Module 4c: Grass Swale Performance and Design

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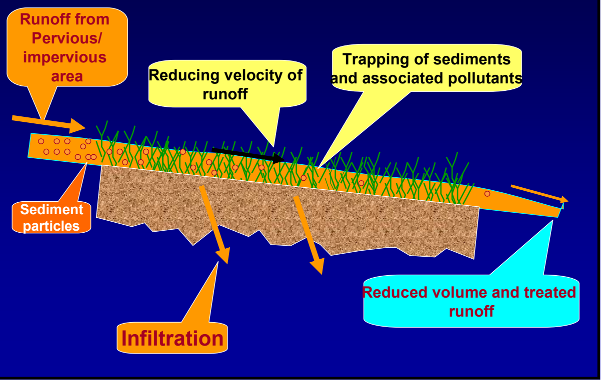
Photo by Shirley Clark

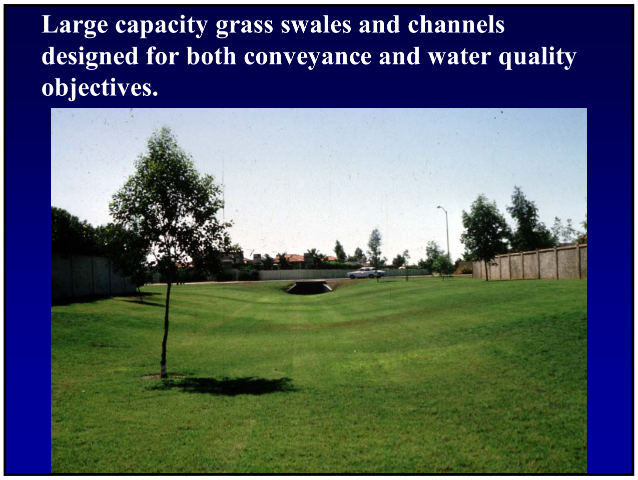
Selected Research Results

- 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.
- Current research (Nara 2005) at the Univ. of Alabama identified significant factor 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

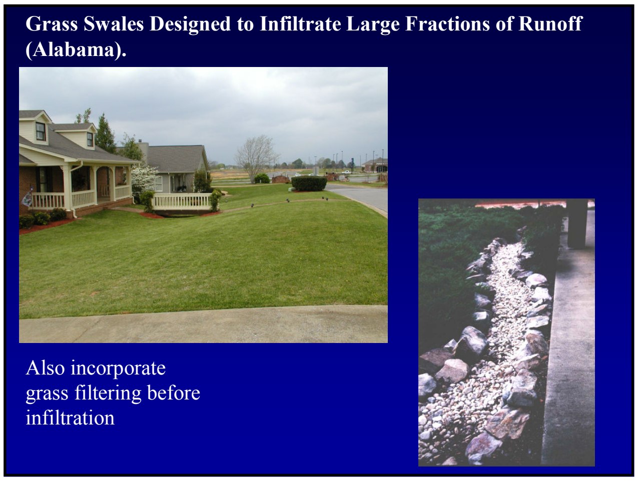


Grass-Lined Swales



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 Fractions 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

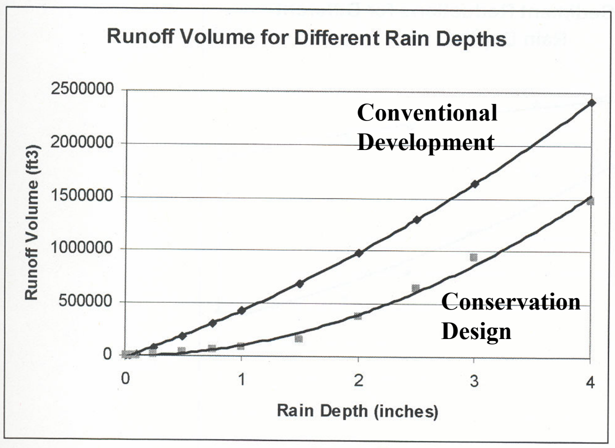
Reductions in Runoff Volume for Cedar Hills (calculated using WinSLAMM and verified by site monitoring)

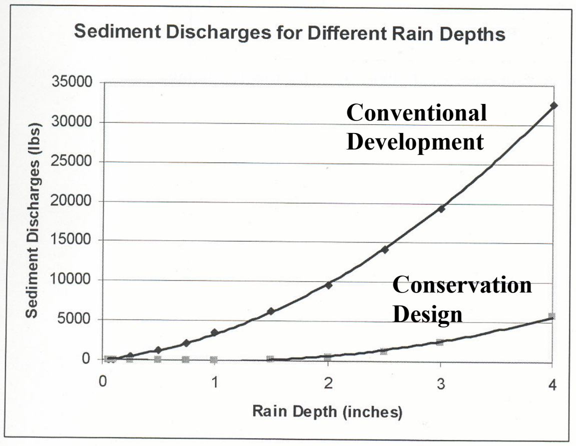
Type of Control	Runoff Volume, inches	Expected Change (being monitored)
Pre-development	1.3	
No Controls	6.7	515% increase
Swales + Pond/wetland + Infiltration Basin	1.5	78% decrease, compared to no controls 15% increase over pre-development

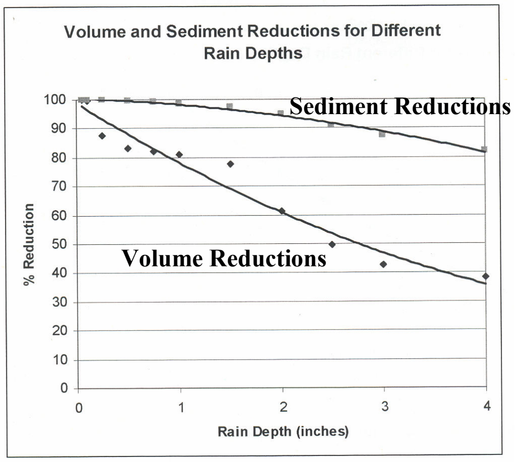
NORTH HUNTSVILLE CONSERVATION DESIGN INDUSTRIAL PARK

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.







