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Module 4c: Stormwater Treatment using Grass Swales

Abstract

The Department of Civil and Environmental Engineering at the University of Alabama has been conducting research investigating the effectiveness of grass swales for stormwater sediment transport to quantify swale hydraulic and sediment transport under relatively small flows. This research has been supported by the Water Environment Research Foundation (Johnson, *et al*. 2003; Kirby 2003) and the University Transportation Center of Alabama (Nara and Pitt 2005). Grass swales are vegetated open channels that collect and transport stormwater runoff. They are often used as an alternative to concrete gutters for stormwater management, such as grass swales in the median of roadways, because of their advantages of infiltration and filtration of stormwater. The objectives of this research are to understand the effectiveness of grass swales in sediment transport, the associated effects of the different swale and hydraulic variables, and to develop a predictive model. To achieve these objectives, experimental grass swales were constructed and tested in an indoor greenhouse facility. The variables tested in the experiments were slope, grass type, depth of flow, sampling time, and length of swales. A water-sediment mixture with a known sediment concentration of sieved sands and fine particles of silica were used to analyze the variables. During the preliminary

set of controlled experiments, 108 samples were collected and analyzed for turbidity, total solids, and particle size distributions to investigate the effects of the experimental variables. After completing the initial tests, a second set of controlled experiments was conducted. During this second set of tests, 108 samples were collected and analyzed for turbidity, total solids, total suspended solids, total dissolved solids, and particle size distribution.

To examine how the results obtained from the indoor swale experiments can be applied to full-scale swales, sediment samples were also collected at an outdoor grass swale located adjacent to the Tuscaloosa City Hall, Alabama, during actual storm events. Sixty-nine samples during 13 storm events from August to December 2004 were collected and analyzed for turbidity, total solids, total suspended solids, total dissolved solids, and particle size distributions. The total suspended solids concentrations observed during different rain events showed significant sediment reductions as a function of the length of the swale. The particle size distributions of the suspended solids at the outdoor swale site showed preferential transport of small particles for all lengths of the swale, and preferential trapping of large particles.

This paper begins with a summary outlining the design of grass swales to minimize scour and channel erosion, specifically examining grass-lined swales and the use of turf-reinforced mats. This paper section also describes the predictive equations developed to describe sediment trapping in the swales. Several example problems are used to illustrate how these data are used to design stable grass-lined drainage swales that maximize particulate and associated pollutant trapping.

Roadside Drainage Design for Channel Stability

Allowable Velocity and Shear Stress

This section of this paper is a summary of selected material from Pitt, R., S. Clark, and D. Lake, *Construction Site Erosion and Sediment Controls: Planning, Design, and Performance*, to be published by DEStech Publications, Lancaster, PA, in 2006. This discussion reviews the basic approaches and techniques available for the stable design of natural and grass-lined drainage channels. There are several alternatives that can be used which are briefly described. Example problems are also presented.

An important reference on general shear stress relationships and channel bed movement is *Engineering and Design: Channel Stability Assessment for Flood Control Projects* (COE 1994; EM 1110-2-1418). Although this reference is for large channels, many of the basic concepts are similar to what occurs for smaller drainage channels, and these are specifically addressed in the following discussion. More extensive information on these topics is available in numerous textbooks and manuals on sediment transport and channel design.

Allowable Velocity Approach to Channel Design

The concept of allowable velocities for various soils and materials dates from the early days of hydraulics. An example of simple velocity criteria is given by Table 1 (COE undated, EM 1110-2-1601). Table 2 is a similar table, from U.S. Bureau of Reclamation research (Fortier and Scobey 1926) that also shows the corresponding allowable shear stresses and Manning’s roughness values.

Table 1. Example of Simple Allowable Velocity Objectives (From COE undated, EM 1110-2-1601)

Channel Material	Mean Channel Velocity (ft/sec)
Fine Sand	2.0
Coarse Sand	4.0
Fine Gravel	6.0
Earth	
Sandy Silt	2.0
Silt clay	3.5
Clay	6.0
Grass-lined Earth (Slopes less than 5%)	
Bermuda Grass	
Sandy Silt	6.0
Silt Clay	8.0
Kentucky Blue Grass	
Sandy Silt	5.0
Silt Clay	7.0
Poor Rock (usually sedimentary)	10.0
Soft Sandstone	8.0
Soft Shale	3.5
Good Rock (usually igneous or hard metamorphic)	20.0

Table 2. Maximum Permissible Velocities and Corresponding Unit Tractive Force (Shear Stress) (U.S. Bureau of Reclamation research, Fortier and Scobey 1926)

		Clear Water (diversion structures)		Water Transporting Colloidal Silts (on site and down slope)	
Material	**n**	**V (ft/sec)**	**τ_o (lb/ft^2)**	**V (ft/sec)**	**τ_o (lb/ft^2)**
Fine sand, colloidal	0.020	1.50	0.027	2.50	0.075
Sandy loam, noncolloidal	0.020	1.75	0.037	2.50	0.075
Silt loam, noncolloidal	0.020	2.00	0.048	3.00	0.11
Alluvial silts, noncolloidal	0.020	2.00	0.048	3.50	0.15
Ordinary firm loam	0.020	2.50	0.075	3.50	0.15
Volcanic ash	0.020	2.50	0.075	3.50	0.15
Stiff clay, very colloidal	0.025	3.75	0.26	5.00	0.46
Alluvial silts, colloidal	0.025	3.75	0.26	5.00	0.46
Shales and hardpans	0.025	6.00	0.67	6.00	0.67
Fine gravel	0.020	2.50	0.075	5.00	0.32
Graded loam to cobbles when noncolloidal	0.030	3.75	0.38	5.00	0.66
Graded silts to cobbles when noncolloidal	0.030	4.00	0.43	5.50	0.80
Coarse gravel, noncolloidal	0.025	4.00	0.30	6.00	0.67
Cobbles and shingles	0.035	5.00	0.91	5.50	1.10

Note:

- an increase in velocity of 0.5 ft/sec can be added to these values when the depth of water is greater than 3 ft.
- a decrease in velocity of 0.5 ft/sec should be subtracted when the water contains very coarse suspended sediments.
- for high and infrequent discharges of short duration, up to 30% increases in velocity can be added

Figure 1 is another guidance illustration showing SCS data (USDA 1977). This figure also differentiates between “sediment-free” and “sediment-laden” flow, with clear water having more restrictive allowable velocities.

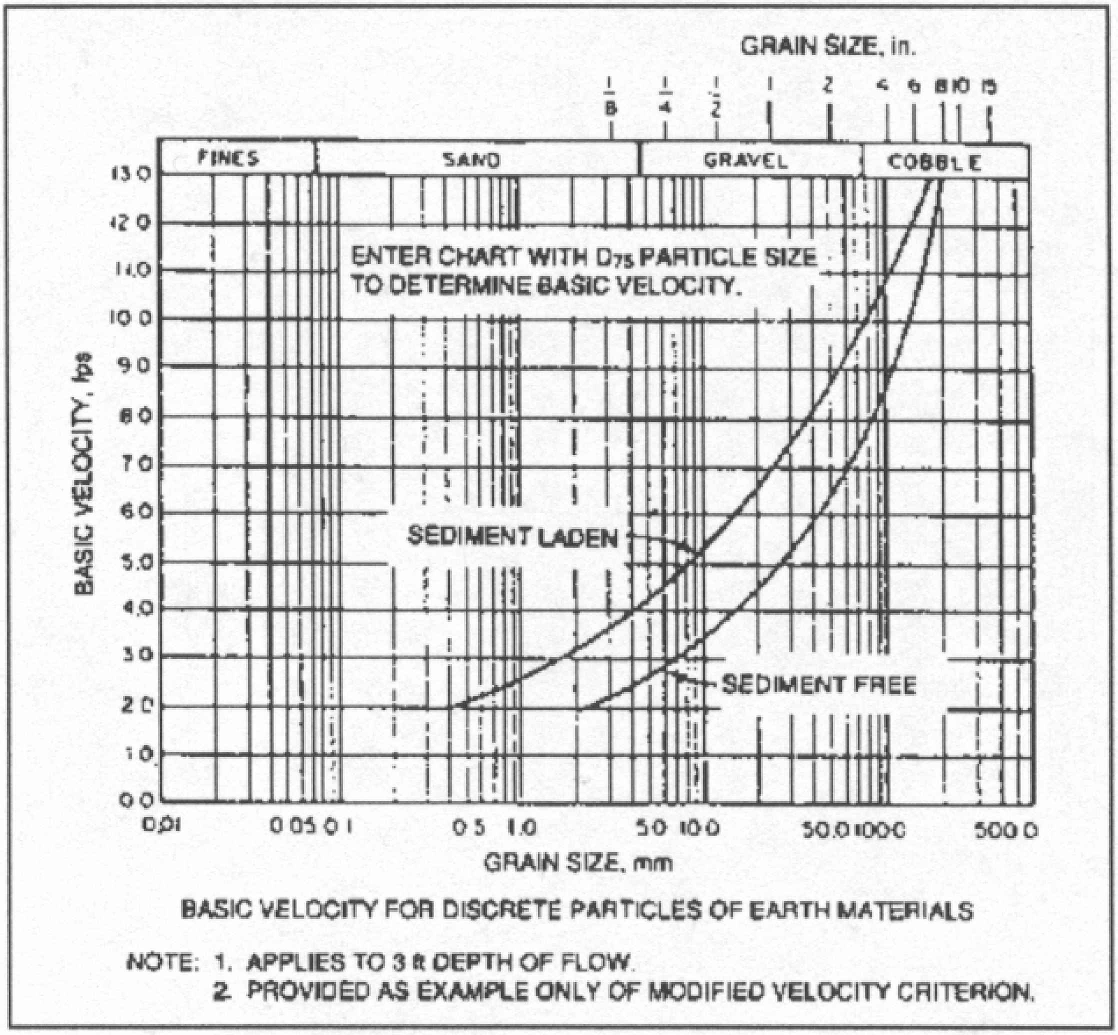


Figure 1. Example of allowable velocity data with provision for sediment transport (USDA 1977)

Allowable Shear Stress Calculations

By the 1930's, boundary shear stress (sometimes called tractive force) was generally accepted as a more appropriate erosion criterion than allowable velocity. The average boundary shear stress in uniform flow (Figure 3) is calculated by

$$\tau_o = \gamma RS \quad (\mathrm{lb/ft^2})$$

where:

γ = specific weight of water (62.4 lbs/ft^3)
R = hydraulic radius (ft)
S = hydraulic slope (ft/ft)

Figure 2 (Chow 1959) shows a typical distribution of the shear stresses in a channel, indicating how the maximum shear stress is applied along the center of the channel for straight channel reaches having constant depths.

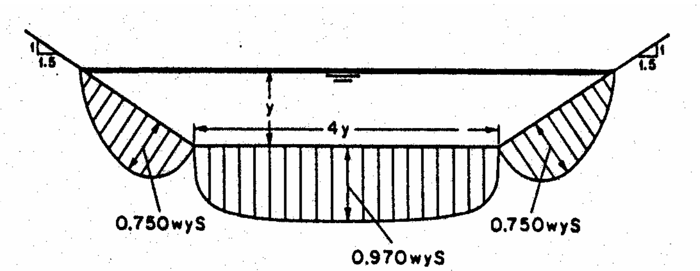


Figure 2. Typical shear stress distributions in a trapezoidal channel (Chow 1959).

If the maximum shear stress is desired (typical for design conditions), then the flow depth is used instead of the hydraulic radius. For sheetflow conditions, the hydraulic radius (R) is very close to the depth of flow, and the above equation is also modified, as shown in Figure 3, by using the depth of flow to replace the hydraulic radius.

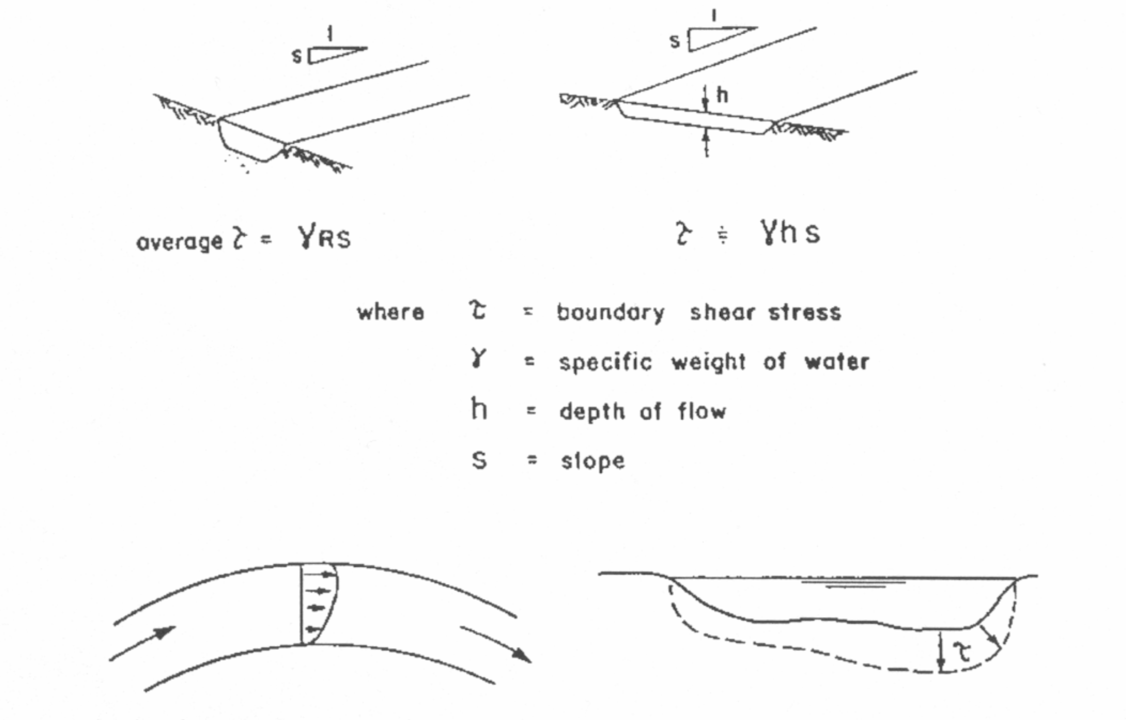


Figure 3. Boundary shear stress in uniform flow (COE 1994).

The COE (1994) shows that the use of the Shield's diagram likely greatly over-predicts the erodibility of the channel bottom material. The expected reason they give is that the Shield's diagram assumes a flat bottom channel and the total roughness is determined by the size of the granular bottom material. The actual Manning's roughness value is likely much larger because it is largely determined by bed forms, channel irregularities, and vegetation. They recommend, as a more realistic assessment, that empirical data based on field observations be used. In the absence of local data, they present Figure 4 (from Chow 1959) for applications for channels in granular materials. This figure shows the permissible unit tractive force (shear stress) as a function of the average particle diameter, and the fine sediment content of the flowing water.

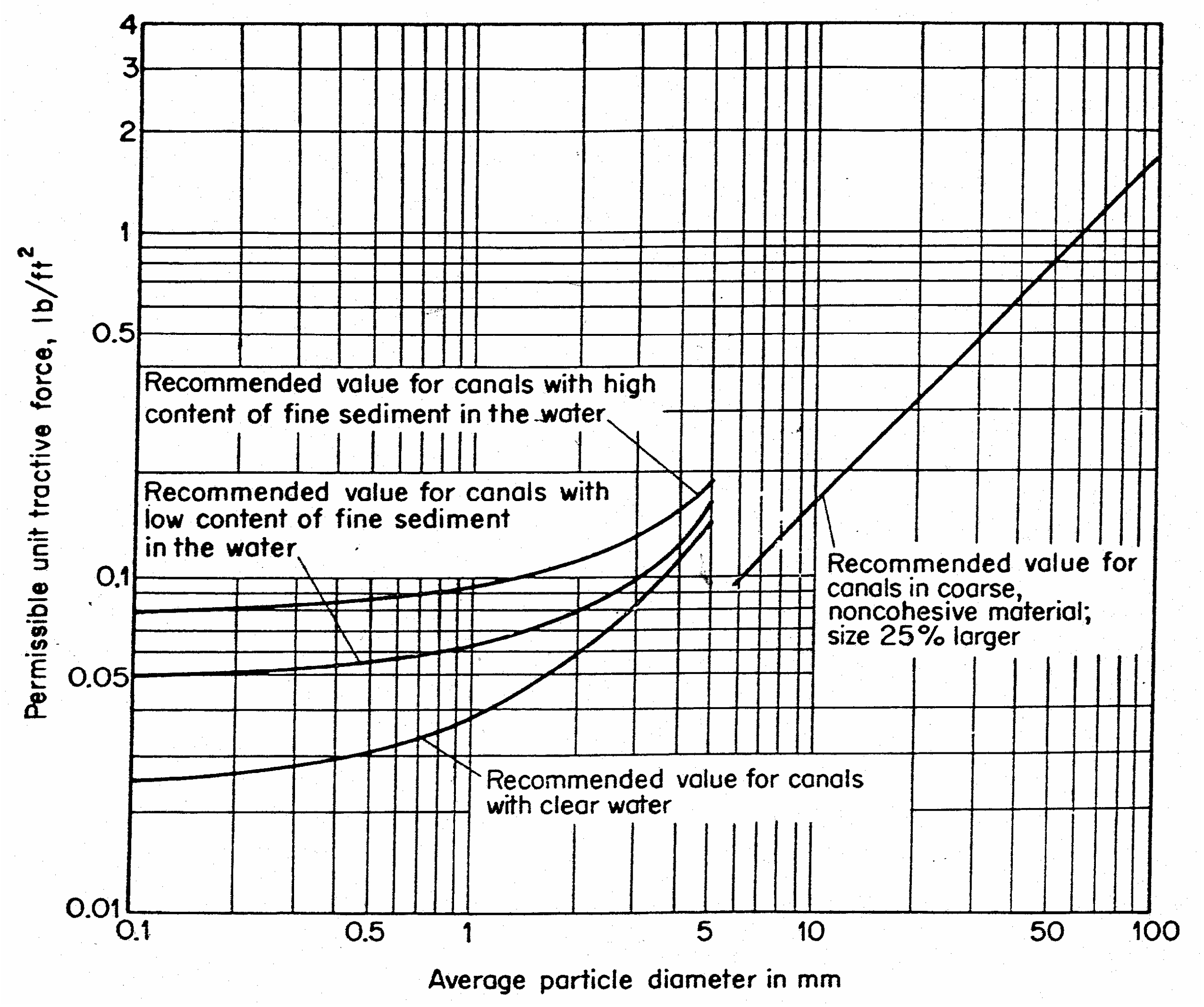


Figure 4. Allowable shear stresses (tractive forces) for canals in granular materials (U.S. Bureau of Reclamation).

