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Hydraulic performance of grass swales for managing highway runoff

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ABSTRACT

The hydraulic performance of grass swales as a highway stormwater control measure was evaluated in a field-scale study adjacent to a Maryland highway. Two common swale design alternatives, pretreatment grass filter strips and vegetated check dams, were compared during 52 storm events over 4.5 years. Swale performance is described via three regimes, dependent on the relative size of the rainfall event. Overall, half of the events were small enough that the entire flow was stored, infiltrated, and evapotranspirated by the swales, resulting in no *net* swale discharge. Swales significantly reduced total volume and flow magnitudes generally during events with rainfall less than 3 cm. While the majority of improvement can be attributed to the swales, inclusion of check dams increases swale effectiveness. Pretreatment grass filter strips produced mixed effects. The swales demonstrated essentially no volumetric reduction during large storm events, functioning instead as conveyance, and smoothing fluctuations in flow.

1. Introduction

Focus on the management and treatment of urban stormwater runoff through the use of stormwater control measures (SCMs) has risen considerably as the negative environmental impacts of increased imperviousness are becoming increasingly understood. Grass swales, shallow grass-lined channels, are one such SCM originally designed simply for stormwater conveyance. Commonly used on highway projects, swales represent a simple, aesthetically pleasing technique for conveying runoff along linear systems.

Historically, highway swales have been designed to convey runoff from the largest storm events quickly away from the roadway infrastructure. Because of this, highway swales commonly are not designed for smaller storm events (0.5–2.5 cm) that produce the majority of annual runoff in most areas (Schueler, 1994).

In addition to conveying stormwater runoff from roadway areas, swales may be capable of creating a hydrologic regime more similar to pre-development conditions. Total runoff volume is reduced through infiltration and storage; peak flows are lowered also through infiltration and flow retardance caused by increased channel roughness. Mean volume reduction due to roadside grass swales has been reported as 30% (Rushton, 2001), 45.7% (Deletic, 2001), 33% (Backstrom, 2002), 47% (Barrett, 2005), and 45% (Ackerman and Stein, 2008). A 10–20% reduction of peak discharges was noted in field studies by Wu et al. (1998) and supported by swale hydrologic models (Deletic, 2006; Ackerman and Stein, 2008). Because grass swales are largely an infiltration-based SCM, their effectiveness is closely related to the timing and magnitude of inflows, coupled with available storage and channel length of the swales. Consequently, complete or significant reduction in runoff volume will occur during small

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storm events. As would be expected due to soil saturation, volume attenuation during large or intense storms tends to be modest or even negligible (Schueler, 1994; Rushton, 2001; Yu et al., 2001; Deletic, 2006).

As the focus of stormwater design transitions from simple conveyance to quantitative treatment and management, it is increasingly important to identify key SCM design parameters and to link them to performance results. The goal of this study, therefore, is to quantify the overall performance of grass swales in improving runoff flow characteristics and to systematically evaluate the effects of several swale design alternatives at the field scale. The design alternatives include an adjacent vegetated filter strip and in-line vegetated check dams, both of which are recommended in several swale design manuals. Field-scale swales constructed in the median of a four-lane highway in Maryland, USA were monitored over the course of 52 storm events, spanning 4.5 years.

A thorough analysis of dynamic flow rates and total runoff volume was subsequently performed to determine the effects of the swales and their associated design alternatives. Swale response to differing rainfall event and design characteristics are evaluated using runoff volume probability plots, as in Davis (2008) and Li et al. (2009), and flow duration curves, which summarize dynamic flow response. In this manner, changes in swale effectiveness due to inflow magnitude and timing can be analyzed in greater detail.

2. Methods and materials

2.1. Site description

The monitoring location for this study was MD Route 32, a four-lane limited access highway near Savage, Maryland, USA. The land adjacent to the sampling area is wooded with nearby residential development; however, the roadway is raised such that runoff is generated solely by the roadway surface (Fig. 1). Two swales were constructed in the highway median to receive runoff laterally from the southbound roadway lanes. The first, designated FS, includes a 15.2 m sloped (6%) grass filter strip pretreatment area between the roadway and the swale channel, constructed based on state guidelines (MDE, 2000). The second swale, constructed just to the north, designated No-FS, was similarly constructed, but lacks a pretreatment filter strip area.

Both swales have identical cross-section designs (side slopes of 3:1 (33%) and 4:1 (25%) on either side of the swale), a 0.61 m bottom width, and approximately 1.4% longitudinal slope. Topsoil used in the swales was classified as loam or sandy loam, per the USDA soil texture classification system. Grass used for the swales and pretreatment area was initially composed of 90% tall fescue, 5% Kentucky bluegrass, and 5% perennial ryegrass. Both swales drain highway areas of 0.22 ha.

A concrete channel draining a 0.27 ha highway area (designated as HWY, Fig. 1, Table 1) was constructed directly adjacent to the highway shoulder, parallel to the highway. This design allows an accurate representation of instantaneous lateral input flow from the roadway surface without disrupting flow into the swales and is considered equivalent to the swale inputs. Sampling of the FS and No-FS swales (and HWY) occurred between November 2004 and May 2006.

After this monitoring period, each swale was modified by installing 2 sets of grass check dams along the swale centerlines (designated − CD). Each 1-m wide check dam was installed using three staggered rows of *Panicum Virgatum* ‘Heavy Metal’, a sturdy plant that remains standing in heavy rain or snow, planted 0.31 m on center with 26 plants total. Cross-sections remained identical to the original swale designs. Sampling of the FS-CD and No-FS-CD swales (and HWY-CD) occurred between April 2007 and July 2009.

2.2. Sampling program

Plywood vee-notch weirs were constructed at the terminus of each swale and the HWY channel to monitor flows. Weirs were built with a θ angle of 125° and C_e value of 0.585 (ASTM, 2001). ISCO Model 6712 Portable Samplers with bubble flow meters were installed in secured vaults adjacent to each weir. Because the swale design physically limited the location of the bubbler line to immediately adjacent to the weir, head was measured directly at the vee-notch, requiring a modification to include velocity head in the calculation of flows. Bubbler modules were zeroed prior to each storm event to ensure an accurate baseline and were checked to ensure that height measurements showed minimal variation with time.

Events were triggered when the head behind the weir reached 3.05 cm, corresponding to a flow of approximately 0.43 L/s. This flow rate is equivalent to a rainfall intensity of 0.64 mm/h, based on the HWY sampler with a drainage area of 0.271 ha and a Rational Method coefficient of 0.9. One ISCO 674 Tipping Bucket Rain Gauge with 0.254-mm sensitivity was installed on site and logged rainfall depth in 2-min increments.