Research Objectives

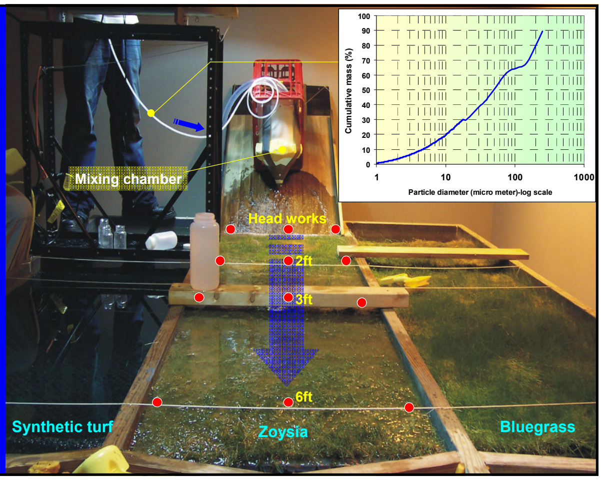
- To understand the effectiveness of grass swales for different sized particles
- To understand the associated effects of different variables
- To develop a predictive model in sediment transport in grass swales

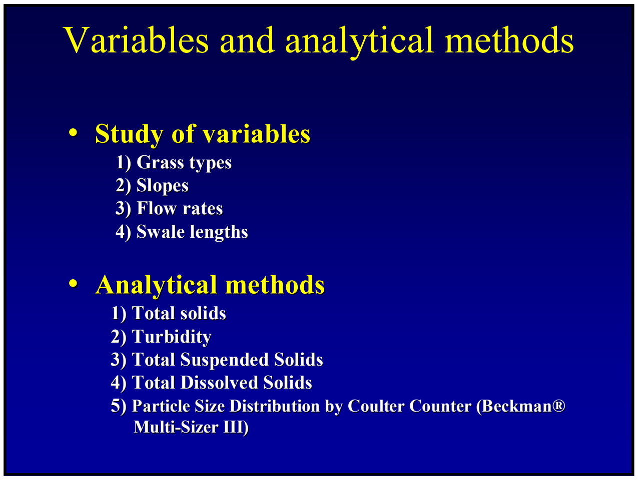
- **Initial indoor grass swale experiment**

  108 samples collected
- **Second indoor grass swale experiment**

  108 samples collected
- **Outdoor grass swale monitoring**

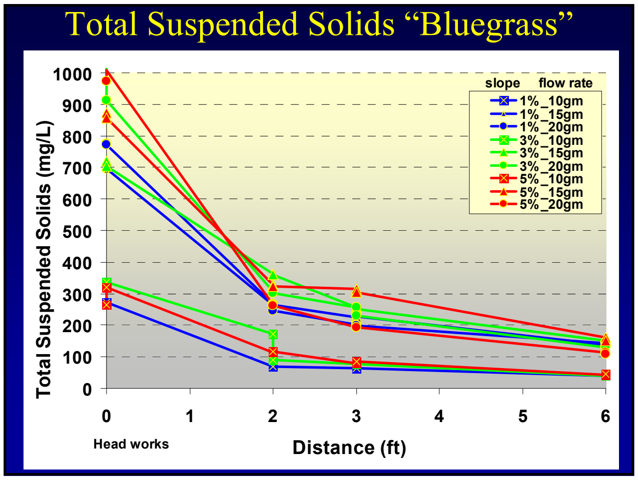
  69 samples collected (13 storm events)



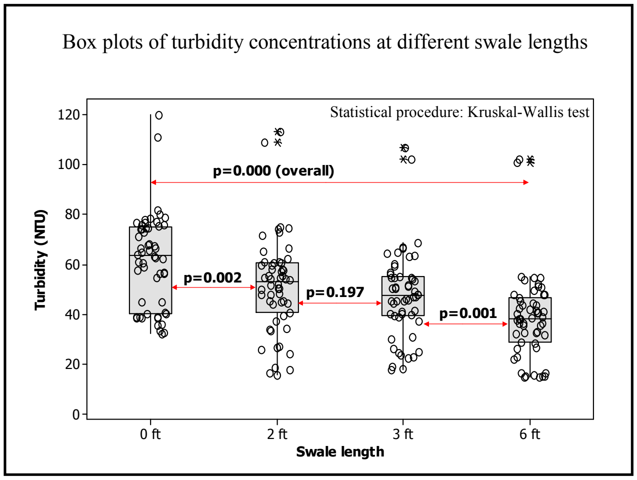


Variables and analytical methods

- **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)

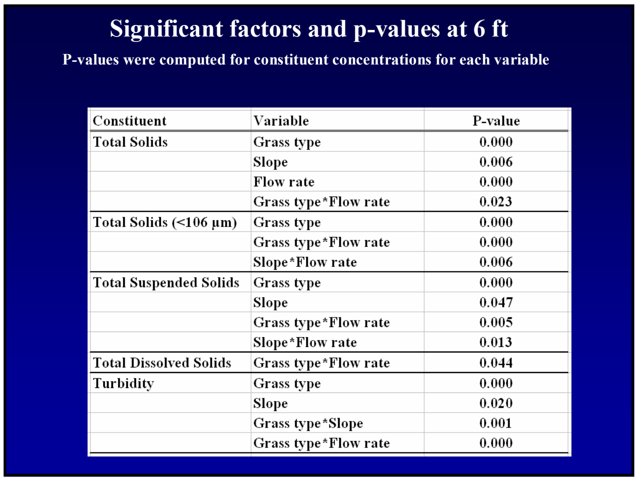


Total Suspended Solids "Bluegrass"



Box plots of turbidity concentrations at different swale lengths

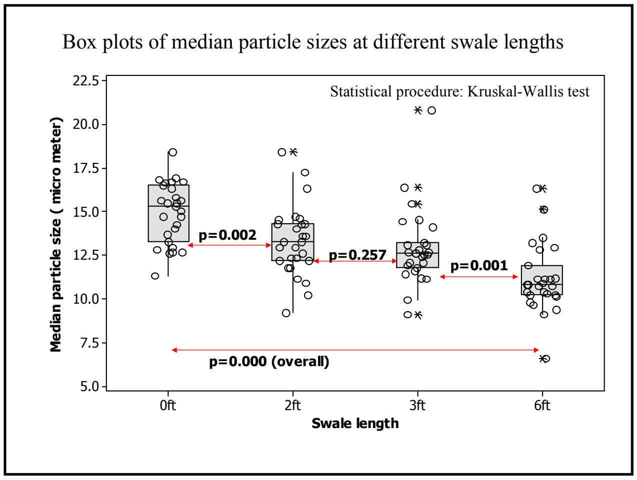
Statistical procedure: Kruskal-Wallis test

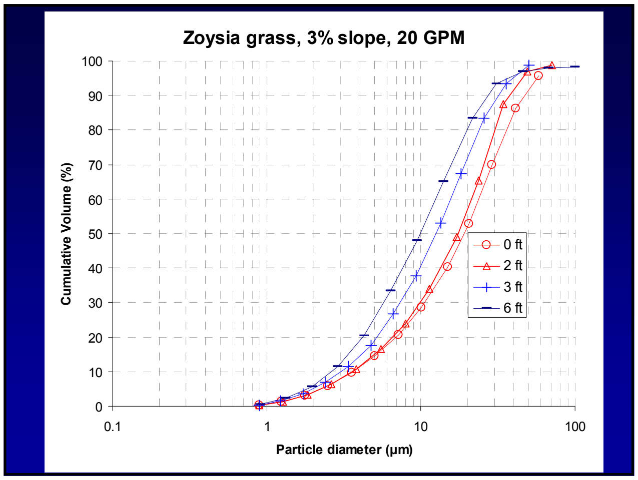


Significant factors and p-values at 6 ft

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





Modeling sediment transport

Concepts:

