Sustainable Hydrology: Integrating Stormwater Management into the Landscape

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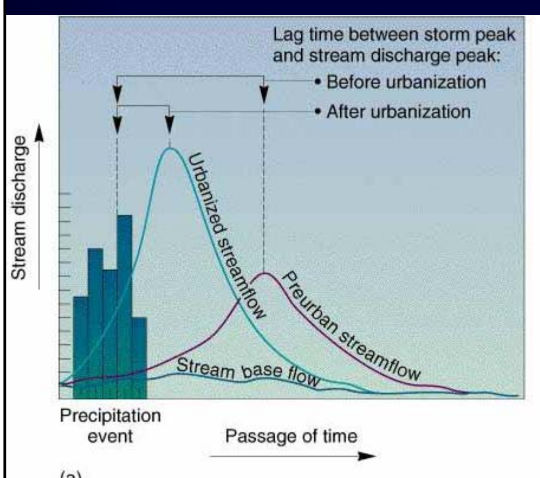
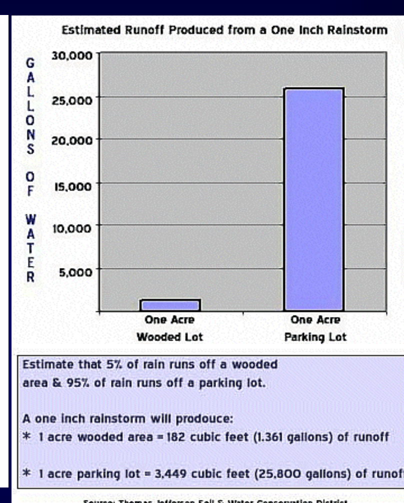
Urbanization often shortens watershed response times and increases flow volumes and rates





Prior development decisions have led to directly connected impervious areas and “pervious” areas with heavily-compacted soils.

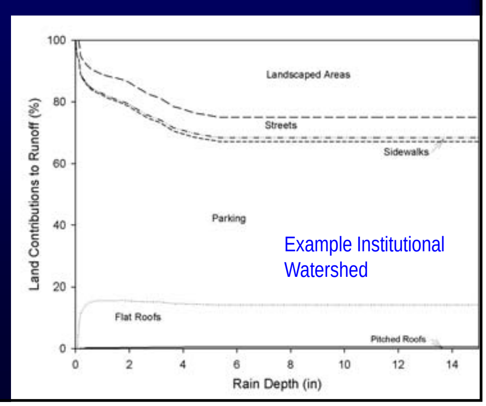
Moving Stormwater Control Into the Watershed

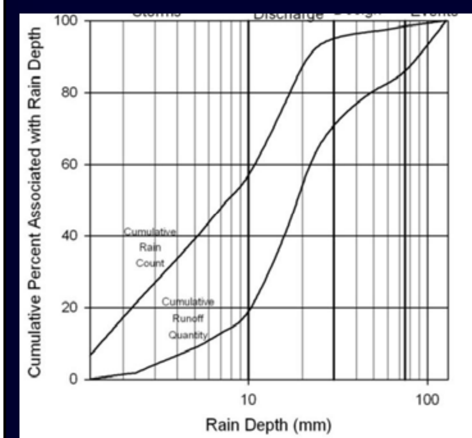
Multiple names for a similar goal/design process:
- Low Impact Development (LID)
- Conservation Design
- Water Sensitive Urban Design (WSUDs)
- Sustainable Urban Drainage Systems (SUDS)
- Distributed Runoff Controls (DRC)

- How can we modify our development designs to encourage stormwater treatment at its sources instead of at the watershed outlet?

Improved Understanding of Runoff Flows and Volumes as a Guide for Stormwater Management

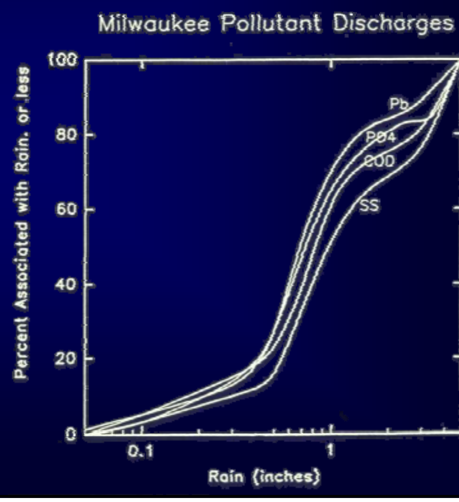
- Usually a simple relationship between rain depth and runoff depth.
- Changes in rain depth affect the relative contributions of land area runoff and pollutant mass discharges:
  - Directly connected impervious areas contribute most flow during relatively small rains
  - Disturbed urban soil areas (“pervious” areas) may dominate during larger rains rains





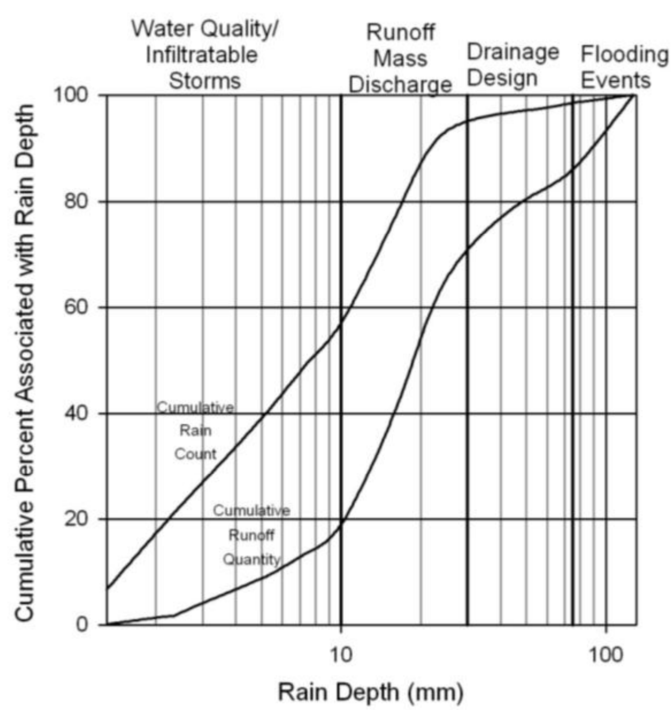
Relating Runoff Distribution to Pollutant Loadings

SCS Type II Rainfall Example



Central and Western PA are in the SCS Type II Rainfall Design Storm area.

Analyzing rainfall and runoff distributions for water quality concerns and water quantity solutions



Design Objectives

- < 0.5 in runoff
  - Most Events (Number of Storms)
  - Little of Annual Runoff Volume and Pollutant Mass Discharge
  - Probable Little Receiving Water Effects
  - Problem: Pollutant Concentrations Likely Exceed Regulations (bacteria, total recoverable metals) for each event
- Water Quality Storms
  - Totally capture runoff
  - Reuse runoff on-site (irrigation?) or infiltrate runoff in upland areas (unless groundwater contamination potential exists)

Design Objectives (cont.)

- 0.5 - 2 inches
  - Majority of Annual Runoff Volume and Pollutant Discharges
  - Occurs Approximately Every Two Weeks
  - Problems:
    - Produce Moderate to High Flows
    - Produce Frequent High Pollutant Loadings
- Pollutant Mass Loading Storms
  - Totally capture up to 0.5 in (12 mm) rains and infiltrate on site. Do not allow in drainage system.
  - Investigate treatment for runoff not captured.

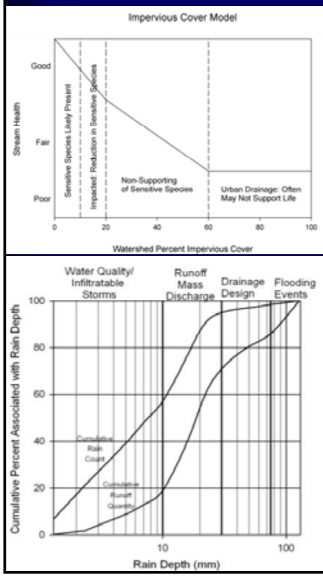
Design Objectives (cont.)