2.3. Hydrology flow calculations and data evaluation

The volumes measured at each swale outlet include that from the highway and runoff generated from the swales themselves.

$$V_{total} = V_{highway} + V_{swale} \quad (1)$$

Therefore, to directly compare highway runoff and swale output, flows must be adjusted to account for the additional drainage area associated with vegetated areas (V_{swale}). Vegetated areas in the non-filter strip (No-FS, No-FS-CD) and filter strip swales (FS, FS-CD) increase the total drainage area by factors of 1.39 and 1.92, respectively. Thus, the contribution of rainfall landing directly on the swales to the water balance, V_{swale}, is estimated using the NRCS rainfall/runoff model. Excess runoff originating from rain directly onto the swales is calculated using a standard curve number of 86.7 based on average grassed area, curve number of 74, with a wet Antecedent Moisture Condition (AMC-III) adjustment. The antecedent moisture adjustment was employed because the swales are operationally in a saturated state, due to runoff from the highway. Using the measured rainfall and the areas of the swale, the excess runoff originating from the swale itself, V_{swale}, was calculated for each event. This excess volume is subtracted from swale discharge to produce

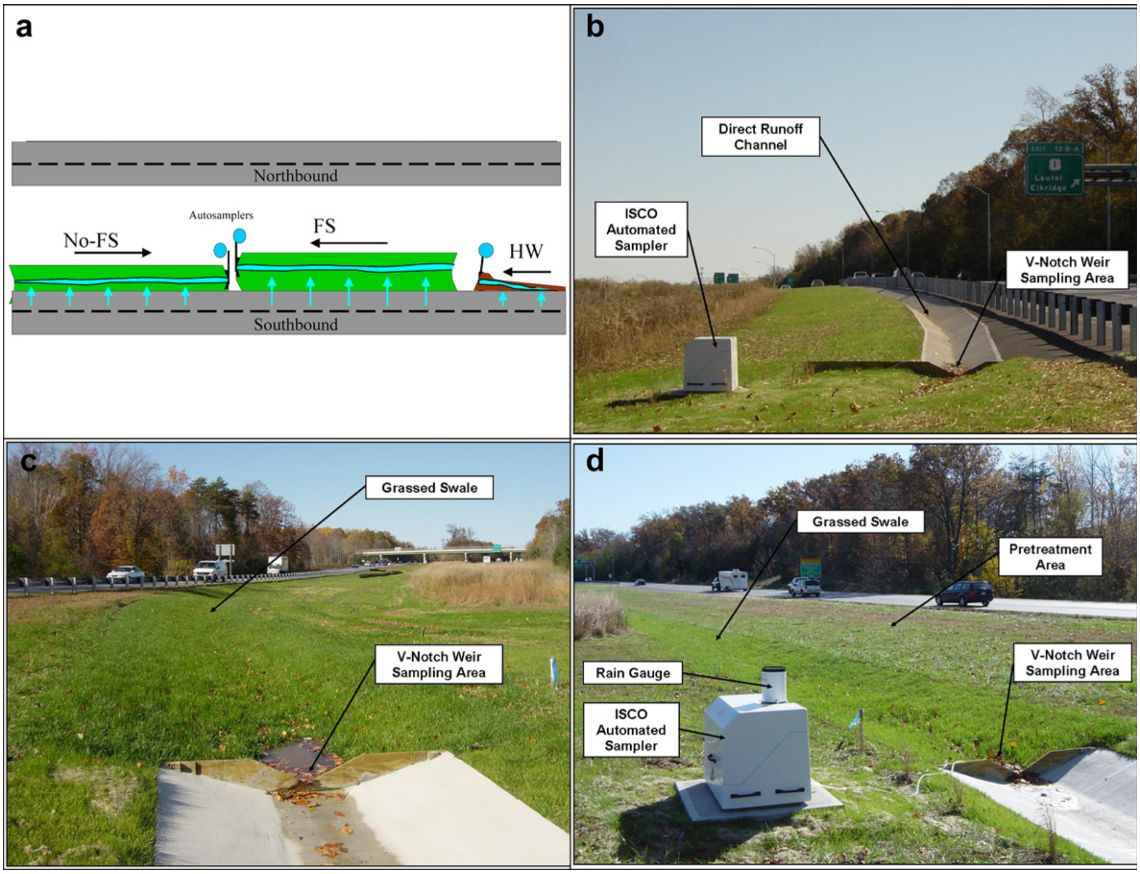

Fig. 1 – Diagram of a) Study site and photos of each channel monitoring area. b) HWY. c) No-FS swale. d) FS swale.

normalized swale discharge volumes, $V_{highway}$. The ratio of normalized volume to measured volume $V_{highway}/V_{total}$, was also employed to adjust instantaneous flow rates used in hydrographs and flow duration curves.

3. Results and discussion

3.1. *Sampled storm characteristics*

Sampled storm events appeared to be representative of the typical variability in rainfall depth and duration in Maryland. Rainfall depths varied between 0.15 cm and 17.32 cm, with median depths of 1.22 and 1.05 cm for the non-check dam and check dam events, respectively (Table 2). Storm durations ranged from 0.1 h to 27 h, with median durations of 7.0 (No-CD) and 5.3 h (CD).

The fractional distribution of storm depth/duration was compared to the historical distribution of rainfall events in Maryland (Kreeb and McCuen, 2003) to evaluate the representative nature of monitored events (Table 3). The top number of each cell in Table 3 contains the fraction of monitored storms of that given depth and duration; the lower numbers are the number of monitored storms in that category and the number of events completely captured by the swales, respectively.

Chi-Square goodness of fit tests were used to quantitatively compare the distribution of monitored storm events to the average historical distribution of Maryland storm events. Combined, the sampled storm events closely resemble the expected distribution for local storm events both with respect to duration ($\chi^2 = 12.62$, $p = 0.049$) and rainfall volume ($\chi^2 = 5.31$, $p = 0.26$). No-CD events closely resemble the historical distribution with respect to duration, but slightly over-represent the largest volume events ($\chi^2 = 12.62$, $p = 0.01$). Alternatively, CD storm events have a slight exaggeration of medium (4–13 h) duration events ($\chi^2 = 16.15$, $p = 0.01$) with a close fit for precipitation volumes. The additional focus on storms within these categories (medium duration, medium-large volume) allows for greater detail in analyzing the behavior of the swales as the performance varies under different storm event regimes.