1) First order decay

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

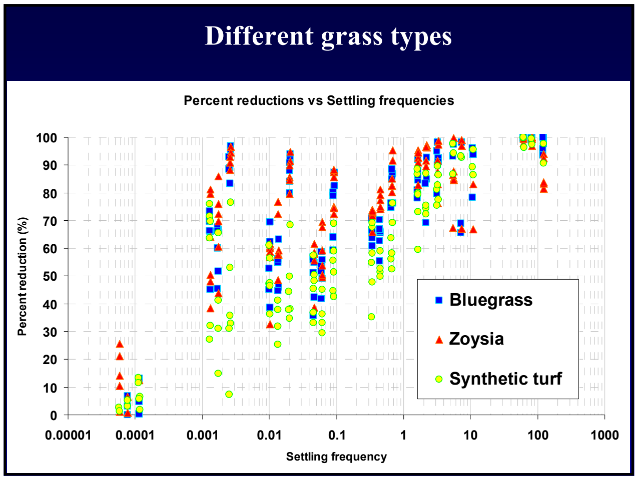
C_{out} = Sediment concentration at sampling locations
C_{in} = Initial sediment concentration at the headwork
k = First order kinetic constant
t = Distance from the headwork

2) "Settling frequency"

= traveling time / settling duration

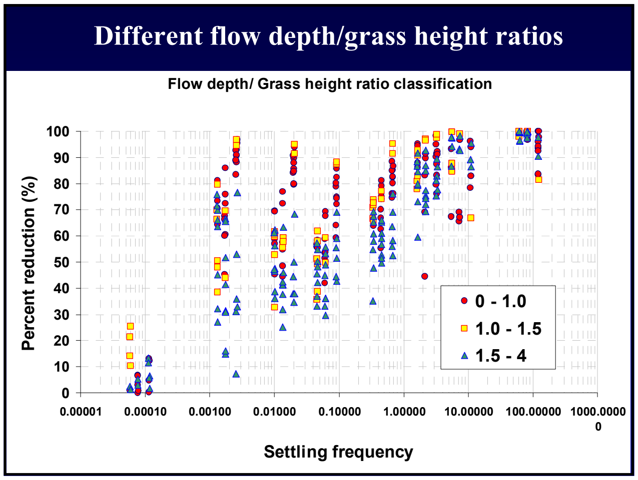
Traveling time = Swale length / flow velocity

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



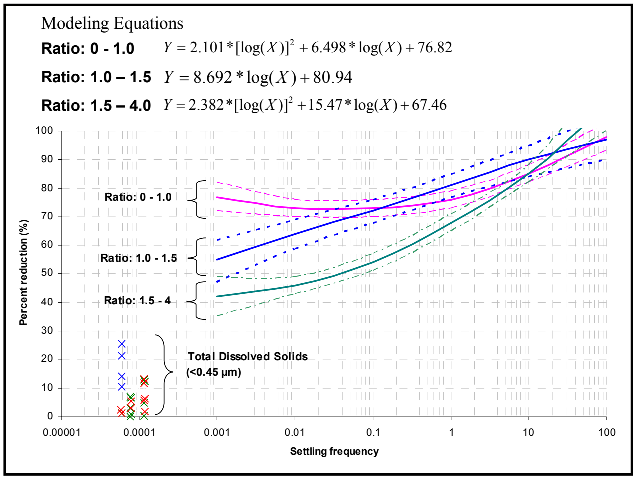
Different grass types

Percent reductions vs Settling frequencies



Different flow depth/grass height ratios

Flow depth/ Grass height ratio classification

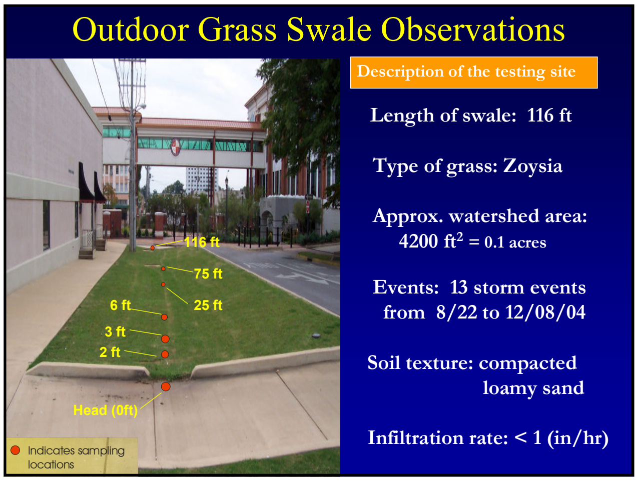


Modeling Equations

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

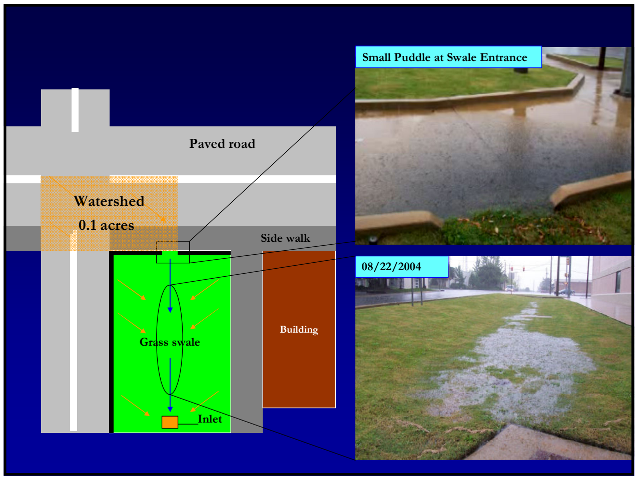
Type of grass: Zoysia

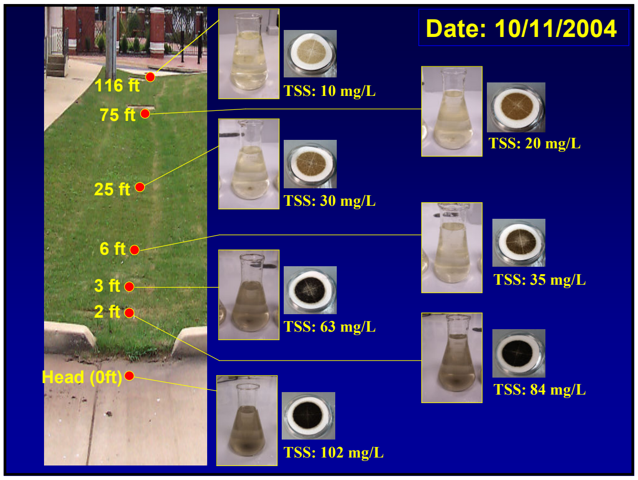
Approx. watershed area:
4200 ft^2 = 0.1 acres