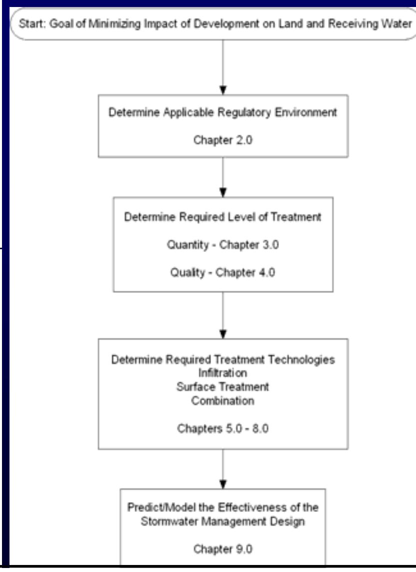
- 2 - 4 inches
  - Current Design Storms
  - Establishes Energy Gradient of Streams
  - Occurs Approximately Every Few Months (once to twice a year)
  - Problems:
    - Unstable Streambanks
    - Habitat Destruction from Damaging Flows
- Drainage Design Storms
  - Remove first portion of events (0.5 in) for on-site reuse or infiltration
  - Treat runoff from middle portion of event
  - Reduce discharge rate for large flows (prevent downstream habitat destruction)

Design Objectives (cont.)

- > 4 inches
  - Occur Rarely (once every several years to once every several decades or centuries)
  - Produce Relatively Little of Annual Pollutant Mass Discharge
  - Produce Extremely Large Flows and Exceed Drainage System Capacity for Most Events
- Flooding Storms
  - Retain on-site first portion
  - Treat middle portion
  - Reduce discharge rate for large flows
  - Convey excessive flows in secondary drainage system to minimize loss of life and property damage

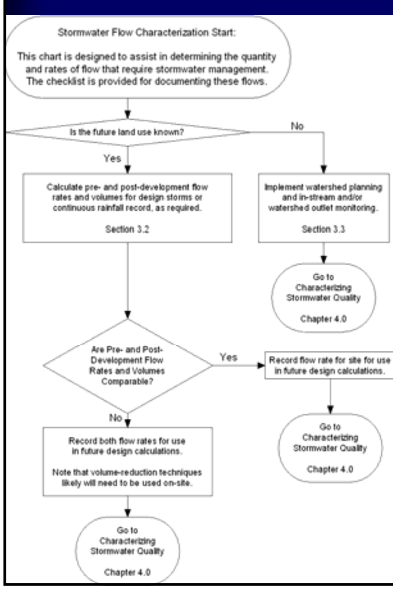
New Guidance Needed for Selecting Stormwater Control Practices

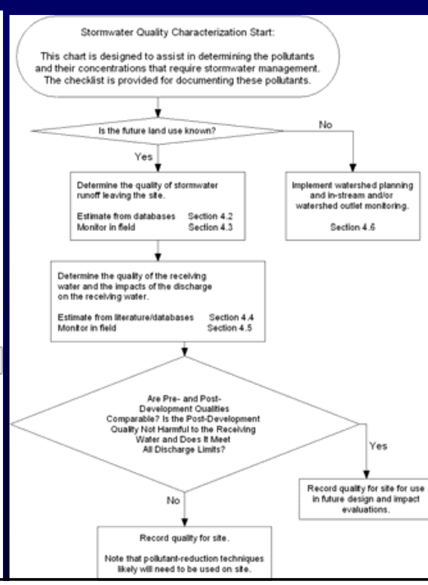




Ref:
Clark et al. 2009.
Infiltration vs. Surface-Water Discharge.
WERF Report 04-SW-3. To be published Summer 2009.

Developing Guidance for Selecting Infiltration vs. Surface Treatment Practices





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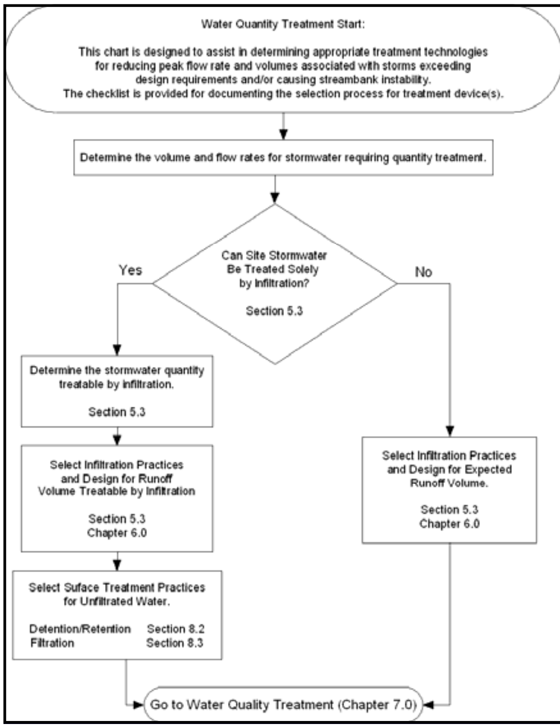


Characterizing the Flow Rates and Volumes Requiring Control

Ref:
Clark et al. 2009. *Infiltration vs. Surface-Water Discharge*. WERF Report 04-SW-3. To be published Summer 2009.

Table 5-2: Summary of Modeling Guidance for Various Site Conditions Rational, Modified Rational and NRCS Methods[1]

Site Condition or Parameter	Rational Method	Modified Rational Method	NRCS-Based Methods
Mixture of pervious and directly connected impervious surface	Use standard procedures	Use standard procedures	Use weighted average runoff volume
Unconnected impervious surface	Use not recommended	Use not recommended	TR-55 or Two-Step Technique
Groundwater recharge areas	Reduce effective size of recharge area[2]	Reduce effective size of recharge area[2]	Reduce runoff volume by recharge volume
Time of concentration	Maximum sheet flow length = 150 feet Maximum sheet flow n = 0.40 Include effects of storage and ponding areas		

Notes: Table presents summaries only. See text for complete descriptions for each computation method.
For sites with combination of recharge and non-recharge areas. Methods not recommended where entire area is recharged. See text for details.

New Jersey Stormwater Best Management Practices Manual • Chapter 5: Computing Stormwater Runoff Rates and Volumes • February 2004 • Page 5-26

Many methods approved to calculate runoff volume.

Other Methods of Calculating Volume and Peak Rate

- Small Storm Hydrology (Pitt 1987, 1994, 1998, etc., etc., etc.):

Table 5. Summary of Volumetric Runoff Coefficients for Urban Runoff Flow Calculations (Pitt 1987).

Runoff Coefficients for Directly Connected Areas:

Rain Depth mm	Rain Depth inches	Flat roofs* (or large unpaved parking areas)	Pitched roofs*	Large impervious areas*	Small impervious areas and streets	Sandy soils	Typical urban soils	Clayey soils
1	0.04	0.00	0.25	0.93	0.26	0.00	0.00	0.00
3	0.12	0.30	0.75	0.96	0.49	0.00	0.00	0.00
5	0.20	0.54	0.85	0.97	0.55	0.00	0.05	0.10
10	0.39	0.72	0.93	0.97	0.60	0.01	0.08	0.15
15	0.59	0.79	0.95	0.97	0.64	0.02	0.10	0.19
20	0.79	0.83	0.96	0.97	0.67	0.02	0.11	0.20
30	1.2	0.86	0.98	0.98	0.73	0.03	0.12	0.22
50	2.0	0.90	0.99	0.99	0.84	0.07	0.17	0.26
80	3.2	0.94	0.99	0.99	0.90	0.15	0.24	0.33
125	4.9	0.96	0.99	0.99	0.93	0.25	0.35	0.45

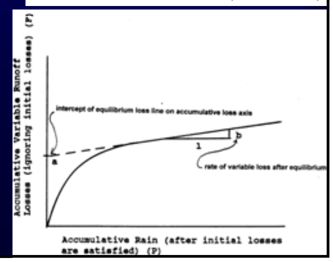
*If these "impervious" areas drain for a significant length across sandy soils, the sandy soil runoff coefficients will usually be applied to these areas, however, if these areas drain across clayey soils, the runoff coefficients will be reduced, depending on the land use and rain depth, according to the following table:

Reduction factors for different rain depths (mm):

	1	3	5	10	15	20	30	50	80	125
Strip commercial and shopping centers:	0.00	0.00	0.47	0.90	0.99	0.99	0.99	0.99	0.99	0.99
Other medium to high density land uses, with alleys:	0.00	0.08	0.11	0.16	0.20	0.29	0.46	0.81	0.99	0.99
Other medium to high density land uses, without alleys:	0.00	0.00	0.11	0.16	0.20	0.21	0.22	0.27	0.34	0.46

