NCSU Urban Waterways Factsheet: Designing Dry Swales for the Water Quality Event

W.F. Hunt, E.A. Fassman, and R.J. Winston[1]

Introduction

Swales are one of the most commonly used stormwater control measures (SCMs) worldwide (Figure 1). Most have been designed for safe conveyance of flows from events with infrequent return periods (e.g., ARI's of 2 or 10 years). Moreover, most swale guidance is based upon anecdotal information. However, these SCMs can also be explicitly designed to improve the quality of runoff and design guidance can be based upon research conducted within the past 10-12 years. The purpose of this publication is to propose some design guidance for non-infiltrating swales specifically intended to provide long-term water quality benefits and to provide an update to the first publication of the Urban Waterways Series (AG-588-1), *Structural Stormwater Best Management Practices*. This guidance is for simple grass-lined dry swales, e.g., those without underlying filter media or underdrains, and does not cover either linear wetland-like swales or those with check dams. The design methodology applies to engineered filter strips as well.

Figure 1. Swales are used world-wide, such as those (left to right) on NCSU campus (Raleigh, NC), under a bridge deck in Knightdale, NC, and serving a parking lot in Albany, New Zealand.

Multiple field studies have shown that pollutant removal by swales is a function of many factors: cross-sectional geometry, slope, flow depth, grass type and height, pollutant type, particle size, etc. (Bäckström 2002, 2003; Barrett et al, 1998; Deletic 1999, Deletic and Fletcher 2006). Research findings are nearly uniform: swales and related filter strips do improve water quality for sediment and sediment-borne pollutants. The researchers agree that a swale's pollutant removal mechanisms, sedimentation and filtration/straining by vegetation, occur when the vegetation is not overtopped. That is, when flow is spread out so that the full measure of water flows *through* the grass (not over it). Thus, a clear distinction exists between swales intended to convey flow for larger events and swales intended to improve water quality. For water quality swales, the water elevation during the design storm stays at or

[1] Professor and Extension Specialist, Biological and Agricultural Engineering, NC State University; Senior Lecturer, Civil and Environmental Engineering, University of Auckland; Extension Associate, Biological and Agricultural Engineering, NC State University; respectively.

below the height of grass lining the swale. It is, of course, recommended that swales be designed for both functions.

Water quality swale design is a two-step process, as is reviewed in the following sequence: first is the hydraulic design. During this phase, the swale's depth of flow, cross-sectional geometry, and slope are determined. Second, the pollutant mitigation design is performed, which establishes the swale's length.

Hydraulic Design

Setting Grass Height (and Depth of Flow)

For water quality purposes, the threshold depth for water quality flow is not to exceed the expected height of grass. The maximum allowed grass height depends on grass species. It is in the designer's interest to choose somewhat tall, stiff grasses that grow uniformly, like a carpet. Clumping grasses are to be avoided. For example, a cool season grass mix in North Carolina able to meet the aforementioned design features is a combination of tall fescue(*Festuca arundinacea*), indiangrass (*Sorghastrum nutans*), switchgrass (*Panicum virgatum*), little bluestem (*Schizachyrium scoparium*), weeping lovegrass (*Eragrostis curvula*),and smooth brome (*Bromis inermis*). An ideal mix of grass is best determined by local grass specialists. Knowing that maximum grass heights may not be maintained, the water quality flow design grass height should be slightly less than the maximum. So, in the case of tall fescue (*Festuca arundinacea*), a recommended design height of grass (and therefore design depth for flow) would be 150 mm (6 in.)

Choosing a water quality flow rate

In SCM water quality design, the amount of water to be treated annually is the basis for selecting a volume (or flow) to be treated by the practice. For example, many jurisdictions require treatment of a particular volume of runoff (e.g., a "first flush" capture rule, other rainfall capture rules based on frequency analysis, or maximized capture volume (Guo and Urbonas 1996)). For some systems, like stormwater wetlands and wet ponds, the amount of water treated is a function of capturing a runoff volume. Other SCMs, like swales and filter strips, should be designed for flow.

Flow rate is the critical hydraulic parameter for swale design. Flow rate is a function of drainage catchment parameters (size, composition and slope), precipitation intensity, and channel characteristics (cross-sectional geometry, slope, and liner). If flow enters the swale by way of grassed batter slope, such as a roadside shoulder (in lieu of a distinct point of entry), water is being treated (by the filter strip) before it enters the swale proper.

The precipitation intensity to be treated should reflect the water quality volume to be treated. In other words, the precipitation intensity chosen to be treated by a conveyance SCM, like a swale, should cumulatively account for between 80% and 99% of runoff. There are different methods to determine the target "water quality" intensity, including determining peak flow using a unit hydrograph.