The allowable shear stress concept has also been applied to semicohesive and noncohesive soils, but values do not correlate well with standard geotechnical parameters because the resistance to erosion is affected by such factors as water chemistry, history of exposure to flows, and weathering (Raudkivi and Tan 1984). Figure 5 gives an example of allowable shear stresses for a range of cohesive materials. Again, the COE recommends that local field observations or laboratory testing results be given preference.

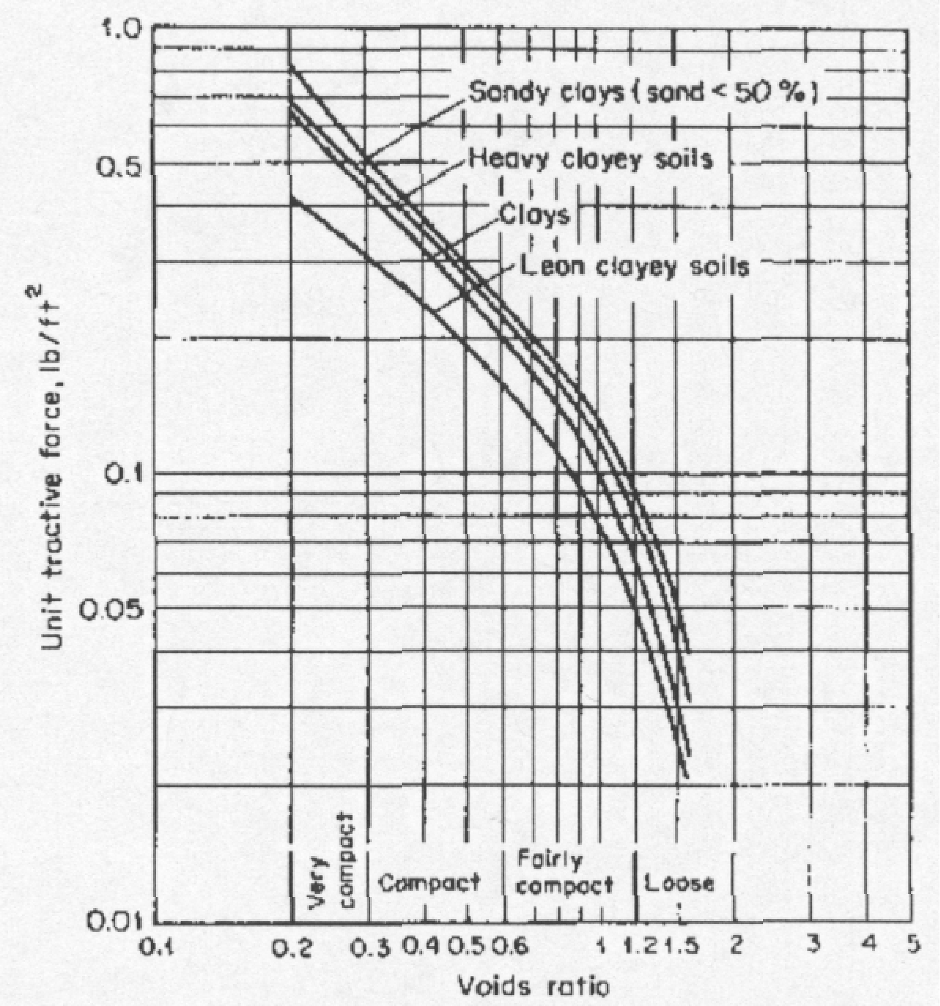


Figure 5. Example of allowable shear stresses (tractive forces) for cohesive materials (COE 1994). Note: Leon clayey soils are hardpan soils where the soil grains become cemented together with bonding agents such as iron oxide or calcium carbonate, forming a hard, impervious mass.

Shear Stress in Channels having Bends

The basic shear stress formulas can be modified to account for the increased shear stress after bends in channels. Normally, the maximum shear stress is along the center part of a channel (usually the deepest area), but a hydrodynamic force is applied to the outside bend after a change in direction. Along the outside of the bend, increased water velocity and shear stress will increase the erosion potential, while sedimentation may occur along the inside of the bend where the water velocity slows. The basic shear stress formula is modified with a bend coefficient, as follows:

$$\tau_o = \frac{\gamma RS}{K_b}$$

where:

γ = specific weight of water (62.4 lbs/ft^3)
R = hydraulic radius (ft) (can be estimated by water depth, for relatively wide channels or sheetflows)
S = hydraulic slope (ft/ft)
K_b = bend coefficient

The bend coefficient can be estimated by (Croke 2001):

$$K_b = \frac{R_c}{B}$$

where:

R_c = bend curvature (radius of the bend)
B = bottom width of the channel

As the bend curvature, R_c, increases, the effect of the bend decreases. These parameters are illustrated in Figure 6 (North American Green).

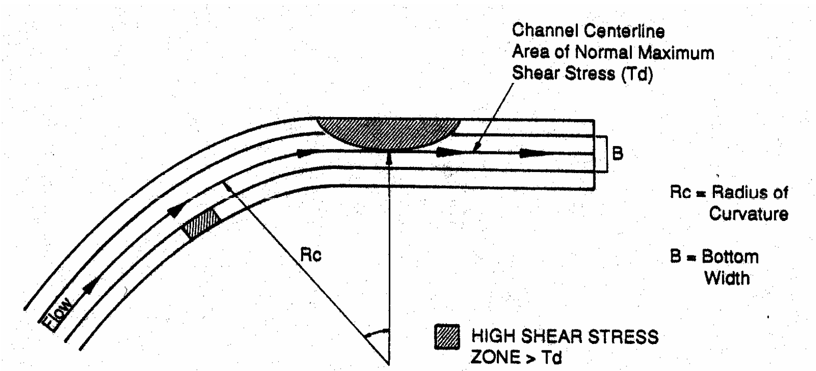


Figure 6. Location of increased shear stress due to channel bend (North American Green).

This formula obviously cannot be used for a V-shaped channel, where the bottom width is zero. The area being affected by the increased shear stress due to channel bends is usually assumed to begin immediately after the bend at the tangent to the downstream channel, as shown in Figure 6. The length of extra shear stress can be estimated by the following formula (after Croke 2001):

$$L_p = \frac{0.604R^{1.17}}{n}$$

where:

L_p = length of extra protection needed due to increased shear stress on outside of bend (same units as R)
R = hydraulic radius = ratio of cross-sectional area of flow to wetted perimeter (A/P)
n = Manning's roughness coefficient for liner in the channel bend

As an example, assume the following conditions:

R = 3.0 ft
n = 0.042

then:

$$L_p = \frac{0.604(3)^{1.17}}{0.042} = 52 \text{ ft}$$

In addition to the increased shear stress being exerted along the outside bend, water elevations will also rise due to momentum. This will require an additional channel depth needing protection at outside bends.

Design Steps for Maximum Permissible Velocity/Allowable Shear Stress Method

McCuen (1998) presents the following steps when designing a stable channel using the permissible velocity/allowable shear stress method:

1) for a given channel material, estimate the Manning's roughness coefficient (n), the channel slope (S), and the maximum permissible velocity (V) (such as from Tables 1 or 2).

2) Compute the hydraulic radius (R) using Manning's equation:

$$R = \left[\frac{Vn}{1.49 S^{0.5}} \right]^{1.5}$$

where:

R = hydraulic radius, ft.
V = permissible velocity, ft/sec
S = channel slope, ft/ft
n = roughness of channel lining material, dimensionless

Some typical values for Manning's n for open channels (Chow 1959) are as follows:

Very smooth surface (glass, plastic, machined metal)	0.010
Planed timber	0.011
Rough wood	0.012 – 0.015
Smooth concrete	0.012 – 0.013
Unfinished concrete	0.013 – 0.016
Brickwork	0.014
Rubble masonry	0.017
Earth channels, smooth no weeds	0.020
Firm gravel	0.020
Earth channel, with some stones and weeds	0.025
Earth channels in bad condition, winding natural streams	0.035
Mountain streams	0.040 – 0.050
Sand (flat bed), or gravel channels, d=median grain diameter, ft.	$0.034d^{1/6}$

Chow (1959) also provides an extensive list of n values, along with photographs. Most engineering hydrology and hydrologic texts (including McCuen 1998) will also contain extensive guidance on the selection of Manning's n values for different channel conditions. A later section presents the usual trial-and-error method for determining Manning's n values for grass-lined channels, using measured VR-n relationships for different grass types.

3) Calculate the required cross-sectional area, using the continuity equation and the previously determined design storm peak flow rate (Q):

$$A = \frac{Q}{V}$$

where:

A = cross-sectional area of channel (wetted portion), ft^2

Q = peak discharge for design storm being considered, ft^3/sec
V = permissible velocity, ft/sec

4) Calculate the corresponding wetter perimeter (P):

$$P = \frac{A}{R}$$

where:

P = wetted perimeter, ft
A = cross-sectional area of channel (wetted portion), ft^2
R = hydraulic radius, ft.

5) Calculate an appropriate channel base width (b) and depth (y) corresponding to a specific channel geometry (usually a trapezoid channel, having a side slope of z:1 side slopes).

Figure 7 (Chow 1959) can be used to significantly shorten the calculation effort for the design of channels, by skipping step 4 above and more effectively completing step 5. This figure is used to calculate the normal depth (y) of a channel based on the channel side slopes and known flow and channel characteristics, using the Manning's equation in the following form:

$$AR^{\frac{2}{3}} = \frac{nQ}{1.49S^{0.5}}$$

Initial channel characteristics that must be know include: z (the side slope), and b (the channel bottom width, assuming a trapezoid or a rectangular cross-section). It is easy to examine several different channel options (varying z and b) by calculating the normal depth (y) for a given peak discharge rate, channel slope, and roughness. The most practical channel can then be selected from the alternatives.

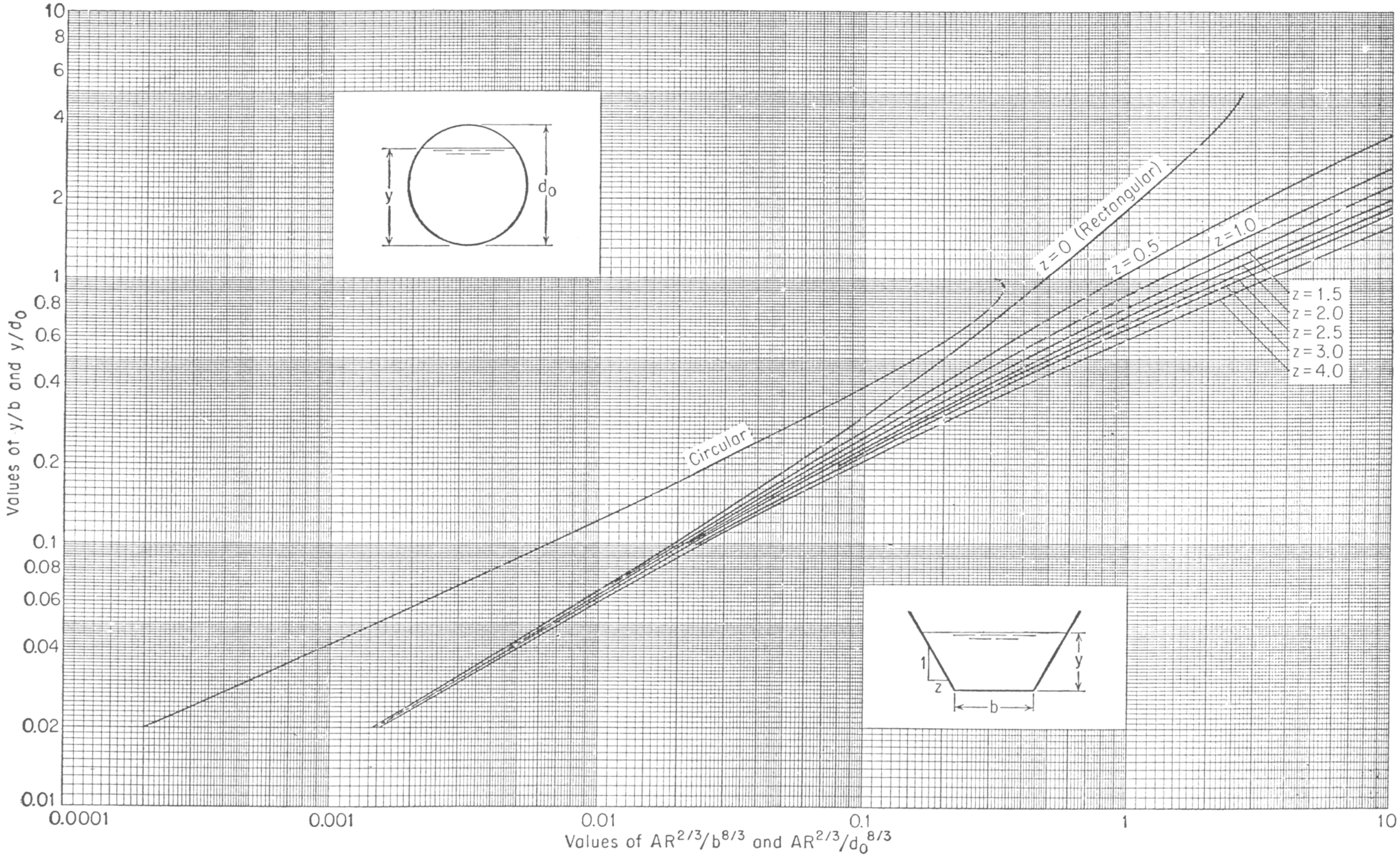


Figure 7. Chow (1959) curves for determining normal depth for various channel geometries.

As an example, assume the following conditions:

Noncolloidal alluvial silts, water transporting colloidal silts:
Manning's roughness coefficient (n) = 0.020
maximum permissible velocity (V) = 3.5 ft/sec
(the allowable shear stress is 0.15 lb/ft^2)

Peak discharge flow rate (Q) = 13 ft^3/sec

Channel slope = 1%, or 0.01 ft/ft

Therefore:

The hydraulic radius (R) using Manning's equation:

$$R = \left[\frac{Vn}{1.49S^{0.5}}\right]^{1.5} = \left[\frac{3.5(0.020)}{1.49(0.01)^{0.5}}\right]^{1.5} = 0.32\,ft.$$

The required cross-sectional area, using the continuity equation and the design storm peak flow rate (Q):

$$A = \frac{Q}{V} = \frac{13}{3.5} = 3.7\,ft^2$$

Therefore, AR$^{2/3}$ = (3.7)(0.32)$^{2/3}$ = 1.7, and the wetted perimeter is A/R = 3.7/0.32 = 12 ft. Table 3 shows the calculated normal depth (y) for different channel options that all meet the allowable velocity criteria. Also shown on this table is the calculated maximum shear stress:

γRS= (62.4 lb/ft^3) (R ft) 0.01 ft/ft) = 0.62R

since the allowable shear stress is 0.15 lb/ft^2, the hydraulic radius must be less than 0.24 ft (only about 3 inches). This will require a relatively wide channel, as the hydraulic radius approximates the depth of flow for wide and shallow channels. Also, the depth of flow can be used instead of the hydraulic radius as a conservative approach to calculate the maximum shear stress, which is important for design purposes.

As the channel becomes wider, the side slopes have little effect on the normal depth and the calculated maximum shear stress, as expected. The safety factors are the ratios of the allowable shear stress (0.15 lb/ft^2) divided by the calculated maximum shear stress. None of these channels can satisfy the allowable shear stress with this natural material, unless the channel is wide. A minimum channel width between 15 and 25 ft would result in a stable channel. However, a channel liner can be used to reinforce the channel, resulting in a larger allowable shear stress, enabling a narrower channel.

Table 3. Alternative Channel Geometries Meeting Maximum Permissible Velocity Criterion (3.5 ft/sec)

Side slope (z)	Bottom width (b), ft	$b^{8/3}$	$AR^{2/3}/b^{8/3}$	y/b	Normal depth (y), ft	Top width (T), ft	Area (A), ft^2	Wetted perimeter (P), ft	Hydraulic radius (R), ft	b/y	R/y	Maximum shear stress using y (τ), lb/ft^2	Safety factor, using the normal depth [1]	Maximum shear stress using R (τ), lb/ft^2	Safety factor, using the hydraulic radius [2]
4	2	6.4	0.27	0.32	0.62	7.0	2.8	10.6	0.26	3.2	0.42	0.32	0.39	0.16	0.92
4	4	41	0.041	0.13	0.52	8.2	3.2	10.5	0.30	7.7	0.58	0.32	0.47	0.19	0.80
4	8	260	0.0066	0.046	0.37	11.0	3.5	11.9	0.30	21.6	0.80	0.23	0.65	0.18	0.81
4	15	1400	0.0012*	0.017	0.26	17.1	4.2	17.3	0.24	57.7	0.93	0.16	0.94	0.15	0.99
4	25	5300	0.00032*	0.008	0.2	26.6	5.2	26.5	0.19	125.0	0.97	0.12	**1.25**	0.12	**1.24**
2	2	6.4	0.27	0.38	0.76	5.0	2.7	6.9	0.39	2.6	0.51	0.47	0.32	0.24	0.62
2	4	41	0.041	0.14	0.56	6.2	2.9	7.0	0.41	7.1	0.73	0.35	0.43	0.26	0.59
2	8	260	0.0066	0.049	0.39	9.6	3.4	9.7	0.35	20.5	0.91	0.24	0.63	0.22	0.68
2	15	1400	0.0012*	0.017	0.26	16.0	4.0	15.9	0.25	57.7	0.98	0.16	0.94	0.16	0.95
2	25	5300	0.00032*	0.008	0.2	25.8	5.1	25.6	0.20	125.0	0.99	0.12	**1.25**	0.12	**1.21**
1	2	6.4	0.27	0.44	0.88	3.8	2.5	5.2	0.49	2.3	0.55	0.55	0.27	0.30	0.49
1	4	41	0.041	0.16	0.64	5.3	3.0	5.8	0.51	6.3	0.79	0.40	0.38	0.32	0.47
1	8	260	0.0066	0.049	0.39	8.8	3.3	8.8	0.37	20.5	0.95	0.24	0.63	0.23	0.65
1	15	1400	0.0012*	0.017	0.26	15.5	4.0	15.4	0.26	57.7	0.99	0.16	0.94	0.16	0.93
1	25	5300	0.00032*	0.008	0.2	25.4	5.0	25.3	0.20	125.0	1.00	0.12	**1.25**	0.12	**1.20**
0.5	2	6.4	0.27	0.5	1	3.0	2.5	4.7	0.53	2.0	0.53	0.62	0.24	0.33	0.45
0.5	4	41	0.041	0.16	0.64	4.6	2.8	5.2	0.53	6.3	0.83	0.40	0.38	0.33	0.45
0.5	8	260	0.0066	0.049	0.69	8.7	5.8	9.4	0.62	11.6	0.89	0.24	0.63	0.38	0.39
0.5	15	1400	0.0012*	0.017	0.26	15.3	3.9	15.2	0.26	57.7	0.99	0.16	0.94	0.16	0.93
0.5	25	5300	0.00032*	0.008	0.2	25.2	5.0	25.1	0.20	125.0	1.00	0.12	**1.25**	0.12	**1.20**

* estimated, as these values are under range from the plotted curves.

