Grass Swale and Grass Filter Performance and Design

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Photo by Shirley Clark

Grass Swale and Filter Strip Topics

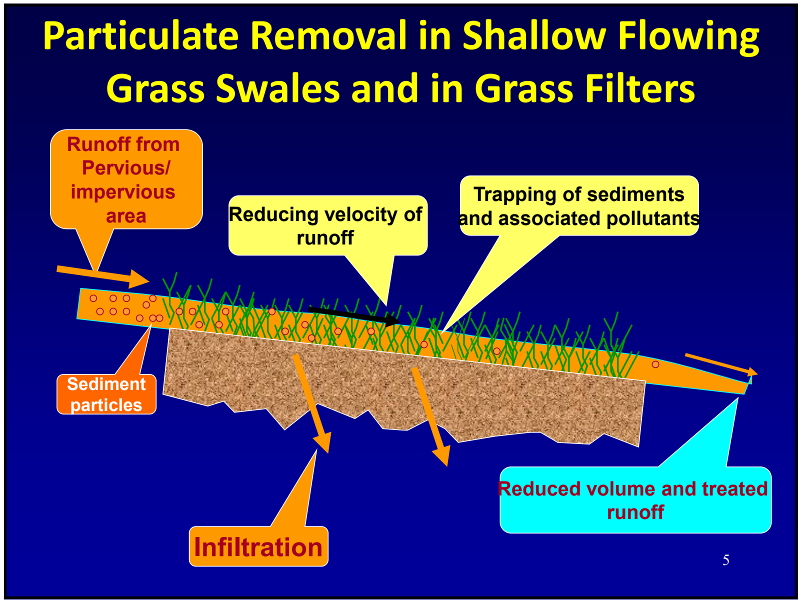
- Main findings from grass swale and grass filter research
- Mechanisms in swales and filters affecting stormwater quantity and quality
- Case studies of grass swale and filter performance
- Univ. of Alabama grass swale research
- Modeling sediment transport in grass swales
- Design of stable open channels
- General design procedures of grass-lines channels
- Conclusions

Selected Grass Swale and Filter Strip Monitoring References

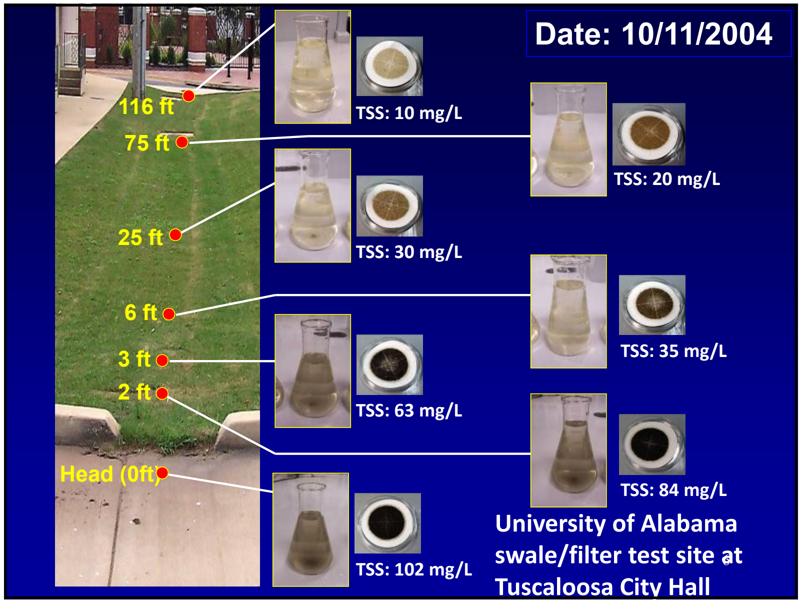
- EPA Report - Infiltration Through Disturbed Urban Soils and Compost (Pitt 1999)
- Alabama Highway Drainage Conservation Design Practices (Nara and Pitt 2005)
- HEC-15, Design of Roadside Channels with Flexible Linings, 2005
- Results of Tests on Vegetated Waterways (Cox and Palmer 1948

Selected Research Results

- IJC (1979) found swale drained areas had up to 95% less flows and pollutant yields compared to curb and gutter.
- NURP (1983) found soluble and particulate heavy metals reduced by 50% and COD, nitrate and ammonia nitrogen reduced by about 25%.
- Pitt & McLean (1986) found about 50% reductions in pollutants and runoff volume; for small frequent rains, very little runoff was observed.
- Johnson, *et al.* (2003) at the Univ. of Alabama identified hydraulic characteristics of stormwater swales under typical flows and plant bioremediation benefits in swales for heavy metal trapping (report available through WERF).
- Research (Nara and Pitt 2005) at the Univ. of Alabama identified significant factors affecting particulate transport in grass swales and developed suitable model algorithms. Modeled procedure joins particle settling with swale hydraulics.

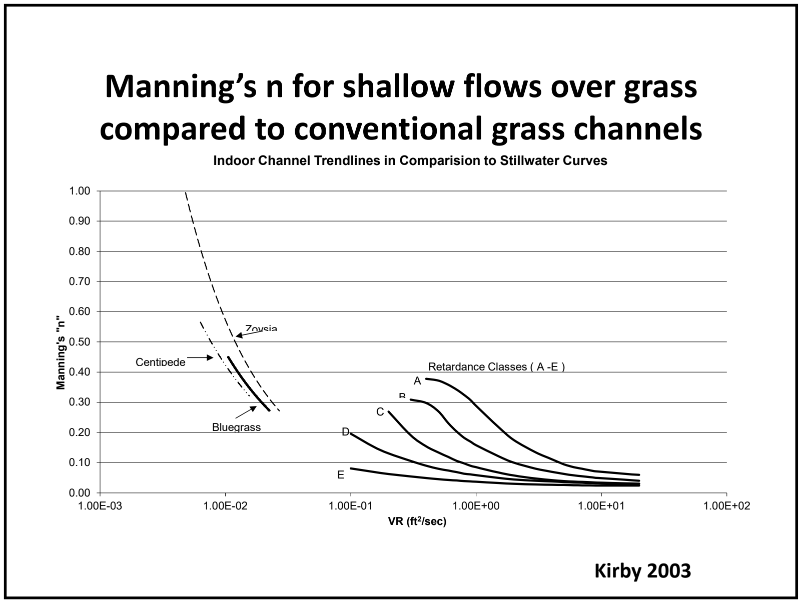


Particulate Removal in Shallow Flowing Grass Swales and in Grass Filters



Date: 10/11/2004

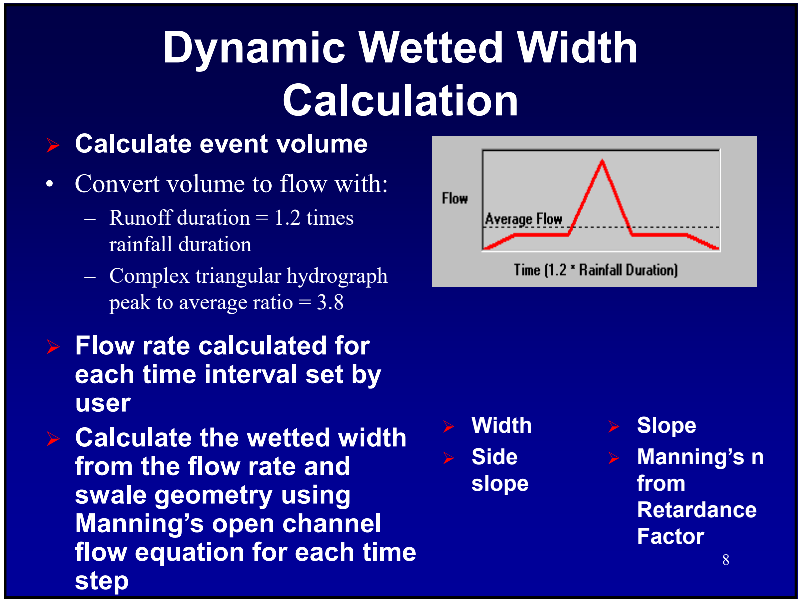
University of Alabama swale/filter test site at Tuscaloosa City Hall



Manning's n for shallow flows over grass compared to conventional grass channels

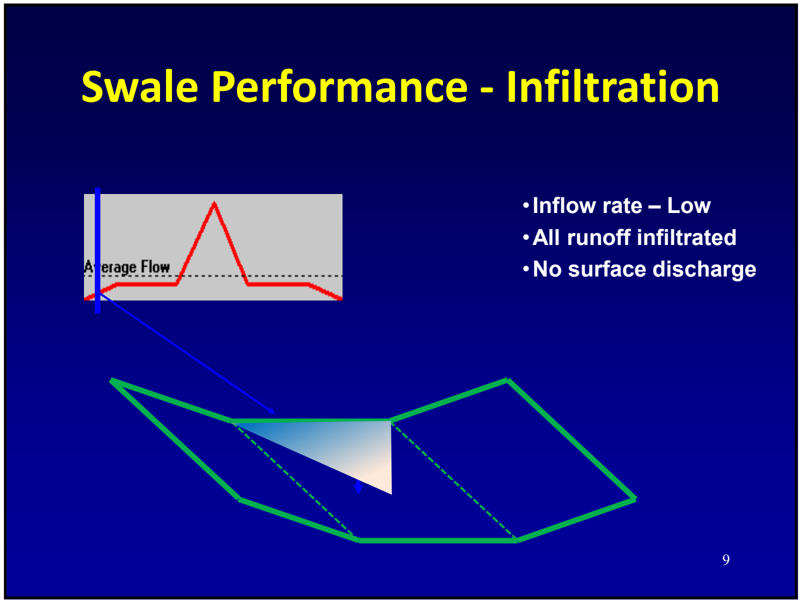
Indoor Channel Trendlines in Comparision to Stillwater Curves