If low density land uses, use clayey soil runoff coefficients.

$$F = losses = bP + a(1 - e^{-gP})$$



Other Methods Listed in the Guidance Documents

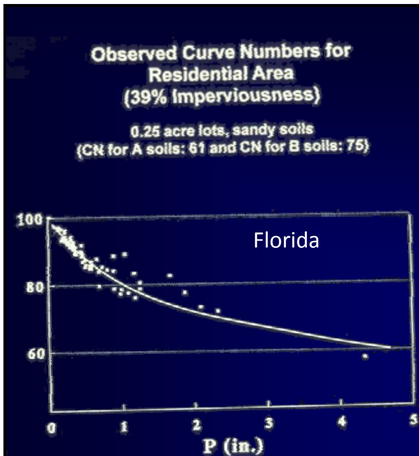
- **Short cut method** (Schueler, 1987). Used where the site consists of predominately one type of land surface or for quick calculations to estimate the water quality treatment volume.
- **Water quality volume (WQv):** $WQ_V = \dfrac{PR_V A}{12}$
- P = rainfall depth in inches for selected area of state (i.e. 1.25 inches) and A = area in acre
- **Volumetric runoff coefficient (R_v):**

$$R_V = 0.05 + 0.009I$$

- I = % impervious area

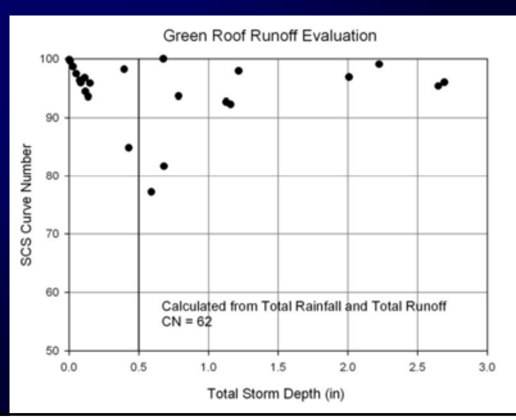
Limitations of Using Drainage Design Models for Small Storms and On-Site Designs

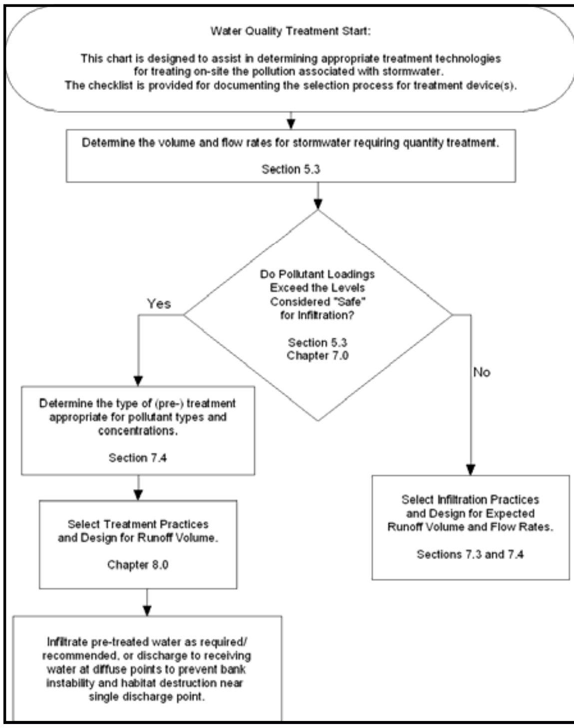
- Problems arise when trying to use drainage design hydrology models for water quality analyses.
  - TR-55 greatly under predicts flows from small rains: NRCS recommends that TR-55 not be used for rains less than 0.5 inch.
  - HEC-HMS has TR-55 “built in” as a option.
- Most drainage models assume that all/most flows originate from directly connected impervious areas, with very little originating from pervious areas.
  - However, with larger rains (drainage design rains), contribution from pervious areas significant.
- Water quality problems typically occurring from small and intermediate sized rains, not drainage design storms.



Curve numbers and the methods that use them don’t work well for single events that are not drainage design depths.

Adam Clark
M. EPC Paper 2009





Characterizing the Stormwater Quality and Receiving Water Standards

Ref:
Clark et al. 2009. *Infiltration vs. Surface-Water Discharge*. WERF Report 04-SW-3. To be published Summer 2009.

Lot Size as a Guide for Stormwater Management Decisions

Stormwater Controls	Low/Very Low Density Residential (> 2 acre lot size)	Medium Density Development (0.5 to 2 acre lot)	High Density Development
On-site infiltration (unless contamination potential exists)	Rooftop and pavement	Rooftop and pavement where space available	Rooftop only, depending on roofing materials
Minimize compaction	YES	YES	Likely not feasible
Grass swale drainage for roads (unless contamination potential exists)	YES	YES	Likely not feasible
Wet ponds	Likely not needed	Commercial and industrial areas	Commercial and industrial areas
High-rate in-line pollutant treatment	Likely not needed	Critical source areas	Critical source areas (may want to send runoff to treatment plant)

Acceptable BMPs for Post Construction Stormwater Management (PA DEP 2000)

GROUNDWATER RECHARGE

BMP	Delaware SW Guidance Manual (1)	Maryland SW Handbook (2)	New Jersey BMP Manual (3)	New York SW Manual (4)	Pennsylvania BMP Handbook (5)	Center for Watershed Protection (6)
Permeable Paving			Ch. 4, Table 2-5; Ch. 5, p. 111		Section 8	Fact Sheets SW Management Porous Pavement
Stormwater Infiltration		Section 3.3	Ch. 4, Table 2-5; Ch. 5, p. 98	Section 6.3	Section 8	Manual Builder Performance Criteria Infiltration Systems
Grass Swale	P. 3-57	Section 3.5	Ch. 5, p. 84	Section 6.5	Section 8	Manual Builder Performance Criteria Open Channels
Bioretention	Appendix A	Section 3.4	Ch. 4, Table 2-5; Ch. 5, p. 55	Section 6.4	Section 8	Manual Builder Performance Criteria Filtering Systems
Filter Strip	P. 3-39		Ch. 4, Table 2-5		Section 8	Fact Sheets SW Management Grassed Filter Strips

WATER QUALITY

BMP	Delaware SW Guidance Manual (1)	Maryland SW Manual (2)	New Jersey BMP Manual (3)	New York SW Manual (4)	Pennsylvania BMP Handbook (5)	Center for Watershed Protection (6)
Permeable Paving			Ch. 4, Table 2-5; Ch. 5, p. 111		Section 8	Fact Sheets SW Management Porous Pavement
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Grass Swale	P. 3-57	Section 3.5	Ch. 5, p. 84	Section 6.5	Section 8	
Bioretention	Appendix A	Section 3.4	Ch. 4, Table 2-5; Ch. 5, p. 55	Section 6.4	Section 8	
Filter Strip	P. 3-39		Ch. 4, Table 2-5		Section 8	
Stormwater Wetlands		Section 3.2	Ch. 4, Table 2-5; Ch. 5	Section 6.2	Section 8	
Water Quality Structures					Section 8	
Sand Filter		Section 3.4	Ch. 4, Table 2-5; Ch. 5, p. 137	Section 6.4	Section 8	
Wet Pond (extended detention pond)		Section 3.1	Ch. 4, Table 2-5; Ch. 5, p. 150	Section 6.1	Section 8	
Riparian Corridor Management	Appendix B		Ch. 4, Table 2-5		Section 8	
Rooftop Runoff Management			Ch. 5, p. 127		Section 8	