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

Soil texture: compacted
loamy sand

Infiltration rate: < 1 (in/hr)

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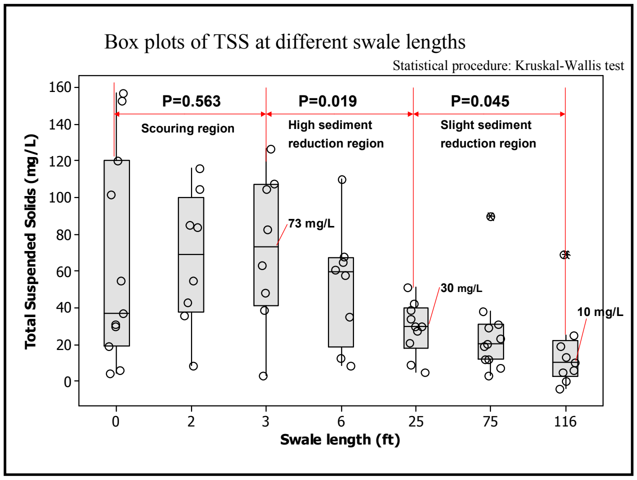
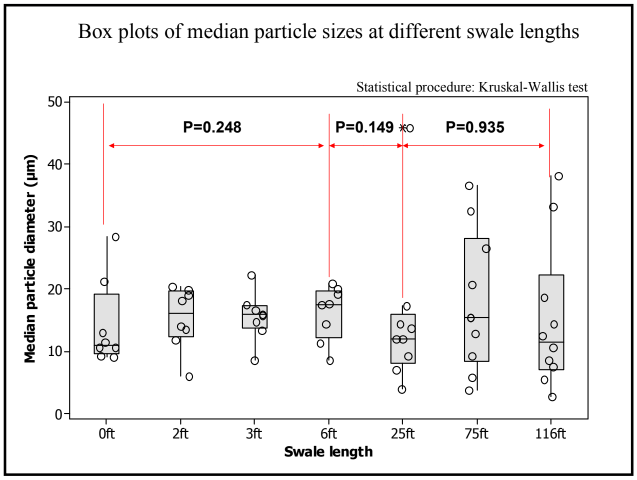
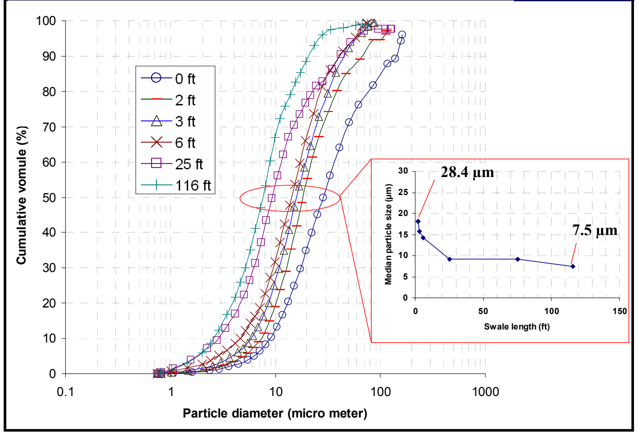

Box plots of TSS at different swale lengths

Statistical procedure: Kruskal-Wallis test


Box plots of median particle sizes at different swale lengths

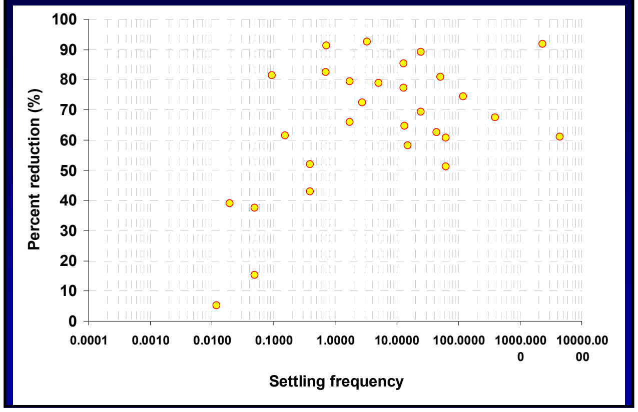
Statistical procedure: Kruskal-Wallis test

Particle size distributions: 12/06/2004

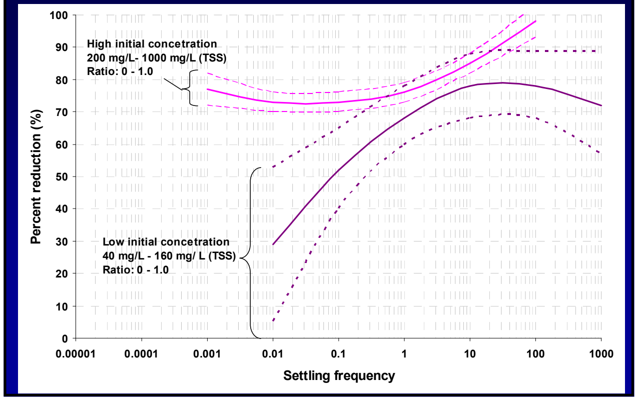


Particulate Transport in Outdoor Swale (6 rain events)

Percent reductions between 3ft and 25 ft vs. settling frequencies



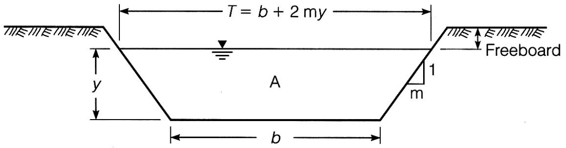
Comparison of regression line with 95% CI from indoor experiments and outdoor observations



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.