[1] safety factor is the ratio of the allowable shear stress/ max. shear stress using y, allowable shear stress = 0.15 lb/ft^2

[2] allowable shear stress/ max. shear stress using R, allowable shear stress = 0.15 lb/ft^2

Table 3 compares the shear stress calculated using the hydraulic radius, R, to the larger shear stress calculated using the normal depth, y. Also shown is the ratio of the hydraulic radius to the normal depth for different channel conditions. Figure 8 is a plot showing how the normal depth approaches the hydraulic depth, for this example, as the channel width to normal depth ratios increase. The maximum shear stress is therefore much larger when the normal depth is used instead of the hydraulic radius for relatively narrow channels, but the results are similar for wider channels.

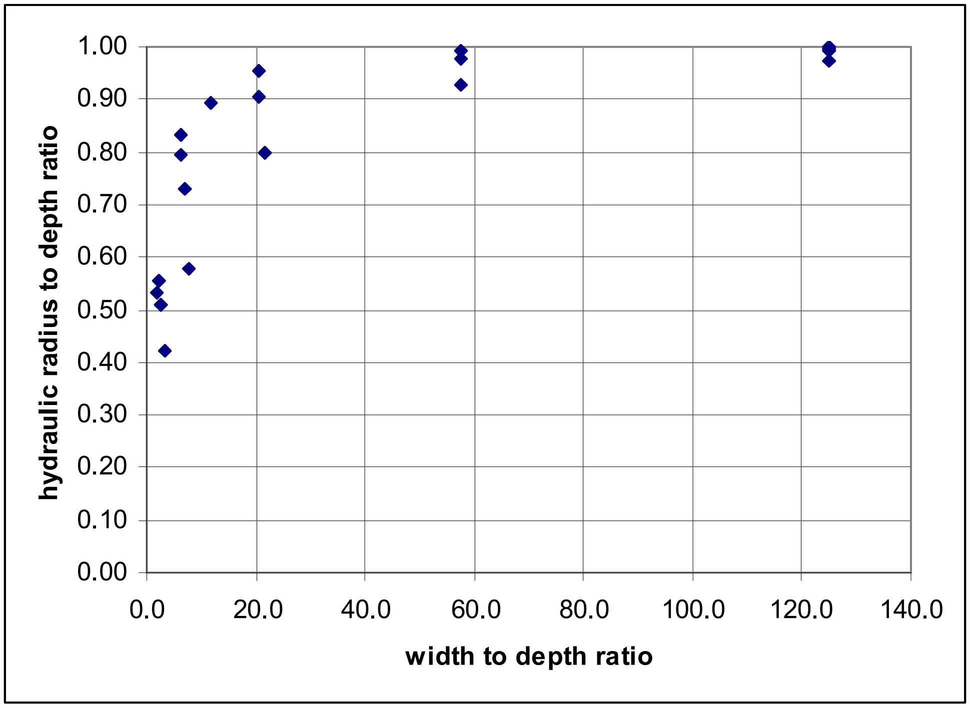


Figure 8. Relationship of hydraulic radius to normal depth for different channel width to depth conditions.

A more direct approach is to use Figure 7 in reverse order. As shown previously, the maximum depth can be calculated based on the maximum allowable shear stress and the channel slope:

$$D = \frac{\tau_c}{\gamma S} = \frac{0.15 lb/ft^2}{\left(62.4 lb/ft^3\right)\left(0.01 ft/ft\right)} = 0.24 ft$$

With the known value for $AR^{2/3}$ ($3.7 \times 0.32^{2/3} = 1.7$), Table 4 shows the calculated maximum side slope for different channel bottom widths (b). All of these options will therefore meet both the allowable velocity and shear stress criteria.

Table 4. Example Calculations for Required Side Slopes for Different Bottom Widths, Meeting Allowable Velocity and Maximum Shear Stress Criteria

b (ft)	y/b (with y = 0.24ft)	$AR^{2/3}/b^{8/3}$	Required side slope (z), or longer
8	0.030	0.0066	>4
10	0.024	0.0036	>4
15	0.016	0.0012*	5 (?)
20	0.012	0.00057*	any (0.5 to 4)

* estimated, as these values are under range from the plotted curves.

For this example, side slopes of about 5:1 and with a bottom width of 15 ft may be stable, or "any" side slope may be suitable for bottom widths of 20 ft, or wider. This example has shown that it may not be possible to design a stable channel only based on allowable maximum velocity. It is a good idea to also calculate the maximum shear stress, based on the normal depth. Without a channel liner, most stable channels in soils will need to be relatively wide. Because of the increased use of land needed for wide channels (see the calculated top width "T" in Table 3), it is usually necessary to consider channel liners, either grass-lined, or re-enforced with netting mats, as described in the following sections.

Design of Grass-Lined Channels

According to Temple, *et al*. (1987) in *Stability Design of Grass-Lined Open Channels*, USDA Agricultural Handbook # 667, it is assumed that grass channel linings are used to protect an erodible soil boundary and prevent channel degradation. They found that detachment begins at levels of total stress low enough to be withstood by the vegetation without significant damage to the plants themselves: it is possible for the vegetation to be undercut and the weaker vegetation washed away. This vegetation loss decreases the density and uniformity of the vegetative cover, which in turn leads to greater stresses at the soil-water interface, resulting in an increased erosion rate. Supercritical channel flows cause a more severe problem compared to subcritical flows because small irregularities in the channel lining cause stress concentrations to develop during supercritical flow conditions. For very erosion-resistant soils, the lining vegetation may sustain damage before the effective stress at the soil-water interface becomes large enough to detach soil material. Although the limiting condition in this case is the stress on the plants, failure progresses in a similar manner: damage to the plant cover results in an increase in effective stress on the soil boundary until conditions critical to erosion are exceeded. The resulting erosion further weakens the cover, and unraveling occurs. When plant failure occurs, it is a complex process involving removing young and weak plants, shredding and tearing of leaves, and fatigue weakening of stems.

Because of the many uncertainties and different methods of failure, the use of an approximate design approach is considered appropriate for most practical applications. Temple, *et al*. (1987) state that conservative design criteria are required, as the potential for rapid unraveling of a channel lining can occur once a weak point has developed; especially considering the variability of vegetative covers. Very dense and uniform covers will likely withstand stresses substantially larger than immature or spotty covers, without significant damage. However, they recommend that poor maintenance should be assumed in conservative designs.

The design of a grass-lined open channel differs from the design of an unlined or structurally lined channel in that (1) the flow resistance is dependent on channel geometry and discharge, (2) a portion of the boundary stress is associated with drag on individual vegetation elements and is transmitted to the erodible boundary through the plant root system, and (3) the properties of the lining vary both randomly and periodically with time. Each of these differences requires special considerations in the design process. Temple, *et al*. (1987) presents detailed descriptions of the generalized step-by-step procedure for grass-lined channel design, including computer codes.

Plant Species Selection for Vegetative-Lined Channels

The following is a general discussion and does not provide site-specific guidance for different climatic regions. However, it does describe the general problems associated with establishing plants in a channel environment. Local guidance (such as from local USDA or University Extension services) needs to be sought for specific recommendations for a specific location. Obviously, channels carrying water for long periods of the year may not be suitably lined with terrestrial vegetation. Extended wet periods will also affect plant selection. Again, local plant specialists need to be consulted for the proper selection of suitable plants for the anticipated growing conditions. The *Alabama Handbook for Erosion Control, Sediment Control, and Stormwater Management on Construction Sites and Urban Areas* (USDA 2003) contains further general guidance on plant selection for Alabama uses, for example.

Site Considerations

When a site will receive heavy use, plant species should be selected that are wear resistant and have rapid wear recovery, such as bermudagrass. Bermudagrass also has a fast establishment rate and is adapted to many geographical areas. Where a neat appearance is desired, plants that respond to frequent mowing should be used. Likely choices for quality turf in north Alabama are bermudagrass or tall fescue, while in central or south Alabama bermudagrass, centipede, or zoysia are good choices. At sites where low maintenance is desired, low fertility requirements and vegetation persistence are particularly important. Sericea lespedeza and tall fescue are good choices in north Alabama, while bahiagrass and centipede do well in central and south Alabama.

Seasonal Considerations

Growing seasons must be considered when selecting species. The most effective times for planting perennial grasses and legumes in Alabama generally extend from March through May and from late August through October. Outside these dates, the probability of failure is higher. Grasses and legumes are usually classified as warm or cool-season in reference to their season of growth. Cool-season species produce most of their growth during the spring and fall and are relatively inactive or dormant during the hot summer months. Therefore, fall is the most dependable time to plant them. Warm-season plants grow most activity during the summer, and go dormant at the first frost in the fall. Spring and early summer are the preferred planting times for warm-season species.

Plant Hardiness Zones

The US Department of Agriculture has produced plant hardiness zone maps that are normally used to help determine the suitability of different plants for an area. These maps are based on the annual average low temperatures and are therefore most appropriate for permanent vegetation. Therefore, short-term vegetation use does not necessarily have to follow the same selection guidelines needed for permanent vegetation. In all cases, it is important to contact the local NRCS office, or other erosion control specialists, for the most suitable vegetation to consider for a specific site. Figure 9 and Table 5 shows the current USDA hardiness zone map and selected cites associated with the different annual average minimum temperatures.

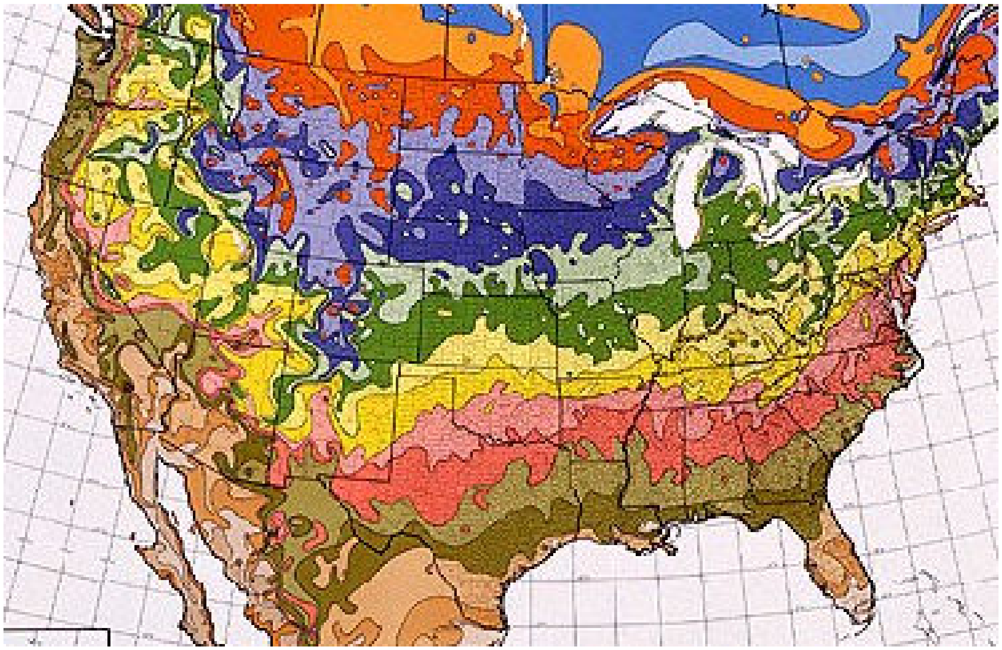


Figure 9. USDA Plant Hardiness Zone Map

Table 5. Annual Average Minimum Temperatures for Selected Cities

Fahrenheit	Celsius	Example Cities
Below -50 F	Below -45.6 C	Fairbanks, Alaska; Resolute, Northwest Territories (Canada)
-50 to -45 F	-42.8 to -45.5 C	Prudhoe Bay, Alaska; Flin Flon, Manitoba (Canada)
-45 to -40 F	-40.0 to -42.7 C	Unalakleet, Alaska; Pinecreek, Minnesota
-40 to -35 F	-37.3 to -39.9 C	International Falls, Minnesota; St. Michael, Alaska
-35 to -30 F	-34.5 to -37.2 C	Tomahawk, Wisconsin; Sidney, Montana
-30 to -25 F	-31.7 to -34.4 C	Minneapolis/St.Paul, Minnesota; Lewistown, Montana
-25 to -20 F	-28.9 to -31.6 C	Northwood, Iowa; Nebraska
-20 to -15 F	-26.2 to -28.8 C	Des Moines, Iowa; Illinois
-15 to -10 F	-23.4 to -26.1 C	Columbia, Missouri; Mansfield, Pennsylvania
-10 to -5 F	-20.6 to -23.3 C	St. Louis, Missouri; Lebanon, Pennsylvania
-5 to 0 F	-17.8 to -20.5 C	McMinnville, Tennessee; Branson, Missouri
0 to 5 F	-15.0 to -17.7 C	Oklahoma City, Oklahoma; South Boston, Virginia
5 to 10 F	-12.3 to -14.9 C	Little Rock, Arkansas; Griffin, Georgia
10 to 15 F	-9.5 to -12.2 C	Tifton, Georgia; Dallas, Texas
15 to 20 F	-6.7 to -9.4 C	Austin, Texas; Gainesville, Florida
20 to 25 F	-3.9 to -6.6 C	Houston, Texas; St. Augustine, Florida
25 to 30 F	-1.2 to -3.8 C	Brownsville, Texas; Fort Pierce, Florida
30 to 35 F	1.6 to -1.1 C	Naples, Florida; Victorville, California
35 to 40 F	4.4 to 1.7 C	Miami, Florida; Coral Gables, Florida
above 40 F	above 4.5 C	Honolulu, Hawaii; Mazatlan, Mexico

Selecting the Right Grasses for Channel Lining

According to Temple, *et al.* (1987), the selection of grass species for use in channels is based on important site-specific factors, including: (1) soil texture, (2) depth of underlying material, (3) management requirements of vegetation, (4) climate, (5) slope, and (6) type of structure or engineering design. The expected flow rates, salt tolerance in northern areas, availability of seed, ease of stand establishment, species or vegetative growth habit, plant cover, and persistence of established species, are other factors that also should be considered in selecting appropriate grasses necessary for stable channel designs for use along roads. Channel construction should be scheduled to allow establishment of the grass stand before subjecting the channel to excessive flows. The uses of modern channel lining systems, as discussed below, help alleviate this problem. The establishment of permanent covers involves liming and fertilizing, seed bed preparation, appropriate planting dates, seeding rates, and mulching.

Plants for Temporary Channel Linings

Based on flow tests on sandy clay channels, Temple, *et al.* (1987) recommends wheat (*Triticum aestivum L.*) for winter and sudangrass [*Sorghum sudanensis* (Piper) *Hitchc.*] for late-summer temporary covers. These temporary covers have been shown to rapidly increase the permissible discharge rate to five times that of an unprotected channel. Other recommended annual and short-lived perennials that can be used for temporary channel linings include:

- barley (*Hordeum vulgare L.*), noted for its early fall growth;
- oats (*Avena) sativa L.*), in areas of mild winters;
- mixtures of wheat, oats, barley, and rye (*Secale cereale L.*);
- field bromegrass (*Bromus spp.*); and
- ryegrasses (*Lolium spp.*).

Summer annuals, including German and foxtail millets (*Setaria spp.*), pearl millet [*Pennisetum americanurn (L.) Leeke*], and certain cultivated sorghums other than sudangrass, may also be used for temporary mid- to late-summer covers, according to Temple, *et al.* (1987). Since millets do not continue to grow as aggressively as sorghums after mowing, they may leave a more desirable, uniformly thin mulch for subsequent permanent seeding. Temporary seedings involve minimal cultural treatment, short-lived but quick germinating species, and little or no maintenance. The temporary covers should be close-drilled stands and not be allowed to go to seed. The protective cover provided by the temporary vegetation should provide stalks, roots, and litter into which permanent grass seeds can be drilled the following spring or fall.

Plants for Permanent Channel Linings

Many grasses can be used for permanent vegetative channel linings. Temple, *et al.* (1987) lists the following tight-sod-forming grasses as the most preferred warm- and cool-season grasses for channel linings: bermudagrass [*Cyodon dactylon var dactylon (L.) Pers*.], bahiagrass (*Paspalum notatum Fluggle*), buffalograss [*Buchloe dactyloides (Nutt.) Enge1m*.], intermediate wheatgrass [*Agropyron intermedium (Host) Beauv.*], Kentucky bluegrass (*Poa ratensis L.*), reed canarygrass (*Phalaris arundinacea L.*), smooth bromegrass, (*Bromus inermis Leyss.*), vine mesquitegrass (*Panicum obtusum H.B.K.*), and Western wheatgrass (*Agropyron Smithii Rydb.*). These grasses are among the most widely used species for channel linings and grow well on a variety of soils. A grass mixture should include species adapted to the full range of soil moisture conditions on the channel side slopes. The local NRCS and University Extension offices know the best soil-binding grass species for a particular areas, along with the associated planting and maintenance information. The most important characteristic of the selected grasses is its ability to survive and thrive in the channel environment.

