouraged to use Runoff Reduction practices in series within individual drainage areas (such as rooftop disconnection to a grass swale to a bioretention area) in order to achieve a higher level of runoff reduction.
>
> Step 3: Compute Pollutant Removal (PR) By Selected BMPs. In this step, the designer uses the spreadsheet to see whether the phosphorus load reduction has been achieved by the application of Runoff Reduction practices. If the target phosphorus load limit is not reached, the designer can select additional, conventional BMPs -- such as filtering practices, wet ponds, and stormwater wetlands -- to meet the remaining load requirement.

In reality, the process is iterative for most sites. When compliance cannot be achieved on the first try, designers can return to prior steps to explore alternative combinations of Environmental Site Design, Runoff Reduction practices, and Pollutant Removal practices to achieve compliance.

A possible Step 4 would involve paying an offset fee (or fee-in-lieu payment) to compensate for any load that cannot feasibly be met on particular sites. The local government or program authority would need to have a watershed or regional planning structure for stormwater management in order to make this option available for sites within the jurisdiction. The fee would be based on the phosphorus “deficit” – that is, the difference between the target reduction and the actual site reduction after the designer makes his or her best effort to apply Runoff Reduction and Pollutant Removal practices. A related, but simpler option would be to allow a developer to conduct an off-site mitigation project in lieu of full on-site compliance.

Figure 1 illustrates the step-wise compliance process described above, and **Table 1** includes a list of site design and stormwater practices that can be used for each step.

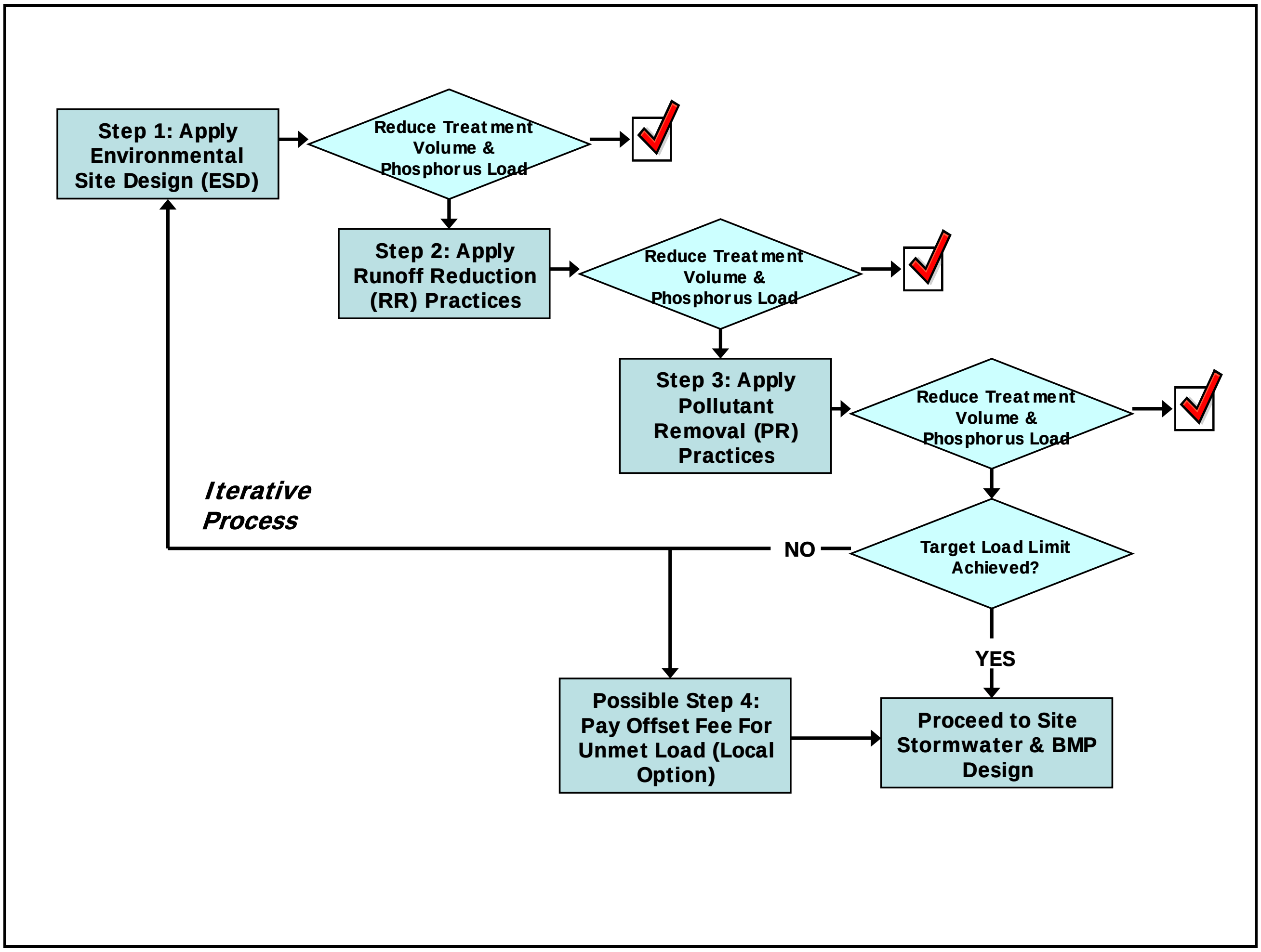

Figure 1. Step-Wise Process for Site Compliance

Table 1. Practices Included in the Runoff Reduction Method

Step 1: Environmental Site Design (ESD)	**Step 2: Runoff Reduction (RR) Practices**	**Step 3: Pollutant Removal (PR) Practices**
Forest Conservation	Sheetflow to Conserved Open Space	Filtering Practice
Site Reforestation	Rooftop Disconnection: ▪ Simple ▪ To Soil Amendments ▪ To Rain Garden or Dry Well ▪ To Rain Tank or Cistern	Constructed Wetland
		Wet Swale
Soil Restoration (combined with or separate from rooftop disconnection)		Wet Pond
Site Design to Minimize Impervious Cover & Soil Disturbance	Green Roof	
	Grass Channels	
	Permeable Pavement	
	Bioretention	
	Dry Swale (Water Quality Swale)	
	Infiltration	
	Extended Detention (ED) Pond	

Practices in shaded cells achieve both Runoff Reduction (RR) and Pollutant Removal (PR) functions, and can be used for Steps 2 and 3 depicted in Figure 1. See Appendices B and C for documentation.

3. DOCUMENTING RUNOFF REDUCTION (RR) & POLLUTANT REMOVAL (PR) CAPABILITIES OF BMPs

CWP and CSN made a significant effort to identify the capabilities of various BMPs to reduce overall runoff volume (Runoff Reduction) in addition to pollutant concentrations (Pollutant Removal). Since various terms are used in this technical memorandum, it is useful to supply some definitions for the purpose of their use within this document.

- *Runoff Reduction (RR)* is defined as the total annual runoff volume reduced through canopy interception, soil infiltration, evaporation, transpiration, rainfall harvesting, engineered infiltration, or extended filtration.

- *Event Mean Concentration (EMC)* is defined as the average concentration of a pollutant in runoff for a monitored storm event.

- *Pollutant Removal (PR)* is defined as the change in EMC as runoff flows into and out of a BMP. Pollutant removal is accomplished via processes such as settling, filtering, adsorption, and biological uptake. This does not account for changes in the overall volume of runoff entering and leaving the BMP.

- *Total Removal* (TR) is the nutrient mass reduction, which is the product of both Runoff Reduction (RR) and Pollutant Removal (PR).

- *Eligibility Criteria* are defined as design factors – such as sizing, pretreatment, flow path geometry, vegetative condition, and treatment processes – that allow a BMP to achieve the RR and PR rates assigned in this document.

Tables 2 and **3** provide a comparative summary of how the combination of Runoff Reduction and Pollutant Removal translate into Total Removal for the range of practices. **Table 2** addresses the values for Total Phosphorus (TP) and **Table 3** for Total Nitrogen (TN). Details on the methodology and derivation of the RR and PR rates are found in **Appendices B and C**, respectively.

Where a range of values is presented in **Tables 2** and **3**, the first number is for Level 1 design and second for Level 2 design. The levels account for the variable Runoff Reduction and Pollutant Removal capabilities based on BMP design features. The concept of design levels is addressed in more detail in **Section 9.** In addition, eligibility criteria for Level 1 and 2 designs are contained in **Appendix E**.

The biggest caveat to the data in **Tables 2** and **3** is the limited number of studies available that reported BMP runoff reduction or EMC based nutrient removal efficiencies. As a result, some of the numbers listed in the tables will be subject to change are more studies and data become available. The numbers in the tables are the authors' best judgment based on currently-available information.

Table 2. Comparative Runoff Reduction, Pollutant Removal, and Total Removal for Total Phosphorus

Practice	**Runoff Reduction (RR) (%)** (Appendix B)	**Pollutant Removal (PR)[1] - Total Phosphorus (%)** (Appendix C)	**Total Removal (TR) [2]**	**NPRPD -- Median to 3rd quartile (Q3)**
Green Roof	*45 to 60*	*0*	*45 to 60*	*NR*
Rooftop Disconnection	*25 to 50*	*0*	*25 to 50*	*NR*
Raintanks and Cisterns	*40*	*0*	*40*	*NR*
Permeable Pavement	*45 to 75*	*25*	*59 to 81*	*NR*
Grass Channel	*10 to 20*	*15*	*23 to 32*	*24 to 46* [3]
Bioretention	*40 to 80*	*25 to 50*	*55 to 90*	*5 to 30*
Dry Swale	*40 to 60*	*20 to 40*	*52 to 76*	*NR*
Wet Swale	*0*	*20 to 40*	*20 to 40*	*NR*
Infiltration	*50 to 90*	*25*	*63 to 93*	*65 to 96*
ED Pond	*0 to 15*	*15*	*15 to 28*	*20 to 25*
Soil Amendments[4]	*50 to 75*	*0*	*50 to 75*	*NR*
Sheetflow to Open Space	*50 to 75*	*0*	*50 to 75*	*NR*
Filtering Practice	*0*	*60 to 65*	*60 to 65*	*59 to 66*
Constructed Wetland	*0*	*50 to 75*	*50 to 75*	*48 to 76*
Wet Pond	*0*	*50 to 75*	*50 to 75*	*52 to 76*

Range of values is for Level 1 and Level 2 designs – see Section 9 & Appendix D

[1] EMC based pollutant removal

[2] TR = RR + [(100-RR) * PR]

[3] Includes data for Grass Channels, Wet Swales and Dry Swales

[4] Numbers are provisional and are not fully accounted for in Version 1 of the BMP Planning spreadsheet (Appendix A); however future versions of the spreadsheet will resolve any inconsistencies.

NR= Not Researched

Table 3. Comparative Runoff Reduction, Pollutant Removal, and Total Removal for Total Nitrogen

Practice	**Runoff Reduction (RR) (%)** (Appendix B)	**Pollutant Removal (PR)[1] - Total Nitrogen (%)** (Appendix C)	**Total Removal (TR) [2]**	**NPRPD -- Median to 3rd quartile (Q3)**
Green Roof	*45 to 60*	*0*	*45 to 60*	*NR*
Rooftop Disconnection	*25 to 50*	*0*	*25 to 50*	*NR*
Raintanks and Cisterns	*40*	*0*	*40*	*NR*
Permeable Pavement	*45 to 75*	*25*	*59 to 81*	*NR*
Grass Channel	*10 to 20*	*20*	*28 to 36*	*56 to 76* [3]
Bioretention	*40 to 80*	*40 to 60*	*64 to 92*	*46 to 55*
Dry Swale	*40 to 60*	*25 to 35*	*55 to 74*	*NR*
Wet Swale	*0*	*25 to 35*	*25 to 35*	*NR*
Infiltration	*50 to 90*	*15*	*57 to 92*	*42 to 65*
ED Pond	*0 to 15*	*10*	*10 to 24*	*24 to 31*
Soil Amendments[4]	*50 to 75*	*0*	*50 to 75*	*NR*
Sheetflow to Open Space	*50 to 75*	*0*	*50 to 75*	*NR*
Filtering Practice	*0*	*30 to 45*	*30 to 45*	*32 to 47*
Constructed Wetland	*0*	*25 to 55*	*25 to 55*	*24 to 55*
Wet Pond	*0*	*30 to 40*	*30 to 40*	*31 to 41*

Range of values is for Level 1 and Level 2 designs – see Section 9 & Appendix D

[1] EMC based pollutant removal

[2] TR = RR + [(100-RR) * PR]

[3] Includes data for Grass Channels, Wet Swales and Dry Swales

[4] Numbers are provisional and are not fully accounted for in Version 1 of the BMP Planning spreadsheet (Appendix A); however future versions of the spreadsheet will resolve any inconsistencies.

NR= Not Researched

For comparative purposes, data from the National Pollutant Removal Performance Database (NPRPD v.3; CWP, 2007) is shown in the last column of **Tables 2** and **3**. The NPRPD analyzes pollutant removal efficiencies of BMPs. The database defines pollutant removal efficiency as the pollutant reduction from the inflow to the outflow of a system. The values included in the NPRPD were derived from two fundamentally different computation methods for pollutant removal efficiency: (1) event mean concentration (EMC) efficiency, and (2) mass or load efficiency. For this reason, the NPRPD mixes analysis for RR and PR capabilities, which does not allow for distinguishing which BMPs may be particularly good for RR versus PR. The analysis done for this document, as portrayed in **Tables 2** and **3,** attempted to better tease out RR and PR results from the research studies.

Despite the differing analysis techniques, Total Removal values provided in **Tables 2** and **3** closely match numbers previously set forth in the NPRPD, with the exception of the total removal rate of Total Phosphorus for bioretention. The discrepancy with the bioretention removal rate is likely due to a disproportionate number of early studies in the NPRPD that tested bioretention media having a high Phosphorus Index (P-index greater than 30), which results in phosphorus leaching. The PR analysis used in this memorandum excluded bioretention practices having a P-index greater than 30.

4. SITE-BASED NUTRIENT LOAD LIMITS

The Runoff Reduction Method for Virginia is focused on site compliance to meet site-based load limits. This means that the proposed Virginia stormwater regulations are aimed at limiting the total load leaving a new development site. This is a departure from water quality computations of the past, in which the analysis focused on comparing the post-development condition to the pre-development, or an average land cover condition (the existing water quality procedures are explained in the *Virginia Stormwater Management Handbook, Volume II, Chapter 5;* VA DCR, 1999).

The chief objective of instituting a site-based load limit is so that land, as it develops, can still meet the nutrient reduction goals outlined in the Tributary Strategies. With the site-based limit, newly-developed land will maintain loadings that replicate existing loading from agricultural, forest, and mixed-open land uses. This is not to say that all developing parcels will maintain the pre-development loading rates, but that the rates, averaged across all development sites, will not increase compared to all categories of non-urban land.

An operational advantage to using site-based load limits is that it simplifies computations by focusing on the post-development condition. This, it is hoped, will reduce sources of contention between site designers and local government plan reviewers by eliminating confusion and conflict about what best constitutes the pre-development condition for a particular site.

The load limit calculations for the proposed Virginia stormwater regulations were performed by Virginia DCR staff, based on model outputs from the U.S. EPA Chesapeake Bay Program Watershed Model Scenario Output Database (Phase 4.3) (Commonwealth of Virginia, 2005). The DCR calculations led to proposed load limits of 0.28 pounds/acre/year for Total Phosphorus and 2.68 pounds/acre/year for Total Nitrogen.

5. RUNOFF COEFFICIENTS – MOVING BEYOND IMPERVIOUS COVER

The negative impacts of increased impervious cover (IC) on receiving water bodies have been well documented (CWP 2003, Walsh et al. 2004; Shuster et al. 2005; Bilkovic et al. 2006). Due to widespread acceptance of this relationship, IC has frequently been used in watershed and site design efforts as a chief indicator of stormwater impacts.

More recent research, however, indicates that other land covers, such as disturbed soils and managed turf, also impact stormwater quality (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 and Holland, 2000). These areas of compacted pervious cover (lawn or turf) have a much greater hydrologic response to rainfall than forest or pasture.

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). An analysis of Virginia-specific data from the National Stormwater Quality Database (Pitt et al. 2004) found that runoff from monitoring sites with relatively low IC residential land uses contained significantly higher nutrient concentrations than sites with higher IC non-residential uses (CWP & VA DCR, 2007). This suggests that residential areas with relatively low IC can have disturbed and intensively managed pervious areas that contribute to elevated nutrient levels.

The failure to account for the altered characteristics of disturbed urban soils and managed turf can result in an underestimation of stormwater runoff and pollutant loads generated from urban pervious areas. Therefore, the computation and compliance system for nutrients should take into account impervious cover as well as other land cover types.

The runoff coefficients provided in **Table 4** were derived from research by Pitt et al (2005), Lichter and Lindsey (1994), Schueler (2001a), Schueler, (2001b), Legg et al (1996), Pitt et al (1999), Schueler (1987) and Cappiella et al (2005). As shown in this table, the effect of grading, site disturbance, and soil compaction greatly increases the runoff coefficient compared to forested areas.

Table 4. Site Cover Runoff Coefficients (Rv)

Soil Condition	Runoff Coefficient
Forest Cover	0.02 to 0.05*
Disturbed Soils/Managed Turf	0.15 to 0.25*
Impervious Cover	0.95

*Range dependent on original Hydrologic Soil Group (HSG)
Forest A: 0.02 B: 0.03 C: 0.04 D: 0.05
Disturbed Soils A: 0.15 B: 0.20 C: 0.22 D: 0.25

The advantage of a computation system for nutrients that takes into account a range of land covers is that site stormwater designs will have a higher likelihood of treating all relevant land uses that contribute nutrients to waterways. In addition, such a system can incorporate site design incentives, such as maintaining or restoring forest cover, as a means of reducing site compliance requirements.

6. TREATMENT VOLUME – THE COMMON CURRENCY FOR SITE COMPLIANCE

Treatment Volume (Tv) is the central component of the Runoff Reduction method. By applying site design, structural, and nonstructural practices, the designer can reduce the treatment volume by reducing the overall volume of runoff leaving a site. In this regard, the Treatment Volume is the main "currency" for site compliance.

Treatment Volume is a variation of the 90% capture rule that is based on a regional analysis of the mid-Atlantic rainfall frequency spectrum. In Virginia, the 90th percentile rainfall event is defined approximately as one-inch of rainfall. Additional rainfall frequency analyses across the State will further refine the one-inch rule.

Figure 2 illustrates a representative rainfall analysis for Reagan Airport in Washington, D.C. (DeBlander, et al., 2008). The figure provides an example of a typical rainfall frequency spectrum and shows the percentage of rainfall events that are equal to or less than an indicated rainfall depth. As can be seen, the majority of storm events are relatively small, but there is a sharp upward inflection point that occurs just above one-inch of rainfall (90th percentile rainfall event).

The rational for using the 90th percentile event is that it represents the majority of runoff volume on an annual basis, and that larger events would be very difficult and costly to control for the same level of water quality protection (as indicated by the upward inflection at 90%). However, these larger storm events would likely receive partial treatment for water quality, as well as storage for channel protection and flood control.

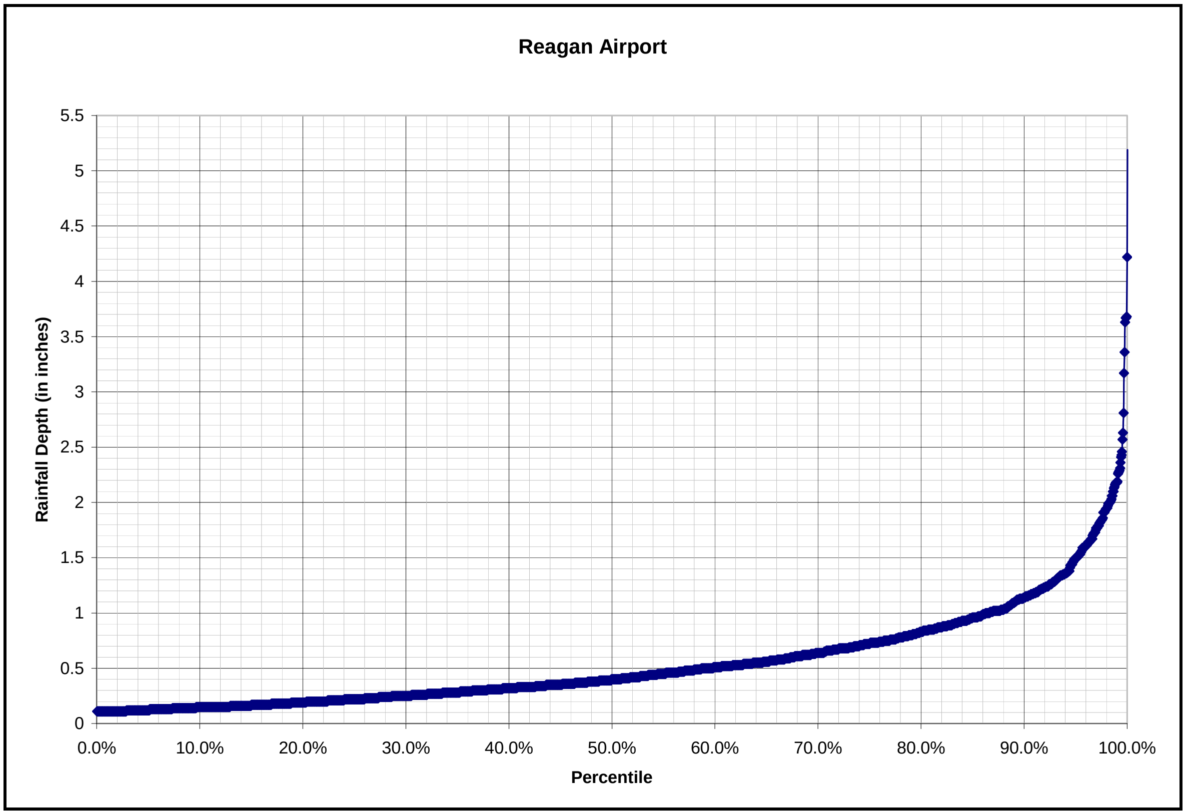

Figure 2. Rainfall Frequency Curve for Reagan Airport in Washington, D.C. The 90th percentile storm event is slightly more than 1" (DeBlander, et al., 2008).

A site's Tv is calculated by multiplying the "water quality" rainfall depth (one-inch) by the three site cover runoff coefficients (forest, disturbed soils, and impervious cover) present at the site, as shown in **Table 5**.

Table 5: Determining the Stormwater Treatment Volume

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

Where

Tv = Runoff reduction volume in acre feet
P = Depth of rainfall for “water quality” event
Rv_I = runoff coefficient for impervious cover[1]
Rv_T = runoff coefficient for turf cover or disturbed soils[1]
Rv_F = runoff coefficient for forest cover[1]
% I = percent of site in impervious cover (fraction)
%T = percent of site in turf cover (fraction)
%F = percent of site in forest cover (fraction)
SA = total site area, in acres

[1] Rv values from **Table 4.**

The proposed Treatment Volume has several distinct advantages when it comes to evaluating runoff reduction practices and sizing BMPs:

- The Tv provides effective stormwater treatment for approximately 90% of the annual runoff volume from the site, and larger storms will be partially treated.

- Storage is a direct function of impervious cover and disturbed soils, which provides designers incentives to minimize the area of both at a site

- The 90% storm event approach to defining the Treatment Volume is widely accepted and is consistent with other state stormwater manuals (MDE, 2000, ARC, 2002, NYDEC, 2001, VTDEC, 2002, OME, 2003, MPCA, 2005)

- The Tv approach provides adequate storage to treat pollutants for a range of storm events. This is important since the first flush effect has been found to be modest for many pollutants (Pitt et al 2005).

- Tv provides an objective measure to gage the aggregate performance of environmental site design, LID and other innovative practices, and conventional BMPs together using a common currency (runoff volume).

- Calculating the Tv explicitly acknowledges the difference between forest and turf cover and disturbed and undisturbed soils. This creates incentives to conserve forests and reduce mass grading and provides a defensible basis for computing runoff reduction volumes for these actions.

7. RUNOFF REDUCTION PRACTICES

Various BMPs are capable of reducing the overall volume of runoff based on the post-development condition. Historically, BMP performance has been evaluated according to the pollutant removal efficiency of a practice. However, in some cases, this underreported the full capabilities of BMPs to reduce pollutant loads. More recent BMP performance research has focused on runoff reduction as well as overall pollutant removal.

A literature search was performed to compile data on the Runoff Reduction capabilities for different BMPs. Runoff Reduction data were limited for most practices. However, many recent studies have started documenting Runoff Reduction performance. Based on the research findings, Runoff Reduction rates were assigned to various BMPs, as shown in **Table 6**. A range of values represents the median and 75th percentile runoff reduction rates based on the literature search. Several BMPs reflected moderate to high capabilities for reducing annual runoff volume. Others – including filtering, wet swales, wet ponds, and stormwater wetlands -- were found to have a negligible affect on runoff volumes, and were not assigned runoff reduction rates.

Table 6. Runoff Reduction for various BMPs (from Table 2)

Practice	**RR (%)**
Green Roof	*45 to 60*
Rooftop Disconnection	*25 to 50*
Raintanks and Cisterns	*40*
Permeable Pavement	*45 to 75*
Grass Channel	*10 to 20*
Bioretention	*40 to 80*
Dry Swale	*40 to 60*
Wet Swale	*0*
Infiltration	*50 to 90*
ED Pond	*0 to 15*
Soil Amendments	*50 to 75*
Sheetflow to Open Space	*50 to 75*
Filtering Practice	*0*
Constructed Wetland	*0*
Wet Pond	*0*

Range of values is for Level 1 and Level 2 designs – see Section 9 & Appendix D

Runoff Reduction data for several practices were limited, so some of the values are considered provisional. Documentation for the recommended Runoff Reduction rates can be found in **Appendix B**. Practice eligibility for the range of Runoff Reduction rates is included in **Appendix E**.

8. POLLUTANT REMOVAL PRACTICES

Pollution removal occurs through a variety of mechanisms, including filtering, biological uptake, adsorption, and settling. There is wide variability in the ability of BMPs to remove nutrients through these mechanisms.

Some of the studies in the National Pollutant Removal Performance Database (version 3; CWP, 2007) reported EMC-based pollutant removal rates. Reporting EMC-based efficiencies can help to isolate the pollutant removal mechanisms of a BMP and offers an approach to assessing BMP performance apart from Runoff Reduction. In this regard, the Runoff Reduction function of a BMP can be seen as the “first line of defense” and the Pollutant Removal mechanisms help to treat the remaining runoff that “passes through” the BMP.

The literature search was expanded to refine EMC-based pollutant removal efficiencies. Studies reporting EMCs were isolated from the NPRPD. The search was then broadened to include more recent studies and studies not included the NPRPD. **Table 7** summarizes the EMC pollutant removal rates of TP and TN for various BMPs. A range of values represents the median and 75th percentile pollutant removal rates. **Appendix C** provides further documentation on the methodology and recommended Pollutant Removal rates.