By integrating average hourly rainfall intensities over a long-term period, the amount of rainfall associated with a given intensity of precipitation can be calculated. In North Carolina, for example, this was done for several cities (Table 2) and precipitation intensities. According to Table 1, 19 mm/h (0.75 in/h) accounts for at least 95% of total rainfall annually in all but one location. Thus, if at least 95% of rainfall is to be treated by the swale SCM, the water quality aspect of the swale should be designed so that it treats a 19 mm/h (0.75 in/h) event (Figure 2).

Table 1. The proportion of rainfall associated with precipitation rates for 5 cities in North Carolina. Data for analysis provided by NCCO (2010).

Precipitation Rate	Raleigh	Greensboro	Charlotte	Asheville	Wilmington
38 mm/h (1.5 in/h)	99.8%	99.6%	99.0%	99.8%	98.9%
25 mm/h (1.0 in/h)	98.5%	98.3%	97.5%	99.0%	95.9%
19 mm/h (0.75 in/h)	96.7%	96.7%	96.0%	97.9%	92.8%
13 mm/h (0.50 in/h)	92.1%	93.4%	92.5%	95.3%	86.5%

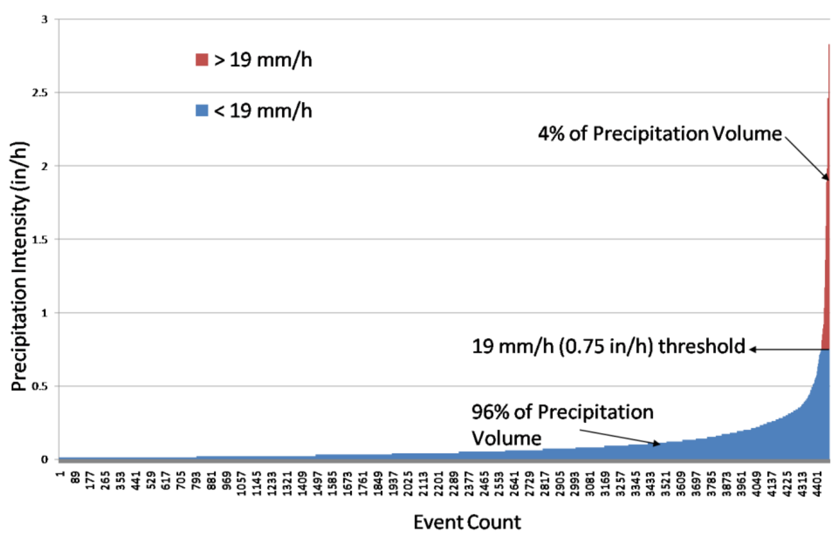

Figure 2. Determining capture volume based upon Charlotte, NC, precipitation intensity (1999-2009). If at least 95% of precipitation is targeted, then a 19 mm/h is satisfactory (as 96% of long term rainfall is associated with a precipitation rate up to 19mm/h).

In this example, the swale needs to be designed so that during a 19 mm/h event, the height of the water in the swale does not exceed the threshold height of grass of 150 mm (6 in.). The swale can, and of course should, be deeper to safely carry less frequent intensities (like 2-yr or 10-yr ARI events). Finally, treating 95% of rainfall does not equate to treating 95% of runoff, but for highly impermeable catchments, basing a broad standard simply on rainfall intensity may be reasonable.

Calculating Flow

Because swales are treating small drainage areas, in the USA the most likely method of calculating peak flow (Q_p) is the rational method (Mulvany 1851), which is explained by the following equation:

$Q_p = ciA$,   (Equation 1)

Where c = runoff coefficient, i = precipitation intensity (in/h), and A = area (ac).

Per the prior section, the precipitation intensity is established by the target water volume to be treated. For example, if that target were 95% of all rainfall in most North Carolina cities, "i" would be set to 19 mm/h (0.75 in/h).

Channel Geometry

Open flow in grassed channels is most commonly described using the Manning's Equation (Manning 1891)

$Q = 1^{**}/n \times A\ R_h^{2/3}\ S^{1/2}$ (Equation 2)

Where n = Manning's roughness coefficient, A = Channel Cross-sectional area, R_h = Hydraulic Radius, and S= Slope (expressed as a decimal)

** In US Customary Units, this is 1.486

The channel geometry is determined by the water quality flow (eq. 1), the roughness of the channel liner (in this case grass), the cross-sectional dimensions (A & R_h), and the slope. In practice, most designers adjust the channel geometry dimensions until the carrying capacity of the channel matches or exceeds the target water quality flow rate.

When designing swales for water quality purposes, some of the Manning's Equation parameters have rather strict bounds.

Flow Impedance by Grass

Unlike channels that are designed to have flow depths easily overtopping the vegetative liner, water quality flows through swales are meant to be at or below grass height. Kirby et al. (2005) calculated flow impedance (or hydraulic resistance) provided by three different grass types for these types of flows. The data were presented using an "apparent" Manning's roughness coefficient, n. The range of values for each of the grasses is found in Table 2. Clearly the roughness coefficient is higher by almost a factor of 10 than what is typically used for grass liners, because when flow does not overtop grass (as is the case here), the grass imparts much more resistance to flow. For use in the rest of this case study, a near median of n=0.35 for bluegrass is used. The n of 0.35 is essentially at the upper end of the range for grass swales examined in Sweden (n = 0.15 to 0.34) (Bäckström 2002). Do note the roughness coefficients were calculated for shorter length grasses (up to 80 mm) than the lengths intended for grasses in water quality swales (150 mm).

