GEORGIA DOT RESEARCH PROJECT 17-22

FINAL REPORT

OPTIMIZING DESIGN OF GDOT POST CONSTRUCTION STORMWATER BMPs FOR PERFORMANCE WHILE MINIMIZING RIGHT-OF-WAY ACQUISITION AND PEAK FLOWS

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16. Abstract

The objectives of this study were to evaluate the performance of stormwater best management practices (BMPs) used for stormwater quantity and quality control. Three field sites were tested to quantify hydraulic conductivity, infiltration, and solids removal efficiency. Removal efficiencies ranged from 12% to 35% of infiltrated runoff for VFS ranging from 15 ft. to 75 ft. long with slopes varying from 2% to 6%. For suspended solids removal, the VFS has the potential to remove between 21% and 43% when their design lengths range from 15 ft. to 75 ft long with slopes varying from 2% to 6%. It is recommended that partial credit be given for solids removal in filter strips that are shorter than the required 15 feet, and that filter strip designs incorporate the shallow grassed highway shoulder.

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Best Management Practice, BMP, Infiltration, Suspended solids, vegetated filter strips

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Final Report

OPTIMIZING DESIGN OF GDOT POST CONSTRUCTION STORMWATER BMPS FOR PERFORMANCE WHILE MINIMIZING RIGHT-OF-WAY ACQUISITION AND PEAK FLOWS

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In cooperation with
U.S. Department of Transportation
Federal Highway Administration

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
	NOTE: volumes greater than 1000 L shall be shown in m^3			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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EXECUTIVE SUMMARY

The Georgia Department of Transportation (GDOT) has recently begun using a variety of permanent stormwater retention/treatment structures, known as high-performance best management practices (BMPs) on right-of-way throughout the State. Typically, the structures are designed for both hydraulic control and for contaminant removal. However, the dimensions of the most commonly implemented BMPs are typically specified by existing standards, for example, the Georgia Stormwater Management Manual (aka the Blue Book) specifies a maximum slope of 6% on swale-type BMPs constructed for solids removal. This mild slope specification results in strict requirements on the associated right-of-way required for construction of the BMP.

This work performed for this report has focused on determining removal rates and dimensions for the commonly implemented vegetated filter strip BMP, specifically focusing on lengths for the design of the common roadside BMP and the efficiency of their solids pollutant removal capabilities. In addition to the development of an analytical model, field and lab tests were performed to assess site specific soil and BMP conditions. Field tests were performed at three vegetated filter strip locations in the metropolitan Atlanta region to gather data to assess the efficiency of the BMP using site specific soil properties. Field tests included infiltration measurement using the MPD-I, in-situ Shelby tube sampling, in-situ and saturated moisture contents, and shoulder grab samples for solids grain size analysis. Laboratory tests that were completed included falling head hydraulic conductivity, moisture content, grain size analysis via sieve tests and PSA, and density via pycnometer.

The soils that were tested were silty sands with hydraulic conductivity ranging from 8.2 x 10^{-5} cm/s to 1.0 x 10^{-4} cm/s. The tested BMPs experienced an inflow of sediments (including vegetation and roadside litter) ranging in size from roughly 0.01 mm to 10 mm. A model was developed that utilized the field and laboratory test results to solve for the travel time of runoff flowing through the BMP system. This value was then used in the model to calculate rate, and removal. The model determined the removal of runoff volume due to infiltration, and consequently, the removal of dissolved solids through dispersion. The last part of the model determined the removal of suspended solids through settlement and retainment. Removal efficiencies ranged from 12% to 35% of infiltrated runoff for VFS ranging from 15 ft. to 75 ft. long with slopes varying from 2% to 6%. For suspended solids removal, the VFS has the potential to remove between 21% and 43% when their design lengths range from 15 ft. to 75 ft long with slopes varying from 2% to 6%.

Based on the work performed for this study, the following recommendations are made:

- Include partial credit for solids removal in the design of vegetated filter strips that may be shorter than the required 15 feet. Literature review of multiple, carefully controlled studies has demonstrated that most solids are deposited in the initial 3 ft to 8 ft of flow length within the filter strip, which is substantially shorter than that required by the Blue Book. Partial credit for this solids deposition could result in significant savings in right-of-way acquisition.

- Include the shallow slope of a grassed roadside shoulder in the design of vegetated filter strips. Slopes of 2% in the shoulder can significantly impact the dimensions required for a VFS, and reduce the sizing requirements.
- Include infiltration of water into partially saturated soils in areas with significant percentages of fine-grained soils. The modeled results presented in this work demonstrated that a substantial volume of water can infiltrate during small storms, resulting in reduced water volume as well as contaminant infiltration and sorption.

CHAPTER 1. INTRODUCTION

The Georgia Department of Transportation (GDOT) has uses a variety of permanent stormwater retention/treatment structures, known as high-performance best management practices (BMPs) on right-of-way throughout the State. Typically, the structures are designed for both hydraulic control and for contaminant removal. However, the dimensions of the most commonly implemented BMPs are typically specified by existing standards, leaving the engineer with limited alternatives in the design and construction of these devices. For example, the Georgia Stormwater Management Manual (aka the Blue Book) specifies a maximum slope of 6% on swale-type BMPs constructed for solids removal. This mild slope specification results in strict requirements on the associated right-of-way required for construction of the BMP.

Post-construction pollutants and mitigation of the pollutants are regulated through the Department's municipal separate storm sewer (MS4) permit and the US Fish and Wildlife Service through the permitting process of the US Army Corps of Engineers 404 permitting. The MS4 regulations are controlled by removal requirements for total suspended solids (TSS), for detention of runoff volume, and for mitigation of overland flow; the 404 regulations are determined by required water quality assessments and implementations. While the current designs for BMPs specified on GDOT right-of-way are functioning well, this research works to determine if the design of the most commonly implemented BMPs, specifically vegetated filter strips (VFS), could be optimized to reduce the cost of right-of-way acquisition, while still maintaining the required environmental protection. The work performed in this report compares the design and performance of several BMP stormwater VFS in terms of the dimensions, slope, and contaminant (solids) removal.

According to the National Water Quality Inventory Report (US EPA, 2009), an assessment of 5.7 million km of rivers and streams [representing 16% of the total in the US] revealed that 44% were found to be impaired, i.e., not able to support one or more of its designated uses. The most common sources of impairment include runoff from agricultural activities, hydro-modification, habitat alteration, unspecified non-point sources, atmospheric deposition, and urban runoff from stormwater (US EPA, 2009). According to the water quality assessment report for Georgia (US EPA, 2010), for the 19% of the total rivers and streams [112896 km] that were assessed, 58% were found to be impaired. In all the impaired rivers and streams, the pollutant contribution from non-point sources was highest at 68%, while urban stormwater related runoff contributions to the impairment was second highest, at 25.3%. For GDOT to maintain runoff water-quality by limiting contaminant discharge to receiving waters, understanding the components of runoff originating from highway surfaces in Georgia and the performance of stormwater BMPs to date is important. Designing and building physically and economically effective solutions to treat pollutants in the highway runoff before they discharge into receiving waters is paramount.

Two of the major questions required to assess the efficiency of any BMP in attaining water quality goals (US EPA 2002) is: (1) How varied is the degree of pollution control performance, i.e., effluent quality, provided by the BMP from pollutant to pollutant? (2) How is stormwater volume mitigated? Hydraulic control is relatively straightforward; however, for contaminants, stormwater runoff contains a variety of pollutants that can impact the quality of receiving waters and some parameters may even be site specific (US EPA 2002). Pollutants may be divided into three basic categories which are useful to assess the efficacy of BMP structures: (1) physical characteristics like temperature, pH, conductivity, etc.; (2) concentration of heavy metals (e.g., lead, copper, etc.); and (3) nutrient loadings (e.g., nitrates, nitrites, phosphates, etc., which impact aquatic life quality).

The work performed in this project focused on two critical Department needs: (1) selection criteria specified to implement low maintenance BMPs in order to reduce the long-term burden on upkeep, and (2) design parameters optimized for design and construction in transportation right-of-way (as opposed to parameters that were optimized for applications with site development criteria).

This work performed in this project focused on vegetated filter strips with the following emphases:

> (1) A comprehensive literature review to examine the factors that control contaminant removal in a variety of optimized stormwater structures. This will include all factors that act to increase, or decrease, contaminant removal in the BMPs that are commonly specified on GDOT right-of-way.
>
> (2) Performance at three field sites to assess suspended solids removal under optimized BMP dimensions.
>
> (3) Statewide guidance for design conditions to optimize contaminant removal, while minimizing right-of-way acquisition for construction of stormwater BMPs, with specific emphasis on refining GDOT specific stormwater parameters for design.

CHAPTER 2. LITERATURE REVIEW

A variety of stormwater BMPs are being used throughout the United States to naturally attenuate contaminated stormwater runoff. Because each BMP has its own specific characteristics and application, any one BMP may not be applicable to all locations and conditions. This tends to make selecting the optimum BMP for a given site and suite of stormwater contaminants somewhat challenging. The current practice is to use selection matrices published in various state DOT manuals to facilitate the selection of an adequate BMP for a particular application. The most common complication is having the desire to optimize pollutant removal while minimizing right-of-way acquisition (Wang et al., 2009). Methods of comparing and balancing these variables have been investigated (Bhatt, 2016), with emphasis on previous work, which laid the foundation for implementation of the Analytical Hierarchy Process (AHP), developed by Saaty et al. (1980) and Young (2010). AHP is a hierarchical technique for organizing and analyzing complex decisions, which can be applied to the complex decisions such as development and placement of BMPs.

The Department's MS4 permit (2017) requires that a "stormwater management system shall be designed to retain up to the first 1.0 inch of rainfall on the site, to the maximum extent practicable" and if that is not feasible, the remaining runoff must be treated to 80% TSS removal. Typically, TSS is taken as a surrogate for other contaminants that are found in stormwater, such as nutrients and heavy metals, and treatment for TSS is assumed to reduce those concentrations as well. Previous research (Bhatt, 2016) on specific contaminant removals resulted in the following conclusions regarding the performance highway runoff into sand filters (for runoff from GDOT right-of-way into the Canton sand filter): the distribution of most incoming pollutants followed a log normal distribution, implying that the occurrence of extreme contaminant loadings was low, and the historical sand filter data revealed that among nutrients, a majority of the total phosphorus was mitigated by the sand filter whereas neither dissolved phosphorus, total NO_X, nor nitrogen was mitigated. Among metals, zinc was mitigated by the sand filter, but copper and lead were not. Additionally, a statistical analysis of data from the International Stormwater BMP Database demonstrated that the design parameters of sand filters that could effectively mitigate total metals had a median pool area of 102 m^2, pool depth of 8 m, filter surface area of 280 m^2, and filter depth of 46 cm. However, investigation into the mechanisms that contribute to these results is still ongoing.

VEGETATED FILTER STRIPS

While filter strips are designed for a minimum length of flow to achieve 60% total suspended solids (TSS) removal, partial removal also occurs when using filter strips that are below the minimum length of flow. Because vegetated filter strips are engineered to treat runoff through multiple removal mechanisms, there are a range of both physical and chemical processes that are important to ensuring contaminant removal. In terms of physical removal, VFS are designed to remove solid particles through sedimentation, with the solid particles settling under gravity as water carrying suspended solids flows through the filter strip. The presence of the vegetation on the filter strip also results in filtration of particles, which is a physical straining mechanism that retains particles in the space between the vegetated leaves by physically blocking their transport. In addition, water flowing through a VFS can transport small suspended solid particles into the underlying soil through infiltration due to gravity flow and/or capillary action. This process will also transport dissolved solids and contaminants into the subsurface below the VFS. In terms of physical/chemical mechanisms, suspended solids can adsorb to the VFS soil and vegetation and plants. While vegetation and microbes are important removal mechanisms for pollutants in filter strips, they are most effective at removing dissolved contaminants.

To ensure field performance and removal, flow through a filter strip must be sheet flow, with a mild slope (2%-6%). The Georgia Stormwater Management Manual (Blue Book, version 2/1/2017) specifies pollutant removal levels in a vegetated filter strip of 60% for TSS, 20% for nutrients, and 40% for metals. The Blue Book specifies a minimum filter strip length equal to 15 feet (4.6 m), with 25 feet (7.6 m) preferred. Note: the dimensions of filter strips can be described with the terms width and length to get the area of drainage. However, these terms are not used consistently in the stormwater literature. To be consistent with the Blue Book, the following terminology will be used:

Width = filter strip dimension perpendicular to flow direction
Length = filter strip dimension parallel to flow path

Vegetated grass filters are common due to their simplicity and relatively low cost to construct. They are effective stormwater controls for removing total suspended solids (60% removal for a 15-foot length); however, to date, no credit is given for TSS removal unless the minimum filter strip length of 15 feet is met. This approach is attractive due to its simplicity, but it contradicts several field and modeling studies that indicate that most of the TSS removal in a filter strip occurs in the first meter on length. Gharabaghi et al. (2006) studied the impact of vegetation type, width of filter strip, runoff flow rate, and inflow sediment characteristics on the removal efficiency of filter strips in Ontario, Canada. Influent with known pollutant characteristics were introduced into filter strips with an approximate slope of 5%, four types of vegetation, and four lengths. The percent removal of TSS was determined as a function of length along the flow path through the filter strip using statistical analysis of 58 different tests. Results were analyzed in the following particle size categories:

0.5 microns < d < 2.9 microns
2.9 microns < d < 6.4 microns
6.4 microns < d < 12 microns
12 microns < d < 39 microns
39 microns < d < 68 microns
68 microns < d < 151 microns

Predictably, larger particles settle very quickly in approximately the initial 3 feet (1 m) of the filter strip, but even the smallest particles saw substantial removal within the first few feet of flow. On average, the experiments in this study demonstrated 50% removal of sediments within the first 8.2 feet (2.5 m) of filter flow length, which is significantly shorter than the minimum length specified in the Blue Book. For longer filter strips with lengths of 16.4 feet (5 m), particles and aggregates larger than 40 microns were removed at 95%, but smaller particle sizes were transported through the length of the grass filter strip.

Barrett et al. (2004) performed a two-year controlled field study on vegetated channels at four locations in California. Stormwater was sampled at the edge of pavement (EOP), and as a function of length of drainage along the filter strip for multiple storms over the two-year study period. The results demonstrated that most of the removal, about

50% of TSS, occurred within the first 3.6 ft (1.1 m) of filter strip length, and leveled to a constant value of removed as filtration length increased (Figure 1).

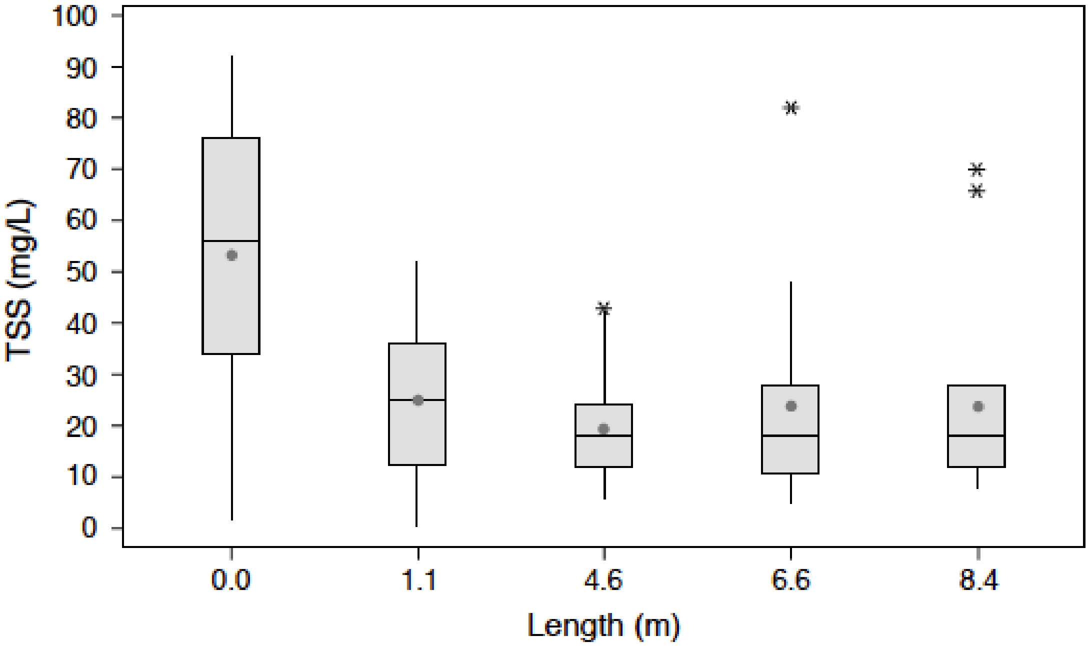


Figure 1. Box plot of TSS event mean concentrations at Sacramento (Figure from Barrett et al., 2004).

A recent numerical study by Winston et al. (2017) combined the rational method and Manning's equation with Stokes' Law to predict the setting velocity of particles flowing in sheet flow through swales and vegetated filter strips. The length of flow, drainage area, and slope of the filter strips were varied within the numerical model to determine the sensitivity of particle removal to each of those factors. The results showed that filter strips were not sensitive to slope as long as sheet flow and low velocity was maintained, and that more than 50% removal of TSS will occur within the first 3 feet (1 m) of the filter strip, with only minimal removal occurring as length extended beyond 25 feet (7.6 m).

INFILTRATION IN PARTIALLY SATURATED SOILS

The Green-Ampt model (1911) is used in infiltration modeling and is based on the assumption that the wetting front (z_f) propagates in a predictable uniform front (Dingman 2008; Ferguson 1994; Lu and Likos 2004). Given the cumulative infiltration (F(t)) as an input parameter, a non-linear expression can be solved iteratively to determine a value of ψ_f (Dingman 2008).

$$ln\left(1-\frac{F(t)}{(\phi-\theta_o)\psi_f}\right)=\frac{K_{sat}t-F(t)}{(\phi-\theta_o)\psi_f}$$

The depth of the wetting front (z_f) and infiltration rate can then be solved.

$$z_f=\frac{F(t)}{(\phi-\theta_o)}$$

GDOT’s current drainage manual uses Manning’s equation to design filter strips, with no consideration for infiltration because Manning’s equation was designed for open-channel flow, with the assumption of saturated boundaries, where little to no infiltration will occur. Accounting for infiltration could help in decreasing the length to which filter strips need to be, as well as removing particulate from the downstream runoff.

For unsaturated soils, the infiltration rate decreases rapidly, due to wetting of the soil; however, at the beginning of the storm, infiltration rates will be very high (Figure 2). For a typical storm in the Piedmont region, infiltration via suction into soil could account for about 75% of rainfall in the first 5 minutes, or the “first flush”, of a 2-year 24-hour design storm, using the 1D Green-Ampt model with typical parameters of Piedmont soil (Figure 3). During the first flush, many dissolved and suspended pollutants are transported with the runoff, so the water and pollutant loss due to suction is not considered when the stormwater is infiltrating.

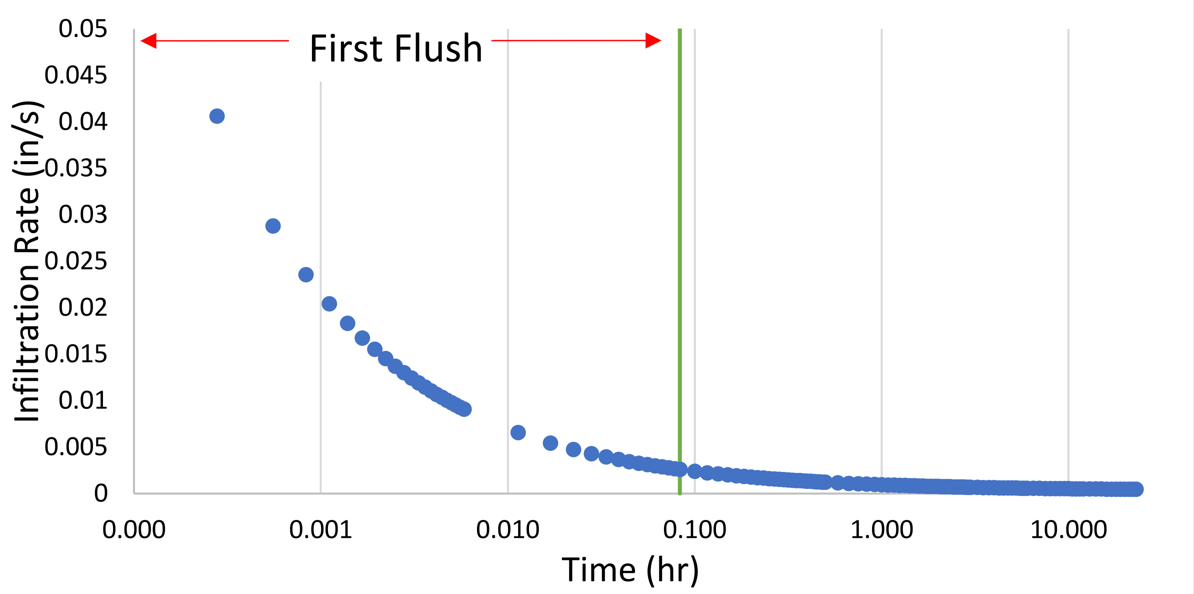


Figure 2. Infiltration rate of a typical Piedmont soil during a 2-year 24-hour design storm.