Table 7. EMC based pollutant removal for various BMPs (from Tables 2 and 3)

Practice	**Total Phosphorus PR (%)**	**Total Nitrogen PR (%)**
Green Roof	*0*	*0*
Disconnection	*0*	*0*
Raintanks and Cisterns	*0*	*0*
Permeable Pavement	*25*	*25*
Grass Channel	*15*	*20*
Bioretention	*25 to 50*	*40 to 60*
Dry Swale	*20 to 40*	*25 to 35*
Wet Swale	*20 to 40*	*25 to 35*
Infiltration	*25*	*15*
ED Pond	*15*	*10*
Soil Amendments	*0*	*0*
Sheetflow to Open Space	*0*	*0*
Filtering Practice	*60 to 65*	*30 to 45*
Constructed Wetland	*50 to 75*	*25 to 55*
Wet Pond	*50 to 75*	*30 to 40*

Range of values is for Level 1 and Level 2 designs – see Section 9 & Appendix D

9. LEVEL 1 & 2 DESIGN FACTORS – ACCOUNTABILITY FOR BETTER BMP DESIGN

Two levels of design are introduced in the Runoff Reduction Method (see values provided in **Tables 2, 3, 6 and 7**). Level 1 can be considered a “standard” design (achieves the median value of Runoff Reduction and Pollutant Removal from the research), and Level 2 an enhanced design (achieves the 75th percentile values).

Based on the evaluation of BMP performance in the literature, design factors that enhance nutrient pollutant removal and runoff reduction of BMPs were isolated. This section documents the scientific rationale and assumptions used to assign sizing and design features to the Level 1 and Level 2 BMPs that are presented in **Appendix D**.

Standard Design Features. The first step involved identifying the “standard” design features that should be included in all designs (i.e., not directly related to differential nutrient removal or runoff reduction rates). These include any features needed to maintain proper function of the BMP, as well as its safety, appearance, safe conveyance, longevity, standard feasibility constraints, and maintenance needs. These standard features will be outlined in the detailed design specifications to be developed by CSN and others later in 2008.

Design Point Tables. The *Stormwater Retrofit Manual, Appendix B* (Schueler et al, 2007) contains a series of tables that describe design factors that increase or decrease overall pollutant removal rates. These were used initially to assign design features into Level 1 and 2. It should be acknowledged that the design point tables were developed primarily to evaluate removal rates for stormwater retrofits that may lack the full range of design features (and design opportunities) present in a new development setting. Also, the original design point method was established to estimate removal for eight different pollutants. Modifications were made in this document to reflect the more specific goal of nutrient removal for BMPs in both new development and redevelopment settings.

Review of 2007 NPRD Rates. The updated NPRPD (CWP, 2007) recently added 27 new performance monitoring studies, mostly for under-represented practices such as bioretention, infiltration and water quality swales. Even so, nearly 80% of the performance entries in the NPRPD were built and monitored from 1980 to 2000, so many of the older designs may not reflect modern design features (particularly for ponds and wetlands).

Review of Individual Studies. To gain additional insight into the value of different sizes and design features, 50 stormwater technical notes were reviewed that provided a more in-depth analysis of more than 70 studies included into the NPRPD (Schueler and Holland, 2000). In addition, selected references were reviewed from the 2000 to 2008 stormwater literature, with an emphasis on design enhancements for infiltration, bioretention, and water quality swales. Greater emphasis was placed on studies in close geographic proximity to Virginia.

Based on the foregoing analysis, five primary design factors were used to define Level 1 and Level 2 design features: (1) increased treatment volume, (2) increased runoff reduction volumes, (3) enhanced design geometry and hydraulics, (4) vegetative condition, and (5) use of multiple treatment methods. More on the basis for each split are provided below.

> 1. *Increased Treatment Volume:* Increasing the treatment volume can enhance nutrient removal rates, up to a point. The existing treatment volume approach captures about 90% of the annual runoff volume, so further increases can only result in modest improvements, unless the larger volumes increase the residence time, or rate of nutrient uptake (which has been documented for ponds and wetlands). Therefore, three incremental levels of greater treatment volume were considered for each BMP: 110%, 125% and 150% of the base Tv.
>
> 2. *Increased Runoff Reduction Volume:* The second strategy to enhance nutrient removal rates is to increase the proportion of the treatment volume that is achieved by runoff reduction. In this instance, design features that could significantly enhance runoff reduction volumes were generally assigned to Level 2 practices.
>
> 3. *Enhanced Design Geometry & Hydraulics:* A third strategy to split BMPs according to nutrient removal is to isolate geometry factors that are known to influence either hydraulic performance or create better treatment conditions. Examples include flow path, depth of filter media, multiple cells, BMP surface area to contributing drainage area ratio, and minimum extended detention time.
>
> 4. *Vegetative Condition:* A fourth splitting strategy involves the ultimate type and cover of vegetation within the BMP insofar as it influences nutrient uptake, increases the evapotranspiration pump, stabilizes trapped sediments or enhances the filter bed. Landscape designs that maximize tree canopy or otherwise increase the ultimate vegetative cover for a practice were often used to support Level 2 designs.
>
> 5. *Multiple Treatment Methods:* The last major strategy is to combine several treatment options within a single practice to increase the reliability of treatment. For instance, a practice that incorporates settling, filtering, soil adsorption, and biological uptake will have a higher level of performance than one that relies on only one of these mechanisms.

Based on the assumptions, **Tables 4** through **13** in **Appendix B** assign Level 1 and 2 design factors and associated expected average runoff reduction, phosphorus removal, and nitrogen removal rates. Importantly, it should be understood that the assigned rates are based on the assumption that BMP designs will meet certain “eligibility criteria.” That is, the BMPs will be located and designed based on appropriate site conditions and limitations with regard to soils, slopes, available head, flow path, and other factors. **Appendix E** details these eligibility criteria for the various BMPs.

10. TRANSFERABILITY OF THE RUNOFF REDUCTION CONCEPT

While the Runoff Reduction Method was originally developed in tandem with Virginia DCR's efforts to update the stormwater regulations and handbook, the concept is widely applicable to other state and local stormwater planning procedures. The focus on runoff volume as the common currency for BMP evaluation is gaining wider acceptance across the county (U.S. EPA, 2008).

Currently, within the Chesapeake Bay Watershed, the States of Delaware, Maryland, Virginia, and the District of Columbia are considering incorporating the concept of runoff reduction into updated stormwater regulations and design manuals (Capiella et al., 2007; DeBlander et al., 2008; MSC, 2008). The *Pennsylvania Stormwater Best Management Practices Manual* (PA DEP, 2006) already incorporates standards for volume control achieved by structural and nonstructural BMPs. The Georgia Coastal Program is also working on a Coastal Stormwater Supplement to the *Georgia Stormwater Management Manual* that will incorporate runoff reduction principles (Novotney, 2008).

Clearly, the concept of runoff reduction marks an important philosophical milestone that will help define the next generation of stormwater design. The promise of runoff reduction is that the benefits go beyond water quality improvement. If site and stormwater designs can successfully implement runoff reduction strategies, then they will do a better job at replicating a more natural (or pre-development) hydrologic condition. This goes beyond peak rate control to address runoff volume, duration, velocity, frequency, groundwater recharge, and protection of stream channels. Important future work will involve integrating the runoff reduction concept with stormwater requirements for channel protection and flood control, so that stormwater criteria can be presented in a unified approach.

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APPENDICES

APPENDICES

APPENDIX A:
BMP Planning Spreadsheet and Guidelines
04/18/08

NOTE: The Spreadsheet Tool referenced here is Version 1. Subsequent versions of the spreadsheet will be developed and released in response to stakeholder feedback, including the site plan charettes sponsored by ASCE and DCR. This guidance will be updated as new versions of the spreadsheet become available.

Click here for Version 1 of the Spreadsheet

NOTES ON THE METHOD

- **Total Phosphorus (TP)** used as keystone pollutant. Total Nitrogen (TN) can also be calculated and BMP designs can address TN removal, but compliance is based on TP.
- Each site also has a **Treatment Volume (Tv)** that is based on post-development land covers. The method uses more than just impervious cover to compute the Tv.
- BMPs are assigned **Runoff Reduction (RR)** and **Pollutant Removal (PR)** rates. Rates vary for Level 1 and Level 2 designs, based on ongoing research (these rates are provisional). Level 2 BMPs have design enhancements to boost performance (see Table 1).
- BMPs are sized and designed based on Level 1 and Level 2 design guidelines (see Tables 2 through 16). The applicable RR and PR rates are based on these sizing and design rules.

OVERVIEW OF METHOD

1. Utilize environmental site design (ESD) techniques to reduce impervious cover and maximize forest and open space cover. This will affect the post-development treatment volume and pollutant load.
2. For the site, measure post-development impervious, managed turf, and forest/open space land cover. If there is more than one Hydrologic Unit for the site, the land cover analysis should be done for each HU. The approval authority may define a planning area for the site where the land cover analysis should be done (e.g., a concentrated area of development within a larger parcel), although this should be based on equitable criteria. Guidance for various land covers is as follows:
    a. Impervious = roads, driveways, rooftops, parking lots, sidewalks, and other areas of impervious cover
    b. Managed Turf = land disturbed and/or graded for turf, including yards, rights-of-way, and turf intended to be maintained and mowed within commercial and institutional settings

   c. Forest/Open Space = pre-existing forest and open land, plus land to be reforested (according to standards), that will remain undisturbed and protected in an easement, deed restriction, protective covenant, etc. If land will be disturbed during construction, but treated with soil amendments, reforested according to the standards, and protected as noted above, then it may also qualify for forest cover.

3. Calculate weighted turf and weighted forest runoff coefficients based on hydrologic soil groups. Combined with impervious cover, the result will be a weighted site runoff coefficient. STEP 1 IN THE SPREADSHEET.

Rv Coefficients				
	A soils	**B Soils**	**C Soils**	**D Soils**
Forest/Reforested	0.02	0.03	0.04	0.05
Managed Turf	0.15	0.20	0.22	0.25
Impervious Cover	0.95			

4. Calculate post-development TP loading & Treatment Volume for the site or each HU on the site. STEP 1 IN THE SPREADSHEET.
5. Apply **Runoff Reduction (RR)** Practices on the site to reduce post-development treatment volume and load. The site designer should select the most strategic locations on the site to place RR practices (e.g., drainage areas with the most developed land). This will likely be an iterative process. Runoff reduction “volume credits” are based on the contributing drainage area (CDA) to each selected BMP. STEP 2 IN THE SPREADSHEET.
6. Based on the RR practices selected, **Pollutant Removal (PR)** rates will be applied to BMPs that achieve both runoff reduction and pollutant removal functions. STEP 3 IN THE SPREADSHEET.
7. If there is still a TP load to remove after applying RR and PR credits to the selected BMPs, the designer can:
   a. Select additional **RR** BMPs in STEP 2 OF THE SPREADSHEET,
   b. Select additional **PR** BMPs in STEP 3 OF THE SPREADSHEET.

RR and PR credits are applied to the BMP’s CDA.
The ultimate goal is to reduce the load to the “terminal load” (0.28 pounds/acre).

APPENDIX B:
DERIVATION OF RUNOFF REDUCTION RATES FOR SELECT BMPs

Runoff reduction (RR) is defined as the average annual reduction in stormwater runoff volume. For stormwater best managment practices (BMPs) runoff can be reduced via canopy interception, soil infiltration, evaporation, transpiration, rainfall harvesting, engineered infiltration, or extended filtration. Extended filtration includes bioretention or dry swales with underdrains that delay the delivery of stormwater from small sites to the stream system by six hours or more.

Prior to 2003, very few research studies reported flow reductions in the literature, reporting instead on the change in inflow and outflow event mean concentrations (EMCs). Recently, more studies have been reporting flow reductions, particularly for LID projects, although data are still limited. For the purposes of this document, studies documenting the runoff reduction of individual BMPs were compiled, and are included in Appendix F. Summaries of the runoff reduction performance for individual BMPs are discussed in this section.

From a design standpoint, the runoff reduction rates are appropriate for use in the Virginia spreadsheet up to the water quality storm event. Runoff reduction rates were generally an annual average based on the study site water balance. These rates may not apply at their full values to storm events larger than the typical “water quality storm,” or approximately one-inch of rainfall (but it is likely that some reduction for larger events will occur). The runoff reduction numbers are dependent on meeting the Level 1 and 2 design criteria (Appendix D) or the eligibility criteria for ESD (Appendix E). Given the limited number of runoff reduction performance studies available, the recommended rates were selected using conservative assumptions and best professional judgment, and some of the numbers are considered provisional until more data become available (these are noted in each subsection below).

Green Roofs

Considerable research has been conducted in recent years to define the runoff reduction capability of extensive green roofs (Table B-1). Reported rates for runoff reduction have been shown to be a function of media depth, roof slope, annual rainfall and cold season effects. Based on the prevailing climate for the region, a conservative runoff reduction rate for green roofs of 45 to 60% is recommended for initial design.

Table B-1. Volumetric Runoff Reduction by Green Roof

LID Practice	Location	Runoff Reduction	Reference
Green Roof	USA	40 to 45%	Jarrett et al (2007)
Green Roof	Germany	54%	Mentens et al (2005)
Green Roof	MI	30 to 85%	Getter et al (2007)
Green Roof	OR	69%	Hutchinson (2003)
Green Roof	NC	55 to 63%	Moran and Hunt (2005)
Green Roof	PA	45%	Denardo et al (2005)
Green Roof	MI	50 to 60%	VanWoert et al (2005)
Green Roof	ONT	54 to 76%	Banting et al (2005)
Green Roof	GA	43 to 60	Carter and Jackson (2007)
RR Estimate		45 to 60%	

Rooftop Disconnection

Very limited research has been conducted on the runoff reduction rates for rooftop disconnection, so initial estimates are drawn from research on filter strips, which operate in a similar manner. The research indicates that runoff reduction is a function of soil type, slope, vegetative cover and filtering distance. Table B-2 summarizes filter strip runoff reduction rates within the first 45 feet (where a range is given, the first number is for filtering distance of 5 to 15 ft and the second for 25 to 45 ft). A conservative runoff reduction rate for rooftop disconnection is 25% for HSG C and D soils and 50% for HSG A and B soils. These values apply to disconnection that meet the feasibility criteria, and do not include any further runoff reduction due to the use of compost amendments along the filter path.

Table B-2. Volumetric Runoff Reduction Achieved by Rooftop Disconnection

LID Practice	Location	Runoff Reduction	Reference
Filter Strip	USA	20 to 62	Abu-Zreig et al (2004)
Filter Strip	USA	40%	Strecker at al (2004)
Filter Strip	CA	40 to 70	Barrett (2003)
Runoff Reduction Estimate		25 to 50%	

Raintanks and Cisterns

The runoff reduction capability of rain tanks and cisterns has not been extensively monitored, but numerous modeling efforts have assigned a runoff reduction rate. Dual use rain tanks provide indoor potable or grey water and outdoor landscaping irrigation. Modeling research indicates that their runoff reduction capability is limited by tank capacity, and the rate of de-watering between storms, which is strongly influenced by indoor and outdoor water demand and overflows (Table

B-3). The actual rate of runoff reduction for an individual project will require simulation modeling of rainfall and the tank. Based on the prevailing climate for this region, a conservative runoff reduction estimate of 40% is recommended for initial design. For the purposes of the Virginia spreadsheet, the actual storage volume is used multiplied by a discount factor of 75% (to account for water that is not used or drained between storm events).

Table B-3. Volumetric Runoff Reduction by Raintanks and Cisterns

LID Practice	**Location**	**Runoff Reduction**	Reference
Dual Use Rain Tanks [1]	AUS (semi-arid)	60 to 90%	Hardy et al (2004)
Dual Use Rain Tanks	AUS (arid)	40 to 45%	Coombes et al (2002)
Dual Use Rain Tanks	NZ	35 to 40%	Kettle et al (2004)
	RR Estimate	40%	

Permeable Pavement

More than a dozen studies are now available to characterize the runoff reduction potential for permeable pavers that are designed with the requisite amount of storage to enable infiltration beneath the paver. The research studies have been classified into two categories: permeable paver applications that have underdrains and those that do not (Table B-4). Assuming the permeable paver is designed with adequate pretreatment and soil infiltration testing, a conservative runoff reduction rate of 75% is assigned to designs that rely upon full infiltration. Permeable paver applications on HSG C and D soils that typically require underdrains should use the lower runoff reduction rate of 45%.

Table B-4. Volumetric Runoff Reduction by Permeable Pavement

LID Practice	**Location**	**Runoff Reduction**	**Reference**
Pervious Pavement *	ONT	99	Van Seters et al (2006)
Pervious Pavement *	PA	94	Traver et al (2006)
Pervious Pavement *	FRA	98	Legret and Colandini (1999)
Pervious Pavement *	NC	100	Bean et al (2007)
Pervious Pavement *	NC	95 to 98%	Collins et al (2007)
Pervious Pavement *	WA	97 to 100	Brattebo and Booth (2003)
Pervious Pavement *	CT	72	Gilbert and Clausen (2006)
Pervious Pavement *	UK	78	Jefferies (2004)
Pervious Pavement #	NC	38 to 66	Collins et al (2007)
Pervious Pavement #	PA	25-45	Pratt et al (1989)
Pervious Pavement #	NC	66	Bean et al (2007)
Pervious Pavement #	UK	53	Jefferies (2004)
Pervious Pavement #	MD	45 to 60	Schueler et al (1987)
Pervious Pavement #	Lab	30 to 55	Andersen et al (1989)
Runoff Reduction Estimate		45# to 75*	
* no underdrain collection/infiltration design; # underdrain collection			

Grass Channels

Runoff reduction by grass channels is generally low, but is influenced strongly by soil type, slope, vegetative cover, and the length of channel (Table B-5). Recent research indicates that a conservative runoff reduction rate of 10 to 20% can be used, depending on whether soils fall in HSG A/B or C/D. The runoff reduction rates can be doubled if the channel is modified to incorporate compost soil amendments.

Table B-5. Volumetric Runoff Reduction Achieved by Grass Channels

LID Practice	**Location**	**% Runoff Reduction**	Reference
Grass Channel	VA	0	Schueler (1983)
Grass Channel	USA	40	Strecker at al (2004)
Grass Channel	NH	0	UNHSC (2007)
Grass Channel	OR	27 to 41	Liptan and Murase (2000)
Runoff Reduction Estimate		10 to 20	

Bioretention

More than 10 studies are now available to characterize the runoff reduction rates for bioretention areas. The research can be classified into bioretention applications that possess underdrains and those that do not (and therefore rely on full infiltration into underlying soils) (Table B-6). A conservative runoff reduction rate of 80% is assigned to designs that rely on full infiltration. Bioretention areas located on HSG C and D soils that typically require underdrains should use the lower runoff reduction rate of 40%.

Table B-6. Volumetric Runoff Reduction Achieved by Bioretention

LID Practice	**Location**	**% Runoff Reduction**	Reference
Bioretention *	CT	99%	Dietz and Clausen (2006)
Bioretention *	PA	86%	Ermilio (2005)
Bioretention *	FL	98%	Rushton (2002)
Bioretention *	AUS	73%	Lloyd et al (2002)
Bioretention #	ONT	40%	Van Seters et al (2006)
Bioretention #	Model	30%	Perez-Perdini et al (2005)
Bioretention #	NC	40 to 60%	Smith and Hunt (2007)
Bioretention #	NC	20 to 29%	Sharkey (2006)
Bioretention #	NC	52 to 56%	Hunt et al. (2006)
Bioretention #	NC	20 to 50%	Passeport et al. (2008)
Bioretention #	MD	52 to 65%	Davis (2008)
Runoff Reduction Estimate		40# to 80*	
*infiltration design; # underdrain design			

Dry Swales

Only a handful of data are available to define the runoff reduction rate for dry swales, but research indicates that they perform as well as, or better than, bioretention with underdrains (Table B-7). Since an underdrain is an integral design feature for dry swales, a conservative runoff reduction of 40% is assigned to dry swales, a value equivalent to the rate assigned to bioretention with underdrains. If a dry swale lacks an underdrain due to highly permeable soils, or is designed with an underground stone storage layer, the runoff reduction rate can be increased to 60%.

Table B-7. Volumetric Runoff Reduction Achieved by Dry Swales

LID Practice	**Location**	**% Runoff Reduction**	Reference
Dry Swale	WA	98%	Horner et al (2003)
Dry Swale	MD	46 to 54%	Stagge (2006)
Dry Swale	TX	90%	Barrett et al (1998)
Runoff Reduction Estimate		40 to 60%	

Wet Swales

Limited runoff reduction data are available on wet swales. Wet swales function similarly to wet ponds and wetlands, retaining a permanent pool of water due to intersection with ground water or siting in poorly drained soils. No runoff reduction rate is recommended for wet swales.

Infiltration

The runoff reduction capability of infiltration practices is presumed to be high, given that infiltration is the design intent of the practice. Some surface overflows do occur when the infiltration storage capacity is exceeded. Assuming the practice is designed with adequate pretreatment and soil infiltration testing, a conservative runoff reduction rate of 90% is assigned to infiltration practices. If an underdrain must be utilized, the recommended runoff reduction rate drops to 50% (Table B-8).

Table B-8. Volumetric Runoff Reduction Achieved by Infiltration

LID Practice	**Location**	**Runoff Reduction**	Reference
Infiltration	NH	90%	UNHSC (2005)
Infiltration	VA	60%	Schueler (1983)
Infiltration	PA	90%	Traver et al (2006)
Infiltration	NC	96-100%	Bright et al (2007)
Runoff Reduction Estimate		50 to 90%	

Extended Detention

In lined extended detention (ED) basins, evaporation reduces a small portion of the runoff volume, and in unlined basins, runoff is further reduced via seepage. Strecker et al. (2004) analyzed the runoff reduction rates for 11 dry extended detention basins in the EPA/ASCE

National Stormwater BMP Database and found a mean runoff volume reduction of 30%; however, more recent research indicates lower reductions (Strecker, 2008). Additionally, two ED basins in NC had negligible runoff reduction rates (Hathway et al, 2007e), and a basin in FL sited in very well drained soils had a 70% runoff reduction rate (Harper et al, 1999). Based on the prevailing climate for the region, a conservative runoff reduction estimate of 0% for lined basins, and 15% for unlined basins is recommended for initial design.

Soil Amendments

Several studies have examined the effect of soil compost amendments to reduce the volume of runoff produced by lawn runoff from compacted soils (Table B-9). This practice can be combined with rooftop disconnection as a complementary strategy (see Table B-2). A runoff reduction rate of 50% is given when compost amended soils receive runoff from an appropriately designed rooftop disconnection or grass channel. A 75% runoff reduction rate can be used for the runoff from lawn areas that are compost amended, but do not receive any off-site runoff from impervious surfaces (in other words, runoff is reduced from the lawn area itself).

Table B-9. Volumetric Reduction in Lawn Runoff Due to Compost Amendments

LID Practice	**Location**	**Runoff Reduction**	Reference
Compost Amendment	WI	74 to 91%	Balusek (2003)
Compost Amendment	AL	84 to 91%	Pitt et al (1999 and 2005)
Compost Amendment	WA	29 to 50%	Kolsti et al (1995)
Compost Amendment	WA	53 to 74%	Hielima (1999)
Runoff Reduction Estimate		50 to 75%	

Sheetflow to Conserved Open Space

Limited data are available to characterize the runoff reduction associated with sending sheet flow to conserved open space, although the process is very similar to using a filter strip (see Table B-2 and the discussion for Rooftop Disconnection). However, the surface area, flow path, and vegetative condition of conserved open space would be greater – and likely provide greater runoff reduction -- than an engineered filter strip. A runoff reduction rate of 50 to 75% can be used provisionally and conditionally, depending on whether the soils in the conserved areas fall in HSG A/B or C/D.

Filtering Practices, Constructed Wetlands, and Wet Ponds

Very little individual performance data are available on the runoff reduction capabilities of sand filters, wet pond, and wetland practices. In pond and wetland applications, evapo-transpiration may occur; however, research suggests that the amount of runoff reduced is very low to negligible (Strecker et al, 2004 ; Hathaway et al, 2007a-d). Therefore, a conservative runoff reduction rate of 0% is recommended for filters, wet ponds, and wetlands.

Stormwater Planters, Tree Pits, and Tree Clusters
Only one study has measured the hydrologic capacity of stormwater planters or tree pits to reduce runoff, and it found they had relatively low capability (UNHSC, 2007). The actual runoff reduction capability for these practices is related to their contributing drainage area, runoff storage capacity and rate of overflow or underdrain. Consequently, these practices are assigned a modest runoff reduction capability of 15%. No specific research has been conducted on the runoff reduction rates for tree clusters as set forth in Cappiella et al (2005), although the value of trees in reducing runoff has been established by Portland BES (2003) and PA DEP (2006). These manuals assign a runoff reduction rate of 6 cubic feet per qualifying deciduous tree and 10 cubic feet per evergreen tree. If planting bed is compost amended, or tree cluster is designed to accept off-site runoff, a higher rate of runoff reduction may be used.

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APPENDIX C:
DERIVATION OF EMC POLLUTANT REMOVAL RATES FOR SELECT BMPs

Pollutant removal efficiency refers to the pollutant reduction from the inflow to the outflow of a system. Pollutant removal efficiency can be calculated using variety of computations, but the two most common methods are event mean concentration (EMC) efficiency and mass or load efficiency. EMC efficiency is derived by averaging the influent and effluent concentrations for storm events, and then calculating the median change. Mass efficiency is calculated by determining the pollutant load reduction from the influent to effluent, and is influenced by the volume of water reduced by the practice (runoff reduction – see Appendix B).

Depending on the method used, reported removal efficiencies of stormwater best management practices (BMPs) can vary widely and are often inconsistent. Further, removal efficiencies do not always address runoff volume reductions in BMPs (Strecker et al, 2004; Jones et al, 2008). However, for the purposes of the analysis in this document, reported EMC based pollutant removal efficiencies can help to isolate the pollutant removal mechanisms of a BMP and offers a better approach to assessing BMP performance apart from runoff reduction (Appendix B).

The following sections discuss the derivation of EMC based pollutant removal efficiencies of BMPs. The NPRPD (CWP, 2007) details the pollutant removal efficiencies of several BMPs that were derived using several different methods. Studies reporting EMC pollutant removal in the NPRPD were isolated and included in the analysis. Further, EMC pollutant removal numbers were compiled from recent studies, which are detailed in Appendix F. When possible, a median and 75th percentile value for nutrient PR was determined.

The EMC nutrient removal rates are appropriate for use in the Virginia spreadsheet (Appendix A). It should be noted that the data used to estimate pollutant removal were derived from practices in good condition; most studies focused on BMPs that were constructed within three years of monitoring. Further, the actual EMC pollutant removal performance can be strongly influenced by the influent quality. Since pollutant removal rates are usually dependent on site characteristics and BMP geometry, the EMC based pollutant removal numbers are dependent on meeting the Level 1 or 2 design criteria (Appendix D) and the eligibility criteria for ESD (Appendix E). Due to the limited number of performance studies, conservative EMC pollutant removal rates were selected. In several cases, provisional numbers are set forth until more data become available.

Green Roofs

In recent years, several studies have been conducted on the nutrient removal capabilities of green roofs. Results confirm that green roofs initially leach nutrients from the compost contained in the growth media used to support initial plant growth (Table C-1). Several studies have suggested that the leaching may subside over time; however, the extent to which nutrient leaching decreases has not been quantified. Media with high initial compost content will leach more nutrients than media with lower compost content. Therefore, to minimize the export of nutrients, media should be selected with the lowest compost content that adequately supports the growth of the desired roof vegetation (unless other factors for overall green roof success supersede this factor). No pollutant removal credit for nitrogen or phosphorus is recommended.