Kirby 2003



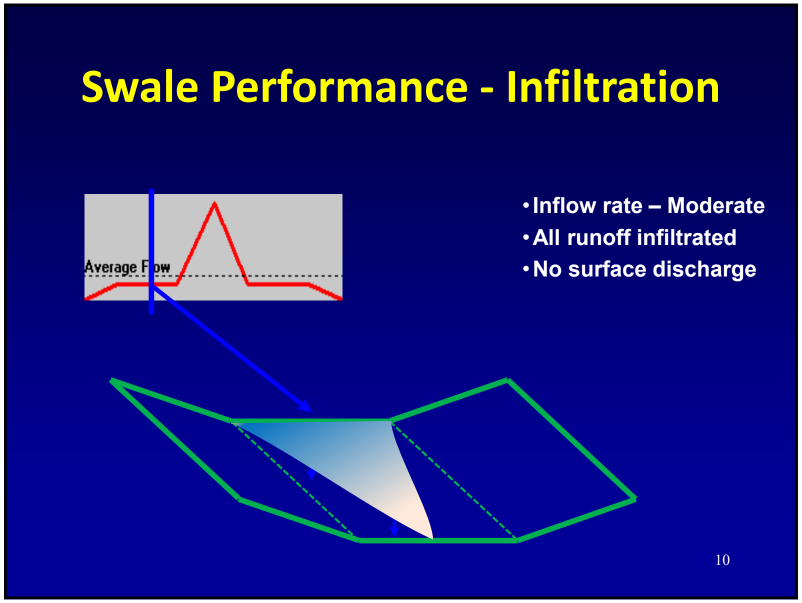
Dynamic Wetted Width Calculation

- Calculate event volume
- Convert volume to flow with:
  - Runoff duration = 1.2 times rainfall duration
  - Complex triangular hydrograph peak to average ratio = 3.8
- Flow rate calculated for each time interval set by user
- Calculate the wetted width from the flow rate and swale geometry using Manning's open channel flow equation for each time step
  - Width
  - Side slope
  - Slope
  - Manning's n from Retardance Factor



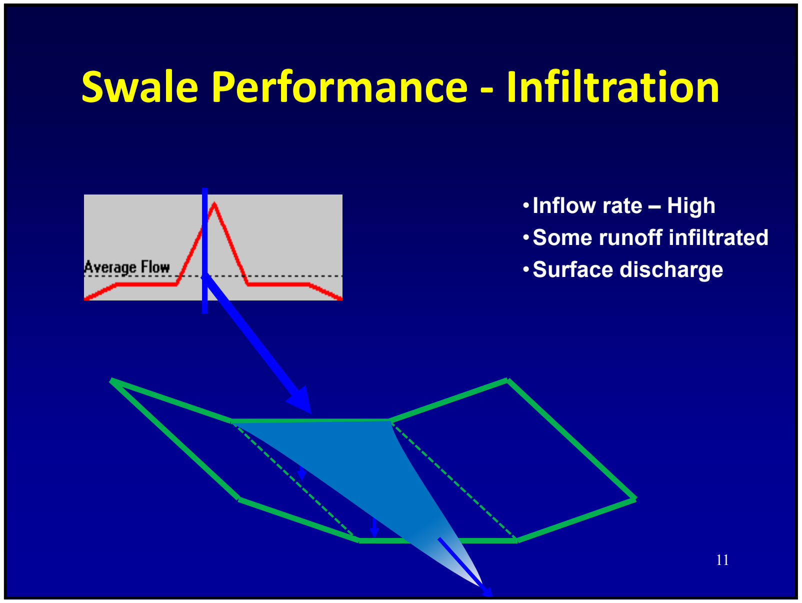
Swale Performance - Infiltration

- Inflow rate – Low
- All runoff infiltrated
- No surface discharge



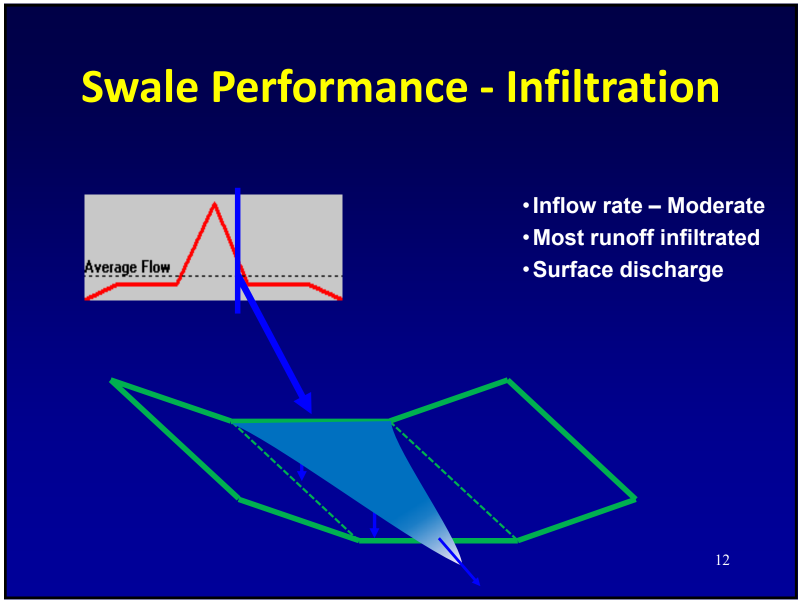
Swale Performance - Infiltration

- Inflow rate – Moderate
- All runoff infiltrated
- No surface discharge



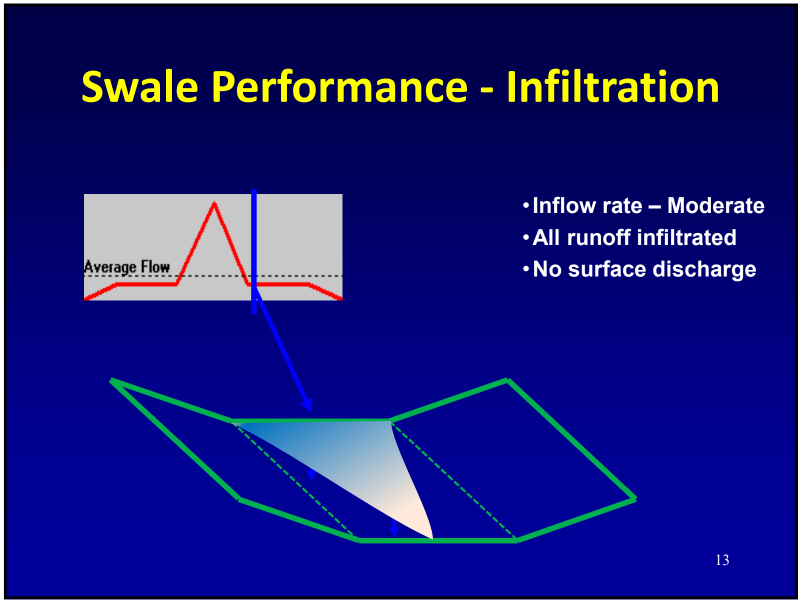
Swale Performance - Infiltration

- Inflow rate – High
- Some runoff infiltrated
- Surface discharge



Swale Performance - Infiltration

- Inflow rate – Moderate
- Most runoff infiltrated
- Surface discharge



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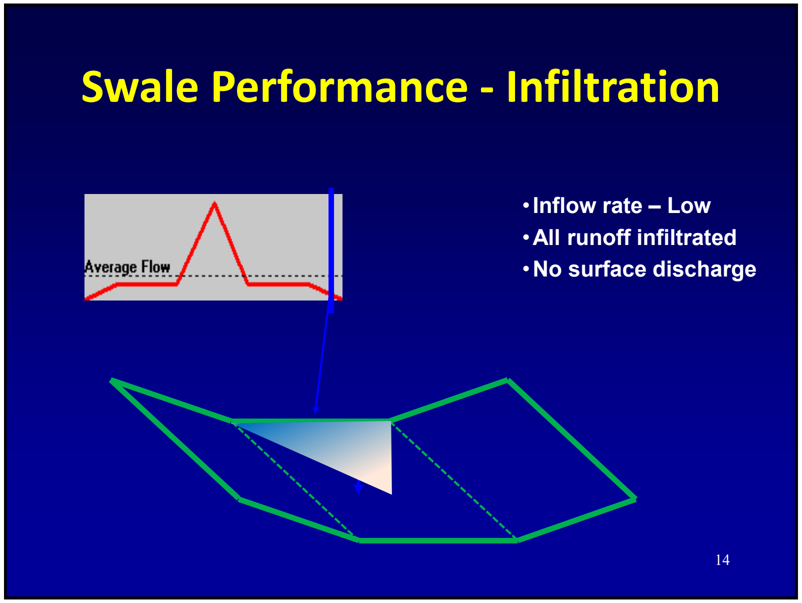

Swale Performance - Infiltration

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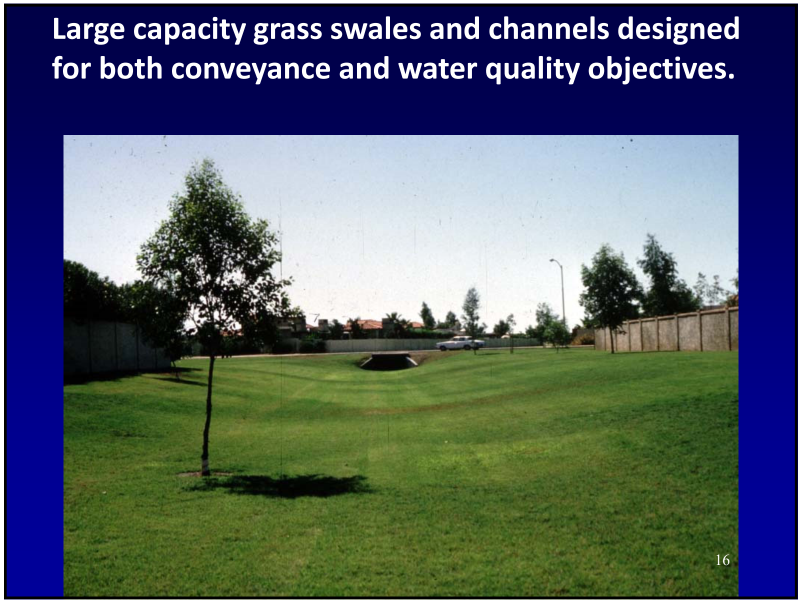
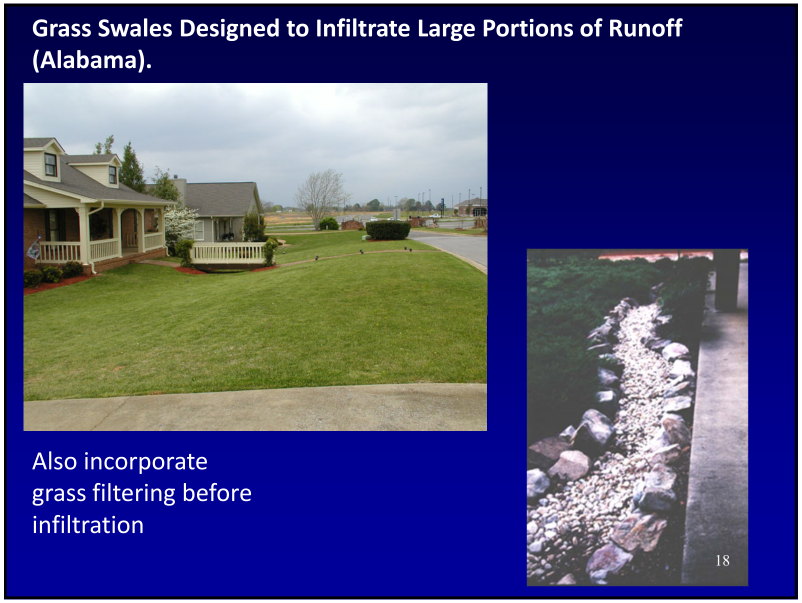
- All runoff infiltrated
- No surface discharge

Grass-Lined Swales



Large capacity grass swales and channels designed for both conveyance and water quality objectives.