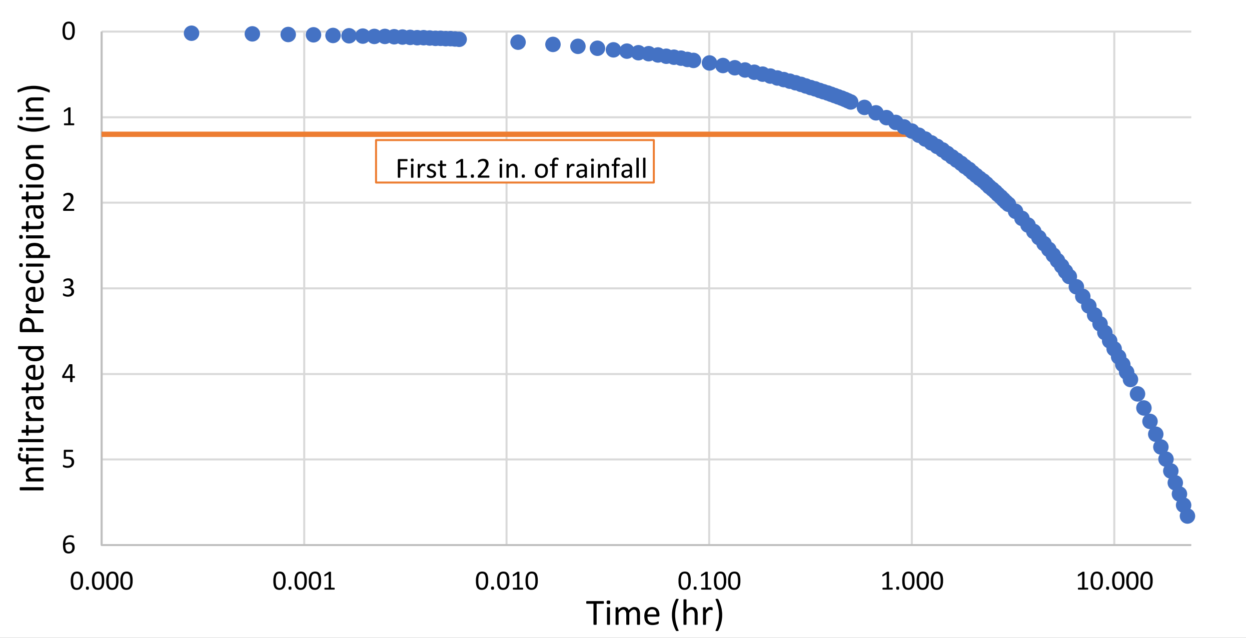


Figure 3. Amount of runoff infiltrated in a typical Piedmont soil during a 2-year 24-hour design storm.

According to permit conditions, GDOT is accountable for the first 1.2 inches of runoff, which consists of the first flush and the first 1.2 inches of rainfall should fully infiltrate if it takes more than an hour for this amount of precipitation to fall (Figure 3). Water quantity has been studied for vegetated filter strips, with measurement of inflow and outflow volume, surface geometry, and some solids deposition (Table 1). These procedures have ranged from controlled, simulated rainfall in laboratory flumes to real-time stormwater sampling over a vegetated slope.

Table 1. Summary of Published VFS Studies

Surface Type	Storm Type	Measurements	Sampling	Reference
Vegetated Grass Swale Shoulder	Simulated	• Surface microtophography • Inlet (controlled) & outlet volume • Outlet intensity/velocity	At the outlet	Gulliver, 2016
Wooden Flume	Simulated	• Inlet (controlled) & outlet volume • Surface microtophography	Subsurface infiltration via drainpipes along strip and at the outlet	Gulliver, 2016
Vegetated filter strip for cropland	Real-time	• Inlet & outlet volume • Hydraulic conductivity (infiltrometer) • Rainfall intensity • Surface geometry	At the outlet	Muñoz-Carpena, 1999
Vegetated filter strip into a biofiltration swale	Simulated and real-time	• Inlet & outlet volume • Rainfall intensity	At the outlet	Flanagan, 2017
Well maintained sloped lawn with vertical metal plates as side boundaries	Simulated	• Inlet (controlled) & outlet water volume • Inlet & outlet sediment concentration • Surface geometry	At the outlet and along the lawn using isokinetic samplers	Deletic, 2006
8 different VFS ranging in slope, width, and length	Real-time	• Rainfall intensity • Surface geometry • Outlet volume • Sediment concentration	Flow-weighted composite samples, at the outlet, and along the strip	Barrett, 2004

SUSPENDED SOLIDS DEPOSITION

Previous work has studied the deposition of solids in roadside vegetated structures. Deletic (2010, 2001) developed different models that predict solids buildup on impervious surfaces (2010), solids wash from impervious surfaces (2010), and trapping efficiency in roadside slopes (2001), using Stoke’s Law and a modified Kentucky Model.

The work of Muñoz-Carpena (1999) focused primarily on the transport of solids and the effects that a buildup of suspended solids (or wedge) would have on the solids transport. The work relies on Manning’s kinematic wave equation and Einstein’s total transport function to model the settlement of solids. Winston (2017) modeled TSS removal in both grassed swales and filter strips using the rationale method, Manning’s equation, and particle settling equations developed by Deletic (2005).

CHAPTER 3. LENGTH DETERMINATIONS FOR VEGETATED FILTER STRIPS

Vegetated filter strips are designed to remove pollutants from stormwater runoff primarily through infiltration of water, deposition of solids, and sorption of dissolved pollutants. Stormwater runoff flows from the highway pavement, through a grassed shoulder, down a sloped grass swale to concentrate for removal through a grassed channel. Because filter strips are intentionally designed for sheet flow to reduce erosion potential and to increase contaminant removal, they are often designed with removal consideration for only the slope of the swale; however, most highway designs include grassed shoulders with gentle slopes that also account for significant deposition of solids and removal of pollutants, this is known as a “Barn Roof” design (GDOT DPM 2021) (Fig. 4). The work in this chapter examines the design procedure for vegetated filter strips as outlined in the Georgia Blue Book, and performs an analysis of design length with grassed highway shoulders included in the length of flow calculations.

DESIGN OF VEGETATED FILTER STRIPS: ANALYSIS OF BLUE BOOK PROCEDURE

According to the Georgia Stormwater Management Manual: Volume 2: Technical Handbook (aka, the Blue Book), vegetated filter strips have the following design requirements:

- Maximum water depth of 1-2 inches to ensure sheet flow and prevent concentrated flow
- Maximum drainage area = 5 acres, though 2 acres is preferred
- Sizing: drainage area/VFS surface area = 10:1 (approximate)

- Maximum flow lengths = 75 ft for runoff from impervious surfaces and 150 ft for runoff from pervious surfaces
- Slopes = 2 – 6 %
- Wetting front must exceed 1 foot below surface (i.e., depth to water table/saturation)
- Minimum travel time = 5 minutes

The equation provided in the Blue Book to determine discharge from a vegetated filter strip is as follows:

$$q = \frac{0.00236}{n} * y^{5/3} * S_o^{1/2} \tag{1}$$

Where q = discharge per foot width of filter strip (cfs/ft)

n = Manning's roughness coefficient (Table 3.1.5-2 of the Blue Book but ideally values are field measured)

y = depth of water entering the VFS (maximum 1-2 inches) (in)

S_o = slope (2 – 6 %)

Because the Blue Book equation is similar to Manning's Equation but differs in some terms, an analysis was performed to determine the assumptions that are implicit in Equation (1):

$$Q = \frac{k}{n} * A * R^{2/3} * S_o^{1/2} \tag{2}$$

Where Q = total discharge (cfs)

k = unit conversion and is equal to 1.49 for U.S. Customary Units (USCU) and 1.0 for SI

n = Manning's roughness coefficient

A = cross-sectional area (depth x width) (ft^2)

R = hydraulic radius (ft) = A/P, where P = wetted perimeter (2*depth + width)

S_o = slope

Note that for very wide and shallow flow paths, the wetted perimeter can be reduced to the width (P = x), and substituting x*y for A and x for P leads to equation (3):

$$Q = \frac{k}{n} * (x * y) * \left(\frac{x*y}{x}\right)^{2/3} * S_o^{1/2} \qquad (3)$$

Simplifying:

$$q = \frac{k}{n} * y^{5/3} * S_o^{1/2} \qquad (4)$$

Where x = VFS width (ft)

y = depth of water entering VFS (ft)

Because of the shallow depth that is to be expected in flow through vegetated filter strips, the Blue Book converted depth in feet to inches by dividing the depth term in the equation (y) by $12^{5/3}$, resulting in (5):

$$q = \frac{k}{n} * y^{\frac{5}{3}} * S_o^{\frac{1}{2}} * 12^{-5/3} \qquad (5)$$

Using U.S. Customary Units and substituting k = 1.49 into the equation followed by simplifying results in equation (6).

$$q = \frac{0.0236}{n} * y^{5/3} * S_o^{1/2} \qquad (6)$$

It is important to note that this equation is one order of magnitude higher than equation provided in the Blue Book (see Equation 1). It is believed that the Blue Book equation derived from Manning’s Formula may have been entered into the Blue Book incorrectly.

The design procedure for vegetated filter strips includes determining the width and length of the filter strip. The minimum width of the filter strip (parallel to the road) can be determined by the following equation:

$$W_{fMIN} = \frac{Q_{WQ}}{q} \tag{7}$$

Where W_{fMIN} = minimum filter strip width, perpendicular to flow and parallel to road (ft)

Q_{WQ} = water quality volume peak flow (ft^3/s)

q = discharge per foot of width of filter strip (cfs/ft) found in equation (6)

The water quality volume peak flow (Q_{WQ}) calculation is a design procedure used to estimate peak discharges for small storm events. In order to quantify the Q_{WQ}, first the water quality volume (WQ_V) must be determined. The WQ_V is the volume of water to be treated to meet the required 80% removal of the average annual post-development total suspended solids (TSS) load. Typically, this is achieved by interception, retainment, or treatment of *some* runoff from *all* storms and *all* runoff from *85%* of the storms annually. The WQ_V is calculated from the following equation:

$$WQ_V = \frac{P_{85\%} * R_v * A}{12} \tag{8}$$

Where WQ_V = water quality volume (acre-feet)

$P_{85\%}$ = average 85th percentile annual rainfall (in)

R_v = volumetric runoff coefficient (-)

A = total drainage (acres)

The volumetric runoff coefficient (R_v) is defined as $R_v = 0.05 + 0.009 * (I)$, where I is the percent of impervious cover that is generating runoff (i.e., the watershed). The Q_{WQ} uses the WQ_V to produce a Curve Number (CN) from the following equation:

$$CN = \frac{1000}{10+5*P_{85\%}+10*Q_{WV}-10*\left(Q_{WV}^2+1.25*Q_{WV}*P_{85\%}\right)^{1/2}} \tag{9}$$

Where CN = Curve Number

Q_{WV} = Water Quality Volume expressed in inches $Q_{WV} = P_{85\%} * R_v$

While there are many tables and charts provided to help determine the CN, the charts are developed from equation 9; therefore, this is the most direct and specific determination of the CN.

Variables such as time of concentration (t_c), initial abstract (I_a), potential maximum soil retention (S), and unit peak discharge (q_u) must be determined to determine Q_{WQ}. The time of concentration is defined as the time it takes from when precipitation begins to when the runoff flows as concentrated flow or the time it takes to travel as concentrated flow to the area of the considered design. In the case of a roadside vegetated filter strip, the time of concentration would be the time that it takes for the runoff to travel over the asphalt to the VFS in a direction perpendicular to the flow of traffic. The following equation was derived from Manning's equation and can be used to determine concentrated flow:

$$t_c = 56 * \frac{L_0^{0.6} * n^{0.6}}{i^{0.4} * S_o^{0.3}} \tag{10}$$

Where t_c = time of concentration (sec)

L_0 = length of flow path to design location (ft)

n = Manning's roughness coefficient of the flow path to the design location

i = rainfall intensity (in/hr) (found in NOAA Atlas 14)

S_o = slope of flow path

The initial abstract and potential maximum soil retention are dependent on CN and can be determined from the following two equations:

$$S = \frac{1000}{CN} - 10 \tag{11}$$

$$I_a = 0.2 * S \tag{12}$$

Where S = potential maximum soil retention (in)

I_a = initial abstract (in) (Table 3.1.5-3, Blue Book)

The unit peak discharge (q_u) (cfs/mi^2/in – shortened to csm/in) can then be determined if the amount of 24-hour precipitation (P (in)) is known. Charts 3.1.5-6 and 3.1.5-7 are provided in the Blue Book to determine q_u and require the use of the ratio of I_a/P and the calculated t_c (in hours). Note: the units for q_u are cubic feet per second of flow per square mile of drainage area per inch of runoff. From this, the water quality volume peak flow (Q_{WQ}) (Equation 7) can be solved, ultimately determining the minimum width for a VFS:

$$Q_{WQ} = q_u * A * Q_{WV} \tag{13}$$

Where Q_{WQ} = water quality volume peak flow (cfs)

q_u = unit peak discharge (csm/in)

A = drainage area (mi2)

Q_{WV} = Water Quality Volume in inches

The minimum filter strip width (W_{fMIN}) is now solvable, which is one necessary dimension for the design process of a VFS.

The next step in the design approach is to ensure that depth of flow is less than 1 inch when it is entering the system. According to the Blue Book, this is determined according to the following equation:

$$D = {(1.04 * q^{0.6} * n^{0.6})}/{S^{0.3}} \qquad (14)$$

D = depth of flow (in) and all other variables are previously defined

However, the derivation of this equation is not completely clear. Derivation from Manning's formula, and subsequently from equation (6), would result in:

$$q = \frac{0.0236}{n} * y^{5/3} * S_0^{1/2}$$

Rearrange to get: $y = \left(\frac{q*n}{0.0236*S_o^{1/2}}\right)^{3/5}$

Simplify: $D = y = {(9.47 * q^{0.6} * n^{0.6})}/{S_o^{0.3}} \qquad (15)$

Based on the result from derivation using Manning's Equation, the coefficient results in a factor of 9 times higher than the equation presented in the Blue Book.

Ideally, to ensure that the depth of water entering the system is less than 1 inch in order to ensure sheet flow instead of concentrated flow, the q, n, and S_o values should be the values determined for the road, not for the vegetated filter strip. Therefore, q_u might be preferred as opposed to q, with the respective n value for asphalt and the grade at which the road is constructed.

The last and final step is to determine the length of the filter strip; that is, the final dimension. The equation provided by the Blue Book is as follows:

$$L_f = \frac{(T_t)^{1.25} * (P_{2-24})^{0.625} S_o^{1/2}}{0.338 * n} \qquad (16)$$

Where L_f = length of VFS (ft)

T_t = travel time through filters trip (min)

$P_{2\text{-}24}$ = 2-year, 24-hour rainfall depth (feet)

The length of filter strip equation was developed from what was originally a sheet flow travel time (hrs) equation and as given in the Blue Book:

$$T_t = \frac{0.42 * (n * L)^{0.8}}{60 * (P_{2-24})^{0.5} * S_o^{0.4}} \qquad (17)$$

Rearranging this equation and setting travel time to minutes simplifies to Equation (16). The minimum travel time required within a vegetated filter strip is 5 minutes. With this detailed description, the VFS has three dimensions: width, flow depth, and length, as well as a slope component, that is typically determined by engineering judgement and land availability.

ANALYSIS OF DRAINAGE LENGTHS FOR REVISION TO THE GDOT DRAINAGE MANUAL

The lengths of vegetated filter strips as specified in the GDOT Design Manual in Table 10.6.1-1 (Table 2) were designed with direct lengths for design of a VFS as a function of pavement width and slope. In the design assumptions, the definition of a filter strip includes a length of grass shoulder of approximately 2% slope followed by grass swale with design slopes that range from 8:1 to 4:1. This is important because the GDOT

Design Manual does not differentiate any changes in slope within the VFS; that is, the shallow slope of the shoulder is not differentiated from the steeper slope of the swale (Fig. 4). It is important to note that many Georgia roads have significant lengths of grass shoulders with gradual slopes that can remove substantial percentages of TSS before runoff enters the sloped VFS. Consequently, analysis was performed to separate varying lengths of grassed shoulder (2, 4, 6, and 8 feet) combined with VFS with slopes (2%, 4%, and 6%) to quantify the difference in design lengths of a VFS, considering all other factors of the GDOT Design Manual remain the same (Table 3). The percent differences for how much land (i.e., VFS length) would be saved by the new design lengths of VFS when the additional length of grass shoulder is considered generally range from 6%-10% (Table 4). The steps taken to calculate the suggested VFS lengths are similar to the previously derived equations and described in the following paragraphs.

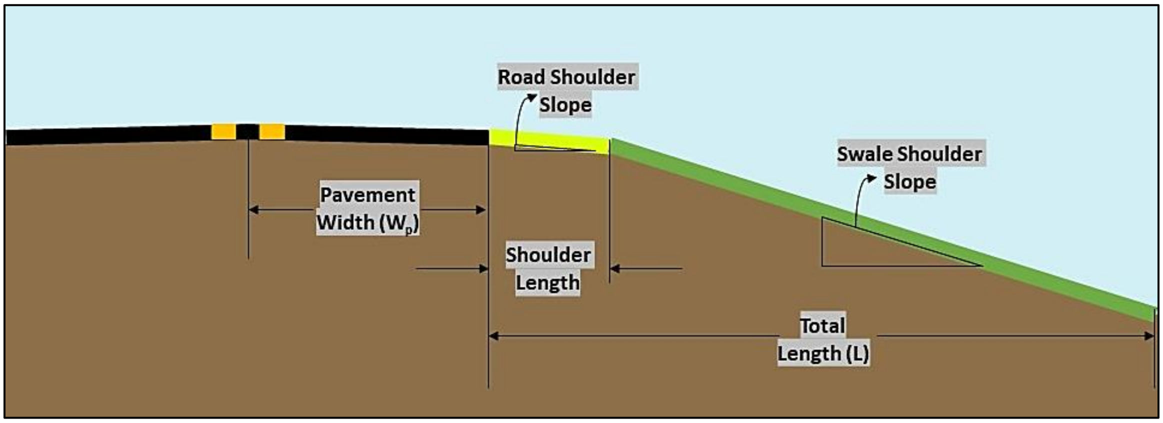


Figure 4. Profile view of vegetated roadside slope with "Barn Door" design. The pavement width is taken from the top of the crown to the edge of the road.