The volumetric performance of the swales varied based on the size of the rainfall event. Smaller events were completely captured by the swales, producing no discharge. Larger events typically exhibited a volume reduction. However, with the largest storms, the swales demonstrated minimal reduction in volume and acted solely as flow conveyance facilities.

3.2. *Complete capture*

From a water balance perspective, the swales are expected to have a decreasing capacity for infiltration storage, with the maximum infiltration rate decaying asymptotically towards the saturated hydraulic conductivity of the soil. Once precipitation exceeds the maximum infiltration rate, surface flow, storage, and eventual discharge from the swale will result.

Table 1 – Swale and channel design characteristics.

	HWY	No-FS Swale	FS Swale
Roadway Area (ha)	0.271	0.224	0.225
Swale Area (ha)	0	0.312	0.431
Total Area (ha)	0.271	0.536	0.656
Channel Material	Concrete	Grass	Grass
Channel Slope	0.2%	1.6%	1.2%
Channel Length (m)	168	198	137
Filter Strip Slope	–	–	6%
Filter Strip Length (m)	–	–	15.2 (from roadway to channel center)

Stored water will infiltrate, which should beneficially contribute to groundwater recharge and baseflow, and some will evapotranspirate. Roadway runoff was completely captured during 9 of the No-CD storm events (36.5%) and 13 of the CD storm events (46.4%). An event is considered completely captured if the storm generates no measurable runoff at the swale outfall structures or net runoff volumes are less than zero following grass area contribution adjustment, as described in the Methods section. Specific events completely captured are shown in bold in Table 2.

A distinct separation between captured storm events and storms producing runoff is apparent when total rainfall is plotted against storm duration (Fig. 2). There is, however, no discernible difference between the swale designs when examined in this manner. Combining the data for No-CD and CD storm events, the boundary equation fit visually for the complete capture threshold is:

$$P = 0.07 \times D + 0.35 \text{ cm} \quad (2)$$

where P represents total rainfall (cm) and D represents storm duration (h).

This boundary equation delineates the threshold at which both swales transition from fully storing and infiltrating runoff to generating measurable flow. Interestingly, the 6/3/2005 event produced minor flow from the FS swale, but complete capture from the No-FS swale and is located almost directly on the complete capture line, suggesting a transitional zone surrounding the capture line. Applying an area ratio to account for the road surface, which receives rainfall but does not contribute to infiltration, results in the following equation:

$$P_{swale} = 0.112 \times D + 0.56 \text{ cm} \quad (3)$$

where P_{swale} represents the adjusted total rainfall (cm) the swale is subjected to and D represents storm duration (h).

Using Eq. (3), average infiltration rates for captured storm events are found to be between 1.5 and 0.3 cm/h, which are similar to swale design criteria that typically recommend infiltration rates of 1.27 cm/h (U.S. EPA, 1999; MDE, 2000). The adjusted slope, 0.112 cm/h, can be interpreted as the steady state infiltration rate, which is similar to published saturated hydraulic conductivity values for loam and sandy loam, 0.34 and 1.09 cm/h respectively (Rawls et al., 1983). The adjusted y-intercept, 0.56 cm, is an estimate of initial abstraction by the swale. Infiltration rates lower than published values can be attributed to the lack of constant head caused by unsteady rainfall.

Table 2a – Rainfall distribution and total volume summary statistics for non-check dam storm events. Events with complete runoff capture by swales are shown in bold type. Data for the No-FS swale was not recorded during the 1/13/2005 storm event due to sampler malfunction.

Date	Total Rainfall (cm)	Duration (h)	Total Runoff Volume (1000 L)		
			HWY	No-FS	FS
11/4/2004	3.15	11.8	70.4	50.9	204
11/12/2004	2.64	12.0	105	108	146
12/19/2004	0.18	4.2	16.8	7.7	4.5
1/13/2005	5.44	12.0	139		423
4/1/2005	5.69	27.0	77.7	398	365
5/19/2005	4.67	15.0	57.9	27.4	93.7
6/3/2005	1.55	16.4	52.0	0	43.1
6/27/2005	**0.43**	**2.5**	12.5	0	0
7/18/2005	**0.28**	**0.2**	8.1	0	0
8/5/2005	**0.48**	**0.2**	9.3	0	0
8/8/2005	0.89	4.7	28.0	7.2	0
9/26/2005	**0.25**	**2.5**	10.4	0	0
10/7/2005	17.32	13.0	639	1,208	872
10/21/2005	**0.23**	**0.3**	8.1	0	0
10/22/2005	1.80	19.0	74.8	68.3	104
10/24/2005	2.62	27.0	88.0	162	179
11/16/2005	1.83	6.2	74.4	33.5	71.3
1/11/2006	0.58	1.4	20.3	17.1	35.9
1/29/2006	**0.15**	**1.5**	9.4	0	0
3/1/2006	**0.25**	**4.2**	19.3	0	0
4/21/2006	**0.74**	**5.6**	36.0	0	0
4/22/2006	3.53	15.5	152	244	231
5/7/2006	**0.25**	**14.8**	13.1	0	0
5/11/2006	4.01	7.7	153	186	168

Table 2b – Rainfall distribution and total volume summary statistics for check dam storm events. Events with complete runoff capture by swales are shown in bold type.

Date	Total Rainfall (cm)	Duration (h)	Total Runoff Volume (1000 L)		
			HWY-CD	No-FS-CD	FS-CD
4/4/2007	1.02	5.3	41.4	62.0	20.6
5/12/2007	**0.43**	**0.4**	13.8	0	0
5/16/2007	1.83	1.8	48.4	58.6	26.5
6/3/2007	2.26	2.3	69.4	20.2	0
7/4/2007	1.65	1.7	48.5	25.9	29.6
9/11/2007	**0.51**	**0.5**	10.7	0	0
10/19/2007	**1.17**	**1.2**	38.1	0	0
10/24/2007	**0.69**	**0.7**	27.1	0	0
11/13/2007	**0.23**	**0.2**	7.0	0	0
12/2/2007	1.24	1.2	69.4	36.9	26.1
12/14/2007	2.06	2.1	123	349	151
1/10/2008	**0.23**	**0.2**	9.1	0	0
2/1/2008	4.75	4.8	214	488	234
3/4/2008	1.73	1.7	60.7	143	74.4
3/16/2008	1.02	1.0	41.2	36.7	15.3
4/26/2008	1.07	1.1	27.7	5.8	0
5/16/2008	1.80	1.8	328	111	56.4
6/3/2008	1.40	1.4	56.2	15.4	1.6
6/10/2008	**0.51**	**0.5**	17.6	0	0
6/16/2008	**0.91**	**0.9**	34.7	0	0
6/30/2008	**0.20**	**0.2**	11.2	0	0
7/5/2008	**0.10**	**0.1**	7.0	0	0
4/29/2009	**0.30**	**0.3**	10.5	0	0
5/16/2009	**0.84**	**0.8**	50.5	0	0
6/3/2009	4.45	4.4	178	249	428
7/1/2009	1.32	1.3	34.5	5.0	7.3
7/23/2009	**0.15**	**0.2**	0.5	0	0
7/31/2009	2.03	2.0	67.4	5.4	15.9