Grass Filtering of Stormwater Sediment



Grass Swales Designed to Infiltrate Large Portions of Runoff (Alabama).

Also incorporate grass filtering before infiltration

Swales can be both interesting and fit site development objectives.

Elements of Conservation Design for Cedar Hills Development

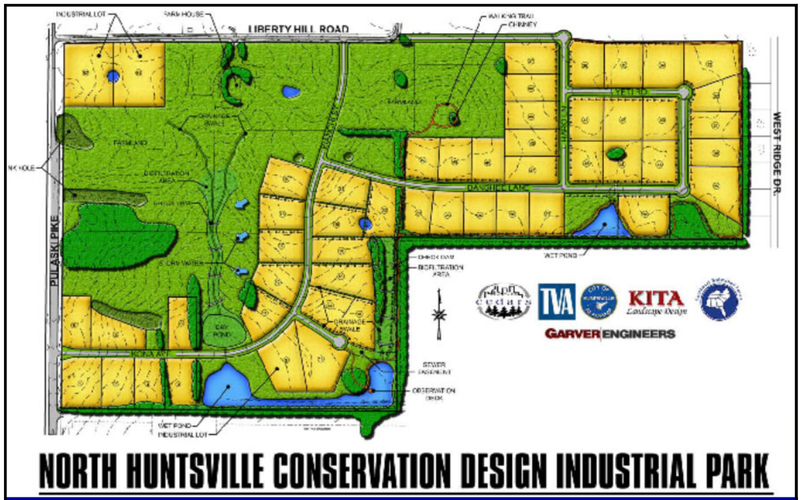
(near Madison, WI, project conducted by Roger Bannerman, WI DNR and USGS)

- Grass Swales
- Wet Detention Pond
- Infiltration Basin/Wetland
- Reduced Street Width

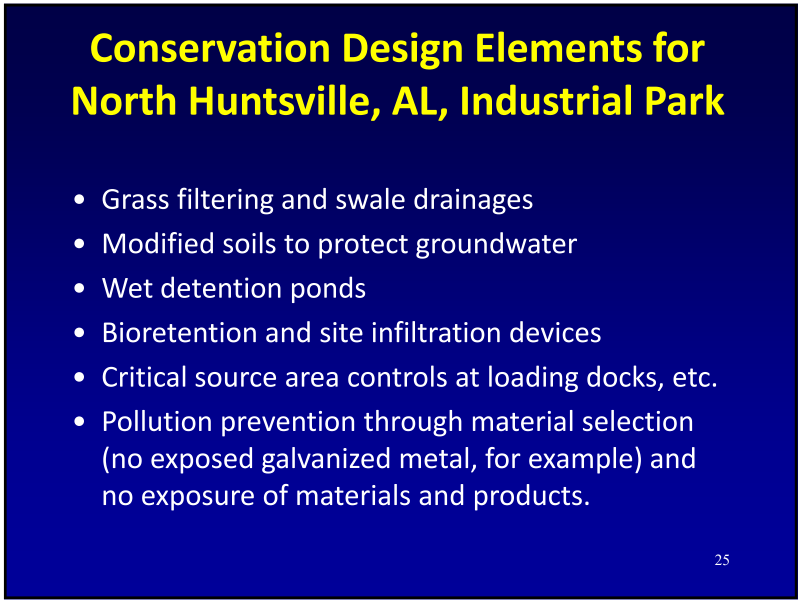
Conventional curbs with inlets directed to site swales

Reductions in Runoff Volume for Cedar Hills (calculated using WinSLAMM and verified by site monitoring)

Type of Control	Runoff Volume, inches	Expected Change (being monitored)
Pre-development	1.3	
No Controls	6.7	515% increase
Swales + Pond/wetland + Infiltration Basin	1.5	78% decrease, compared to no controls 15% increase over pre-development

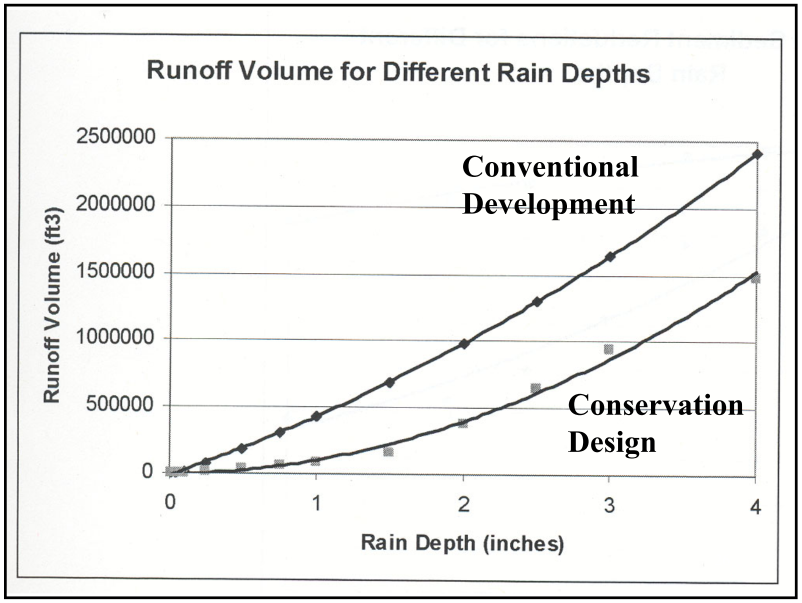


NORTH HUNTSVILLE CONSERVATION DESIGN INDUSTRIAL PARK

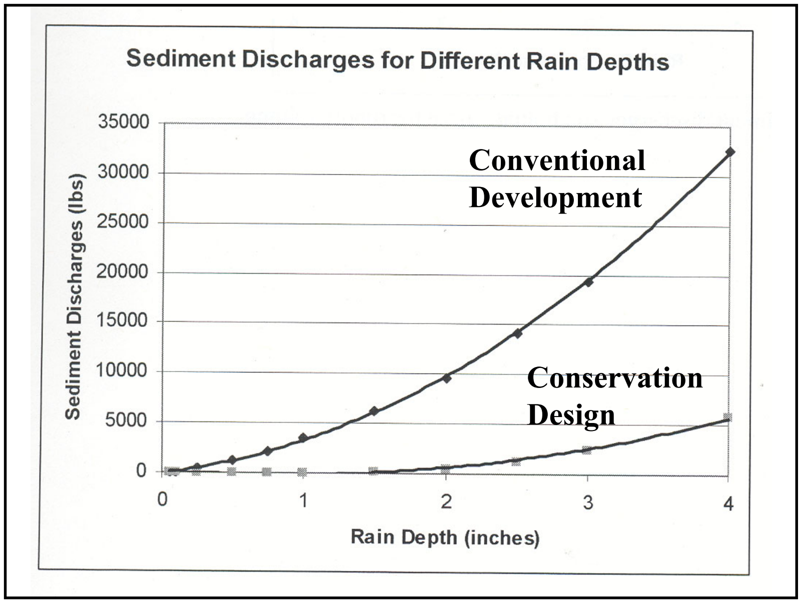


Conservation Design Elements for North Huntsville, AL, Industrial Park

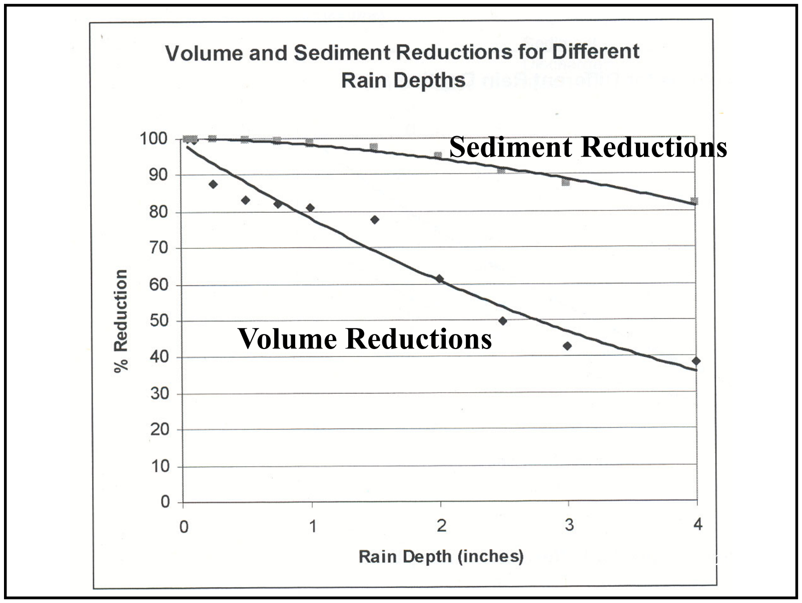
- Grass filtering and swale drainages
- Modified soils to protect groundwater
- Wet detention ponds
- Bioretention and site infiltration devices
- Critical source area controls at loading docks, etc.
- Pollution prevention through material selection (no exposed galvanized metal, for example) and no exposure of materials and products.