Table 2. GDOT's Current Design Manual for Determining VFS Length

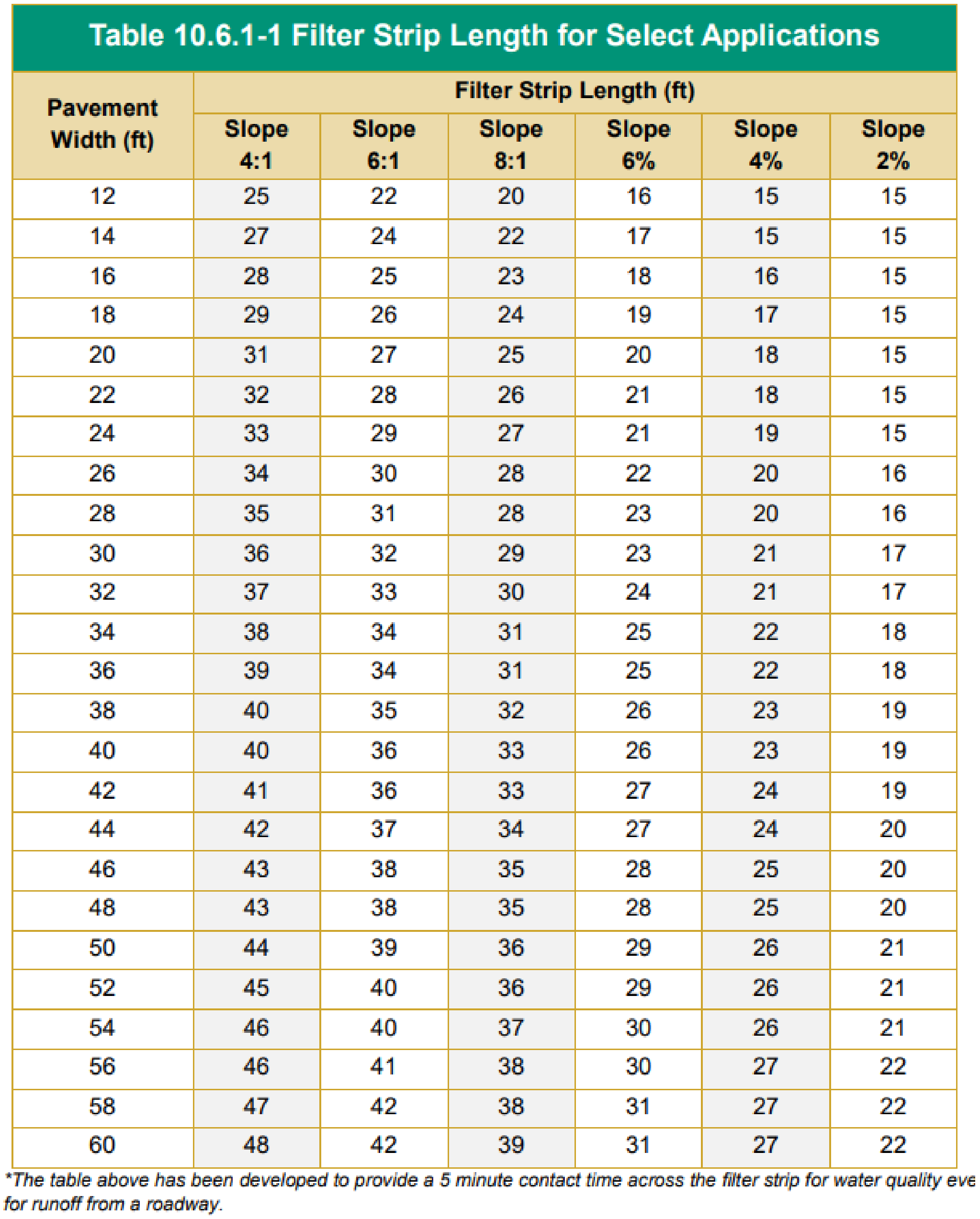


Table 10.6.1-1 Filter Strip Length for Select Applications

Pavement Width (ft)	Filter Strip Length (ft)					
	Slope 4:1	Slope 6:1	Slope 8:1	Slope 6%	Slope 4%	Slope 2%
12	25	22	20	16	15	15
14	27	24	22	17	15	15
16	28	25	23	18	16	15
18	29	26	24	19	17	15
20	31	27	25	20	18	15
22	32	28	26	21	18	15
24	33	29	27	21	19	15
26	34	30	28	22	20	16
28	35	31	28	23	20	16
30	36	32	29	23	21	17
32	37	33	30	24	21	17
34	38	34	31	25	22	18
36	39	34	31	25	22	18
38	40	35	32	26	23	19
40	40	36	33	26	23	19
42	41	36	33	27	24	19
44	42	37	34	27	24	20
46	43	38	35	28	25	20
48	43	38	35	28	25	20
50	44	39	36	29	26	21
52	45	40	36	29	26	21
54	46	40	37	30	26	21
56	46	41	38	30	27	22
58	47	42	38	31	27	22
60	48	42	39	31	27	22

**The table above has been developed to provide a 5 minute contact time across the filter strip for water quality eve for runoff from a roadway.*

Flow depth entering the system and initially traveling through the shoulder is calculated first, followed by determination of the initial velocity according to:

$$y_{gs} = \left[n * Q_{wq}/(k * WP * S_r^{0.5})\right]^{3/5} \qquad (18)$$

$$v_{gs} = Q_{wq}/(WP * y_{gs}) \tag{19}$$

y_{gs} = flow depth through grass shoulder (ft)

v_{gs} = velocity through grass shoulder (ft/s)

WP = width of VFS (ft)

The travel time through the shoulder ($T_{t,gs}$) can then be calculated in minutes:

$$T_{t,gs} = L_{gs}/(v_{gs} * 60) \tag{20}$$

These steps are then repeated for the grass swale and solved for varying swale slopes, ranging from 8:1 to 4:1. The travel times are then combined to estimate the travel time through the entire system (shoulder plus swale side slope). The suggested lengths are for the swale side slope and do not include the length of the grass shoulder with a smaller slope, instead the grass shoulder lengths are used as a determining factor:

$$L_{ss} = (5 - T_{t,gs}) * 60 * v_{ss} \tag{21}$$

L_{ss} = length of swale shoulder (ft)

v_{ss} = velocity of swale shoulder (ft/s)

Table 3 and Table 4 present the results for filter strip lengths and the percent differences from the GDOT table (Table 2). The data were determined by including road shoulder lengths. Table 3 and Table 4 assume the road shoulder slope is 6%, while table A1 and A2 in the appendix show results for a road shoulder slope of 2% and 4%, respectively. Table A3 and A4 display the percent differences from the original table used in GDOTs Drainage Manual (Table 2) of each respective slope. Consideration of the road shoulder will result in length reductions of roughly 5-10%, depending on the design.

Table 3. Filter Strip Length with Increased Shoulder Length

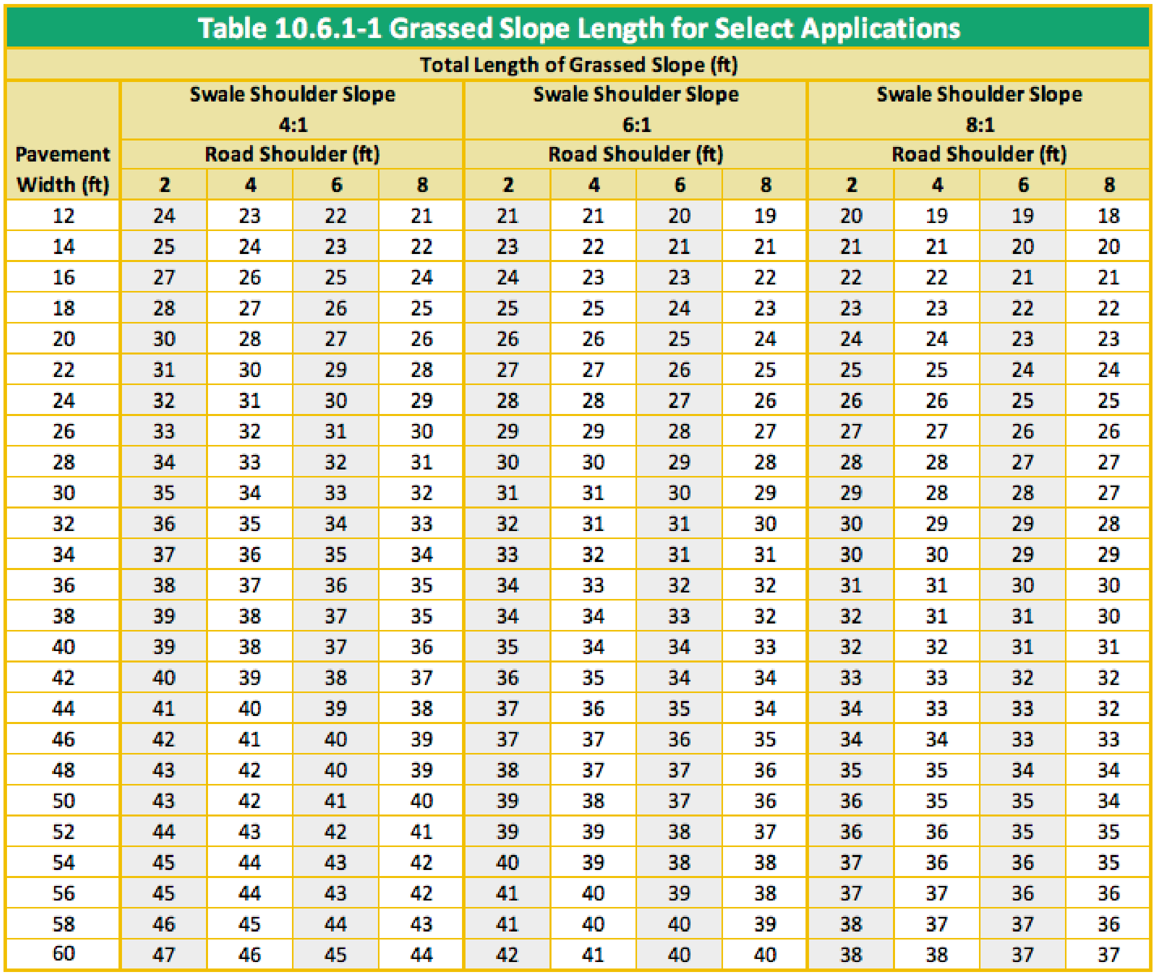


Table 10.6.1-1 Grassed Slope Length for Select Applications

	Total Length of Grassed Slope (ft)											
	Swale Shoulder Slope 4:1				Swale Shoulder Slope 6:1				Swale Shoulder Slope 8:1			
Pavement Width (ft)	Road Shoulder (ft)				Road Shoulder (ft)				Road Shoulder (ft)			
	2	4	6	8	2	4	6	8	2	4	6	8
12	24	23	22	21	21	21	20	19	20	19	19	18
14	25	24	23	22	23	22	21	21	21	21	20	20
16	27	26	25	24	24	23	23	22	22	22	21	21
18	28	27	26	25	25	25	24	23	23	23	22	22
20	30	28	27	26	26	26	25	24	24	24	23	23
22	31	30	29	28	27	27	26	25	25	25	24	24
24	32	31	30	29	28	28	27	26	26	26	25	25
26	33	32	31	30	29	29	28	27	27	27	26	26
28	34	33	32	31	30	30	29	28	28	28	27	27
30	35	34	33	32	31	31	30	29	29	28	28	27
32	36	35	34	33	32	31	31	30	30	29	29	28
34	37	36	35	34	33	32	31	31	30	30	29	29
36	38	37	36	35	34	33	32	32	31	31	30	30
38	39	38	37	35	34	34	33	32	32	31	31	30
40	39	38	37	36	35	34	34	33	32	32	31	31
42	40	39	38	37	36	35	34	34	33	33	32	32
44	41	40	39	38	37	36	35	34	34	33	33	32
46	42	41	40	39	37	37	36	35	34	34	33	33
48	43	42	40	39	38	37	37	36	35	35	34	34
50	43	42	41	40	39	38	37	36	36	35	35	34
52	44	43	42	41	39	39	38	37	36	36	35	35
54	45	44	43	42	40	39	38	38	37	36	36	35
56	45	44	43	42	41	40	39	38	37	37	36	36
58	46	45	44	43	41	40	40	39	38	37	37	36
60	47	46	45	44	42	41	40	40	38	38	37	37

Table 4. Percent Differences Between VFS Lengths with Shoulder Length Increased

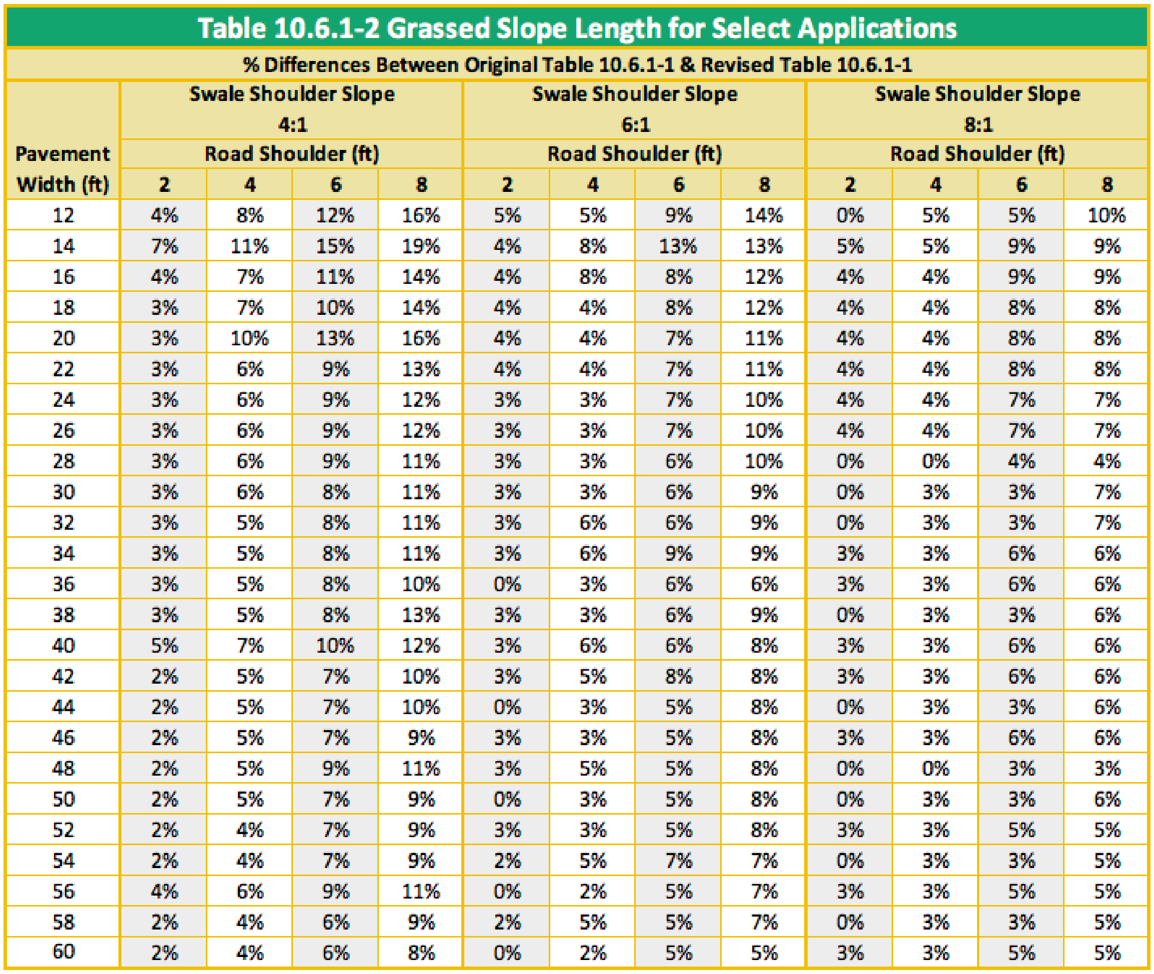


Table 10.6.1-2 Grassed Slope Length for Select Applications

% Differences Between Original Table 10.6.1-1 & Revised Table 10.6.1-1

	Swale Shoulder Slope 4:1				Swale Shoulder Slope 6:1				Swale Shoulder Slope 8:1			
	Road Shoulder (ft)				Road Shoulder (ft)				Road Shoulder (ft)			
Pavement Width (ft)	**2**	**4**	**6**	**8**	**2**	**4**	**6**	**8**	**2**	**4**	**6**	**8**
12	4%	8%	12%	16%	5%	5%	9%	14%	0%	5%	5%	10%
14	7%	11%	15%	19%	4%	8%	13%	13%	5%	5%	9%	9%
16	4%	7%	11%	14%	4%	8%	8%	12%	4%	4%	9%	9%
18	3%	7%	10%	14%	4%	4%	8%	12%	4%	4%	8%	8%
20	3%	10%	13%	16%	4%	4%	7%	11%	4%	4%	8%	8%
22	3%	6%	9%	13%	4%	4%	7%	11%	4%	4%	8%	8%
24	3%	6%	9%	12%	3%	3%	7%	10%	4%	4%	7%	7%
26	3%	6%	9%	12%	3%	3%	7%	10%	4%	4%	7%	7%
28	3%	6%	9%	11%	3%	3%	6%	10%	0%	0%	4%	4%
30	3%	6%	8%	11%	3%	3%	6%	9%	0%	3%	3%	7%
32	3%	5%	8%	11%	3%	6%	6%	9%	0%	3%	3%	7%
34	3%	5%	8%	11%	3%	6%	9%	9%	3%	3%	6%	6%
36	3%	5%	8%	10%	0%	3%	6%	6%	3%	3%	6%	6%
38	3%	5%	8%	13%	3%	3%	6%	9%	0%	3%	3%	6%
40	5%	7%	10%	12%	3%	6%	6%	8%	3%	3%	6%	6%
42	2%	5%	7%	10%	3%	5%	8%	8%	3%	3%	6%	6%
44	2%	5%	7%	10%	0%	3%	5%	8%	0%	3%	3%	6%
46	2%	5%	7%	9%	3%	3%	5%	8%	3%	3%	6%	6%
48	2%	5%	9%	11%	3%	5%	5%	8%	0%	0%	3%	3%
50	2%	5%	7%	9%	0%	3%	5%	8%	0%	3%	3%	6%
52	2%	4%	7%	9%	3%	3%	5%	8%	3%	3%	5%	5%
54	2%	4%	7%	9%	2%	5%	7%	7%	0%	3%	3%	5%
56	4%	6%	9%	11%	0%	2%	5%	7%	3%	3%	5%	5%
58	2%	4%	6%	9%	2%	5%	5%	7%	0%	3%	3%	5%
60	2%	4%	6%	8%	0%	2%	5%	5%	3%	3%	5%	5%

CHAPTER 4. METHODOLOGY: FIELD SITES, EQUIPMENT, AND EXPERIMENTATION

Field tests were performed to measure various properties of vegetated filter strips commonly constructed in the Metropolitan Atlanta region. In order to determine the site locations to be used for testing, a number of characteristics were considered including: a vegetated slope adjacent to an urban non-OGCF road, a slope that was installed more than 5 years earlier than the testing time to ensure well-developed grass cover, along with the following safety requirements: light high-speed traffic or dense low-speed traffic, room for parking out of the way of testing and traffic, and plenty of space between traffic and testing location.

SELECTED SITES

Many locations were observed throughout the course of this research, with the following locations chosen to meet the necessary conditions: north of Atlanta in Cherokee County on Interstate 575 near Ball Ground, GA, west of Atlanta just off of Interstate 20 in Villa Rica, GA, and SR20 / SR19 near Cumming, GA also north of Atlanta.

The first site chosen for this research is titled the Ball Ground Salt Shack (SS), with approximate coordinates: 34.370573, -84.376692. This site is located just off Interstate 575 on an access road that leads to State Route 372. The location had multiple vegetated slopes with good cover and had a nearby GDOT salt shack in the median that was easily accessible for parking and unloading equipment (Figure 4). The tests performed at this location were the modified Philip-Dunne infiltrometer (MPD-I), soil sampling, and topographical surveying.

Figure 4. Ball Ground, GA off of I-575 South (SS).

The next chosen site was titled the Villa Rica Captain D's (CD) due to the parking lot used to access this location from the fast-food seafood chain Captain D's, with approximate coordinates for this location: 33.719712, -84.939244. The site is located where Interstate 20 crosses State Route 61, and was easily accessible due to the suburban locality. The vegetated cover was well established and plush throughout many seasons (Figure 5). Similar to location SS, tests performed at this location were modified Philip-Dunne infiltrometer (MPD-I), soil sampling, and topographical surveying.

Figure 5. Villa Rica, GA at the crossing of SR-61 and I-20 in front of Captain D's fast-food restaurant (CD).

The final location chosen for field testing is titled McFarland Pkwy (McP) and is located off GA 400 Southbound Exit 12 (McFarland Parkway exit) in Alpharetta, GA (Figure 6). The approximate coordinates for this location are: 34.117687, -84.220319. The vegetated cover was somewhat established at the time of testing (Spring 2021), and tests performed at this location included modified Philip-Dunne infiltrometer (MPD-I) and shoulder solids grab sampling (i.e., suspended solids entering the system). Table 5 includes the experimental matrix for the field and laboratory tests that were performed at all chosen testing sites.

Figure 6. Alpharetta, GA at the 400 southbound off ramp for exit 12 (McFarland Parkway, McP).

Table 5. Experimental Matrix for Field Sampling at GDOT Sites

Experiment Type	**Field / Lab**	**Location**		
		Salt Shack	**Captain D's**	**McFarland Parkway**
MPD-I	Field	X	X	X
Shelby Tube in-situ Sample	Field	X	X	
Shoulder Grab Sample	Field			X
Falling Head Hydraulic Conductivity	Lab	X	X	
Water Content	Lab	X	X	
Sieve Analysis	Lab	X	X	X
Particle Size Analyzer (PSA)	Lab	X	X	X
Pycnometer Density Test	Lab			X

INFILTRATION METHODOLOGY

Equipment Development

Frequently, single and double ring infiltrometers, boreholes, and porous probes tests have been used to measure infiltration into soils. Each of these tests have advantages and disadvantages, and can be fairly successful in a range of natural soils (Daniel, 1989). The work in this project focused on a popular method for infiltration testing known as the Philip-Dunne permeameter, which is a falling head device that is inserted into an excavated borehole, where water is allowed to infiltrate into the soil and forms the shape of a bulb around the device as the wetting front advances. Measurement of the infiltration rate allows calculation of the saturated hydraulic conductivity (K_s) and suction (ψ) (Figure 7). In order to follow best practices for the design criteria of infiltration stormwater BMPs, measurement of K_s and ψ at the soil surface is required; however, the traditional Philip-Dunne permeameter is tested in a borehole, typically at a depth greater than one foot below the surface. Consequently, the modified Philip-Dunne infiltrometer (MPD-I) is a device that was developed for use at the surface of the soil to measure K_s and ψ. While the infiltration theory is the same, the device is driven 2 inches into the soil to measure surficial infiltration instead of being placed in a borehole below ground surface. Due to the shallow depth of installation, the geometry of the wetting front changes from a spherical bulb around the device to a hemisphere of water infiltrating under the device (Figure 7).

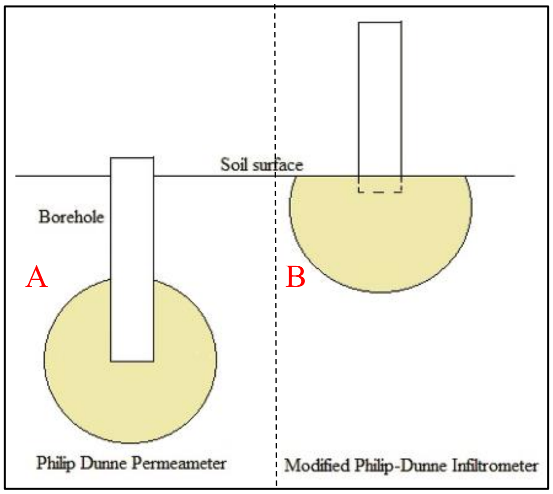


Figure 7. Comparison of the geometry of the wetting front of: (a) the Phillip-Dunne Permeameter and (b) the modified Phillip-Dunne Infiltrometer (Ahmed et al., 2014).