Bermudagrass is probably the most widely used grass in the southern region of the U.S. It will grow on many soil types, but may require extra management. It forms a dense and persistent sod, if managed properly. Temple, *et al.* (1987) recommend that when bermudagrass is used, winter-hardy varieties should be obtained. Improved varieties, such as “Coastal,” “Midland,” “Greenfield,” “Tifton,” and “Hardie,” do not produce seed, and must be established by sprigging. Where winters are mild, channels can be established quickly with seed of “Arizona Common” bermudagrass. “Seed of bermudagrass,” a new seed-propagated variety with greater winter hardiness than Arizona Common, should now be available commercially. Bermudagrass is not shade tolerant and should not be used in mixtures containing tall grasses. However, the inclusion of winter annual legumes such as hairy vetch (*Vicia villosa Roth*.), narrowleaf vetch [*V. sativa L. subspecies nigra (L.) Ehrh.*], and/or a summer annual such as Korean lespedeza (*Lespedeza stipulacea Maxim.*) may be beneficial to stand maintenance.

The selection of grasses used in channels often depends on availability of seed or plant material. Chronic national seed shortages of some warm-season grasses, especially seed of native species, have often led to planting seed marginally suited to site situations. Lack of available seed of desired grass species and cultivars adapted to specific problem sites is a major constraint often delaying or frustrating seeding programs. In addition to the grass species or base mixture of grasses used for erosion control, carefully selected special-use plants may be added for a specific purpose or situation. Desirable wildlife food plants may be included in the mixture if they do not detrimentally compete with the base grasses used for erosion control. Locally adapted legumes are often added if they are compatible with the grasses and noncompetitive. Additional information on establishment and maintenance of grass-lined channels is provided in Temple, *et al*, (1987).

Determination of Channel Design Parameters

The conditions governing the stability of a grass-lined open channel are the channel geometry and slope, the erodibility of the soil boundary, and the properties of the grass lining that relate to flow retardance potential and boundary protection.

Vegetation Parameters

The design of a stable grass-lined open channel needs to consider the effective stress imposed on the soil layer (Temple, *et al*, 1987). This requires the determination of two vegetation parameters: 1) the retardance curve index (C_I) which describes the potential of the vegetal cover to develop flow resistance, and 2) the vegetation cover factor (C_f) which describes the degree to which the vegetation cover prevents high velocities and stresses at the soil-water interface. These are described below.

Retardance Potential. The parameter describing the retardance potential of a vegetal cover is the retardance curve index, C_I. This parameter determines the limiting vegetation stress. Its relation to the measurable physical properties of the vegetal cover is given by:

$$C_I = 2.5\left(h\sqrt{M}\right)^{\frac{1}{3}}$$

where:

h is the representative stem length
M is the stem density in stems per unit area.

When consistent units are used, the relation is dimensionless. This factor is commonly used in the following equation to estimate the maximum allowable stress on the vegetation (τ_{va}, in lb/ft^2):

$$\tau_{va} = 0.75C_I$$

The stem length will usually need to be estimated directly from knowledge of the vegetation conditions at the time of anticipated maximum flow. When two or more grasses with widely differing growth characteristics are involved, the representative stem length is determined as the root mean square of the individual stem lengths.

When this equation is used to estimate the retardance potential, an estimate of the stem density is also required. The reference stem densities shown in Table 6 may be used as a guide in estimating this parameter.

Table 6. Properties of Grass Channel Linings (Temple, *et al.* 1987)

Cover Factor (C_f) (good uniform stands)	Covers Tested	Reference stem density (M), stem/ft^2
0.90	bermudagrass	500
0.90	centipedegrass	500
0.87	buffalograss	400
0.87	kentucky bluegrass	350
0.87	blue grama	350
0.75	grass mixture	200
0.50	weeping lovegrass	350
0.50	yellow bluestem	250
0.50	alfalfa	500
0.50	lespedeza sericea	300
0.50	common lespedeza	150
0.50	sudangrass	50

Since cover conditions will vary from year to year and season to season, establishing an upper and a lower bound for the curve index (C_I) is often more realistic than selecting a single value. When this approach is taken, the lower value should be used in stability computations and the upper value should be used in determining channel capacity. Such an approach will normally result in satisfactory operation for lining conditions between the specified bounds. Whatever the approach used to obtain the flow retardance potential of the lining, the values selected should represent an average for the channel reach in question, since it will be used to infer an average energy loss per unit of boundary area for any given flow.

Vegetation Cover Factor. The vegetation cover factor, $C_{f,}$ is used to describe the degree to which the vegetation cover prevents high velocities and stresses at the soil-water interface. Because the protective action described by this parameter is associated with the prevention of local erosion damage which may lead to channel unraveling, the cover factor should represent the weakest area in a reach, rather than an average for the cover type.

Observations of flow behavior and available data indicate that the cover factor is dominated by the density and uniformity of density in the immediate vicinity of the soil boundary. For relatively dense and uniform covers, uniformity of density is primarily dependent on the growth characteristics of the cover, which are in turn related to grass type. This relationship was used by Temple, *et al* (1987) in the development of Table 6. This table can not obviously account for such considerations as maintenance practices, or uniformity of soil fertility or moisture conditions.

Soil Parameters

Two soil parameters are required for the application of effective stress concepts to the design of stable lined or unlined channels having an erodible soil boundary: 1) soil grain roughness (n_s), and 2) allowable effective stress (τ_a).

When the effective stress approach is used, the soil parameters are the same for both lined and unlined channels, satisfying sediment transport restrictions. The relations presented here were presented by Temple, *et al* (1987) and were taken from the SCS (1977) channel stability criteria: the desired parameters, soil grain roughness and allowable stress, are determined from basic soil parameters. Ideally, the basic parameters should be determined from tests on representative soil samples from the site.

For effective stress design, soil grain roughness is defined as the roughness associated with particles or aggregates of a size that may be independently moved by the flow at incipient channel failure. Although this parameter is expressed in terms of a flow resistance coefficient (n_s), its primary importance in design of vegetated channels is its influence on effective stress, as shown below. Its contribution to the total flow resistance of a grass-lined channel is usually negligibly small.

The allowable stress is key to the effective stress design procedure. It is defined as that stress above which an unacceptable amount of particle or aggregate detachment would occur.

Noncohesive Soil. Noncohesive soils are defined as fine- or coarse-grained, based on whether d75 (the diameter for which 75 percent of the material is finer) is less than, or greater than, 0.05 in. For fine-grained soils, the soil grain roughness and allowable effective stress are constant, while for a coarse-grained soil, these parameters are a function of particle size. The allowable effective stress and roughness parameters for noncohesive soils are given in Figures 10 and 11, as a function of particle size.

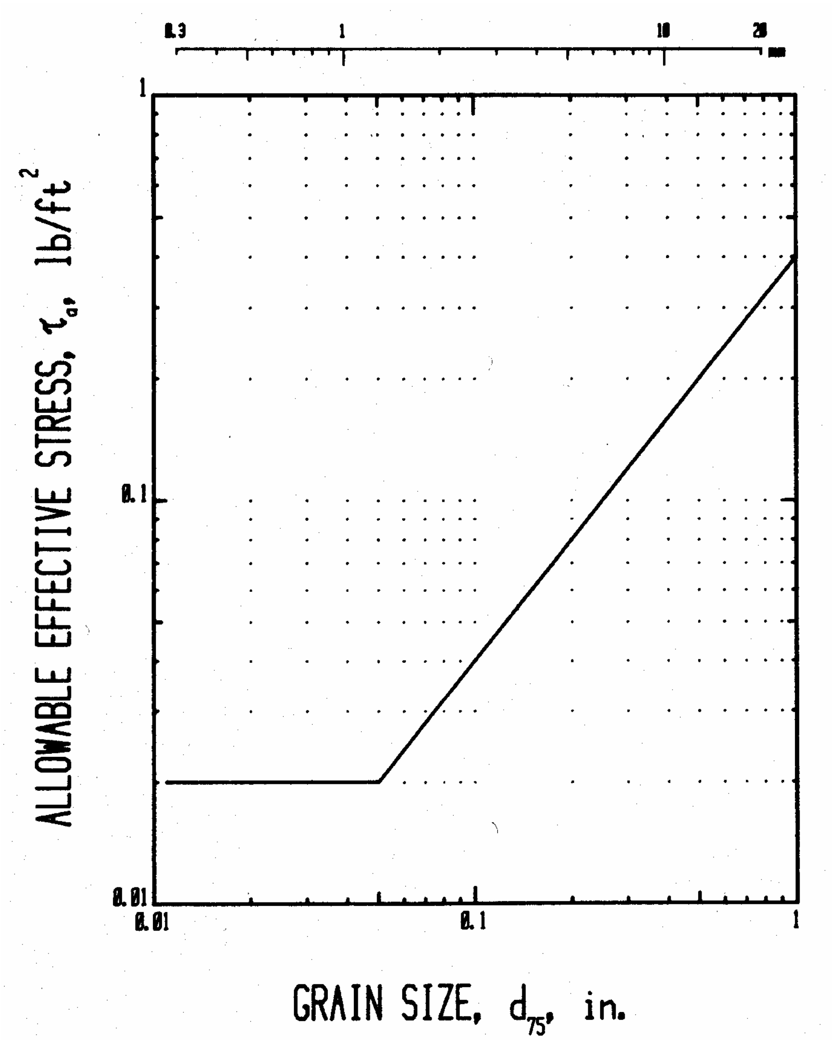


Figure 10. Allowable effective stress for noncohesive soils (Temple, *et al.* 1987).

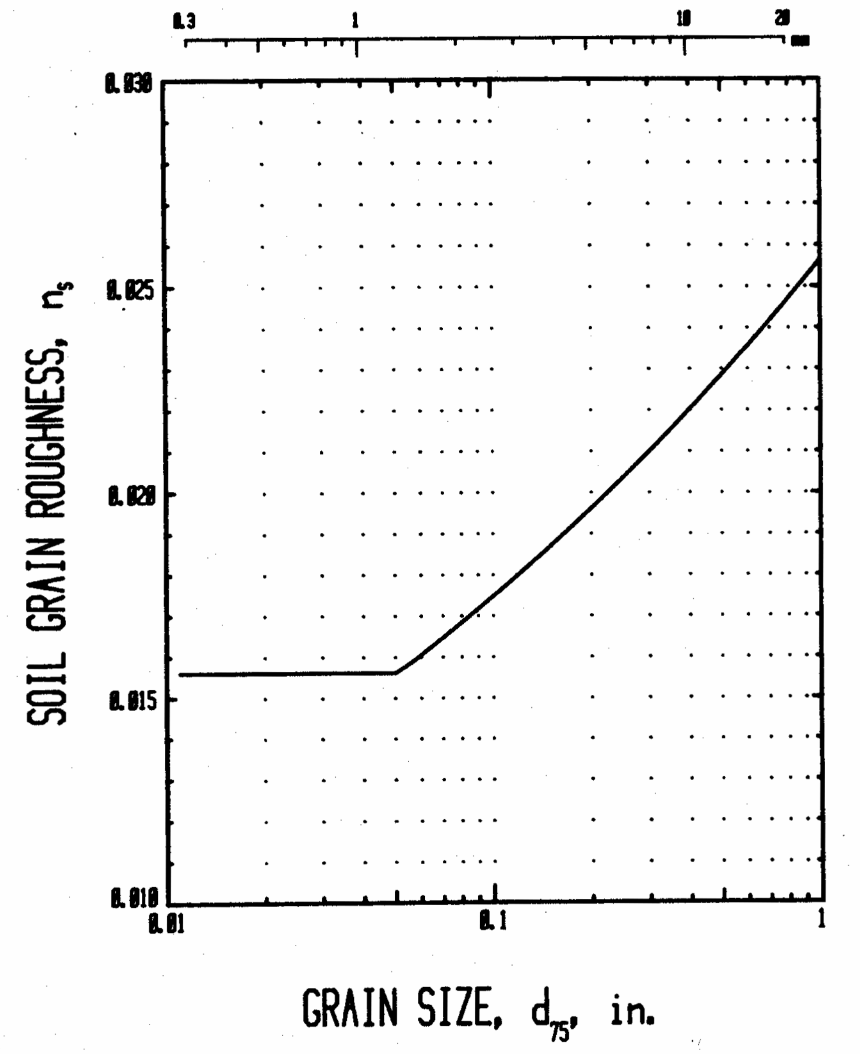


Figure 11. Soil grain roughness for noncohesive soils (Temple, *et al.* 1987).

Cohesive Soil. All cohesive soils are treated as fine-grained soils, having a constant soil grain roughness (about 0.0155, according to Figure 11). The allowable effective stresses presented here are taken directly from SCS (1977) permissible velocity design criteria. The soil properties required to determine the allowable effective stress are the soil's classification in the unified soil classification system, its plasticity index (I_w), and its void ratio (e). This calculation requires that a basic allowable effective stress (τ_{ab}) be determined from the soil classification and plasticity index. This basic value is then corrected for void ratio, according to the relation:

$$\tau_a = \tau_{ab} C_e^2$$

The basic allowable shear stress (τ_{ab}) is given in Figure 12, while the void ratio correction factor (C_e) is given in Figure 13. The soil classification information (plasticity index, I_w, and void ratio, e) are readily available for cohesive soils in standard soils references, and in Temple, *et al.* (1987).

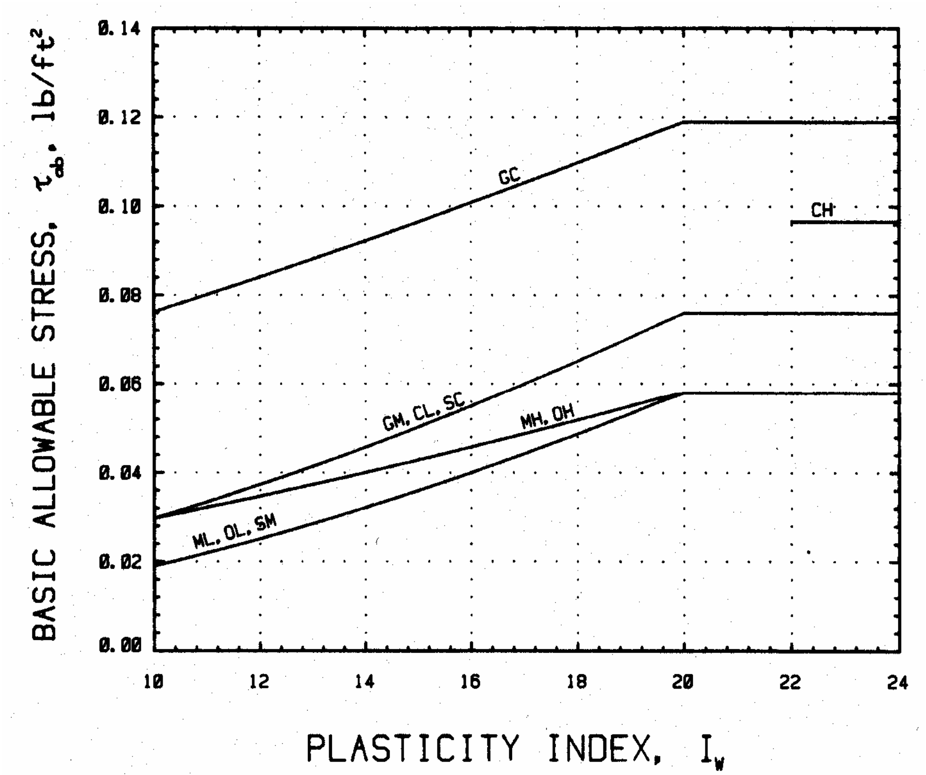


Figure 12. Basic allowable effective stress for cohesive soils (Temple, *et al.* 1987 and SCS 1977).

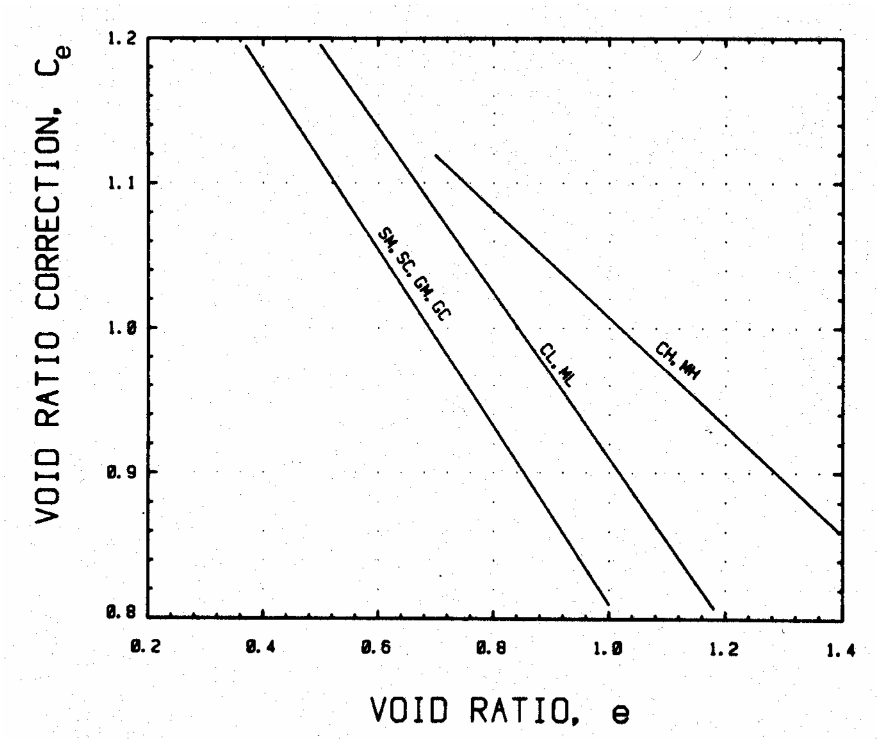


Figure 13. Void ratio correction factor for cohesive soils (Temple, *et al.* 1987 and SCS 1977).