Runoff Volume for Different Rain Depths



Sediment Discharges for Different Rain Depths



Volume and Sediment Reductions for Different Rain Depths

University of Alabama Grass Swale Research Objectives

- To understand the effectiveness of grass swales for different sized particles
- To understand the associated effects of different variables
- To develop a predictive model of sediment transport in grass swales

- Initial indoor grass swale experiment

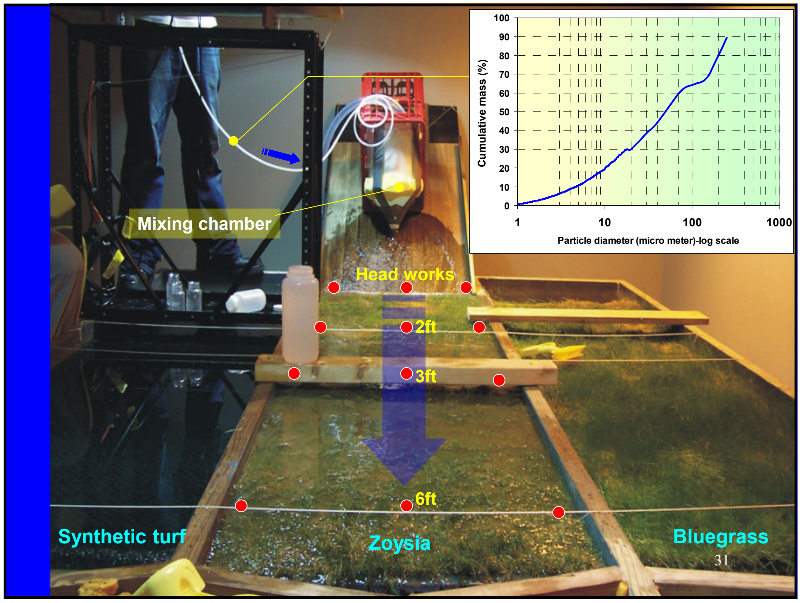
  108 samples collected

- Second indoor grass swale experiment

  108 samples collected

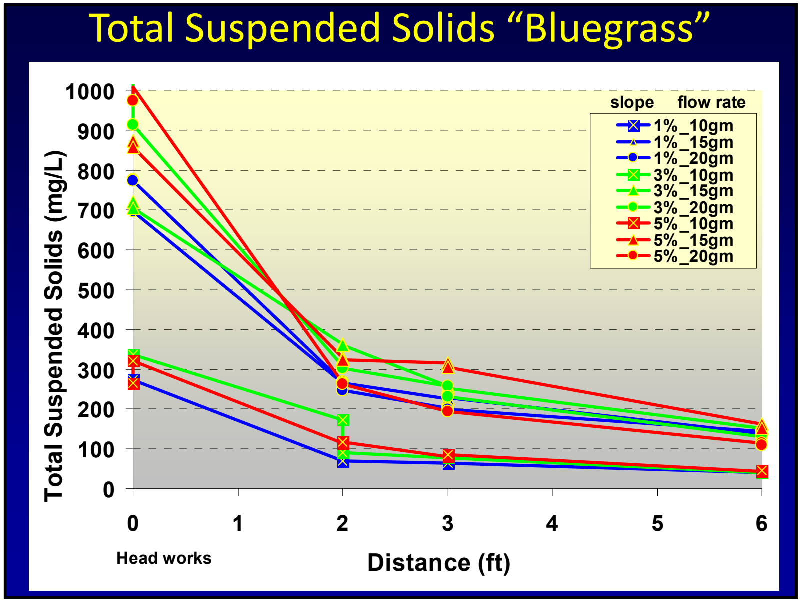
- Outdoor grass swale monitoring

  69 samples collected (13 storm events)

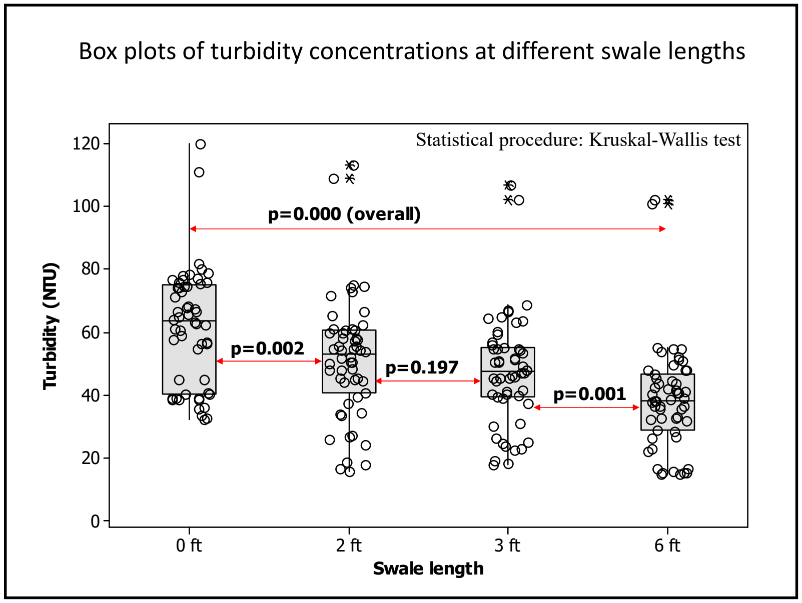


Variables and analytical methods

- **Study of variables**
  1) Grass types
  2) Slopes
  3) Flow rates
  4) Swale lengths
- **Analytical methods**
  1) Total solids
  2) Turbidity
  3) Total Suspended Solids
  4) Total Dissolved Solids
  5) Particle Size Distribution by Coulter Counter (Beckman® Multi-Sizer III)

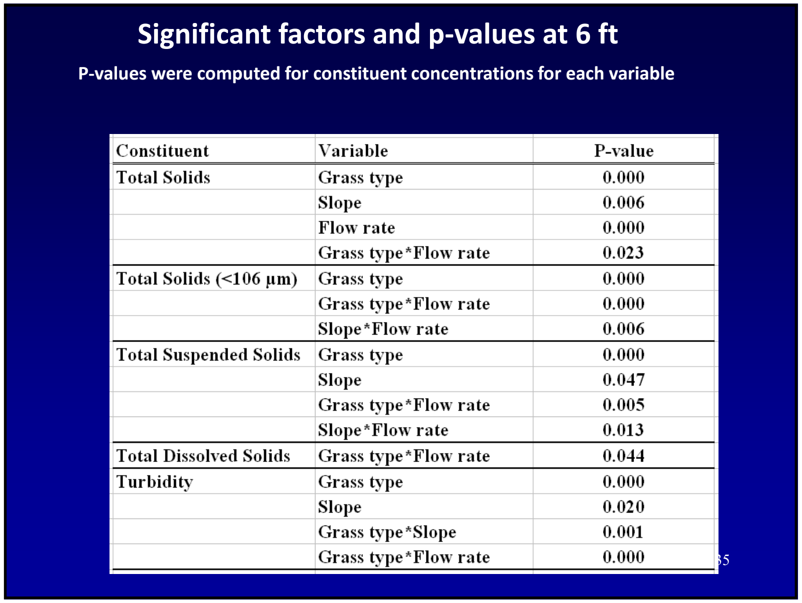


Total Suspended Solids “Bluegrass”



Box plots of turbidity concentrations at different swale lengths

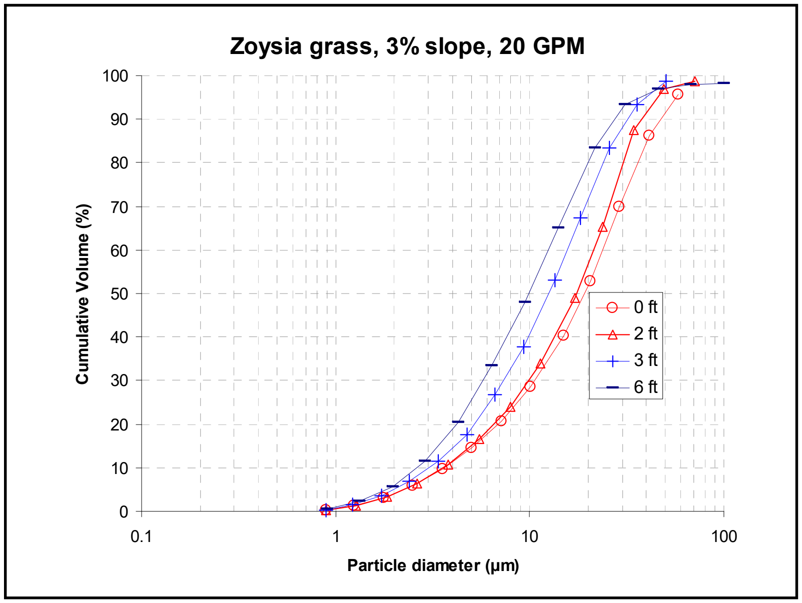
Statistical procedure: Kruskal-Wallis test



Significant factors and p-values at 6 ft

P-values were computed for constituent concentrations for each variable

Constituent	Variable	P-value
Total Solids	Grass type	0.000
	Slope	0.006
	Flow rate	0.000
	Grass type*Flow rate	0.023
Total Solids (<106 µm)	Grass type	0.000
	Grass type*Flow rate	0.000
	Slope*Flow rate	0.006
Total Suspended Solids	Grass type	0.000
	Slope	0.047
	Grass type*Flow rate	0.005
	Slope*Flow rate	0.013
Total Dissolved Solids	Grass type*Flow rate	0.044
Turbidity	Grass type	0.000
	Slope	0.020
	Grass type*Slope	0.001
	Grass type*Flow rate	0.000



Zoysia grass, 3% slope, 20 GPM

Modeling sediment transport

Concepts:

1) First order decay (for sensitivity analyses)

$$Ln(C_{out} / C_{in}) = -kt$$

C_{out} = Sediment concentration at sampling locations
C_{in} = Initial sediment concentration at the headwork
k = First order kinetic constant
t = Distance from the headwork

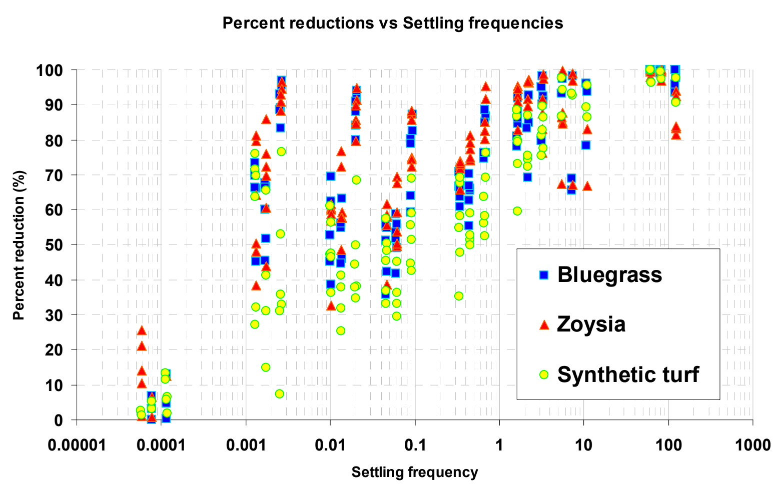
2) "Settling frequency" (for design)