RATE AND VOLUME CONTROL

BMP	Delaware SW Guidance Manual (1)	Maryland SW Manual (2)	New Jersey BMP Manual (3)	New York SW Manual (4)	Pennsylvania BMP Handbook (5)	Center for Watershed Protection (6)
Permeable Paving			Ch. 4, Table 2-5; Ch. 5, p. 111		Section 8	Fact Sheets SW Management Porous Pavement
Stormwater Infiltration		Section 3.3	Ch. 4, Table 2-5; Ch. 5, p. 98	Section 6.3	Section 8	Manual Builder Performance Criteria Infiltration Systems
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Bioretention	Appendix A	Section 3.4	Ch. 4, Table 2-5; Ch. 5, p. 55	Section 6.4	Section 8	Manual Builder Performance Criteria Filtering Systems
Dry Pond					Section 8	Manual Builder Performance Criteria Ponds
Stormwater Wetlands		Section 3.2	Ch. 4, Table 2-5; Ch. 5	Section 6.2	Section 8	Manual Builder Performance Criteria Wetlands
Wet Pond (extended detention pond)		Section 3.1	Ch. 4, Table 2-5; Ch. 5, p. 150	Section 6.1	Section 8	Manual Builder Performance Criteria Ponds
Riparian Corridor Management	Appendix B		Ch. 4, Table 2-5		Section 8	
Rooftop Runoff Management			Ch. 5, p. 127		Section 8	

New Solutions for Peak Flow Control: Maintain Time of Concentration

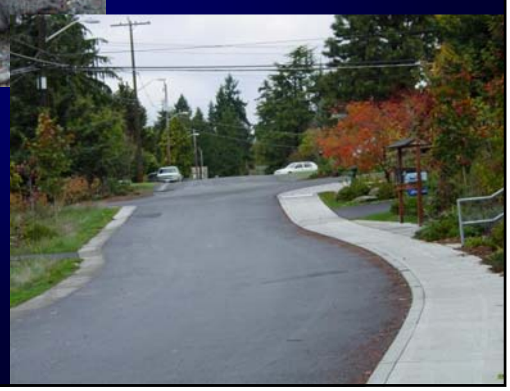
- Open drainage
- Use green space
- Flatten slopes
- Disperse drainage
- Lengthen flow paths
- Save headwater areas
- Vegetative swales
- Maintain natural flow paths
- Increase distance from streams
- Maximize sheet flow

Maintaining pre-development time of concentration essential to mimicking pre-development hydrology! Reduce peak flows in receiving waters!

Disconnect Impervious Areas and Infiltrate "Clean Stormwater" for Groundwater Recharge

- Directs water from streets and driveways
- Disconnects roof drains to cisterns or infiltration areas
- Reduces the amount & velocity of water flowing into piping system and the receiving water.
- Reduces the amount of pollution entering the drainage system.

Street Edge Alternative
Seattle, Washington



Disconnection of streets from traditional drainage system.

Photos by Shirley E. Clark

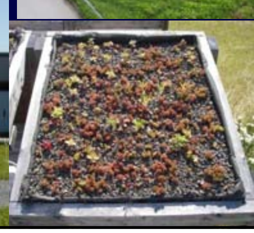
On-Site Water Disposal Options

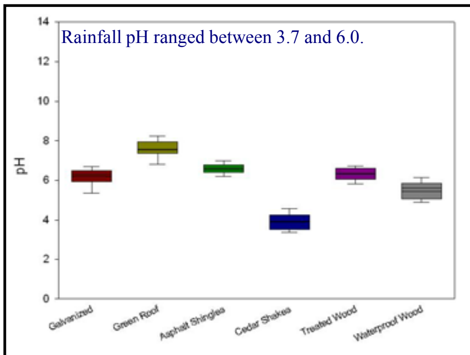
Rainwater Harvesting

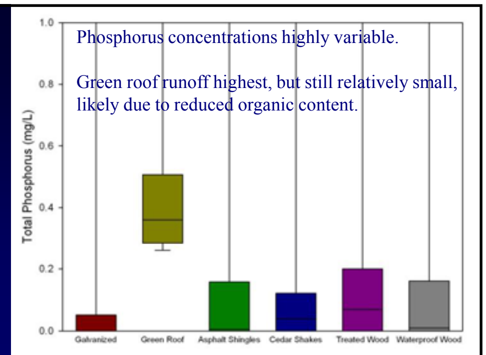
Infiltration (with or without subdrains)

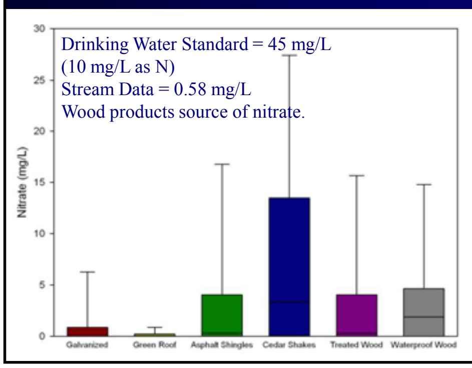
Roofing for Rainwater Harvesting – Consider the Materials