Selection of Roughness Factor for Grass Lined Channels
The value of Manning's "n" in grasses is a function of grass type, and the product of velocity and hydraulic radius (VR). Grasses are divided into retardance classes based on their physical characteristics (height, width, density, etc.). Most sod forming grasses are classified as type C. These grasses can have "n" values ranging from 0.03 - 0.3 depending on VR, with a typical value of 0.03 in open channels. The following example shows how the correct n value is selected through a trial-and-error method, depending on the product of the velocity (V) and hydraulic radius (R).

Example Problem for the Selection of Roughness for Grass-Lined Channels
The appropriate Manning's "n" to use varies on the time frame: bare soil retention and vegetation establishment (short-term) and for fully grassed conditions (long-term) (Chow 1959). Bare soil conditions can be examined using the procedures presented earlier. Mature grass-lined channel roughness values can be determined using typical procedures as illustrated in the following example which shows how VR-n curves can be used for the proper selection of a roughness value for a grass-lined channel:

> Determine the roughness value for a 10-year design storm of 70 ft^3/sec (2 m^3/sec) in a grass-lined drainage channel having a slope of 0.05 ft/ft and a 4 foot (1.2 m) bottom width and 1:1 side slopes. The grass cover is expected to be in retardance group D.

Long-term design, based on vegetated channel stability:

- use $Q_{peak} = Q_{10year} = 70\ ft^3/s\ (2\ m^3/s)$
- initially assume that $n_{vegetated} = 0.05$

Determine the normal depth of flow, using Figure 7 (from Chow 1959):

$$AR^{\frac{2}{3}} = \frac{nQ}{1.49S^{0.5}} = \frac{0.05(70cfs)}{1.49(0.05)^{0.5}} = 10.51$$

and $b^{8/3} = (4\ ft)^{8/3} = 40.32$

therefore $AR^{2/3}/b^{8/3} = 10.51/40.32 = 0.26$

With a 1:1 side slope trapezoidal channel, the ratio of y/b from Figure 7 is 0.43, and the depth is therefore: 4(0.43) = 1.7 ft.

The cross-sectional area is therefore 9.7 ft^2, the velocity is (70 ft^3/sec)/(9.7 ft^2) = 7.2 ft/sec, P is 8.8 ft, and R is 9.7/8.8 = 1.1 ft. VR is therefore (7.2 ft/sec)(1.1 ft) = 7.9 ft^2/sec. From Figure 14, the estimated new value for n is therefore 0.032, using a retardance class of D. The depth must therefore be recalculated, using this new value for n:

$$AR^{\frac{2}{3}} = \frac{nQ}{1.49S^{0.5}} = \frac{0.032(70cfs)}{1.49(0.05)^{0.5}} = 6.72$$

and $b^{8/3} = (4\ ft)^{8/3} = 40.32$

therefore $AR^{2/3}/b^{8/3} = 6.72/40.32 = 0.17$

With a 1:1 side slope trapezoidal channel, the ratio of y/b from Figure 7 is 0.34, and the depth is therefore: 4(0.34) = 1.4 ft.

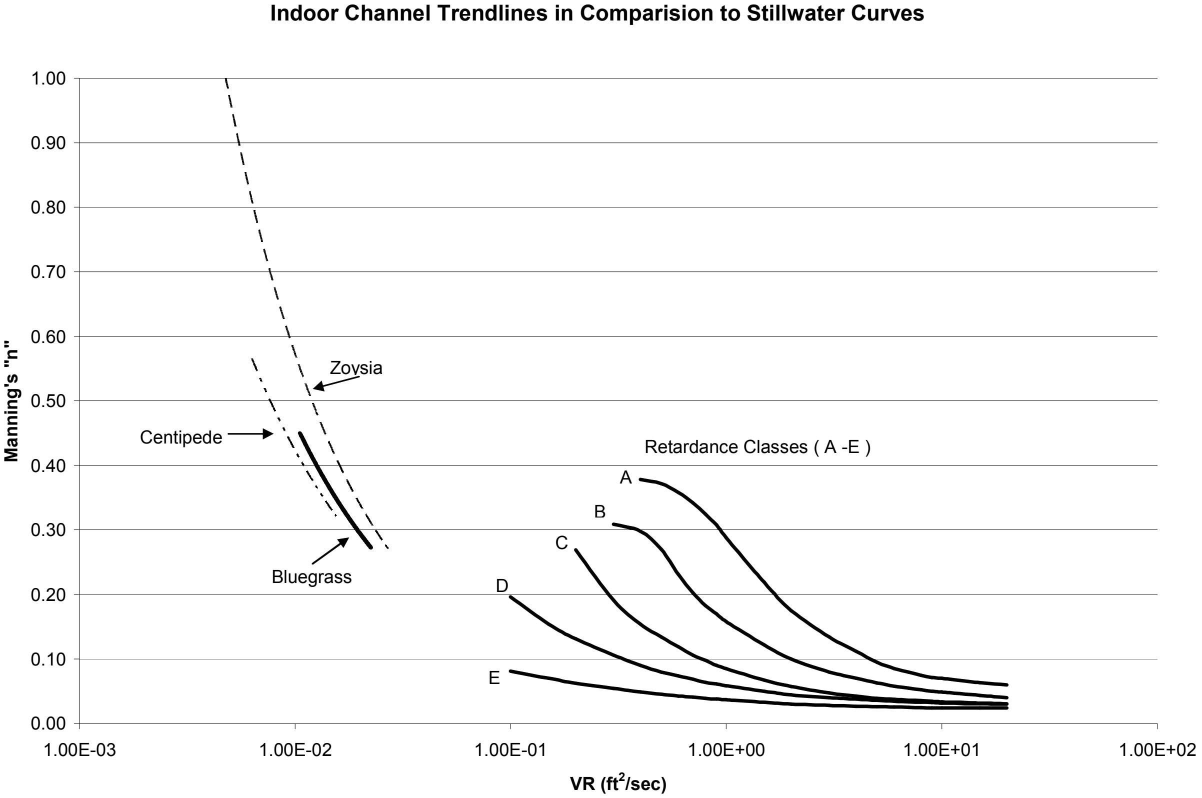


Figure 14. Hydraulic roughness of grass (Kirby 2003).

The area is therefore 7.6 ft^2, the velocity is 70/7.6 = 9.2 ft/sec, P is 8.0 ft, and R is 7.6/8.0 = 0.95 ft. The revised VR is therefore (9.2 ft/sec)(0.95 ft) = 8.7 ft^2/sec. Figure 14 shows that the revised value of n is still close to 0.032.

The maximum shear stress (using normal depth instead of hydraulic radius) is therefore:

$$\gamma DS = (62.4\ lb/ft^3)\ (1.4\ ft)\ 0.05\ ft/ft) = 4.4\ lb/ft^2$$

This channel would therefore be stable if the acceptable value is greater than this rather high value. A following discussion presents additional guidance on the selection and evaluation of a turf reinforcing mat that would likely be needed for this high shear stress condition. Currently, the use of channel lining mats protecting immature vegetation allows immediate protection of the sensitive soil boundary layer, as described in the following discussions. Also, free computer programs, such as supplied by North American Green (http://www.nagreen.com/), greatly help in the design of the most appropriate channel cross section and liner system.

Drainage Design using Turf-Reinforcing Mats

Current practice is to design channel linings based on shear stress and less on allowable velocity. Shear stress considers the weight of the water above the lining and therefore does a better job of predicting liner stability compared to only using velocity. However, allowable velocity and the flow regime (if the flow is supercritical or subcritical) still should be examined to minimize the occurrence of unusual conditions.

If a channel will have intermittent flows, it is common to use turf-reinforcing mats liners to increase the channel stability. However, if the channel will have perennial (or long-term) flows, grass will not be successful and mechanical liners must be used.

Installation of reinforced liner along thalweg of channel, with other material along sides (VA photo).

Large rocks for channel reinforcement and to reduce the velocity.

Plastic tarp, with coir logs, for a temporary liner and to slow the velocity.

Reinforced liner along channel thalweg.

Plastic tarp used as a temporary liner.

Examples of Channels Lined with Vegetation and other Materials

According to Croke (2000), drainage channel design using turf reinforcement mats must consider three phases: (1) the original channel in an unvegetated state to determine if the matting alone will provide the needed protection before the vegetation is established, (2) the channel in a partially vegetated state, usually at 50% plant density, and (3) the permanent channel condition with vegetation fully established and reinforced by the matting's permanent net structure. The basic shear stress equation can be modified to predict the shear stress applied to the soil beneath a channel mat (Temple, *et al*. 1987):

$$\tau_e = \gamma DS\left(1 - C_f\right)\left(\frac{n_s}{n}\right)^2$$

where:

τ_e = effective shear stress exerted on soil beneath vegetation
γ = specific weight of water (62.4 lbs/ft^3)
D = the maximum flow depth in the cross section (ft)
S = hydraulic slope (ft/ft)
C_f = vegetation cover factor (this factor is 0 for an unlined channel)
n_s = roughness coefficient of underlying soil
n = roughness coefficient of vegetation and/or erosion control blanket (if vegetated, or not)

The flow depth, rather than the hydraulic radius, is used in this equation because this will result in the maximum shear stress developed, rather than the average stress (Temple, *et al.* 1987), plus the depth value is very close to the hydraulic radius for most channels, especially as sheetflow conditions are approached. The cover factor is a function of the grass and stem density, as previously described, while the roughness coefficients are standard Manning's roughness values for channels. The permissible shear stress for a liner mat should also be available from manufacture's specifications, but it will vary for different growth phases, if vegetated. Obviously, the liner matting significantly reduces the shear stress exerted on the soil. The following tables summarize some typical values for some of these equation parameters for turf-reinforcing mats, for different products supplied by North American Green (from www.nagreen.com). Included on these tables are conservation factor, C, values used in RUSLE for slope protection, along with roughness coefficients and maximum permissible shear stress values used in channel lining analyses. Only the P300 and C350 mats shown here are permanent liners and therefore have different values for different plant growth stages.

S75 straw erosion control blanket (12 month life; 314 g/m^2 mass per unit area)

RUSLE Conservation coefficients (C):		Channel Roughness Coefficients (n)	
	Slope Gradient (S)	Flow depth	Manning's n (unvegetated)
Slope length (L)	All ≤ 3:1 slope:	≤ 0.50 ft (0.15 m)	0.055
≤ 20 ft (6 m)	0.029	0.50 – 2.00 ft	0.055 - 0.021
20 to 50 ft	0.110	≥ 2.00 ft (0.60 m)	0.021
≥ 50 ft (15 m)	0.190	Max. permissible shear stress: 1.55 lbs/ft^2 (74.4 Pa)	

S150 straw erosion control blanket (12 month life; 323 g/m^2 mass per unit area)

RUSLE Conservation coefficients (C):			Channel Roughness Coefficients (n)	
	Slope Gradient (S)		Flow depth	Manning's n (unvegetated)
Slope length (L)	≤ 3:1	3:1 to 2:1	≤ 0.50 ft (0.15 m)	0.055
≤ 20 ft (6 m)	0.004	0.106	0.50 – 2.00 ft	0.055 - 0.021
20 to 50 ft	0.062	0.118	≥ 2.00 ft (0.60 m)	0.021
≥ 50 ft (15 m)	0.120	0.180	Max. permissible shear stress: 1.75 lbs/ft^2 (84.0 Pa)	

S150BN straw erosion control blanket (10 month life; 352 g/m^2 mass per unit area)

RUSLE Conservation coefficients (C):			Channel Roughness Coefficients (n)	
	Slope Gradient (S)		Flow depth	Manning's n (unvegetated)
Slope length (L)	≤ 3:1	3:1 to 2:1	≤ 0.50 ft (0.15 m)	0.055
≤ 20 ft (6 m)	0.00014	0.039	0.50 – 2.00 ft	0.055 - 0.021
20 to 50 ft	0.010	0.070	≥ 2.00 ft (0.60 m)	0.021
≥ 50 ft (15 m)	0.020	0.100	Max. permissible shear stress: 1.85 lbs/ft^2 (88.0 Pa)	

SC150 straw erosion control blanket (24 month life; 424 g/m^2 mass per unit area)

RUSLE Conservation coefficients (C):				Channel Roughness Coefficients (n)	
	Slope Gradient (S)			Flow depth	Manning's n (unvegetated)
Slope length (L)	≤ 3:1	3:1 to 2:1	≥ 2:1	≤ 0.50 ft (0.15 m)	0.050
≤ 20 ft (6 m)	0.001	0.048	0.100	0.50 – 2.00 ft	0.050 - 0.018
20 to 50 ft	0.051	0.079	0.145	≥ 2.00 ft (0.60 m)	0.018
≥ 50 ft (15 m)	0.100	0.110	0.190	Max. permissible shear stress: 2.00 lbs/ft^2 (96.0 Pa)	

SC150BN straw erosion control blanket (18 month life; 424 g/m^2 mass per unit area)

RUSLE Conservation coefficients (C):				Channel Roughness Coefficients (n)	
	Slope Gradient (S)			Flow depth	Manning's n (unvegetated)
Slope length (L)	≤ 3:1	3:1 to 2:1	≥ 2:1	≤ 0.50 ft (0.15 m)	0.050
≤ 20 ft (6 m)	0.00009	0.029	0.063	0.50 – 2.00 ft	0.050 - 0.018
20 to 50 ft	0.005	0.055	0.092	≥ 2.00 ft (0.60 m)	0.018
≥ 50 ft (15 m)	0.010	0.080	0.120	Max. permissible shear stress: 2.10 lbs/ft^2 (100 Pa)	

C125 coconut fiber erosion control blanket (36 month life; 274 g/m^2 mass per unit area)

RUSLE Conservation coefficients (C):				Channel Roughness Coefficients (n)	
	Slope Gradient (S)			Flow depth	Manning's n (unvegetated)
Slope length (L)	≤ 3:1	3:1 to 2:1	≥ 2:1	≤ 0.50 ft (0.15 m)	0.022
≤ 20 ft (6 m)	0.001	0.029	0.082	0.50 – 2.00 ft	0.022 – 0.014
20 to 50 ft	0.036	0.060	0.096	≥ 2.00 ft (0.60 m)	0.014
≥ 50 ft (15 m)	0.070	0.090	0.110	Max. permissible shear stress: 2.25 lbs/ft^2 (108 Pa)	

C125BN coconut fiber erosion control blanket (24 month life; 360 g/m^2 mass per unit area)

RUSLE Conservation coefficients (C):				Channel Roughness Coefficients (n)	
	Slope Gradient (S)			Flow depth	Manning's n (unvegetated)
Slope length (L)	≤ 3:1	3:1 to 2:1	≥ 2:1	≤ 0.50 ft (0.15 m)	0.022
≤ 20 ft (6 m)	0.00009	0.018	0.050	0.50 – 2.00 ft	0.022 – 0.014
20 to 50 ft	0.003	0.040	0.060	≥ 2.00 ft (0.60 m)	0.014
≥ 50 ft (15 m)	0.007	0.070	0.070	Max. permissible shear stress: 2.35 lbs/ft^2 (112 Pa)	

P300 polypropylene fiber erosion control blanket (permanent use; 456 g/m^2 mass per unit area)

RUSLE Conservation coefficients (C):	Slope Gradient (S)			Channel Roughness Coefficients (n)		Maximum Permissible Shear Stress	
Slope length (L)	≤ 3:1	3:1 to 2:1	≥ 2:1	Flow depth	Manning's n (unvegetated)		
≤ 20 ft (6 m)	0.001	0.029	0.082	≤ 0.50 ft (0.15 m)	0.049 – 0.034	Unvegetated	3.00 lb/ft^2 (144 Pa)
20 to 50 ft	0.036	0.060	0.096	0.50 – 2.00 ft	0.034 – 0.020	Partially vegetated	5.50 lb/ft^2 (264 Pa)
≥ 50 ft (15 m)	0.070	0.090	0.110	≥ 2.00 ft (0.60 m)	0.020	Fully vegetated	8.00 lb/ft^2 (383 Pa)

Additional permissible shear stress information for vegetated North American Green products (permanent liners):

	Manning's roughness coefficient (n) for flow depths:			Maximum Permissible Shear Stress	
Vegetated blanket type[1]:	0 to 0.5 ft	0.5 to 2 ft	>2 ft.	Short duration (<2 hours peak flow)	Long duration (>2 hours peak flow)
C350 Phase 2	0.044	0.044	0.044	6.00 lb/ft^2 (288 Pa)	4.50 lb/ft^2 (216 Pa)
P300 Phase 2	0.044	0.044	0.044	5.50 lb/ft^2 (264 Pa)	4.00 lb/ft^2 (192 Pa)
C350 Phase 3	0.049	0.049	0.049	8.00 lb/ft^2 (384 Pa)	8.00 lb/ft^2 (384 Pa)
P300 Phase 3	0.049	0.049	0.049	8.00 lb/ft^2 (384 Pa)	8.00 lb/ft^2 (384 Pa)

[1] Phase 2 is 50% stand maturity, usually at 6 months, while Phase 3 is mature growth

Values of C_f, the grass cover factor, were given in Table 6 (Temple, *et al.* 1987). They recommend multiplying the stem densities given by 1/3, 2/3, 1, 4/3, and 5/3, for poor, fair, good, very good, and excellent covers, respectively. C_f values for untested covers may be estimated by recognizing that the cover factor is dominated by density and uniformity of cover near the soil surface: the sod-forming grasses near the top of the table have higher C_f values than the bunch grasses and annuals near the bottom. For the legumes tested (alfalfa and lespedeza sericea), the effective stem count for resistance (given on the table) is approximately five times the actual stem count very close to the bed. Similar adjustment may be needed for other unusually large-stemmed, branching, and/ or woody vegetation.

As an example, consider the following conditions for a mature buffalograss on a channel liner mat:

$\tau_o = \gamma DS = 2.83$ lb/ft^2 (previously calculated), requiring a NAG P300 permanent mat, for example
n_s for the soil is 0.016
n for the vegetated mat is 0.042
C_f for the vegetated mat is 0.87

The permissible shear stress for the underlying soil is 0.08 lb/ft^2

Therefore:

$$\tau_e = 2.83(1-0.87)\left(\frac{0.016}{0.042}\right)^2 = 0.053 \text{ lb/ft}^2$$

The calculated shear stress being exerted on the soil beneath the liner mat must be less than the permissible shear stress for the soil. In this example, the safety factor is 0.08/0.053 = 1.5 and the channel lining system is expected to be stable.