Table 2. "Apparent" Mannings roughness coefficients from Kirby et al. (2005).

Common Name	Scientific Name	Blade Length	Manning's n
Centipede	Ermochloa ophiuroides	50-80 mm	0.27-0.95
Bluegrass	Poa pratensis	35-80 mm	0.26-0.56
Zoysia	Zoysia x 'Emerald'	40-80 mm	0.28-1.35

Cross-sectional Geometry

Ranges for cross-sectional parameters are understood as well. Several researchers and guidance documents recommend trapezoidal cross-sections to maximize flow contact with water (USEPA 2004), prevent formation of erosive channels, and for ease of mowing. Additionally, anecdotal observations have led several authorities to restrict the maximum bottom width of the swale to approximately 2 m (6 ft).

Secondly, the maximum height at which water is allowed to flow is capped at the height of grass, typically 120 to 150 mm (5 to 6 in); this is established as the maximum flow depth allowed in a water quality swale.

An example is provided in Table 3 for selecting a bottom width based on Equations 1 and 2, with a 4:1 side-slope (batter) in North Carolina. The calculations assume a rational coefficient of 0.90 for a parking lot and 0.50 for a residential development. Mannings "n" is 0.35; rainfall intensity is set at 0.75 in/h (19 mm/h).

Table 3. Selecting bottom widths for various swales using a rainfall intensity of 0.75 in/h (19 mm/h).

Swale Bottom Width (@ 4:1 Batter)										
D.A. =	*0.5ac*	*1 ac*	*1.5 ac*	*2 ac*		*0.5ac*	*1 ac*	*1.5 ac*	*2 ac*	*2.5 ac*
slope (%)	**Parking Lot (c=0.9)**					**Residential (c=0.5)**				
0.5	3 ft	-	-	-		1 ft	3 ft	5 ft	-	-
1	2 ft	5 ft	-	-		1 ft	2 ft	4 ft	5 ft	-
1.5	1 ft	4 ft	6 ft	-		1 ft	2 ft	3 ft	4 ft	5 ft
2	1 ft	3 ft	5 ft	-		1 ft	1 ft	2 ft	3 ft	5 ft
2.5	1 ft	3 ft	4 ft	6 ft		1 ft	1 ft	2 ft	3 ft	4 ft
3	1 ft	2 ft	4 ft	5 ft		1 ft	1 ft	2 ft	3 ft	4 ft
4	1 ft	2 ft	3 ft	5 ft		1 ft	1 ft	1 ft	2 ft	3 ft
5	1 ft	2 ft	3 ft	4 ft		1 ft	1 ft	1 ft	2 ft	3 ft
7.5	1 ft	1 ft	2 ft	3 ft		1 ft	1 ft	1 ft	1 ft	2 ft
10	1 ft	1 ft	2 ft	3 ft		1 ft	1 ft	1 ft	1 ft	2 ft

As evidenced in the chart, both parking lots and residential applications have some combinations of slope and flow that do not allow a water quality dry swale to be constructed. The shallower slopes are simply unable to convey water at a small enough depth (less than or equal to grass height). In situations where this is the case, other practices, such as a wetland swale should be considered (Winston et al. 2012, USEPA 2004).

To verify the flow's velocity does not exceed erosional rates, the Mass Continuity Equation may be employed:

$V = Q \div A$ (equation 3)

But flow velocities at the water quality flow intensity (e.g. 19mm/h) are not expected to approach grass-tolerance thresholds, which are near 1.2 m/s (4 ft/s) (Malcom 1993).

Designing for Pollutant Capture: Length of Swale

The catalyst for (sediment-borne) pollutant removal is settling or deposition. The settling rate of particulates is governed by Stokes' Law (eq. 4)

$Vs = (g / 18\mu) (\rho_s - \rho) d_s^2$ (equation 4)

Where:

g = gravity, μ= dynamic viscosity of water (kg/s/m), ρ_s is particle density (kg/m^3), ρ = water density (kg/m^3), and d_s = particle diameter (m).

Particle removal by settling is a function of residence time in the swale and the size and density of the particle; only particles with settling velocities greater than or equal to the residence time will be removed. Residence time (T_{ahr}) in the swale is determined by dividing the length of the swale (L_{swale}) by the peak flow velocity (V) of the water quality event (eq 5)

$T_{ahr} = L_{swale} \div V$ (equation 5)

Other pollutant removal, like that of nitrogen or phosphorus, is only partially explained by particle settling. Biological processes, such as nitrification and denitrification, account for much of nitrogen removal, and phosphorus removal is in part predicated upon adsorption. As T_{ahr} increases, more nutrients are removed from the swale, provided a condition conducive to these mechanisms exists, as these processes are given more time to act.