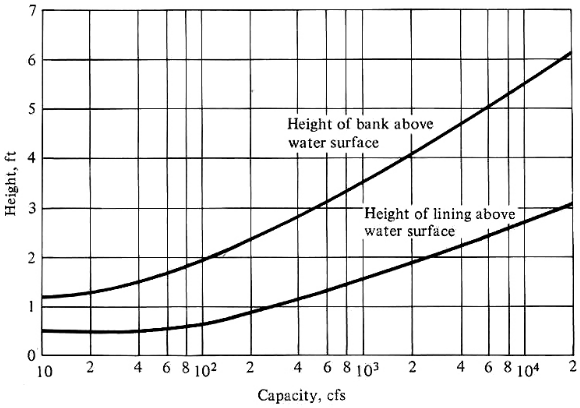
Trapezoidal Section



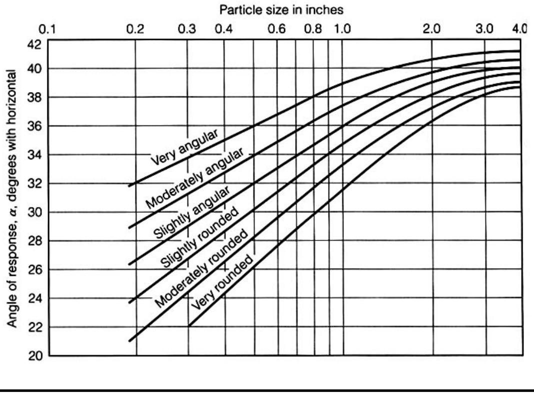
$$A = by + zy^2$$

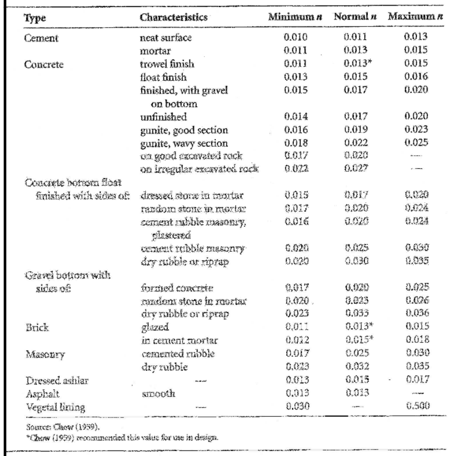
$$P = b + 2y\sqrt{1 + z^2}$$

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.

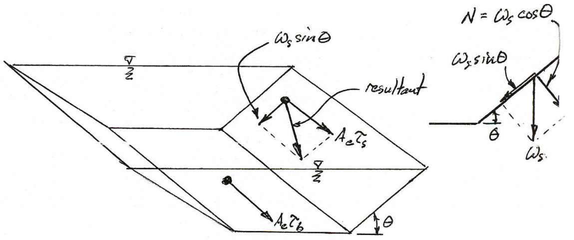
Roughness Coefficients in Lined Open Channels (Table 4.14, Chin 2000)

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**
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**

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

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

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

$$\tau_o = \gamma R S$$

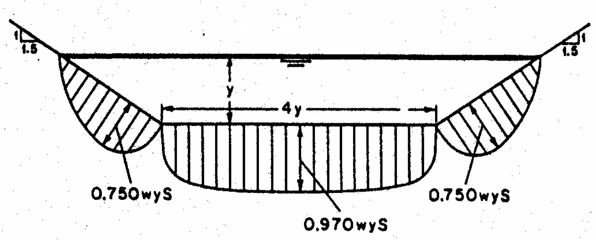
US customary units of lb/ft^2
where:
γ = specific weight of water (62.4 lbs/ft^3)
R = hydraulic radius (ft)
S_o = hydraulic slope (ft/ft) for uniform flow; this is substituted with S_f for non-uniform flow conditions

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

$$\tau_o = \gamma y S_f$$

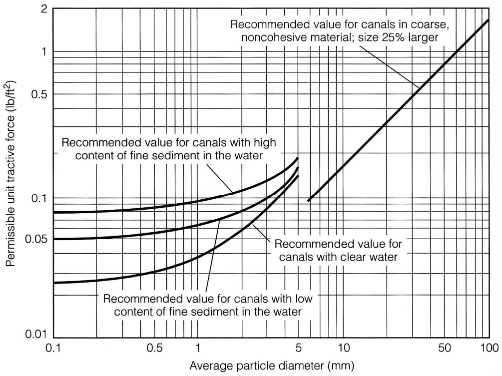
Research by the USBR has shown that the distribution of the shear stress is not uniform and that the maximum values of shear stress on the channel bottoms and side slopes are approximately:

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

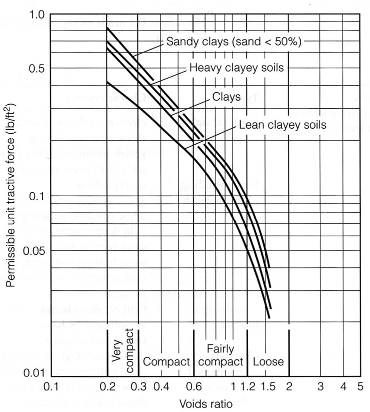


At "incipient motion," the forces causing a particle to move are just equal to those resisting motion.

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

3) Calculate the required cross-sectional area, using the continuity equation and the previously 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.

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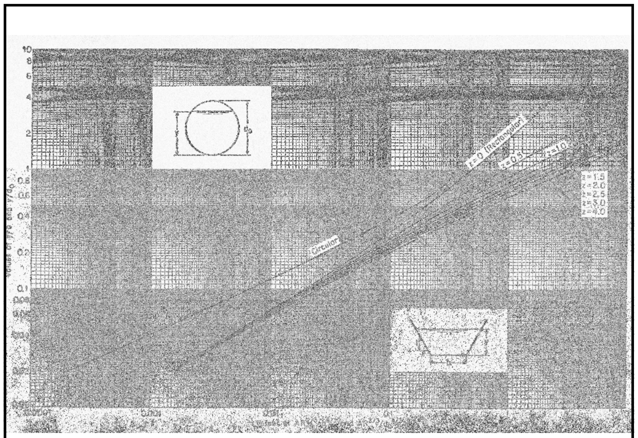
5) Calculate an appropriate channel base width (b) and depth (y) corresponding to a specific channel geometry (usually a trapezoid channel, having a side slope of z:1 side slopes).

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.

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

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.

In-Class 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 In-Class Problem

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

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

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

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

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

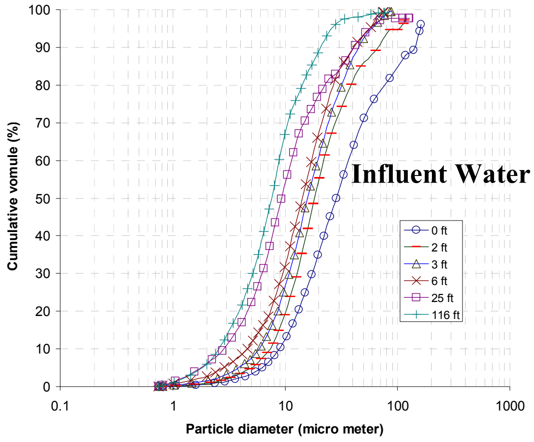
Check with full Manning’s equation, Q = 1478 cfs

Sediment Capture in Grass Swale

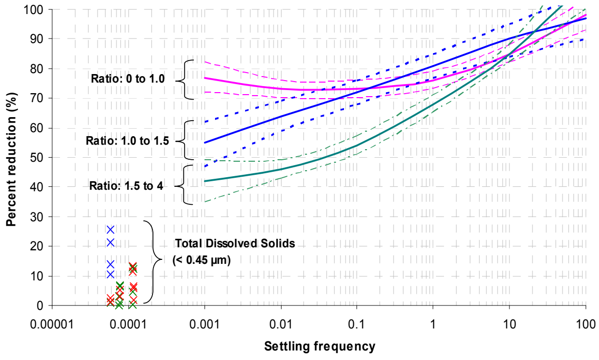
- **the discharge rate is 29 ft^3/sec (0.80 m^3/sec)**
- **the channel bottom width is 5 ft (1.5 m) wide, with 3 (H) to 1 (V) side slopes**
- **the calculated normal depth is 0.7 ft (210 mm, 21 cm) and the velocity is calculated to be 5.8 ft/sec (1.8 m/sec) after mature vegetation is established**
-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

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.