= traveling time / settling duration

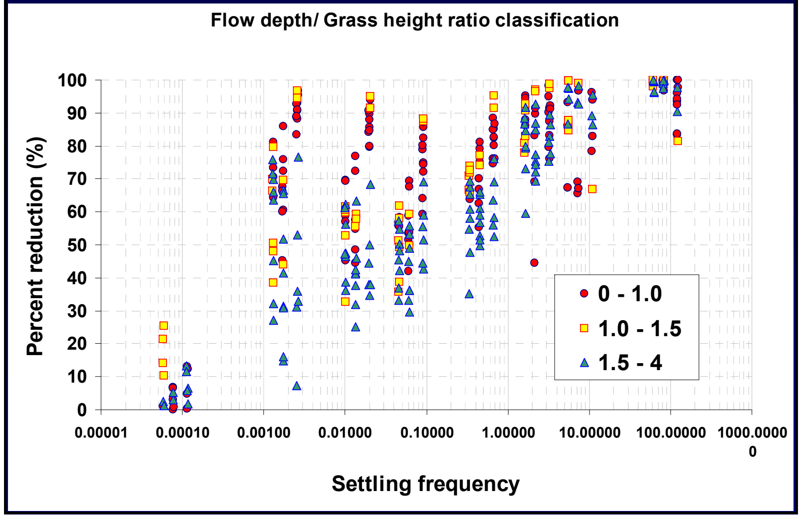
Traveling time = Swale length / flow velocity

Settling duration = flow depth / settling velocity (Stoke's Law)

Different grass types



Different flow depth/grass height ratios

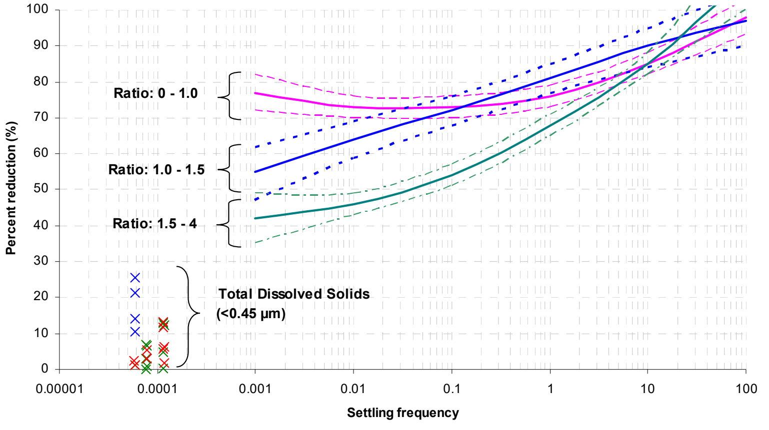


Modeling Equations

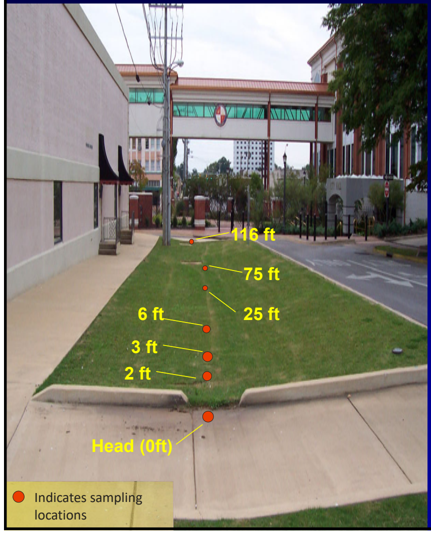
Ratio: 0 - 1.0 $Y = 2.101*[\log(X)]^2 + 6.498*\log(X) + 76.82$

Ratio: 1.0 – 1.5 $Y = 8.692*\log(X) + 80.94$

Ratio: 1.5 – 4.0 $Y = 2.382*[\log(X)]^2 + 15.47*\log(X) + 67.46$



Outdoor Grass Swale Observations



Description of the testing site

Length of swale: 116 ft

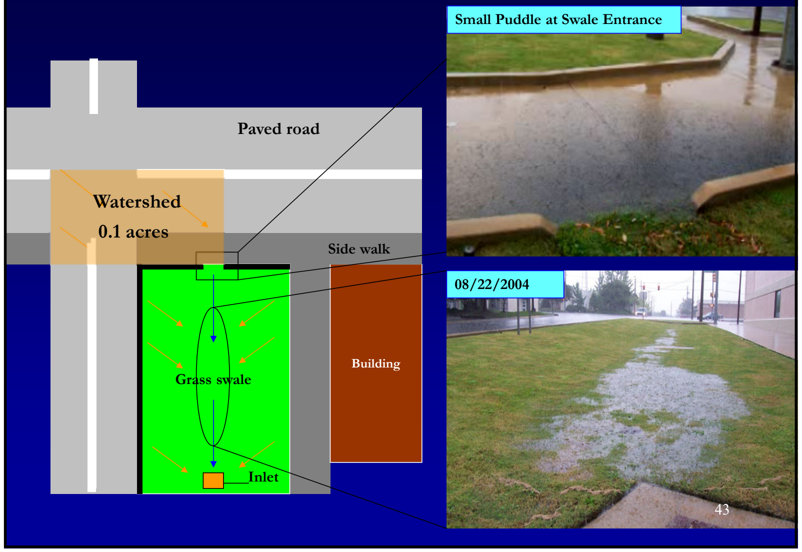
Type of grass: Zoysia

Approx. watershed area:
4200 ft^2 = 0.1 acres

Events: 13 storm events
from 8/22 to 12/08/04

Soil texture: compacted
loamy sand

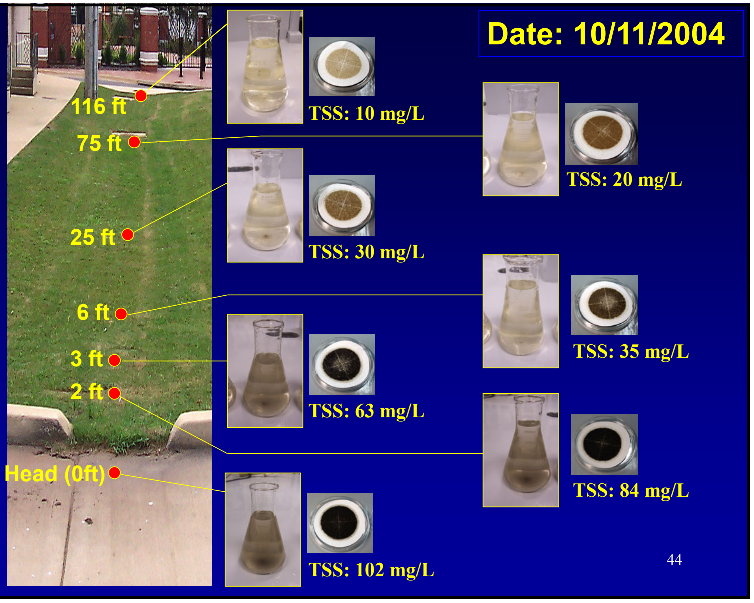
Infiltration rate: < 1 (in/hr)