A modified Philip-Dunne infiltrometer was designed in accordance with ASTM Standard D8152 in SOLIDWORKS (Dassault Systèmes). The device was then constructed in the Georgia Tech Civil Engineering Machine Shop (Figure 8). The data measured using the MPD-I were used to calculate the value of K and ψ, using a falling head method to gather in-situ data for surficial soil infiltration characteristics. The analysis follows the Green-Ampt theory connecting the water content and depth of wetting front through the sharp transition from initial saturation to fully saturated water content (i.e., porosity). To calculate the in-situ K and ψ, two primary equations are used that minimize the difference between measured change in head vs. measured time and calculated change in head vs. calculated time, according to the following:

$$dt_M - dt_C = dt_M + \left[\frac{dH_M * L_{max} - \beta * \left\{(\theta_{sat} - \theta_{init}) * \frac{R^2(t) + R(t) * L_{max}}{K} * dR * B\right\}}{K * (\psi + \beta * G - H_M(t) - L_{max}}\right] \tag{22}$$

$$dH_M - dH_C = dH_M - \frac{K}{L_{max}} * \left[\beta * \left\{(\theta_{sat} - \theta_{init}) * \frac{R^2(t) + R(t) * L_{max}}{K} * dR * B\right\} - dt_M * \{\psi + \beta * G - H_M(t) - L_{max}\}\right] \tag{23}$$

H_M = measured head (mm)

dt_M = change in measured time (sec)

dt_C = change in calculated time (sec)

dH_M = change in measured head (mm)

dH_C = change in calculated head (mm)

$Lmax$ = depth inserted into the ground (mm)

β = hydraulic inefficiency coefficient, found from the following equation:

$$\beta = {}^{\pi^2}\!/_{8}$$

θ_{sat} = saturated (or final) water content

θ_{init} = initial water content

R = distance to wetted front $> \sqrt{r^2 + L_{max}^2}$, where r = the inside radius of the apparatus. R is found from the following equation:

$$[H_0 - H(t)]r^2 = \frac{\theta_{sat} - \theta_{init}}{3}\left[2[R(t)]^3 + 3[[R(t)]^2 L_{max} - L_{max}^3]\right]$$

K = field-saturated hydraulic conductivity (mm/s)

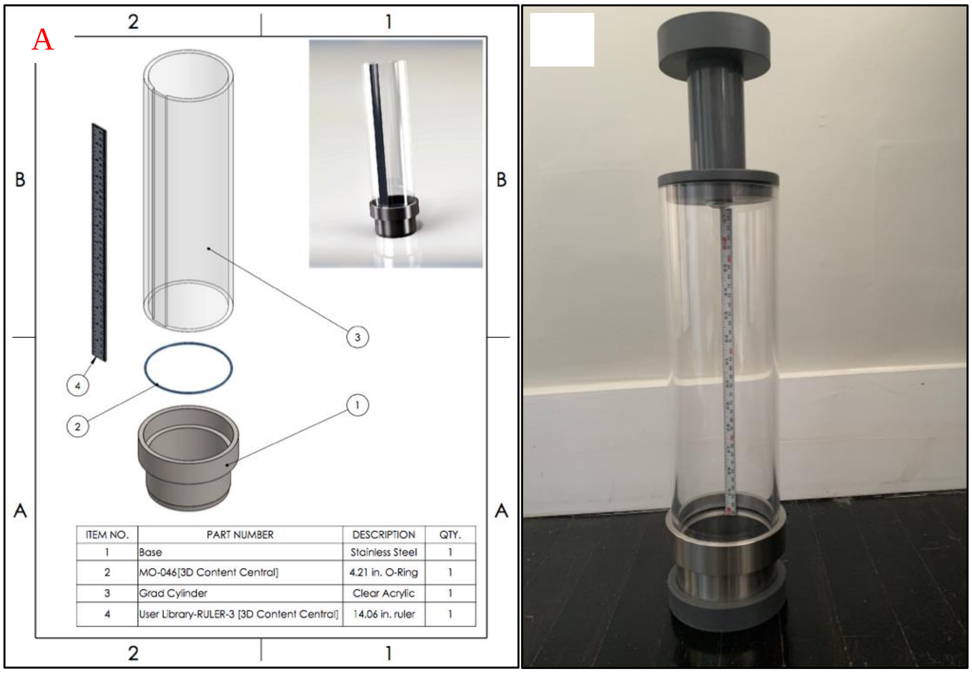
B = hydraulic inefficiency of the actual flow path of infiltrated water. The following equation is used to find B:

$$B = \frac{1}{L_{max}} * \left[\ln\left\{R(t)\frac{r + L_{max}}{r}(R(t) + L_{max})\right\}\right]$$

ψ = Green-Ampt wetting front suction

G = term for the gravity-driven component of the flow, calculated from the following equation:

$$G = 2r^2B$$



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Base	Stainless Steel	1
2	MO-046[3D Content Central]	4.21 in. O-Ring	1
3	Grad Cylinder	Clear Acrylic	1
4	User Library-RULER-3 [3D Content Central]	14.06 in. ruler	1

Figure 8. (a) MPD-I SOLIDWORKS design drawing and (b) device constructed in Georgia Tech's Civil Engineering Machine Shop.

The stated variables that are known or measured by the test method using the MDP-I apparatus are given in Figure 9. Compared to the traditional borehole method, the analysis of the MPD-I is much more extensive due to the complexity in the geometry of the bulb; however, the analytical solution is explained in detail in ASTM D8152. A MATLAB script was written to aide in the analysis of the field data.

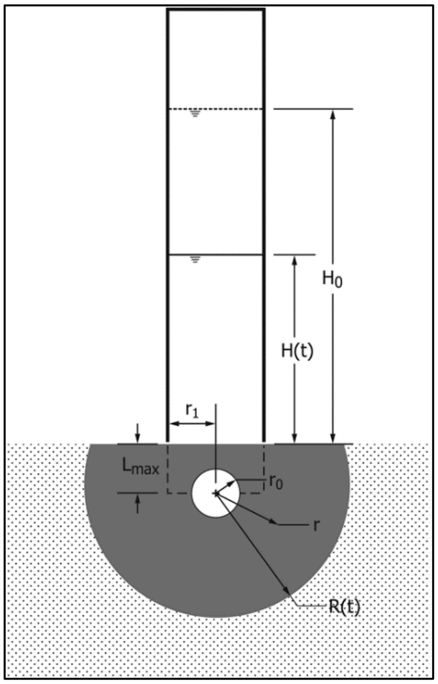


Figure 9. MPD-I apparatus showing known or measured values.

Field Testing Methodology

The field work consisted of performing falling head infiltration tests using the MPD-I (ASTM D 8152), initial and saturated water content measurements ($\theta_{initial}$ and θ_{sat} respectively) (Luster Leaf Analog Moisture Meter and a TDR 150 Soil Moisture Meter), and a stopwatch to measure time. At two of the field sites, the MPD-I was driven into the ground using a mallet; however, for one of the sites, hand pushing was sufficient to install the MPD-I (location SS). The MPD-I was then filled with approximately one gallon of water and head measurements were taken in intervals of 0, 5, 10, 30, and 60 seconds, and then every 5 minutes up to 30 minutes, followed by readings every 10 minutes until the test was completed by readings leveling out or until 2 hours had passed. Shelby tube samples were collected from the MPD-I location at two of the three testing sites (SS and CD) for laboratory hydraulic conductivity tests to compare field and lab results.

Laboratory Testing Methodology

Laboratory tests included falling head hydraulic conductivity tests (ASTM 5084) performed on Shelby tube samples collected from locations SS and CD, saturated water content (ASTM 2216), grain size analysis (ASTM D6913) using sieves (coarse grain particles) and a particle size analyzer (PSA) (fine grain particles).

The falling head hydraulic conductivity tests were done in accordance with ASTM D5084, using a flexible wall permeameter. The Shelby tube sample was extracted from the Shelby tube and then encased by a latex membrane. The sample was assembled with saturated porous stones and filter paper on the top and bottom of the soil (inflow and outflow). The sample was then placed into the testing chamber and saturated using gravity flow. Once the sample achieved a B-value greater than 0.95, the sample was tested to determine hydraulic conductivity, with tests repeated under increasing confining pressure. Once the hydraulic conductivity tests were completed, the sample was disassembled and smaller samples were taken to measure the saturated water content of the sample using the oven-drying method.

Grain size was quantified using sieve analysis and a laser particle size analyzer. Sieve analysis was performed on the coarse fraction according to ASTM D6913. The particle size analyzer was used to quantify grain size for the fine grain soils. Particle size distributions were performed for the in-situ samples collected from locations SS and CD, as well as for the shoulder grab sample collected from location McP. Pycnometer tests were performed for the shoulder grab samples collected from location McP to determine particle density used in the calculations of Stoke's Law. Two pycnometer tests were performed to quantify the particle density (ρ_p) of the solids with approximate median diameter (D_{50}) and approximate 10% diameter of the solids (D_{10}).

SETTLEMENT OF SUSPENDED SOLIDS: METHODOLOGY

Field Testing Methodology

To quantify the solid diameters that were leaving the pavement and being deposited in the vegetated filter strips, grab samples from the shoulder of the road were collected at the McP location. The solids had been deposited due to particle trapping and were evaluated for particle size entering the filter strip.

Laboratory Testing Method

The solids collected from location McP were brought into the lab and particle size analysis was completed using the same method used for the Shelby Tube samples (ASTM D6913) (i.e., sieve analysis to separate the coarse grain soils and PSA for the fine grain soils). A pycnometer density test was done to estimate the particle density according to ASTM D854-14. Densities were measured for two different grain size ranges, one for the approximate 50% diameter (D_{50}) and one for the approximate 10% diameter (D_{10}). This procedure uses a dried soil and water to create a slurry inside of a pycnometer. The pycnometer, water, and soil are weighed, the slurry is then emptied into a pan and allowed to dry in an oven. The dry soil is then weighed, and the particle density is found through the following equation:

$$\rho_p = \frac{M_s}{V_p - M_f/\rho_f} \tag{24}$$

ρ_p = particle density

M_s = mass of solids

V_p = volume of pycnometer

M_f = fluid mass determined from loss of mass after drying

ρ_f = fluid (or water) density

CHAPTER 5. MODEL DEVELOPMENT: ANALYTICAL SOLUTIONS FOR INFILTRATION AND SOLIDS DEPOSITION

The results of the laboratory and field tests were used to analytically determine the efficiency of a vegetated filter strip. Removal of water and solids in a vegetated filter strip will include loss of water through infiltration and the removal of suspended solids by settling. In order to quantify the performance in terms of removal in the filter strip, three steps must be followed: first, analyze site and topographical data within the study area and apply standards established in the Blue Book and GDOTs Drainage Manual to determine travel time; second, use the infiltration results to solve a 2-D overland flow and infiltration model providing infiltrated water volume; and third: use Stoke’s Law to quantify the volume of removed suspended solids.

STEP 1: TRAVEL TIME

In order to determine travel time at a given site, topographical data and storm conditions are considered. Manning’s formula, previously derived (Eq. 2), was used to determine travel time and a wide, shallow, flow path was assumed (i.e. perimeter = width). A further simplification of Equation 4 provides overland flow velocity (Eq. 25), and travel time was calculated for various lengths of VFS (Eq. 26).

$$v_x = \frac{k}{n} * y^{2/3} * S^{0.5} \tag{25}$$

$$T_t = \left(\frac{L}{v_x}\right)/60 \tag{26}$$

Where v_x = overland flow velocity (ft/s)

T_t = travel time (min)

L = length of VFS (ft)

For previously derived equations, the flow depth (y) was kept in inches, however for equation 22 it was converted to feet. A Manning's roughness coefficient of 0.25 was used, slopes ranging from 2% – 6%, and travel time was calculated for runoff depths of 0.25, 0.65, and 1.2 inches and for filter strip lengths of 15-75 feet. These results are displayed in Table A4 in the Appendix.

STEP 2: 2-D INFILTRATION AND OVERLAND FLOW MODEL

For simplicity, most current models for overland flow assume soils are saturated during the entire length of the storm and as a result, underestimate the infiltration effects due to partially saturated soils, especially fine-grained soils. Consequently, a model was developed to include infiltration while considering capillary effects in unsaturated soil, which reduces water quantity as well as the quality via dispersion and infiltration into the soil. This model was based on the Green-Ampt method to calculate the infiltration volume and Manning's equation to calculate overland flow.

In order to solve for infiltration rate, calculations were very tedious and required two-step functions as well as creating a MATLAB code for determination of infiltration. The following paragraphs detail the steps and derivation of the Green-Ampts equation that was used to determine infiltration, infiltration rate, and percent of runoff infiltrated.

Because the governing equation describing infiltration ($F(t)$) contains the value on both sides of the equation, the equation must be solved iteratively, which was done by creating a MATLAB code that minimizes the difference between each side of the equation until $F(t)$ is observed:

$$F(t) = K_{sat} * T_t + \Delta\theta\psi * \ln\left(1 + \frac{F(t)}{\Delta\theta\psi}\right) \tag{27}$$

Infiltration rate is taken as the derivative of the previous equation with respect to time.

$$f(t) = K * \left(1 + \frac{\Delta\theta\psi}{F(t)}\right) \tag{28}$$

Infiltration rate was then compared to travel time (step 1) for the same variation of the vegetated filter strip determined in step 1 and then used in step 2 to obtain infiltration into the VFS surface:

$$P_{inf} = f(t) * T_t \tag{29}$$

Where $F(t)$ = Infiltration (in.)

K_{sat} = Saturated hydraulic conductivity (in./s)

Tt = Travel time (s)

$\Delta\theta$ = effective water content (--)

ψ = water front suction (in.)

P_{inf} = Infiltrated runoff (in.)

STEP 3: REMOVAL OF SUSPENDED SOLIDS MODEL

Using the travel times determined in step one and the parameters determined from the lab and field tests, the settlement of suspended solids was quantifed using the Stoke's Law equation for settling velocity (Eq. 30).

$$v_s = \frac{2}{9} * \frac{(\rho_p - \rho_f)}{\mu} * g * R^2 \tag{30}$$

Where v_s = settling velocity (m/s)

ρ_p = particle density (kg/m^3)

ρ_f = fluid density (kg/m^3)

μ = dynamic viscosity (kg/(m s))

g = acceleration of gravity (m/s^2)

R = particle radius (m)

Stoke's Law is customarily performed using SI units; therefore, the calculations for step two were done completely using SI units. By combining the travel time for each VFS scenario with the settling velocity, an estimate of the minimum diameter that will settle was determined according to the steps outlined in the following derivation.

The flow depth divided by the travel time represents the minimum settling velocity that the VFS can execute, therefore a minimum settling velocity was calculated according to:

$$v_{s-observed} = \frac{y}{T_t} = \frac{2}{9} * \frac{(\rho_p - \rho_f)}{\mu} * g * R^2 \tag{31}$$

Rearranging the equation provided the minimum radius of particles that will settle, and it was assumed that any larger sized or heavier particles would settle as well.

$$R = \left[\frac{y}{T_t} * \frac{9}{2*g} * \frac{\mu}{(\rho_p - \rho_f)}\right]^{0.5} \tag{32}$$

**Ensure that Tt for this equation has been converted to seconds.*

$$D_p = 2000 * R = 2000 * \left[\frac{y}{T_t} * \frac{9}{2*g} * \frac{\mu}{(\rho_p - \rho_f)}\right]^{0.5} \tag{33}$$

Where D_p = particle size diameter that will settle in the system (mm).

The steps outlined in this chapter allow determination of the volume of infiltration into vegetated filter strips with partially saturated soils, as well as determination of the percentage removal and deposition of suspended solids from stormwater runoff during a rainfall event.

CHAPTER 6. RESULTS

This chapter details the results of the field and laboratory testing, as well as model calculated results.

FIELD AND LABORATORY RESULTS

The summary values of hydraulic conductivity measured in the lab and field tests are given in Table 6, along with the MPD-I wetting front suction, the saturated water content, and the particle density. These results were then used as inputs for the infiltration and solids deposition models.

Table 6. MPD-I Test & Hydraulic Conductivity Test Results

Test	Field Locations		
	SS	CD	McP
USCS Classification	SM	SM	--
Falling Head K_{sat} (cm/s)	9.58×10^{-5}	$4.27 \times 10\ 10^{-5}$	--
MPD-I K_{sat} (cm/s)	1.02×10^{-4}	8.22×10^{-5}	3.86×10^{-5}
MPD-I ψ (cm) Wetting Front Suction	74.7	523.2	352.5
θ_{sat} Saturated Water Content	0.27	0.38	--
ρ_p (g/cm^3)	--	--	2.28

The difference between the falling head hydraulic conductivity tests and the MPD-I hydraulic conductivity tests were found to be 6.2×10^{-6} cm/s and 3.9×10^{-5} cm/s for locations SS and CD respectively. At both the SS and CD locations, the in-situ soil samples were classified as silty sands according to the Unified Soil Classification System, and the hydraulic conductivity results lie within the typical range for silty sands

(Budhu, 2015). Grain size distribution curves for samples from each of the three sites are given in Figure 10 through Figure 12.

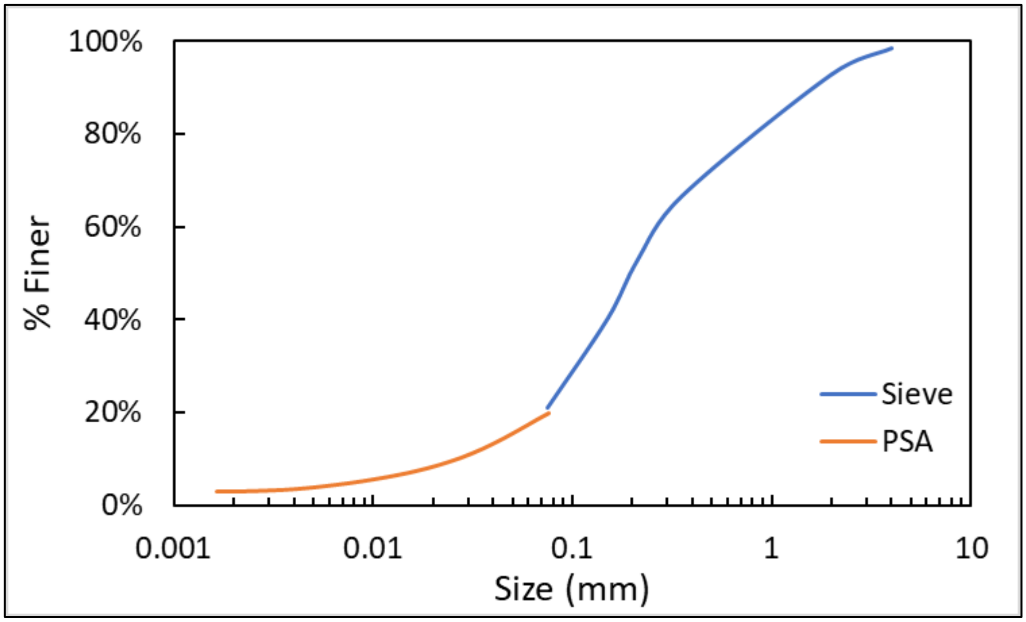


Figure 10. Grain size distribution (GSD) of the in-situ Shelby tube sample collected from location SS, coarse grain material measured by sieve analysis and fine grain material measured using a PSA. Soil classified as a silty sand (SM).

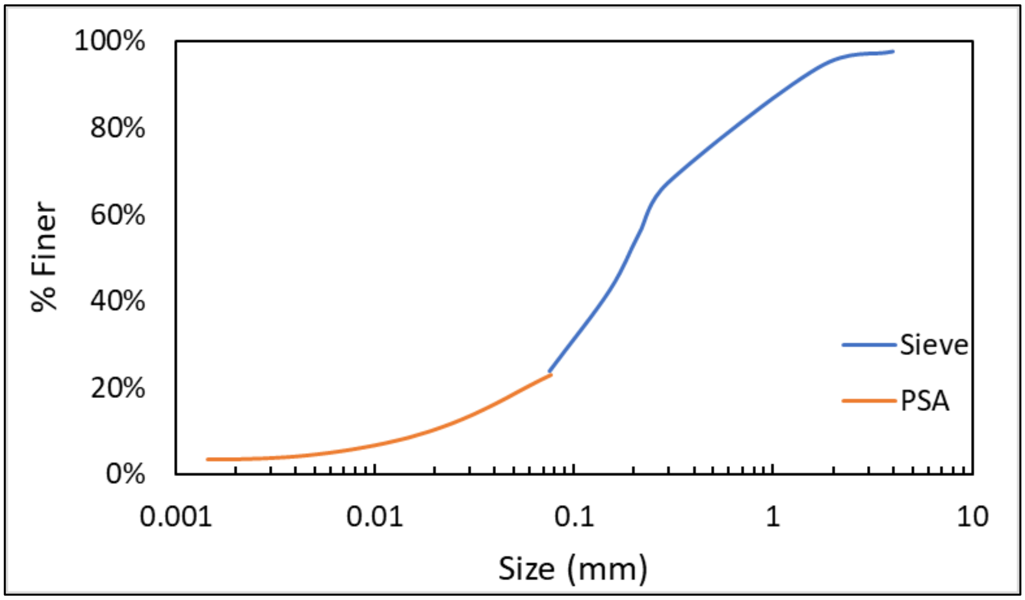


Figure 11. Grain size distribution of the in-situ Shelby tube sample collected from location CD, with coarse grain material measured by sieve analysis and fine grain material measured using a PSA. Soil classified as a silty sand (SM).