Applying the complete capture equation to the typical distribution of storm events in Maryland (Table 3) it is estimated that the grass swales would fully capture an average of 59% of storm events in a typical year. Nearly half of these captured storm events would have rainfall volume less than 0.254 cm and durations less than 2 h. This estimate assumes full capture of half of the events for depth/duration cells (Table 3) through which Eq. (2) intersects.

3.3. *Volume attenuation*

Probability plots are commonly used to visually examine the distribution of hydrologic data (Cunnane, 1978; Looney and Gelledge, 1985), and more recently those of SCM performance (Davis, 2008; Li et al., 2009); they are employed here to summarize and compare swale inflow and discharge volumes (Fig. 3). All four swale designs produce similar patterns of volume attenuation – completely capturing the smallest 40% of monitored storm events, reducing total runoff volume for an additional 40% of events, and performing simply as flow conveyance with negligible volume attenuation for the largest 20% of events. This variable performance pattern results because swales inherently have minimal storage capacity. Runoff volume is reduced during typical storm events through infiltration; however, little volume attenuation occurs once the soil becomes completely saturated.

Transition from complete capture to volume attenuation is described above by the complete capture line (Eq. (2)) and the discontinuities in Fig. 3. The transition from volume attenuation to flow conveyance is visible as a distinct change in slope in the swale probability plots, occurring at approximately 1×10^5 L (Fig. 3). This volume corresponds to a rainfall depth of 3.7 cm over the highway area. Above this point, volume attenuation becomes negligible and in some more extreme cases, the measured swale discharges exceed inflows. Because of these differences in water management mechanisms, analysis of volume reduction is divided into moderate (HWY $< 1 \times 10^5$ L) storm events and large (HWY $> 1 \times 10^5$ L) storm events.

During moderate storm events, the No-FS swale performed better than the FS swale with respect to reducing total runoff volume (Fig. 3). The No-FS swale significantly reduced runoff volume, with a mean reduction of 33.8% (compared to HWY, 10 events), while the FS swale had no statistically significant effect on runoff volume (10 events). This difference between the No-FS and FS swale is statistically significant ($p = 0.0361$), with an average difference of 32,800 L (per event).

Inclusion of check dams appears to further decrease total runoff volume relative to swale inflow, HWY-CD, for moderate events (Fig. 3). Volume attenuation in both check dam swales during moderate storm events is statistically significant, with mean reductions of 27.1% and 62.7% (compared to HWY) for the No-FS-CD (11 events) and FS-CD (11 events) swales, respectively. With the inclusion of check dams, unlike the standard swale designs, the FS-CD swale performed significantly better than the No-FS-CD swale, with an average improvement of 18,000 L (reduction per event). The difference between the swale designs becomes less apparent with the

Table 3 – Summary of rainfall distributions based on rainfall depth and duration. Each condition shows the fraction of monitored storms of that given depth and duration. Below the fraction, the total number of monitored storms of that category is given, followed by the number of monitored storms completely captured. Darkly shaded boxes represent storm categories that were completely captured by the swale. Lighter shaded boxes represent categories with some captured storm events and some events with measurable flow. White boxes represent categories with measurable flow from the swales. Non-check dam storm events are labeled as No-CD, check dam storm events are labeled as CD, and Maryland Averages (Kreeb and McCuen, 2003) are labeled as MD.

Event Duration		Rainfall Depth (cm)					Sum
		0.0254–0.254	0.255–0.635	0.636–1.27	1.28–2.54	>2.54	
0–2 h	No-CD	0.083 2, 2	0.125 3, 2	0 0, 0	0 0, 0	0 0, 0	0.208 5, 4
	CD	0.143 4, 4	0.071 2, 2	0 0, 0	0.071 2, 2	0 0, 0	0.286 8, 8
	MD	0.2857	0.0214	0.0167	0.0043	0.0008	0.3289
2–3 h	No-CD	0.042 1, 1	0.042 1, 1	0 0, 0	0 0, 0	0 0, 0	0.083 2, 2
	CD	0 0, 0	0.036 1, 1	0 0, 0	0 0, 0	0 0, 0	0.036 1, 1
	MD	0.0164	0.0257	0.0221	0.0089	0.0025	0.0756
3–4 h	No-CD	0 0, 0	0 0, 0	0 0, 0	0 0, 0	0 0, 0	0 0, 0
	CD	0 0, 0	0 0, 0	0.036 1, 1	0 0, 0	0.036 1, 1	0.071 2, 2
	MD	0.0085	0.0223	0.0198	0.0083	0.0038	0.0627
4–7 h	No-CD	0.083 2, 1	0 0, 0	0.083 2, 1	0.042 1, 0	0 0, 0	0.208 5, 2
	CD	0.036 1, 1	0.036 1, 1	0.107 3, 0	0.107 3, 1	0 0, 0	0.286 8, 2
	MD	0.0099	0.0351	0.0475	0.0221	0.0087	0.1233
7–13 h	No-CD	0 0, 0	0 0, 0	0 0, 0	0 0, 0	0.208 5, 0	0.208 5, 0
	CD	0 0, 0	0 0, 0	0.143 4, 0	0.143 4, 0	0.036 1, 0	0.321 9, 0
	MD	0.0058	0.0337	0.0629	0.0528	0.0266	0.1818
13–24 h	No-CD	0.042 1, 1	0 0, 0	0 0, 0	0.083 2, 0	0.083 2, 0	0.208 5, 1
	CD	0 0, 0	0 0, 0	0 0, 0	0 0, 0	0 0, 0	0 0, 0
	MD	0.0024	0.007	0.0397	0.0611	0.0515	0.1617
>24 h	No-CD	0 0, 0	0 0, 0	0 0, 0	0 0, 0	0.083 2, 0	0.083 2, 0
	CD	0 0, 0	0 0, 0	0 0, 0	0 0, 0	0 0, 0	0 0, 0
	MD	0	0.0009	0.0043	0.0172	0.0435	0.0659
Sum	No-CD	0.25 6, 6	0.167 4, 3	0.083 2, 2	0.125 3, 1	0.375 9, 0	1.0 24, 12
	CD	0.179 5, 4	0.143 4, 4	0.286 8, 1	0.321 9, 3	0.071 2, 1	1.0 28, 13
	MD	0.3287	0.1461	0.213	0.1747	0.1374	1

inclusion of check dams. Volume attenuation of moderate storm events measured in this study (27.1–62.7%) is similar to results reported in similar studies of grass swales: 30% (Rushton, 2001), 45.7% (Deletic, 2001), 33% (Backstrom, 2002), 47% (Barrett, 2005), and 45% (Ackerman and Stein, 2008).