Penn State – Harrisburg test site

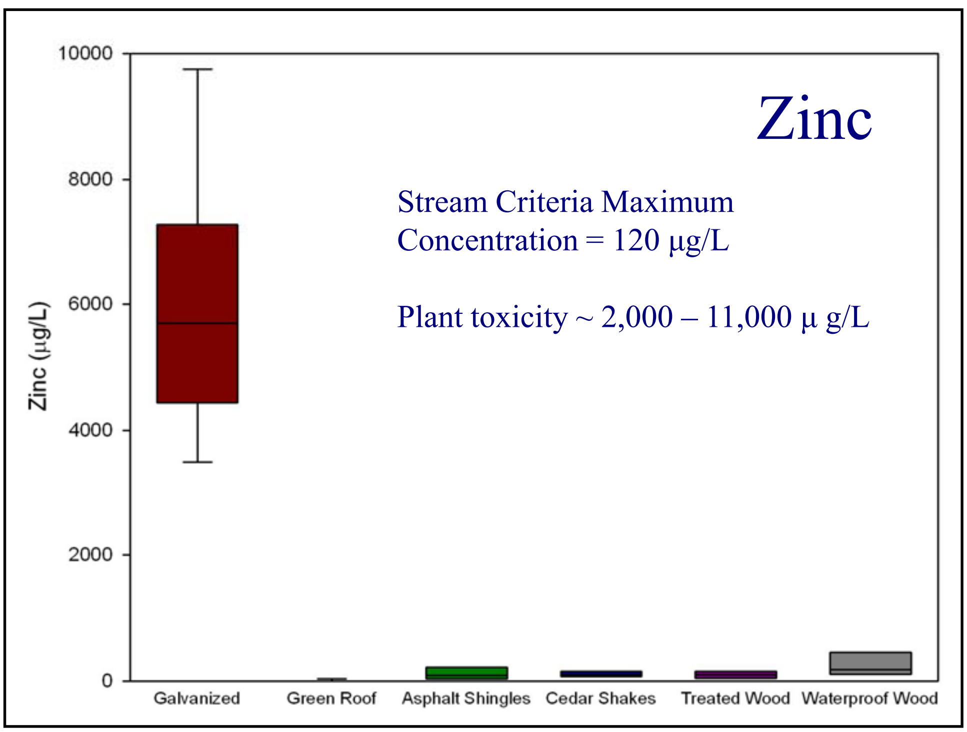


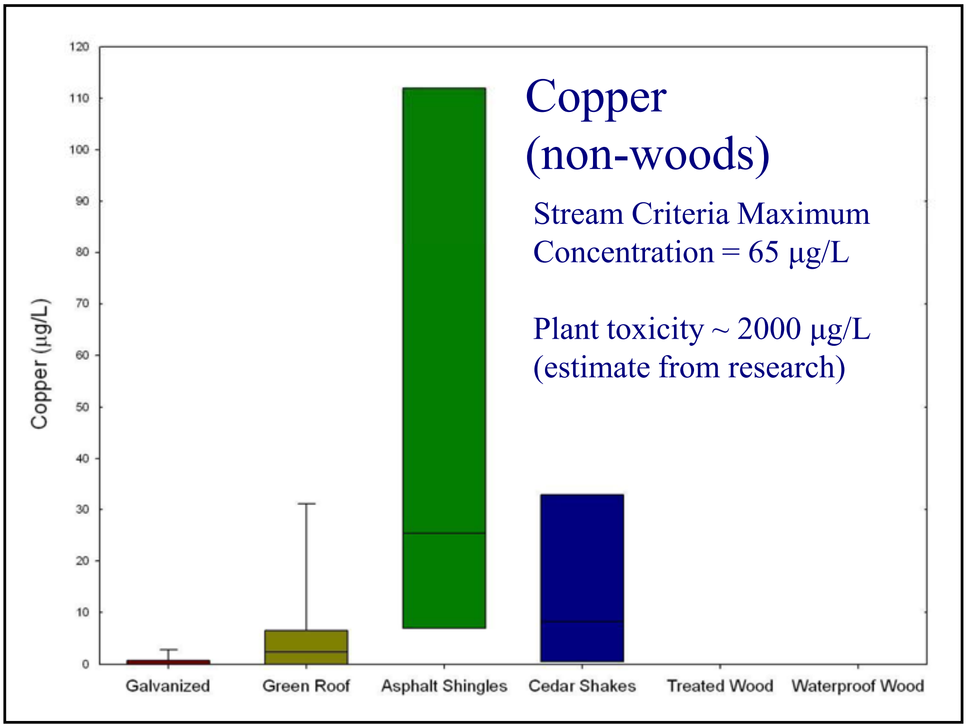


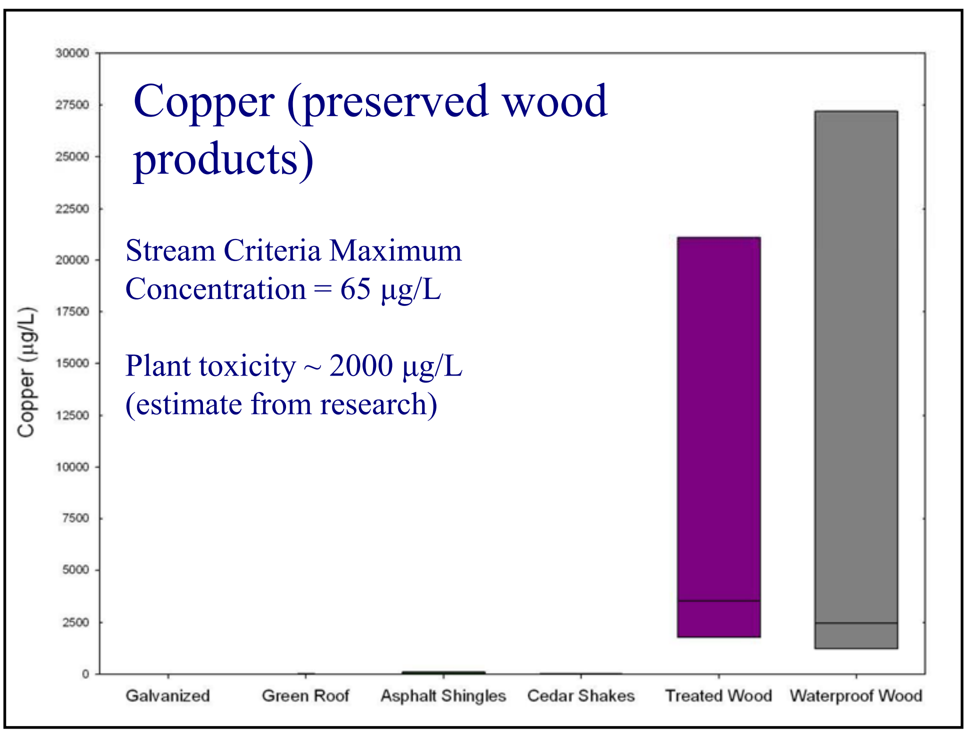




Roof runoff quality over first year of life.




Copper
(non-woods)
Stream Criteria Maximum
Concentration = 65 µg/L
Plant toxicity ~ 2000 µg/L
(estimate from research)
Copper (µg/L)
120
110
100
90
80
70
60
50
40
30
20
10
0
Galvanized
Green Roof
Asphalt Shingles
Cedar Shakes
Treated Wood
Waterproof Wood

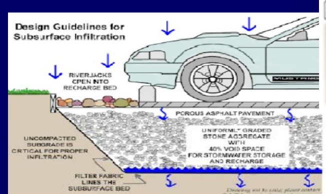

Copper (preserved wood
products)
Stream Criteria Maximum
Concentration = 65 µg/L
Plant toxicity ~ 2000 µg/L
(estimate from research)
Copper (µg/L)
30000
27500
25000
22500
20000
17500
15000
12500
10000
7500
5000
2500
0
Galvanized
Green Roof
Asphalt Shingles
Cedar Shakes
Treated Wood
Waterproof Wood

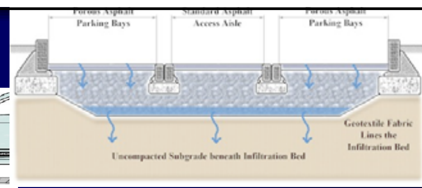
Infiltration

General Types of Devices

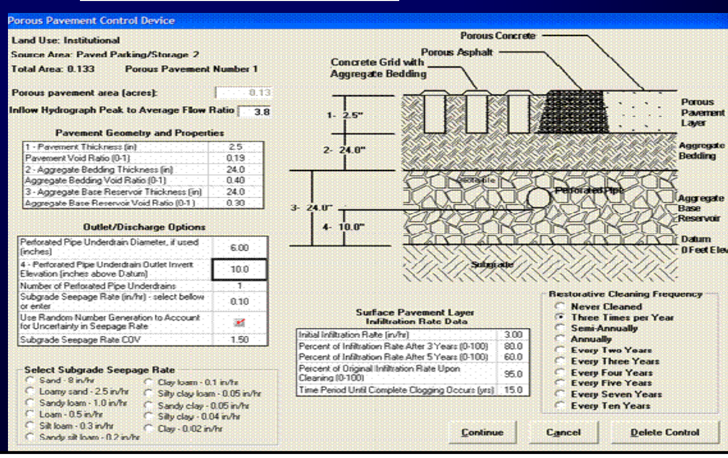
Design Concerns

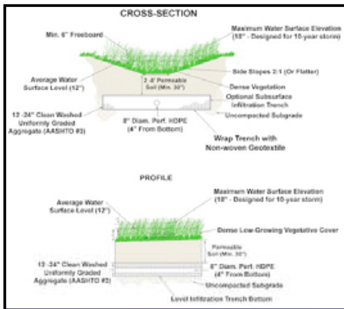
Porous Pavement Design

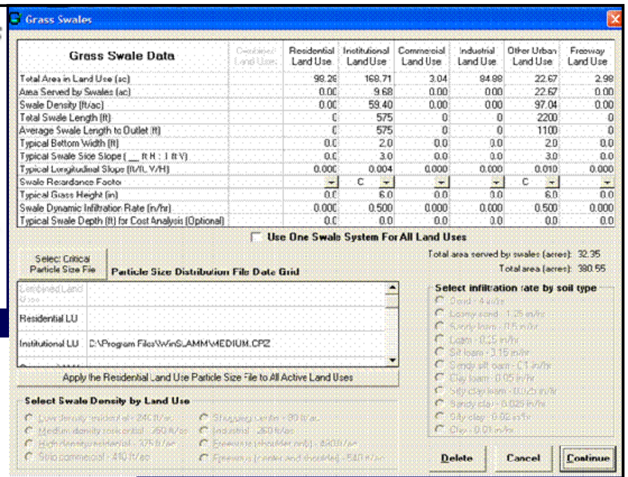




PADEP, 2006







Q_p = C * i * A = 57.13 cfs

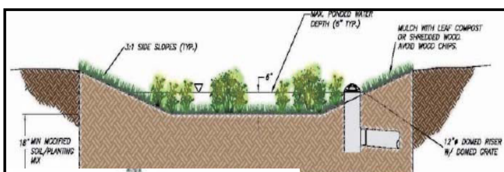
Q_p = peak discharge (cfs)
C = runof coefficient, 0.72 (McCuen, 2004)
i = 3.5 in/hr, rainfall instensity calculated for a 10 year storm event
A = drainage area, 22.67 acres

Effective Shear Stress

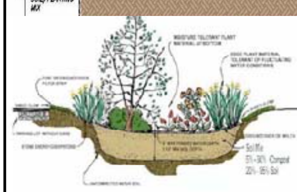
$$\tau_e = \delta * D * S\,(1-Cf) \left(\frac{n_s}{n}\right)^2 = 0.025 \text{ lb/ft}^2 \quad (1$$