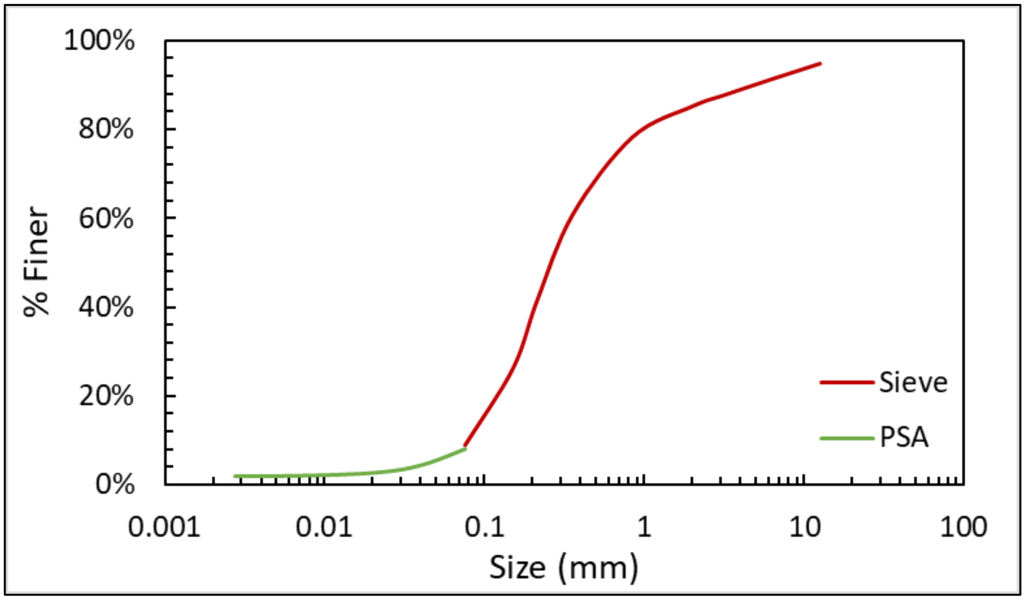


Figure 12. Grain size distribution of the road-side shoulder grab sample collected from location McP, coarse grain material measured by sieve analysis and fine grain material measured using a PSA.

The pycnometer density test was done on the shoulder grab sample to quantify the incoming particles that were analyzed using Stoke's Law, which requires particle density. Densities were found to be 2.26 g/cm^3 and 2.29 g/cm^3 respectively for the D_{50} and D_{10} diameters. These values are lower than what is typical of soil; however, the material entering the BMP was observed to not only be soil. The grab sample contained a considerable volume of organics, various objects such as metal scraps and plastic, and the occasional cigarette butt as observed by the eye (Figure 13). These other materials can alter the density, and silty soil with organics typically have a lower density (Budhu, 2015).

Figure 13. Shoulder grab sample before separation by grain size.

MODEL RESULTS

Infiltration

Values obtained through the field and laboratory results were then used in the model to predict infiltration of water and deposition of suspended solids. The results of the water loss 2-D overland flow and predictions were compared to the flow depth to estimate the percentage of runoff infiltrated. **Error! Reference source not found.** and Figure 14 present the percent of infiltrated runoff for a flow depth of 1.2 inches and a 6:1 and 4% swale shoulder slope and road shoulder slope respectively with road shoulder lengths ranging from 2-feet to 8-feet. All other infiltration results of varying road and swale shoulder lengths and slopes can be found in Appendix A, Tables A5-A12 and Figures A1-A8. It can be assumed that along with infiltration, dissolved solids are being removed from the runoff through dispersion within the subsurface.

Suspended Solids Removal

The model based on Stoke's Law provide a minimum radius of settled suspended solids for given conditions. This value was compared to the grain size diameter of the incoming suspended solids (Figure 12), and a percentage of suspended solids removed (SSR) as a function of flow conditions was estimated (Table 7 and Figure 14). Specific percentages for each respective diameter were determined through interpolation of the results provided from the sieve and PSA tests (Figure 12). Results of SSR from a runoff depth of 1.2 inches are displayed for a 6:1 swale shoulder slope and 4% road shoulder slope with road shoulder lengths ranging from 2-feet to 8-feet. All other SSR results are shown in Appendix A, Tables A5-A12 and Figures A1-A8.

It is important to note that these results are for particles that are discrete, and the results displayed for SSR do not consider the impact aggregation or particles that are removed by particle trapping, actions that are likely to be occurring that will result in higher rates of removal. Therefore, these results are lower bound and conservative.

Table 7. Slope Length and Efficiency for a 6:1 Swale Shoulder and a 4% Road Shoulder

Road Shoulder Slope:		4%											
Shoulder Length:		2 ft.			4 ft.			6 ft.			8 ft.		
Pavement Width		L	DSR	SSR	L	DSR	SSR	L	DSR	SSR	L	DSR	SSR
Swale Shoulder Slope: 6:1	12	21	0.35%	21%	20	0.36%	21%	19	0.37%	21%	18	0.37%	21%
	14	22	0.36%	21%	21	0.36%	21%	20	0.37%	21%	19	0.38%	22%
	16	24	0.37%	21%	23	0.38%	22%	22	0.39%	22%	21	0.39%	22%
	18	25	0.38%	22%	24	0.39%	22%	23	0.39%	22%	22	0.40%	22%
	20	26	0.39%	22%	25	0.39%	22%	24	0.40%	22%	23	0.41%	22%
	22	27	0.39%	22%	26	0.40%	22%	25	0.41%	22%	24	0.41%	22%
	24	28	0.40%	22%	27	0.41%	22%	26	0.41%	22%	25	0.42%	22%
	26	29	0.41%	22%	28	0.41%	22%	27	0.42%	22%	26	0.43%	23%
	28	30	0.41%	22%	29	0.42%	22%	28	0.43%	23%	27	0.43%	23%
	30	31	0.42%	22%	30	0.43%	23%	29	0.43%	23%	28	0.44%	24%
	32	32	0.43%	23%	31	0.43%	23%	30	0.44%	23%	29	0.45%	24%
	34	33	0.43%	23%	31	0.43%	23%	30	0.44%	23%	29	0.45%	24%
	36	33	0.43%	23%	32	0.44%	23%	31	0.45%	24%	30	0.45%	24%
	38	34	0.44%	23%	33	0.45%	24%	32	0.45%	24%	31	0.46%	25%
	40	35	0.44%	24%	34	0.45%	24%	33	0.46%	25%	32	0.46%	25%
	42	36	0.45%	24%	34	0.45%	24%	33	0.46%	25%	32	0.46%	25%
	44	36	0.45%	24%	35	0.46%	25%	34	0.46%	25%	33	0.47%	25%
	46	37	0.46%	25%	36	0.46%	25%	35	0.47%	25%	34	0.48%	26%
	48	38	0.46%	25%	37	0.47%	25%	35	0.47%	25%	34	0.48%	26%
	50	38	0.46%	25%	37	0.47%	25%	36	0.48%	26%	35	0.48%	26%
	52	39	0.47%	25%	38	0.47%	26%	37	0.48%	26%	36	0.49%	26%
	54	40	0.47%	26%	38	0.47%	26%	37	0.48%	26%	36	0.49%	26%
	56	40	0.47%	26%	39	0.48%	26%	38	0.49%	26%	37	0.49%	26%
	58	41	0.48%	26%	40	0.49%	26%	39	0.49%	26%	38	0.50%	27%
	60	41	0.48%	26%	40	0.49%	26%	39	0.49%	26%	38	0.50%	27%

*L (ft) = slope length including Road Shoulder Length
*DSR = dissolved solids removal (i.e. infiltrated runoff)
*SSR = suspended solids removal

6:1 Swale Shoulder 4% Road Shoulder

W_P (ft)	L_2 (ft)	L_4 (ft)	L_6 (ft)	L_8 (ft)
12	21	20	19	18
14	22	21	20	19
16	24	23	22	21
18	25	24	23	22
20	26	25	24	23
22	27	26	25	24
24	28	27	26	25
26	29	28	27	26
28	30	29	28	27
30	31	30	29	28
32	32	31	30	29
34	33	31	30	29
36	33	32	31	30
38	34	33	32	31
40	35	34	33	32
42	36	34	33	32
44	36	35	34	33
46	37	36	35	34
48	38	37	35	34
50	38	37	36	35
52	39	38	37	36
54	40	38	37	36
56	40	39	38	37
58	41	40	39	38
60	41	40	39	38

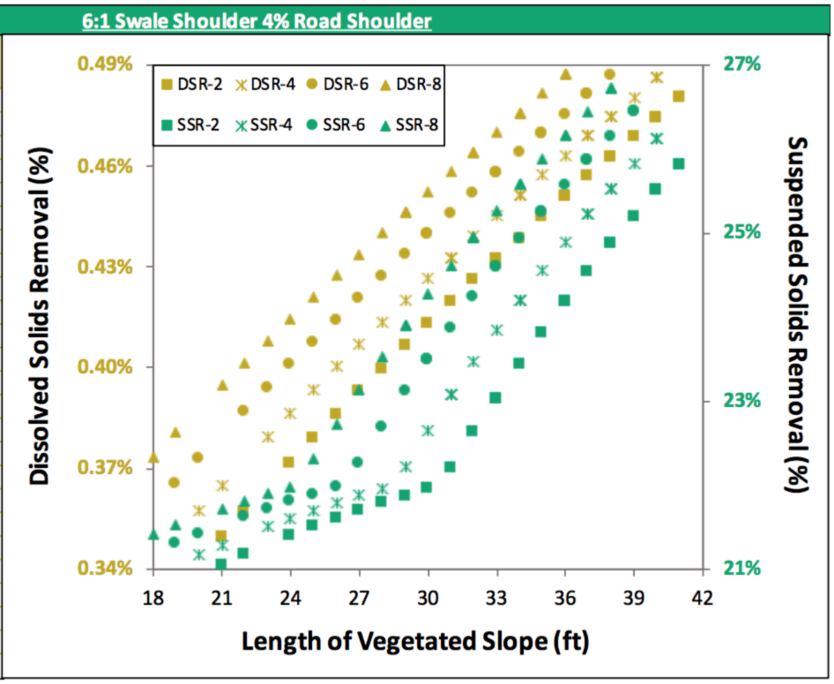


Figure 14. Swale efficiency for varying lengths of grassed slope. The legend reads DSR-2 for dissolved solids removal of 2 feet (yellow-square) and SSR-2 for suspended solids removal of 2 feet (green-square), which aligns with the lengths listed under L_2. This same labeling pattern is continued for all legend entries.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

This work performed for this report has focused on determining removal rates and dimensions for the commonly implemented vegetated filter strip BMP, specifically focusing on lengths for the design of the common roadside BMP and the efficiency of their solids pollutant removal capabilities. Examination and derivation of design calculations from the Georgia Blue Book and GDOTs Drainage Manual were performed to clarify the derivation of the governing relationships for design of vegetated filter strips used in practice.

Using the design methodology for a VFS, in combination for a gently sloped grass shoulder, the suggested lengths for VFS have been modified to include the shoulder of the road which consists of a shallower slope than that of the swale shoulder. When the two slopes are combined, the travel time through which runoff flows through the system is reduced which results in a reduced design length for the VFS. When considering the removal capacity of the shoulder, it was shown that the length of required VFS could be reduced by approximately 6% to 10%, or possibly even higher if an even more shallow slope is used.

Field tests were performed at three vegetated filter strip locations in the metropolitan Atlanta region to gather data to assess the efficiency of the BMP using site specific soil properties. Field tests included infiltration measurement using the MPD-I, in-situ Shelby tube sampling, in-situ and saturated moisture contents, and shoulder grab samples for solids grain size analysis. Laboratory tests that were completed included falling head hydraulic conductivity, moisture content, grain size analysis via sieve tests and PSA, and density via pycnometer.

The soils that were tested were silty sands with hydraulic conductivity ranging from 8.2 x 10^{-5} cm/s to 1.0 x 10^{-4} cm/s. The tested BMPs experienced an inflow of sediments (including vegetation and roadside litter) ranging in size from roughly 0.01 mm to 10 mm with a density of about 2.28 g/cm^3. The density is lower than a typical density value of soil due to the presence of the materials besides soils, with the most abundant being organics which are known to decrease the density of soil (Budhu, 2015). A model was developed that utilized the field and laboratory test results to solve for the travel time of runoff flowing through the BMP system. This value was then used in the model to calculate rate, and removal. The model determined the removal of runoff volume due to infiltration, and consequently, the removal of dissolved solids through dispersion. The last part of the model determined the removal of suspended solids through settlement and retainment. Removal efficiencies ranged from 12% to 35% of infiltrated runoff for VFS ranging from 15 ft. to 75 ft. long with slopes varying from 2% to 6%. For suspended solids removal, the VFS has the potential to remove between 21% and 43% when their design lengths range from 15 ft. to 75 ft long with slopes varying from 2% to 6%.

It is important to note the efficiency of BMPs are site specific and can vary with maintenance, season, storm intensity, road usage, as well as other characteristics. The calculations and evaluations included in this report for the VFS are meant to be generally applicable and target the most common situations that are observed in the metropolitan Atlanta region. The recommendations that follow this are based on observation, field and laboratory results, modeled calculations, and best engineering judgement.

Based on the work performed for this study, the following recommendations are made:

- Include partial credit for solids removal in the design of vegetated filter strips that may be shorter than the required 15 feet. Literature review of multiple, carefully controlled studies has demonstrated that most solids are deposited in the initial 3 ft to 8 ft of flow length within the filter strip, which is substantially shorter than that required by the Blue Book. Partial credit for this solids deposition could result in significant savings in right-of-way acquisition.
- Include the shallow slope of a grassed roadside shoulder in the design of vegetated filter strips. Slopes of 2% in the shoulder can significantly impact the dimensions required for a VFS, and reduce the sizing requirements.
- Include infiltration of water into partially saturated soils in areas with significant percentages of fine-grained soils. The modeled results presented in this work demonstrated that a substantial volume of water can infiltrate during small storms, resulting in reduced water volume as well as contaminant infiltration and sorption.

APPENDIX A: DETAILED SAMPLE CONCENTRATION DATA FOR TESTED STORMWATER BMPS

Table A 1. Filter Strip Length with Increased Shoulder Length for Shoulder Slope of 2%

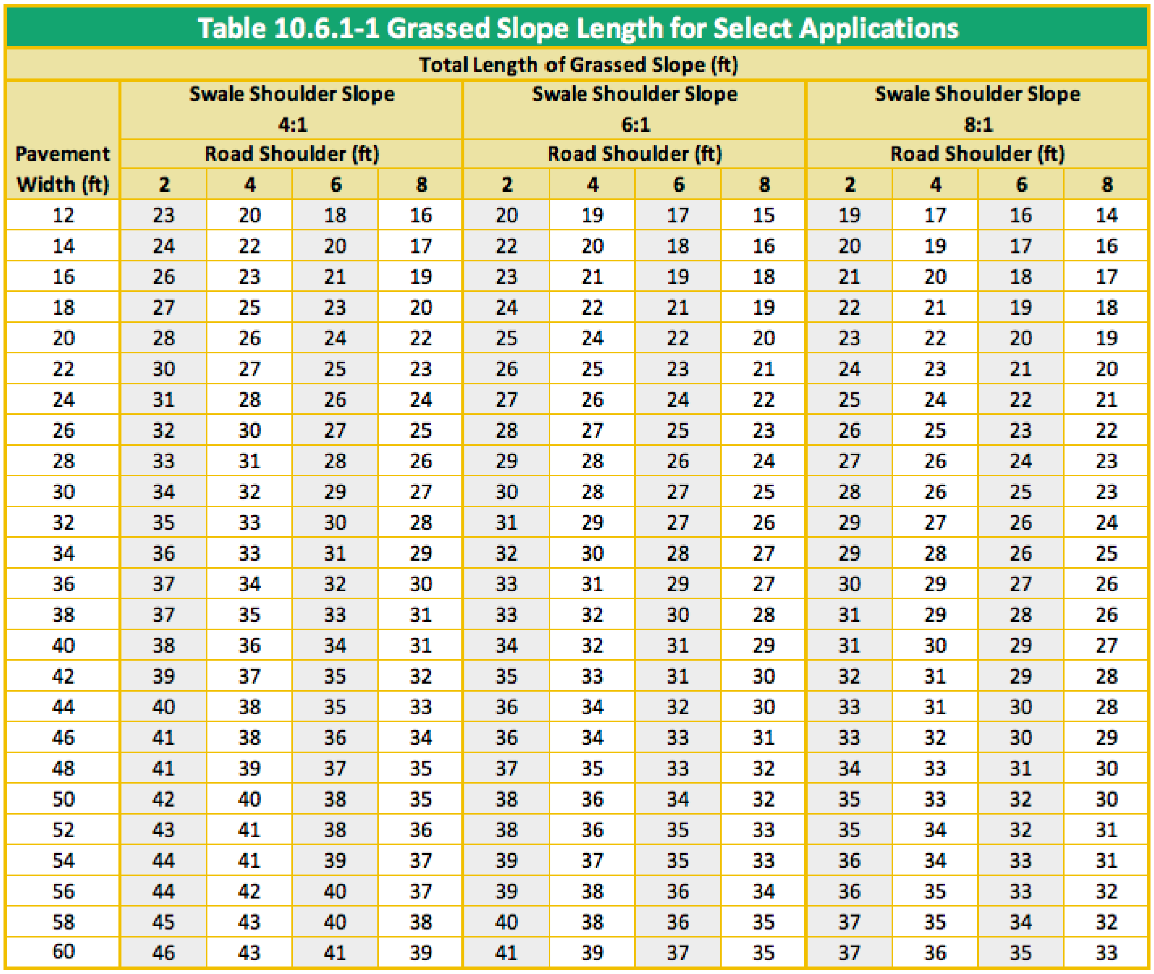


Table 10.6.1-1 Grassed Slope Length for Select Applications

	Total Length of Grassed Slope (ft)											
	Swale Shoulder Slope 4:1				Swale Shoulder Slope 6:1				Swale Shoulder Slope 8:1			
Pavement	Road Shoulder (ft)				Road Shoulder (ft)				Road Shoulder (ft)			
Width (ft)	2	4	6	8	2	4	6	8	2	4	6	8
12	23	20	18	16	20	19	17	15	19	17	16	14
14	24	22	20	17	22	20	18	16	20	19	17	16
16	26	23	21	19	23	21	19	18	21	20	18	17
18	27	25	23	20	24	22	21	19	22	21	19	18
20	28	26	24	22	25	24	22	20	23	22	20	19
22	30	27	25	23	26	25	23	21	24	23	21	20
24	31	28	26	24	27	26	24	22	25	24	22	21
26	32	30	27	25	28	27	25	23	26	25	23	22
28	33	31	28	26	29	28	26	24	27	26	24	23
30	34	32	29	27	30	28	27	25	28	26	25	23
32	35	33	30	28	31	29	27	26	29	27	26	24
34	36	33	31	29	32	30	28	27	29	28	26	25
36	37	34	32	30	33	31	29	27	30	29	27	26
38	37	35	33	31	33	32	30	28	31	29	28	26
40	38	36	34	31	34	32	31	29	31	30	29	27
42	39	37	35	32	35	33	31	30	32	31	29	28
44	40	38	35	33	36	34	32	30	33	31	30	28
46	41	38	36	34	36	34	33	31	33	32	30	29
48	41	39	37	35	37	35	33	32	34	33	31	30
50	42	40	38	35	38	36	34	32	35	33	32	30
52	43	41	38	36	38	36	35	33	35	34	32	31
54	44	41	39	37	39	37	35	33	36	34	33	31
56	44	42	40	37	39	38	36	34	36	35	33	32
58	45	43	40	38	40	38	36	35	37	35	34	32
60	46	43	41	39	41	39	37	35	37	36	35	33

Table A 2. Filter Strip Length with Increased Shoulder Length for Shoulder Slope of 4%