Table C-1. Pollutant Removal Achieved by Green Roofs

LID Practice: Green Roof[1]	Location	Pollutant Removal (TP)	Pollutant Removal (TN)	Study
Green Roof	NC	negative	negative	Moran et al, 2005
Green Roof	OR	negative	negative	Hutchinson, 2003
Green Roof	CAN	negative	negative	Banting et al, 2005
EMC PR estimate		0%	0%	

[1] Pollutant removal values are EMC based for all studies
[+] Study included in NPRPD (CWP, 2007)

Disconnection (Vegetated Filter Strips)

Limited research has been conducted on the pollutant removal rates for rooftop disconnection. Initial estimates are drawn from research on filter strips, which operate in a similar manner. The research indicates that nutrient reduction is a function of filtering distance and vegetative cover (Abu-Zreig et al, 2003; Barrett et al, 1998; CALTRANS, 2004; Goel et al, 2004). Since very little information regarding the EMC based nutrient removal rates of vegetated filter strips has been published, no pollutant removal rate for TP or TN is recommended at this initial stage. Pollutant removal rates for downspout disconnection may likely change as more data become available.

Raintanks and Cisterns

Limited research has been conducted to evaluate the pollutant removal capabilities of rain tanks and cisterns. However, it is generally understood that no primary pollutant removal benefits exist (MPAC, ND). Based on this assumption, no pollutant removal credit for TP and TN is recommended for raintanks and cisterns.

Permeable Pavement

While several studies have documented high heavy metal and TSS removal efficiencies of permeable pavements, few studies have evaluated permeable pavement nutrient removal capabilities. Limited results indicate that permeable pavement TP and TN removal rates vary widely (Table C-2). TP can potentially be reduced by adsorption to the aggregate and soils in the pavement subbase layers, but may also leach from underlying soils or surface fill material in pavement void spaces. Provisional EMC pollutant removal rates of 25% for both TP and TN are recommended.

Table C-2. Pollutant Removal Achieved by Permeable Pavements				
LID Practice: Permeable Pavement[1]	**Location**	**Pollutant Removal (TP)**	**Pollutant Removal (TN)**	**Study**
Permeable Pavement#	Lab	60%		Day et al, 1981
Permeable Pavement#	CAN	0%		James and Shahin, 1998
Permeable Pavement#	GA	10%	negative	Dreelin et al, 2006
Permeable Pavement#	NC	65%	36%	Bean et al, 2007[+]
Permeable Pavement#	NC	negative	negative	Bean, 2005[+]
Permeable Pavement#	NH	38%		UNH, 2007
Permeable Pavement#	NC	0%	25%*	Collins et al., 2008
Permeable Pavement#	CT	34%	88%	Gilbert and Clausen, 2006
EMC PR estimate		25%	25%	

[1] Pollutant removal values are EMC based for all studies
[+] Study included in NPRPD (CWP, 2007)
* for one pavement type only
\# underdrain design

Grass Channels (Drainage Swales)

Several studies have documented the nutrient removal rates of grass channels (Table C-3). Nutrient removal is generally low, but is influenced by vegetative cover and flow velocity. The removal of mowed grass clippings may also increase nutrient removal. Fertilization of channel vegetation should be avoided. Conservative pollutant removal rates of 15% for TP and 20% for TN are recommended.

Table C-3. Pollutant Removal Achieved by Grass Channels				
LID Practice: Drainage Swale[1]	**Location**	**Pollutant Removal (TP)**	**Pollutant Removal (TN)**	**Study**
Grass Channel	MD	0%	37%	OWML, 1983[+]
Grass Channel	MD	0%	negative	OWML, 1983 [+]
Grass Channel	TX	34 to 44%	38%	Walsh et al, 1995 [+]
Grass Channel	TX	negative	negative	Welborn and Veehuis, 1987 [+]
Grass Channel	FL	13%	21%	Harper, 1988[+]
Grass Channel	FL	25%	11%	Yousef et al, 1986[+]
Grass Channel	WA	29 to 45		Seattle Metro, 1992 [+]
Grass Channel	CA	negative	30%	CALTRANS, 2004
Grass Channel	USA	29		Schueler and Holland, 2000 (article 116)
EMC PR estimate		15%	20%	

[1] Pollutant removal values are EMC based for all studies except NPRPD
[+] Study included in NPRPD (CWP, 2007)

Bioretention

Several recent studies have indicated that bioretention practices are effective at removing nutrients, as well as metals, pathogens, oil and grease. Much of this research has reported mass based pollutant removal rates, but ten studies reporting EMC based removal rates were examined (Table C-4). The extent of TP removal is related to bioretention cell depth, mulching, plant cover, and the organic matter content of the soil media. The primary phosphorus removal mechanism is soil adsorption. It is imperative that the P-index of the media be tested to ensure a low number (less than 30), as earlier studies have found that soil media with a high P-index will leach phosphorus.

Nitrogen is removed through mineralization and denitrification near the surface of bioretention cells and also by denitrification in anaerobic zones that often develop deeper in the cells. Design of an internal water storage zone (sump) using an upturned underdrain (or stone sump below the underdrain pipes) may increase TN removal. A summary of bioretention mass removal included in the NPRPD lists lower median and 75th percentile pollutant removal rates for TP; however, many of these earlier studies tested practices with high P-index media. Conservative EMC pollutant removal rates of 25 to 50% for TP removal and 40 to 60% for TN removal are recommended. TP removal is credited only if the media is tested to ensure that the media P-index is less than 30.

Table C-4. Pollutant Removal Achieved by Bioretention

LID Practice: Bioretention[1]	**Location**	**Pollutant Removal (TP)**	**Pollutant Removal (TN)**	**Study**
NPRPD (N=10)		5[a]-30[b]	46[a]-55[b]	CWP, 2007
Bioretention#	MD	81%		Davis et al., 2001
Bioretention#	MD	65%	49%	Davis et al., 2006
Bioretention#	MD	87%	59%	Davis et al., 2006
Bioretention#	Lab	81%	60%	Davis et al., 2006
Bioretention#	PA	1%	48%	Ermilio, 2005[+]
Bioretention#	NC	8%	61%	Smith and Hunt, 2006[+]
Bioretention#	NC	32%	38%	Hunt et al. 2008
Bioretention#	NC	60%	54%	Passeport et al. 2008
Bioretention#	NC	66%	62%	Sharkey, 2006
Bioretention#	VA	13%		Yu and Stopinski, 2001[+]
EMC PR estimate		25 to 50%	40 to 60%	

[1] Pollutant removal values are EMC based for all studies

[a] Median pollutant removal rate

[b] 75th Percentile pollutant removal rate

[+] Study included in NPRPD (CWP, 2007)

underdrain design

Water Quality Swales

Compared to bioretention, fewer monitoring studies are available to define the EMC pollutant removal rate for water quality swales, which include wet swales and dry swales with an underdrain. Research suggests that pollutant removal mechanisms of dry swales are similar to those of a bioretention cell with an underdrain, because a portion of water is filtered through a soil media. Wet swales, which typically contain a shallow permanent pool, may function similar to, but less efficient than, wetlands or wet ponds with respect to pollutant removal. Conservative and provisional EMC pollutant removal rates of 20 to 40% for TP and 25 to 35% for TN are recommended for both wet and dry swales (Table C-5).

Table C-5. Pollutant Removal Achieved by Water Quality Swales

LID Practice: Water Quality Swales[1]	**Location**	**Pollutant Removal (TP)**	**Pollutant Removal (TN)**	**Study**
Wet swale	FL	17%	40%	Harper, 1988[+]
Wet swale	WA	39		Koon, 1995[+]
Dry swale	AUS	65%	52%	Fletcher et al, 2002
Dry swale with Underdrain	TX	31		Barrett et al, 1997
Wet Ponds		50 to 75%	30 to 40%	This study
Bioretention with Underdrain		25 to 50%	25%	This study
EMC PR estimate		20 to 40%	25 to 35%	

[1] Pollutant removal values are EMC based for all studies

[+] Study included in NPRPD (CWP, 2007)

Infiltration

Because of the difficulty associated with monitoring infiltration practices, very limited data are available on EMC nutrient removal capability. Studies have indicated that stormwater pollutants, including nutrients, can be filtered out in the soils underlying infiltration basins (Mikkelson et al, 1994; Barraud et al, 1999; Dechesne et al, 2003). A summary of 12 infiltration practices included in the NPRPD lists the median and 75th percentile mass pollutant removal rates as 65 to 96 for total phosphorus (TP), and 42 to 65 for total nitrogen (TN). However, the majority of mass removal in infiltration practices occurs in the form of runoff reduction (Appendix B). Therefore, provisional EMC pollutant removal rates of 25% for TP removal and 15% for TN removal are specified until more research becomes available.

Extended Detention

Extensive research on ED ponds has indicated that these practices can effectively remove particulate pollutants, primarily thorough sedimentation. Documented nutrient removal rates are variable (Table C-6). Based on several studies, conservative EMC pollutant removal rates of 15% for TP and 10% for TN are recommended. The EMC pollutant removal differs from the removal rates in the NPRPD, which did not include any ED studies that analyzed EMC based pollutant removal.

Table C-6. Pollutant Removal Achieved by Extended Detention

LID Practice: Extended Detention[1]	**Location**	**Pollutant Removal (TP)**	**Pollutant Removal (TN)**	**Study**
NPRPD (N=10)		20[a]-25[b]	24[a] -31[b]	CWP, 2007
Dry ED pond	CA	15 to 39%	14%	CALTRANS, 2004
Dry ED pond	NC	0%	10 to 13%	Hathaway et al, 2007e,f
Dry ED pond	NJ	34%	0%	Harper et al, 1999[+]
Dry ED pond	TX	7%		Middleton and Barrett, 2006
EMC PR estimate		15%	10%	

[1] Pollutant removal values are EMC based for all studies except NPRPD

[a] Median pollutant removal rate

[b] 75th Percentile pollutant removal rate

[+] Study included in NPRPD (CWP, 2007)

Soil Amendments

Few studies have reported on the pollutant removal capabilities of amended soils. Both Glanville, et al. (2003) and Pitt et al, (2005) found that the pollutant concentrations in runoff from compost amended soils were higher than in runoff from un-amended soils. Pitt et. al. (2005) found that subsurface flows had an increased amount of nitrogen and phosphorus as compared to un-amended soils. This difference was present at newly constructed sites but was less prominent at older sites. Due to the high compost or organic matter content that is added to amended soils, it can be assumed that negligible removal of nutrients would occur, and nutrients may, in fact, leach from soil runoff, similar to documented pollutant dynamics of green roof media containing compost. As such, no pollutant removal credit for TP and TN is recommended for soil amendments.

Sheet Flow to Open Space

Limited research has been conducted on the pollutant removal rates for sheetflow to open space. Initial estimates may be drawn from research on filter strips or buffer areas, which demonstrate pollutant removal via plant uptake and soil filtering (Abu-Zreig et al, 2003; Desbonnet et al, 1994). For initial design, no pollutant removal rate for TP or TN is recommended for open space; however, pollutant removal rates may likely change as more data become available.

Filtration

Numerous studies have evaluated the nutrient removal capabilities of various stormwater filtration practices (Table C-7). Phosphorus is removed via chemical precipitation in the filter bed media, and although organic filters may export nitrates, studies have indicated that TN is typically reduced. The use of some organic materials in the filter bed, which can improve heavy metal removal rates, may cause nutrient leaching (Leif, 1999). An analysis of individual studies in which the EMC pollutant removal rates were reported yielded EMC removal rates for TP (N=7 studies) and TN (N=4 studies) similar to the pollutant removal rates in the NPRPD (N=18 studies). Since runoff reduction in filtration practices is negligible (Appendix B), mass removal and EMC removal rates are roughly equivalent. Due to the limited number of filtration studies reporting EMC pollutant removal rates, filtration practices are therefore assigned EMC pollutant removal rates based on the values in the NPRPD, since the NPRPD contains more studies. These rates are 60 to 65% for TP, and 30 to 45% for TN.

Table C-7. Pollutant Removal Achieved by Filtration

LID Practice: Sand Filters[1]	**Location**	**Pollutant Removal (TP)**	**Pollutant Removal (TN)**	**Study**
NPRPD (N=18)		59[a]-66 [b]	32 [a] -47 [b]	CWP, 2007
Sand Filter	TX	39 %	22%	Barrett, 2003
Sand Filter	VA	66%	47%	Bell et al, 1995[+]
Peat Sand Filter	TX	48%	30 to 51%	LCRA, 1997 [+]
Sand Filter	WA	20 to 41%		Horner, 1995 [+]
Sand Filter	TX	45%	15%	Barton Springs, 1996[+]
Organic filter	WI	88%		Corsi and Greb, 1997[+]
Compost filter	TX	41%		Stewart, 1992[+]
EMC PR estimate		60 to 65%	30 to 45%	

[1] Pollutant removal values are EMC based for all studies except NPRPD

[a] Median pollutant removal rate

[b] 75th Percentile pollutant removal rate

[+] Study included in NPRPD (CWP, 2007)

Wetlands

Studies indicate that wetlands can effectively remove TP and TN, primarily through sedimentation and plant nutrient uptake (Table C-8). Nutrient removal is related to the vegetative covering, wetland geometry, and the drawdown time of the temporary storage volume.

An analysis of individual studies in which the EMC pollutant removal rates were reported yielded EMC removal rates for TP (N=8 studies) and TN (N=4 studies) similar to the pollutant removal rates in the NPRPD (N=40 studies). Since runoff reduction in wetland practices is negligible (Appendix B), mass removal and EMC removal rates can be evaluated equivalently. Due to the smaller number of studies reporting wetland EMC pollutant removal rates, wetlands are assigned EMC pollutant removal rates based on the values in the NPRPD: 50 to 75% for TP, and 25 to 55% for TN.

Table C-8. Pollutant Removal Achieved by Wetlands

LID Practice: Wetlands[1]	Location	Pollutant Removal (TP)	Pollutant Removal (TN)	Study
NPRPD (N=40)		48[a]-76[b]	24[a]-55[b]	CWP, 2007
Wetland	FL	28%	10%	Martin, 1988[+]
Wetland	FL	48%	13%	Blackburn et al, 1986[+]
Wetland	WA	33%		Koon, 1995[+]
Wetland	FL	57%		Rushton and Dye, 1993[+]
Wetland	VA	69%		Yu et al, 1998[+]
Wetland	VA	15%		Yu et al, 1998[+]
Submerged gravel wetland	CA	46%	negative	Reuter et al, 1992[+]
Wetland	NC	45%	35 to 45%	Hathaway et al, 2007a,b
EMC PR estimate		50 to 75%	25 to 55%	

[1] Pollutant removal values are EMC based for all studies except NPRPD

[a] Median pollutant removal rate

[b] 75th Percentile pollutant removal rate

[+] Study included in NPRPD (CWP, 2007)

Wet Ponds

Numerous studies have evaluated the nutrient removal capabilities of wet ponds (Table C-9). Several factors appear to affect removal rates, such as the treatment volume captured, presence of emergent vegetation, and length of the flow path in the pond. The establishment of a diverse, dense plant community around the perimeter of the pond may increase nutrient removal, and may also discourage water fowl activity, potentially reducing organic nutrient and pathogen inputs. An analysis of individual studies in which the EMC pollutant removal rates were reported yielded EMC removal rates for TP (N=16 studies) and TN (N=12 studies) similar to the pollutant removal rates in the NPRPD (N=46 studies). Since runoff reduction in wet pond practices is negligible (Appendix B), mass removal and EMC removal rates can be evaluated equivalently. Due to the smaller number of studies reporting wet pond EMC pollutant removal rates, these practices are assigned EMC pollutant removal rates based on the values in the NPRPD: 50 to 75% for TP, and 30 to 40% for TN.

Table C-9. Pollutant Removal Achieved by Wet Ponds

LID Practice: Wet Ponds[1]	**Location**	**Pollutant Removal (TP)**	**Pollutant Removal (TN)**	**Study**
NPRPD (N=46)		52[a]-76[b]	31[a]-41[b]	CWP, 2007
Wet Pond	TX	87%	50%	City of Austin, TX 1996[+]
Wet Pond	WA	19%		Comings et al, N.D[+]
Wet Pond	FL	55%	12%	Cullum, 1984[+]
Wet Pond	FL	30%	16%	Gain, 1996[+]
Wet Pond	FL	40%		Kantrowitz and Woodham, 1995[+]
Wet Pond	FL	22%	15%	Martin, 1988[+]
Wet Pond	CAN	72%		SWAMP, 2000[+]
Wet Pond	CA	29%	0%	Taylor et al, 2001
Wet Pond	NC	57%	40%	Mallin et al, 2002
Wet Pond	CA	5%	51%	CALTRANS, 2004
Wet Pond	NC	15 to 41%	19 to 23%	Hathaway et al, 2007c,d
Wet ED pond	CAN	37%	28%	Fellows et al, 1999[+]
Wet ED pond	CO	52%	55%	LCRA, 1997[+]
Wet ED pond	FL	75%	28%	Rushton et al, 1995[+]
Wet ED pond	FL	50%	25%	Rushton et al, 2002[+]
Wet ED pond	CAN	56 to 65%		SWAMP, 2000
EMC PR estimate		50 to 75%	30 to 40%	

[1] Pollutant removal values are EMC based for all studies except NPRPD
[a] Median pollutant removal rate
[b] 75th Percentile pollutant removal rate
[+] Study included in NPRPD (CWP, 2007)

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APPENDIX D:
LEVEL 1 AND 2 BMP DESIGN FACTORS

Based on the assumptions in Section 9 of the technical memorandum, the following tables assign design factors to Level 1 or 2 that will achieve the indicated average runoff reduction and nutrient removal rates.

D-1	Green Roof
D-2	Permeable Pavement
D-3	Bioretention
D-4	Dry Swale
D-5	Wet Swale
D-6	Infiltration
D-7	Extended Detention Pond
D-8	Filtering Practice
D-9	Constructed Wetland
D-10	Wet Pond

The base pollutant removal and runoff reduction are the median values for Level 1, whereas Level 2 corresponds to the 75th percentile values. These tables do not include the standard setbacks, restrictions, feasibility constraints and minimum design features that apply to each practice for all site applications.

Table D-1. Green Roof Design Guidance

Level 1 Design (RR:45; TP:0; TN:0)	Level 2 Design (RR: 60; TP:0; TN:0)
Depth of media four to six inches[1]	Media depth greater than six inches
Soil media not tested for P-index	Soil media with P index less than 10
Green roof receives roof runoff	Green roof does not receive roof runoff or is designed with additional media depth
All Designs: shall be in conformance to ASTM (2005) International Green Roof Standards. Appropriate media and plant selection for harsh rooftop conditions and shallow media depths. Filter media mix should have the minimum organic matter/nutrient content to maintain fertility for plant growth but not contribute to nutrient leaching. [1] If media depth is less than 4 inches, the runoff reduction credit is adjusted so that each inch of media provides a 10% reduction in runoff volume.	

Table D-2. Permeable Pavement Design Guidance

Level 1 Design (RR:45; TP:25; TN:25)	Level 2 Design (RR: 75 TP:25; TN:25)
TV= (1.0)(Rv)(A)	TV = (1.1)(Rv) (A)
Soil infiltration less than one-inch/hr	Soil infiltration rate exceeds one-inch/hr
Underdrain needed	Underdrain not required
CDA ≥ The pervious paver area	CDA = The pervious paver area
Slopes from 2 to 5%	Slopes less than 2%

Table D-3. Bioretention Design Guidelines

Level 1 Design (RR:40; TP:25; TN:40)	**Level 2 Design (RR:80; TP:50; TN:60)**
TV= (1.0)(Rv)(A)	TV= (1.25) (Rv)(A)
SA of filter exceeds 3% of CDA	SA of filter bed exceeds 5% of CDA
Filter media at least 24" deep	Filter media at least 36" deep
One form of accepted pretreatment	Two or more forms of accepted pretreatment
At least 75% plant cover w/ mulch	At least 90% plant cover, including trees.
One cell design	Two cell design
Underdrain needed	Infiltration design or underground stone sump
All Designs: acceptable media mix tested for phosphorus index, does not treat stormwater hotspot or baseflow.	

Table D-4. Dry Swale Design Guidance

Level 1 Design (RR:40; TP:20; TN:25)	**Level 2 Design (RR:60; TP:40; TN: 35)**
TV= (1.0)(Rv)(A)	TV= (1.1)(Rv)(A)
Swale slopes from <0.5% or >2.0%	Swale slopes from 0.5% to 2.0%
Soil infiltration rates less than 0.5 in	Soil infiltration rates exceed one inch
Swale served by underdrain	Lacks underdrain or uses underground stone sump
On-line design	Off-line or multiple treatment cells
Media depth less than 18 inches	Media depth more than 24 inches
Turf cover	Turf cover, with trees, shrubs, or herbaceous plantings
All Designs: acceptable media mix tested for phosphorus index	

Table D-5. Wet Swale Design Guidance

Level 1 Design (RR:0; TP:20; TN:25)	**Level 2 Design (RR:0; TP:40; TN:35)**
TV= (1.0)(Rv)(A)	TV= (1.25)(Rv)(A)
Swale slopes more than 1%	Swale slopes less than 1%
On-line design	Off-line swale cells
No planting	Wetland planting within swale cells
Turf cover in buffer	Trees and shrubs planted within swale cells
Note: Generally recommended only for flat coastal plain conditions with high water table. Linear wetland always preferred to wet swale	

Table D-6. Infiltration Design Guidelines

Level 1 Design (RR:50; TP:25; TN:15)	**Level 2 Design (RR:90; TP:25; TN:15)**
TV= (1.0)(Rv)(A)	TV= (1.1)(Rv)(A)
Maximum CDA of one acre	Max CDA of 0.5 acre, nearly 100% IC
At least one form of pretreatment	At least two forms of pretreatment
Soil infiltration rate of 0.5 to 1.0 in/hr	Soil infiltration rates of 1.0 to 4.0 in/hr
Underdrain needed due to soils	No underdrain utilized
All Designs: no hotspot runoff	

Table D-7. Extended Detention (ED) Pond Guidance

Level 1 Design (RR:0; TP:15; TN:10)	Level 2 Design (RR:15; TP:15; TN:10)
TV= (1.0)(Rv)(A)	TV = (1.25)(Rv) (A)
At least 15% of TV in permanent pool	More than 40% of TV in deep pool or wetlands
Flow path at least 1:1	Flow path at least 1:5 to 1
Average ED time of 24 hours or less	Average ED time of 36 hours
vertical ED fluctuation exceeds 4 feet	Maximum vertical ED limit of 4 feet
Turf Cover on floor	Trees and wetlands in the planting plan
Forebay and micropool	Additional cells or treatment methods within areas of pond floor (e.g., sand filter, biotretention soils or plantings)
CDA less than ten acres	CDA greater than ten acres

Table D-8. Filtering BMP Design Guidance

Level 1 Design (RR:0; TP:60; TN:30)	Level 2 Design (RR:0 [1]; TP:65; TN:45)
TV= (1.0)(Rv)(A)	TV= (1.25)(Rv)(A)
One cell design	Two cell design
Sand media	Sand media w/ organic layer
CDA contains pervious area	CDA is nearly 100% impervious
Not a confirmed stormwater hotspot	Site is a confirmed stormwater hotspot
[1] can be increased to up to 50% if or second cell is used for infiltration	

Table D-9. Constructed Wetland Design Guidance

Level 1 Design (RR:0; TP:50; TN:25)	Level 2 Design (RR:0; TP:75; TN:55)
TV= (1.0)(Rv)(A)	TV = (1.5)(Rv)(A)
Single cell (with forebay)	Multiple cells or pond/wetland design
ED wetland	No ED in wetland
Uniform wetland depth	Diverse microtopography
Mean wetland depth more than one foot	Mean wetland depth less than one foot
Wetland SA/CDA ratio less than 3%	Wetland SA/CDA ratio more than 3%
Flow path 1:1 or less	Flow path 1.5:1 or more
Emergent wetland design	Combined emergent and wooded wetland design

Table D-10. Wet Pond Design Guidance

Level 1 Design (RR:0; TP:50; TN:30)	**Level 2 Design (RR:0; TP:75; TN:40)**
TV= (1.0)(Rv)(A)	TV = (1.5)(Rv) (A)
Single Pond Cell (w/ forebay)	Wet ED or Multiple Cell Design
Pool Depth Range of 3 to 12 feet	Pool Depth Range of 4 to 8 feet
Flow path 1:1 or less	Flow path 1.5:1 or more
Pond intersects with groundwater	Adequate water balance
CDA less than 15 acres	CDA greater than 15 acres

APPENDIX E:
MINIMUM CRITERIA FOR SELECT ESD PRACTICES

From a design standpoint, it is still important to establish qualifying criteria for the following ESD practices:

- Site Reforestation
- Soil Restoration
- Sheetflow to Conserved Open Space
- Rooftop Disconnection
- Grass Channels

The updated design criteria for these ESD practices are provided in the tables below. In most cases, the design criteria were based on the original qualifying credit criteria contained in the 2000 MDE Manual, but they have been updated to reflect local experience and credit details in other manuals produced since 2000 (e.g., Minnesota, Credit River, DCR). The soil restoration and site reforestation criteria were drafted using recent research.

Table E-1. Site Reforestation
Description: Site reforestation involves planting trees on existing turf or barren ground at a development site with the explicit goal of establishing a mature forest canopy that will intercept rainfall, increase evapo-transpiration and enhance soil infiltration rates. Reforestation areas at larger development sites and for individual trees for smaller development sites are eligible under certain qualifying conditions.
Computation: A runoff coefficient of twice the forest runoff coefficient may be used for the entire combined areas of reforestation in the contributing drainage area, since it may take several decades for the replanted area to mature and provide full hydrologic benefits. If reforestation is combined with soil amendments, then the forest cover coefficient area can be used instead (see Table E-2 for soil restoration criteria). The runoff reduction calculation for individual qualifying trees or tree clusters is 6 cubic feet per deciduous tree and 10 cubic feet per evergreen tree [1]
Eligibility for Reforestation Practice (sites greater than one acre in size) • The minimum contiguous area of reforestation must be greater than 5000 square feet • A long term vegetation management plan must be prepared and filed with the local review authority to maintain the reforestation area in a natural forest condition • The reforestation area must be protected by a perpetual stormwater easement or deed restriction that indicates that no future development or disturbance can occur within the area • Reforestation methods should be designed to achieve 75% forest canopy within ten years • The planting plan must be approved by the appropriate local forestry or conservation authority, including any special site preparation needs • The construction contract should contain a care and replacement warranty

Table E-1. Site Reforestation

extending at least three growing seasons to ensure adequate growth and survival of the plant community

- The reforestation area shall be shown on all construction drawings and ESC plans, and adequately protected during construction

Eligibility for Individual Tree Practice (Sites less than one acre in size).

- Qualifying trees on small sites include native tree at less two inches in caliper planted in expanded tree pits with adequate soil volume to ensure future growth and survival

[1] The individual tree runoff credits were developed from data contained in Portland BES(2004), PA DEP (2006) and Cappiella et al (2005a and 2005b)

Table E-2. Soil Restoration Criteria

Application: Compost amended soils can be used to reduce the generation of runoff from compacted urban lawns and may also be used to enhance the runoff reduction performance of downspout disconnections and grass channels.