An example of a permanent channel design and the selection of an appropriate reinforced liner is given below. The following example is for a channel that collects runoff from 14.6 acres. This channel is 900 ft. long and has an 8% slope. The peak discharge was previously calculated to be 29 ft^3/sec.

Using the Manning's equation and the VenTe Chow (1959) shortcut on channel geometry (Figure 7):

$$AR^{\frac{2}{3}} = \frac{nQ}{1.49S^{0.5}}$$

Where n = 0.02
Q = 29 CFS
S = 8% (0.08)

$$AR^{\frac{2}{3}} = \frac{(0.02)(29)}{1.49(0.08)^{0.5}} = 1.38$$

The following drawing illustrates the channel components for this basic analysis:

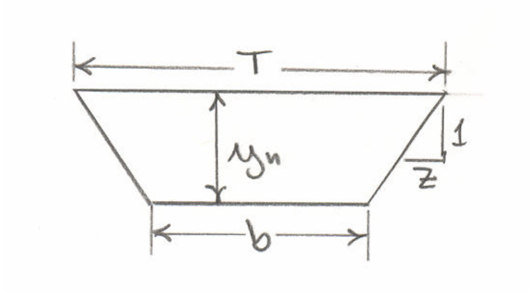
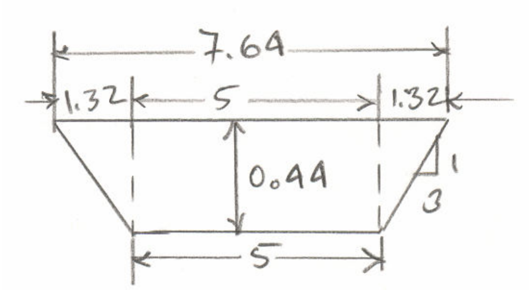


Figure 7 can be used to determine the normal depth (y_n) for many combinations of bottom with (b), and side slope (z). As an example, assume that the bottom width is 5 ft. and the side slope parameter, z, is 3. The calculated $AR^{2/3}$ value (1.38) needs to be divided by $b^{8/3}$ ($5^{8/3} = 73.14$) for the shape factor used in Figure 7. This value is therefore: 1.38/73.14 = 0.018. For a side slope of z = 3, the figure indicates that the ratio of the depth to the bottom width (y/b) is 0.088. In this example, the bottom width was 5 ft, so the normal depth is: y_n = 0.088 (5 ft.) = 0.44 ft., which is only 5.3 inches. The following shows these dimensions on the channel cross-section:



It is now possible to calculate the velocity and shear stress associated with this set of channel conditions:

$A = [(7.64+5)/2]\ (0.44) = 2.78\ ft^2$
$V = Q/A = 29\ ft^3/sec/2.78\ ft^2 = 10.4\ ft/sec$
$R = A/P$, and $P = 5 + 2(3.16)(0.44) = 7.78$ ft.; $R = A/P = 2.78\ ft^2/7.78$ ft. = 0.36 ft.

and $\tau = \gamma RS = (62.4 lb/ft^3)(0.36\ ft.)(0.08) = 1.8\ lb/ft^2$

With a velocity of 10.4 ft/sec and a shear stress of 1.8 lb/ft^2, it is obvious that some type of channel reinforcement will be needed (refer to Table 2), or another design option. Using Figure 7, plus liner information (such as listed previously), it is possible to create a simple spreadsheet with multiple cross section and liner alternatives, as shown in Table 7. Table 7 shows the unvegetated conditions and calculations, along with the phase 2 and phase 3 vegetation conditions, for several channel cross-sections, considering both NAG P300 and C350 permanent channel liner mats. The shear stress values are calculated using the normal depth of flow, for worst-case design conditions, and not the hydraulic radius.

Table 7. Characteristics for Alternative Designs for Drainage Channel (Q = 29 ft^3/sec and S = 8%)

		Unvegetated NAG P300, n = 0.02 (allowable shear stress = 3.0 lb/ft^2) [data not given for C350, assumed to be similar to P300 for this example]					Channel with Reinforced Liner and Vegetation						
Bottom width (b), ft	Side slope (z)	Normal depth (y_n), ft	Top width (T), ft	Hydraulic radius (R), ft	Shear stress (τ), lb/ft^2 (using depth)	Velocity (V), ft/sec	Assumed NAG material and growing conditions	Manning's roughness (n)	Normal depth (y_n), ft	Shear stress (τ), lb/ft^2 (using depth and peak Q)	Peak Velocity (V), ft/sec	Allowable shear stress for NAG product (short and long exposures), lb/ft^2	Effective soil shear stress (τ_e), $n_s = 0.016$; $C_f = 0.50$ phase 2 $C_f = 0.87$ phase 3
3	1	0.63	4.3	0.48	3.1	12.7	P300 phase 2	0.044	0.80	4.0	9.5	5.5/4.0	0.26
							P300 phase 3	0.049	0.89	4.4	8.4	8.0/8.0	0.06
6	4	0.31	8.5	0.26	1.5	12.9	P300 phase 2	0.044	0.57	2.8	6.1	5.5/4.0	0.19
							P300 phase 3	0.049	0.65	3.2	5.2	8.0/8.0	0.04
8	4	0.30	10.4	0.14	1.5	11.0	P300 phase 2	0.044	0.54	2.7	5.3	5.5/4.0	0.18
							P300 phase 3	0.049	0.88	4.4	3.4	8.0/8.0	0.06
5	3	0.44	7.6	0.36	2.2	10.4	C350 phase 2	0.044	0.66	3.3	6.3	6.0/4.5	0.22
							C350 phase 3	0.049	0.70*	3.5*	5.8*	8.0/8.0	0.05*
6	1.5	0.43	7.3	0.38	2.1	10.1	C350 phase 2	0.044	0.68	3.4	6.1	6.0/4.5	0.22
							C350 phase 3	0.049	0.72	3.6	5.7	8.0/8.0	0.05
10	3	0.26	11.6	0.26	1.3	10.4	C350 phase 2	0.044	0.49	2.4	5.2	6.0/4.5	0.16
							C350 phase 3	0.049	0.52	2.6	4.8	8.0/8.0	0.04

* example calculations for permanent C350 liner, 5 ft bottom width, z=3 side slope, and phase 3 vegetation plant stage (mature):

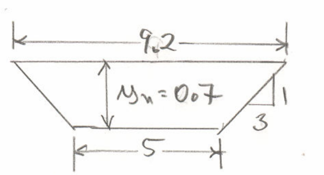
$$AR^{\frac{2}{3}} = \frac{nQ}{1.49S^{0.5}} \frac{(0.049)(29)}{1.49(0.08)^{0.5}} = 3.38$$

$b^{8/3} = 5^{8/3} = 73.1$

$AR^{2/3} / b^{8/3} = 3.38/73.1 = 0.046$

With $z = 3$, $y/b = 0.14$

Therefore $y_n = 0.14\ (5) = 0.7$ ft



$A = [(5+9.2)/2]\ (0.7) = 4.97\ \text{ft}^2$

$P = 5 + 2(1.21) = 7.42$ ft

$R = A/P = 4.97/7.42 = 0.67$

$\tau = \gamma RS = (62.4\text{lb/ft}^3)(0.67\ \text{ft.})(0.08) = 3.34\ \text{lb/ft}^2$ (analysis case using hydraulic radius)

$\tau = \gamma DS = (62.4\text{lb/ft}^3)(0.70\ \text{ft.})(0.08) = 3.49\ \text{lb/ft}^2$ (design case using normal depth)

$V = Q/A = 29\ \text{ft}^3/\text{sec}/4.97\ \text{ft}^2 = 5.8$ ft/sec

$$\tau_e = \gamma DS(1 - C_f)\left(\frac{n_s}{n}\right)^2 = 3.49 lb/ft^2(1 - 0.87)\left(\frac{0.016}{0.049}\right)^2 = 0.048 lb/ft^2$$

$n_s = 0.016$; $C_f = 0.87$ phase 3

Based on these calculations, either the P300 or the C350 liner will be suitable for most conditions for this example. When newly placed, with no vegetation growth, the Manning's n roughness is 0.02 for these liners. The maximum calculated maximum shear stress is 3.1 lb/ft^2 for the narrowest cross section examined, slightly greater than the maximum allowable value of 3.0 lb/ft^2. The calculated shear stresses are less than this allowable maximum value for the other cross-sections. Therefore, one of the wider channels should be used. Unfortunately, the velocities are all very high, ranging from 10.1 to 12.9 ft/sec before the establishment of vegetation. The use of check dams is therefore highly recommended for this channel. These can range from coir logs, to rock check dams.

The calculations after vegetative growth show that the either liner is also acceptable. A range of conditions were examined for phase 2 (50% stand maturity) and phase 3 (mature growth), with Manning's roughness values of 0.044 and 0.049. The smallest (and steepest side sloped) channel resulted in the highest shear stress of 4.4 lb/ft^2, less than the maximum acceptable values. The short exposure critical values are for peak flows of <2 hours peak flow durations. After mature plant establishment in the channel, the maximum allowable shear stress increases to 8.0 lb/ft^2 for all conditions. The effective soil shear stress is also shown, which would be applicable for temporary channel liners. During the phase 2 plant growth stage (50% plant growth), the resulting values are larger than typical soil tolerance conditions, while they are acceptable during the phase 3 growth stage (mature plant growth). This emphasizes the need for a permanent liner in this case where the additional protection provided by the vegetation is not necessary. The steep slope (8% in this case) results in these relatively extreme solutions. If the slope for this example was about 2%, or less, temporary liners may be suitable (assuming that suitable growth conditions exist).

Historical Use of Grass Swales for Stormwater Quality Control

Introduction

The treatment of stormwater is becoming more demanding as land development and urbanization increase nationwide. Urbanization changes the dynamics of stormwater conveyance systems by increasing the amounts of impervious areas. Impervious surfaces (such as a paved streets or parking lots) significantly reduce stormwater infiltration, resulting in increased stormwater runoff volumes and associated contaminant discharges. Even low density residential areas (less than 4 units/hectare) can have significant impacts on water quality by increasing phosphorus discharges 5 to 10 times over undisturbed forested areas (Dennis 1985). Moreover, urbanization radically changes the stream hydrologic balance. Research conducted by Sovern and Washington (1997) showed that the frequency of high flow rates in urbanized areas can be 10 to 100 times more than in predevelopment areas in Western Washington. They also reported decreases of low flows during dry periods, and increases in the sediment and pollutant discharges from urbanized watersheds. This paper section is from the master's thesis prepared by Yukio Nara (2005).

Among the various stormwater management practices, grass swales are cost efficient and a proven method to treat stormwater runoff. A grass swale is a broad, shallow open channel covered by dense vegetation on the sides and bottom of a channel as an alternative to conventional stormwater conveyance such as curbs and gutters (Kirby 2003). Grass swales are often the preferred stormwater design control practice over other practices particularly because of performance and low cost, but many public works departments and developers resist their use due to perceived maintenance issues and the implication of substandard developments. Grass swales can be applied in most regions of the country where grass can be established and maintained in local climates and soils, and where sufficiently frequent rains occur for irrigation. They are not applicable in arid areas where insufficient moisture is available to keep the grass healthy. Vegetated swales cost much less to construct and maintain than curbs and gutters with underground storm sewers. As an example, a 10 ft wide, 1-1/2 ft deep grass swale was reported to have an average cost of about \$12 per ft (SEWRPC 1991), while a a 36 inch diameter concrete pipe costs about \$50 per ft (Heaney, *et al*. 2001). Curbs and gutter costs plus inlet costs would still have to be added to the conventional drainage system costs. SEWRPC (1991) estimated the annual maintenance costs for grass swales to be about \$0.60 per ft per year. Conventional drainage pipes also have maintenance costs associated with cleaning the inlets and pipes of sediment, plus other periodic repairs. Overall, cost comparisons of swales with curb and gutter systems always show significant cost savings if swales are used (Heaney, *et al*. 2001). Besides the cost savings, existing natural features and processes can be utilized and integrated into the grass swale system to treat stormwater, rather than constructing and installing other more expensive stormwater controls, if properly planned prior to urbanization.

Many studies have shown that grass swales are an effective stormwater control practice in reducing runoff volume, sediments (total suspended solids, etc), nutrients (nitrate and phosphate), heavy metals (copper, cadmium, lead, and others), hydrocarbons, oil and grease. Particulates and other pollutants can have mass removal efficiencies ranging from 60 to 90%, as reported in numerous studies on both experimental and actual grass swales. For instance, Khan *et al.* (1992) observed average oil and grease removals of greater than 75% and an average total petroleum hydrocarbon removal of greater than 74% on a 60 m (196 ft) long grass swale. A number of researchers have concluded that grass swales are an effective method for treating stormwater based on actual measurements.

The Department of Civil and Environmental Engineering has been conducting research investigating the effectiveness of grass swales for treating stormwater pollutants, supported by the Water Environment Research Foundation (WERF) and the University Transportation Center of Alabama (UTCA). The prior WERF-supported research conducted by Johnson *et al.* (2003) focused on the removal of stormwater heavy metals (Cd, Cr, Cu, Pb, Fe, Hg, Ni, and Zn) and hydraulic characteristics of shallow open channel flow in grass swales.

The recent UTCA-supported research provides information to (1) understand the effectiveness of grass swales for different sized particles, (2) understand the associated effects of different variables on these removals, and (3) to develop a predictive model in sediment transport in grass swales (Nara and Pitt 2005). To achieve these objectives, experimental grass swales were constructed and tested in an indoor greenhouse facility (Kirby 2003). The sediment-water mixture of known sediment concentrations of sieved sands and fine particles of silica were used to simulate sediment characteristics of stormwater. For the preliminary experiments, 108 samples were collected and analyzed for turbidity, total solids, and particle size distributions to investigate the effects of swale length, grass type, flow rate, slope, and duration of the experiments. After completing the initial tests, additional experiments were conducted, with 108 samples collected and analyzed for total suspended solids, total dissolved solids, and total solids greater than and less than 106 µm, plus those listed for the first set of experiments. Using the results obtained from the second set of experiments, a predictive model of sediment transport in grass swales was developed. This model is similar to past models developed by Barfield *et al*. (1979) and Deletic (2001), but is more detailed due to the investigations of very small particle sizes and it is based on actual experimental conditions in grass swales having different height grasses. The main feature of the model is that it combines recently developed swale hydraulic information by Kirby (2003) and conventional particle settling information. The experimental tests determined the varying efficiencies of trapping different particle sizes under different hydraulic conditions. Particles from about 1 to 425 µm in diameter were included in these tests.

Terminology

The term grass swale refers to a vegetated, open channel stormwater management practice that comprises a grass-lined drainage channel. Grass filters and buffer strips applied in agricultural management practices are similar (EPA 1999; Pope and Stoltenberg 1991). The EPA Office of Water (1999) presents the following definition for these related control practices:

Grass Channel:

> "Grass channels are the most similar to a conventional drainage ditch, with the major differences being flatter slopes and longitudinal slopes, and a slower design velocity for water quality treatment of small storm events."

Dry Swale:

> "Dry swales are similar in design to bioretention areas. The existing soil is replaced with a sand/soil mix that meets minimum permeability requirements. An underdrain system is used under the soil bed. This system is a gravel layer that encases a perforated pipe. Stormwater treated in the soil bed flows through the bottom into the underdrain, which conveys treated stormwater to the drainage system."

Wet Swale:

> "Wet swales intersect the ground water, and behave almost like a linear wetland cell. This design variation incorporates a shallow permanent pool and wetland vegetation to provide treatment. This design also has potentially high pollutant removal. It cannot be used in residential or commercial settings because the shallow standing water in the swale is viewed as a potential nuisance by homeowners."

Vegetated Buffer Strip (VBF):

> R.P. Beasley (1978) describes a vegetated buffer strip as: "Areas seeded to grasses or legumes between strips of cultivated crops, the number and location of these are selected to give desired protection from erosion."

Filter Strip:

> Anderson (1983) defines a filter strip as: "A strip or area of vegetation for removing sediment, organic matter, and other pollutants from runoff and wastewater."

Reported Pollutant Removal Efficiencies for Grass Swales

Numerous studies on both experimental and actual grass swales have reported a wide range of efficiencies in reducing stormwater sediments and other pollutants. One of the main reasons for these differences is that most studies only examined concentrations in the grass swales, and did not measure volume reductions. During very low flows where shallow flow depths occur in relation to the grass height, pollutant concentration reductions can be high. However, as the flow depth increases, especially to more than 4 or 5 times the grass height, concentration reductions are greatly reduced. However, infiltration of water is usually significant in a swale-drained area. Unfortunately, not all published research reports make it clear that they only considered concentration reductions and that they did not measure flow changes, and associated pollutant mass reductions.

Most of the studies reported relatively high efficiencies in sediment removal, ranging 60% to 90%, as shown in Table 8. For example, Woodard and Rock (1995) studied phosphorus and total suspended solids retention in buffer strips (which would have shallow flows). The areas draining to the buffer strips were composed of a residential area, but in different construction phrases. Therefore, the initial total suspended solids concentrations were very high, ranging from 700 mg/L to 3,700 mg/L. The buffer strip slopes ranged from 2.3% to 12.0%, and high reductions were observed for both phosphorus and total suspended solids, ranging from 60% to 97%. Beyond 98 ft (30 m), both phosphorus and total suspended solids concentrations reached background (irreducible) concentrations. They found higher percentage reductions when the initial phosphorus and total suspended solids concentrations were higher.

Studies show that the effectiveness of grass swales in reducing soluble nutrients and metals is significant, but is highly variable, as indicated in Table 8 (Goldberg 1993; Wang *et al*. 1981). Khan *et al.* (1992) recorded average oil and grease and total petroleum hydrocarbon removals of greater than 75% for a 197 ft (60 m) long grass swale. However, studies also show that bacteria levels could increase instead of decrease in grass swales (Goldberg 1993; Wang *et al*. 1981; Seattle Metro Washington Dept. of Ecology 1981). One explanation is that bacteria thrive in the warm swale soils (EPA 1999).