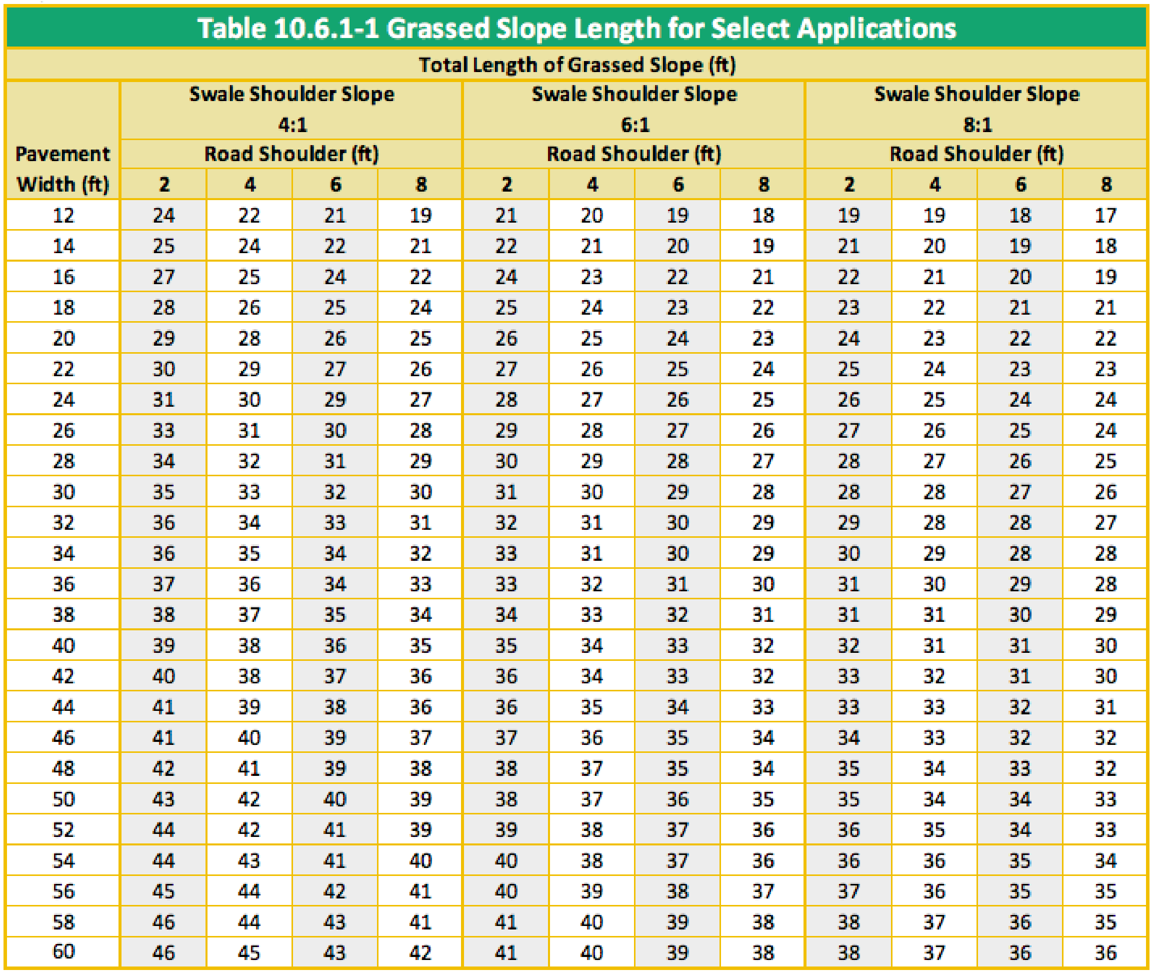


Table 10.6.1-1 Grassed Slope Length for Select Applications

	Total Length of Grassed Slope (ft)											
	Swale Shoulder Slope 4:1				Swale Shoulder Slope 6:1				Swale Shoulder Slope 8:1			
Pavement Width (ft)	Road Shoulder (ft)				Road Shoulder (ft)				Road Shoulder (ft)			
	2	4	6	8	2	4	6	8	2	4	6	8
12	24	22	21	19	21	20	19	18	19	19	18	17
14	25	24	22	21	22	21	20	19	21	20	19	18
16	27	25	24	22	24	23	22	21	22	21	20	19
18	28	26	25	24	25	24	23	22	23	22	21	21
20	29	28	26	25	26	25	24	23	24	23	22	22
22	30	29	27	26	27	26	25	24	25	24	23	23
24	31	30	29	27	28	27	26	25	26	25	24	24
26	33	31	30	28	29	28	27	26	27	26	25	24
28	34	32	31	29	30	29	28	27	28	27	26	25
30	35	33	32	30	31	30	29	28	28	28	27	26
32	36	34	33	31	32	31	30	29	29	28	28	27
34	36	35	34	32	33	31	30	29	30	29	28	28
36	37	36	34	33	33	32	31	30	31	30	29	28
38	38	37	35	34	34	33	32	31	31	31	30	29
40	39	38	36	35	35	34	33	32	32	31	31	30
42	40	38	37	36	36	34	33	32	33	32	31	30
44	41	39	38	36	36	35	34	33	33	33	32	31
46	41	40	39	37	37	36	35	34	34	33	32	32
48	42	41	39	38	38	37	35	34	35	34	33	32
50	43	42	40	39	38	37	36	35	35	34	34	33
52	44	42	41	39	39	38	37	36	36	35	34	33
54	44	43	41	40	40	38	37	36	36	36	35	34
56	45	44	42	41	40	39	38	37	37	36	35	35
58	46	44	43	41	41	40	39	38	38	37	36	35
60	46	45	43	42	41	40	39	38	38	37	36	36

Table A 3. Percent Differences Between VFS Lengths with Shoulder Length Increased for Shoulder Slope of 2%

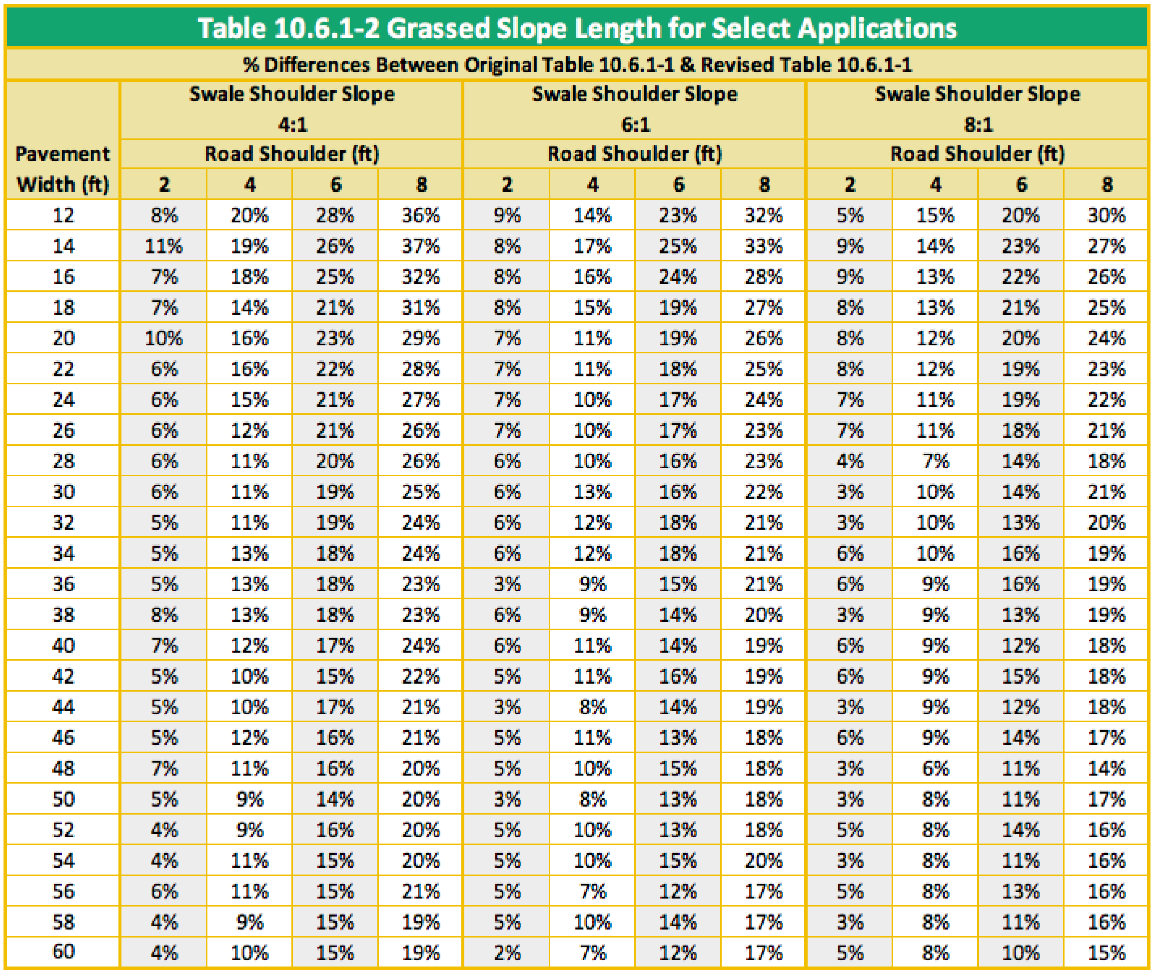


Table 10.6.1-2 Grassed Slope Length for Select Applications

% Differences Between Original Table 10.6.1-1 & Revised Table 10.6.1-1

Pavement Width (ft)	Swale Shoulder Slope 4:1				Swale Shoulder Slope 6:1				Swale Shoulder Slope 8:1			
	Road Shoulder (ft)				Road Shoulder (ft)				Road Shoulder (ft)			
	2	4	6	8	2	4	6	8	2	4	6	8
12	8%	20%	28%	36%	9%	14%	23%	32%	5%	15%	20%	30%
14	11%	19%	26%	37%	8%	17%	25%	33%	9%	14%	23%	27%
16	7%	18%	25%	32%	8%	16%	24%	28%	9%	13%	22%	26%
18	7%	14%	21%	31%	8%	15%	19%	27%	8%	13%	21%	25%
20	10%	16%	23%	29%	7%	11%	19%	26%	8%	12%	20%	24%
22	6%	16%	22%	28%	7%	11%	18%	25%	8%	12%	19%	23%
24	6%	15%	21%	27%	7%	10%	17%	24%	7%	11%	19%	22%
26	6%	12%	21%	26%	7%	10%	17%	23%	7%	11%	18%	21%
28	6%	11%	20%	26%	6%	10%	16%	23%	4%	7%	14%	18%
30	6%	11%	19%	25%	6%	13%	16%	22%	3%	10%	14%	21%
32	5%	11%	19%	24%	6%	12%	18%	21%	3%	10%	13%	20%
34	5%	13%	18%	24%	6%	12%	18%	21%	6%	10%	16%	19%
36	5%	13%	18%	23%	3%	9%	15%	21%	6%	9%	16%	19%
38	8%	13%	18%	23%	6%	9%	14%	20%	3%	9%	13%	19%
40	7%	12%	17%	24%	6%	11%	14%	19%	6%	9%	12%	18%
42	5%	10%	15%	22%	5%	11%	16%	19%	6%	9%	15%	18%
44	5%	10%	17%	21%	3%	8%	14%	19%	3%	9%	12%	18%
46	5%	12%	16%	21%	5%	11%	13%	18%	6%	9%	14%	17%
48	7%	11%	16%	20%	5%	10%	15%	18%	3%	6%	11%	14%
50	5%	9%	14%	20%	3%	8%	13%	18%	3%	8%	11%	17%
52	4%	9%	16%	20%	5%	10%	13%	18%	5%	8%	14%	16%
54	4%	11%	15%	20%	5%	10%	15%	20%	3%	8%	11%	16%
56	6%	11%	15%	21%	5%	7%	12%	17%	5%	8%	13%	16%
58	4%	9%	15%	19%	5%	10%	14%	17%	3%	8%	11%	16%
60	4%	10%	15%	19%	2%	7%	12%	17%	5%	8%	10%	15%

Table A 4. Percent Differences Between VFS Lengths with Shoulder Length Increased for Shoulder Slope of 4%

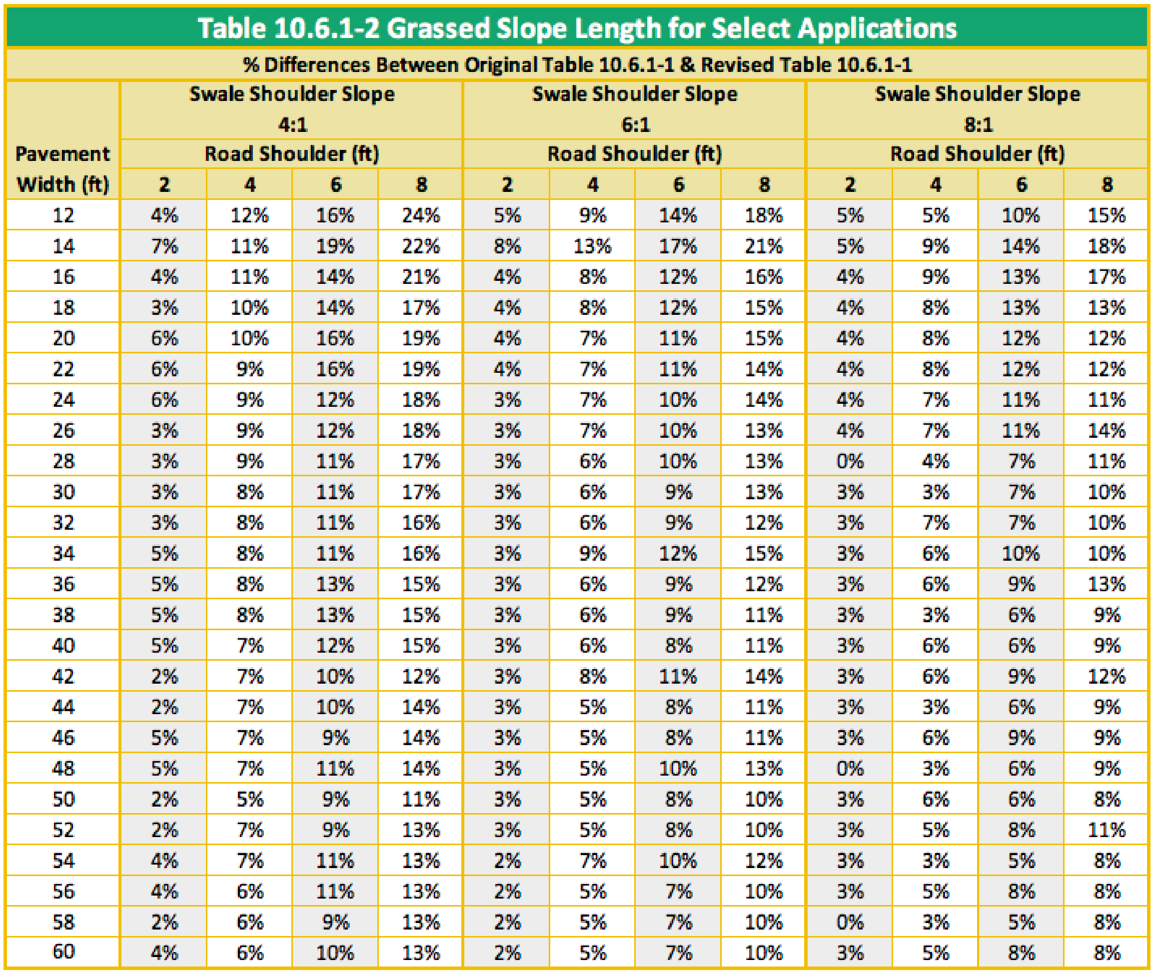


Table 10.6.1-2 Grassed Slope Length for Select Applications

% Differences Between Original Table 10.6.1-1 & Revised Table 10.6.1-1

Pavement Width (ft)	Swale Shoulder Slope 4:1				Swale Shoulder Slope 6:1				Swale Shoulder Slope 8:1			
	Road Shoulder (ft)				Road Shoulder (ft)				Road Shoulder (ft)			
	2	4	6	8	2	4	6	8	2	4	6	8
12	4%	12%	16%	24%	5%	9%	14%	18%	5%	5%	10%	15%
14	7%	11%	19%	22%	8%	13%	17%	21%	5%	9%	14%	18%
16	4%	11%	14%	21%	4%	8%	12%	16%	4%	9%	13%	17%
18	3%	10%	14%	17%	4%	8%	12%	15%	4%	8%	13%	13%
20	6%	10%	16%	19%	4%	7%	11%	15%	4%	8%	12%	12%
22	6%	9%	16%	19%	4%	7%	11%	14%	4%	8%	12%	12%
24	6%	9%	12%	18%	3%	7%	10%	14%	4%	7%	11%	11%
26	3%	9%	12%	18%	3%	7%	10%	13%	4%	7%	11%	14%
28	3%	9%	11%	17%	3%	6%	10%	13%	0%	4%	7%	11%
30	3%	8%	11%	17%	3%	6%	9%	13%	3%	3%	7%	10%
32	3%	8%	11%	16%	3%	6%	9%	12%	3%	7%	7%	10%
34	5%	8%	11%	16%	3%	9%	12%	15%	3%	6%	10%	10%
36	5%	8%	13%	15%	3%	6%	9%	12%	3%	6%	9%	13%
38	5%	8%	13%	15%	3%	6%	9%	11%	3%	3%	6%	9%
40	5%	7%	12%	15%	3%	6%	8%	11%	3%	6%	6%	9%
42	2%	7%	10%	12%	3%	8%	11%	14%	3%	6%	9%	12%
44	2%	7%	10%	14%	3%	5%	8%	11%	3%	3%	6%	9%
46	5%	7%	9%	14%	3%	5%	8%	11%	3%	6%	9%	9%
48	5%	7%	11%	14%	3%	5%	10%	13%	0%	3%	6%	9%
50	2%	5%	9%	11%	3%	5%	8%	10%	3%	6%	6%	8%
52	2%	7%	9%	13%	3%	5%	8%	10%	3%	5%	8%	11%
54	4%	7%	11%	13%	2%	7%	10%	12%	3%	3%	5%	8%
56	4%	6%	11%	13%	2%	5%	7%	10%	3%	5%	8%	8%
58	2%	6%	9%	13%	2%	5%	7%	10%	0%	3%	5%	8%
60	4%	6%	10%	13%	2%	5%	7%	10%	3%	5%	8%	8%

Table A 5. Slope Length and Efficiency 4:1 Swale Shoulder / 6% Road Shoulder

Road Shoulder Slope:		**6%**											
Road Shoulder Length:		**2 ft.**			**4 ft.**			**6 ft.**			**8 ft.**		
Pavement Width		**L**	**DSR**	**SSR**	**L**	**DSR**	**SSR**	**L**	**DSR**	**SSR**	**L**	**DSR**	**SSR**
Swale Shoulder Slope: 4:1	12	24	0.34%	21%	23	0.34%	21%	22	0.35%	21%	21	0.36%	21%
	14	25	0.34%	21%	24	0.35%	21%	23	0.36%	21%	22	0.36%	21%
	16	27	0.35%	21%	26	0.36%	21%	25	0.37%	21%	24	0.37%	21%
	18	28	0.36%	21%	27	0.37%	21%	26	0.37%	21%	25	0.38%	22%
	20	30	0.37%	21%	28	0.37%	21%	27	0.38%	22%	26	0.39%	22%
	22	31	0.38%	21%	30	0.38%	22%	29	0.39%	22%	28	0.40%	22%
	24	32	0.38%	22%	31	0.39%	22%	30	0.40%	22%	29	0.40%	22%
	26	33	0.39%	22%	32	0.40%	22%	31	0.40%	22%	30	0.41%	22%
	28	34	0.40%	22%	33	0.40%	22%	32	0.41%	22%	31	0.41%	22%
	30	35	0.40%	22%	34	0.41%	22%	33	0.41%	22%	32	0.42%	22%
	32	36	0.41%	22%	35	0.41%	22%	34	0.42%	22%	33	0.42%	22%
	34	37	0.41%	22%	36	0.42%	22%	35	0.42%	22%	34	0.43%	23%
	36	38	0.42%	22%	37	0.42%	22%	36	0.43%	23%	35	0.43%	23%
	38	39	0.42%	22%	38	0.43%	23%	37	0.43%	23%	35	0.43%	23%
	40	39	0.42%	22%	38	0.43%	23%	37	0.43%	23%	36	0.44%	23%
	42	40	0.43%	23%	39	0.43%	23%	38	0.44%	23%	37	0.44%	24%
	44	41	0.43%	23%	40	0.44%	23%	39	0.44%	24%	38	0.45%	24%
	46	42	0.44%	23%	41	0.44%	24%	40	0.45%	24%	39	0.45%	24%
	48	43	0.44%	24%	42	0.45%	24%	40	0.45%	24%	39	0.45%	24%
	50	43	0.44%	24%	42	0.45%	24%	41	0.45%	24%	40	0.46%	25%
	52	44	0.45%	24%	43	0.45%	24%	42	0.46%	25%	41	0.46%	25%
	54	45	0.45%	24%	44	0.46%	25%	43	0.46%	25%	42	0.47%	25%
	56	45	0.45%	24%	44	0.46%	25%	43	0.46%	25%	42	0.47%	25%
	58	46	0.46%	25%	45	0.46%	25%	44	0.47%	25%	43	0.47%	25%
	60	47	0.46%	25%	46	0.47%	25%	45	0.47%	25%	44	0.48%	26%

*L (ft) = slope length including Road Shoulder Length

*DSR = dissolved solids removal (i.e. infiltrated runoff)