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.

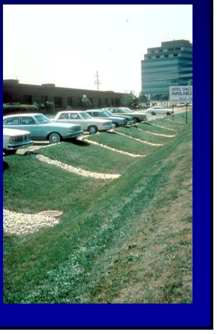
** the treated concentration for these particle size ranges are less than the irreducible concentrations, so the treated concentrations are not reduced to values smaller than the irreducible concentrations.

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

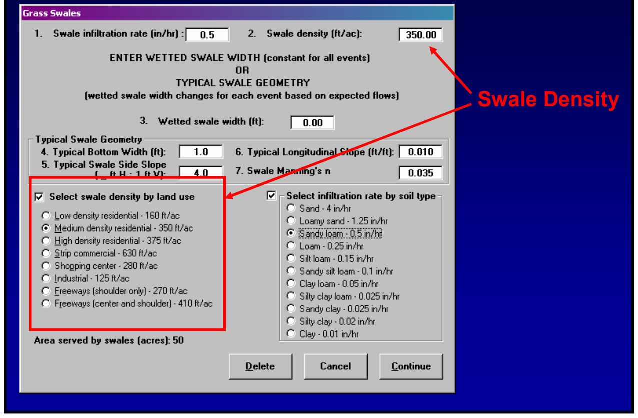
An overall 62% reduction in suspended solids concentration was achieved.

Three Components to Modeling Grass Swales

- Swale Density
- Swale Infiltration Rate
- Swale Geometry



Swale Density



Grass Swales

1. Swale infiltration rate (in/hr) : 0.5
2. Swale density (ft/ac): 350.00

ENTER WETTED SWALE WIDTH (constant for all events)
OR
TYPICAL SWALE GEOMETRY
(wetted swale width changes for each event based on expected flows)

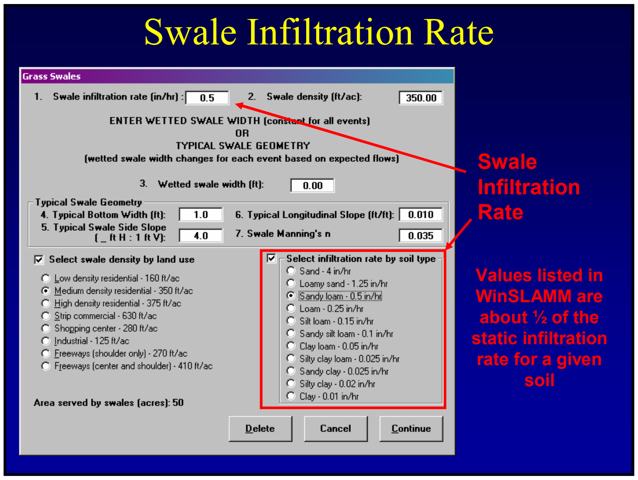
3. Wetted swale width (ft): 0.00

Typical Swale Geometry
4. Typical Bottom Width (ft): 1.0
5. Typical Swale Side Slope (_ ft H : 1 ft V): 4.0
6. Typical Longitudinal Slope (ft/ft): 0.010
7. Swale Manning's n 0.035

☑ Select swale density by land use
- ○ Low density residential - 160 ft/ac
- ● Medium density residential - 350 ft/ac
- ○ High density residential - 375 ft/ac
- ○ Strip commercial - 630 ft/ac
- ○ Shopping center - 280 ft/ac
- ○ Industrial - 125 ft/ac
- ○ Freeways (shoulder only) - 270 ft/ac
- ○ Freeways (center and shoulder) - 410 ft/ac

☑ Select infiltration rate by soil type
- ○ Sand - 4 in/hr
- ○ Loamy sand - 1.25 in/hr
- ● Sandy loam - 0.5 in/hr
- ○ Loam - 0.25 in/hr
- ○ Silt loam - 0.15 in/hr
- ○ Sandy silt loam - 0.1 in/hr
- ○ Clay loam - 0.05 in/hr
- ○ Silty clay loam - 0.025 in/hr
- ○ Sandy clay - 0.025 in/hr
- ○ Silty clay - 0.02 in/hr
- ○ Clay - 0.01 in/hr

Area served by swales (acres): 50



Swale Infiltration Rate

Grass Swales

1. Swale infiltration rate (in/hr) : 0.5
2. Swale density (ft/ac): 350.00

ENTER WETTED SWALE WIDTH (constant for all events)
OR
TYPICAL SWALE GEOMETRY
(wetted swale width changes for each event based on expected flows)

3. Wetted swale width (ft): 0.00

Typical Swale Geometry
4. Typical Bottom Width (ft): 1.0
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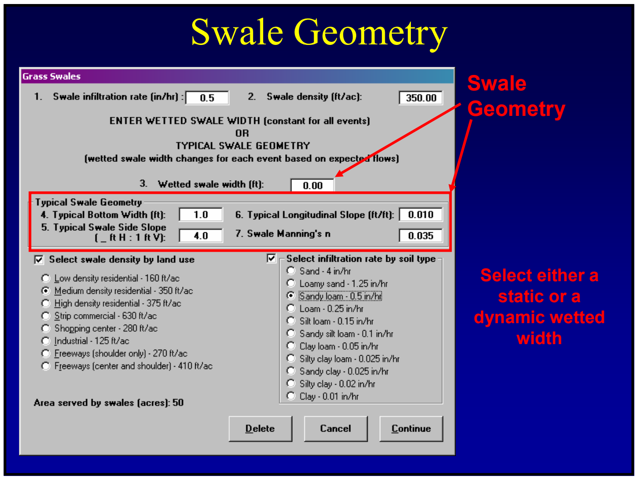
- ○ Sandy clay - 0.025 in/hr
- ○ Silty clay - 0.02 in/hr
- ○ Clay - 0.01 in/hr

Area served by swales (acres): 50

Swale Infiltration Rate

Values listed in WinSLAMM are about ½ of the static infiltration rate for a given soil



Swale Geometry

Grass Swales

1. Swale infiltration rate (in/hr) : 0.5
2. Swale density (ft/ac): 350.00

ENTER WETTED SWALE WIDTH (constant for all events)
OR
TYPICAL SWALE GEOMETRY
(wetted swale width changes for each event based on expected flows)