Table 8. Summary of Reported Efficiencies of Grass Swales (EPA 1999: Many of the reports were summarized by EPA, but the list was expanded to include new reports)

Study	Type	Total suspended solids (%)	Total phosphorus (%)	Total nitrogen (%)	Nitrate (%)	Metals (%)	Bacteria (%)
Goldberg (1993)	Grassed channel	67.8	4.5	N/A	31.4	42 to 62	-100
Seattle Metro and Washington Dept of Ecology (1992)	Grassed channel	60 to 83	29 to 45	N/A	25	46 to 73	-25
Wang *et al.* (1981)	Dry swale	80	N/A	N/A	N/A	70 to 80	-25
Dorman *et al.* (1989)	Dry swale	98	18	N/A	45	37 to 81	N/A
Harper (1988)	Wet swale	81 to 87	17 to 83	40 to 84	52 to 80	37 to 90	N/A
Kercher *et al.* (1983)	Dry swale	99	99	99	99	99	N/A
Koon (1995)	Wet swale	67	39	N/A	9	-35 to 6	N/A
Daniels and Gilliam (1996)	Dry swale	60 to 90	50	50	N/A	N/A	N/A
Dillaha *et al.* (1989)	Dry swale	70 to 84	61 to 79	54 to 73	N/A	N/A	N/A
Barrett *et al.* (1998)	Grass swale	25 to 80	N/A	N/A	N/A	N/A	N/A
Fletcher *et al.* (2002)	Grass swale	73 to 94	58 to 72	44 to 57	N/A	N/A	N/A
Horner and Mar (1982)	N/A	80	N/A	N/A	N/A	N/A	N/A
EPA (1999)	grass swale	81	9	38	N/A	42 to 71	N/A

Note: N/A = not available

Modeling

Despite the numerous studies that have discussed grass swale performance in reducing sediments and other pollutants, few have suggested a predictive model to describe sediment retention in the grass swales. The most cited mathematical model was developed in the 1970s at the University of Kentucky (in Lexington, USA), the "Kentucky model" (Tollner *et al*. 1976, Barfield *et al*. 1979, Hayes *et al*. 1984). Metal rods were used to simulate grass, and data were obtained by measuring sedimentation of very high concentrations of beads. Deletic (2001) suggested that the Kentucky model was not accurate for urban conditions, especially for smaller particles and low concentrations, and proposed an alternative approach.

Kentucky Model

According to the Kentucky model (Tollner, *et al*. 1976, Barfield, *et al*. 1979, Hayes, *et al*. 1984), the grass strip is divided into four separate zones: A, B, C, and D as shown in Figure 15.

- Zone A: All sediments are transported.
- Zone B: sediment is deposited all along the deposition front with slope corresponding to that required to yield a transport capacity.
- Zone C: Sediment is transported as bedload.
- Zone D: All sediment reaching the bed is trapped.

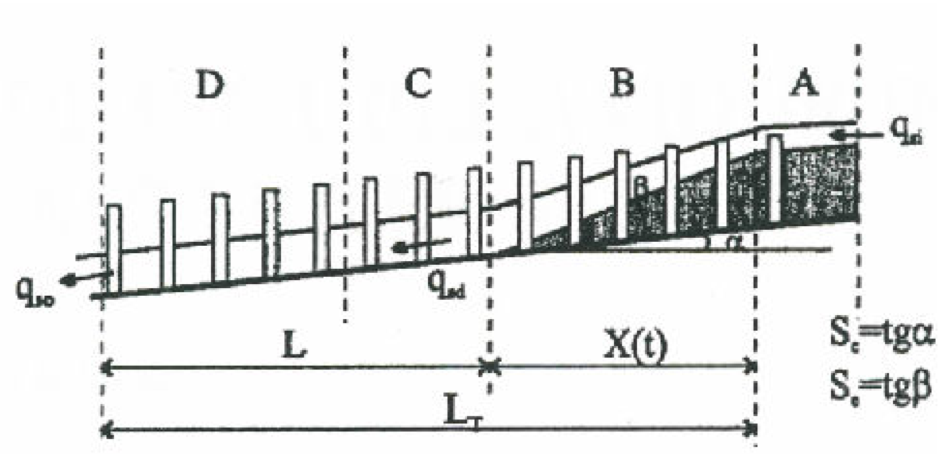


Figure 15. Schematic of sediment deposition (Tollner, *et al.* 1976; Barfield, *et al.* 1979; Hayes, *et al.* 1984).

The trapping efficiency is calculated as:

(2.1) $$Tr = \frac{q_{si} - q_{so}}{q_{si}} = 1 - \frac{q_{sd}}{q_{si}}\left[1 - \frac{q_{sd} - q_{so}}{q_{sd}}\right]$$

Where:

q_{si} = Incoming sediment load per unit channel width (g/m^2)

q_{so} = Outgoing sediment load per unit channel width (g/m^2)

q_{sd} = Total sediment load transported immediately downstream of the deposition wedge (g/m^2)

The sediment loads are calculated using the following equations:

(2.2) Zone B: $$X(t) = \frac{2(q_{si} - q_{sd})t}{\rho_{sb} g S_e}$$

Where:

$X(t)$ = Length of the swale in Zone B (m)

t = Time after beginning of the flow (s)

ρ_{sd} = Blunk density of deposited sediment (g/m^3)

g = Gravity acceleration (m/s^2)

S_e = Slope of the swale in Zone B

(2.3) Zone C: $$q_{sd} = \rho_s \sqrt{(\rho_s / \rho - 1) g d_p^{\,3}} * \left[\frac{1.08 S_c R_s}{(\rho_s / \rho - 1) d_p}\right]^{3.571}$$

Where:

ρ = Density of water (g/m^3)

ρ_s = Density of particles (g/m^3)
d_p = Particle diameter (m)
$S_c =$ Channel slope
R_s = Spacing hydraulic radius (m) calculated as:

$$R_s = \frac{bh}{b + 2h} \tag{2.4}$$

Where:
b = Spacing between two grass blades (m)
h = Flow depth (m)

$$\text{Zone D: } \frac{q_{sd} - q_{so}}{q_{sd}} = \exp\left[-1.05 \times 10^{-3} \left(\frac{VR_s}{\nu}\right)^{0.82} \left(\frac{hV}{LV_s}\right)^{0.91}\right] \tag{2.5}$$

Where:
V = Mean flow velocity (m/s)
V_s = Terminal settling velocity of particles (Stoke's settling velocity) (m/s)
ν = Kinetic viscosity of the water sediment mixture (m^2/s)
h = Flow depth (m)
R_s = Spacing hydraulic radius (m)
$L = L_t \sim X(t)$ effective length of grass filter strip (m)
L_t = Total length of grass filter strip.

Deletic Model

Unlike the Kentucky model, Ana Deletic (2001) used substantial amounts of very fine sediments (sediment particles less than 20 μm) as well as large particles to develop a comprehensive model. The model was developed by using an artificial medium (Astroturf) mounted on a 41 ft (12.5 m) long and 1 ft (0.3 m) wide channel, to simulate actual grass. Samples were collected at various swale locations and were analyzed for particulate concentrations and size distributions. Data obtained from the experiments were used to develop the sediment transport model by incorporating the concept of particle falling number. Three major processes of sediment behavior in grass swales were modeled: (a) particle deposition, (b) sediment transport, and (3) surface level and slope changes.

(a) Particle Deposition:

The particle fall number ($N_{f,s}$) is calculated as:

$$N_{f,s} = \frac{lV_s}{hV} \tag{2.6}$$

Where:
l = Grass length (m)
h = Depth of the flow (m)
V_s = Stoke's settling velocity (m/s)
V = Average mean flow velocities were calculated as:

$$V = \frac{q}{B_o h} \tag{2.7}$$

$$V_s = \frac{g}{18\mu}\left(\rho_s - \rho\right)d_s^2 \tag{2.8}$$

Where:

B_o = Open (unblocked by grass) flow width per unit width
μ = Dynamic viscosity of water (kg $s^{-1}m^{-1}$),
ρ = Water density (kg m^{-3})
d_s = Particle diameter (m)
ρ_s = Particle density (kg m^{-3}).

The trapping efficiency ($T_{r,s}$) for the sediment fraction s (particles of diameter ds) is expressed as:

$$T_{r,s} = \frac{N_{f,s}^{0.69}}{N_{f,s}^{0.69} + 4.95} \tag{2.9}$$

(b) Sediment Transport:
Assuming that the particles transported in grass swales are very small (most of the particles are less than 20 µm (Neibling and Alberts 1979)), the model describes transport of suspended solids in grass swales. The model does not consider infiltration of water and re-suspension of deposited particles. The model is expressed as:

$$\frac{\partial\left(hq_{s,s}/q\right)}{\partial t} + \frac{\partial q_{s,s}}{\partial x^2} = Dis\frac{\partial^2\left(hq_{s,s}/q\right)}{\partial x^2} - \lambda_s q_{s,s} \tag{2.10}$$

Where:

$q_{s,s}$ = Sediment loading rate of fraction s per unit width (g $s^{-1}m^{-1}$)
Dis = Dispersion coefficient (m^2 s)
λ_s = Trapping efficiency of fraction s per unit length (m^{-1}) calculated as:

$$\lambda_s = \frac{T_{r,s}\left(\frac{lV_s}{Vh}\right)}{l} \tag{2.11}$$

(c) Surface Level and Slope Changes:
This model considers the channel slope changes due to deposition of sediments, especially at the upstream end of grass strips. The changes in slope (S) is expressed as:

$$S(x,t) = -\frac{\partial z(x,t)}{\partial x} \tag{2.12}$$

Where:

$\partial z(x,t)$ = Rise in the surface level expressed as:

(2.13) $$\frac{\partial z(x,t)}{\partial t} = \frac{1}{1-p}\int_s \frac{1}{\rho_s}\lambda_s q_{s,s} d_s$$

Where:

P = Porosity of deposited sediment

$q_{s,s}$ = Sediment loading rate of fraction s per unit width (g $s^{-1}m^{-1}$)

d_s = Particle diameter (m)

λ_s = Trapping efficiency of fraction s per unit length (m^{-1})

Sediment Trapping Model for Grass Swales and Grass Filters

Introduction

Nara (2005) conducted a set of experiments using controlled flows at indoor swale facilities that were designed to identify the significant factors affecting trapping of particulates in grass swales. From the results of these initial experiments, more carefully designed and detailed experiments were conducted in follow-up experiments. Full-scale outdoor experiments were then conducted to verify that the variables identified in the controlled indoor experiments were valid during actual rain events and in full-scale conditions. This section presents a sediment trapping model for grass swales (and grass “filters”) using these experimental results.

Modeling Sediment Reductions in Grass Swales

The primary focus on the second set of indoor experiments conducted by Nara (2005) was to develop a model to predict the reduction of stormwater sediments in actual grass swales. This discussion describes the model using the analytical results (total solids, total solids less than 106 µm, total suspended solids, total dissolved solids, turbidity, and particle size distribution analyses) obtained during the second series of experiments and supplemented with the outdoor observations.

Settling Frequency

The settling frequency is the number of times that sediment particles of a specific size category would fall to the bottom of the swale through the depth of water while flowing through the swale. Particles having a large settling frequency are assumed to have higher sediment removal rates than particles having a small settling frequency.

It is likely that more than 90% of all runoff particulates are in the 1 to 100 µm range, corresponding to particles that will settle with low Reynolds’s numbers, and hence laminar flow conditions, and the settling rates can therefore be calculated using Stoke’s law. In most cases, stormwater particulates have specific gravities in the range of 1.5 to 2.5, while construction site runoff particles would be closer to 2.5, and silica test particles have specific gravities of 2.65. This corresponds to a relatively narrow range of settling rates for a specific particle size. Settling frequency can therefore be calculated using Stoke’s law to determine the settling velocity for a specific particle size class, the length of the swale, the flow rate, and the depth of flow. Larger particles have higher chances of settling for the same flow and swale conditions than smaller particles since they have larger settling velocities. Stoke’s law is commonly expressed as:

(6.2) $$Vs = \frac{2}{9}\frac{\left(R^2 g\left(\rho_p - \rho_f\right)\right)}{U}$$

Where:

Vs = Settling velocity of a particle (cm/s)

R = Equivalent radius of a particle, considering shape (cm)

g = Gravitational constant = 980 cm/s^2

ρ_p = Density of a particle = 2.65 g/cm^3 (assuming silica)

ρ_f = Density of fluid = 1.0 g/cm^3 (assuming water at standard temperature conditions)

U = Dynamic Viscosity = 0.01 g/(cm*s) (assuming water at standard temperature conditions)

The following example is a calculation of the settling frequency for one of the experimental conditions: a silica particle whose diameter is 2 µm (2 x 10^{-4} cm in diameter, or 1 x 10^{-4} cm in radius) in a 6 ft long section of a 2 ft wide synthetic turf lined swale at 1% slope and at 10 GPM (0.038 m^3/min) flow rate. The first step is to calculate the settling velocity of the particle:

(6.3) $$Vs = \frac{2}{9} * \frac{\left(\left(1x10^{-4} cm\right)^2 * 980 cm/s^2 * (2.65 g/cm^3 - 1.0 g/cm^3)\right)}{0.01 g/(cm * s)}$$

Thus:

(6.4) Vs = 3.59*10^{-4} cm/s (1.41*10^{-4} inch/s)

To calculate the settling duration of the 2 µm particle for the synthetic turf at 1% slope and 10 GPM (0.038 m^3/min) of flow, the averaged flow depth of the water for these experimental conditions was divided by the settling velocity of 2 µm particles. The average flow depth of water on the synthetic turf, at 1% slope and 10 GPM (0.038 m^3/min) flow rate, was 0.87 inches (2.2 cm). Thus,

(6.5) $$Settling\_Duration(\sec ond) = \frac{flow\_depth}{Settling\_velocity} = \frac{0.87(inch)}{1.41*10^{-4}(inch/s)} = \frac{2.2(cm)}{3.6*10^{-4}(cm/s)}$$

= 6,170 (seconds)

The average velocity of the water flow on the synthetic turf, at 1% slope and 10 GPM (0.038 m^3/min) flow rate, was 1.86 inch (4.7 cm) /s. Since the length of the indoor swale was 6 ft (72 inches or 182.8 cm):

(6.6) $$Traveling\_time(\sec ond) = \frac{Swale\_length}{Flow\_velocity} = \frac{72(inch)}{1.86(inch/s)} = \frac{182.8(cm)}{4.7(cm/s)}$$

= 38.7 (seconds)

The settling frequency is the number of times which a particle settles through the flow depth on a grass swale.

(6.7) $$Settling\_frequency = \frac{Traveling\_time}{Settling\_duration} = \frac{38.7(\sec onds)}{6170(\sec onds)}$$

Settling frequency = 0.0063

Therefore, the retention of 2 µm particles in this swale under these conditions is expected to be rather poor, as the particle would barely start to settle before it reached the end of the swale. The swale would have to be about 1,000 ft long (305 m) before these small particles would strike the bottom of the swale (assuming the worst case condition of the particle starting at the top of the flow depth).

The following is an example for a larger particle (100 µm in diameter, 0.01 cm diameter, or 0.005 cm in radius) during another test condition:

(6.8) $$Vs = \frac{2}{9} * \frac{\left((0.005cm)^2 * 980cm/s^2 * (2.65g/cm^3 - 1.0g/cm^3)\right)}{0.01g/(cm*s)}$$

Vs = 0.9 cm/s (0.35 inch/s)

The flow conditions for the Zoysia-lined swale, at 3% slope and 15GPM (0.064 m^3/min) flow rate, resulted in an average flow depth of 1.91 inches.

Thus,

(6.9) $$Settling\_Duration(\sec ond) = \frac{flow\_depth}{Settling\_velocity} = \frac{1.91(inch)}{0.35(inch/s)} = \frac{4.8(cm)}{0.9(cm)}$$

= 5.4 seconds

The average flow velocity for this swale and flow condition was 1.28 inch/s (3.2 cm/s). Since the length of the indoor swale was 6 ft (72 inches or 183 cm):

(6.10) $$Traveling\_time(\sec ond) = \frac{Swale\_length}{Flow\_velocity} = \frac{72(inch)}{1.28(inch/s)} = \frac{182.8(cm)}{3.2(cm/s)}$$

= 56 seconds

The settling frequency is the number of times which a particle settles through the flowing water column while flowing along the grass swale:

(6.11) $$Settling\_frequency = \frac{Traveling\_time}{Settling\_duration} = \frac{56(\sec onds)}{5.4(\sec onds)}$$

Settling frequency = 10

This settling frequency corresponds to a very high sediment removal rate for 100 µm particles, for this flow swale condition.

Summarized Information used to Predict Grass Swale Performance

The following figures and tables summarize important information from this research, and the previous WERF work (Johnson, *et al.* 2003), to determine the hydraulic conditions in small grass swales and to predict sediment capture.

Roughness Curves

Figure 16 is the final VR-n curve developed by Kirby (2003), showing the data for the small swales (both for the controlled indoor swale tests and for outdoor tests that were conducted during the WERF research). This figure shows how the roughness relationships are extended to very high Manning's n values for small flows that occur in roadside grass swale drainages.