*SSR = suspended solids removal

Table A 6. Slope Length and Efficiency 4:1 Swale Shoulder / 4% Road Shoulder

Road Shoulder Slope:		**4%**											
Road Shoulder Length:		**2 ft.**			**4 ft.**			**6 ft.**			**8 ft.**		
	Pavement Width	**L**	**DSR**	**SSR**	**L**	**DSR**	**SSR**	**L**	**DSR**	**SSR**	**L**	**DSR**	**SSR**
Swale Shoulder Slope: 4:1	12	24	0.34%	21%	22	0.35%	21%	21	0.36%	21%	19	0.37%	21%
	14	25	0.35%	21%	24	0.36%	21%	22	0.37%	21%	21	0.38%	21%
	16	27	0.36%	21%	25	0.37%	21%	24	0.38%	21%	22	0.38%	22%
	18	28	0.37%	21%	26	0.37%	21%	25	0.38%	22%	24	0.40%	22%
	20	29	0.37%	21%	28	0.38%	22%	26	0.39%	22%	25	0.40%	22%
	22	30	0.38%	21%	29	0.39%	22%	27	0.40%	22%	26	0.41%	22%
	24	31	0.38%	22%	30	0.40%	22%	29	0.41%	22%	27	0.41%	22%
	26	33	0.40%	22%	31	0.40%	22%	30	0.41%	22%	28	0.42%	22%
	28	34	0.40%	22%	32	0.41%	22%	31	0.42%	22%	29	0.42%	22%
	30	35	0.41%	22%	33	0.41%	22%	32	0.42%	22%	30	0.43%	23%
	32	36	0.41%	22%	34	0.42%	22%	33	0.43%	23%	31	0.43%	23%
	34	36	0.41%	22%	35	0.42%	22%	34	0.43%	23%	32	0.44%	23%
	36	37	0.42%	22%	36	0.43%	23%	34	0.43%	23%	33	0.44%	24%
	38	38	0.42%	22%	37	0.43%	23%	35	0.44%	23%	34	0.45%	24%
	40	39	0.43%	23%	38	0.44%	23%	36	0.44%	24%	35	0.45%	24%
	42	40	0.43%	23%	38	0.44%	23%	37	0.45%	24%	36	0.46%	25%
	44	41	0.44%	23%	39	0.44%	24%	38	0.45%	24%	36	0.46%	25%
	46	41	0.44%	23%	40	0.45%	24%	39	0.46%	25%	37	0.46%	25%
	48	42	0.44%	24%	41	0.45%	24%	39	0.46%	25%	38	0.47%	25%
	50	43	0.45%	24%	42	0.46%	25%	40	0.46%	25%	39	0.47%	25%
	52	44	0.45%	24%	42	0.46%	25%	41	0.47%	25%	39	0.47%	25%
	54	44	0.45%	24%	43	0.46%	25%	41	0.47%	25%	40	0.48%	26%
	56	45	0.46%	25%	44	0.47%	25%	42	0.47%	25%	41	0.48%	26%
	58	46	0.46%	25%	44	0.47%	25%	43	0.48%	26%	41	0.48%	26%
	60	46	0.46%	25%	45	0.47%	25%	43	0.48%	26%	42	0.49%	26%

*L (ft) = slope length including Road Shoulder Length

*DSR = dissolved solids removal (i.e. infiltrated runoff)

*SSR = suspended solids removal

Table A 7. Slope Length and Efficiency 4:1 Swale Shoulder / 2% Road Shoulder

Road Shoulder Slope:		2%											
Road Shoulder Length:		2 ft.			4 ft.			6 ft.			8 ft.		
Pavement Width		L	DSR	SSR	L	DSR	SSR	L	DSR	SSR	L	DSR	SSR
Swale Shoulder Slope: 4:1	12	23	0.35%	21%	20	0.36%	21%	18	0.38%	22%	16	0.40%	22%
	14	24	0.35%	21%	22	0.37%	21%	20	0.39%	22%	17	0.40%	22%
	16	26	0.37%	21%	23	0.38%	21%	21	0.40%	22%	19	0.41%	22%
	18	27	0.37%	21%	25	0.39%	22%	23	0.41%	22%	20	0.42%	22%
	20	28	0.38%	21%	26	0.40%	22%	24	0.41%	22%	22	0.43%	23%
	22	30	0.39%	22%	27	0.40%	22%	25	0.42%	22%	23	0.43%	23%
	24	31	0.40%	22%	28	0.41%	22%	26	0.42%	22%	24	0.44%	23%
	26	32	0.40%	22%	30	0.42%	22%	27	0.43%	23%	25	0.44%	24%
	28	33	0.41%	22%	31	0.42%	22%	28	0.43%	23%	26	0.45%	24%
	30	34	0.41%	22%	32	0.43%	23%	29	0.44%	23%	27	0.45%	24%
	32	35	0.42%	22%	33	0.43%	23%	30	0.44%	24%	28	0.46%	25%
	34	36	0.42%	22%	33	0.43%	23%	31	0.45%	24%	29	0.46%	25%
	36	37	0.43%	23%	34	0.44%	23%	32	0.45%	24%	30	0.47%	25%
	38	37	0.43%	23%	35	0.44%	24%	33	0.46%	25%	31	0.47%	25%
	40	38	0.43%	23%	36	0.45%	24%	34	0.46%	25%	31	0.47%	25%
	42	39	0.44%	23%	37	0.45%	24%	35	0.47%	25%	32	0.48%	26%
	44	40	0.44%	24%	38	0.46%	25%	35	0.47%	25%	33	0.48%	26%
	46	41	0.45%	24%	38	0.46%	25%	36	0.47%	25%	34	0.49%	26%
	48	41	0.45%	24%	39	0.46%	25%	37	0.48%	26%	35	0.49%	26%
	50	42	0.45%	24%	40	0.47%	25%	38	0.48%	26%	35	0.49%	26%
	52	43	0.46%	25%	41	0.47%	25%	38	0.48%	26%	36	0.50%	27%
	54	44	0.46%	25%	41	0.47%	25%	39	0.49%	26%	37	0.50%	27%
	56	44	0.46%	25%	42	0.48%	26%	40	0.49%	26%	37	0.50%	27%
	58	45	0.47%	25%	43	0.48%	26%	40	0.49%	26%	38	0.51%	27%
	60	46	0.47%	25%	43	0.48%	26%	41	0.50%	27%	39	0.51%	27%

*L (ft) = slope length including Road Shoulder Length

*DSR = dissolved solids removal (i.e. infiltrated runoff)

*SSR = suspended solids removal

Table A 8. Slope Length and Efficiency 6:1 Swale Shoulder / 6% Road Shoulder

	Road Shoulder Slope:	**6%**											
	Shoulder Length:	**2 ft.**			**4 ft.**			**6 ft.**			**8 ft.**		
	Pavement Width	**L**	**DSR**	**SSR**	**L**	**DSR**	**SSR**	**L**	**DSR**	**SSR**	**L**	**DSR**	**SSR**
Swale Shoulder Slope: 6:1	12	21	0.34%	21%	21	0.35%	21%	20	0.36%	21%	19	0.36%	21%
	14	23	0.36%	21%	22	0.36%	21%	21	0.36%	21%	21	0.37%	21%
	16	24	0.37%	21%	23	0.37%	21%	23	0.38%	21%	22	0.38%	22%
	18	25	0.37%	21%	25	0.38%	22%	24	0.39%	22%	23	0.39%	22%
	20	26	0.38%	22%	26	0.39%	22%	25	0.39%	22%	24	0.39%	22%
	22	27	0.39%	22%	27	0.40%	22%	26	0.40%	22%	25	0.40%	22%
	24	28	0.39%	22%	28	0.40%	22%	27	0.41%	22%	26	0.41%	22%
	26	29	0.40%	22%	29	0.41%	22%	28	0.41%	22%	27	0.41%	22%
	28	30	0.41%	22%	30	0.42%	22%	29	0.42%	22%	28	0.42%	22%
	30	31	0.41%	22%	31	0.42%	22%	30	0.43%	23%	29	0.43%	23%
	32	32	0.42%	22%	31	0.42%	22%	31	0.43%	23%	30	0.43%	23%
	34	33	0.43%	23%	32	0.43%	23%	31	0.43%	23%	31	0.44%	24%
	36	34	0.43%	23%	33	0.44%	23%	32	0.44%	23%	32	0.45%	24%
	38	34	0.43%	23%	34	0.44%	24%	33	0.44%	24%	32	0.45%	24%
	40	35	0.44%	24%	34	0.44%	24%	34	0.45%	24%	33	0.45%	24%
	42	36	0.45%	24%	35	0.45%	24%	34	0.45%	24%	34	0.46%	25%
	44	37	0.45%	24%	36	0.45%	24%	35	0.46%	25%	34	0.46%	25%
	46	37	0.45%	24%	37	0.46%	25%	36	0.46%	25%	35	0.46%	25%
	48	38	0.46%	25%	37	0.46%	25%	37	0.47%	25%	36	0.47%	25%
	50	39	0.46%	25%	38	0.47%	25%	37	0.47%	25%	36	0.47%	25%
	52	39	0.46%	25%	39	0.47%	25%	38	0.47%	25%	37	0.48%	26%
	54	40	0.47%	25%	39	0.47%	25%	38	0.47%	25%	38	0.48%	26%
	56	41	0.48%	26%	40	0.48%	26%	39	0.48%	26%	38	0.48%	26%
	58	41	0.48%	26%	40	0.48%	26%	40	0.49%	26%	39	0.49%	26%
	60	42	0.48%	26%	41	0.48%	26%	40	0.49%	26%	40	0.49%	26%

*L (ft) = slope length including Road Shoulder Length
*DSR = dissolved solids removal (i.e. infiltrated runoff)
*SSR = suspended solids removal

Table A 9. Slope Length and Efficiency 6:1 Swale Shoulder / 2% Road Shoulder

Road Shoulder Slope:		2%											
Shoulder Length:		2 ft.			4 ft.			6 ft.			8 ft.		
Pavement Width		L	DSR	SSR	L	DSR	SSR	L	DSR	SSR	L	DSR	SSR
Swale Shoulder Slope: 6:1	12	20	0.35%	21%	19	0.37%	21%	17	0.39%	22%	15	0.40%	22%
	14	22	0.37%	21%	20	0.38%	22%	18	0.39%	22%	16	0.41%	22%
	16	23	0.38%	21%	21	0.39%	22%	19	0.40%	22%	18	0.42%	22%
	18	24	0.38%	22%	22	0.40%	22%	21	0.41%	22%	19	0.43%	23%
	20	25	0.39%	22%	24	0.41%	22%	22	0.42%	22%	20	0.43%	23%
	22	26	0.40%	22%	25	0.42%	22%	23	0.43%	23%	21	0.44%	23%
	24	27	0.40%	22%	26	0.42%	22%	24	0.43%	23%	22	0.44%	24%
	26	28	0.41%	22%	27	0.43%	23%	25	0.44%	24%	23	0.45%	24%
	28	29	0.42%	22%	28	0.44%	23%	26	0.45%	24%	24	0.46%	25%
	30	30	0.42%	22%	28	0.44%	23%	27	0.45%	24%	25	0.46%	25%
	32	31	0.43%	23%	29	0.44%	24%	27	0.45%	24%	26	0.47%	25%
	34	32	0.44%	23%	30	0.45%	24%	28	0.46%	25%	27	0.47%	26%
	36	33	0.44%	24%	31	0.45%	24%	29	0.46%	25%	27	0.47%	26%
	38	33	0.44%	24%	32	0.46%	25%	30	0.47%	25%	28	0.48%	26%
	40	34	0.45%	24%	32	0.46%	25%	31	0.48%	26%	29	0.49%	26%
	42	35	0.45%	24%	33	0.47%	25%	31	0.48%	26%	30	0.49%	26%
	44	36	0.46%	25%	34	0.47%	25%	32	0.48%	26%	30	0.49%	26%
	46	36	0.46%	25%	34	0.47%	25%	33	0.49%	26%	31	0.50%	27%
	48	37	0.47%	25%	35	0.48%	26%	33	0.49%	26%	32	0.50%	27%
	50	38	0.47%	25%	36	0.48%	26%	34	0.49%	26%	32	0.50%	27%
	52	38	0.47%	25%	36	0.48%	26%	35	0.50%	27%	33	0.51%	27%
	54	39	0.48%	26%	37	0.49%	26%	35	0.50%	27%	33	0.51%	27%
	56	39	0.48%	26%	38	0.49%	27%	36	0.50%	27%	34	0.51%	27%
	58	40	0.48%	26%	38	0.49%	27%	36	0.50%	27%	35	0.52%	28%
	60	41	0.49%	26%	39	0.50%	27%	37	0.51%	27%	35	0.52%	28%

*L (ft) = slope length including Road Shoulder Length

*DSR = dissolved solids removal (i.e. infiltrated runoff)

*SSR = suspended solids removal

Table A 10. Slope Length and Efficiency 8:1 Swale Shoulder / 6% Road Shoulder

Road Shoulder Slope:		6%											
Shoulder Length:		2 ft.			4 ft.			6 ft.			8 ft.		
Pavement Width		L	DSR	SSR	L	DSR	SSR	L	DSR	SSR	L	DSR	SSR
Swale Shoulder Slope: 8:1	12	20	0.37%	21%	19	0.36%	21%	19	0.37%	21%	18	0.37%	21%
	14	21	0.37%	21%	21	0.39%	21%	20	0.38%	21%	20	0.39%	22%
	16	22	0.38%	21%	22	0.39%	22%	21	0.38%	22%	21	0.39%	22%
	18	23	0.39%	22%	23	0.40%	22%	22	0.39%	22%	22	0.40%	22%
	20	24	0.40%	22%	24	0.40%	22%	23	0.40%	22%	23	0.41%	22%
	22	25	0.41%	22%	25	0.41%	22%	24	0.41%	22%	24	0.42%	22%
	24	26	0.42%	22%	26	0.42%	22%	25	0.42%	22%	25	0.43%	22%
	26	27	0.43%	22%	27	0.43%	22%	26	0.43%	22%	26	0.44%	23%
	28	28	0.43%	22%	28	0.44%	23%	27	0.43%	23%	27	0.45%	23%
	30	29	0.44%	23%	28	0.43%	23%	28	0.44%	23%	27	0.44%	23%
	32	30	0.45%	23%	29	0.45%	23%	29	0.45%	24%	28	0.45%	24%
	34	30	0.44%	23%	30	0.45%	24%	29	0.45%	24%	29	0.46%	24%
	36	31	0.45%	24%	31	0.46%	24%	30	0.46%	24%	30	0.46%	24%
	38	32	0.47%	24%	31	0.46%	24%	31	0.47%	24%	30	0.46%	24%
	40	32	0.46%	24%	32	0.47%	25%	31	0.46%	24%	31	0.47%	25%
	42	33	0.47%	25%	33	0.48%	25%	32	0.47%	25%	32	0.48%	25%
	44	34	0.48%	25%	33	0.47%	25%	33	0.48%	25%	32	0.48%	25%
	46	34	0.48%	25%	34	0.48%	25%	33	0.48%	25%	33	0.49%	26%
	48	35	0.48%	25%	35	0.49%	26%	34	0.48%	26%	34	0.49%	26%
	50	36	0.49%	26%	35	0.49%	26%	35	0.50%	26%	34	0.49%	26%
	52	36	0.49%	26%	36	0.49%	26%	35	0.49%	26%	35	0.50%	26%
	54	37	0.50%	26%	36	0.49%	26%	36	0.50%	26%	35	0.49%	26%
	56	37	0.49%	26%	37	0.50%	26%	36	0.50%	26%	36	0.51%	27%
	58	38	0.50%	26%	37	0.50%	26%	37	0.51%	27%	36	0.50%	27%
	60	38	0.50%	26%	38	0.51%	27%	37	0.51%	27%	37	0.51%	27%

*L (ft) = slope length including Road Shoulder Length
*DSR = dissolved solids removal (i.e. infiltrated runoff)
*SSR = suspended solids removal

Table A 11. Slope Length and Efficiency 8:1 Swale Shoulder / 4% Road Shoulder

Road Shoulder Slope:		**4%**											
Shoulder Length:		**2 ft.**			**4 ft.**			**6 ft.**			**8 ft.**		
Pavement Width		**L**	**DSR**	**SSR**	**L**	**DSR**	**SSR**	**L**	**DSR**	**SSR**	**L**	**DSR**	**SSR**
Swale Shoulder Slope: 8:1	12	19	0.36%	21%	19	0.38%	21%	18	0.38%	21%	17	0.38%	21%
	14	21	0.39%	21%	20	0.39%	21%	19	0.39%	22%	18	0.39%	22%
	16	22	0.39%	22%	21	0.39%	22%	20	0.39%	22%	19	0.39%	22%
	18	23	0.40%	22%	22	0.40%	22%	21	0.40%	22%	21	0.41%	22%
	20	24	0.40%	22%	23	0.41%	22%	22	0.41%	22%	22	0.42%	22%
	22	25	0.41%	22%	24	0.41%	22%	23	0.42%	22%	23	0.43%	22%
	24	26	0.42%	22%	25	0.42%	22%	24	0.42%	22%	24	0.44%	23%
	26	27	0.43%	22%	26	0.43%	22%	25	0.43%	23%	24	0.43%	23%
	28	28	0.44%	23%	27	0.44%	23%	26	0.44%	23%	25	0.44%	23%
	30	28	0.43%	23%	28	0.45%	23%	27	0.45%	24%	26	0.45%	24%
	32	29	0.44%	23%	28	0.44%	23%	28	0.46%	24%	27	0.46%	24%
	34	30	0.45%	24%	29	0.46%	24%	28	0.46%	24%	28	0.47%	25%
	36	31	0.46%	24%	30	0.46%	24%	29	0.46%	24%	28	0.46%	25%
	38	31	0.46%	24%	31	0.47%	25%	30	0.47%	25%	29	0.47%	25%
	40	32	0.46%	24%	31	0.47%	25%	31	0.48%	25%	30	0.48%	25%
	42	33	0.47%	25%	32	0.48%	25%	31	0.48%	25%	30	0.48%	25%
	44	33	0.47%	25%	33	0.49%	25%	32	0.49%	26%	31	0.49%	26%
	46	34	0.48%	25%	33	0.48%	25%	32	0.48%	26%	32	0.49%	26%
	48	35	0.49%	26%	34	0.49%	26%	33	0.49%	26%	32	0.49%	26%
	50	35	0.49%	26%	34	0.49%	26%	34	0.50%	26%	33	0.50%	26%
	52	36	0.49%	26%	35	0.50%	26%	34	0.50%	26%	33	0.50%	26%
	54	36	0.49%	26%	36	0.51%	26%	35	0.51%	27%	34	0.51%	27%
	56	37	0.50%	26%	36	0.50%	26%	35	0.50%	27%	35	0.52%	27%
	58	38	0.51%	27%	37	0.51%	27%	36	0.51%	27%	35	0.51%	27%
	60	38	0.51%	27%	37	0.51%	27%	36	0.51%	27%	36	0.52%	27%

*L (ft) = slope length including Road Shoulder Length

*DSR = dissolved solids removal (i.e. infiltrated runoff)

*SSR = suspended solids removal

Table A 12. Slope Length and Efficiency 8:1 Swale Shoulder / 2% Road Shoulder

Road Shoulder Slope:		**2%**											
Shoulder Length:		**2 ft.**			**4 ft.**			**6 ft.**			**8 ft.**		
Pavement Width		**L**	**DSR**	**SSR**	**L**	**DSR**	**SSR**	**L**	**DSR**	**SSR**	**L**	**DSR**	**SSR**
Swale Shoulder Slope: 8:1	12	19	0.38%	21%	17	0.39%	21%	16	0.42%	22%	14	0.43%	22%
	14	20	0.39%	21%	19	0.42%	22%	17	0.43%	22%	16	0.45%	22%
	16	21	0.39%	22%	20	0.42%	22%	18	0.43%	22%	17	0.45%	22%
	18	22	0.40%	22%	21	0.43%	22%	19	0.44%	22%	18	0.46%	23%
	20	23	0.41%	22%	22	0.44%	22%	20	0.44%	22%	19	0.47%	23%
	22	24	0.42%	22%	23	0.44%	22%	21	0.45%	23%	20	0.47%	24%
	24	25	0.43%	22%	24	0.45%	23%	22	0.46%	23%	21	0.48%	24%
	26	26	0.44%	22%	25	0.46%	23%	23	0.47%	24%	22	0.49%	25%
	28	27	0.45%	23%	26	0.47%	24%	24	0.48%	24%	23	0.50%	25%
	30	28	0.45%	23%	26	0.46%	24%	25	0.48%	25%	23	0.49%	25%
	32	29	0.46%	24%	27	0.47%	24%	26	0.49%	25%	24	0.50%	25%
	34	29	0.46%	24%	28	0.48%	25%	26	0.49%	25%	25	0.51%	26%
	36	30	0.47%	24%	29	0.49%	25%	27	0.50%	25%	26	0.52%	26%
	38	31	0.48%	25%	29	0.48%	25%	28	0.50%	26%	26	0.51%	26%
	40	31	0.47%	25%	30	0.49%	25%	29	0.51%	26%	27	0.52%	26%
	42	32	0.48%	25%	31	0.51%	26%	29	0.51%	26%	28	0.53%	27%
	44	33	0.49%	25%	31	0.50%	26%	30	0.52%	26%	28	0.53%	27%
	46	33	0.49%	25%	32	0.51%	26%	30	0.51%	26%	29	0.53%	27%
	48	34	0.49%	26%	33	0.51%	26%	31	0.53%	27%	30	0.55%	27%
	50	35	0.51%	26%	33	0.51%	26%	32	0.53%	27%	30	0.54%	27%
	52	35	0.50%	26%	34	0.52%	27%	32	0.53%	27%	31	0.55%	28%
	54	36	0.51%	26%	34	0.52%	27%	33	0.54%	27%	31	0.55%	28%
	56	36	0.51%	26%	35	0.53%	27%	33	0.53%	27%	32	0.55%	28%
	58	37	0.51%	27%	35	0.52%	27%	34	0.54%	28%	32	0.55%	28%
	60	37	0.51%	27%	36	0.53%	27%	35	0.55%	28%	33	0.56%	28%

*L (ft) = slope length including Road Shoulder Length

*DSR = dissolved solids removal (i.e. infiltrated runoff)

*SSR = suspended solids removal

4:1 Swale Shoulder 6% Road Shoulder

W_P (ft)	L_2 (ft)	L_4 (ft)	L_6 (ft)	L_8 (ft)
12	24	23	22	21
14	25	24	23	22
16	27	26	25	24
18	28	27	26	25
20	30	28	27	26
22	31	30	29	28
24	32	31	30	29
26	33	32	31	30
28	34	33	32	31
30	35	34	33	32
32	36	35	34	33
34	37	36	35	34
36	38	37	36	35
38	39	38	37	35
40	39	38	37	36
42	40	39	38	37
44	41	40	39	38
46	42	41	40	39
48	43	42	40	39
50	43	42	41	40
52	44	43	42	41
54	45	44	43	42
56	45	44	43	42
58	46	45	44	43
60	47	46	45	44

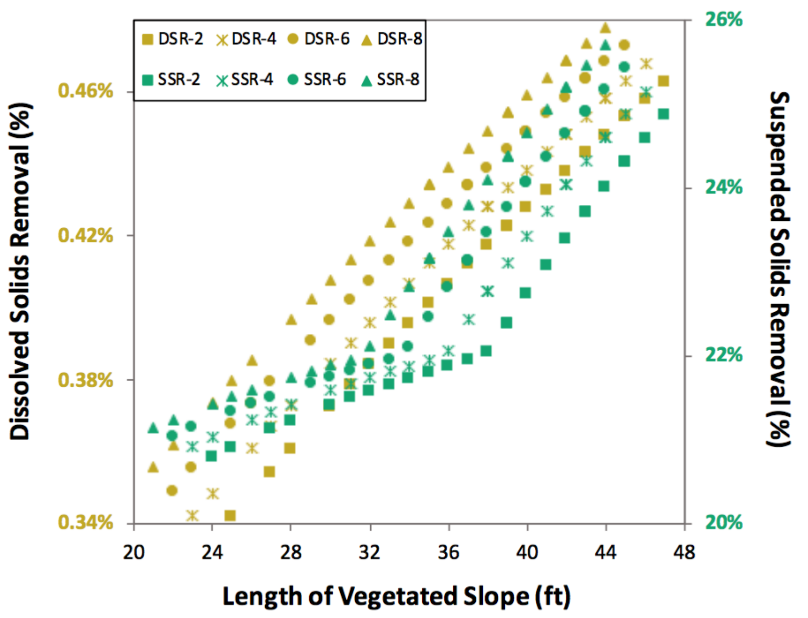


Figure A 1. Swale efficiency for varying lengths of grassed slope with 4:1 swale shoulder and 6% road shoulder.