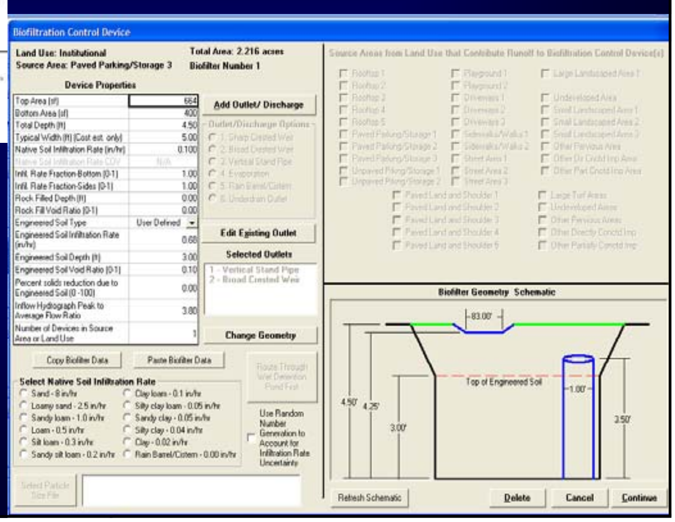
τ_e = effective shear stress on soil beneath vegetation
δ = specific wt of water, 62.4 lb/ft^3
D = max flow depth in cross section, 1 ft (PADEP, 2006)
S = hydraulic slope, 0.01 ft/ft
C_f = vegetation cover factor, 0.75 (Pitt *et al* , 2007)
n_s = roughness coefficient of soil, 0.02 (Pitt *et al* , 2007)
n = roughness coefficient of vegetation, 0.05 (Pitt *et al* , 2007)

Grass Swale/Filter Strip Design



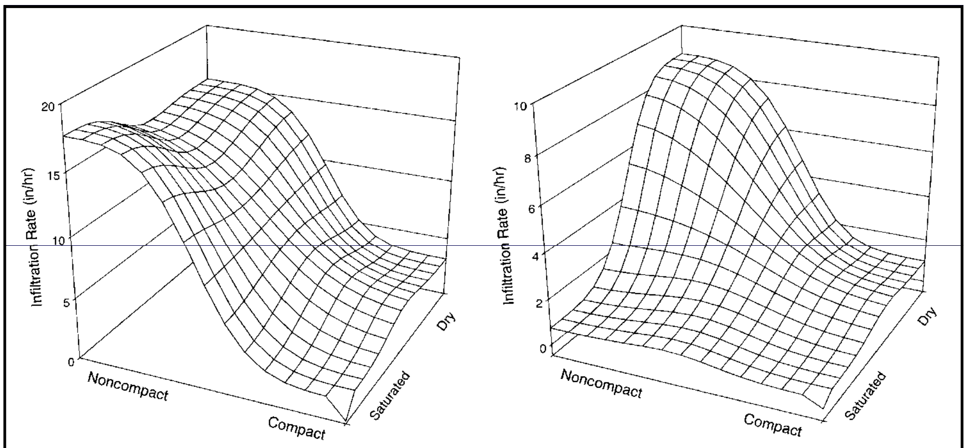
PADEP, 2006





Soil Compaction and Recovery of Infiltration Rates

- Typical site development dramatically alters soil density.
- This significantly reduces infiltration rates, especially if clays are present.
- Also hinders plant growth by reducing root penetration (New Jersey NRCS was one of the first groups that researched this problem).
- Compaction should be prevented in areas selected for infiltration. Position equipment outside the area.



Disturbed Sandy Urban Soils

Disturbed Clayey Urban Soils

Pitt, *et al.* 1999

Long-Term Sustainable Average Infiltration Rates

Soil Texture	Compaction Method	Dry Bulk Density (g/cc)	Long-term Average Infilt. Rate (in/hr)
Sandy Loam	Hand	1.595	35
	Standard	1.653	9
	Modified	1.992	1.5
Silt Loam	Hand	1.504	1.3
	Standard	1.593	0.027
	Modified	1.690	0.0017
Clay Loam	Hand	1.502	0.29
	Standard	1.703	0.015
	Modified	1.911	<<0.001

Compaction, especially when a small amount of clay is present, causes a large loss in infiltration capacity.

Pitt, *et al.* 2002

Solutions to Compaction Problems

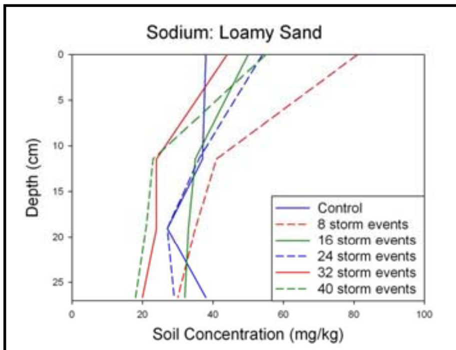
- Use soil amendments to improve existing soil structure or restore soil structure after construction
- Remove soil layer with poor infiltration qualities
- Replace soil with improved soil mix
  - Mix sand, organic matter, and native soil (if no clay)
- Use deep rooted plants or tilling to improve structure (but only under correct moisture conditions)
  - Chisel plow, deep tilling, native plants
- Pre-treat water
- Select different site

Typical household lawn aerators are ineffective in restoring infiltration capacity in compacted soils.

Chemical Changes Affecting Soil Infiltration Rates

$$SAR = \frac{Na^{+}}{\sqrt{\frac{(Ca^{+2} + Mg^{+2})}{2}}}$$

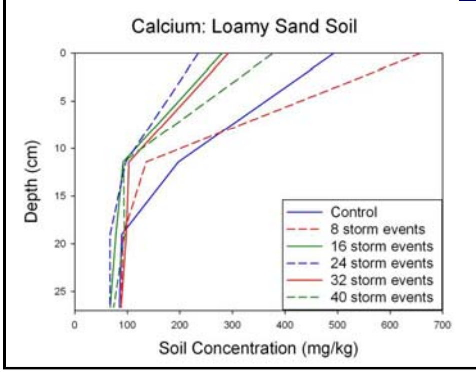
- Sodium adsorption ratio (SAR)
  - From agriculture
  - Noted that as the ratio of sodium concentrations to the square root of the calcium and magnesium concentrations increased, soil clays dispersed and soil became impenetrable.
- SAR > 15 indicates excess of sodium adsorbed
- SAR > 4 can cause decreased infiltration rates in clay soils
- SAR > 2 can cause decreased infiltration rates in loam soils
- Gypsum as a soil amendment can resolve problems.

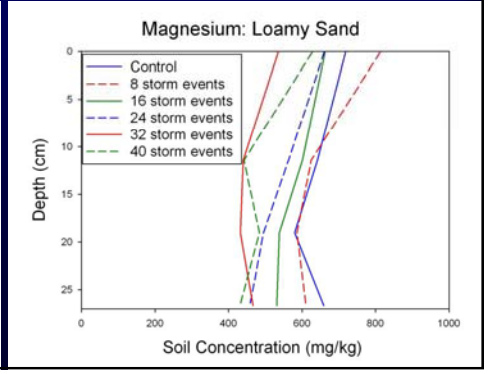


Changes in Soil Chemistry over Time

Minimal to no change in sodium and calcium.
Potential decrease in magnesium.

May result in increase in SAR and infiltration rate.



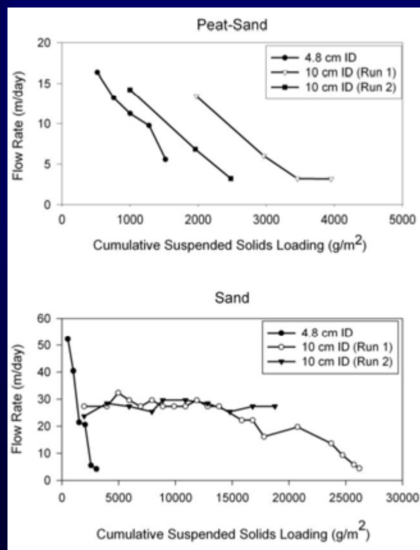


Clogging and Pretreatment

- Infiltration devices, especially non-vegetated ones, clog over time.
  - Soil testing of infiltration rate at design only looks at initial conditions.
  - Many states require initial high infiltration rates because of clogging concerns.
  - However, this may eliminate slow infiltration sites (which may work well over time with solids pretreatment).
- Clogging may be predicted (Urbonas 1999):

$$u = k_i \bullet L_m^{-c}$$

Clogging Predictions and Pretreatment of Solids



Small sediment forebay also reduces the amount of infiltration bed area requiring maintenance.