Attenuation of large storm events (HWY $> 1 \times 10^5$ L) tends to be negligible and highly variable, with some events generating greater discharge than the calculated input, even after subtracting the volume generated on the swale (Fig. 3). High variability and relatively small sample sizes of large storm events preclude any conclusions being drawn regarding the differences between swale designs. The seemingly anomalous result of swale discharges exceeding their calculated inflow is likely caused by otherwise unconnected

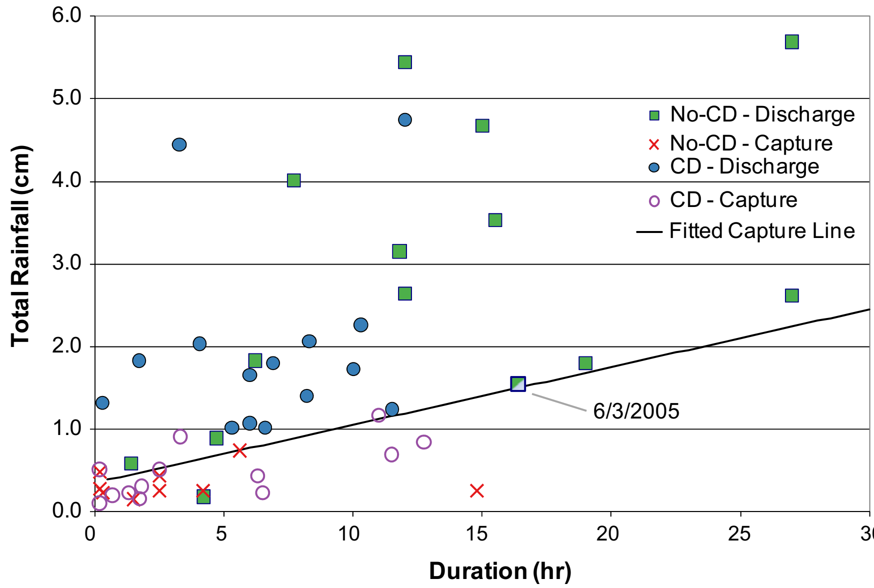

Fig. 2 – Total Rainfall Depth versus Duration. Events completely captured by the swales are indicated as open symbols (×, ○). Events with measurable swale discharge are indicated as filled symbols (■, ●). The 6/3/2005 event, labeled as such in the figure, produced measurable flow from the FS swale, but a complete capture from the No-FS swale. Fitted capture line is of the form: *P* (cm) = 0.07 × *D* (h) + 0.35 cm.

drainage areas contributing to the swale drainage during peak flows. Others have found similar results, in which runoff volume exiting grass swales is equal to or larger than that entering the swale during large or intense storms (Schueler, 1994; Rushton, 2001; Yu et al., 2001).

The overall volumetric performance of the swales is shown in Fig. 4. Again, 3 "treatment zones" can be defined. For many of the smallest events, and some larger events, no discharge was measured from the swales, indicating a volumetric storage/infiltration capacity for the swales of between 18,000 (lowest volume to show discharge) and 70,000 L (largest volume to show complete capture). These values correspond to 0.4–2.2 cm of water depth over the vegetated swale area.

Fig. 4 also includes the 45° line of equivalence between volume in and out. For most events, output volume was less than the input. The reduction was highly variable and cannot

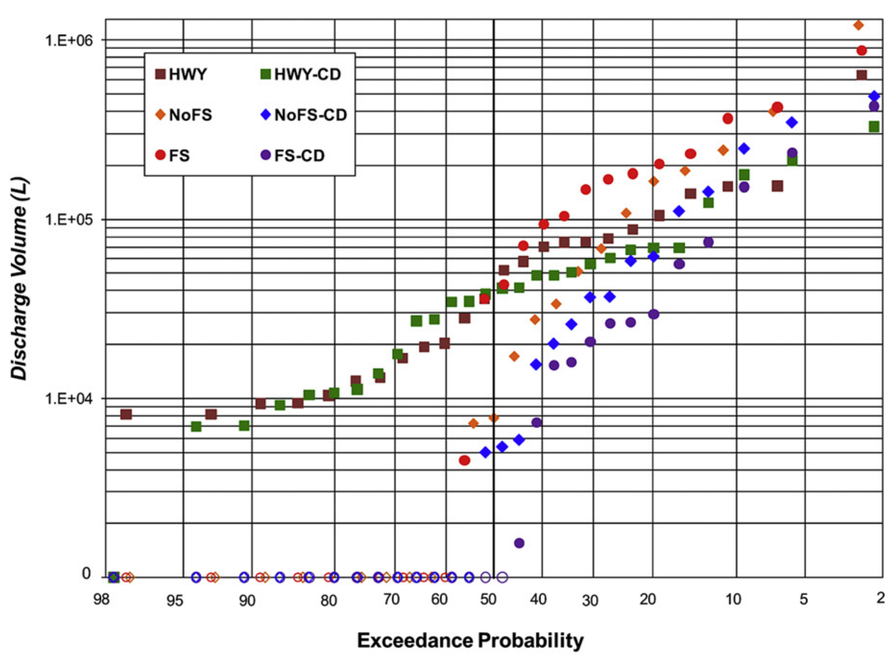

Fig. 3 – Normalized total volume distribution for all storm events for influent (HWY) and swale discharge (No-FS and FS). Hollow points represent storm events with complete capture of inflow.