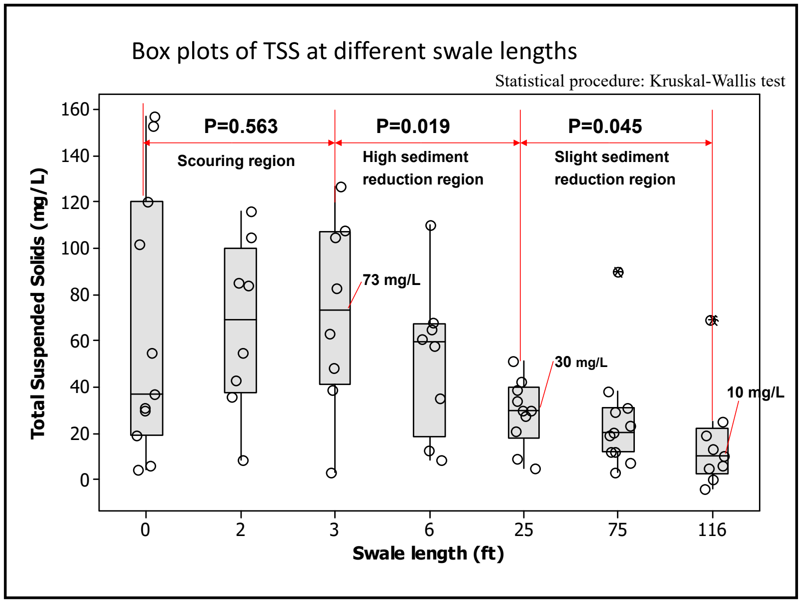


Small Puddle at Swale Entrance

08/22/2004

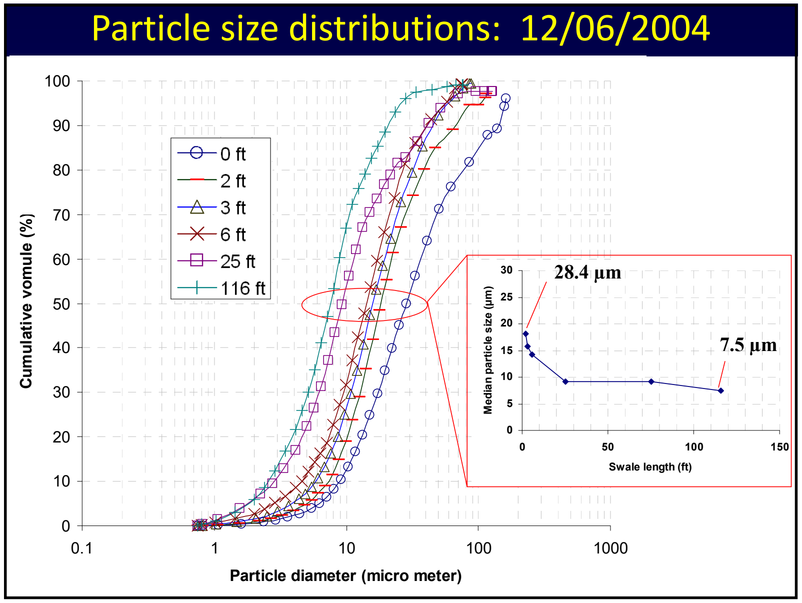
Date: 10/11/2004



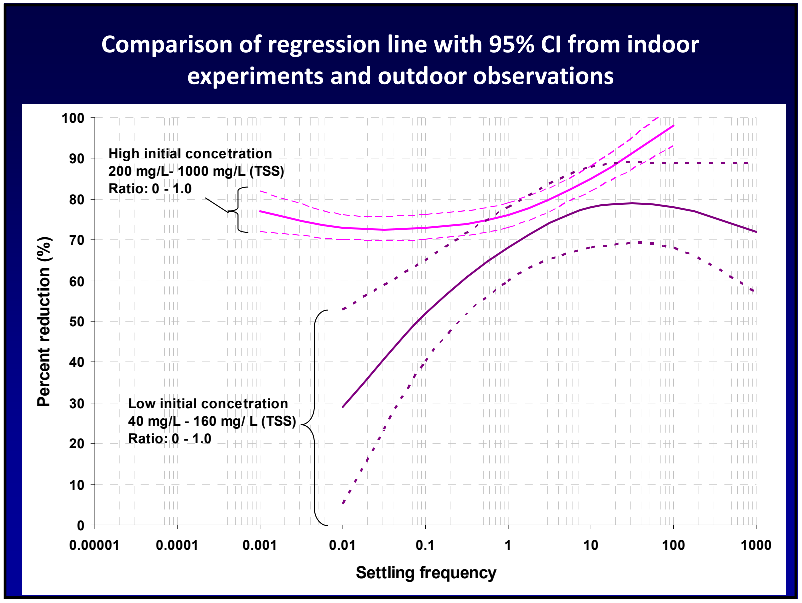


Box plots of TSS at different swale lengths

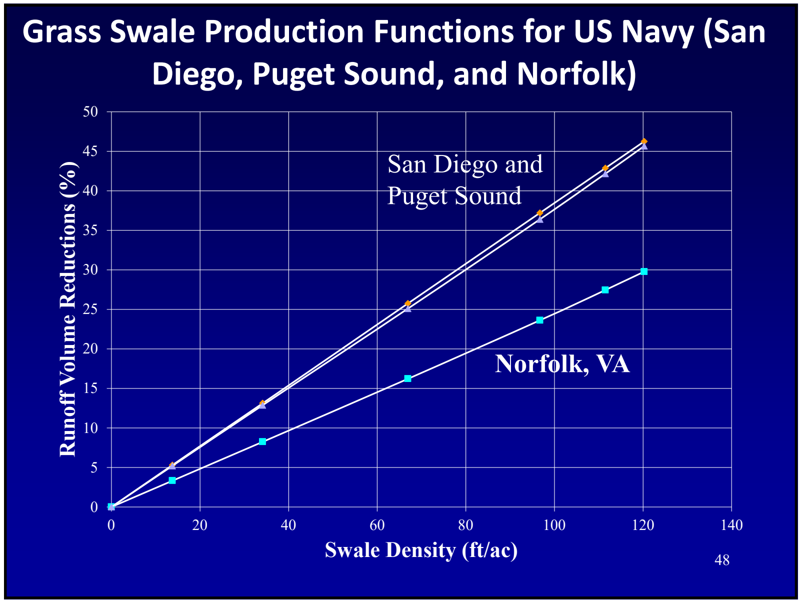
Statistical procedure: Kruskal-Wallis test



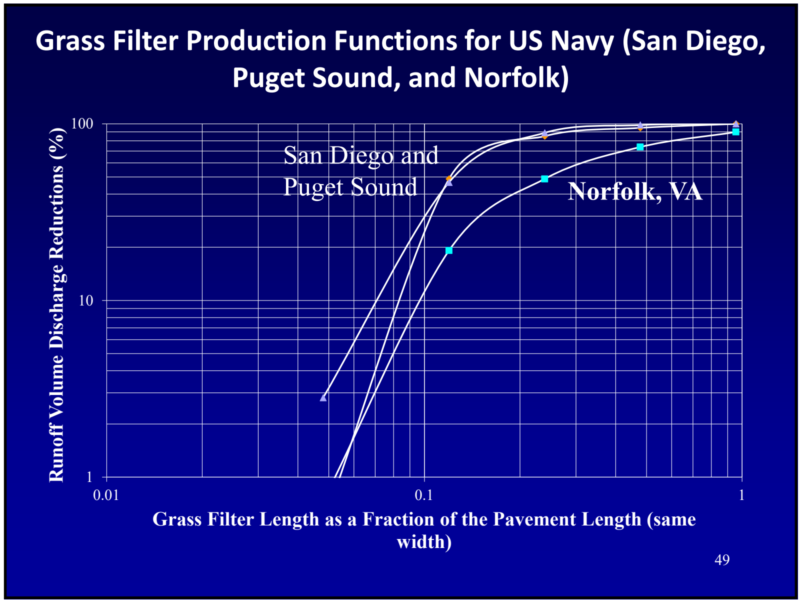
Particle size distributions: 12/06/2004



Comparison of regression line with 95% CI from indoor experiments and outdoor observations



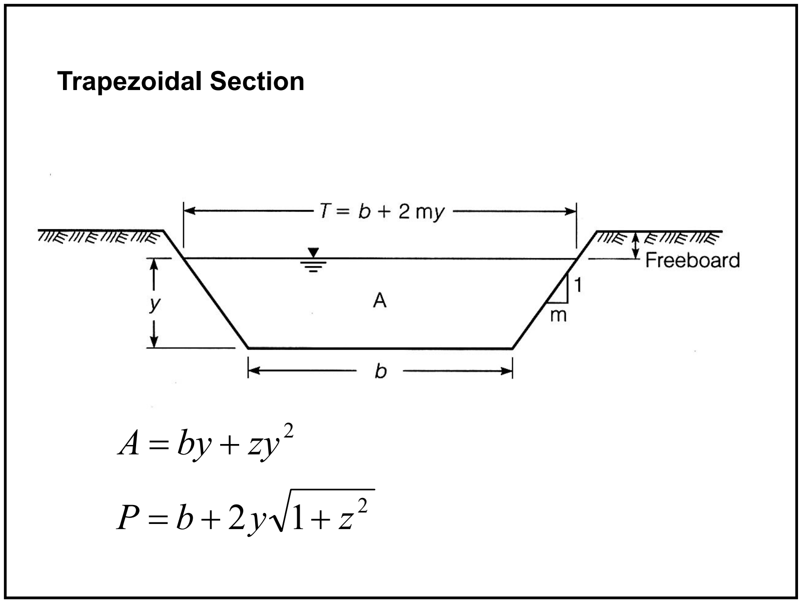
Grass Swale Production Functions for US Navy (San Diego, Puget Sound, and Norfolk)



Grass Filter Production Functions for US Navy (San Diego, Puget Sound, and Norfolk)

Design of Stable Open Channels

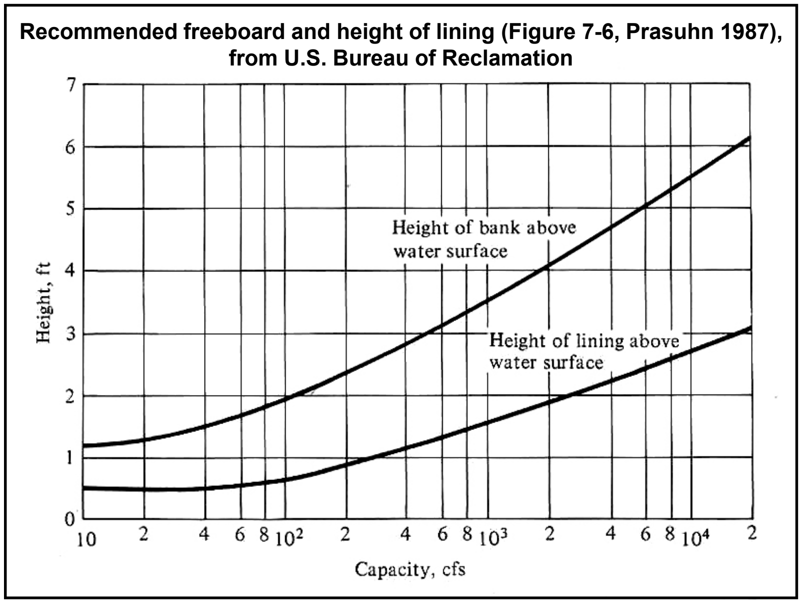
- Adequate conveyance capacity
- Stable channel
- Provide aquatic life habitat
- These objectives must be met considering future conditions, reasonable cost, minimal land consumption, and safety.



Trapezoidal Section

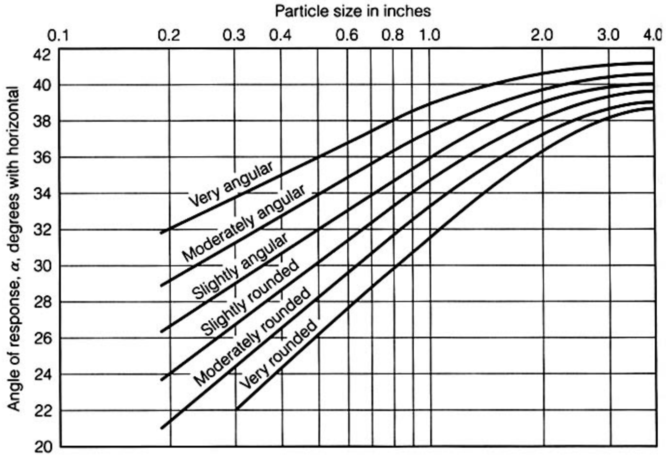
$$A = by + zy^2$$

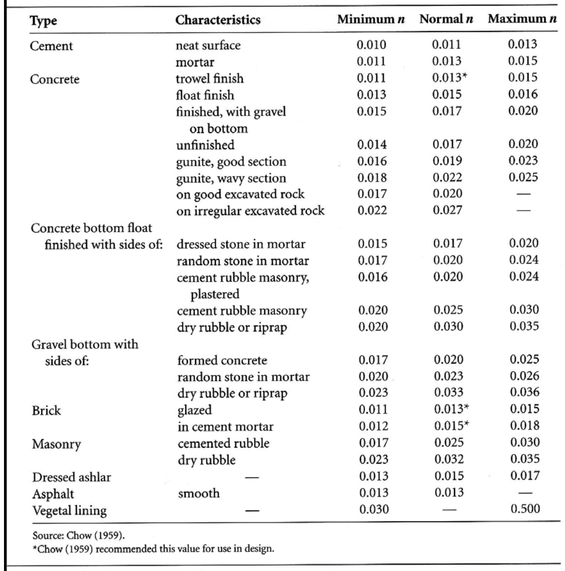
$$P = b + 2y\sqrt{1+z^2}$$



Recommended freeboard and height of lining (Figure 7-6, Prasuhn 1987), from U.S. Bureau of Reclamation

Angles of Repose of Noncohesive Material (Chin 2000)





Type	Characteristics	Minimum *n*	Normal *n*	Maximum *n*
Cement	neat surface	0.010	0.011	0.013
	mortar	0.011	0.013	0.015
Concrete	trowel finish	0.011	0.013*	0.015
	float finish	0.013	0.015	0.016
	finished, with gravel on bottom	0.015	0.017	0.020
	unfinished	0.014	0.017	0.020
	gunite, good section	0.016	0.019	0.023
	gunite, wavy section	0.018	0.022	0.025
	on good excavated rock	0.017	0.020	—
	on irregular excavated rock	0.022	0.027	—
Concrete bottom float finished with sides of:	dressed stone in mortar	0.015	0.017	0.020
	random stone in mortar	0.017	0.020	0.024
	cement rubble masonry, plastered	0.016	0.020	0.024
	cement rubble masonry	0.020	0.025	0.030
	dry rubble or riprap	0.020	0.030	0.035
Gravel bottom with sides of:	formed concrete	0.017	0.020	0.025
	random stone in mortar	0.020	0.023	0.026
	dry rubble or riprap	0.023	0.033	0.036
Brick	glazed	0.011	0.013*	0.015
	in cement mortar	0.012	0.015*	0.018
Masonry	cemented rubble	0.017	0.025	0.030
	dry rubble	0.023	0.032	0.035
Dressed ashlar	—	0.013	0.015	0.017
Asphalt	smooth	0.013	0.013	—
Vegetal lining	—	0.030	—	0.500

Source: Chow (1959).
*Chow (1959) recommended this value for use in design.