Computation: A runoff reduction rate of 50% is given when compost amended soils receive runoff from an appropriately designed rooftop disconnection (Table E-4) or grass channel (Table E-5). A 75% runoff reduction rate can be used for the runoff from lawn areas that are compost amended, but do not receive any off-site runoff from impervious surfaces (e.g., rooftops). [1]

Suitability for Soil Restoration: Compost amended soils are suitable for any pervious area where soils have been or will be compacted by the grading and construction process. They are particularly well suited when existing soils have low infiltration rates (HSG C and D) and when the pervious area will be used to filter runoff (downspout disconnections and grass channels). The area or strip of amended soils should be hydraulically connected to the stormwater conveyance system. Compost amendments are not recommended where:

- Existing soils have high infiltration rates
- The water table or bedrock is located within 1.5 feet of the soil surface.
- Slopes exceed ten percent
- Existing soils are saturated or seasonally wet
- They would harm roots of existing trees (stay outside the tree drip line)
- The downhill slope runs toward an existing or proposed building foundation

Sizing: Several simple sizing criteria are used when soil compost amendments are used to enhance the performance of a downspout disconnection

- Flow from the downspout should be spread over a 10 foot wide strip extending down-gradient from the building to the street or conveyance system.
- Existing soils in the strip will be scarified or tilled to a depth of 12 to 18 inches and amended with well-aged compost to achieve a organic matter content in the range of 8 to 13%.

Table E-2. Soil Restoration Criteria

- The depth of compost amendment is based on the relationship of the contributing rooftop area to the area of the soil amendment strip, using the following general guidance (RA is the contributing roof area in square feet, and SA is the surface area (sf) of compost amendments on the lawn):
  - RA/SA= 1, use 4 inches of compost,
  - RA/SA= 2, use 8 inches of compost,
  - RA/SA= 3, use 12 inches of compost, till to 18 to 24 inches depth

Similar sizing criteria are used when soil compost amendments are used to enhance the performance of a grass channel

- Flow in the grass channel should be spread over a 10-foot long strip at the appropriate channel dimension
- Existing soils in the strip will be scarified or tilled to a depth of 12 inches and soils mixed with 6 to 8 inches of well-aged compost to achieve an organic matter content in the range of 8 to 13%.
- The amended area will need to be rapidly stabilized with perennial, salt tolerant grass species. For grass channels on relatively steep slopes, it may be necessary to install a protective biodegradable geotextile fabric
- Designers will need to ensure that the final elevation of the grass channel meets original hydraulic capacity

Design Specifications: Leaf compost should be made exclusively of fallen deciduous leaves with less than 5% dry weight of woody or green yard debris materials. The compost shall contain less than 0.5% foreign material such as glass or plastic contaminants and be certified as pesticide free. The use of leaf mulch, composted mixed yard debris, biosolids, mushroom compost or composted animal manures is prohibited.

The compost shall be matured and been composted for a period of at least one year and exhibit no further decomposition. Visual appearance of leaf matter in the compost is not acceptable. The compost should have a dry bulk density ranging from 40 to 50 lbs/ft^3, a pH between 6 to 8 and a CEC in excess 50 meq/100 grams dry weight.

Construction Sequence: The construction sequence for compost amendments differs depending whether the practice will be applied to a large area or a narrow filter strip such as in a rooftop disconnection or grass channel. For larger areas, a typical construction sequence is as follows.

1. Prior to building, the proposed area should be deep tilled to a depth of 2 to 3 feet using a tractor with two deep shanks (curved metal bars) to create rips perpendicular to the direction of flow.
2. A second deep tilling is needed after final building lots have been graded to a depth 12 to 18 inches
3. An acceptable compost mix is then incorporated into the soil using a rototiller or similar equipment at the volumetric rate of one part compost to two parts soils
4. The site should be leveled and seed or sod used to establish a vigorous grass

Table E-2. Soil Restoration Criteria

cover. Lime or irrigation may initially be needed during start

5. Compost amendment areas exceeding 2500 square feet should employ simple erosion control measures, such as silt fence, to reduce the potential for erosion
6. If the compost amendment area is receiving any runoff from upslope, then erosion control measures are needed to keep upslope runoff and sediment from compromising the amended area, particularly during any land disturbance in the upslope area.
7. Construction inspection involves digging a test pit to verify the depth of mulch, amended soil and scarification. A rod penetrometer should be used to establish the depth of uncompacted soil at one location per 10,000 square feet

The first step is usually omitted when compost is used for narrower filter strips.

[1] The computation is not consistent with Version 1 of the BMP Planning spreadsheet (Appendix A); however future versions of the spreadsheet will resolve this discrepancy

Table E-3. Sheetflow To Conserved Open Space

Description: Sending sheetflow from developed areas of the site to protected conservation areas

Computation: The runoff coefficient for conservation area will be forest or restoration area, depending on predevelopment land cover. Qualifying contributing areas include any turf and impervious cover that is hydrologically connected to the protected conservation area and is effectively treated by it. A 75% runoff reduction practice is given for qualifying HSG A and B soils (within the conservation area), and a 50% runoff reduction is given for qualifying HSG C and D soils.

Basic Eligibility for the Conservation Area

- The minimum combined area of all natural areas conserved within the appropriate drainage area must exceed 0.5 acres.
- No major disturbance may occur within the open space during or after construction (i.e., no clearing or grading allowed except temporary disturbances associated with incidental utility construction, restoration operations or management of nuisance vegetation). The conservation area shall not be stripped of topsoil. Some light grading may be needed at the boundary using tracked vehicles to prevent compaction.
- The limits of disturbance should be clearly shown on all construction drawings and protected by acceptable signage and fencing.
- A long term vegetation management plan must be prepared to maintain the conservation area in a natural vegetative condition. Managed turf is not considered an acceptable form of vegetative management, and only the passive recreation areas of dedicated parkland are eligible for the practice (e.g., ball fields and golf courses are not eligible).
- The conservation area must be protected by a perpetual easement or deed restriction that assigns the responsible party to ensure no future development, disturbance or clearing can occur within the area.

Table E-3. Sheetflow To Conserved Open Space

- The practice does not apply to jurisdictional wetlands that are sensitive to increased inputs of stormwater runoff.

Basic Eligibility for the Runoff Generating Area

- The maximum contributing sheet flow path from adjacent pervious areas should not exceed 150 feet
- The maximum contributing sheet flow path from adjacent impervious areas should not exceed 75 feet
- For average slopes exceeding 3%, graded terraces should be placed every 20 longitudinal feet along the flow path

Runoff should enter the boundary of the open space as sheetflow for the one-inch storm. A depression, berm or level spreader may be used to spread out concentrated flows generated during larger storm events.

Table E-4. Rooftop Disconnection

Description:
This runoff reduction practice is offered when rooftop runoff is disconnected, and then filtered, treated, or reused before it moves from roof to the storm drain system.

Computation:
Two kinds of practices are allowed. One is for simple rooftop disconnection, whereas the second involves disconnection combined with supplementary runoff treatment involving:

(a) Compost amended soils in the filter path
(b) Installation of rain gardens or dry wells
(c) Storage and reuse in a rain tank, cistern or foundation planter.

Simple disconnection is assigned a runoff reduction rate of 50% on A/B soils and 25% on C/D soils. Disconnection to amended soils is assigned a 50% reduction.[2] Disconnection to rain gardens or dry wells is assigned a 75% reduction on A/B soils and 50% for C/D soils.[2] The runoff reduction for rain tanks and cisterns is 40%, but varies depending on design and the degree of water reuse. See Figure E-1 to determine the most appropriate rooftop disconnection option.

Table E-4. Rooftop Disconnection

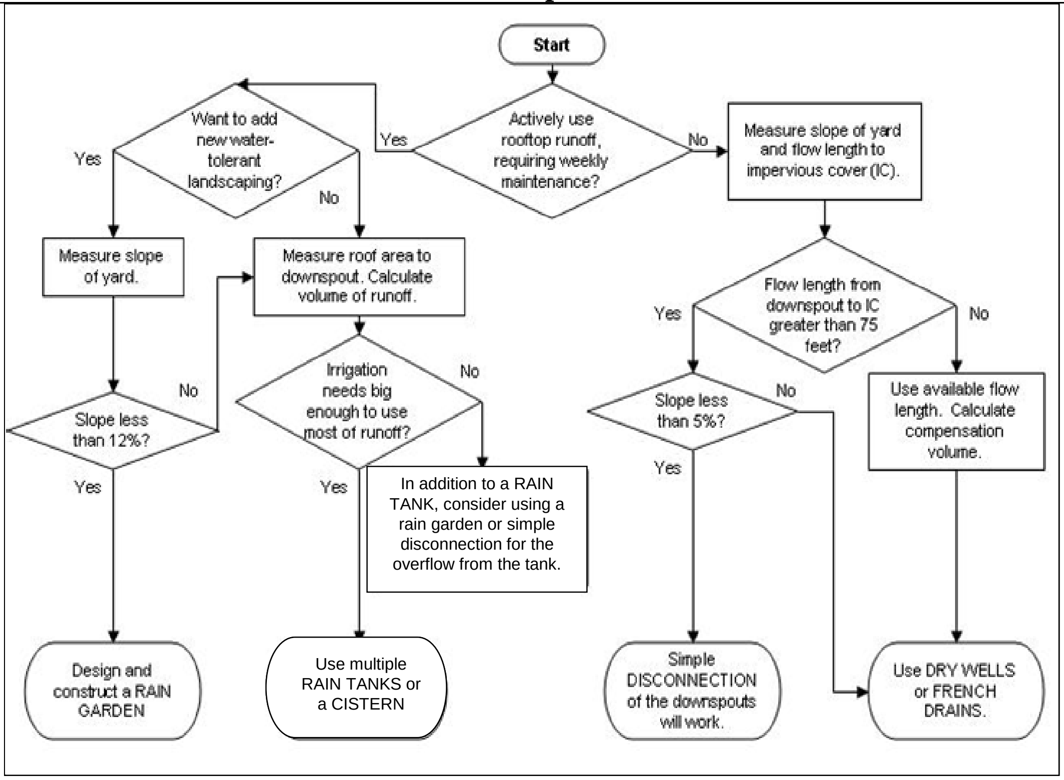

Figure E-1. Rooftop disconnection options.

Eligibility for Simple Downspout Disconnection (25 to 50% RR)

- Simple disconnection is only allowed for residential lots greater than 6000 sf. For lot sizes smaller than 6000 sf, disconnection with supplementary runoff treatment can be considered.
- The contributing flow path from impervious areas should not exceed 75 feet
- The disconnection length must exceed the contributing flow path
- If suitable soil amendments are provided (see Table E-2), the 50% runoff reduction rate for lawn runoff may be used for C/D soils
- A compensatory mechanism is needed if the disconnection length is less than 40 feet and/or the site has been mass-graded and has a Hydrologic Soil Group in the B, C or D category
- Pervious areas used for disconnection should be graded to have a slope in the 1 to 5% range
- The total impervious area contributing to any single discharge point shall not exceed 1000 square feet and shall drain through a pervious filter until reaching a property line or drainage swale
- The disconnection shall not cause basement seepage. Normally, this involves extending downspouts at least ten feet from the building if the ground does not slope away from the building

Disconnection with Soil Amendment (50% RR)

- See Table E-2
- If an amended lawn area does not receive any off-site runoff from impervious

Table E-4. Rooftop Disconnection

surfaces, a 75% runoff reduction can be used.[2]

Disconnection to Rain Garden or Dry Well (50% to 75% RR)

- Depending on soil properties, roof runoff may be filtered in a shallow rain garden or infiltrated into a shallow dry well.
- In general, these areas will require 10 to 15% of the area of the contributing roof area
- An on-site soil test is needed to make the choice of what option to use.
- The facility should be located in an expanded right of way or stormwater easement so that it can be accessed for maintenance.
- For high density sites, front yard bioretention may be an attractive option

Disconnection to Rain Tanks or Cisterns (40% RR)

- The practice for each of these devices depends on their storage capacity and ability to drawdown water in between storms for reuse as potable water, greywater or irrigation use.
- Designers will need to estimate the water reuse volume, based on the method of distribution, frequency of use, and seasonally adjusted indoor and/or outdoor water demands for the building
- Based on the prevailing climate for the region, a conservative runoff reduction estimate of 40% is recommended for initial design
- Pretreatment measures may need to be employed to keep leaves, bird droppings and other pollutants from entering the tank or cistern
- All devices should have a suitable overflow area to route extreme flows into the next treatment practice or stormwater conveyance system

[1] If the site is mass-graded, designers need to shift predevelopment HSG up one letter

[2] The computation is not consistent with Version 1 of the BMP Planning spreadsheet (Appendix A); however future versions of the spreadsheet will resolve this discrepancy

Table E-5. Grass Channels

Description: The area draining to the grass channel (rooftop, driveway and sidewalk impervious cover and turf cover)

Computation: A 20% reduction in runoff volume is offered for combined turf and impervious cover draining to qualifying swales on A/B soils and 10% on C/D soils.

Eligibility: A qualifying grass channel meets the following criteria:

- Primarily serves low to moderate residential development, with a maximum density of 4 dwelling units per acre
- The bottom width of the channel should be between 4 to 8 feet wide. If suitable soil amendments are provided (see Table E-2), the 20% runoff reduction rate may be used for C/D soils
- Swale side-slopes should be no steeper than 3H:1V

- The longitudinal slope of the channel should be no greater than 2%. (Checkdams or a terraced swale design may be used to break up slopes on steeper grades)
- 5 acres maximum contributing drainage area to any individual grass channel
- The dimensions of the channel should ensure that runoff velocity is non-erosive during the two-year design storm event and safely convey the locals design storm (e.g., ten year design event)
- Designers should demonstrate that the channel will have a maximum flow velocity of one foot per second during a one-inch storm event

Note: Where feasible, the dry swale is always the preferable option due to its greater runoff reduction and pollutant reduction capability.

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Appendix F – BMP Research Summary Tables

List of Practices:

- Green Roofs
- Vegetated Filter Strips
- Permeable Pavement
- Drainage Swales
- Bioretention
- Water Quality Swales
- Infiltration
- Extended Detention Ponds
- Filtering Practices
- Stormwater Wetlands
- Wet Ponds

GREEN ROOFS LITERATURE SUMMARY

Study	Description	Pollutant Reductions	Runoff Reductions	Implications for Design
Banting et al, 2005 CitedRefs: Thompson, 1998 Liesecke, 1998 Zinco Roof Gardens, 1997			Thompson, 1998: 60-80%, depending on substrate depth Liesecke, 1998: 40-45% for 2-4cm of media 60% for 10 cm of media Zinco, 1997: 70-90% Summer 40-50% Winter	
Denardo et al, 2005	7 rainfall events monitored on GR's with a media depth of 89 mm, 8% slope in State College, PA (PSU).		Avg Runoff reduction: 45% (range 19-98%). Rainfall 3.7-13.6mm (2 mo. period in Fall) Tp delay: 1-3hrs Peak Flow reduction: 56%	Runoff reduction was higher during smaller rainfall events. RR is not an annual average, but rather a two month average during Fall months. Expected RR would be higher during summer period.
DeNardo et al, 2005 CitedRefs: Miller (1998) and Scholz (2001)	3" media depth		38-45% 38-54%	

Emilisson et al, 2007	Investigated nutrient runoff, storage, and plant uptake after fertilization of vegetated roof systems during simulated rainfalls over a 6 mo. Period in Sweden. Three levels of fertilizers were applied as either controlled release fertilizer (CRF), or combo CRF and conventional fertilizer. Conventional fertilizers yielded the highest runoff nutrient concentrations. Runoff concentrations decreased over time, but remained higher than CRF runoff conc. Nutrient leaching from established vegetation mats was lower than that from newly established surfaces.			Green roofs applied with low dose fertilizers exported less nutrients than those with conventional fertilizers. Conventional fertilizers should be avoided, or runoff water should be recycled or reused on the roofs or other vegetated surfaces, particularly during the first weeks following fertilization.
Farzaneh et al, 2005	89 mm thick media in beds were tested in a control greenhouse at Pennsylvania State University. The greenhouse temperatures were adjusted to simulate four seasonal climatic conditions, which correlated to the ambient season. 4 different models were used to calculate ET.			ET rates from vegetated beds averaged 0.61 mm/d (winter) and 1.12 mm/d (spring/fall) Vegetated beds lost 28% and 57% more water than unplanted beds in winter and spring, respectively.
Getter et al, 2007	Examined RR for GRs constructed on 2, 7, 15, and 25% slopes at MSU. All roofs		Avg: 80.8% For Light (<2mm),	Green roofs constructed with lower slopes have the potential to retain more water

	contained a 6 cm media layer and 0.75 cm of a moisture retention fabric. Mean retention was least on the 25% slope (76.4%) and greatest at the 2% slope (85.6%). Overall average retention was 80.8% (P<40mm, 62 events) CN for all roofs ranged from 84 (2% slope) to 90 (25% slope), for all rainfall events		Med (2-10mm) and Heavy (>10mm) rainfall events on the 2% slope: 93.3, 92.2, 71.4 (mean 85.6) 62 rain events 0<P<40mm	
Hutchinson et al, 2003	A GR in Portland Ore with a 4-5" media depth was monitored for hydrologic and water quality data.	TP export conc. was high, but showed a decreasing trend over course of 1 yr study. Pollutant load reductions were possible due to the large reduction in runoff vol.	69% average Rainfall over 15 mo. Period. Summer:92% Winter: 59% During dry season, removal approached 100%	
Liptan and Strecker, 2003	A GR in Portland, OR was monitored for hydrologic data. The roof was designed with 2-3" of topsoil and compost mix and planted with seven species of sedum. The roof slope was		Monthly retention ranged from <10% for an 11 in. rainfall, to 100% in dry season months. Over a two year study,	

	~7%.		average annual retention was 28%.	
Long et al, 2007	Columns were filled with 4" of different GR mineral media: two grades of expanded shale, two expanded clays (one with nutrient additives), and an expanded slate. Rainfall was simulated using synthetic rainwater. The study is still ongoing, but preliminary conclusions indicate GR media can effectively buffer rainfall pH and remove heavy metals. The finer graded expanded shale was most effective in pH buffering and metal removal.			The authors forecast that the engineering of a green roof media for water quality improvement is possible. It is recommended that expanded shale be used in green roof media mixes, due to the increase pollutant removal capabilities of this mix. To allow for proper drainage in the media, the fines should be mixed with medium grade materials. The mix ratio is still being studied.
Moran et al, 2005	Location: Kinston, Goldsboro, NC. Media depths and slope were 75mm (3 in) and ~0% for Goldsboro, and 100 mm (4 in) and 7% for Raleigh. Rainfall monitored over 6 month pd.	Green roof drainage exhibited and increase in N and P conc. from rainfall	Average 63% (Goldsboro) and 55% (Raleigh) For P>1.5", C=0.50 Tp delay 2-4.5 hrs	Results of a related laboratory test showed that soil media with a lower compost content will leach less N and P from the GR runoff. Further, the amount of nutrient leached over time should decrease.
MSU Research 2001-2004	3 year study of plant survival and drought tolerance in Michigan. Sedum and native species were planted and evaluated. The roof was irrigated regularly during the first year; irrigation was reduced and then eliminated in the 2nd and 3rd years. Upon			All tested (9) varieties of *Sedum* and *A. cernuum, C. lanceolata,* and *T. ohiensis* were the most suitable for unirrigated roofs in the Upper Midwest. Species of native plants could be used in GR applications so long as irrigation occurred regularly.

	cessation of irrigation, most native plants died. Only Sedum species survived on natural rainfall.			
MSU Research 2001-2004	9 species of Sedum were planted at depths of 4.0, 7.0, and 10.0 cm on green roof platforms in autumn and spring			Spring plantings had better survival rates (81%) compared to autumn (23%).
MSU Research 2001-2004	Chlorophyll fluorescence (F_v/F_m) measurements were taken on plant leaves to monitor plant stress. Chlorophyll fluorescence can indicate plant photosynthetic potential.			Water was required at least once every 14 days and 28 days to support growth in green roof substrates with 2 cm and 6 cm media depths respectively. Sedum vegetation was still viable after 88 days of drought
Teemusk and Mander, 2007	A study in Tartu, Estonia, compared runoff and WQ from a vegetated GR to a reference bituminous roof. Three rainfall events and two snow melt events were observed. The GR contained 100mm of media and 80 mm or rock wool (for additional water retention). The media layer consisted of a lightweight arrogate (LWA) (66%), humus (30%) and clay (4%). The rainfall was characterized by low intensity.	TP: 12-65% TN: 7-19% First number is avg during heavy storms (P<12.1mm) and second number is avg during small storms (P<2.5mm)	For P<2.5mm, 86% For P>12.5 mm, 0% During snow melt, pollutant concentrations were greater on the greenroof. Greenroof runoff had higher sulphates and Ca–Mg salts conc., due to leaching from the LWA-material.	The quality of the runoff water varied based on rainfall amt, and the amt of pollutants accumulated on the roof. GR effluent conc. of TN and TP were much lower than observed by Moran et al. (2003) or Liptan and Strecker (2003), because the Estonian greenroof did not contain compost The composition of the media layer should be taken into consideration in selecting the soil mix. P and N effluent concentration increased during heavy rainfall events; however, concentrations were still lower than those from the reference roof.
TRCA, 2005	Runoff from a GR was compared to control roof runoff in York, Toronto. Both roofs	Calculated Removal (GR compared to	RR: 54-76%	Fertilizers in the GR media were the primary source of phosphorus.

	were constructed on 10% slopes. The GR was planted with wildflowers and contained 140 mm of growing media consisting of crushed volcanic rock, compost, blonde peat, cooked clay and washed sand.	control roof): TSS: 69% TP: negative TKN: negative Cu: 66% Zn: 18% EColi: negative Al: 18% PAHs: 83-89%		GR phosphorus concentrations decreased more than 50% over two consecutive monitoring years, likely a result of leaching out from the media. Clearing of debris and bird feces from the GR should be done regularly to prevent clogging and decrease pollution export.
VanWoert et al, 2005	Compared RR of three roofs: gravel ballast (2 cm), extensive green roof without vegetation (2.5 cm media), and extensive green roof with vegetation (2.5 cm media) in East Lansing, MI (MSU)		Avg RR: Veg: 60.6% Media: 50.4% Gravel: 27.2% 0.08<P< 53.59 mm (83 events)	GRs with lower slopes and deeper media depth retained more rainfall RR depended on rainfall depth. Overall, vegetated roofs were most effective in retaining rainfall For Light (<2mm), Medium (2-6mm) and Heavy (>6mm) storms, % retention, respectively: Veg: 96.2, 82.9, 52.4 Media: 99.3, 82.3, 38.9 Gravel: 79.9, 33.9, 22.2
Schueler and Brown, 2004 Appendix B, Manual 3				Not included

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VEGETATED FILTER STRIP LITERATURE SUMMARY

Study	**Description**	**Pollutant Reductions** (conc. based unless noted)	**Runoff Reduction**	**Implications for Design**
Abu-Zreig et al, 2003	20 filters with varying length (2 to 15 m), slope (2.3 and 5%), and vegetation cover, were evaluated for phosphorus removal efficiency. Runoff was produced by rainfall simulators. The average P trapping efficiency of vegetated filters was 61%, ranging from 31% in a 2-m filter to 89% in a 15-m filter. Filter length was found to be the largest factor in removal; inflow rate, vegetation type, and density vegetative coverage had secondary influences.	MASS REMOVAL: The average phosphorus trapping efficiencies of the 2, 5, 10, and 15-m-long strips were 32, 54, 67, and 79%, respectively		Short filters (2 and 5 m), which are somewhat effective in sediment removal, are much less effective in P removal. For sediment trapping, increasing filter length beyond 15 m is not at all effective in increasing sediment removal but it is expected to further increase P removal.
Abu-Zreig et al, 2004	20 filters with varying length (2 to 15 m), slope (2.3 and 5%), and vegetation cover, were evaluated for sediment removal efficiency. Runoff was produced by rainfall simulators. TSS removal increased with increasing flowpath	For inflow rates of 0.3, 0.65 and 1.0 L/s TSS mass removal rates were 90%, 82% and 82%, respectively.	Water retention was related to filter length. WR ranged from 20% for the 2m filters to 62% in the 10m filters.	Greater vegetation cover increased TSS removal. Optimum filter length for TSS removal was approximately 10m.

	length up until 10m. Average TSS removal was 84%, ranging from 68% for a 2m filter to 98% for a 15m filter. No difference between the 10 m and 15m filters was observed.			
Barrett, 2005	Used data from the International Stormwater BMP database to analyze performance based on BMP design techniques			Vegetation coverage is important for pollutant removal. Little relationship between pollutant removal and vegetation height or type exists.
Barrett et al, 1998	Measured the efficiency of two highway runoff VFS in Austin, TX. Walnut creek and US 183 filters, respectively, had a centerline lengths of 1055 and 356 m, filter lengths of 7.8-8.1 and 7.5-8.8 m, 9.4% and 12.1% side slopes, 1.7% and 0.73% centerline slopes, 104,600 and 13.000 m2 drainage areas, and 38% and 52% paved CDA.	US 183: TSS: 87% FC: neg COD: 61% TOC: 51% Nitrate: 50% TKN: 33% TP: 44% Zn: 91% Pb: 41% Fe: 79% Walnut Creek: TSS: 85% FC: neg COD: 63% TOC: 53% Nitrate: 23% TKN: 44% TP: 34% Zn: 75%	P avg = 25mm (median = 16mm) 8.4 mm	Highway medians with a length of at least 8m, full vegetation, and slopes less than 12% are viable alternatives to structural controls to reduce highway pollutants and loads. Removal efficiencies of the two strips were similar, despite geometric and vegetative differences. Most pollutant removal occurred on the sides of the median, so a V-shaped median is recommended over a trapezoidal shape.

		Pb: 17% Fe: 75% Load reductions were slightly higher		
CALTRANS, 2004	Filter strips were sited, constructed, and monitored at three sites as a part of this study. CDA had I=100% for all locations.	TSS: 69% TP: neg TN: neg Total Cu: 85% Total Pb: 88% Total Zn: 72% Load reductions were higher due to RR from infiltration	RR: 30% (range 14-80%)	Check that the specified vegetation provides a dense enough surface in the climate to stabilize the swale bottom provide effective pollutant removal. Site in areas where sheet flow predominates.
CWP, 2007 NPRPD v.3	See table for WQ Swale			
Garabaghi et al, 2001	An experiment in Guelph, Ontario compared runoff treatment performance of perennial rye grass (*Lolium perenne* L.) VFS under different flow and pollution load conditions. Effects of flowpath length and flow rate on performance was evaluated. The plots were 1.2 m wide, and parallel to each other with a slope of 5.1% to 7.2%.			About 50% of sediments were removed within the first 2.5 m of the filter. An additional 25% to 45% of sediments (depending on flow rate) were removed within the next 2.5 m of the filter. Almost all of the aggregates larger that forty microns in diameter can be captured within the first five meters of the filter strip.
Goel et al, 2004	12 filter strips of 1.2 m width, 3% slope, different lengths (5, 10, 15 m), and different vegetation covers were studied.	Avg EMC removal for all filter strips: NO3-N: 21% PO4: 49% TP: 88%		Generally, denser vegetation and longer filter strips were more efficient in trapping different pollutants.