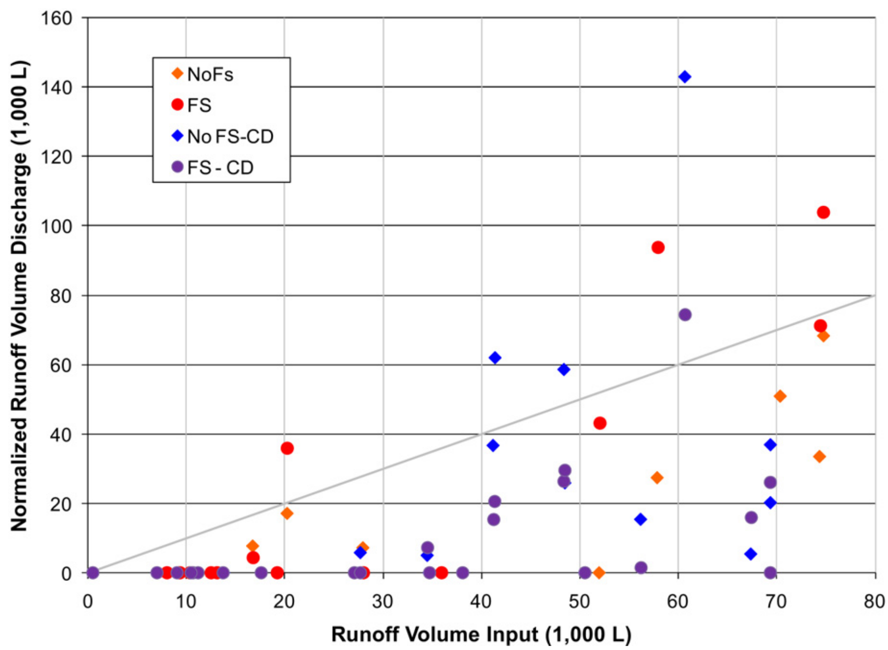

Fig. 4 – Normalized runoff volume discharged by the swales plotted against total input volume. The 1:1 line is plotted for reference, representing no volume attenuation. Completely captured storms are plotted on the abscissa.

be adequately defined by a simple "percent reduction." Nonetheless, at higher volumes, excess discharge volume is noted, as discussed above.

Based on these analyses, it is proposed that swale hydrologic design and analysis be based on two criteria: The first is the depth of water that can be infiltrated by the swale, producing no runoff. The second is the swale water depth in which no volume reduction occurs. For the swales in this study, the capture depth ranges from about 0.4 to 2.2 cm (1.3 cm mean) of water over the vegetated swale area. The capacity depth is about 2.3–3.3 cm (2.8 cm mean). Ranges are necessary because of the different designs employed and the impacts of infiltration that will occur concurrent with the input runoff loading. This behavior, perhaps not surprisingly, follows closely that predicted by the NRCS "Curve Number" procedure.

3.4. *Dynamic flow response*

Examination of individual storm event hydrographs provides greater detail of swale response to differing rainfall/runoff inputs. A typical hydrograph for storms represented by complete capture is presented in Fig. 5a. The HWY hydrograph responds rapidly to fluctuations in rainfall. However, at only 0.25 cm total rainfall, no discharge is produced from either swale.

The 11/16/05 storm event is classified as moderate (1.83 cm, 6.2 h) and the hydrograph responds as expected based on volume attenuation (Fig. 5b). Both swales capture the first input peak through initial abstraction. While the later rainfall generates runoff, the peak flow rate is reduced, with smoothing of flow variation and a decrease in overall runoff volume. This behavior is typical of moderate storm events and explains the volume attenuation noted above. Similar to the volume attenuation analysis, the No-FS swale reduces peak flow more effectively than the FS swale.

Finally, a large storm event hydrograph (5/19/2005) shows swale response when subjected to intense precipitation (4.67 cm, 1.5 h). The hydrograph contains some general characteristics found in moderate events, such as peak smoothing and initial abstraction, but confirms the lack of total volume attenuation and exhibits no net peak flow reduction (Fig. 5). In this case, swale discharge volume in excess of the input is exhibited and occurs throughout the duration of the storm event. This further confirms that additional, unaccounted for runoff may be entering the swales during large storm events. The No-FS swale appears more effective at reducing flows during this storm event, however, the difference in total volume reduction across all large events was not statistically significant.

Evaluation of dynamic hydraulic response to storm events provides insight into the processes responsible for flow attenuation. Flow duration curves (Fig. 6) are used to summarize hydraulic response by compiling flows measured at 2 min intervals across all storm events into a single distribution. Flow duration curves include not just the peak values of flow, but show the entire duration of flow. Dynamic performance can be evaluated in terms of a metric such as a threshold erosive flow or with comparison to various types of land uses.

Fig. 6a shows that the highest flows directly from the roadway (HWY) exceeded 20 L/s, which corresponds to a flow depth of 2.66 cm/h, or 638 mm/day over the roadway area. The median value for the HWY flow was approximately 0.33 L/s (0.044 cm/h equal to 10.6 mm/day). For perspective, Shields et al. (2008) indicate that a small forested watershed stream near Baltimore MD discharges about 1 mm/day, with storm excursions generally less than 5 mm/day.

From Fig. 6, it is noted that the swales do little to reduce the highest flows discharging from the highway. However, smaller flows are greatly reduced. This supports the volumetric