Designing for Sediment (TSS) Removal

Swale length is calculated by establishing a target sediment removal. Thus, the particle size distribution (PSD) "typical" for that location needs to be known. Short swales can trap large particles (Barrett et al 1998, Deletic et al. 1999). Some fine particles are essentially untreated (Deletic and Fletcher 2006), even by long swales.

The particle "Fall Number," N_f (Deletic 2005), is a suggested tool for determining whether a particle is trapped. This model was specifically designed for urban flows and the low to moderate concentrations of sediment associated with the developed (not active construction) condition. In this way Deletic's (2005) model distinguishes itself from earlier agricultural swale design models (Hayes et al. 1984, Tollner et al. 1982). Deletic (2005) calculates the fall number as:

$N_f = xV_s \div hV$ (equation 6)

Where:

X = length of grass strip/ swale (m), V_s is the particle settling velocity (calculated using Stokes' Law, eq 4) (m/s), h is flow depth (m), and V = flow velocity (m/s).

N_f is integral to the empirically-based Aberdeen equation (eq 7) to predict sediment removal, also presented in Deletic (2005):

$Tr_s = N_f^{0.69} \div (N_f^{0.69} + 4.95)$ (equation 7)

Where:

Tr_s = Trapping Efficiency (in decimal form)

The model is used to set the length of the swale to meet a target removal rate for TSS. For example, if 50% of a TSS load is to settle or be filtered in the swale, the designer would adjust the length of the swale (Equation 6) until at least a 50% removal has been achieved (Equation 7). The particle sizes of the inflow sediment are critical to this calculation.

Testing the Model

Deletic's (2005) model was used to predict removal efficiencies for two swales: (1) in the Albany suburb of Auckland, New Zealand (NZ) receiving parking lot runoff and (2) in Knightdale, NC, receiving bridge deck runoff. Both swales are pictured in Figure 1. The predicted results were then compared to actual field data collected for that swale (Fassman et al. 2010, unpublished NC data). The Albany (NZ) swale was 73.6 m long and 1.0 m wide with nominally 150 mm tall grass. The Knightdale, NC, swale was 36.5 m long, 1.2m wide with nominally 225 mm tall grass. Inflow runoff and PSD were both available for three storms at each site. These predicted values were compared to actual field measurements for the events during which flow regimes were within their intended range (Table 4). The model was very accurate (within 8.4%) for 4 of the six events, while somewhat under-predicting removal efficiency for one event (Knightdale, 13-Dec-10) and over-predicting efficiency for the final event (Albany, 23-Nov-10). When viewed collectively, the Aberdeen Equation provides reasonably good accuracy.

Table 4. Actual and theoretical Removal Efficiencies for two swales near Auckland, New Zealand, and Knightdale, NC.

Location	Event Date	Qp (field measured)	Qp Depth of Flow (Calculated)	Calculated Removal Efficiency	Actual Removal Efficiency	Difference
Albany, NZ	23-Nov-08	12.9 L/s	0.12 m	90.9%	70.2%	-20.7%
Albany, NZ	23-Dec-08	20.7 L/s	0.15 m	83.5%	81.9%	-1.6%
Albany, NZ	16-Aug-09	25.9 L/s	0.17 m	88.0%	94.1%	6.1%
Knightdale, NC	15-Oct-10	22.5 L/s	0.24 m	65.0%	71.4%	6.4%
Knightdale, NC	05-Nov-10	8.5 L/s	0.17 m	48.5%	56.9%	8.4%
Knightdale, NC	13-Dec-10	3.65 L/s	0.13 m	34.3%	49.2%	14.9%

Because Deletic's (2005) model did not consistently under-predict the actual removal efficiency of swales (though in 4 of the 6 cases the model was conservative), designers may want to consider adding a factor of safety (either added swale length or a reduced amount of assigned removal). An exact factor of safety may be a case-by-case example, but perhaps 1.3 to 1.5 seems reasonable. A factor of safety is further needed due to potentially unreliable maintenance of swales. The grass may be cut too low or so infrequently that the grass liner loses stiffness.

Applying Deletic's (2005) method to Highway Runoff PSDs

Swales are frequently used to convey and treat stormwater along linear transportation corridors (Barrett et al. 1998, Yu et al. 2001, Winston et al. 2012). Particle size distributions for highway runoff tend to be coarser than the soils of the surrounding catchment, which is in great part driven by the material composition of pavement. Sansalone et al.'s (1998) thorough examination of urban roadway solids in Cincinnati, OH, for example, identified mean and median d_{50}s of 555 and 570 μm, respectively. Particles of this size can easily be trapped within the first meter or so of vegetation, as has been shown through field data collection (Barrett et al. 2004) and the use of predictive models. Employing Deletic's (2005) Aberdeen equation predicts greater than a 90% removal rate for a 570 μm particle within the first 1.5 m (5 ft).