Groundwater Contamination Concerns

- Must address potential groundwater contamination.
  - Residential stormwater (typically the largest fraction of total runoff volume) can generally be safely infiltrated, if use surface infiltration practices.
  - Commercial runoff likely would require pre-treatment.
- Possible to amend or replace soils.
  - Soil amendments should contain low phosphorus to prevent phosphorus migration from the soil to the groundwater.
  - Use cation and anion exchange capacity to predict lifespan of soil media for pollutant removal. (NOTE: CEC and AEC are pH-dependent <u>and</u> several metals are more soluble at the pHs seen in native PA soils).

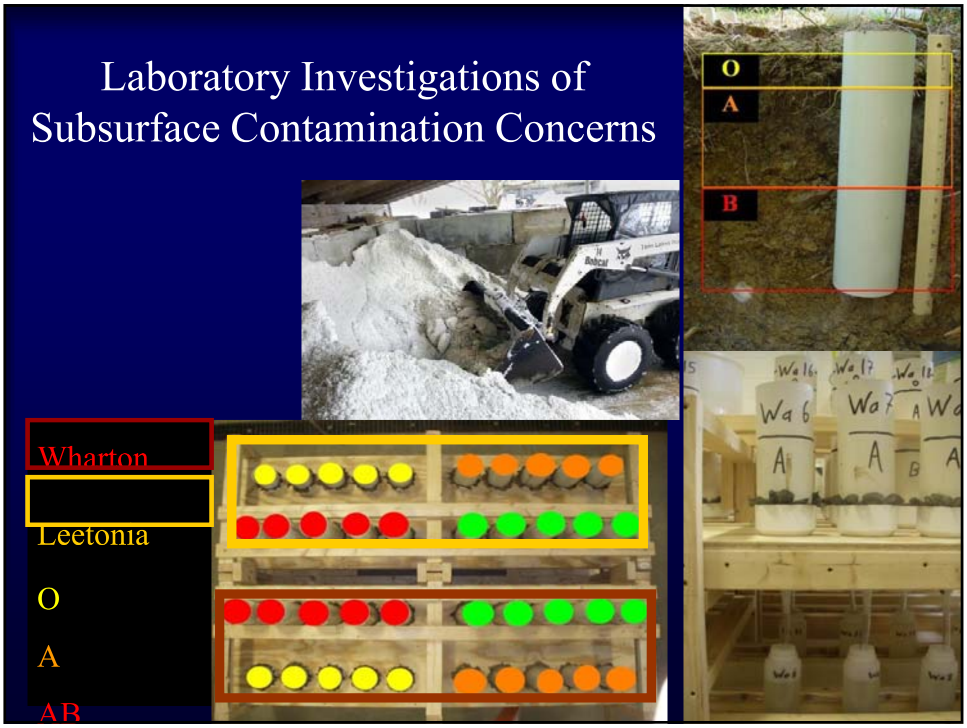
Benefits of Urban Stormwater Infiltration/Soil Media Treatment?

	Biofilter-Grass Swale		Biofilter-Grass Swale		Biofilter-Grass Swale	
Analytical Parameter	**Inflow**	**Outflow**	**Inflow**	**Outflow**	**Inflow**	**Outflow**
Ammonia, Total as N (mg/L)	0.1192	**0.05027**	0.1192	**0.0305**	0.1192	0.1246
Calcium, Total (mg/L)	9.579	11.43	9.579	11.98	9.579	9.155
Chloride, Total (mg/L)	1.006	1.658	1.006	1.438	1.006	1.767
Copper, Total (µg/L)	10.05	**4.047**	10.05	**3.604**	10.05	10.4
Iron, Total (mg/L)	419.1	**98.81**	419.1	**64.6**	419.1	**331.2**
Lead, Total (µg/L)	4.763	**1.965**	4.763	**2.045**	4.763	**3.577**
Magnesium, Total (mg/L)	1.081	**0.5604**	1.081	**0.3621**	1.081	**0.4085**
Manganese (µg/L)	12.59	**6.765**	12.59	**2.08**	12.59	13.79
Nitrate, Dissolved (mg/L)	0.2716	0.29	0.2716	**0.1696**	0.2716	0.2689

Source: International Stormwater BMP Database

Is Groundwater or Soils Contamination of Concern?

- Mass Balance (Conservation of Mass):
  Input = Output
- If reduction seen between surface inflow and outflow, then the pollutants either are (1) trapped in the infiltration device or (2) transported in the subsurface below the device.
- How likely are they to be transported "far enough" to cause problems?


Laboratory Investigations of
Subsurface Contamination Concerns
O
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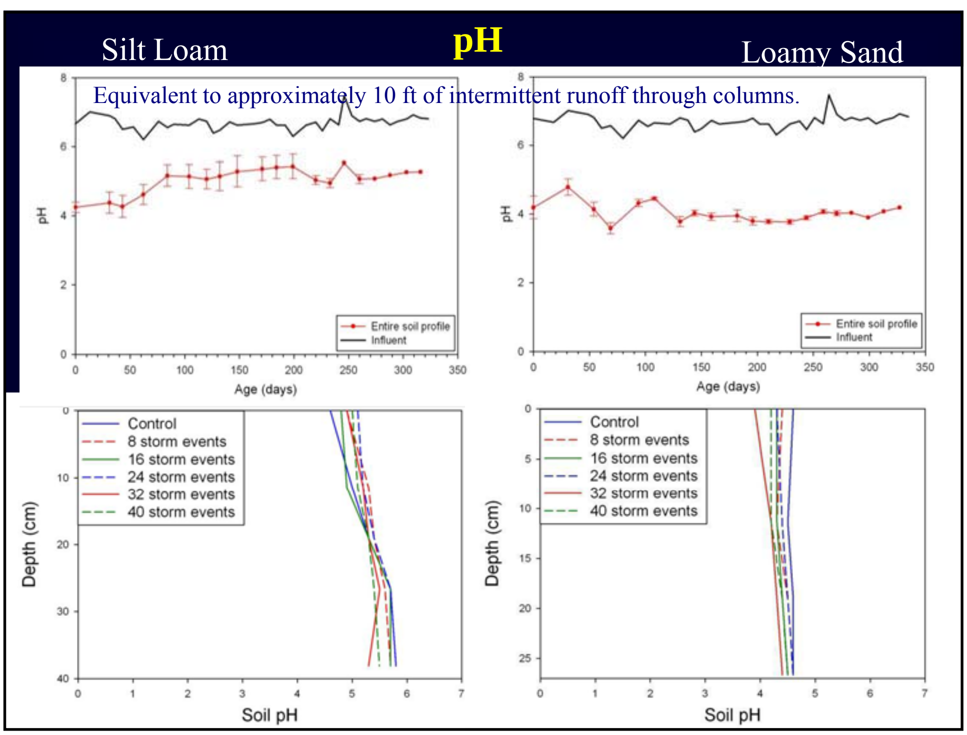
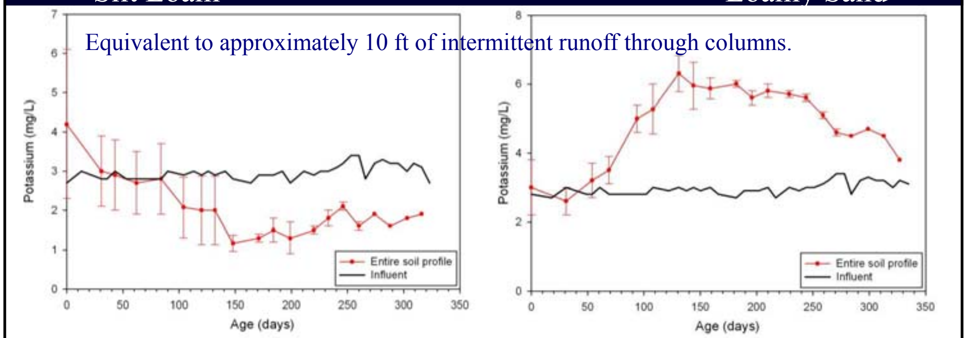
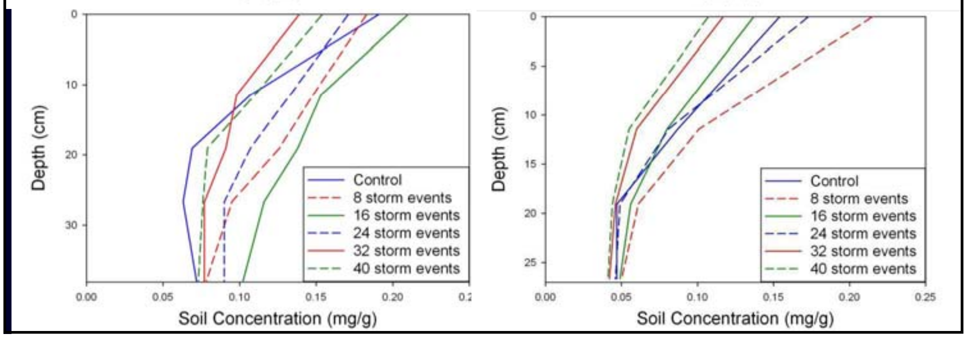