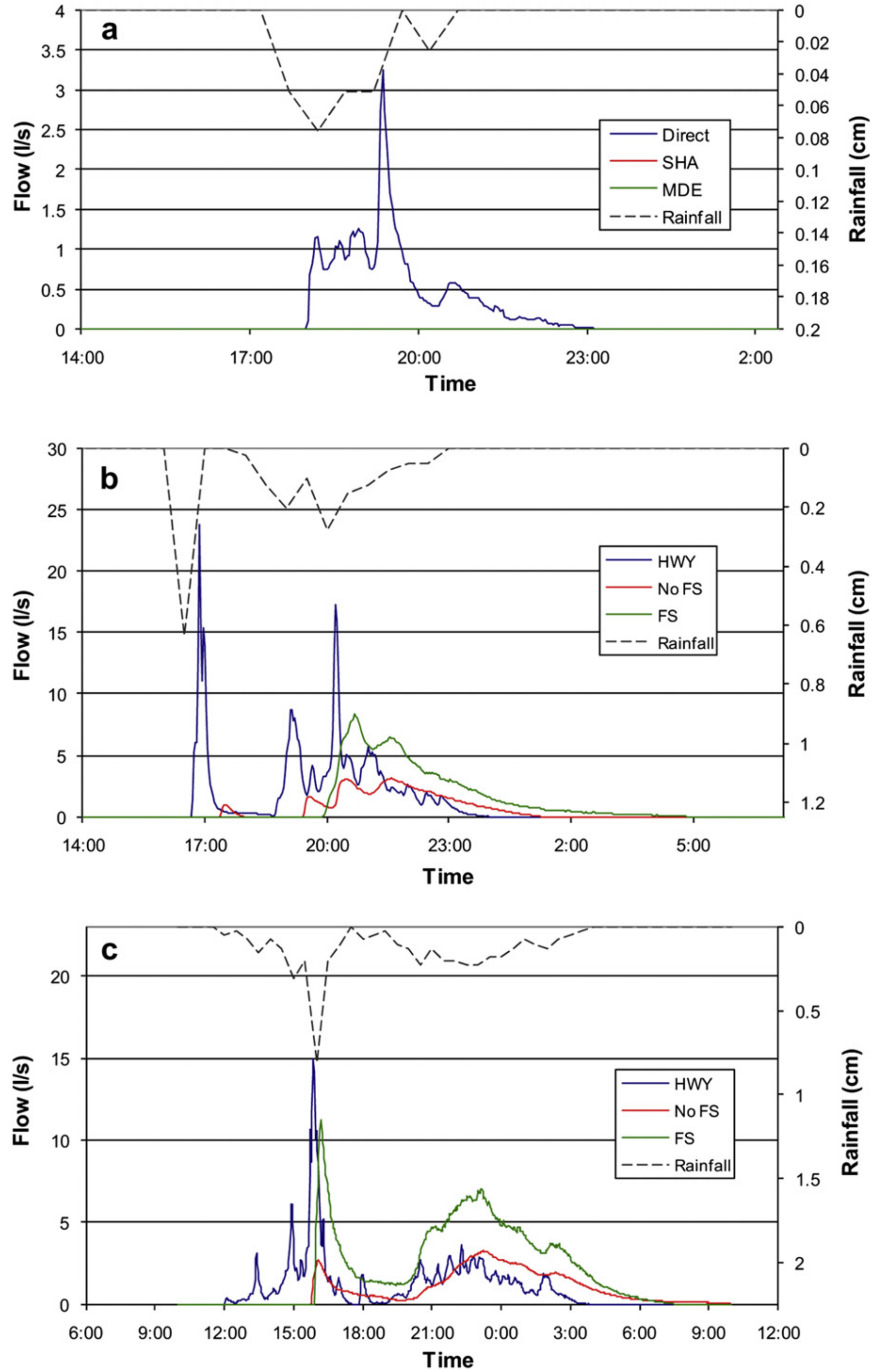

Fig. 5 – Normalized flow for three rainfall events a) 9/26/05 0.25 cm event showing no runoff from swales (1000 L Direct). b) 11/16/05 1.83 cm (moderate) event (74,400 L Direct, 33,500 L No-FA, 71,300 L FS). c) 5/19/05 large 4.67 cm event (81,500 L Direct, 238,000 L No-FS, 251,000 L FS). Note differences in scales.

discussions above. The swales cannot manage the largest events through storage/infiltration and provide little protection against the largest flows, as these occur when the swales are saturated.

In addition to preferentially reducing total volume, the No-FS swale is more capable than the FS swale in reducing flow magnitude across nearly the entire flow duration distribution (Fig. 6a). The nearly vertical distribution of low flows in the swales, relative to the HWY distribution, confirms that the lowest flow inputs (<0.5 L/s) tend to be effectively managed by the swales. The total duration of measurable discharge from the swales is reduced from the highway through the swales by 52.0% (No-FS) and 44.7% (FS).

Non-check dam swales have a greater distribution of high flows than their input, suggesting that the increase in total