Estimating Sediment Removal

A simple, but only approximate, way to estimate the removal efficiency of sediment is by calculating the removal efficiency for the d_{50} sediment particle. If, for example, 50% of TSS is meant to be removed by the swale, the length of the swale could be set such that at least 50% of the d_{50} particle is trapped within that distance.

The actual removal efficiency for the entire sediment load is determined by the PSD. PSDs with low d_{90}/d_{50} ratios or high d_{50}/d_{10} ratios probably have a cumulative removal efficiency lower than that calculated for the d_{50} particle alone. The ideal way is to determine performance is to model a PSD-weighted removal efficiency to calculate the removal efficiency, as is summarized in the Table 5.

Table 5. Calculating a Weighted Trapping Efficiency for a 10-m long swale using PSD.

PSD: d_	Size	Vs	Nf	Trs	Trs*Mass
100	0.0022	4.22	15900	99.4%	
80	0.0013	1.47	5540	98.7%	19.81
60	0.00097	0.82	3090	98.1%	19.68
50	0.00082	0.59	2210	97.6%	9.79
30	0.00059	0.30	1140	96.3%	19.39
10	0.00013	0.015	55.4	76.3%	17.26
0	0.000016	0.0002	0.84	15.2%	4.58
	Cumulative Removal Efficiency				90.5%

Both the d_{50} "short-cut" method and the PSD-based weighted trapping efficiency methods were used to predict how well a 10m long, 1.5m wide swale on a 2% slope, receiving runoff from 0.2ha (0.5ac) would treat the sediment particle size distribution collected by Sansalone et al. (1998). Calculating the Trs (removal efficiency) for solely the d_{50} (570 μm), yielded an 89.8% removal rate. When applying a more accurate estimation based upon weighting PSDs, a 71.1% removal rate is estimated.

Can sediment removal rates be applied to those of other pollutants?

Metals. Metals follow similar, but not exact, patterns of capture as sediment. Finer fractions of sediment carry a proportionally higher fraction of metals (Zanders 2005). Zanders (2005) found that Cu and Zn were both associated at much higher franctions to particle sizes less than 250 μm, than for sediment particle sizes greater than 250 μm (Table 6). The relationship for Pb was much weaker. Smaller particles (< 125 μm) also had lower particle densities (< 2200 kg/m^3) than larger particles (densities ranging from >2300 to > 2500 kg/m^3), further diminishing the fraction of metal able to be captured. Because the study was conducted in New Zealand, it should be noted that Zander's relatively low particle density may in part be due to lighter weight volcanic rock-based sediment.

Table 6. Total metal concentrations as a function of particle-size fraction (adapted from Zanders (2005)).

Particle-size fraction (μm)	**Total Metal Concentration (mg/Kg)**			**Particle Density (kg/m3)**
	Cu	*Zn*	*Pb*	
0-32	181	2080	316	2140
32-63	197	1695	322	2150
63-125	212	1628	334	2190
125-250	184	1073	251	2330
250-500	85	507	193	2530
500-1000	26	268	323	2540
1000-2000	21	226	36	2390

So, 50% TSS removal would not equate to 50% Cu or Zn removal. The latter would be lower, as revealed by coupling Zanders' (2005) data with the Aberdeen model (Deletic 2005). The following assumptions were made: the PSD was comprised of equal parts of each sediment particle size listed by column in Table 9 and a 10 m-long, 2.4 m-wide swale that received 0.5 ha of highway drainage on a 2% slope. When estimating efficiency of that swale, greater than 56% of solids would be captured. However, only 39% of Cu and 34% of Zn would likewise be captured. Because Pb was almost as likely to be associated with larger particles as smaller particles, 48% of it was retained by the swale.

Phosphorus and Nitrogen. Studies are inconclusive as to how much TN and TP can be removed by a swale (Table 7). Certainly, particulate or particulate-bound N and P would be sequestered in a swale, but dissolved fractions likely would not be, unless the swale is a wetland-like SCM with a high T_{ahr}. Studies with high nitrogen inlet concentrations (relative to Passeport and Hunt (2009) who found an average TN of 1.63 mg/L for impermeable surfaces) had nitrogen removal (Barrett et al. 1998, Deletic and Fletcher 2006, Winston et al. 2012). Sites with low nitrogen influent concentrations (Rushton 2001 and Winston et al. 2012) saw an *increase* in effluent concentrations. A similar trend was found for phosphorus. Because Rushton's (2001) swales had a high volume of infiltration due to their location in sandier coastal plain soils of Florida, modest to moderate load reductions for TN were observed. TP load results were mixed. Deletic and Fletcher (2006) examined a swale in Brisbane, Australia, and showed that TP and TN concentrations were lower than influent concentrations but did not appeciably change with flow rate.

Table 7. Influent and effluent concentrations from applied field studies.