		TN: 90% E.Coli: 13% FC: 54% TSS: 88%		
Lim et al, 1998	Tested the effects VFS length on runoff concentrations from cattle-manure treated plots. Runoff was produced by rainfall simulators.	MASS REMOVAL: 6.1 m TKN: 78% PO4: 74.5% TP: 76.1% TSS: 70% TS:23.6% FC: 100% 12.2 m TKN: 89.5% PO4: 87.8% TP: 90.1% TSS: 89.5% TS: 40.8% FC: 100% 18.3 m TKN: 95.3% PO4: 93% TP: 93.6% TSS: 97.6% TS: 69.8% FC: 100%	Runoff Reduction (from simulated rainfall): 98%	75% of TKN, TP, OPO4, and TSS, and 100% of fecal coliform, were removed in first 6.1m of the VFS.
Schueler and Holland, 2000 (Practice) Article 118 Yu et al, 1992	A study on the pollutant removal capacity of a level spreader/grass filter strip designed to capture approximately 0.4 watershed-inches of runoff from a 10-acre shopping center. Eight storms were monitored at distances of 75 and 150	MASS REMOVAL: 75 ft. Filter Strip TSS: 54% NOx: -27% TP: -25% Extractable Pb: -16% Extractable Zn: 47% 150 ft. Filter Strip TSS: 84%		Sparse vegetation and gulley erosion was cited as reasons for poor removal rates in the first 75 feet of the strip. The authors recommend an optimal filter strip length of 80 to 100 feet with the level spreader.

	feet. Removal of particulates increased greatly after 150 feet of treatment but removal of nitrate and total phosphorus was modest.	Nitrate+Nitrite: 20% TP: 40% Extractable Pb: 50% Extractable Zn: 55%		
Strecker et al, 2004	Review of 32 grassed swales and vegetated filter strip studies found in the International Stormwater BMP database	Mass Removal: TSS: 45-75% Average effluent concentrations were published for Cu, TP, Zn, but no PR rate was specified.	40% Runoff Reduction	PR variability was high for all BMPs in the database; however, effluent quality was less variable. PR appeared to be dependent on the quality of the influent runoff.

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PERMEABLE PAVEMENT LITERATURE SUMMARY

Study	**Description**	**Pollutant Removal** (conc. based unless noted)	**Runoff Reduction**	**Implications for Design**
Andersen *et al.*, 1999;	Performed a **laboratory** study (simulated rainfall) to evaluate permeable pavement hydrological response. For PICP with a base course depth ranging from 30-70cm, a substantial portion of rainfall was retained under both dry and wet initial conditions.		Avg Rainfall Retention: Dry: 55% Wet: 30% (for a 15mm/hr, one hour duration storm)	Evaporation, drainage and retention in the structures were found to be a function of the particle size distribution of the bedding material and water retention in the surface blocks Pavements with smaller grain-sized substrate retained more water and increased attenuation. Evaporation rates were greatest from pavements with the highest retention of water. Pavement systems constructed over subbase materials had higher evaporation rates than systems with no subbase.
Balades et al, 1995	Field study on the clogging rates and effective maintenance of permeable pavements. Found that surface infiltration rates could be decreased by 50% after 2-3 years of use. Clogging was prevented by routine suction sweeping.			Clogging of permeable pavements occurs in the surface open void spaces, due to accumulating material that is retained on the permeable pavement surface. Clogging was effectively prevented through suction sweeping. In cases where severe clogging had occurred, high infiltration rates could be restored via use of a costly high-pressure water jet.
Bean et al, 2007a	Surface infiltration rates of 40 permeable pavement sites in NC, MD, VA, and DE were measured. PICP and PC in close proximity to disturbed soil sites had significantly lower surface infiltration rates than permeable pavements in			To sustain higher surface infiltration rates of CGP with sand, maintenance using a vacuum sweeper, should be performed at regular intervals. The top 13–18 mm of material accumulated within void spaces should be removed and replaced. The location of permeable pavement sites plays an important role in surface clogging rates. PICP and PC

	stable watersheds. Study concluded that the location of permeable pavements away from fines and disturbed sites, as well as maintenance of pavements, were critical to maintaining high surface infiltration rates.			sites should not be located adjacent to areas with disturbed soils
Bean, 2005, 2007b (in NPRPD)	In Goldsboro, NC, nutrient concentrations from PICP subsurface drainage were compared to those in adjacent asphalt runoff. In Cary, NC, PICP subsurface drainage was compared to rainfall. At both sites, NO3-N in the subsurface drainage was higher than the asphalt runoff and rainfall and NH4-N was lower. TP removal varied. In Swansboro, NC, a site was constructed and instrumented to monitor runoff flow and rainfall rates and collect exfiltrate and runoff samples from the permeable pavement lot; however, no site runoff resulted during the study period.	Calculated Removal: Goldsboro: TP: 65% OPO4: 50% TN: 36% NH4: 86% TKN: 55% NO3: -47% TSS: 72% Cu: 63% Zn: 88% Cary: TP: -54% OPO4: -100% TN: -2.2% NH4: 90.6% TKN: 52.4% NO3: -100%	Cary: 66% Swansboro: 100% (complete infiltration)	Increased concentrations of NO3-N in the PICP subsurface drainage were attributed to the probability that aerobic conditions occurred throughout the pavement that nitrified NH4-N to NO3-N. At Cary site, the addition of TP was attributed to atmospheric deposition (dry).
Booth and Brattebo, 2003 (in NPRPD)	Examined long term effectiveness of 4 types of pervious pavement and asphalt with respect to hydrology, water quality, and structural	Calculated Removal: Gravelpave: Zn: 91.6% Cu: 88.8% Grasspave:	Runoff Reduction: 97-100% Study	Permeable pavements can exhibit long term (5 yr) runoff and pollutant reductions Hardness and conductivity levels were significantly higher in permeable pavement subsurface drainage

	durability. All pavements endured structurally. PP drainage, as compared to asphalt, had significantly lower concentrations of Zn, Cu, and motor oil. Conversely, hardness and conductivity levels were significantly higher in pervious pavement drainage.	Zn: 38.9% Turfstone: Zn: 64.4% Cu: 83.3% Uni-Ecostone: Zn: 68.5% Cu: 89.2%	characterized by low rainfall intensities (avg intensity was less than 5mm/hr)	than asphalt runoff. Metals and motor oil concentrations were higher in asphalt runoff. Among the permeable sections, hardness and conductivity were significantly higher in the concrete systems (PICP and CGP) than the plastic grid systems.
Collins, 2008a	Compared 4 types of permeable pavement (PC, PICP1 (12.9% voids), CGP, and PICP2 (8.5% voids)) and standard asphalt in clayey subsoils. PICP1 and CGP cells had the highest volume and peak flow reductions. CGP also had the highest volume of surface runoff. The response of the PICP1 cell was attributed to an increased subsurface storage volume resulting from an elevated outlet pipe; whereas, the CGP cell response was attributed to the properties of sand fill media		Runoff Reductions: 94 - 98% Volume reductions: 32.1, 43.9, 66.3, 63.6, and 37.7% of rainfall volumes for asphalt, PC, PICP1, CGP, and PICP2, respectively. 56 monitored events, 3.1<P<88.9 mm Mean= 20.6 mm Median = 14.7 mm	Hydrologic differences among the permeable pavements, with respect to runoff reduction and peak flow mitigation, did exist mainly due to the properties of sand versus aggregate fill materials; however, they were small in comparison to the overall substantial improvements from asphalt. Among permeable pavements evaluated, CGP generated the greatest runoff volumes, attributed to the lower hydraulic conductivity of the sand fill media, and the resulting lower surface infiltration rate of this section. For the PICP sections, paver geometry seemed to influence surface runoff generation more than percent of open surface void space The sand fill media in CGP likely retained the most runoff, and was most effective in mitigating peak rainfall intensities. Sand fill, which is often seen as a detriment because of increased surface runoff, appears to have the benefit of holding additional water, which then slowly leaks or evaporates. If the installation of underdrains is recommended or

				necessary, design of the subbase can be altered to increase detention time within the pavement subbase by raising the perforated underdrain pipe elevations to create an internal storage zone. Further, an ISZ may decrease total outflow volumes and delay time to peak for small-medium rainfall events
Collins, 2008b	Compared 4 types of permeable and standard asphalt in clayey subsoils. Permeable pavement drainage had higher NO3-N concentrations, and no difference in TP or TSS concentrations were observed. Permeable pavement drainage had lower NH4 and TKN concentrations.	PC, which provided influent water the greatest contact time with cementitious materials, had the highest drainage pH values. For CGP, TN removal: 25%	20 storm events 3.1<P<88.9 mm Mean= 22.1 mm Median = 14.0 mm	The PC cell was most effective in buffering rainfall pH, because it provided influent water the greatest contact time with cementitious materials. Permeable pavement pH values were such that the leaching of metals through the pavements would not be expected. Authors suggest that permeable pavements with sand fill or bedding material may act similarly to a sand filter, and be efficient in TN removal. TP was likely leached from underlying high P-index soils into underdrains. No liner separated the permeable pavements' subbase from the in-situ soils. TSS (and TP) may be reduced by installing a permeable geo-fabric or raising the drainage pipe several inches above the underlying soils, encasing it in a washed aggregate layer.
Day *et al.*, 1981	**Laboratory** experiment (simulated rainfall) on three types of grid pavements and asphalt. Compared to asphalt, surface runoff was much lower from all three CGP systems. High removal rates of TP, organic phosphorus, and heavy metals were observed in CGP	For Monoslab, Grasscrete, Turfstone, respectively (overlying 1-2" gravel and 10-12" soil layer) TP: 70, 60, 59% OPO4: 40, 35, -285%	Runoff Reduction >99% for all CGP types. 10 simulated events: 0.9-3.5 in/hr, return pd <10	CGP systems dramatically reduce stormwater runoff. High phosphorus removal rates in the CGP systems was attributed to P adsorption to the aggregate and soils in the subbase layers Nitrate-nitrite removal rates were minimal; high leaching rates through the pavements were observed.

	subsurface drainage	Org-P: 76, 86, 68% NOx: -928, -777, -593% NH4: 44, 34, 32% ON: 76, 57, 39% TOC: 45, 26, -50% Pb: 92, 94, 93% Zn: 77, 92, 93% Cr: 77, 80, 26%	year storm.	
Dierkes *et al.* 2002	Field Study: Investigation of clogging materials and their distribution in permeable pavement surface. Found that metal conc. in PP decrease rapidly with depth. Most heavy metals were captured in the top 2 cm of the void space fill media. **Lab Study**: Evaluated heavy metal reduction efficiencies of four pavements: solid concrete block pavers with open infiltration joints, concrete block pavers with greened joints (topsoil fill with planted grass), pervious concrete pavers, and pervious concrete pavers with greened joints. All four pavements retained some amount of Cd, Cu, Pb, and Zn.	**Lab results:** Specific removal values were not published by the authors of the study		Field Study: Since metals are captured in top layers of the pervious pavement, through regular maintenance, where the top layer of fill media is removed and then refilled with new material, permeable pavements have the potential to remove heavy metals over long periods of time. **Lab Study:** Systems with pervious concrete or greened joints demonstrated higher pollution retention capacities than those without. The permeable concrete pavers with greened joints had the highest pollutant trapping efficiency.
Dreelin et al,	Compared performance of	For 7 of 9 sampled	RR: 93%	The majority of RR was attributed to infiltration into

2006	plastic grid grass pavers with a conventional asphalt in Athens, GA. The in-situ soils had a relatively high clay content (35-60%). During the 2 of 9 storms when metal and nutrient concentrations could be detected, pollutants were higher at the asphalt, except for TN. Overall pollutant loadings were low due to minimal parking lot use.	rain events, metal and nutrient conc. were below the detection limit at both lots Calculated Removal: Ca: 17% Zn: 80% Si: 50% TP:11% TN: negative	when compared to asphalt lot 0.03<P<1.83 cm	the clay soils. The permeable pavements sited in clay soils effectively to reduce runoff during small storm events It is likely that larger or intense storms would have decreased the pavement runoff reduction. The permeable pavement gravel subbase base storage capacity would be exceeded, and runoff from the practice would increase.
Fach and Geiger, 2005	**Laboratory** experiment to examine pollution removal rates of Cd, Zn, Pb, Cu for pervious concrete pavers, as well as for three variations of solid concrete block pavers; one with wide infiltration joints (29mm), another with narrow infiltration joints (3mm), and a third with narrow joints filled with crushed brick substrate. When set over a 4 cm crushed basalt or brick substrate roadbed and a 40 cm limestone base course, average pollution removal rates for all pavements and substructures were higher, ranging from 96 to 99.8% for all metals analyzed.	Calculated avg. heavy metal removal rate (Zn, Cu, Pb): solid concrete block pavers with brick substrate infill: 93, 92, 94% narrow joint spaces 59, 58, 79% wide joints spaces: 73, 77, 93% PC: 96, 96, 97%		No significant differences for pollution removal between the narrow and wide joint spacing were observed. PC had the highest pollutant removal rates, followed by the block pavers with substrate infill.
Gilbert and Clausen,	22 month study evaluated runoff EMC from three types of	PP runoff: Calculated removal:	Runoff Reduction:	Pollutant concentrations of permeable pavement runoff were significantly lower than asphalt runoff for

2006	driveways: asphalt, crushed stone, and permeable pavement. Permeable pavement driveways had significantly lower concentrations of TP, TN, NO_3-N, NH_3-N, TKN, TSS, Cu, Pb, and Zn than runoff from asphalt driveways. Runoff from the crushed stone driveways was similar to that of asphalt.	TSS: 67% NO3: 50% NH4: 72% TKN: 91% TP: 34% Cu: 65% Pb: 67% Zn: 71%	72% 104 events. Median rainfall = 9mm/h, 3.5 hr duration. 90% of storms < 29mm/h , 10.75 hr duration.	all constituents evaluated.
Hunt et al, 2002	Study of CGP application in permeable soils. The authors conclude that if CGP is properly maintained, nearly all events less than one inch will not produce runoff.		For P>12.7 mm, runoff coefficients ranged from 0.15 - 0.30	Surface runoff from the CGP lot was dependent on rainfall intensity rather than volume. The suggested required maintenance for this application was a street sweeper pass, about once every 9-12 months.
James and Gerritts, 2003	Studied clogging on an 8-year old installation of PICP in Canada.			Infiltration of water through permeable pavements decreased with increasing traffic loads, and also with increasing organic and fine matter in the open void spaces. In low to medium traffic areas, removing the top 15-20 mm of permeable pavement fill material significantly improved the surface infiltration rate. In areas of higher traffic, infiltration rate improved when 20-25mm of the fill material was removed.
James and Shahin, 1998	**Laboratory** study that compared the quantity and quality of runoff from PICP and rectangular concrete pavers to	PICP drainage reduced the concentrations of heavy metals, oils,		The increase in NO3-N and a decrease in TKN was attributed to oxidation within the pavement subbase The low concentrations of heavy metal, oils, grease,

	runoff from a standard asphalt block. Compared to applied rain water concentrations, PICP subsurface drainage exhibited an overall increase in pH and NO3, and a decrease heavy metals, oils, grease, and TSS. No change in TP was observed.	grease, and TSS. An increase in NO3 and pH was observed. Specific removal rates were not provided by the authors		and TSS, in the PICP drainage was likely due to adsorption or filtering by PICP open-graded aggregate base materials. Total void size (not joint size) in the surfaces of permeable pavements was a controlling factor in the amount of surface runoff generated. Pavements with sand and sand/gravel joint fills generated more runoff than those with gravel fill. Water drained faster through subgrades of gravel material compared to sand or a gravel/sand mixture subgrades. Permeable pavements were effective at buffering acidic rainfall pH. The pH of permeable pavement drainage was such that leaching of metals would not be expected.
Jefferies, 2004	Monitoring summary of several SUDS practices in Scotland. Includes runoff reduction data on 2 permeable pavement applications, one having an impermeable liner.		RR (compared to rainfall): 78% with no underdrains, 53% for lined system	RR (compared to conventional surface): 50% with no underdrains, 5% for lined system
Karasawa *et al*., 2006	Temperature study on PICP and standard asphalt.	Compared to asphalt, 15 PICP test stalls suppressed the temperature rise by 7.2 - 16.6ºC the day after rain and at 33.8ºC air temperature.		Generally, pavements having higher evaporation rates had lower road surface temperature. Pavements with higher water content had a lower road surface temperature. The lower temperatures were attributed to the removal of heat by the evaporation of moisture retained in

				pavement blocks
Kresin *et al.*, 1996	Evaluated PICP installations of various ages for infiltration capacities			The effective surface infiltration rate of PICP decreases with increasing age and compaction. By removing the top material of the block paver fill, surface infiltration rates can be improved.
Legret and Colandini, 1999	Compared porous asphalt (PA) drainage to conventional stormwater drainage. PA drainage had lower concentrations of TSS and heavy metals.	Concentrations of SS, Pb, Zn, and Cd were lower in permeable pavement drainage. Calculated removal: TSS: 65% Pb: 83% Cu: 0% Cd: 80% Zn: 73%	Runoff Red = 98-100% $12.7 < P < 52.1$ mm	Samples taken from PA structure and underlying soils indicated that metals are retained in PA and that leaching to the underlying soils is low, even after 8 years of use. Metal pollution concentrations were highest in the pavement surface clogging materials
Pagotto et al, 2000	In Nantes, France, a section of asphalt highway was monitored for 1 year, which was then replaced with PA and monitored for another year. PA runoff yielded lower concentrations of TSS, TKN, hydrocarbons and heavy metals.	PA runoff: TSS: 81% COD: 0.3% TKN: 43% Hydro: 92% Pb: 78% Cu: 35% Cd: 69% Zn: 66% NO3: 69% Cl: 77% SO4: 23% NH4: 74%	Individual storm data not included (only annual summary)	Hydrocarbon and particulate metal removal were attributed to the filtration of fine particulates on the porous asphalt surface. Dissolved metal removal was due to possible adsorption to pavement materials.
Pratt *et al.* 1989	4 pervious pavement stalls were fitted with underdrains and impermeable liners. The stalls		Total Vol. Reduction: 25-45% of	Pavements with subbase materials containing the greatest surface area were able to retain higher amounts of runoff.

	consisted of various subbase materials: pea gravel, blast furnace slag, granite, and carboniferous limestone. All stalls retained some portion of rainfall. Peak flow reductions and time to peak delays were also observed.		rainfall retained (3 events: 19.5<P<34.8 mm) Note: For P < 5 mm, retention = 100%	In areas of low soil permeability, the installation of underdrains in pervious pavement subsurface can still yield reductions in outflow volume and peak flow rate, and delay the time to peak flow.
Rushton, 2001	In Tampa, FL, three parking lot paving surfaces were compared, along with basins with and without swales. Pervious paving with a swale reduced runoff volumes and pollutant loads of metals and suspended solids.		RR: 50% for pervious paving with a swale. RR attributed to permeable paving alone was 32%	Increases in P were attributed to landscaping practices on the grassed swales. Pervious pavement with swales was most effective in reducing runoff during small storms.
Schueler and Brown, 2004. Appendix B, Manual 3				Not included (assumed under infiltration practices)
Traver (2006)	A porous concrete (PC) demonstration walkway site was sampled from 2003-2006 at the Villanova campus in PA. The main traffic on the walkway is pedestrian. As such, pollutant loadings were low. The PC drainage had low loadings of nutrients and metals; however, chloride	MASS REMOVAL: TSS: 99.9% TN: 95% TP: 97% Cl: negative	RR: 94%	Some P leached out of the soil as runoff infiltrated, but this is predicted to decrease as the soil washes out.

	loadings were high.			
Valavala et al, 2006	Rainfall events up to the 100 year frequency were simulated on unclogged PC pavement slabs ranging from 0-10% slopes. The slabs were 17 cm thick and underlain by a 15 cm thick sand bedding layer. Study determined that for unclogged PC with 16-27% porosity overlying a sand bedding layer, little to no runoff results from typical rainfall intensities.		Only during extremely high intensity events (21-47 cm/h) was runoff observed from the slabs with 10% slopes. For the same high rainfall intensities, no runoff resulted from the 2% sloped slabs	Unclogged PC can effectively reduce runoff volumes. Runoff from high intensity storms was generated on steeply sloped slabs; the same intensities did not produce runoff from low sloping slabs.
Van Seters et al, 2006	In King City, Ontario, long term performance of permeable pavers and bioretention were monitored. Virtually no surface runoff left the permeable pavement surface. Initial monitoring data indicates that water infiltrating into pervious pavements has lower pollutants than runoff from conventional pavement.	TP: 33% TKN: 26% Cu: neg Zn: 55% Oil/Grease: 64% (preliminary results from 8 storm events)		
UNH, 2007	Summary of 2 year pollutant removal data for various LID practices, including a porous	% Removal: TSS:99 TP: 38%		

	asphalt parking lot.	Zn: 96% TPH: 99%		

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DRAINAGE SWALE LITERATURE SUMMARY

Study	**Description**	**Pollutant Reductions** (conc. based unless noted)	**Runoff Reduction**	**Implications for Design**
Barrett, 2005	Used data from the International Stormwater BMP database to analyze performance based on BMP design techniques	TSS: 50% Nutrient reductions were not observed.	RR: approaches 50% in a semi-arid climate with permeable soils or low initial moisture content.	Removal of mowed grass clippings may result in nutrient reductions. Vegetation coverage is important for pollutant removal. Little relationship between pollutant removal and vegetation height or type exists.
CALTRANS, 2004	Six swales were sited, constructed and monitored for this study. Each of the swales treated runoff from highways and had CDA I=0.9-0.95.	TSS: 49% TN: 30% TP: negative Total Cu: 63% Total Pb: 68% Total Zn: 77% Higher load reductions were observed due to high RR though infiltration.	RR: avg 50% (range 33-80%)	Proposed sites should receive sufficient sunlight to support vegetation growth. Check that the specified vegetation provides a dense enough surface in the climate to stabilize the swale bottom provide effective pollutant removal.
Liptan, and Murase, 2000	This study compared the pollutant removal performance between a grass turf and native grass swale. Each swale was identical in geometric shape and soil type. The turf swale was mowed regularly and the native grass swale was allowed to grow naturally. Identical flow volumes were pumped into both from a 50-acre urban area. A total of six events over	MASS BASED: Turf Native Grass TSS: 69% 81% TP: 38% 50% Nitrate–N 8% 16% TKN: 40% 54% O-Phosphate-Phosphorus, diss -45% -75% Cu: 53% 65% Pb: 62% 72% Zn: 63% 76% Cu diss: 38% 52% Pb diss:	Native grass swale runoff attenuation: 41% Grass turf swale runoff attenuation: 27%	There is larger runoff attenuation in native grass swale compared to grass turf swale, presumably from a better infiltration rate from more organic material and robust root systems. Native grass performed better overall except for phosphorus, authors attributed this to accumulation of organic matter in the swale. Pollutant removal efficiency better in warm seasons.

	two years were sampled.	36% 53% Zn diss: 48% 64%		
Schueler and Brown, 2004 Appendix B, Manual 3				Swale should exceed WQv by more than 25%-50% Use dry or wet swale designs Longitudinal swale slope should be between 0.5 to 2.0% Velocity within swale <1 fps during WQv storm Soil infiltration rates should exceed 1.0 in/hr Provide multiple cells with pretreatment Provide off-line design w/ storm bypass
Schueler and Holland, 2000 (Practice) Article 113 Harper, 1988	This study compares surface and groundwater quality as runoff from an interstate highway flows through a vegetated wet and dry swale. Both had the same length (200 feet) but the wet swale had groundwater at the surface, wetland plants and zero infiltration. The dry swale had groundwater two feet below surface, sparse grass cover and high infiltration rate.	Wet Swale TSS: 81% BOD (5 day): 48% TN: 40% TP: 17% Nitrate-N: 52% Organic Nitrogen: 39% NH4: -11% Ortho-phosphorus: -30% Cd: 42% Cu: 56% Cr: 37% Pb: 50% Nickel: 32% Zn: 69% Dry Swale	Dry Swale: 80% of runoff infiltrated before it reached outlet	The dry swale performed better based on the gentle slope and the fact that most of the runoff was infiltrated. The major pollutant removal process appeared to be infiltration and sedimentation. The wet swale outperformed the dry swale in runoff that reached the outlet. The major pollutant removal process appeared to be settling and vegetative filtering. Long swales are effective in treating urban stormwater and groundwater plays an important role when designing them in sandy, low-relief environment.

	Dry swale runoff that did reach the outlet had a higher pollutant load than the wet swale. Trace metals were trapped in surface soils. Dissolved metals were not removed as well as particulate – the sandy soils may not have provided enough binding sites to capture soluble metals. Soluble nutrients migrated into groundwater, especially from dry swale but overall had a modest impact on groundwater quality.	TSS: 87% BOD (5 day): 69% TN: 84% TP: 83% Nitrate-N: 80% Organic Nitrogen: 86% NH4: 78% Ortho-phosphorus: 70% Cd: 89% Cu: 89% Cr: 88% Pb: 90% Nickel: 88% Zn: 90%		
Schueler and Holland, 2000 (Practice) Article 114 Dorman et al, 1989	Pollutant removal performance of highway swales in Florida, Maryland and Virginia. Three swales of similar length (approx. 200 feet) but different slope, cover and soils. Florida - flat with sandy soils and high grass – had the best pollutant removal. Maryland - slope was moderate (3.2%) with short grass, experienced erosion, was a sediment exporter and had low pollutant removal rates.	MASS REMOVAL: Florida (#storms sampled: 8) Sediment: 98% Organic Carbon: 64% TKN: 48% Nitrate: 45% TP: 18% Cd: 29%– 45% Cr: 51%– 61% Cu: 62%– 67% Pb: 67%– 94% Zn: 81% Maryland (#storms sampled: 4) Sediment: -85%	During small storms, no measurable flow detected in VA swale (infiltration of runoff)	Important factors for pollutant removal are higher and better grass cover, flat slope and soils with high infiltration rates. Since slope, soil type and cover can't always be controlled, designs should incorporate features such as sand layers, check dams, underdrains and diversions to off-line swales or pocket wetlands.

	Virginia had steepest slope (4.7%), better grass cover, minor erosion and moderate removal rates.	Organic Carbon: 23% TKN: 9% Nitrate: -143% TP: 12% Cd: 85%-91% Cr: 22%-72% Cu: 14% Pb: 18%-92% Zn: 47% Virginia (#storms sampled: 9) Sediment: 65% Organic Carbon: 76% TKN: 17% Nitrate: 11% TP: 41% Cd: 12%-98% Cr:12%-16% Cu: 28% Pb: 41%-55% Zn: 49% Pollutant removal rates as % long term mass reduction.		
Strecker et al, 2004	Review of 32 grassed swales and vegetated filter strip studies found in the International Stormwater BMP database	Mass Removal: TSS: 45-75% Average effluent concentrations were published for Cu, TP, Zn, but no PR rate was specified.	40% Runoff Reduction	PR variability was high for all BMPs in the database; however, effluent quality was less variable. PR appeared to be dependent on the quality of the influent runoff.
Yu et al, 2001	Field tests were conducted in Taiwan and Virginia on the pollutant	MASS REMOVAL: 14 to 99% for TSS, COD, TN, and TP.		Grassed swales can be an effective storm-water BMP, particularly for areas subject to low intensity storms.

	removal rates of grassed swales. Virginia experiments tested a highway median swale (274.5 m length, 3% slope), while the Taiwan experiments tested an agricultural swale. (30m length, 1% slope)			Swales should be at least 75 m in long with a minimum longitudinal slope of 3%. Check dams can improve swale performance.