3. Wetted swale width (ft): 0.00

Typical Swale Geometry
4. Typical Bottom Width (ft): 1.0
5. Typical Swale Side Slope (_ ft H : 1 ft V): 4.0
6. Typical Longitudinal Slope (ft/ft): 0.010
7. Swale Manning's n 0.035

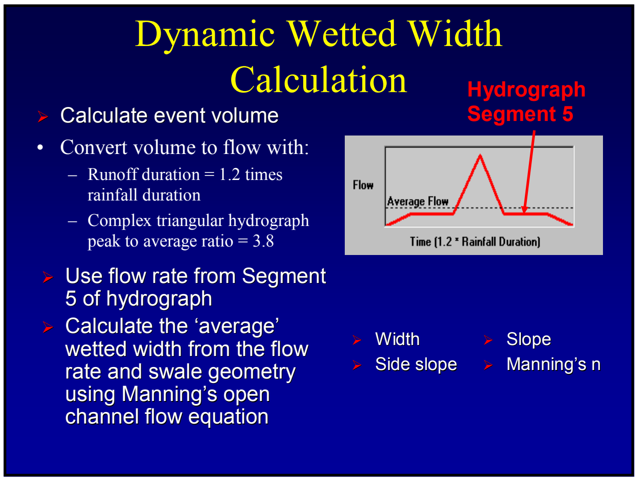
☑ Select swale density by land use
- ○ Low density residential - 160 ft/ac
- ● Medium density residential - 350 ft/ac
- ○ High density residential - 375 ft/ac
- ○ Strip commercial - 630 ft/ac
- ○ Shopping center - 280 ft/ac
- ○ Industrial - 125 ft/ac
- ○ Freeways (shoulder only) - 270 ft/ac
- ○ Freeways (center and shoulder) - 410 ft/ac

☑ Select infiltration rate by soil type
- ○ Sand - 4 in/hr
- ○ Loamy sand - 1.25 in/hr
- ● Sandy loam - 0.5 in/hr
- ○ Loam - 0.25 in/hr
- ○ Silt loam - 0.15 in/hr
- ○ Sandy silt loam - 0.1 in/hr
- ○ Clay loam - 0.05 in/hr
- ○ Silty clay loam - 0.025 in/hr
- ○ Sandy clay - 0.025 in/hr
- ○ Silty clay - 0.02 in/hr
- ○ Clay - 0.01 in/hr

Area served by swales (acres): 50

Swale Geometry

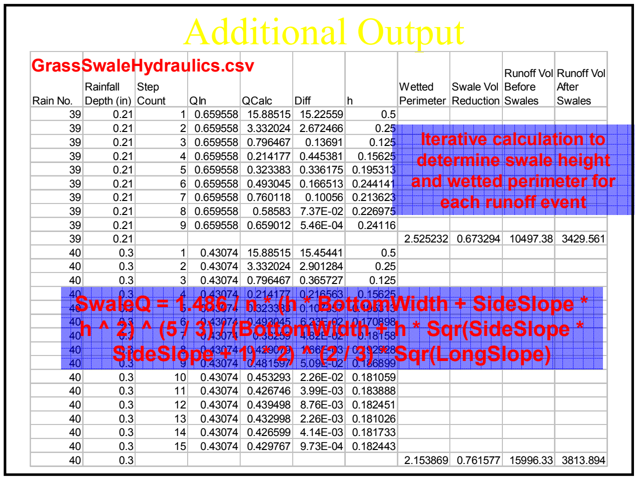
Select either a static or a dynamic wetted width



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
- Use flow rate from Segment 5 of hydrograph
- Calculate the 'average' wetted width from the flow rate and swale geometry using Manning's open channel flow equation
  - Width
  - Side slope
  - Slope
  - Manning's n

Hydrograph Segment 5



Additional Output

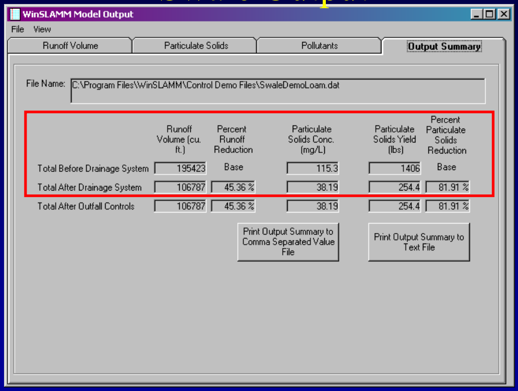
GrassSwaleHydraulics.csv

Rain No.	Rainfall Depth (in)	Step Count	QIn	QCalc	Diff	h	Wetted Perimeter	Swale Vol Reduction	Runoff Vol Before Swales	Runoff Vol After Swales
39	0.21	1	0.659558	15.88515	15.22559	0.5				
39	0.21	2	0.659558	3.332024	2.672466	0.25				
39	0.21	3	0.659558	0.796467	0.13691	0.125				
39	0.21	4	0.659558	0.214177	0.445381	0.15625				
39	0.21	5	0.659558	0.323383	0.336175	0.195313				
39	0.21	6	0.659558	0.493045	0.166513	0.244141				
39	0.21	7	0.659558	0.760118	0.10056	0.213623				
39	0.21	8	0.659558	0.58583	7.37E-02	0.226975				
39	0.21	9	0.659558	0.659012	5.46E-04	0.24116				
39	0.21						2.525232	0.673294	10497.38	3429.561
40	0.3	1	0.43074	15.88515	15.45441	0.5				
40	0.3	2	0.43074	3.332024	2.901284	0.25				
40	0.3	3	0.43074	0.796467	0.365727	0.125				
40	0.3	4	0.43074	0.214177	0.216563	0.15625				
40	0.3	5	0.43074	0.323383	0.107357	0.195313				
40	0.3	6	0.43074	0.493045	6.23E-02	0.170898				
40	0.3	7	0.43074	0.38259	4.82E-02	0.18158				
40	0.3	8	0.43074	0.429079	1.66E-03	0.192928				
40	0.3	9	0.43074	0.481597	5.09E-02	0.186899				
40	0.3	10	0.43074	0.453293	2.26E-02	0.181059				
40	0.3	11	0.43074	0.426746	3.99E-03	0.183888				
40	0.3	12	0.43074	0.439498	8.76E-03	0.182451				
40	0.3	13	0.43074	0.432998	2.26E-03	0.181026				
40	0.3	14	0.43074	0.426599	4.14E-03	0.181733				
40	0.3	15	0.43074	0.429767	9.73E-04	0.182443				
40	0.3						2.153869	0.761577	15996.33	3813.894

Iterative calculation to determine swale height and wetted perimeter for each runoff event