Study	Location	Influent TN	Effluent TN	Type Change
Winston et al. (2012)	Site A	1.48	1.65	Increase
Winston et al. (2012)	Site D	2.60	1.62	Decrease
Rushton (2001)	F7	0.55[1]	0.64	Increase
Rushton (2001)	F8	0.55	0.72	Increase
Barrett et al (1998)[2]	US 183	3.08	1.92	Decrease
Barrett et al. (1998)	MoPac	3.88	2.42	Decrease
Deletic and Fletcher (2006)	Brisbane Swale[3]	2.6	1.12 to 1.46	Decrease

1 – Influent TN calculated as average of "Asphalt, no swale," F1 (0.556 mg/L) and F2 (0.548 mg/L)

2 – TN calculated as TKN + NO_3-N, herein, for Barrett et al. (1998)

3 - Experimental test with various flow rates

While dry swales did not clearly improve the concentrations of nitrogen or phosphorus, Winston et al. (2012) found that TN and TP concentrations leaving a wetland-like swale were lower than those of dry swales, indicating that creating an anaerobic condition in the swale, while maximizing T_{ahr}, may be a design tool used to improve nitrogen removal performance where conditions allow. Finally, Table 7 suggests that the removal efficiency metric may not be the most appropriate tool to assess how well a swale sequesters nitrogen (Lenhart and Hunt 2011, Strecker et al. 2001).

An Alternative Design Goal: Target Effluent Concentration

The concept of not designing SCMs to remove a percentage of a pollutant, but rather to release a target concentration, has gained recent popularity (Jones et al. 2009, McNett et al. 2010). Barrett et al. (2004) state that the grassed filter strips that were examined across California, USA, nearly uniformly reduced

TSS concentrations to approximately 25 mg/L. The final concentration did not appear to be impacted by filter strip width. Winston et al. (2011) found similar results: increasing the width of the vegetated filter strips only modestly improved the effluent concentration of TSS. Winston et al.'s (2011) effluent TSS concentrations were essentially 20 to 30 mg/L. While not examined in either Barrett et al. (2004) or Winston et al. (2011), the "remnant" concentration may have been influenced by finer particle sizes within the PSD. Provided the grass swale or filter strip is sufficiently large, the influent pollutant load can be quite substantial without much impact on effluent design concentrations.

A compilation of swale studies from the International BMP Database (http://www.bmpdatabase.org/) (IBMPD, 2010) is presented as Figure 3. The majority of swales' TSS effluent concentrations are less than the 25 mg/L target, suggested by Barrett et al. (2004). In fact, 80% of all swales included in the database had effluent concentrations less than 30 mg/L. The median observed effluent concentration was 8 mg/L. Perhaps the reason for this low effluent TSS concentration was that most of the results in the IBMPD were for swales exceeding 30 m (100 ft) in length. If more detail were available for these studies, namely contributing watershed area, it may be possible to design swales such that specific drainage area to swale length ratios ($DA:L_{swale}$) be selected to achieve a target effluent concentration. The design would probably need to consider PSD.