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BIORETENTION LITERATURE SUMMARY

Study	**Description**	**Pollutant Reductions** (conc. based unless noted)	**Runoff Reductions**	**Implications for Design**
CWP, 2007 NPRPD v.3	Summary of performance for 10 bioretention practices	Removal Efficiency: Q1-Q3 (median) TSS: 15-74% (59) TP: -76-30 (5) SolP: -9-49% (-9) TN: 40-55% (46) NOx: 16-67% (43) Cu: 37-97% (81) Zn: 37-95% (79) Bacteria: N/A		Bioretention practices had relatively high TN, heavy metal removal rates
Davis et al., 2001	A detailed study on the removal of heavy metals (copper, lead, and zinc) and nutrients (phosphorus, total kjeldahl nitrogen, ammonium, and nitrate) from synthetic stormwater runoff. Batch, column and pilot-scale experiments found that bioretention areas provide significant reduction of heavy metals, moderate reduction of TP, TKN and NH_3 and poor reduction of NO_3 (in many cases, nitrate production was noted).	Cu: 92% ± 3% Pb: > 98% Zn: > 98% TP: 81% ± 4% TKN: 68% ± 27% NH_3-N: 79% ± 11% NO_3-N: 24% ± 102% Higher mass removal was provided due to water retention within the bioretention areas.		The depth of bioretention areas was found to play a key role in providing phosphorus removal; soil adsorption was cited as the primary phosphorus removal mechanism. Soil adsorption, through ion exchange, was cited as mechanisms that provided NH_3 removal. Organic matter (e.g. peat) is thought to increase removal of ammonia. Confirms that the transformation of organic nitrogen (through mineralization and nitrification) and ammonia (through nitrification) occurs in bioretention areas, especially near the surface. Some denitrification (nitrogen removal) was found to occur toward the bottom of the bioretention areas. The mulch layer was found to play a key role in metal removal; significant accumulation of heavy metals was found

				within the mulch layer, while no heavy metal accumulation was observed within the soil.
Davis et al., 2003	An investigation using pilot-scale bioretention systems and two existing bioretention areas (one in Greenbelt, MD and one in Largo, MD). The study documents the effectiveness of bioretention areas in removing low levels of lead, copper and zinc from synthetic stormwater runoff. The laboratory results of Davis et al. (2001) are presented.	Laboratory Cu: 92% ± 3% Pb: > 98% Zn: > 98% Field Greenbelt, MD: Cu: 97% ± 2% Pb: > 95% Zn: > 95% Largo, MD: Cu: 43% ± 11% Pb: 70% ± 23% Zn: 64% ± 42% Higher mass removal was provided due to water retention within the bioretention areas.	Laboratory Avg. RR: 63% (range 19-99%) Attributed to ET loss	As with the laboratory results presented in Davis et al. (2001) the mulch layer of field bioretention areas was found to play a key role in metal removal; significant accumulation of heavy metals was found at the top of the bioretention areas, especially within the mulch layers. Increased flow rates were not found to significantly affect the amount of heavy metal removal provided by the bioretention areas, unless mass removal is considered (due to overflow). The differences between the Greenbelt, MD and Largo, MD bioretention areas were explained by the differences in the filter bed media. The facility at Largo, MD was built with a filter bed consisting mainly of sand, while the facility at Greenbelt, MD was built with a higher percentage of topsoil and fines.
Davis et al., 2006	This work provides an in-depth analysis of the ability of bioretention areas to remove nutrients from synthetic stormwater runoff. The study involves pilot-scale bioretention systems and two existing bioretention areas (one in Greenbelt, MD and one in Largo, MD). The laboratory results of	Laboratory TP: 81% ± 4% TKN: 68% ± 27% NO_3-N: 24% ± 102% TN: 60% ± 31% Field Greenbelt, MD: TP: 65% ± 8% TKN: 52% ± 7%		Increased flow rates were not found to significantly affect the amount of nutrient removal provided by the bioretention areas, unless mass removal is considered (due to overflow). The authors expected to find better nutrient removal at the Greenbelt, MD facility because the filter bed had a higher percentage of topsoil and fines, but this

	Davis et al. (2001) are presented.	NO$_3$-N: 16% ± 6% TN: 49% ± 6% Largo, MD: TP: 87% ± 2% TKN: 67% ± 9% NO$_3$-N: 15% ± 12% TN: 59% ± 6% Higher mass removal was provided due to water retention within the bioretention areas.		was not found. The engineered media at the Largo, MD facility provided better nutrient removal. The depth of bioretention areas was not found to play as significant a role in the removal of TKN, with much of the removal occurring at the top of the bioretention areas within the mulch layer. TN removal was dominated by TKN removal, and little NO$_3$ removal was provided by the bioretention areas, except at the bottom, where the conditions necessary for dentrification may exist.
Davis, 2008	In College Park, MD, 2 bioretention areas, each 28m^2 in size, were built to treat runoff from a 0.24 ha section of parking lot. One cell (B) was 0.9m deep with conventional drainage, and the other cell (A) was 1.2m deep and contained an anoxic zone to encourage denitrification. Both cells were lined and fitted **underdrains** for monitoring purposes. Hydrologic analyses found that both cells reduced runoff volumes and peak flow rates. Delays in peak flow were also observed.		(49 rainfall events) Cell A: RR: median 77%, mean 52% Peak flow reduction: 63% Cell B; median 82%, mean 65% Peak flow reduction: 44%	
Dietz and Clausen, 2005	A study on the pollutant removal capacity of two rain gardens constructed in Haddam, CT designed to capture the first inch of runoff from shingled rooftops.	Mass Based Removal: TP: -111% NH$_3$-N: 85% NO$_3$-N: 36% TKN: 31%		The mechanisms responsible for NH$_3$ were nitrification and soil adsorption.

	The rain gardens were found to be effective in providing peak flow rate reduction and in removing NH_3, NO_3, TKN and TN from rooftop runoff.	TN: 32%		
Dietz and Clausen, 2006 (in NPRPD)	A study on the pollutant removal capacity of two rain gardens (**with underdrains**) constructed in Haddam, CT designed to capture the first inch of runoff from shingled rooftops. The rain gardens were effective in reducing the concentrations of NH_3, NO_3, and TN in the rooftop runoff. However, TP concentrations were significantly increased by both of the rain gardens.	Mass Based Removal: TP: -108% NH_3-N: 82% NO_3-N: 67% TKN: 26% TN: 51%	Runoff Reduction: 99.2% Total Volume Reduction: 3.7% (assumed to be ET) 12 month P= 172.8cm	Mulch was found to play a significant role in the removal of TN and TP, as the concentrations of these pollutants increased over time. The rain garden soils were found to be a source of TN and TP, as the concentrations of these pollutants decreased over time. No significant changes in NO_3-N concentrations occurred as a result of raising the underdrain to create a saturated zone at the bottom of one of the rain gardens in an attempt to increase denitrification. The mulch layer was also found to play a key role in metal removal, as the concentrations of these pollutants increased over time.
Dougherty et al, 2007	A rain garden in Auburn, AL, was monitored for nutrient removal data. The garden was 1.2m deep and was filled with native soils mixed with shredded pine bark mulch to improve cell infiltration and the organic content. The cell was lined and	TP and SolP reductions from the bioretention cell were observed under both drainage configurations. TN removal. NH4 was reduced significantly towards the end of the		Peak outflow rates gradually decreased over the entire study period, a probable result of media settlement and consolidation after construction.

	fitted with an **underdrain**. Conventional drainage occurred for the first 2 months (8 runoff events) of monitoring, and then modifications were made to create an IWS zone in the cell (monitoring for 9 subsequent runoff events).	study for the configuration with an IWS zone.		
Ermilio, 2005 (in NPRPD)	A thesis completed at Villanova University and based on the bioretention traffic island built at Villanova University's BMP demonstration park. Water quality results show a significant reduction in many common stormwater pollutants as a result of capturing and treating the first flush runoff of rainfall events.	TSS: 92% TDS: 38% Cu: 47% Pb: 55% Cr: 62% Zn: 17% TN: 48% TP: 1% Higher mass removal was provided due to water retention within the bioretention areas.	Runoff Reduction: 86% 30 rain events 0.23<P<7.1in Mean=1.55 in	Although the bioretention area is designed to infiltrate stormwater runoff, it does not appear the quality of groundwater beneath the basin is being significantly affected. TN and TP are retained during periods of increased plant activity in the summer and fall months and are released during periods of low plant activity in the winter and spring months.
Glass and Bissouma, 2005 (in NPRPD)	In this study, the ability of a bioretention area (**with underdrain**) to remove nutrients and heavy metals was evaluated over a period of 15 rain events. The results indicate that bioretention facilities can be moderately to very effective in removing heavy metals and nutrients from stormwater runoff.	Zn: 79% Cu: 81% Pb: 75% Cd: 66% Fe: 53% Cr: 53% Al: 17% As: 11% Higher mass removal was provided due to water retention within the bioretention areas.		Organic matter and plants were believed to be the dominant mechanisms that provided the removal of heavy metals within the bioretention area. Lack of regular maintenance on the mulch layer of the bioretention area was cited as a reason for lower heavy metal removals than those found by Davis.

		Mass Based Removal: TSS: 98% Zn: 80% Cu: 75% Pb: 71% Cd: 70% Fe: 51% Cr: 42% Al: 17% NH_3-N: 65% NO_3-N: 27% PO_4-P: 3%		
Hsieh and Davis, 2005a	In this study, a bioretention test column was set up and subjected to regular testing once a week for 12 weeks to investigate the ability of bioretention areas to treat frequent storm events. All 12 tests demonstrated that improvements in stormwater quality and excellent removal efficiencies for TSS, oil/grease, and lead were found.	Mass Based Removal: TSS: 91% Pb: > 98% TP: 63% NH_3-N: 13% NO_3-N: -16% Oil/Grease: > 97%		Most of the TSS in the stormwater runoff was removed by the top (mulch) layer of the bioretention test column. This helped prevent clogging within the rest of the test column. Organic matter and Ca content of the filter bed was found to increase during testing. This may have increased the ability of the bioretention test column to remove phosphorus through precipitation and adsorption (ion exchange).
Hsieh and Davis, 2005b	The objective of this study was to provide insight on the filter media characteristics that define the pollutant removal performance of bioretention areas. Eighteen bioretention test columns and six existing bioretention facilities were evaluated using synthetic stormwater runoff. In the laboratory studies, two types of sand and three types of soil with	Mass Based Removal: Field TSS: 72% - 99% Pb: 80% - 98% TP: 37% - 99%		Removal of metals, TSS, and oil/grease were not affected by the chemical properties of the filter bed media. This is not surprising given that these pollutants are removed through filtration, which is a physical, not chemical or biological, process. Permeable sands were found to provide the best overall removal of these pollutants, although all fill media performed well. Although TP removal was expected to

	various physical and chemical properties were used. The field experiments were conducted in Maryland (one in Greenbelt, MD, two in Hyattsville, MD, and three in Landover, MD).			correlate with the chemical properties of the filter bed media (e.g. P content, organic matter, and CEC), based on the laboratory results these characteristics were not found to have a significant statistical correlation with TP removal. In the field, however, a good correlation between TP removal and filter bed depth and organic matter content were found. Filter bed media with higher levels of fines and organic matter were found to provide greater removal of TN. A filter bed media with a coarse sand/sandy soil mixture appears to provide the best overall pollutant removal performance within bioretention areas.
Hunt and White, 2001	This profile sheets contains a good description of the pollutant removal mechanisms at work within bioretention areas and offers guidance on the sizing and design of bioretention areas, with variations for clayey and sandy soils. Contains no performance data, but does provide cost data.			Bioretention areas installed in clayey soils need to be provided with an underdrain and provided with engineered filter bed media. Bioretention areas installed in sandy soils do not need an underdrain do not require the use of an underdrain, provided that the infiltration rate of the native soils is greater than 1.0 in/hr.
Hunt, 2003	Provides a summary of bioretention research conducted at the University of Maryland, Pennsylvania State University and in North Carolina. Summarizes pollutant removal			If a bioretention area is being designed for metals removal, a deep filter bed may not be needed because of the significance of the mulch layer to remove heavy metals. Anaerobic zones appear to develop within

	data presented by Davis et al. (2001) and Davis et al. (2003).			bioretention areas regardless of the drainage configuration of the design cell (although they may be dependent upon the filter bed media) and there does not appear to be a need for the use of engineered saturated zones to increase NO_3 removal.
Hunt et al., 2006 (in NPRPD)	The pollutant removal and runoff reduction abilities of three bioretention areas in North Carolina (Two in Greensboro, NC and one in Chapel Hill, NC) were examined. Sufficient flow data and water quality samples were only collected for two of the bioretention areas (one in Greensboro and one in Chapel Hill). Both bioretention areas were designed with conventional **underdrains**. The field studies found high heavy metals and total nitrogen removal rates in the two conventional bioretention area (e.g. without engineered saturated zones). High TP removal for the cell with a low P-index was observed.	Mass Based Removal Greensboro (G2): P-Index 86-100 (high) TSS: -170% Zn: 98% Cu: 99% Pb: 81% TN: 40% NH_3-N: -1% NO_3-N: 75% TKN: -5% TP: -240% PO_4-P: -9% Mass Based Removal Chapel Hill: P-index 4-12 (low) TN: 40% NH_3-N: 86% NO_3-N: 13% TKN: 45% TP: 65% PO_4-P: 69%	RR: 52-56% (personal communication)	Small saturated, anaerobic zones were found within the Greensboro cell, perhaps created by the presence of clay soils within the fill media. These isolated zones were though to provide the conditions necessary for dentrification, which would explain the high level of NO_3 removal. Similar conditions were not found in the Chapel Hill bioretention cell. The P-index of the fill media used in the Greensboro cell was very high (86 to 100), indicating that the media was saturated with phosphorus. Comparatively, the P-index of the fill media used in the Chapel Hill cell was low (4 to 12), indicating that the media could accept more phosphorus. A lower P-index, along with high amount of cation exchange sites (provided by organic matter), enhances the removal of phosphrous through adsorption. The impact of drainage configuration on TN removal was not statistically significant (e.g. Cell G1 was designed with a saturated zone), which suggests that engineered saturated zones are not needed to increase NO_3 removal. Fill soil content may play a more important role in

				providing the conditions necessary for denitrification.
Hunt et al, 2008	Bioretention cell with underdrain	TN: 38% TP: 32%		
Hunt and Lord, 2006	This profile sheet presents information on the performance of bioretention cells installed in Greensboro, NC, Chapel Hill, NC, Louisburg, NC, and Charlotte, NC. The bioretention cells were found to provide moderate to high removal of nutrients and other stormwater pollutants. Summarizes the pollutant removal data presented by Hunt et al. (2006) and includes some additional data. Pollutant specific design guidance, guidelines for selecting fill soil and vegetation, and information about maintenance are also provided within the profile sheet.	Mass Based Removal Greensboro (G1) (**underdrain**): TN: 33% - 40% TP: -39% - (-240%) Soil P-Index: 86 - 100 Cu: 65% - 99% Zn: 65% - 99% Mass Based Removal Greensboro (G2) (IWS): TN: 43% TP: 9% Soil P-Index: 35 - 50 Cu: 56% - 86% Zn: 56% - 86% Mass Based Removal: Chapel Hill (**underdrain**): TN: 40% TP: 65% Soil P-Index: 4 - 12 Mass Based Removal: Louisburg (L1) (**underdrain**): TN: 64% TP: 66% Soil P-Index: 1 - 2 Mass Based Removal:	Runoff Reduction: 33% - 50% Attributed to exfiltration and ET.	Phosphorus removal can be enhanced with proper fill soil selection. As the pollutant removal rates show, using low P-Index soils increases TP removal, while high P-Index soils decrease performance. The recommended P-Index for fill soils is between 10 - 30. Fill soils with a relatively high cation exchange capacity (CEC) are recommended to increase TP removal. While a minimum CEC is not provided, soils with CECs exceeding 10 are expected to provide better pollutant removal. Deeper bioretention cells (36 inches or more) and fill soils with lower infiltration rates are recommended to enhance TN removal and reduce runoff temperature. The addition of fines to the fill soil will help reduce infiltration rates and may promote the formation of small anaerobic zones within the fill soil to remove NO_3. Bioretention cell surfaces should be planted with less vegetation to allow promote bacteria removal through exposure to sunlight. Cleaner stormwater runoff appears to decrease pollutant removal efficiency. Of

		Louisburg (L2) (**underdrain**): TN: 68% TP: 22% Soil P-Index: 1 - 2 Mass Based Removal Charlotte (**underdrain**): TN: 65% TP: 68% Bacteria: >90% Soil P-Index: 7 – 14		the cells that had low P-Index soils, bioretention cell L2, which treated stormwater runoff with the lowest TP concentrations, provided the lowest TP removal. Addition of an IWS zone may reduce effluent temperature and reduce TN concentrations. Tests for TN reduction in these systems did not produce statistically significant results.
Kim et al., 2003	This study systematically evaluated a reengineered concept of a bioretention area designed to promote nitrogen removal via microbial denitrification. An engineered saturated zone was built into bioretention test columns. Inorganic and organic substrates, as electron donors, were mixed with sand and used to fill continuously submerged **anaerobic zones** at the bottom of the bioretention columns. Overdrains were provided to ensure that the anaerobic zones remained saturated. The test columns demonstrated good removal of NO_3.	Mass Based Removal: NO_3-N: 70% - 80%		A saturated, anaerobic zone provided at the bottom of the bioretention cell may help improve nitrogen removal. An electron donor (organic or inorganic substrate) is needed to drive the denitrification process. Denitrifying bacteria (*nitrosomonas* and *nitrobacter*) require both an electron donor substrate and a carbon source as they synthesize by converting NH_3 to N_2. This study found newspaper to be the most effective electron donor, but wood chips and small sulfur particles were also identified as potentially viable substrates.
McCuen and Okunola, 2002	This research extends the widely used Natural Resources Conservation Service TR-55 design procedures for use on microwatersheds. Specifically,		Runoff Reduction: **underdrains**: 19% Infiltration:	Based on the methods presented within this study, bioretention areas able to fully contain all of the runoff from a given design storm (e.g. infiltration-based bioretention) provide a runoff reduction of

	the graphical peak discharge estimation method is extended so that it can be used for catchments with times of concentration as small as 0.02 h. The kinematic-wave time of concentration estimation method is made applicable for multiple-section sheet flow, and a new pond-and-swamp adjustment procedure enables the design and evaluation of small on-site bioretention areas. Estimates of the hydrologic benefits of bioretention areas are provided.		38%	about 38%, while those only able to partially contain the runoff (e.g. underdrained bioretention) provide a runoff reduction of about 19%.
Passeport et al, 2008	Evaluated 2 grassed bioretention areas in NC (depths = 0.75 and 1.05m), both having an expanded slate fill media and internal storage zones. The system efficiently reduced nutrients loads and EMCs. Removal was highest during warmer months.	TKN: 49, 59 NH4: 70, 84 NO3: 33, - TN: 54, 54 TP: 63, 58 OPO4: 78, 74 FC: 95, 85	RR: 20-50%	The deeper media depth did not increase nutrient EMC removal. The grass vegetated bioretention cells performed favorably to conventionally vegetated (trees, shrubs and mulch) bioretention cells studied in North Carolina.
Perez-Pedini et al., 2005	A distributed hydrologic model of an urban watershed was developed and combined with an algorithm to determine the optimal location of infiltration-based BMPs. Model results show that optimal location of infiltration-based BMPs can provide a significant reduction of runoff.		Runoff Reduction: 30%	

Schueler and Brown, 2004 Manual 3 (Appendix B)				Pollutant removal can be increased by designing the filter to treat a larger WQv . Filter media should be tested and have a P Index less than 30. If possible, bioretention areas should be placed in permeable soils, eliminating the need for an underdrain. If underdrain is necessary, putting an upflow pipe can help remove more pollutants. The filter bed should be deeper than 30 inches for additional pollutant removal. A two cell design with pretreatment is recommended. Bioretention cell SA should be more than 5% of CDA.
Sharkey, 2006	Evaluated 2 field sites in NC and performed a laboratory simulation to evaluate nutrient removal and hydrologic response of bioretention cells. The laboratory results showed that a 91% sandy soil was unable to reduce phosphorus concentrations at all P-Index levels.	TN: 62% TP: 66%	RR: 20-29%	The P-Index for bioretention fill soil should be no greater than 40 and contain between 75% and 85% sand.
Smith and Hunt, 2006 (in NPRPD)	This study evaluated the performance of two bioretention cells, vegetated with bermuda grass and containing IWS zones, in removing nitrogen, phosphorus, metals and sediment. The two cells that were tested	Calculated Removal: Graham (N): TSS: 63% Cu: 9% Zn: 37% TN: 61% TKN: 65%	Graham (N): Runoff Reduction: 40% Graham (S): Runoff	Higher pollutant removal efficiency was associated with the cell that had deeper filter media and well-drained (S) underlying soils.

	(both located in Graham, NC) had filter beds with different depths. Sufficient flow data and water quality samples were only collected for one of the bioretention cells (N). The other cell (S) did not produce any measurable outflow on many occasions.	NH_3-N: 79% NO_3-N: 43% TP: 8% PO_4-P: -127% Bacteria: 97% Higher mass removal was provided due to water retention within the bioretention areas. Mass Based Removal: TN: 70-80% TP: 35-50% FC: 97%	Reduction: 60% 12 events 0.19<P<1.88in	
UNHSC, 2005	The performance of a bioretention cell in Durham, NH was evaluated.	Mass Based Removal: TSS: 97% Zn: 99% NO_3-N: 44% TPH-D: 99%	Peak Flow Red'n: 85%	Design of the bioretention cell was based upon the guidance provided in the New York State Stormwater Management Design Manual.
Van Seters et al., 2006	The performance of a bioretention area (located in King City, ON) was evaluated. The bioretention area showed that it was effective in reducing peak flows and in improving water quality from parking lot runoff. Three equal-sized parking lot sections were monitored. The first consisted of porous pavement, the second was conventional asphalt (control section), while the third was conventional asphalt but was treated by a bioretention area.		Runoff Reduction: 40%	

	The porous pavement and bioretention sections were effective at infiltrating stormwater runoff and reducing peak flow.			
Yu and Stopinski, 2001 (in NPRPD)	This study monitored the field performance of four ultra-urban stormwater BMPs: three oil and grit separators (Isoilater, Stormceptor™, and Vortechs Stormwater Treatment System™) and a bioretention area located in Charlottesville, VA. Storm sampling data for each site were analyzed to calculate the removal efficiency for each constituent monitored.	TSS: 53% TP: 13% Oil/Grease: 66%		TSS removal in the bioretention area was found to be affected by rainfall depth. Small-to-medium storms yielded positive removal efficiencies, while large storms yielded negative removal efficiencies.

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WATER QUALITY SWALE LITERATURE SUMMARY

Study	**Description**	**Pollutant Reductions** (conc. based unless noted)	**Runoff Reduction**	**Implications for Design**
Barrett et al, 1997	In Austin, TX, a swale was constructed with an underdrain. Influent runoff EMCs were compared to infiltrated runoff EMCs from the swale underdrain.	TSS: 74% BOD:46% COD: 35% NO3: 59% TP: 31% Oil and Grease: 88% Cu: 49% Fe: 79% Pb: 35% Zn: 74% Reductions in pollutant load were even higher due to a large volume of infiltrated runoff.	RR: 90%	
CWP, 2007 NPRPD v.3	Summary of the performance of 17 open channel practices, including 3 grass channels, 12 dry swales, and 2 wet swales.	Removal Efficiency: Q1-Q4 (median) TSS: 69-87% (81) TP: (-15-46% (34) SolP: -94-26% (-38) TN: 40-76% (56) NOx: 14-65% (39) Cu: 45-79% (65) Zn: 58-77% (71) Bacteria:-63 to -25% (-25)		Bacteria removal rates were negative, while removal rates for metals, and TSS tended high.
Horner et al, 2003				
Fletcher et al, 2002	In Brisbane, Austrailia, pollutant removal rates of a residential swale (65m long, 1.6% longitudinal slope, 1:13 side slopes,	TSS: 83 (73-94)% TP: 65 (58-72)% TN: 52 (44-57)%		TSS removal decreased with increasing flow rate, reflecting the importance of physical processes (sedimentation and filtration) in TSS removal.

	and catchment area of 1.03ha, triangular cross section, 67% vegetative cover). Synthetic rainwater was tested. High concentration reductions were observed for TSS, TP, and TN.			TN and TP removal were less dependent on flow, reflecting more importance of chemical processes (e.g. soil sorption). TSS removal also increased with increasing swale length. TP and TN concentrations decreased rapidly in the first quarter of the swale length
Jefferies, 2004	Monitoring summary of several SUDS practices in Scotland. Includes runoff reduction data on 2 swales compared to runoff from a car taramac. The runoff reduction values are for surface runoff only, and do not include flow through the underlying pipes		RR (compared to conventional surface): 85%	
Schueler and Brown, 2004 Appendix B, Manual 3				Should exceed target WQv by more than 50% Use dry or wet swale design Should exceed target WQv by more than 25% Longitudinal swale slope between 0.5 to 2.0% Velocity within swale < 1 fps during WQ storm Measured soil infiltration rates should exceed 1.0 in/hr Use multiple cells with pretreatment Use off-line design w/ storm bypass
Schueler and	The purpose of this study	200-foot		Authors suggest the following design criteria

Holland, 2000 (Practice) Article 112 Seattle Metro, 1992	was to determine the pollutant removal capability of a 200-foot long, trapezoidal biofilter and test the performance after its length was reduced to 100 feet. Six storm events were monitored for both lengths. The study took place in the Pacific Northwest.	TSS: 83% TPH: 75% Total Zinc: 63% Diss Zn: 30% Total Pb: 67% Total Aluminum: 63% Total Cu: 46% TP: 29% Nitrate-N: negative 100-foot TSS: 60% TPH: 49% Total Zn: 16% Diss Zn: negative Total Pb: 15% Total Aluminum: 16% Total Cu: 2% TP: 45% Nitrate-N: negative		based on both monitoring and field experience. One additional improvement would be to place more biofilters off-line to treat the water quality design storm. Key Biofilter design criteria: • geometry (gentle slopes, parabolic or trapezoidal shape, sideslopes no greater than 3:1) • longitudinal slope (2 to 4%, check dams should be installed if slopes exceed 4% and underdrains installed if slopes are less than 2%) • swale width (no more than 8 feet unless structural measures are used to ensure uniform spread of flow) • maximum residence time (hydraulic residence time for the 6 month 24 hour storm of about 9 or 10 minutes) • maximum runoff velocity (no more then 0.9 fps for 6 month, 24 hour storm, and no more than 1.5 fps for 2 year storm event) • mannings n value (use 0.20 for design) • mowing (routine mowing to keep grass in active growth phase and maintain dense cover) • grass height (should be at least two inches above design flow depth) • biofilter soils (sandy loam topsoil layer, with an organic matter content of 10 to 20%, and no more than 20% clay.) • water table (if seasonal groundwater table is within a foot of the bottom of the biofilter, then select wetland species.) • plant selection (grass species that produce a uniform cover of fine-hardy vegetation that

				can withstand the prevailing moisture condition. *Juncus* and *Scirpus* may be used if drainage is poor.) • landscaping (other plant material can be integrated into biofilter; but care should be taken to prevent shading or leaffall into swale. • Construction (use of manure mulching or high fertilizer hydroseeding to establish ground cover should be avoided during construction, as these can result in nutrient export.)
Schueler and Holland, 2000 (Practice) Article 116	Sixteen historical performance monitoring studies of grass swales were reanalyzed based on the open channel classification (drainage channel, grass channel, dry swale and wet swale).	(includes a summary of pollutant removal capabilities of 10 drainage channels and 6 water quality channels)		Open channels should be designed to increase the volume of runoff that is retained or infiltrated within the channel. Designs should be based on water quality volume not flow. Key design criteria for dry swale: • Design to retain full water quality volume over entire length • Pretreatment is required. For pipe inlets, 0.1 inch per contributing acre should be temporarily stored behind a checkdam. For lateral flows, gentle slopes or a pea gravel diaphragm can be used. • Modify soils to improve infiltration rate. Use 30-inch filter bed composed of 50% sand and 50% silt loam. • Filter beds are drained by perforated pipes to keep swale dry after storm events • Parabolic or trapezoidal shapes with gentle side slopes (3:1 or less), and bottom widths ranging from 2 – 8 feet.