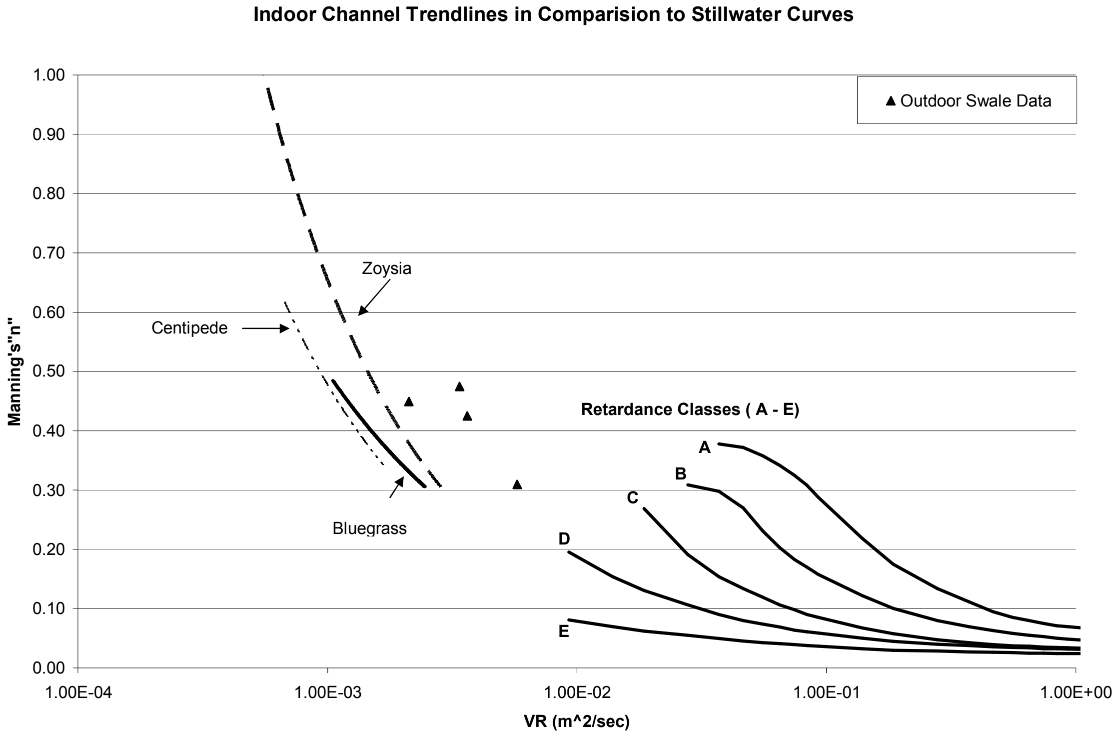


Figure 16. VR-n curve for different grasses, showing results for shallow flows (Kirby 2003) (Multiply ft^2/sec by 0.092 to obtain m^2/sec units).

Settling Frequency and Particulate Retention

Table 9 summarizes the percentage reduction values (including the confidence intervals of the means, along with the coefficient of variation (COV) values) for each set of settling frequencies for each flow depth to grass height range. These were calculated by statistically summarizing all the data observations contained in each cluster of settling frequency for all the tests combined for the indoor experiments conducted with relatively high suspended solids concentrations. Table 10 is a similar table summarizing the observations for the full-scale tests that represent shallow flows and low concentrations.

Table 9. Statistical Summaries of the Percent Reductions for High Sediment Concentrations (200 to 1,000 mg/L) and for Different (flow depth)/(grass height) Ratio Categories

Ratio: 0 to 1.0

Settling frequency	Mean reduction (%)	95% CI (lower limit)	95% CI (upper limit)	COV
TDS (< 0.45 µm)	5	1	8	0.99
0.0013 to 0.0026	75	70	80	0.19
0.01 to 0.02	72	69	75	0.23
0.045 to 0.093	72	69	75	0.18
0.33 to 0.69	75	72	78	0.11
1.6 to 3.3	80	78	82	0.15
5.4 to 11.1	85	82	88	0.14
60.6 to 124.1	97	92	100	0.05

Ratio: 1.0 to 1.5

Settling frequency	Mean reduction (%)	95% CI (lower limit)	95% CI (upper limit)	COV
TDS (< 0.45 µm)	18	7	28	0.39
0.0013 to 0.0026	56	49	63	0.37
0.01 to 0.02	64	60	68	0.28
0.045 to 0.093	70	66	74	0.25
0.33 to 0.69	77	73	81	0.13
1.6 to 3.3	84	80	88	0.09
5.4 to 11.1	88	83	93	0.12
60.6 to 124.1	97	89	100	0.08

Ratio: 1.5 to 4.0

Settling frequency	Mean reduction (%)	95% CI (lower limit)	95% CI (upper limit)	COV
TDS (< 0.45 µm)	6	2	9	0.75
0.0013 to 0.0026	43	38	48	0.5
0.01 to 0.02	46	42	50	0.24
0.045 to 0.093	52	48	56	0.19
0.33 to 0.69	63	60	66	0.14
1.6 to 3.3	74	71	77	0.11
5.4 to 11.1	84	80	88	0.05
60.6 to 124.1	99	95	100	0.03

Table 10. Statistical Summary of the Percent Reductions for Low Sediment Concentrations (40 to 160 mg/L)

Ratio: 0 to 1.0

Settling frequency	Mean reduction (%)	95% CI (Lower limit)	95% CI (Upper limit)	COV
0.02 to 0.05	41	25	58	0.32
0.09 to 0.39	58	48	68	0.28
0.7 to 5.15	71	62	81	0.14
12.99 to 24.8	78	67	87	0.11
62.6 and larger	78	67	87	0.13

Settling Rates for Different Particle Sizes

Tables 11 through 13 summarize calculated settling rates based on Stokes' Law, as presented previously. These rates can be used to predict the capture of the sediment in these particle sizes for specific grass swale flow conditions. Tables 12 and 13 show how the settling rates vary for different specific gravities. Stormwater particulates have specific gravities of about 2.5, but they can be as low as about 1.5 under some conditions.

Table 11. Particle Settling Rates (2.65 specific gravity)

Particle size range	Approx. midpoint	Settling rate of midpoint size (cm/sec)	(in/sec)
0.45 to 2 µm	1.2	1.52×10^{-4}	5.98×10^{-5}
2 to 5 µm	3.5	1.10×10^{-3}	4.34×10^{-4}
5 to 10 µm	7.5	5.05×10^{-3}	1.99×10^{-3}
10 to 30 µm	20	3.59×10^{-2}	1.42×10^{-2}
30 to 60 µm	45	0.182	0.0717
60 to 106 µm	83	0.619	0.243
106 to 425 µm	266	6.22	2.45

Table 12. Particle Settling Rates (2 µm particle) for Different Specific Gravities

Settling units	2.65 g/cm^3	2.5 g/cm^3	2.0 g/cm^3	1.5 g/cm^3
cm/sec	3.6×10^{-4}	3.27×10^{-4}	2.18×10^{-4}	1.09×10^{-4}
in/sec	1.42×10^{-4}	1.29×10^{-4}	8.58×10^{-5}	4.29×10^{-5}

Table 13. Particle Settling Rates (100 µm particle) for Different Specific Gravities

Settling units	2.65 g/cm^3	2.5 g/cm^3	2.0 g/cm^3	1.5 g/cm^3
cm/sec	0.899	0.818	0.545	0.273
in/sec	0.354	0.322	0.215	0.107

Example Problem

The channel and flow characteristics from the channel-lining example design presented earlier will be used to predict the sediment retention in this grass swale:

- the discharge rate is 29 ft^3/sec (0.80 m^3/sec)
- the channel bottom width is 5 ft (1.5 m) wide, with 3 (H) to 1 (V) side slopes
- the calculated normal depth is 0.7 ft (210 mm, 21 cm) and the velocity is calculated to be 5.8 ft/sec (1.8 m/sec) after mature vegetation is established
- the swale length for this area is 1250 ft (378 m)

With water is assumed to enter the swale at the midpoint location, resulting in an effective treatment swale length of 625 ft (189 m). With a water velocity of 5.8 ft/sec (1.8 m/sec), the average travel time is 189 m/1.8 m/sec = 105 sec (1.8 m) for this length.

The mature grass is about 3 inches (75 mm) in height, so the flow depth to grass height ratio is 210 mm/75 mm = 2.8. The suspended solids concentration is determined to be 250 mg/L and the particle size distribution of the water entering the swale is typical, as shown on Figure 17 for the December 6, 2004 observations.

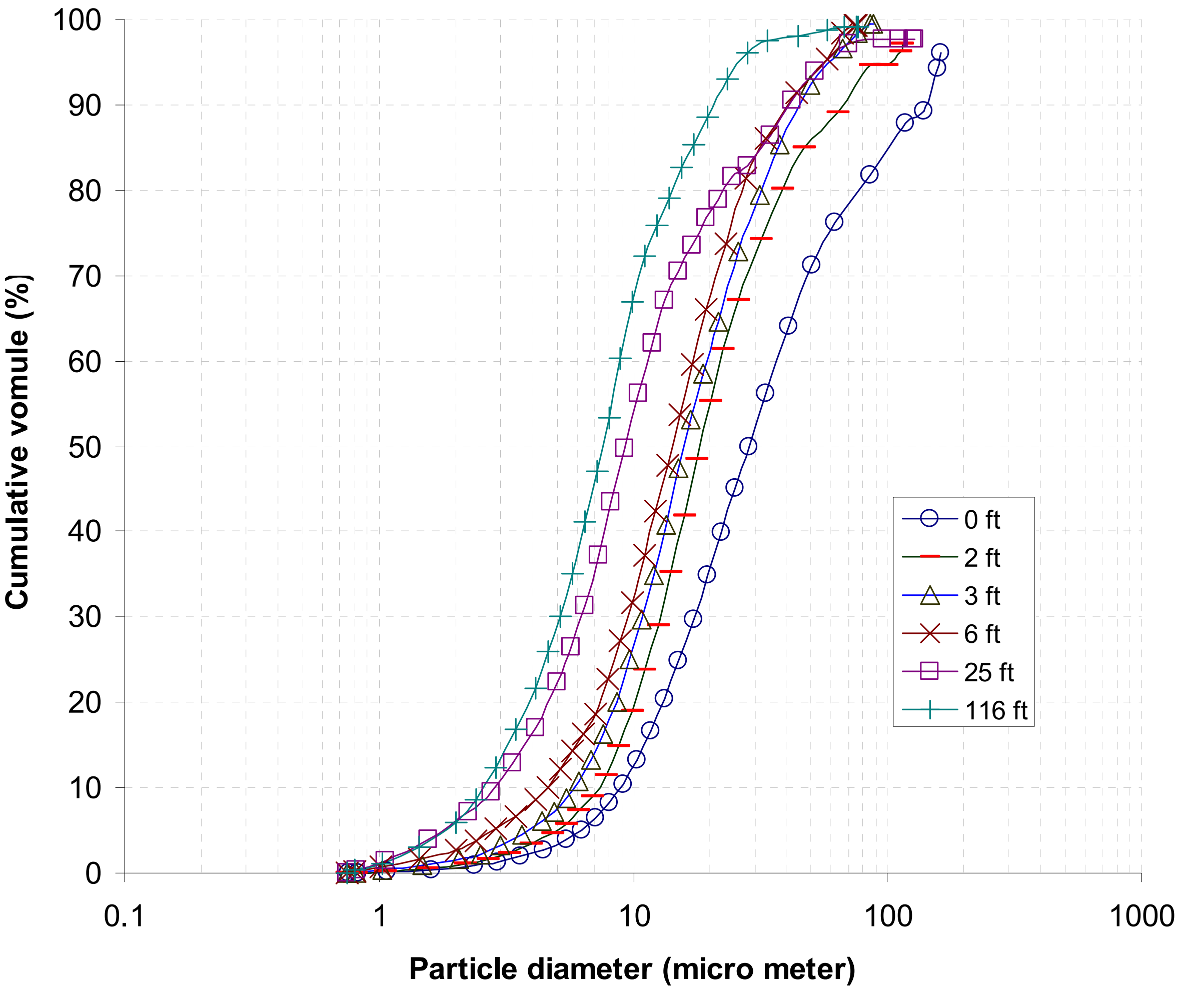


Figure 17. Example particle size distributions for different swale lengths observed on December 6, 2004.

Tables 14 and 15 show the particle size information for each size range (extracted from Figure 17) and the resulting sediment concentrations calculated using these values.

Table 14. Particle Size Distribution for Influent Water

Particle Size (µm)	% smaller than size indicated (Dec. 6, 2004 influent)
0.45	0
2	0.5
5	3.2
10	12.4
30	52.8
60	74.6
106	85.2
425	100.0

Table 15. Particulate Concentration for Each Particle Range

Particle Size Range	Approx. % of Suspended Solids in Range	Particulate Concentration in Size Range
0.45 to 2 µm	0.5	1.3
2 to 5 µm	2.7	6.8
5 to 10 µm	9.2	23.0
10 to 30 µm	40.4	101.0
30 to 60 µm	21.8	54.4
60 to 106 µm	10.6	26.5
106 to 425 µm	14.8	37.0
Total:	100.0	250 mg/L

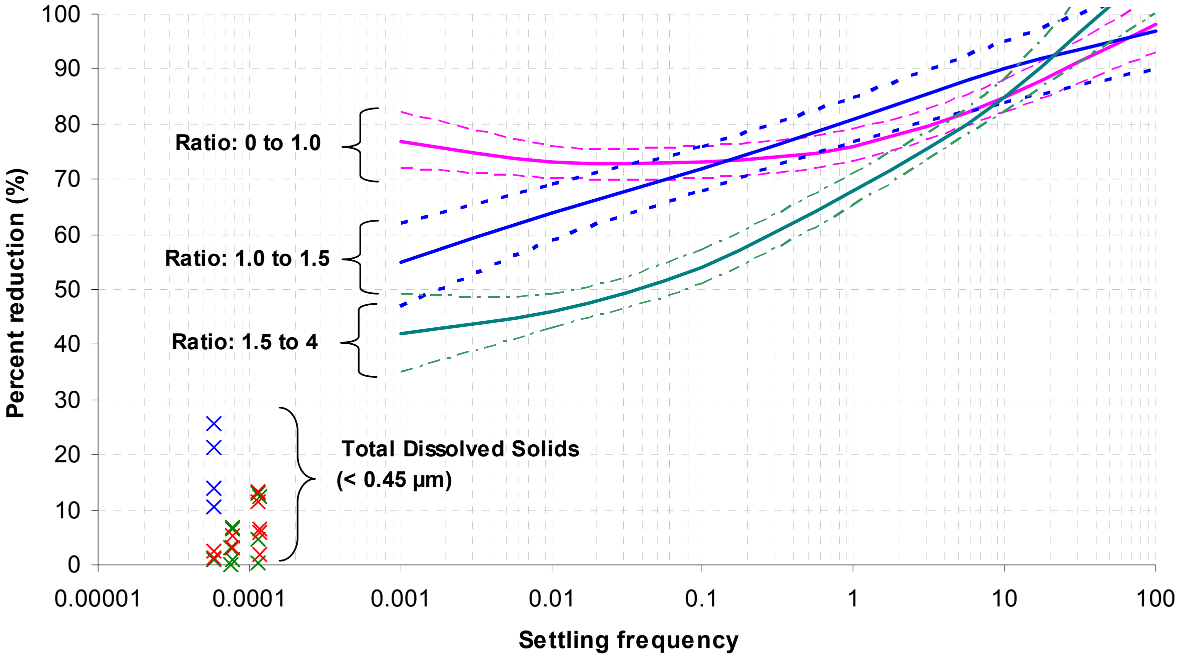


Figure 18. Comparison of regression lines with 95% confidence intervals for different (flow depth)/(grass height) ratios and for high concentrations (200 to 1,000 mg/L).

Table 16 shows the performance calculations for each particle size range.

Table 16. Particulate Trapping Calculations for Example Problem

Particle Size Range	Approx. Settling Rate (cm/sec)	Settling Time for 21 cm Flow Depth (sec)	Settling Frequency for Swale (105 sec travel time)	Percent Reduction for Particles in Size Range (from Figure 18)	Influent Particulate Concentration in Size Range (mg/L)	Irreducible Concentration for Size Range (mg/L)	Particulate Concentration for Size Range after Treatment (mg/L)	Final Resultant Concentration for Size Range (mg/L)
0.45 to 2 µm	1.52×10^{-4}	138,000	0.00076	42	1.3	7	0.8	1.3*
2 to 5 µm	1.10×10^{-3}	19,000	0.0055	44	6.8	5	3.8	5**
5 to 10 µm	5.05×10^{-3}	4,160	0.025	48	23.0	5	12.0	12.0
10 to 30 µm	3.59×10^{-2}	585	0.18	57	101.0	10	43.4	43.4
30 to 60 µm	0.182	115	0.91	68	54.4	5	17.4	17.4
60 to 106 µm	0.619	33.9	3.1	74	26.5	5	6.9	6.9
106 to 425 µm	6.22	3.38	31	96	37.0	10	1.5	10**
Total:				66% (weighted by mass), reduced by irreducible concentrations	250 mg/L	20 mg/L	86 mg/L	96 mg/L

Notes:

* the influent concentration for this particle size range is less than the irreducible concentration, so the influent concentration is not reduced by the swale treatment.

** the treated concentration for these particle size ranges are less than the irreducible concentrations, so the treated concentrations are not reduced to values smaller than the irreducible concentrations.

An overall 62% reduction in suspended solids concentration was achieved. Table 17 shows the resultant particle size distribution for the treated water, compared to the influent water.

Table 17. Particle Size Distribution for Treated Water

Particle Size (μm)	% smaller than size indicated (Dec. 6, 2004 influent)	Concentration smaller than size indicated (treated), mg/L	% smaller than size indicated, treated
0.45	0	0	0
2	0.5	1.3	1.4
5	3.2	6.3	6.6
10	12.4	18.3	19.1
30	52.8	61.7	64.3
60	74.6	79.1	82.4
106	85.2	86.0	90.0
425	100.0	96.0	100.0

Summary of Findings

This paper presented a method to predict stormwater sediment retention in grass-lines swales or grass filters. The main factors affecting the sediment trapping in the swales was the settling frequency, which in turn is dependent on particle settling rate, flow rate, flow depth, and swale length; the ratio of the flow depth to the grass height; and the initial sediment concentration. During shallow flow conditions, relatively flat swales will provide large amounts of sediment retention, down to an irreducible concentration of about 20 mg/L of total suspended solids. Steep swales and deeper flows result in less sediment retention.

The indoor swale experiments resulted in larger sediment reductions than observed during the outdoor tests due to several reasons, including:

- The initial sediment concentrations during the second set of indoor experiments were much higher than during the outdoor swale observations. The mean of the indoor experiment total suspended solids concentrations was 480 mg/L, and ranged from 200 mg/L to 1,000 mg/L. The outdoor swale observations had mean total suspended solids concentrations of 60 mg/L, and ranged from 10 mg/L to 160 mg/L.

- There was a large fraction of larger sand particles applied to the indoor swales, while very little, if any, sand-sized particles were found at the head of the outdoor swale for most of the events. The settling frequency calculations partially accounted for this, but irreducibly low concentrations of the larger material occurred before the end of the longer outdoor swale, limiting the overall percentage removal calculations.

The regression model does not consider erosion or scour that likely occurs at the beginning of the swale. There is obviously some initial length, likely dependent on flow conditions and shear stress, where the turbulent flows are more erosive before they become more stable. This length is probably on the order of several feet for small flows, like observed during this research, but may extend longer for larger flows.

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