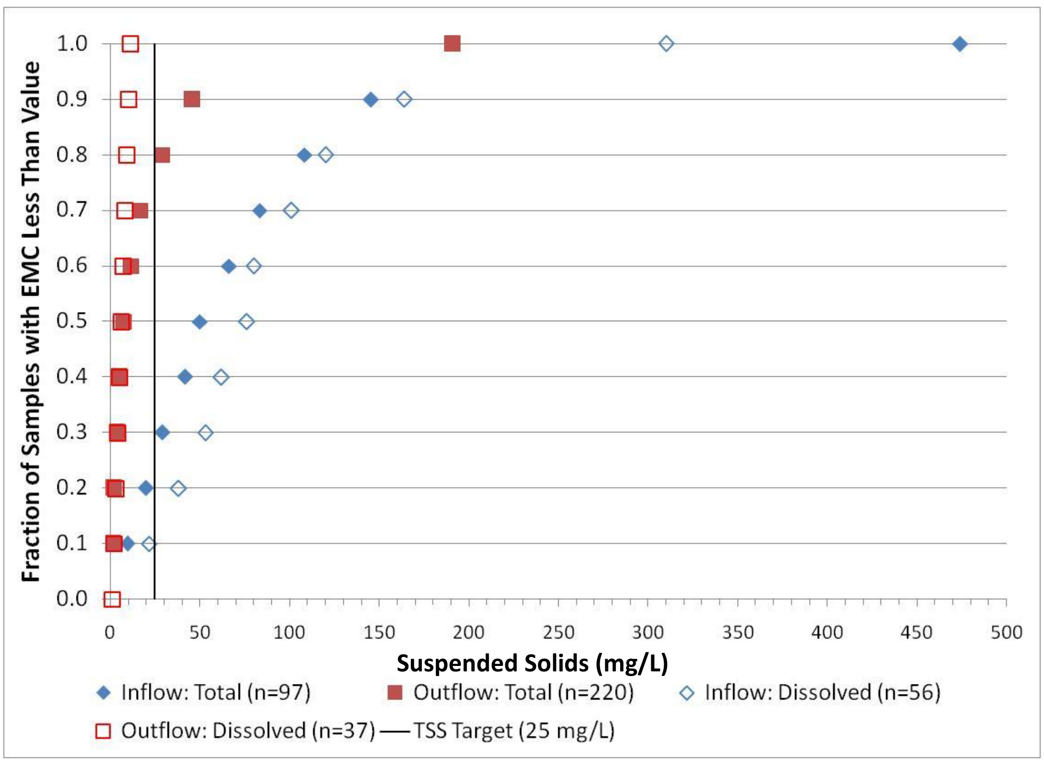

Figure 3. Summary of sediment effluent concentrations (summarized from IBMPD, 2010), illustrating a typically low effluent concentration for TSS. (Figure adjusted from Fassman 2010.)

Summary

Water quality swale design can be separated into two general parts: hydraulic and pollutant capture. The hydraulic design is predicated upon several factors, with two of the most influential being the maximum depth of water allowed in the swale and the designed rainfall intensity the swale is expected to treat. The suggested maximum water height allowed in the swale mirrors that of the target grass height (perhaps 150 mm or 6 inches, but exact depth is a function of grass species). The water quality design flow was based on having at least 95% of water pass through the swale at a height no greater than that of the grass. Thus, the rainfall intensity most appropriate for much of North Carolina appears to be 19 mm/h (0.75 in/h). Once the vegetative liner (a grass), slope and cross-sectional dimensions have been determined, it is then time to focus on pollutant capture to determine the swale's length.

Average hydraulic residence time is a key to predicting pollutant removal; that is, runoff must be exposed to treatment mechanisms (sedimentation, grass filtration) for an adequate period. This establishes the swale's length.

Several studies have documented sediment capture in swales and filter strips. A few have in turn, attempted to model the results. One model, the Aberdeen equation (Deletic 2005), was selected in part because of its relatively extensive documentation and testing under typical *urban* stormwater conditions. For both sediment and sediment-borne metals, the particle size distribution (PSD) is the critical component for predicting pollutant capture. Coarser particles, such as those found in some highway runoff studies, need very little grass verge widths or swale lengths to be almost completely removed from stormwater. Conversely, extremely fine particles are not at all likely to collect in even a rather long swale. The Aberdeen equation predicted suspended solids capture with rather good accuracy, albeit tending slightly conservative, for six events from two swales examined herein.

Metal removal by a given swale will be similar to, but typically slightly less than, that of sediment, because metals like Cu and Zn are more closely associated with finer – and harder to remove – particle sizes. Nitrogen and phosphorus removal is best explained by (1) average hydraulic retention time and (2) the fraction of each nutrient that is in particulate form. In the limited studies conducted, nutrient removal is mixed, but inlet concentration does appear to influence performance on a removal efficiency basis.

An important implication of this guidance is that swales are appropriately maintained. A design factor-of-safety of 1.3 to 1.5 is presented to account for potential maintenance lapses. Additionally, landscapers and other maintainers of stormwater systems should be made aware of the importance of grass height and cover to the success of a swale's water quality performance.

Acknowledgements

The authors would like to thank several individuals who assisted in the preparation of this manscript, including Bill Lord and Stacy Luell (NCSU), Minyang (Mona) Liao and Richard Greatrex (University of Auckland, New Zealand), Matt Lauffer (NC DOT), and Annette Lucas (NCDENR).

References

Auckland Regional Council. 2003. *Stormwater management devices: Design guidelines manual. Technical Publication 10*. Auckland, New Zealand.

Bäckström, M. 2002. Sediment transport in grassed swales during simulated runoff events. *Water Science and Technology*, 45(7), 41-49.

Bäckström, M. 2003. Grassed swales for stormwater pollution control during rain and snowmelt. *Water Science and Technology*, 48(9), 123-134.

Barrett, M.E., P.M. Walsh, J.F. Malina, and R.J. Charbeneau. 1998. Performance of vegetative controls for treating highway runoff. *Journal of Environmental Engineering*, 124(11), 1121-1128.

Barrett, M.E., A. Lantin, and S. Austrheim-Smith. 2004. Stormwater Pollutant Removal in Roadside Vegetated Buffer Strips. *Transportation Research Record*. 1890, 129-140.

Deletic, A. 1999. Sediment behaviour in grass filter strips. *Water Science and Technology*, 39(9), 129-136.

Deletic, A. 2005. Sediment transport in urban runoff over grassed areas. *Journal of Hydrology*, 301, 108-122.

Deletic, A. and T.D. Fletcher. 2006. Performance of grass filters used for stormwater treatment – a field and modelling study. *Journal of Hydrology*, 317, 261-275.