Roughness Coefficients in Lined Open Channels (Table 4.14, Chin 2000)

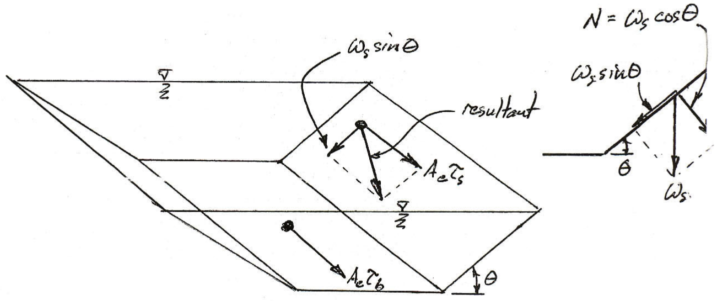
Maximum Permissible Velocity

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

Minimum velocity should be 2 to 3 ft/sec.
Also check Froude number (≤ 0.8, to ensure subcritical flow)

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

Method of Tractive Force



ω_s = submerged weight of particle
A_e = effective area of particle
τ_b = shear stress on channel bottom
τ_s = shear stress on channel side

Rocky Durrans

Average Shear Stress on Channel Boundary (the Tractive Force):

$$\tau_o = \gamma RS$$

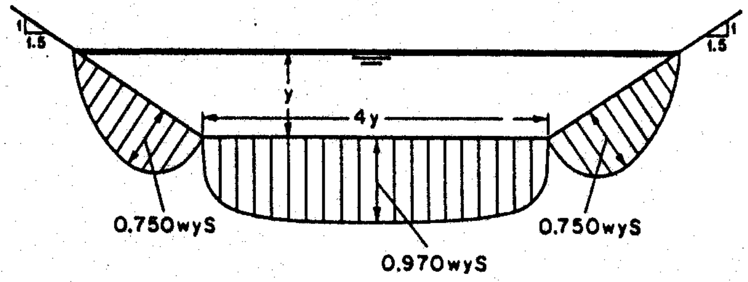
US customary units of lb/ft^2
where:
γ = specific weight of water (62.4 lbs/ft^3)
R = hydraulic radius (ft)
S_o = hydraulic slope (ft/ft) for uniform flow; this is substituted with S_f for non-uniform flow conditions

If the channel is very wide (B>>y), such as for sheetflow conditions, the hydraulic radius (R) is substituted by the flow depth:

$$\tau_o = \gamma y S_f$$

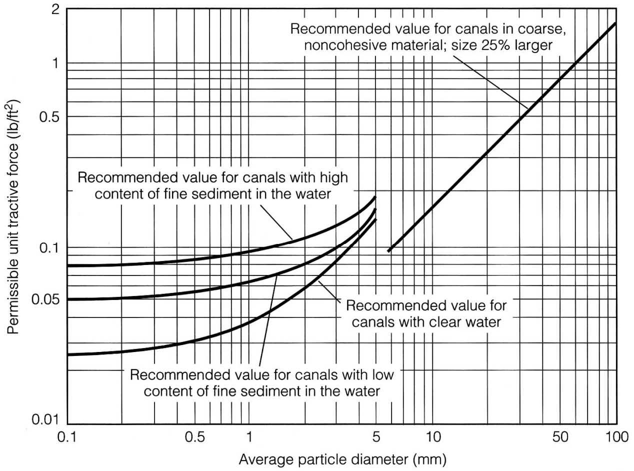
Research by the USBR has shown that the distribution of the shear stress is not uniform and that the maximum values of shear stress on the channel bottoms and side slopes are approximately:

$$\tau_b = \gamma y S_f \qquad \tau_s = 0.76\gamma y S_f$$

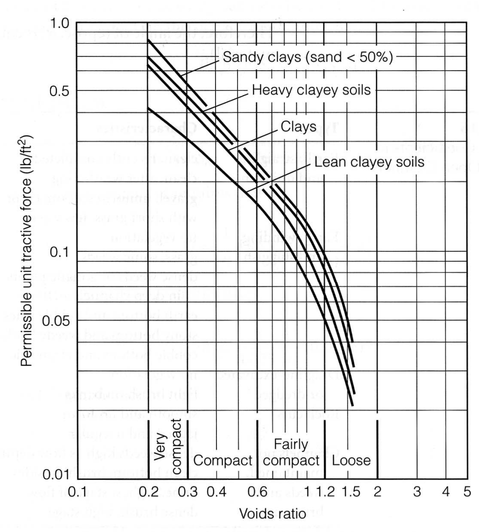


At "incipient motion," the forces causing a particle to move are just equal to those resisting motion.

Permissible Unit Tractive Force for Channels in Noncohesive Material (Figure 4.32a, Chin 2000)



(a) Non-Cohesive Material



(b) Cohesive Material

Permissible Unit Tractive Force in Channels in Cohesive Material (Figure 4.32b, Chin 2000)

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).

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

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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 wetted 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.

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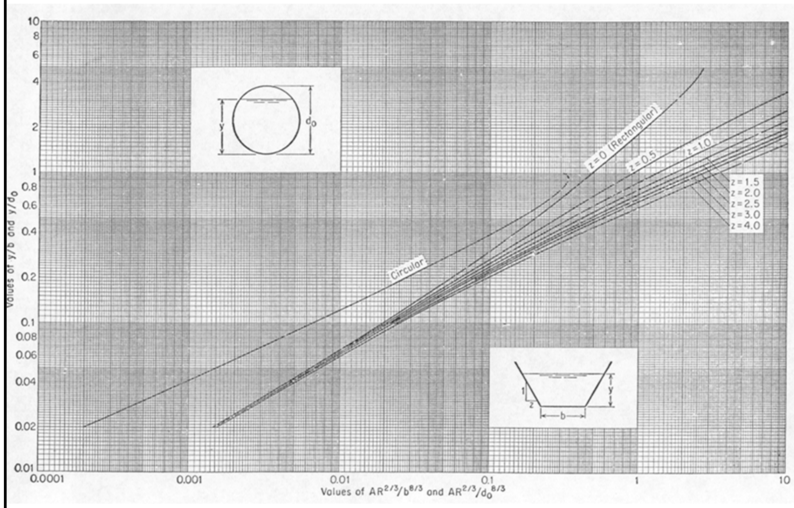
5) Calculate an appropriate channel base width (b) and depth (y) corresponding to a specific channel geometry (usually a trapezoid channel, having a side slope of z:1 side slopes).

Chow's figure (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:

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

Initial channel characteristics that must be know include: z (the side slope), and b (the channel bottom width, assuming a trapezoid). It is easy to examine several different channel options (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.



Chow 1959

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)

The previously calculated peak discharge (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. There are many channel options than can meet this objective. The calculated maximum shear stress is:

γyS= (62.4 lb/ft^3) (y ft) 0.01 ft/ft) = 0.62d

since the allowable shear stress is 0.15 lb/ft^2, the normal depth must be less than 0.24 ft (only about 3 inches). This will require a relatively wide channel.

Different flexible "solutions" to provide bank stability

General Design Procedure for Grass-Lined Channels

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 consideration in the design process.

Design using Vegetated Channel Liner Mats

Current practice is to design channel linings based on shear stress and not 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.

Turf reinforcement mats (TRM) design 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. It is also important to base the matting failure on soil loss (usually 0.5 inch of soil; greater amounts greatly hinder plant establishment) instead of physical failure of the matting material. The basic shear stress equation can be modified to predict the shear stress applied to the soil beneath a channel mat.

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

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

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

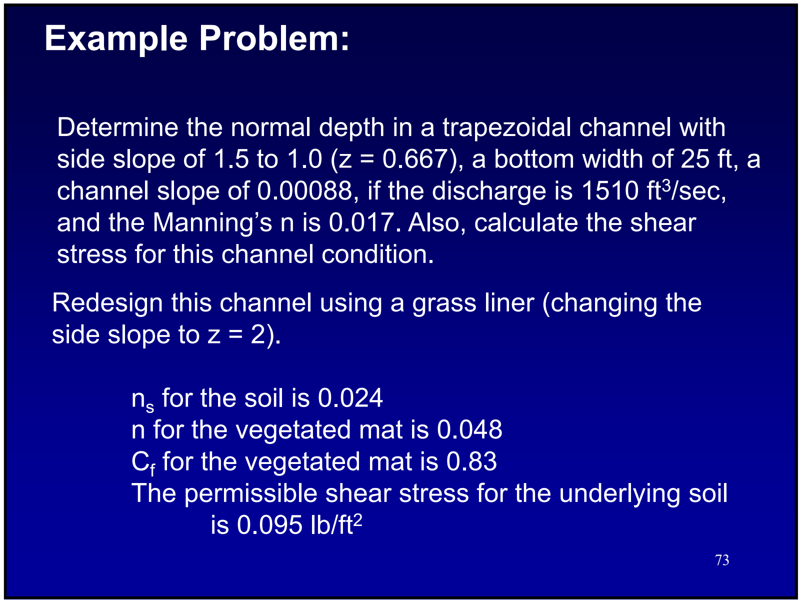
$\tau_o = \gamma DS$ = 2.83 lb/ft^2 (previously calculated), requiring a NAG P300 permanent mat, for example

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 therefore expected to be stable.