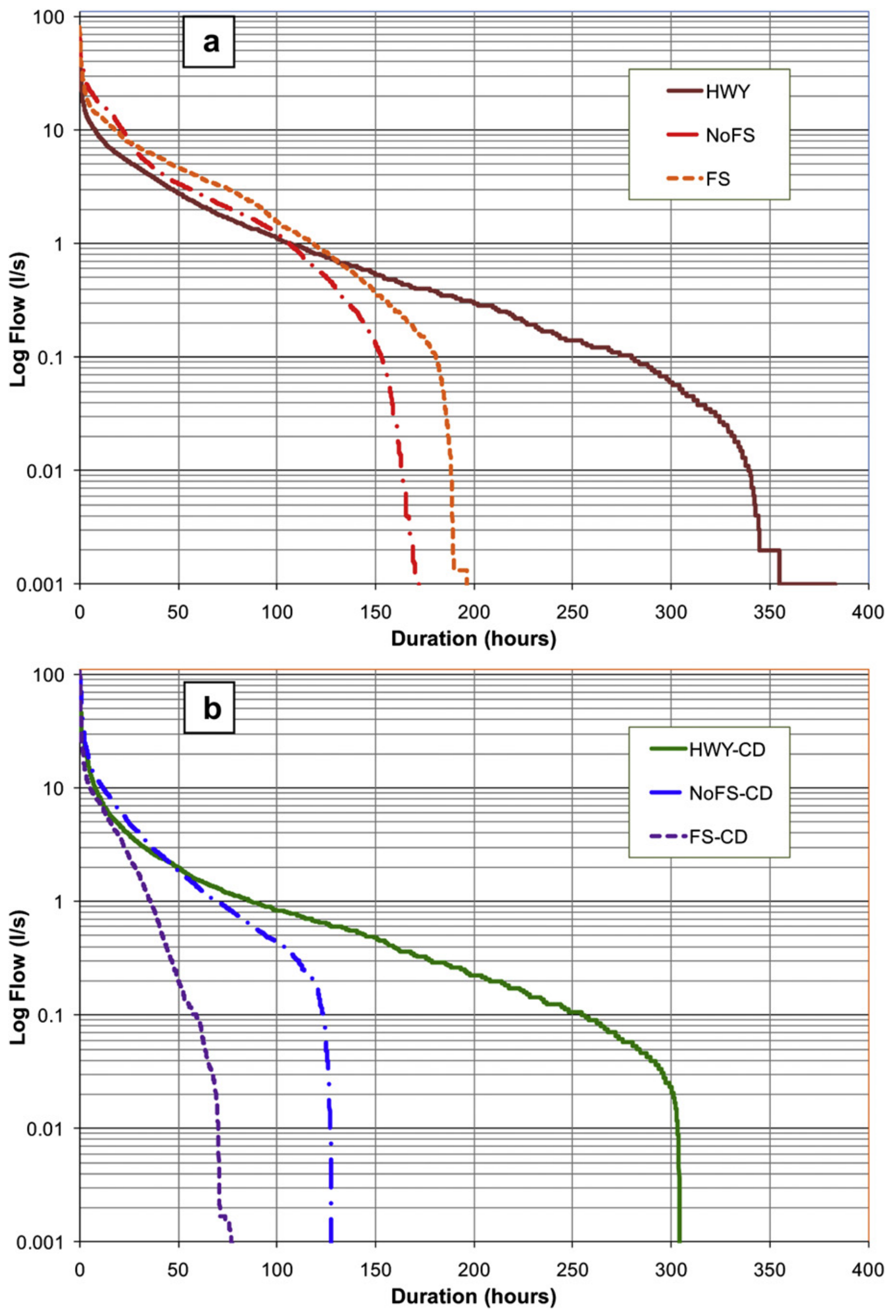

Fig. 6 – Flow-duration curves for swales and highway runoff. Summary of normalized flow rates for all storm events using the sampler time of 2 min. Values at the abscissa represent the lowest measurable flow within detection limits. Inflow duration to the non-check dam and check dam swales was 383 h and 308 h, respectively. a) without check dams. b) with check dams.

runoff volume during large storm events can be attributed to an increase in flow throughout much of the storm event, not only during peak flows.

The distribution of flows for swales with check dams is similar in form to the swales alone. In this case, the FS-CD swale significantly decreases flows relative to the No-FS-CD swale (Fig. 6b). This also agrees with the total runoff volume findings. As in the non-CD swales, the check dam swales have a nearly vertical distribution of low flows (<0.01 L/s), decreasing the duration of measurable discharge by 58.1% (No-FS-CD) and 75.1% (FS-CD). Unlike the swales alone, check dam swale discharges do not exceed the input distribution (HWY-CD) at the highest flow rates.

3.5. *Check dam effects*

The effect of check dams could not be analyzed directly because the swales were subjected to different storm events, unlike the paired No-FS/FS tests. To account for this variation, a two-way ANCOVA design was employed, comparing fractional volume reduction with treatment levels of No-FS vis-à-vis FS and No-CD vis-à-vis CD. Within-group variance was controlled by inclusion of swale inflow (HWY or HWY-CD) as covariate.

The four swale designs significantly differ in volume reduction of moderate storm events ($F = 21.23$, $p = 0.046$). This difference is primarily attributed to the inclusion of check dams, as confirmed through Tukey post-hoc tests. The inclusion of check dams therefore significantly improves the swales ability to reduce runoff volume during moderate storm events. Check dams provide greater water storage inside the swale channel, allowing increased infiltration and evapotranspiration.

No significant effect was found for either the inclusion of check dams or the swale designs during large storm events.

4. Conclusions

Four full-scale grass swale designs were subjected to a range of natural storm events to determine their effectiveness as SCMs, with particular focus on the effect of adjacent vegetated filter strips and in-line check dams. Swale discharge monitoring was designed to allow evaluation of flow response, i.e., hydrographs, as well as calculation of summary metrics, such as total volume attenuation. Monitored storm events closely fit the average distribution of storm events in Maryland in terms of rainfall volume and duration.

Swales are shown as conditionally effective SCMs, capable of reducing the deleterious effects of increased imperviousness by completely infiltrating the smallest storm events, attenuating volume and peak flows for moderate events and operating as conveyance with some flow smoothing for the largest events. In terms of creating a hydrologic regime close to pre-development conditions, the grass swales themselves produced the greatest effect relative to the concrete conveyance structure, with the alternative designs only augmenting their impact. As such, design guidelines should consider swales as a primary runoff control mechanism, with vegetated filter strips and in-line check dams included, where practical, to improve performance.

Because grass swales were found to have three distinct treatment zones (infiltration, attenuation, and conveyance), it is proposed that future design criteria consider two important hydrologic parameters: The first is the depth of water that can be infiltrated by the swale, producing no runoff. The second is the swale water depth in which no volume reduction occurs. For the swales in this study, the capture depth ranges from about 0.4 to 2.2 cm (1.3 cm mean) of water over the vegetated swale area. The capacity depth is about 2.3–3.3 cm (2.8 cm mean).

Complete infiltration of small events was independent of the swale alternative designs, but was found to be infiltration rate-limited, as suggested by the boundary equation:

$$P_{swale} = 0.112 \times D + 0.56 \text{ cm}$$

suggesting that swales of this design are capable of capturing 0.56 cm of rainfall through initial abstraction, with infiltration rates of completely captured storms ranging between 1.5 and 0.3 cm/h. No discernible difference is noted among the swale designs, suggesting that filter strips and check dams have little effect on complete capture of small storm events. Using the capture regression equation, it is predicted that grass swales of this design would capture 59% of storm events in a typical Maryland year, as noted by the depth-duration data of Table 1. These results imply that check dams and grass filter strips have negligible effect on the complete capture of small storm events, and therefore other parameters such as soil permeability likely control this treatment regime.

However, for moderate storms events (2.3–3.3 cm rainfall), check dams and filter strips significantly improve grass swale performance, both in terms of total volume reduction and dynamic flow attenuation. Events of this magnitude represent 40% of storm events monitored in this study. Hydrographs indicate that the swales capture initial runoff by abstraction and reduce subsequent flow rates throughout the duration of the storm event. The most significant design alternative is the inclusion of in-line vegetated check dams. Because of their potential hydrologic impact and the lack of additional right-of-way needed for installation, in-line vegetated check dams should be considered in swale design guidelines.

Adjacent filter strips produced mixed hydrologic results, generating significant improvement when coupled with check dams, but significant decline without check dams. Based on these results, adjacent filter strips should be considered as a design alternative where space allows, but not considered necessary because of their moderate impact relative to the grass swales.

During relatively infrequent large events, the swales function primarily as flow conveyance due to their limited storage volume. As such, there is negligible volume reduction and no discernible differences among the swale designs. The transition to flow conveyance during large events, described above as the capacity depth, appears to be governed by total runoff volume, suggesting a complete saturation of the soil. Therefore, if the capacity depth were to be increased, designs would require larger or longer swales, with greater storage capacity, or a separate SCM as part of a treatment train for extreme event storage. Because swales generally have less storage volume than other SCMs, management of extreme events is not typically considered a priority in design criteria.

Results and recommendations provided herein are based solely on hydrologic performance. Water quality improvement is also an important consideration when designing or outlining specifications for grass swales. Further study of the water quality benefits of grass swales and impacts of design variations is necessary to fully understand their effects and to make informed design recommendations.

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