Fassman, E.A., Liao, M., Shadkam Torbati, S., Greatrex, R. (2010). *Stormwater Mitigation through a Treatment Train*. Prepared by Auckland UniServices, Ltd. for Auckland Regional Council (Auckland, New Zealand). Auckland Regional Council Technical Report TR19/2010.

Fassman, E.A. (2011 in review). Stormwater BMP treatment performance variability for sediment and heavy metals. *Journal of Separation and Purification Technology.*

Guo, JCY and Urbonas, B. 1996. Maximized detention volume determined by runoff capture ratio. *Journal of Water Resources Planning and Management*, 122(1), 33-39.

Hayes, J.C., Barfield, B.J., and Barnhisel, R.I. 1984. Performance of grass filters under laboratory and field conditions. *Transactions of the ASAE*, 27(5), 1321-1331.

International BMP Database (IBMPD), 2010. Denver, CO. <www.bmpdatabase.org>

Jones, J. E., Clary, J., Strecker, E., and Quigley, M. M. _2008_. “15 reasons you should think twice before using percent removal to assess BMP performance.” *Stormwater*, 9, <http://www.stormh2o.com/january-february-2008/pollutants-research-bmp.aspx>.

Kirby, J.T., S.R. Durrans, R. Pitt, and P.D. Johnson. 2005. Hydraulic Resistance in Grass Swales Designed for Small Flow conveyence. *Journal of Hydraulic Engineering*, 131(1), 65-68.

Lenhart, H.A. and W.F. Hunt. 2011. Evaluating Four Storm-Water Performance Metrics with a North Carolina Coastal Plain Storm-Water Wetland. *Journal of Environmental Engineering*, 137(2), 155-162.

Malcom, H.R. 1993. *Fundamentals of Urban Hydrology*. NCSU Industrial Extension. Raleigh, NC.

Manning, R. 1891. On the flow of water in open channels and pipes. *Transactions of the Institution of Civil Engineers of Ireland*, 20, 161-207.

Mulvany, T.J. 1851. On the use of self registering rain and flood gauges in making observations of the relation of rainfall and flood discharges in given catchment. *Transactions of the Institution of Civil Engineers of Ireland*, 4, 18-33.

McNett, J.K. W.F. Hunt, J.A. Osborne. 2010. Establishing Stormwater BMP Evaluation Metrics Based upon Ambient Water Quality Associated with Benthic Macro-invertebrate populations. *Journal of Environmental Engineering*, 136(5), 535-541.

North Carolina Climate Office (NCCO). 2010. (http//www.nc-climate.ncsu.edu/cronos/) (September 5, 2010).

Passeport E. and W.F. Hunt. 2009. Asphalt Parking Lot Runoff Nutrient Characterizationfor Eight Sites in North Carolina, USA. *Journal of Hydrologic Engineering*, 14(4), 352-361

Rushton, BT. 2001. Low-impact parking lot design reduces runoff and pollutant loads. *Journal of Water Resources Planning and Management*, 127(3), 172-179.

Sansalone, J.J., J.M. Koran, J.A. Smithson, S.G. Buchberger. 1998. Physcial characteristics of urban roadway solids transported during rain events. *Journal of Environmental Engineering*, 124(5), 427-440.

Strecker, E. W., Quigley, M. M., Urbonas, B. R., Jones, J. E., and Clary, J. K. _2001_. "Determining urban storm water BMP effectiveness." *Journal of Water Resources Planning and Management*, 127(3), 144–149.

Tollner, E.W., B.J. Barfield, J.C. Hayes. 1982. Sedimentology of erect vegetal filters. *Journal of the Hydraulic Division, ASCE*, 108(12), 1518-1531.

United States Environmental Protection Agency (USEPA). 2004. *Stormwater Best Management Practice Design Guide: Volume 2 Vegetative Biofilters*. EPA/600/R-04/121A, Office of Research and Development, Washington DC.

Urban Drainage and Flood Control District (UDFCD). 2008. *Urban Storm Drainage Criteria Manual, Volume 3. Structural BMPs*. Denver, Colorado.

Winston, R.J., W.F. Hunt, D.L. Osmond, W.G. Lord, and M.D. Woodward. 2011. Field Evaluation of Four Level Spreader-Vegetative Filter Strips to Improve Urban Stormwater Quality. *Journal of Irrigation and Drainage Engineering,* 137(3): 170-182.

Winston, R.J., W.F. Hunt, S.G. Kennedy, J.D. Wright, and M.S. Lauffer. 2012. Field Evaluation of Stormwater Control Measures for Highway Runoff Treatment. *Journal of Environmental Engineering*, 138(1): 101-111.

Yu, S.L., J-T Kuo, E.A. Fassman, and H. Pan. 2001. Field Test of Grassed-swale performance in removing runoff pollution. *Journal of Water Resources Planning and Management*, 127(3), 168-171.

Zanders, J.M. 2005. Road sediment: characterization and implications for the performance of vegetated strips for treating road run-off. *Science of the Total Environment*, 339(1), 41-47.