SwaleQ = 1.486 / n * (h * BottomWidth + SideSlope * h ^ 2) ^ (5 / 3) / (BottomWidth + h * Sqr(SideSlope * SideSlope + 1) * 2) ^ (2 / 3) * Sqr(LongSlope)

Swale Output

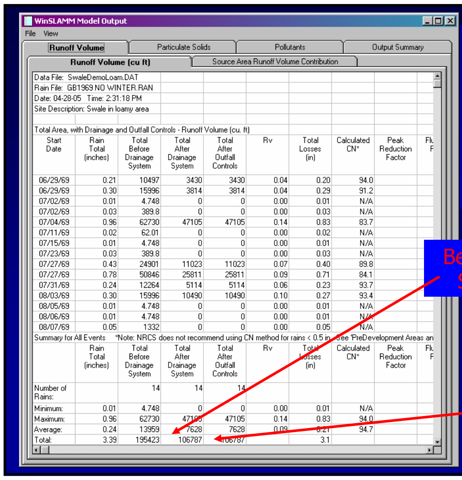


File Name: C:\Program Files\WinSLAMM\Control Demo Files\SwaleDemoLoam.dat

	Runoff Volume (cu. ft.)	Percent Runoff Reduction	Particulate Solids Conc. (mg/L)	Particulate Solids Yield (lbs)	Percent Particulate Solids Reduction
Total Before Drainage System	195423	Base	115.3	1406	Base
Total After Drainage System	106787	45.36 %	38.19	254.4	81.91 %
Total After Outfall Controls	106787	45.36 %	38.19	254.4	81.91 %

Grass Swale Model Results

Drainage System Runoff Volume



Data File: SwaleDemoLoam.DAT
Rain File: GB1969 NO WINTER.RAN
Date: 04-28-05 Time: 2:31:18 PM
Site Description: Swale in loamy area

Total Area, with Drainage and Outfall Controls - Runoff Volume (cu. ft)

Start Date	Rain Total (inches)	Total Before Drainage System	Total After Drainage System	Total After Outfall Controls	Rv	Total Losses (in)	Calculated CN*	Peak Reduction Factor	Flu F
06/29/69	0.21	10497	3430	3430	0.04	0.20	94.0		
06/29/69	0.30	15996	3814	3814	0.04	0.29	91.2		
07/02/69	0.01	4.748	0	0	0.00	0.01	N/A		
07/02/69	0.03	389.8	0	0	0.00	0.03	N/A		
07/04/69	0.96	62730	47105	47105	0.14	0.83	83.7		
07/11/69	0.02	62.01	0	0	0.00	0.02	N/A		
07/15/69	0.01	4.748	0	0	0.00	0.01	N/A		
07/23/69	0.03	389.8	0	0	0.00	0.03	N/A		
07/27/69	0.43	24901	11023	11023	0.07	0.40	89.8		
07/27/69	0.78	50846	25811	25811	0.09	0.71	84.1		
07/31/69	0.24	12264	5114	5114	0.06	0.23	93.7		
08/03/69	0.30	15996	10490	10490	0.10	0.27	93.4		
08/05/69	0.01	4.748	0	0	0.00	0.01	N/A		
08/06/69	0.01	4.748	0	0	0.00	0.01	N/A		
08/07/69	0.05	1332	0	0	0.00	0.05	N/A		

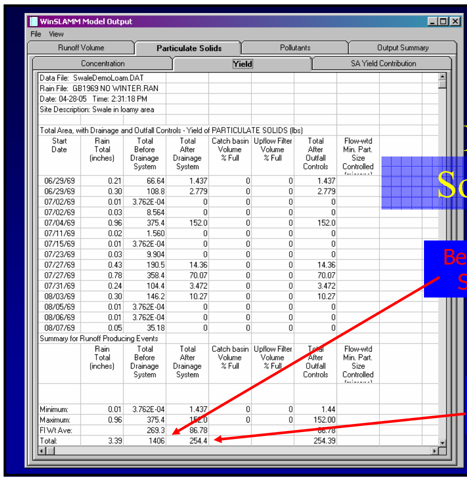
Summary for All Events *Note: NRCS does not recommend using CN method for rains < 0.5 in. See 'PreDevelopment Areas an

	Rain Total (inches)	Total Before Drainage System	Total After Drainage System	Total After Outfall Controls	Rv	Total Losses (in)	Calculated CN*	Peak Reduction Factor	Flu F
Number of Rains:		14	14	14					
Minimum:	0.01	4.748	0	0	0.00	0.01	N/A		
Maximum:	0.96	62730	47105	47105	0.14	0.83	94.0		
Average:	0.24	13959	7628	7628	0.09	0.21	94.7		
Total:	3.39	195423	106787	106787		3.1			

Before Drainage System Total

After Drainage System Total

Drainage System Particulate Solids Yield



Data File: SwaleDemoLoam.DAT
Rain File: GB1969 NO WINTER.RAN
Date: 04-28-05 Time: 2:31:18 PM
Site Description: Swale in loamy area

Total Area, with Drainage and Outfall Controls - Yield of PARTICULATE SOLIDS (lbs)

Start Date	Rain Total (inches)	Total Before Drainage System	Total After Drainage System	Catch basin Volume % Full	Upflow Filter Volume % Full	Total After Outfall Controls	Flow-wtd Min. Part. Size Controlled
06/29/69	0.21	66.64	1.437	0	0	1.437	
06/29/69	0.30	108.8	2.779	0	0	2.779	
07/02/69	0.01	3.762E-04	0	0	0	0	
07/02/69	0.03	8.564	0	0	0	0	
07/04/69	0.96	375.4	152.0	0	0	152.0	
07/11/69	0.02	1.560	0	0	0	0	
07/15/69	0.01	3.762E-04	0	0	0	0	
07/23/69	0.03	9.904	0	0	0	0	
07/27/69	0.43	190.5	14.36	0	0	14.36	
07/27/69	0.78	358.4	70.07	0	0	70.07	
07/31/69	0.24	104.4	3.472	0	0	3.472	
08/03/69	0.30	146.2	10.27	0	0	10.27	
08/05/69	0.01	3.762E-04	0	0	0	0	
08/06/69	0.01	3.762E-04	0	0	0	0	
08/07/69	0.05	35.18	0	0	0	0	

Summary for Runoff Producing Events

	Rain Total (inches)	Total Before Drainage System	Total After Drainage System	Catch basin Volume % Full	Upflow Filter Volume % Full	Total After Outfall Controls	Flow-wtd Min. Part. Size Controlled
Minimum:	0.01	3.762E-04	1.437	0	0	1.44	
Maximum:	0.96	375.4	152.0	0	0	152.00	
Fl Wt Ave:		269.3	86.78			86.78	
Total:	3.39	1406	254.4			254.39	

Before Drainage System Total

After Drainage System Total