4:1 Swale Shoulder 4% Road Shoulder

W_P (ft)	L_2 (ft)	L_4 (ft)	L_6 (ft)	L_8 (ft)
12	24	22	21	19
14	25	24	22	21
16	27	25	24	22
18	28	26	25	24
20	29	28	26	25
22	30	29	27	26
24	31	30	29	27
26	33	31	30	28
28	34	32	31	29
30	35	33	32	30
32	36	34	33	31
34	36	35	34	32
36	37	36	34	33
38	38	37	35	34
40	39	38	36	35
42	40	38	37	36
44	41	39	38	36
46	41	40	39	37
48	42	41	39	38
50	43	42	40	39
52	44	42	41	39
54	44	43	41	40
56	45	44	42	41
58	46	44	43	41
60	46	45	43	42

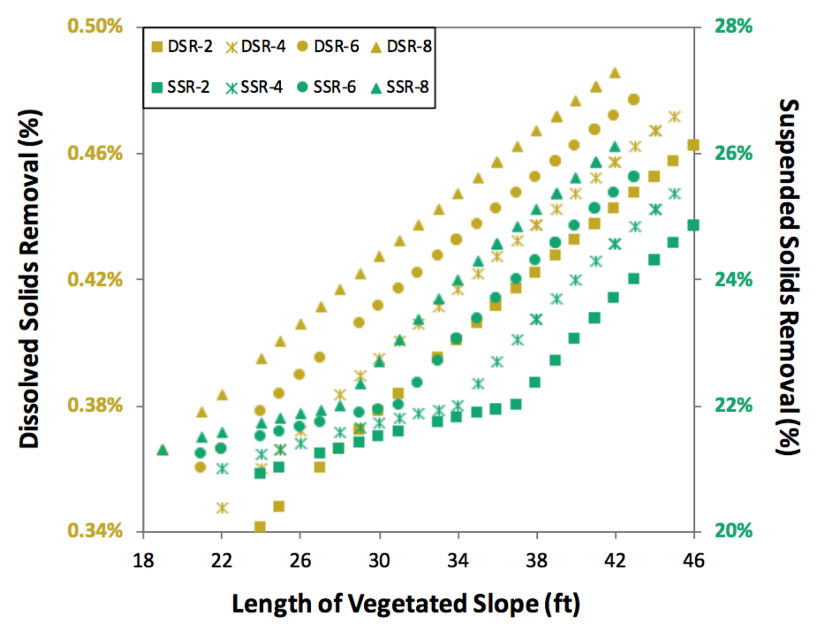


Figure A 2. Swale efficiency for varying lengths of grassed slope with 4:1 swale shoulder and 4% road shoulder.

4:1 Swale Shoulder 2% Road Shoulder

W_P (ft)	L_2 (ft)	L_4 (ft)	L_6 (ft)	L_8 (ft)
12	23	20	18	16
14	24	22	20	17
16	26	23	21	19
18	27	25	23	20
20	28	26	24	22
22	30	27	25	23
24	31	28	26	24
26	32	30	27	25
28	33	31	28	26
30	34	32	29	27
32	35	33	30	28
34	36	33	31	29
36	37	34	32	30
38	37	35	33	31
40	38	36	34	31
42	39	37	35	32
44	40	38	35	33
46	41	38	36	34
48	41	39	37	35
50	42	40	38	35
52	43	41	38	36
54	44	41	39	37
56	44	42	40	37
58	45	43	40	38
60	46	43	41	39

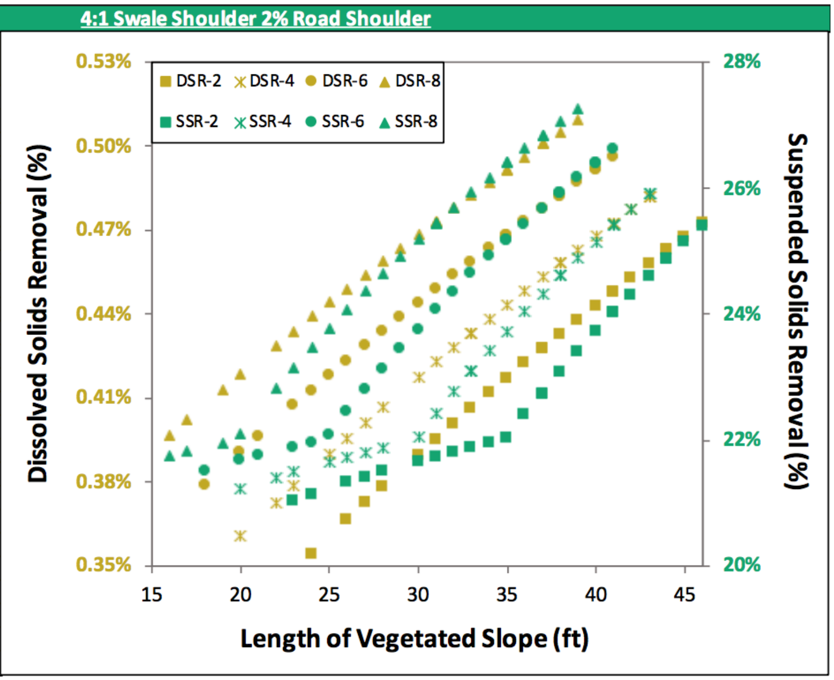


Figure A 3. Swale efficiency for varying lengths of grassed slope with 4:1 swale shoulder and 2% road shoulder.

6:1 Swale Shoulder 6% Road Shoulder

W_P (ft)	L_2 (ft)	L_4 (ft)	L_6 (ft)	L_8 (ft)
12	21	21	20	19
14	23	22	21	21
16	24	23	23	22
18	25	25	24	23
20	26	26	25	24
22	27	27	26	25
24	28	28	27	26
26	29	29	28	27
28	30	30	29	28
30	31	31	30	29
32	32	31	31	30
34	33	32	31	31
36	34	33	32	32
38	34	34	33	32
40	35	34	34	33
42	36	35	34	34
44	37	36	35	34
46	37	37	36	35
48	38	37	37	36
50	39	38	37	36
52	39	39	38	37
54	40	39	38	38
56	41	40	39	38
58	41	40	40	39
60	42	41	40	40

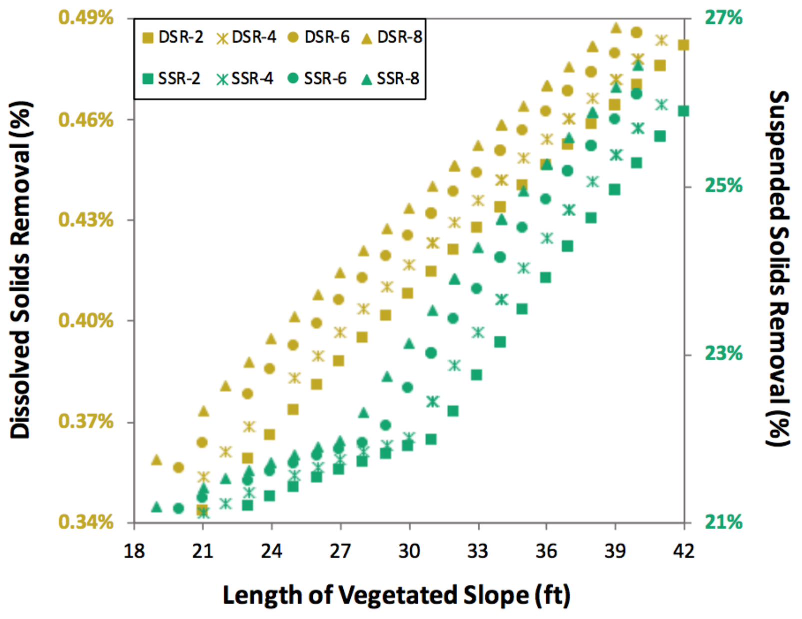


Figure A 4. Swale efficiency for varying lengths of grassed slope with 6:1 swale shoulder and 6% road shoulder.

6:1 Swale Shoulder 2% Road Shoulder

W_P (ft)	L_2 (ft)	L_4 (ft)	L_6 (ft)	L_8 (ft)
12	20	19	17	15
14	22	20	18	16
16	23	21	19	18
18	24	22	21	19
20	25	24	22	20
22	26	25	23	21
24	27	26	24	22
26	28	27	25	23
28	29	28	26	24
30	30	28	27	25
32	31	29	27	26
34	32	30	28	27
36	33	31	29	27
38	33	32	30	28
40	34	32	31	29
42	35	33	31	30
44	36	34	32	30
46	36	34	33	31
48	37	35	33	32
50	38	36	34	32
52	38	36	35	33
54	39	37	35	33
56	39	38	36	34
58	40	38	36	35
60	41	39	37	35

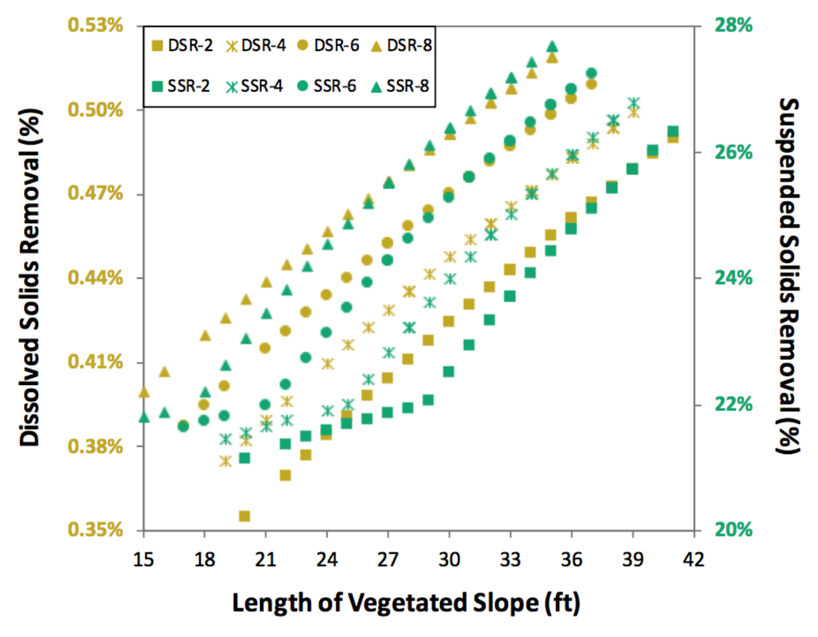


Figure A 5. Swale efficiency for varying lengths of grassed slope with 6:1 swale shoulder and 2% road shoulder.

8:1 Swale Shoulder 6% Road Shoulder

W_P (ft)	L_2 (ft)	L_4 (ft)	L_6 (ft)	L_8 (ft)
12	20	19	19	18
14	21	21	20	20
16	22	22	21	21
18	23	23	22	22
20	24	24	23	23
22	25	25	24	24
24	26	26	25	25
26	27	27	26	26
28	28	28	27	27
30	29	28	28	27
32	30	29	29	28
34	30	30	29	29
36	31	31	30	30
38	32	31	31	30
40	32	32	31	31
42	33	33	32	32
44	34	33	33	32
46	34	34	33	33
48	35	35	34	34
50	36	35	35	34
52	36	36	35	35
54	37	36	36	35
56	37	37	36	36
58	38	37	37	36
60	38	38	37	37

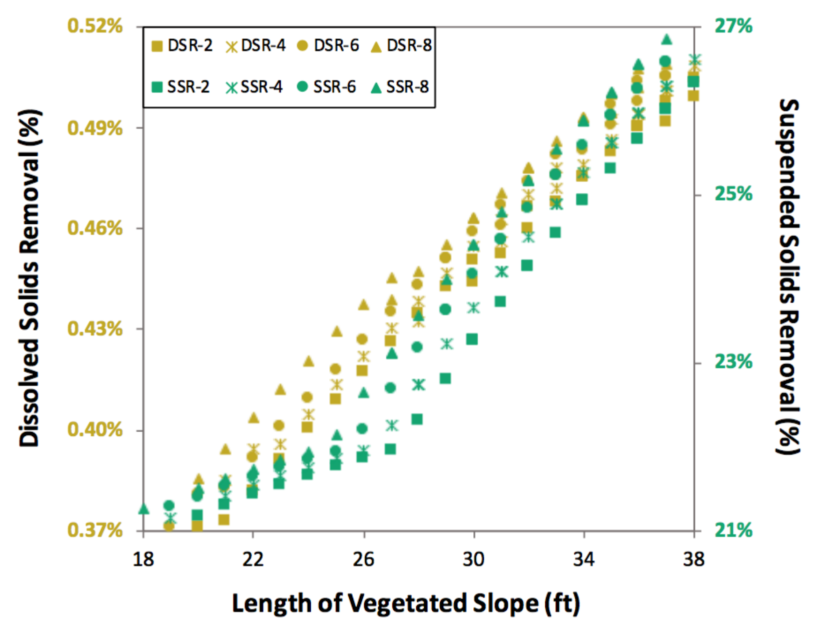


Figure A 6. Swale efficiency for varying lengths of grassed slope with 8:1 swale shoulder and 6% road shoulder.

8:1 Swale Shoulder 4% Road Shoulder

W_P (ft)	L_2 (ft)	L_4 (ft)	L_6 (ft)	L_8 (ft)
12	19	19	18	17
14	21	20	19	18
16	22	21	20	19
18	23	22	21	21
20	24	23	22	22
22	25	24	23	23
24	26	25	24	24
26	27	26	25	24
28	28	27	26	25
30	28	28	27	26
32	29	28	28	27
34	30	29	28	28
36	31	30	29	28
38	31	31	30	29
40	32	31	31	30
42	33	32	31	30
44	33	33	32	31
46	34	33	32	32
48	35	34	33	32
50	35	34	34	33
52	36	35	34	33
54	36	36	35	34
56	37	36	35	35
58	38	37	36	35
60	38	37	36	36

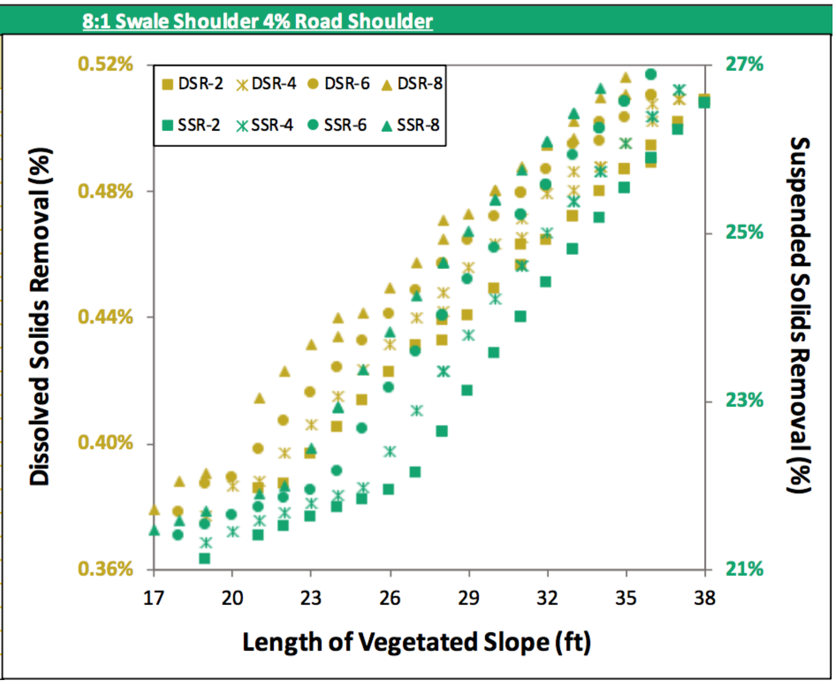


Figure A 7. Swale efficiency for varying lengths of grassed slope with 8:1 swale shoulder and 4% road shoulder.

8:1 Swale Shoulder 2% Road Shoulder

W_P (ft)	L_2 (ft)	L_4 (ft)	L_6 (ft)	L_8 (ft)
12	19	17	16	14
14	20	19	17	16
16	21	20	18	17
18	22	21	19	18
20	23	22	20	19
22	24	23	21	20
24	25	24	22	21
26	26	25	23	22
28	27	26	24	23
30	28	26	25	23
32	29	27	26	24
34	29	28	26	25
36	30	29	27	26
38	31	29	28	26
40	31	30	29	27
42	32	31	29	28
44	33	31	30	28
46	33	32	30	29
48	34	33	31	30
50	35	33	32	30
52	35	34	32	31
54	36	34	33	31
56	36	35	33	32
58	37	35	34	32
60	37	36	35	33

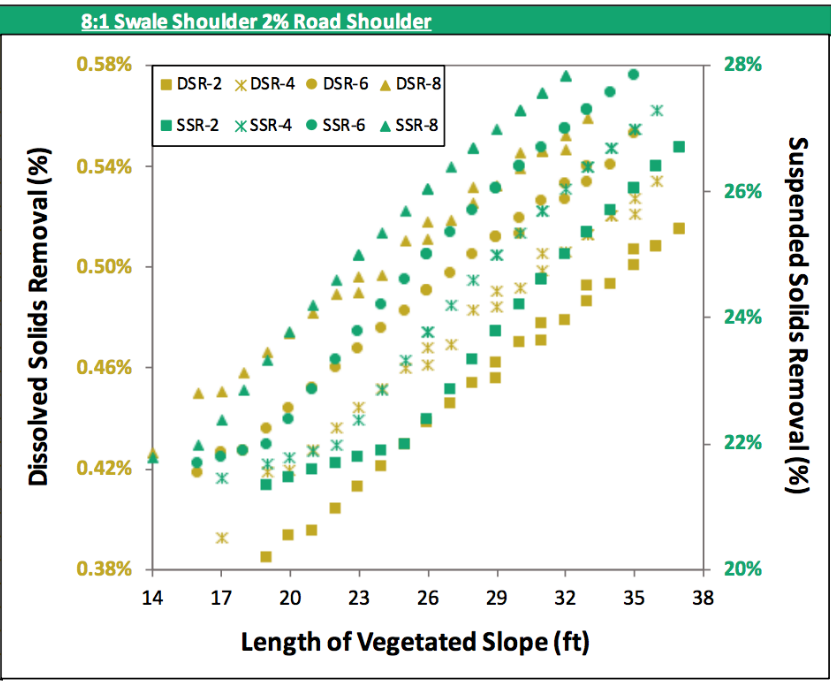


Figure A 8. Swale efficiency for varying lengths of grassed slope with 8:1 swale shoulder and 2% road shoulder.

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