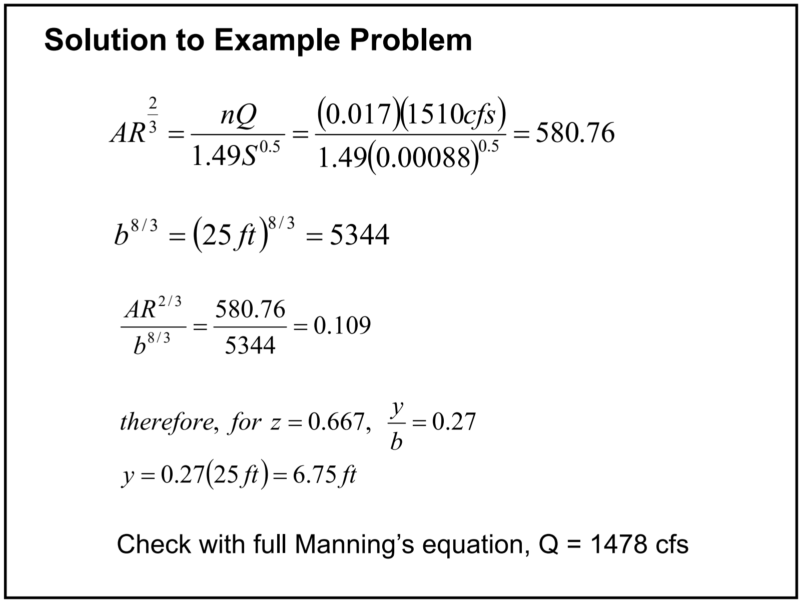


Example Problem:

Determine the normal depth in a trapezoidal channel with side slope of 1.5 to 1.0 (z = 0.667), a bottom width of 25 ft, a channel slope of 0.00088, if the discharge is 1510 ft^3/sec, and the Manning's n is 0.017. Also, calculate the shear stress for this channel condition.

Redesign this channel using a grass liner (changing the side slope to z = 2).

n_s for the soil is 0.024
n for the vegetated mat is 0.048
C_f for the vegetated mat is 0.83
The permissible shear stress for the underlying soil is 0.095 lb/ft^2



Solution to Example Problem

$$AR^{\frac{2}{3}} = \frac{nQ}{1.49S^{0.5}} = \frac{(0.017)(1510cfs)}{1.49(0.00088)^{0.5}} = 580.76$$

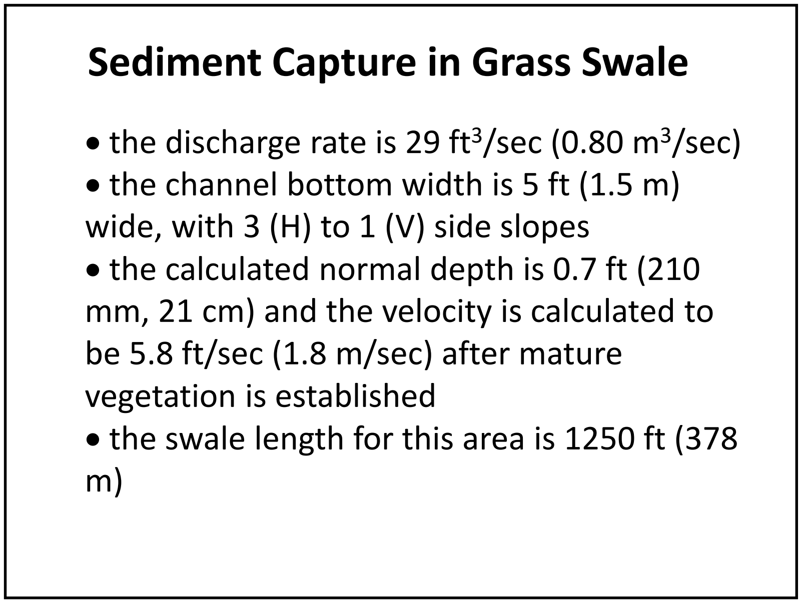
$$b^{8/3} = (25\,ft)^{8/3} = 5344$$

$$\frac{AR^{2/3}}{b^{8/3}} = \frac{580.76}{5344} = 0.109$$

$$therefore,\ for\ z = 0.667,\ \frac{y}{b} = 0.27$$

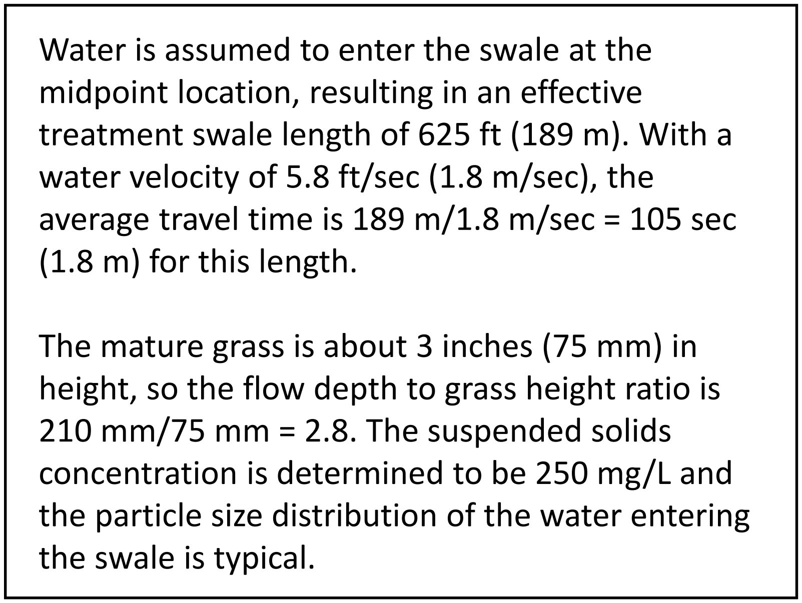
$$y = 0.27(25\,ft) = 6.75\,ft$$

Check with full Manning's equation, Q = 1478 cfs



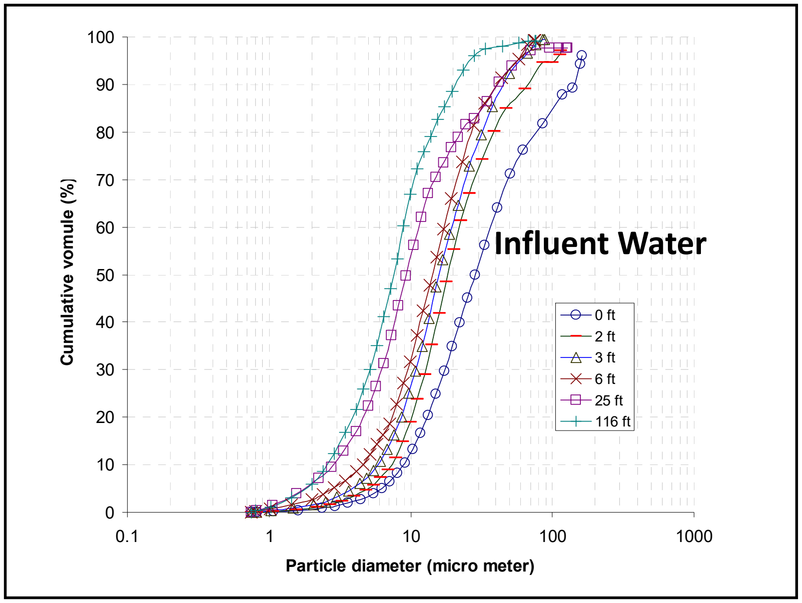
Sediment Capture in Grass Swale

- 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)

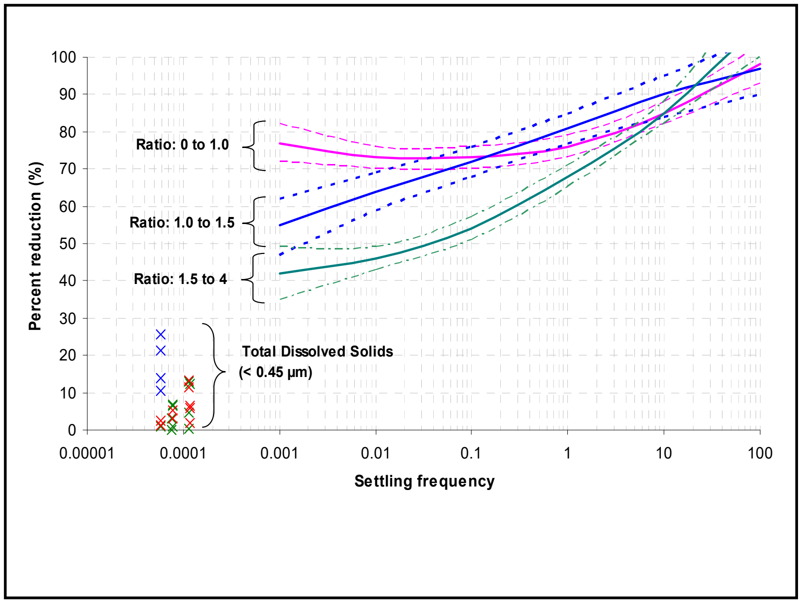


Water is assumed to enter the swale at the midpoint location, resulting in an effective treatment swale length of 625 ft (189 m). With a water velocity of 5.8 ft/sec (1.8 m/sec), the average travel time is 189 m/1.8 m/sec = 105 sec (1.8 m) for this length.

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.



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



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 in Size Range
0.45 to 2 µm	1.52×10^{-4}	138,000	0.00076	42
2 to 5 µm	1.10×10^{-3}	19,000	0.0055	44
5 to 10 µm	5.05×10^{-3}	4,160	0.025	48
10 to 30 µm	3.59×10^{-2}	585	0.18	57
30 to 60 µm	0.182	115	0.91	68
60 to 106 µm	0.619	33.9	3.1	74
106 to 425 µm	6.22	3.38	31	96

Particle Size Range (µm)	Influent Particulate Conc. in Size Range	Irreducible Conc. for Size Range (mg/L)	Particulate Conc. for Size Range after Treatment (mg/L)	Final Resultant Conc. for Size Range (mg/L)
0.45 to 2	1.3	7	0.8	1.3*
2 to 5	6.8	5	3.8	5**
5 to 10	23.0	5	12.0	12.0
10 to 30	101.0	10	43.4	43.4
30 to 60	54.4	5	17.4	17.4
60 to 106	26.5	5	6.9	6.9
106 to 425	37.0	10	1.5	10**

*** 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.**

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

An overall 62% reduction in suspended solids concentration was achieved.

Conclusions

- Grass swales are relatively robust stormwater controls
- In most low and medium density urban areas, sufficient space is available alongside roads to provide effective grass swales
- Harder to locate in high density urban areas
- Traditional design approaches can be used in conjunction with additional features to support water quality and infiltration objectives.