				• Determine location of water table. If water table is within 2 feet of proposed swale bottom , a dry swale is not feasible.
Schueler and Holland, 2000 (Practice) Article 117 Goldberg, 1993	Two studies of biofilters in Seattle: one was a biofilter retrofit (Dayton Ave.) and one was designed as a conveyance channel but was constructed with dimensions similar to a wet biofilter (Uplands). Eight storm events were sampled for Dayton Ave. and 17 events for the Uplands.	Dayton Ave. TSS: 68% TP: 4.5% Soluble Reactive Phosphorus: 35% Bio-Active Phosphorus: 32% Nitrate-Nitrogen: 31% Total Pb: 62% Total Cu: 42% Diss Cu: 21% FC: -264 Oil/Grease: not detected Uplands TSS: 67% TP: 39% Soluble Reactive Phosphorus: -45% Bio-Active Phosphorus: -31% Nitrate-Nitrogen: 9% Total Pb: 6% Total Cu: -35% Total Pb: 6% Total Zn: -3%	Dayton Ave.: 30 – 80% of runoff infiltrated into soil	Pets and beavers were cited as source of bacteria in the Dayton Ave. biofilter. Poor design, construction and maintenance are cited as reasons for reduced pollutant removal Require performance bonds for biofilters to make sure they are correctly installed, vegetated and protected from construction sediment. Key design criteria: • Require pretreatment at upper end of bioflter • Limit longitudinal slopes to 1% or greater, unless it is intentionally designed as a wet biofilter. • Develop more specific design criteria for wet biofilters that govern ponding, wetland stabilization, check dams and other criteria. • Require stringent geo-technical testing prior to design and construction. • Train public works crews on the best techniques for maintaining the long-term performance of biofilters.
Stagge, 2006	Evaluated highway grass swales with a grass filter strip pretreatment area in Maryland.	EMC removal: TSS: 41-52% NO3: 56-66% Zn: 30-40% Pb: 3-11%	RR: 46-54% of total volume 22 rainfall events over 1.5 years	

		Cu: 6-28% Swales exported Chloride, and did not significantly effect nutrient concentrations		
Strecker et al, 2004	Review of 32 grassed swales and vegetated filter strip studies found in the International Stormwater BMP database	Mass Removal: TSS: 45-75% Average effluent concentrations were published for Cu, TP, Zn, but no PR rate was specified.	40% Runoff Reduction	PR variability was high for all BMPs in the database; however, effluent quality was less variable. PR appeared to be dependent on the quality of the influent runoff.

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INFILTRATION LITERATURE SUMMARY

(include applications of pervious pavement that demonstrate complete infiltration of runoff (no underdrains))

Study	**Description**	**Pollutant Reductions (PR)** (conc. based unless noted)	**Runoff Reduction (RR)**	**Implications for Design**
Barraud *et al.*,1999	Examined subsoil pollution concentrations from a newly installed infiltration basin and a 30 year old basin in a similar catchment area.	MASS BASED: Newer application: Zn: 54-88% Pb: 98% Older Application: Zn: 31% Cd: 29.5%		Over time there is a slight spread of pollution downward through underlying soils Older basin had detectable pollutant concentrations up to depths of 1m.
Bright, T 2007	Two field dune infiltration systems were installed in Kure Beach, NC to capture ocean outfall runoff from up to 1.3 cm of rainfall. Data was collected from 25 storms (rainfall 4-105mm). Runoff samples were compared to groundwater samples underneath DIS.	Calculated PR: FC: 99.3-100% E.Coli: 87-100% Note: For 23% of storms GW samples exceeded State bacteria standards. Lab Study: lower infiltration rates decreased E.coli conc. in effluent	Site L: 100% Site M: 95.9% (over entire study period)	For effective FC treatment, DIS system should be designed to treat runoff from smaller watersheds (<16 ac) and lower intensity storms
CWP, 2007 NPRPD v.3	Summary of the performance of 12 infiltration practices, including 3 infiltration trenches and 9 pervious pavement studies	Removal Efficiency: Q1-Q3 (median) TSS: 62-96% (89) TP: 50-96% (65) SolP: 55-100% (85) TN: 2-65% (42) NOX: -100 -82% (0) Cu: 62-89% (86) Zn: 63-83% (66%)		Infiltration removal efficiencies are high, mainly due to the large amounts of runoff reduction provided by these practices

		Bacteria: N/A		
Schueler and Brown, T.E. (2004). Appendix B, Manual 3				Pollutant removal can be increased by designing the filter to treat a larger WQv . Ideal tested infiltration rates for infiltration practices should be between 1.0 and 4.0 in/hr. Pretreatment practices, preferably two, prior to runoff infiltration is recommended. CDA should be nearly 100% impervious (with few fines or disturbed areas) and less than 1.0 acre in size. Design should be off-line and include cleanout pipes. When possible, underdrains or filter fabric on trench bottom should be avoided.
Schueler and Holland, 2000 (Practice) Article 101 Galli, 1993	A field survey on the performance of over 60 infiltration trenches and basins in MD.			Regular maintenance is important and should be performed regularly (particularly sump cleanout) Adequate pretreatment helps reduce clogging of trenches Setting a maximum ponding depth can reduce basin compaction Geotechnical and groundwater investigations for good soils and low water tables may increase infiltration performance.
Schueler and Holland, 2000	Survey of 23 infiltration basins in Puget Sound Basin of the Pacific Northwest. Basin soils had high infiltration rates and			Pretreat runoff to reduce sediment clogging in infiltration basins. Avoid installing basins in areas with a high water

(Practice) Article 102 Gaus, 1993	low clay contents. Most sites had experienced regular maintenance and inspections.			table. Basins located in coarse, gravelly soils demonstrated subsoil metal migration, potentially a source of GW contamination
Schueler and Holland, 2000 (Practice) Article 104 Pitt et al, 1994	Three year study of infiltration basins to evaluate potential GW contamination risks.			Pretreatment may lower GW contamination potential for several stormwater pollutants, particularly heavy metals, pesticides, and other organic coumpounds. Due to potential for GW contamination, runoff from CSOs, impervious area snowmelt, manufacturing and construction sites should be directed away from infiltration practices. Runoff from gas stations, vehicle maintenance operations, and large parking lots should be adequately pretreated prior to being infiltrated
UNH, 2007	Summary of 2 year pollutant removal data for various LID practices, including an ADS water quality and infiltration unit	% Removal: TSS: 99% TP: 81% Zn: 99% TPH: 99%		

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EXTENDED DETENTION LITERATURE SUMMARY

Study	**Description**	**Pollutant Reductions** (conc. based unless noted)	**Runoff Reductions**	**Implications for Design**
Barrett, 2005	Used data from the International Stormwater BMP database to analyze performance based on BMP design techniques			No relationship between basin depth and TSS removal was observed in the data set. Total metals removal was high. Little effect on bacteria and nutrient removal was observed. Percent reductions (if observed) were highly dependent on influent concentrations.
CALTRANS, 2004	Five extended detention basins were sited as part of this study, 4 unlined earthen and 1 lined concrete basin. All sites were located within the highway right-of-way and collected runoff exclusively from the highway.	Unlined only: TSS: 72% TN: 14% Particulate P: 39% TP: 39% Total Cu: 58% Total Pb: 72% Total Zn: 73% Percent removal in unlined basins was higher on a load basis due to RR through infiltration. Lined: TSS: 40% (ns) TN: 14% (ns) TP: 15% (ns)	40 % in unlined ED basins	Contributing watershed area should be at least 2 ha to reduce fixed costs and minimize clogging small orifices. Due to lower initial cost and better pollutant removal, use earthen (unlined) basins where possible and groundwater conditions allow.
CWP, 2007 NPRPD v3	Summary of the performance of 10 dry Ponds, including 3 quality control ponds and 7 dry ED ponds	Removal Efficiency Q1-Q3 (median) TSS: 18-71% (49) TP: 15-25% (20)		Dry ponds appear to be efficient at removing bacteria and TSS.

		Sol P: -8-8% (-3) TN: 5-31% (24) NOx: -2-36% (9) Cu: 22-42% (29) Zn: 1-59% (29) Bacteria: 83-92% (88)		
Hathaway et al, 2007a,b.	Two dry detention basins were monitored in Charlotte, NC. The basins treated runoff from commercial office parks, parking lots, and landscaped areas. The University basin had 5.9 ac CDA and I = 0.7. The Morehead basin had 3.8 ac CDA and I = 0.7	University: BOD: 22% COD: neg NH4: 29% NOx: 31% TKN: 2% TN: 13% TP: neg TSS: 39% Cu: 11% Zn: 32% Morehead: BOD: 18% COD: 33% NH4: 14% NOx: -11% TKN: 20% TN: 10% TP: -13% TSS; 65% Cu: 17% Fe: 68% Mn: 56% Zn: 34%		Pollutant removal efficiency was high for TSS, but lower for nutrients. Low TP removal was attributed to clean inflow. Based on these results, ED is recommended for TSS removal credit, but not nutrient removal credit in NC. Sedimentation is considered the dominant pollutant removal mechanism
Harper et al., 1999	Monitoring study of a dry ED pond with CDA=23.86 ac and	TN: neg% TP: 34%	9% ET. 71% infiltrated.	Migration through the filter system provided little additional removal for most parameters, with the

(NPRPD v3)	single-family residential land use (I=37%) in DeBary, FL. Pond contained a small filter system near the outfall structure. Concentration pollutant removal efficiencies of the pond measured 30-90% except for dissolved organic nitrogen, particulate nitrogen, total nitrogen, and BOD. Load removals were higher due to volume seepage to GW. The filter system reduced concentrations of ON and Particulate N, but increased concentrations of NH4-N, NO3-N, TP, OPO4, and Particulate P. TN concentrations were reduced 37% within the filter system.	TSS: 90% FC: 97% Metals: 33-76% Mass removal: TN:86% TP: 84% TSS: 99% BOD: 82% Heavy metals: 88-96% Large mass removal efficiencies were attributed to high runoff reduction through pond bottom seepage.	Individual rainfall events ranged from 0.03-4.70 cm (0.01-1.85 in), with avg of 0.9 cm (0.36 in) per rain event. 35 storm events monitored.	exception of TN.
Middleton and Barrett, 2006	In Austin, TX, the outlet of an existing detention basin was modified to allow for batch treatment of runoff and control over the hydraulic residence time. Significant reductions for TSS, total metals, COD, nitrate and nitrite, and TKN were observed, while an increase in dissolved copper and dissolved phosphate occurred.	Total Cu: 46% Total Pb:63% Total Zn:48% COD: 23% NOx: 70% DP:-12% TP: 7% TKN: 28% TSS: 91%	Sampled 5 storm events 2.3<P<10.5mm	
Schueler and Brown, 2004 Manual 3				Design should be a Wet ED or contain multiple cells. Pollutant removal can be increased by designing

(appendix B)				the ED pond to treat a larger WQv. Design should be off-line and not intersect with groundwater. Design should contain a sediment forbay and include constructed wetland elements. The flow path should be greater than 1.5:1(not less than 1:1). The pond SA/CDA ratio should be greater than 2%
Schueler and Holland, 2000 (Practice) Article 76 Borden et al, 1997	Monitoring study of pollutant removal performance for 2 wet ED ponds in NC piedmont: one in a rural watershed (Davis), and one in an industrial watershed with 2x the impervious cover (Peidmont). Each CDA~ 2 sq.mi. Monitored storm and baseflow inflow/outflow for TSS, nutrients, TC, COD, bacteria and metals. Residence time of the Davis pond ~ 60 hrs and Piedmont pond ~ 8hrs	MASS REMOVAL: Davis: TSS: 60% TOC: 22% TP: 46% OPO4: 58% TN: 16% NO3: 18% FC: 48% Cu: 15% Pb: 51% Zn: 39% Piedmont TSS: 20% TOC: 27% TP: 40% OPO4: 15% TN: 30% NO3: 66% FC: neg		Davis pond (rural watershed) had higher algal production, which allowed for more nutrient uptake during the summer months, but then exported nutrients in the winter months. The longer residence time in this basin allowed for greater removal of TSS. The Piedmont basin had stormwater pretreatment

Schueler and Holland, 2000 (Practice) Article 77 Stanley, 1994	A dry ED basin was monitored in NC coastal plain. 200 ac CDA (I=0.29). Designed to treat 0.5” of runoff. The basin demonstrated high removal rates of particulate nutrients, but low removal rates of soluble nutrients.	(0.5”<P<2”) TSS: 71% TN: 17% TP: 23% Cd: 0% Cr: 60% Cu: 35% Pb: 63% Zn: 40%	30% from a 9.8” event.	Pollutant removal during the large event was still positive, despite the large volume of overflow. This suggests that treating the first 0.5” of runoff is still effective, even during large events. Dry ED ponds can effectively remove particulate pollutants, but not soluble pollutants.
Strecker et al, 2004	Review of 24 detention basins found in the International Stormwater BMP database	Mass based: TSS: 55-75% Average effluent concentrations were published for Cu, TP, Zn, but no PR rate was specified.	RR:30%	PR variability was high for all BMPs in the database; however, effluent quality was less variable. PR appeared to be dependent on the quality of the influent runoff.

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FILTRATION LITERATURE SUMMARY

Study	**Description**	**Pollutant Reductions** (conc. based unless noted)	**Runoff Reductions**	**Implications for Design**
Aulenbach and Chan (1988)	Laboratory experiment that examined sand filtration removal rates of TOC, TP, and heavy metals from applied wastewater. (3.8 d x 100 cm long sand packed glass column). Phosphorous removal rates were very high. For trails where 2.0<pH<11.0, releases of metals from the filters were observed.	TOC: 20% TP: 99% Cd: 15% Cu: 25% Pb: 35% Zn: 45% Addition of CaCo3 increased pollutant removal to ~50% (excluding Zn)		Mechanism responsible for P removal is primarily chemical precipitation. Sand filters should not be used to treat acid or base spills, due to the potential for metal leaching.
Barrett, 2003	Evaluated performance of 5 retrofitted Austin sand filters in southern CA in small watersheds (<1.1ac) with high impervious cover (56-100% I). Flow weighted composite samples were collected for storm events (no characterization of storms included in ref). Using linear regression techniques, effluent EMC was found to be *independent* of the influent EMC.	TSS: 90% NO3: -74% TN: 22% TP: 39% Cu: 50% Pb: 87% Zn : 80% *TPH: 25-30% *FC: 65% * grab sample, not EMC		Percent removal may not be an accurate characterization of sand filter performance, particularly for runoff with high influent pollutant concentrations. Author suggests it may be better to characterize performance by an “expected effluent concentration.”
CWP, 2007 NPRPD v.3	Summary of performance for 18 filtration practices: 7 organic filters and 11 sand	Removal Efficiency Q1-Q3 (median) TSS:80-92% (86)		Filters are very effective at reducing TSS and heavy metals, but do tend to export nitrates (although not TN).

	filters.	TP: 41-66% (59) solP: -11-63% (3) TN: 30-47% (32) NOx: -70-21% (-14) Cu: 33-67% (37) Zn: 71-91% (87) Bacteria: 36-70% (37)		
Nielsen *et al.*, 1993	A laboratory study that evaluated pollution removal in sand filter columns.	30-45% nitrogen removal and 40-60% phosphorous sequestration. 70-90% phosphorous sequestration rates were achieved by sands containing natural iron compounds		Removal of P was determined to be the result of chemical precipitation.
Schueler and Brown, 2004. Appendix B, Manual 3				Pollutant removal can be increased by designing the filter to treat a larger WQv. Filters can be used to treat severe pollution sites or hotspots. For additional pollutant removal (not N/P), an organic media can be used in filter bed. A wet pretreatment practice (for at least 25% WQv) is recommended. Filter bed should be exposed to sunlight and sized as >2.5% CDA. Design should be off-line and include storm bypass and an easy maintenance access.

				Designs should be above ground (except MCTT).
Schueler and Holland, 2000 (Practice) Article 105 City of Austin, 1990	Performance review of various types of sand filters.	High removal rates (> 75%) of TSS, TOC, Pb, Zn, and ON, and variable removal rates (20-75%) of FC, NH4, OPO4, and Cu have been documented TP: 19-80% TN: 31-71%		Pollutant removal can be improved by adding an organic layer to the filter bed. Designing an anaerobic zone in the bottom of a filter bed may promote denitrification, and potentially increase nitrate removal. Sand filters must be regularly maintained to prevent clogging and failure.
Schueler and Holland, 2000 (Practice) Article 106 COA, 1997 LCRA, 1997 Leif, 1999 Davis et al, 1998	Review of peat sand and organic sand filters.	Basic sand filter removal rates (no peat or compost) TSS: 80% TP: 40% Metals: 60% Barton Creek sediment/sand system TSS: 89% TN: 17% TP: 59% 2 peat systems: TSS: 88, 84% TN: 51, 30% TP: 47, 48% NO3: negative Compost Filter: TSS: 43% TP: neg Soil/Mulch filter (MASS BASED): TP: 65%		Organic filter media can effectively reduce hydrocarbons and metals, and should be considered for treatment of hotspot runoff. Decomposition of this layer can export NO3 and OPO4. TP removal can be boosted to 60-70% removal by using soil filtration. Peat filters can potentially remove up to 50% of TP. Vertical sand filters should be avoided, due to rapid clogging rates.

		TN: 49%		
Schueler and Holland, 2000 (Practice) Article 107 Horner, 1995 Bell et al, 1995	Assessment of a DE sand filter performance.	Concentration removal for 2 Seattle filters: TSS: 83, 8% Oil and Grease: 84, 69% Hydro: 84%, 55% TP: 41, 20% Zn: 33, 69% Cu:22, 31% Mass removal rates: for a filter in Alexandria, VA TSS: 79% TOC: 66% TP: 63% OPO4: 63% TN: 47% NOx: -53% TKN:71% Zn: 91% Cu:25%		A relationship exists between pollutant removal efficiency and inflow pollutant concentrations. The sand layer in a filter system should be designed with positive drainage to prevent areas from becoming anaerobic and releasing previously captured phosphorus. If runoff contains TOC, increased N removal may be possible by designing a layer of flooded gravel below the sand filter. When possible, sand filters should treat runoff from 100% IC watersheds, to reduce possibility of failure due to clogging.
Schueler and Holland, 2000 (Practice) Article 109 Stewart, 1992	Performance review of an organic leaf compost filter.	TSS: 95 TDS: -37% COD: 67% TP: 41% OPO4: negative ON: 56% NO3: -34% Zn: 88% Hydro: 87% Cr: 61%		Higher pollutant removal rates may be attained by increasing SA or storage volume of filter. Compost should be removed and replaced annually.

		Cu: 67% Pb, Cd: no difference		
Schueler and Holland, 2000 (Practice) Article 111 Pitt, 1996	MCTT design utilizes screening, settling, and filtering in underground chambers to effectively treat pollutants in hotspot runoff.	Mass Based: TSS: 85-98% TP:50-84% Zn: 71-93% Cu: 43-89%		MCTT can be used to treat runoff in areas where there is limited space for surface filters. Tests have shown high removal rates of TSS, nutrients, metals, and hydrocarbons. The screening process does not remove pollutants, but rather captures larger materials to reduce maintenance concerns.
Strecker et al, 2004	Review of 30 media filter studies found in the International Stormwater BMP database	Mass Based: TSS: 80-90% Average effluent concentrations were published for Cu, TP, Zn, but no PR rate was specified.	No runoff reduction	PR variability was high for all BMPs in the database; however, effluent quality was less variable. PR appeared to be dependent on the quality of the influent runoff.

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STORMWATER WETLANDS LITERATURE SUMMARY

Study	**Description**	**Pollutant Reductions** (conc. based unless noted)	**Runoff Reduction**	**Implications for Design**
CWP, 2007 NPRPD v.3	Evaluation of 40 wetland studies, including 24 shallow marshes, 4 ED wetlands, 10 pond/wetland systems, and 2 submerged gravel wetlands	Removal Efficiency: Q1-Q3 (median) TSS: 46-86% (72) TP: 16-76% (48) SolP: 6-53% (25) TN: 0-55% (24) NOx: (22-80% (67) Cu: 18-63% (47) Zn: 31-68% (42) Bacteria: 67-88% (78)		
Hathaway et al, 2007a	A 0.32 ac stormwater wetland was analyzed for pollutant removal performance in Charlotte, NC. CDA was 15.8 ac, I=0.6	FC: 70% Oil and Grease: 15% NH4: 55% NOx: 20% TKN: 35% TN: 35% TP: 45% TSS: 55% Cu:5% Zn: 55%	RR: Negative	Overland flow may have contributed to additional pollutant loadings to wetland. The pollutant removal rates represent the best estimates. TSS removal ranged between 50 and 66%, with an estimated reduction of 55%, well below the state standard of 85% TSS removal. According to authors, 85% TSS removal is a likely an overestimation of what *any* BMP can reliably remove.
Hathaway et al, 2007b.	A 0.5 ac wetland with an avg depth of 1.5 ft in Charlotte, NC, was monitored for pollutant removal performance. The drainage watershed Mainly consisted of single family homes.	FC: 99% E-coli: 92% BOD: 82% COD: 63% NH4: 62% NOx: 62% TKN: 41% TN: 45% TP: 45% TSS: 15%	RR: negligible	The observed 45% TN and 45% TP removal was at or above the NC State standard for these nutrients.

		Cu: 57% Fe: neg Zn: 71% Pb: 32%		
Li et al, 2007	A laboratory study investigated the TSS removal in 4 wetland cells: three having different densities of well-established vegetation, and one without any vegetation. All cells contained a 0.4 m thick sandy loam layer. A simple non-linear two-parameter regression model is defined for prediction of TSS trapping efficiency in constructed stormwater wetlands.			Confirmed that sediment concentration decreases exponentially with distance travelled. TSS removal was not dependent on vegetation density, flow turbulence, or shear flow velocity. Particle diameter, and flow characteristics (flow rate and velocity) had the greatest influence on TSS removal.
Schueler and Brown, 2004 Appendix B, Manual 3				Use pond-wetland or multiple cell design Should exceed target WQv by more than 50% Use complex wetland micro-topography Should exceed target WQv by more than 25% Flow path should be greater than 1.5 to 1 Wooded wetland design is a benefit Off-line designs preferred
Schueler and Holland, 2000 (Practice)	A study comparing the pollutant removal performance between two stormwater wetlands in the coastal plain of	MASS BASED: TSS: 65.0% OPO4: 68.7% Total Diss Phosphorus:		Authors expected better overall removal rates and attributed it to the fact that the sand substrate did not contain enough organic matter to trap pollutants.

Article 89 Athanas and Stevenson, 1991	Maryland – one site had been planted with wetland vegetation and the other had volunteer colonization.	44.3% Total OP: -5.7% TPP: 7.2% TP: 39.1% NOx: 54.5% NH4: 55.8% Total ON: -5.4% Total Particulate Nitrogen: -5.0% TN: 22.8% Numbers are from the planted site only. Percent mass reduced for both storm and baseflow events over 23 months		The planted species survived well but invasive species did appear. The volunteer site was completely dominated by cattail and phragmites. It appears that intentional planting has value.
Schueler and Holland, 2000 (Practice) Article 90 OWML and GMU, 1990	A study on the performance of a small stormwater wetland (created within an existing detention basin) over a 2-year period. Storm event and baseflow monitoring were performed and biomass was examined for nutrient dynamics.	MASS BASED: Small Storms: OPO4: 59% Total Soluble Phosphorus: 66% TP: 76% NH4: 68% TSS: 93% TKN: 81% NOx: 68% TN: 76% All Storms: OPO4: -5.5% Total Soluble Phosphorus: -8.2% TP: 8.3% NH4: -3.4% TSS: 62.0%		The wetland was found to be effective in removing nutrients and sediment during small storm events (runoff volumes < 0.1watershed inches of storage provided by the wetland) but ineffective during larger storms. Stormwater wetlands need an appropriately sized treatment volume to remove pollutants from larger storm events. Sediment forebays help to prevent sediment deposition and resuspension. A wide range of depth zones promotes rapid establishment of diverse wetland species.

		TKN: 15.0% NOx: 1.2% TN: -2.1% Smaller storms had higher mass removal. Larger storms had smaller or negative removal rates.		
Schueler and Holland, 2000 (Practice) Article 91 Hey et al, 1994 Mitsch et al, 1995	Two independent studies were done to analyze the ability of off-line wetlands to remove sediment and nutrient levels from river runoff. Four wetlands were constructed in the floodplain of the Des Plaines River, located near Chicago. Water from the river was pumped into the wetlands and sampling occurred at the inlet and outlet of each wetland. Summarizes pollutant removal data presented by Hey et al., 1994a and Mitsch et al., 1995.	These numbers show the range over two years and represent percent removal efficiency based on mass balance and flux. TSS: 77%-99% Nitrate-N: 39%-99% TP: 53%-99%		In the first two years the pollutant removal efficiency was high. The third year yielded lower phosphorus removal rates prompting the question of whether wetlands have a limited life span for pollutant removal. Need to continue long-term monitoring. The off-line riverine wetlands were found to be beneficial for pollutant removal and wildlife habitat. Consideration must be given to designing these systems so they don't raise local flood elevations. Also, they will require maintenance and power to pump water to and from the river.
Schueler and Holland, 2000 (Practice) Article 97 Egan et al, 1995	In this study, the ability of crushed concrete and granite rock wetland cells to remove pollutants was evaluated for 15 simulated storm events. The cells were part of a larger treatment train, the first components providing some pretreatment. The results indicate that these cells can be an effective enhancement to	MASS REMOVAL: TSS: 81% TOC: 38% TKN: 63% NO3: 75% TN: 63% OPO4: 14% TP: 82% Cd: 80% Cr: 38% Cu: 21%		The rock surfaces were believed to be the key factor in pollutant removal by creating substrate area for epilithic algae and microbes, reducing flow rates and providing more contact surfaces. Recycled crushed concrete cells performed better than granite rock perhaps due to the higher pH promoting greater epilithic algae and bacterial growth. To prevent clogging or sediment deposition, the

	stormwater wetland designs, especially in coastal regions where greater nitrogen removal is desired.	Pb: 73% Zn: 55% FC: 78%		cells should be located off-line and protected by pretreatment cells.
Strecker et al, 2004	Review of 29 wetland basins found in the International Stormwater BMP database	Mass based: TSS: 70-75% Average effluent concentrations were published for Cu, TP, Zn, but no PR rate was specified.	RR: 5%	PR variability was high for all BMPs in the database; however, effluent quality was less variable. PR appeared to be dependent on the quality of the influent runoff.

