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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