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WET PONDS LITERATURE SUMMARY

Study	**Description**	**Pollutant Reductions** (conc. based unless noted)	**Runoff Reduction**	**Implications for Design**
Barrett, 2005	Used data from the International Stormwater BMP database to analyze performance based on BMP design techniques			Emergent vegetation around the pond perimeter is responsible for a small percentage of overall nutrient and metal removal (<5%). Larger permanent pools (Sized to capture 4-6x the runoff from mean rainfall events) reduce dissolved P, but had little effect on other pollutants. Removal of N and P tends to decline in winter months.
CALTRANS, 2004	One wet basin was sited as part of this study. The site was located within the highway right-of-way and had CDA of 1.7 ha, I=0.47, collected highway runoff.	Storm Reductions: TSS: 94% NO3: 77% TN: 51% TP: 5% (ns) Total Cu: 80% Total Pb: 76% Total Zn: 41% Baseflow Reductions: TSS: 21% (ns) TN:43% TP: 49% (ns) Total Cu: 54% (ns) Total Pb: 62% (ns) Total Zn: 62%		Locate, size, and shape wet basins relative to topography and provide extended flow paths to maximize pollutant removal potential.
CWP, 2007 NPRPD v.3	Summary of 46 wet pond studies, including 12 wet ED ponds, 1 multiple pond system, and 30 wet ponds.	Removal Efficiency: Q1-Q3 (median) TSS: 60-89% (80) TP: 39-76% (52) SolP: 41-74% (64) TN: 16-41% (31)		

		NOx: 24-67% (45) Cu: 45-74% (57) Zn: 40-72% (64) Bacteria: 52-94% (70)		
Guo, 2007	An existing detention basin in NJ was retrofitted to an extended detention basin-surface wetland system, to have flood control and pollutant removal functions. Performance was field monitored, and the system was found to be effective.	TSS: 48% TP: 51% Influent TSS concentrations were low, which resulted in lower TSS removal efficiency.	7 monitored storm events $7.4<P<76.5$mm	The extended detention- wetlands system effectively removed TSS and TP from stormwater runoff. The system required no or minimal maintenance over a long period of time.
Hathaway et al, 2007a	Monitoring was performed on a residential pond in Charlotte, NC, estimated to be 50-70 years old. CDA was 120 ac of commercial and residential development. Pond was 1 ac with avg. depth 3-6 ft.	BOD: 45% COD: 42% NOx: 45% TN: 23% TP: 41% TSS: 56% Cu: 40% Mn: negative Zn: 49% Pb: 26%	negligible	The studied pond removed TN and TP with efficiencies of 23% and 41%, respectively. TSS removal was 56%, lower than the state of NC recommended 85%. 85% TSS removal is unlikely for ponds sited in clayey watersheds Aged ponds are able to provide substantial stormwater treatment for various nutrients, sediment, pathogens, and metals. The establishment of a diverse, dense plant community around the perimeter of the pond may increase nutrient removal. This may also discourage water fowl activity, potentially reducing organic nutrient and pathogen inputs.
Hathaway et al, 2007b	In Charlotte, NC, performance of an urban wet pond was studied. The CDA of the pond	NH4: 22% NOx: 74% TKN: negative TN:19%	negligible	Removal efficiencies of TSS, TN, and TP were 63%, 19%, and 15%, respectively. TSS removal was lower than the 85% removal

	was 27.3 ac and consisted of commercial, residential, and transportation land uses. I=0.86. Wet pond was 0.6 ac with an average depth of 3 ft.	TP: 15% TSS: 63% Cu: 63% Fe: 49% Zn: 49% Pb: 18%		credit assigned to wet ponds by the state of NC.
Mallin et al, 2002.	Monitored performance of 3 wet ponds in Wilmington, NC for 29 months. One pond had high pollutant removal. The other two ponds were less effective; one experienced additional overland inflow which short-circuited pollutant contact time, and the other had high pollutant inflow from a golf course in the CDA.	Calculated removal: TN: 40% TP: 57% FC: 86%		A high length-to-width ratio and establishment of a diverse vegetation community is recommended to obtain better pollutant removal by maximizing inflow contact time with vegetation and organic sediments.
Rushton et al, 2002 (NPRPD v3)	Studied pollutant removal and runoff reduction of a wet detention pond in an agricultural basin in Ruskin, FL over a 4-year period. Influent runoff received pretreatment from a roadside ditch. The watershed was 85 ha and the pond was 5.8 ha. Influent and effluent samples were obtained to determine differences for event EMCs.	For 1998, 1999, 2000, and 2001, resp. TP: 37%, 63%, 52%, 46% TN: 28%, neg, 28%, 44% TSS: neg, neg, neg, 85% Load reductions were higher due to runoff reduction in the basin.	25% RR (45% if rainfall is considered as an input) 8% loss due to evaporation, 15% to seepage	Runoff coefficient was 0.4 for storms greater than 2.0 in. TP effluent concentrations, although lower than influent, were still above national standards.
Schueler and				Use wet ED or multiple pond design

Brown, 2004 Appendix B, Manual 3				Should exceed target WQv by more than 50% Should exceed target WQv by more than 25% Use off-line design Flow path should be greater than 1.5 to 1 Use sediment forebay at major outfalls Wetland elements should cover at least 10% of surface area
Schueler and Holland, 2000 (Practice) Article 73 Wu, 1989	In this study, the role of permanent pool volume on pollutant removal performance is examined. Investigators found that the pond with the larger permanent pool volume performed better than the smaller pond with >80% removal of TSS and some metals. However, the performance of the larger pond in removing nutrients was modest, only 10% higher. It was speculated that a large population of geese at the larger pond could have reduced its efficiency. Short-circuiting and low inflow concentrations were also cited as reasons. Dry weather	Mass Removal: Lakeside Pond Drainage area: 65 acre Volume: 38.8 acre-ft Mean Depth: 7.9 ft Equiv. watershed storage: 7.1 inches TSS: 93% TP: 45% TKN: 32% Zn: 80% Fe: 87% Runaway Bay Drainage area: 437 acre Volume: 12.3 acre-ft Mean Depth: 3.8 ft Equiv. watershed storage: 0.33 inches TSS: 62% TP: 36% TKN: 21%		Satisfactory pollutant removal performance could be achieved if wet ponds were sized to be at least 2% of the contributing drainage area, with an average depth of six feet. Treatment volume alone does not guarantee good performance – need to provide good internal geometry and pondscaping to discourage large geese populations.

	sampling yielded higher nutrient levels than during storm events. Eleven storm events were monitored, ranging from 0.5” - 3.6” of rainfall.	Zn: 32% Fe: 52%		
Schueler and Holland, 2000 (Practice) Article 72 Urbonas et al, 1994	A study of the pollutant removal performance of a stormwater pond/wetland system. The watershed draining to the system was 550 acres. Runoff entered the wet pond then exited over a spillway and into a series of six cascading wetland cells. In general the combined system worked effectively with the bulk of the pollutant removal coming from the pond. The wetland cells provided pollutant removal during dry periods where the pond tended to be an exporter. Thirty six storm events were samples over a three year period during the growing season (May to September).	Mass Removal: By Wetpond- TP: 49% Dissolved P: 32% Nitrate-Nitrogen: -85% Organic- Nitrogen: 32% TN: -12% Total Copper: 57% Diss Cu: 53% Total Zn: 51% Diss Zn: 34% TSS: 78% Mass Removal: By Wetland- TP: 3% Diss P: 12% Nitrate-Nitrogen: 5% Organic- Nitrogen: -1% TN: 1% Total Cu: 2% Diss Cu: -1% Total Zn: 31% Diss Zn: -5% TSS: -29% Mass Removal:		Greater pollutant removal rates are achieved by having multiple and redundant treatment systems. Dry weather sampling should not be neglected in pond systems serving large drainage areas.

		By System TP: 51% Diss P: 40% Nitrate-Nitrogen: -76% Organic- Nitrogen: 31% TN: 19% Total Cu: 57% Diss Cu: 58% Total Zn: 66% Diss Zn: 30% TSS: 72%		
Schueler and Holland, 2000 (Practice) Article 70 Leersnyder, 1993	A study on the pollutant removal capacity of a pond/marsh system at an industrial site in New Zealand. The system was found to be very effective in the removal of sediment, nutrients and metals. However it was an exporter of ammonia and ineffective in removing COD. Six storm events were monitored.	Mass Removal: TSS: 78% TP: 79% Sol. Reactive Phosphorus: 75% Nitrate: 62% NH4: -43% COD: 2% Total Cu: 84% Total Pb: 93% Total Zn: 88%		A large treatment volume and good design features (oil trap at inlet, long flow path, submerged berm, shallow marsh zone, micropool at outlet) were cited as the reasons for effective pollutant removal.
Strecker et al, 2004	Review of 33 retention ponds found in the International Stormwater BMP database	Mass based: TSS: 60-95% Average effluent concentrations were published for Cu, TP, Zn, but no PR rate was specified.	RR: 7%	PR variability was high for all BMPs in the database; however, effluent quality was less variable. PR appeared to be dependent on the quality of the influent runoff.
Taylor et al, 2001	A wet pond in San Diego County, CA, was	TSS: 94% NO3-N: negative		Vegetation in and around the basin provides for enhanced solids, and potentially dissolved

	constructed as a retrofit project to treat highway stormwater runoff from a 4.2 ac CDA. The pond was designed to capture the 1-yr, 24hr rainfall event (1.34 in) and have a 24 hr drawdown time (orifice d=3in). The wet pond demonstrated high removal of TSS and metals, and low nutrient removal, particularly for nitrate. Nitrate and TN concentrations did decrease in the dry flows.	TKN: 44% TN: negative TP: 29% Total Cu: 99% Total Pb: 99% Total Zn: 93% Diss Cu: 27% Diss Pb: 94% Diss Zn: 33% TPH-oil: 21% TPH-diesel: 92% FC: 100%		metal removal. Vegetation re-growth was most rapid after a harvest. The 3 in orifice remained submerged to avoid clogging by floating debris. There were no clogging problems observed during this one-year study.
Teague and Rushton, 2005 (in NPRPD)	A filter pond treated parking garage and throughfare runoff a from 10.4 ac watershed. N and P concentrations were reduced in the system, but effluent concentrations remained above water quality standards.	The effluent filtration system was effective in reducing metals and suspended solid loads, but not successful in reducing soluble nutrients.	negligible	Provide some pre-treatment to further reduce metals, oils, and greases. Clean out the concrete lined sedimentation basin and vacuum out underdrain pipes at least once a year to remove pollutants. Restrict mowing too close to littoral zone vegetation. Use material in the filter system designed to remove nutrients.

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APPENDIX G:
DERIVATION OF EVENT MEAN CONCENTRATIONS FOR VIRGINIA

1. Introduction -- Adjusted Virginia Event-Mean-Concentrations

The Center for Watershed Protection (CWP) analyzed the National Stormwater Quality Database (NSQD) version 1.1 to compare Virginia and National Event Mean Concentrations (EMCs) derived for total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS). Statistical trends were examined for the EMCs based on land use (residential/non-residential) and physiographic province (Piedmont/Coastal Plain). Table 1 provides the EMCs for Virginia, as well as the National EMCs for comparison. The following sections discuss the methods and implications of this analysis, as well as recommended EMCs for inclusion in Virginia's stormwater management program.

Table 1. National vs Virginia Event Mean Concentrations

Parameter	**Median EMC (mg/L)**
Total Nitrogen	
National	1.9
Virginia	1.86
Residential	2.67
Non-Residential	1.12
Virginia Coastal Plain	2.13
Residential	2.96
Non-Residential	1.08
Virginia Piedmont	1.70
Residential	1.87
Non-Residential	1.30
Total Phosphorus	
National	0.27
Virginia	0.26
Residential	0.28
Non-Residential	0.23
Virginia Coastal Plain	0.27
Virginia Piedmont	0.22
Total Suspended Solids	
National	62
Virginia	40

2. EMC Statistical Analysis

Virginia entries were separated from the NSQD and compared to the remaining entries in the database (NSQD – VA data). A significant percentage (approximately 22%) of the NSQD sites are located within Virginia, supporting the feasibility of the statistical comparison. The number of entries used in the statistical analysis is summarized in Table 2. A list of Virginia jurisdictions where NSQD data was available and utilized is included in Table 3. The following criteria were used to determine the entries included in the analysis:

- All sites that contained best treatment practices (BMPs) within their drainage areas were excluded from the analysis to obtain EMCs for untreated stormwater.

- Only observations above the detection limit for each pollutant were included.
- All sites located east of I-95 were considered coastal plain and sites located west of I-95 were considered Piedmont.

Table 2. Number of NSQD Entries

	Virginia	National (NSQD – VA entries)
# Total Individual Sites	78	282
# Sites with BMP Treatment	11	3
# Sites included in the Analysis	67	279
# Observations Included in the Analysis	753	2834
	Piedmont	**Coastal Plain**
# VA Sites Included in the Analysis	23	44
# VA Observations Included in the Analysis	150	603

Table 3. Virginia Jurisdictions within the NSQD

Jurisdiction	# Sites
Arlington	2
Chesapeake	7
Chesterfield County	9
Fairfax County	6
Hampton	7
Henrico County	6
Newport News	7
Norfolk	9
Portsmouth	5
Virginia Beach	9

Two statistical tests were used to determine if the Virginia EMCs were significantly different from National EMCs; Mann-Whitney (two-tailed) and one-way ANOVA statistical tests. The ANOVA was available from the Analysis Tools Add-In for Excel and the Mann-Whitney was set up as a spreadsheet in Excel. For both tests, p-values < 0.05 indicate that the samples are statistically different at the 95% or greater confidence level. P-values for the Mann-Whitney test are generally obtained from a critical values table for the test when the sample sizes are less than 20. However, sample sizes exceeded 20 for all of the EMC comparisons conducted as part of this analysis. For these large sample sizes, the Mann-Whitney was approximated by a normal distribution

(z) and the p-value was obtained from a standard normal curve area table. The results of the Mann-Whitney and ANOVA are provided in Tables 4, 5, and 6, and the calculations are provided in Appendix A. Land use included in this analysis included residential, non-residential (institutional, commercial, industrial, and freeway), and open space. Entries from mixed land use classifications were categorized according to the highest percentage land use in the drainage area.

Table 4. VA Comparison to National Data

Parameter	Mann-Whitney p-value	ANOVA p-value	Significant Difference Between VA and National Data	# VA Samples	# National Samples
TN	0.0366	0.000289	yes	664	2463
TP	0.2302	0.00262	ANOVA: yes Mann-Whitney: no	651	2368
TSS	<4E-04*	2.87E-17	yes	662	2603
Residential TN	<4E-04*	0.004514	yes	363	1002
Residential TP	0.002	0.000124	yes	399	967
Residential TSS	<4E-04*	2.88E-10	yes	400	1070
Non-Residential TN	<4E-04*	9.30E-22	yes	288	1277
Non-Residential TP	0.9204	0.464218	no	247	1221
Non-Residential TSS	<4E-04*	3.20E-07	yes	256	1347
Open Space TN	<4E-04*	0.454971	ANOVA: no Mann-Whitney: yes	13	184
Open Space TP	0.1616	0.62312	no	5	180
Open Space TSS	0.009	0.164779	ANOVA: no Mann-Whitney: yes	6	186

**Approximated from the highest value (z = 3.49) in a standard normal curve area table*

Table 5. VA Land Use Comparison

Parameter	Mann-Whitney p-value	ANOVA p-value	Significant Difference Between Land Use Data	# Residential Samples	# Commercial Samples
Residential/Non-Residential TN	4E-04*	3.73E-75	yes	363	288
Residential/Non-Residential TP	0.0238	0.295137	ANOVA: no Mann-Whitney: yes	399	247
Residential/Non-Residential TSS	0.61	0.733315	no	400	256
				# Residential Samples	**# Open Space Samples**
Residential/Open Space TN	4E-04*	9.59E-04	yes	363	13
Residential/Open Space TP	0.0702	0.175480	no	399	5
Residential/Open Space TSS	0.1096	0.338883	no	400	6
				# Commercial Samples	**# Open Space Samples**
Non-Residential/Open Space TN	4E-04*	2.15E-08	yes	288	13
Non-Residential/Open Space TP	0.1528	0.465171	no	247	5
Non-Residential/Open Space TSS	0.1528	0.246322	no	256	6

**Approximated from the highest value (z = 3.49) in a standard normal curve area table*

Table 6. VA Coastal Plain / Piedmont Comparison

Parameter	Mann Whitney p-value	ANOVA p-value	Significant Difference Between Coastal Plain and Piedmont Data	# VA Coastal Plain Samples	# VA Piedmont Samples
TN	<4E-04*	7.06E-09	yes	538	126
TP	0.0024	0.100758	ANOVA: no Mann Whitney: yes	522	129
TSS	0.0048	0.670342	ANOVA: no Mann Whitney: yes	531	131
Coastal Plain				**# Residential Samples**	**# Non-Residential Samples**
Residential/Non-Residential TN	<4E-04*	5.35E-73	yes	298	235
Residential/Non-Residential TP	0.0308	0.166395	ANOVA: no Mann Whitney: yes	324	198
Piedmont					
Residential/Non-Residential TN	<4E-04*	2.10E-22	yes	65	53
Residential/Non-Residential TP	0.6818	0.435501	no	75	49

**Approximated from the highest value (z = 3.49) in a standard normal curve area table*

The results show a significant difference between Virginia EMCs and National EMCs. Appendix B contains the median EMCs for all sample categories included in the statistical analysis. From the analysis, the following observations were made:

- VA has lower median EMCs for TN, TP, and TSS than the national data.
- Within VA, residential areas contain higher median TN, TP, and TSS EMCs than non-residential areas. Analysis of open space areas was disregarded due to limited data available in those locations.
- Within VA, the Coastal Plain contains higher median TN, TP, and TSS EMCs than the Piedmont physiographic region.
- TN- The following EMCs are significantly different within VA: residential/non-residential; Coastal Plain/Piedmont; Coastal Plain residential/non-residential; and Piedmont residential/non-residential.
- TP- The following EMCs are significantly different within VA: residential/non-residential; and Coastal Plain/Piedmont.
- TSS- While VA has lower median TN, TP, and TSS EMCs than the National median EMCs; no difference exists between residential/non-residential areas or Coastal Plain/Piedmont regions within the state. It is important to keep in mind that stream bank erosion is the main component of TSS within streams/rivers, as opposed to input from stormwater runoff.

3. Land Use loading Rates

The adjusted EMCs for Virginia were used to update previous land use loading rates (pounds/acre/year). Previous land use loading rates (Table 5-15 from the Virginia Stormwater Management Handbook) are presented in Appendix C, as well as updated rates based on the adjusted EMCs. The loading rates were computed using the Simple Method computation for Virginia by using residential and non-residential EMCs. Figures 1 and 2 show the original loading rates, as well as the adjusted loading rates for TN and TP.

Figure 1. Annual Total Nitrogen Load Calculated from the Simple Method

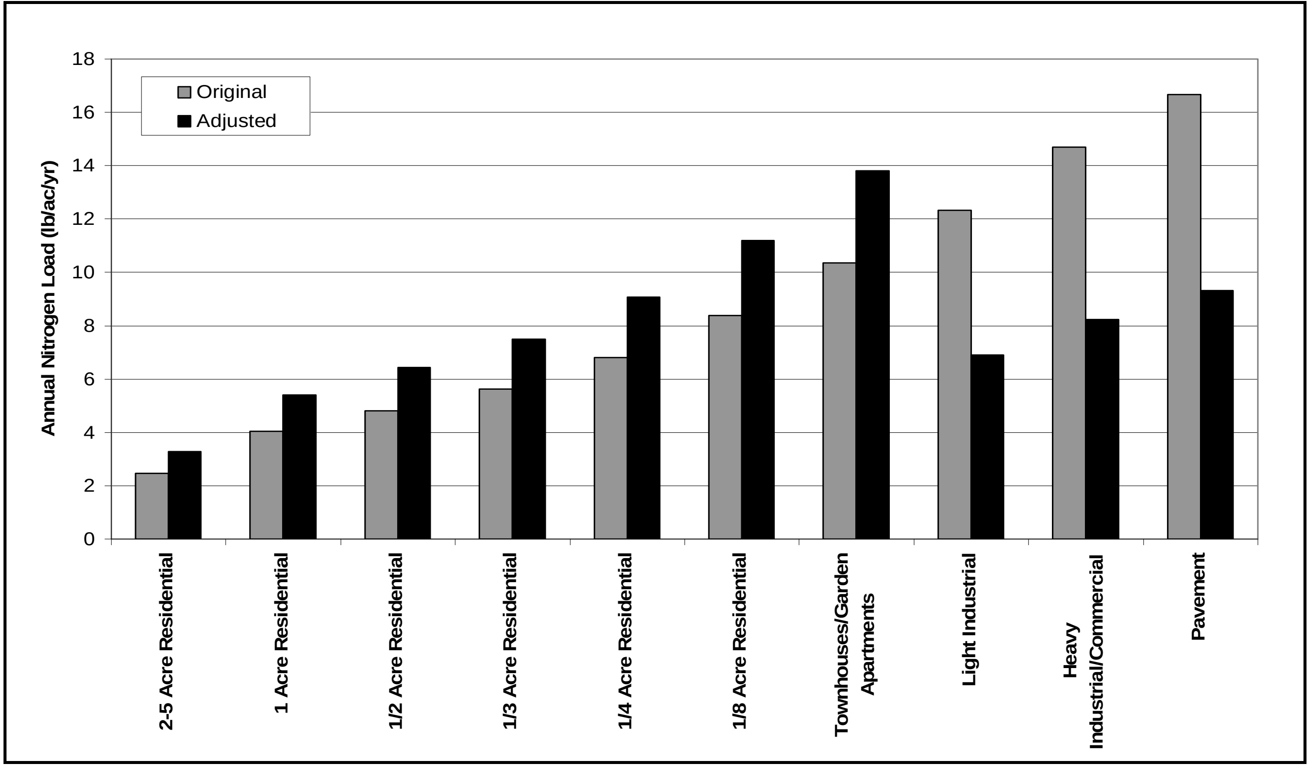
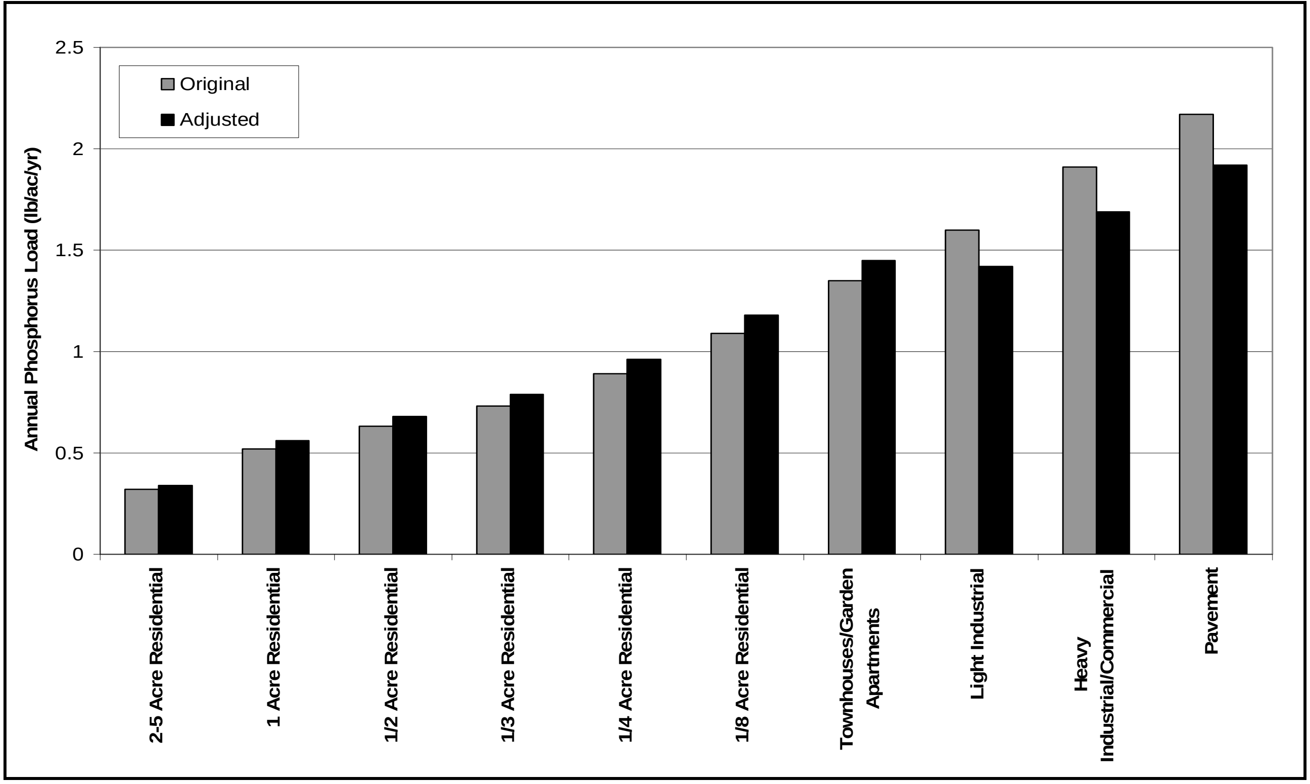


Figure 2. Annual Total Phosphorus Load Calculated from the Simple Method



4. Conclusions and Recommendation

Based on the statistical analysis, the options listed below for TN and TP are available for adjusting Virginia EMCs. As was previously mentioned, open space was not included in these recommendations due to the limited amount of data available for the statistical analysis. TSS was also disregarded because input from stormwater runoff is minimal in comparison to streambank erosion.

In Virginia, there is a statistically significant difference between residential and non-residential sites, particularly for TN. This provides justification for using different EMCs for the two categories of land use. Since the EMC for non-residential is lower, it also means that commercial sites have somewhat of a compliance “handicap,” which is balanced by their generally higher levels of impervious cover.

Total Nitrogen
Option 1: Virginia Residential and Non-Residential EMCs – National EMCs were not considered an option based on the statistical analysis results that Virginia TN EMCs are significantly different than the National TN EMCs.
Option 2: Virginia Coastal Plain/Piedmont Residential and Non-Residential EMCs – While this option is statistically supported, it results in four EMC options and may be too complicated for utilization. The Piedmont also results in a lower standard and there may be equity problems with having Piedmont and Coastal Plain sites achieve different standards. Finally, since there is no data from the “mountain” physiographic provinces, there is no basis to recommend an EMC for those areas other than the State-wide numbers.

Total Phosphorus
Option 1: National EMC
Option 2: Virginia EMC
Option 3: Virginia Residential and Non-Residential – The national data provides justification that residential TP is greater than non-residential TP. This option would provide an incentive for compliance.

The recommended approach is to use Virginia residential and non-residential EMCs for both TN and TP due to the feasibility of implementation and the supporting data in the analysis.