Silt Loam
pH
Loamy Sand
Equivalent to approximately 10 ft of intermittent runoff through columns.
pH
Age (days)
Entire soil profile
Influent
Depth (cm)
Soil pH
Control
8 storm events
16 storm events
24 storm events
32 storm events
40 storm events

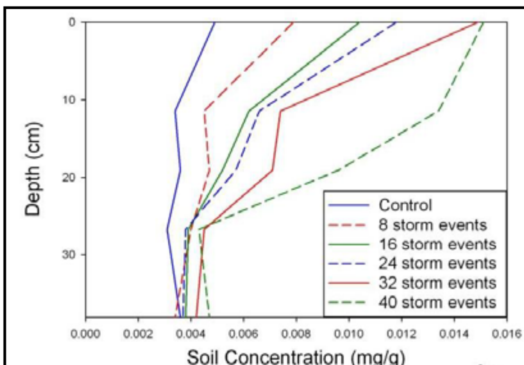
Potassium

Silt Loam | Loamy Sand

Equivalent to approximately 10 ft of intermittent runoff through columns.

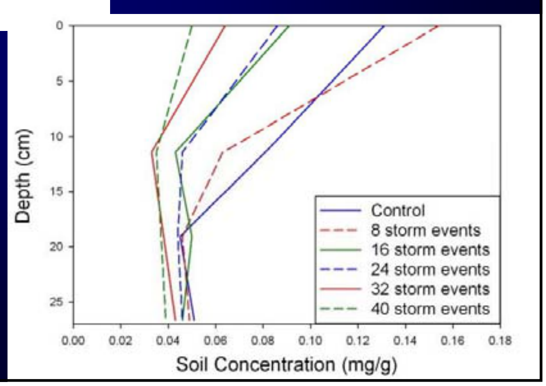






Soil Accumulation of Toxic Metals and Loss of Beneficial Nutrients

Copper
(extracted by Mehlich 3)



Magnesium
(extracted by Mehlich 3)

Groundwater Contamination Concerns

- Why did groundwater contamination occur in some areas and not in others?
  - Depth to water table
  - Soil Type
  - Pollutant interaction with the soil
- Models can be used to predict depth of pollutant penetration in the subsurface.
  - Two types of models:
    - Simple, Linked Model
    - Computer Vadose Zone Model

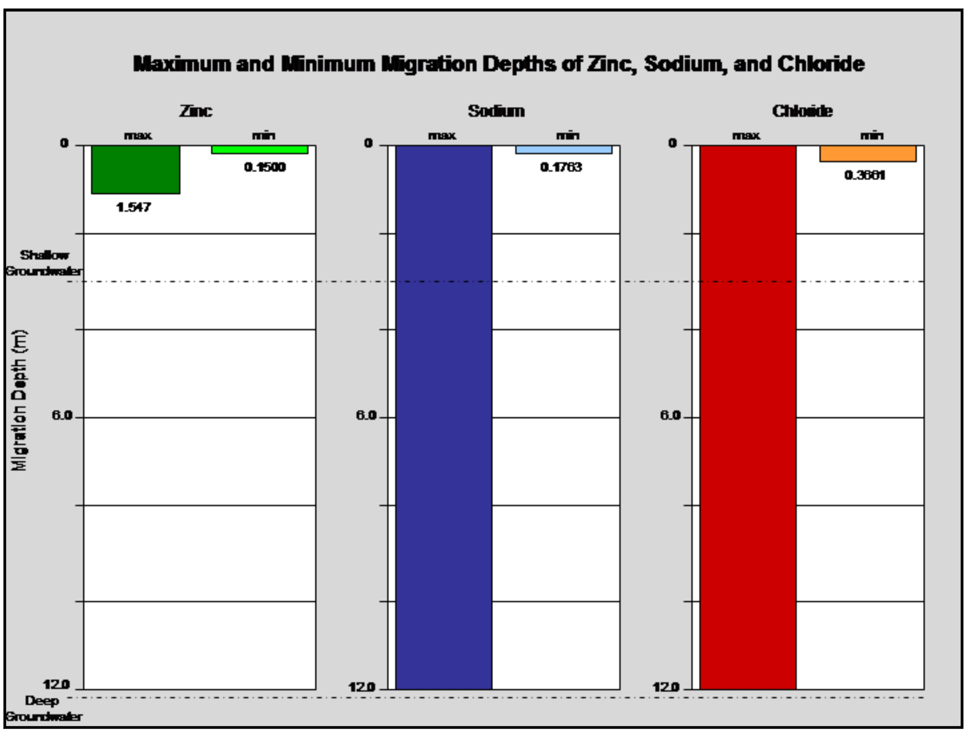
Simple Weak-Linked Model for Potential Problem Pollutants

Model incorporates information about soils and pollutants to predict migration potential, including:

- Pollutant abundance in stormwater,
- Pollutant mobility through the unsaturated zone above the groundwater (related to soil characteristics), and
- Pollutant treatability before discharge.

Computer Modeling Objectives

- Determine the controlling factors (and interactions) have the greatest influence on the migration of selected pollutants (Zn and NaCl) in the vadose zone.
- Improve the siting and design of infiltration devices.
  - Create infiltration devices that encourage groundwater recharge while reducing or preventing groundwater contamination.
- Evaluate use of factorial analysis to determine where to focus data collection to support modeling efforts.



Issues to be Addressed in Stormwater Infiltration Design

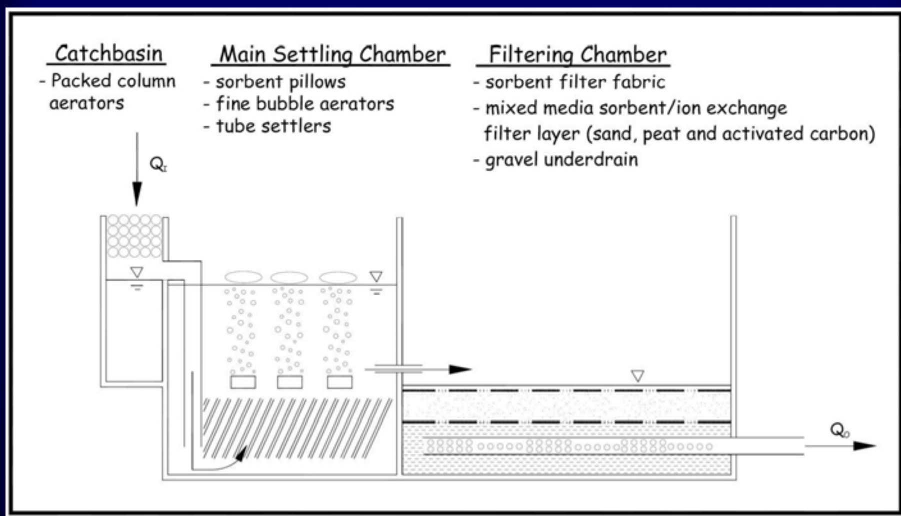
- Poor infiltration capabilities for many urban soils. Therefore:
  - Requiring less infiltration in clayey soils than in sandy soils may need to be adjusted because of compaction vs. soil texture effects.
  - Designs of infiltration practices (“size”) should be more closely related to the impervious-surface areas and runoff solids concentration than to soil texture.
  - Soil disturbance (compaction) is also a critical factor hindering infiltration but can at least be partially controlled.

Critical Source Area Controls

- Control/treatment still required for areas where runoff is polluted.
  - Treatment of water prior to either infiltration/groundwater recharge or discharge to surface receiving water.
- Common Control Technologies:
  - Oil/grease/solids separators
  - Filters
  - Ion exchange/sorption
  - Chemical addition

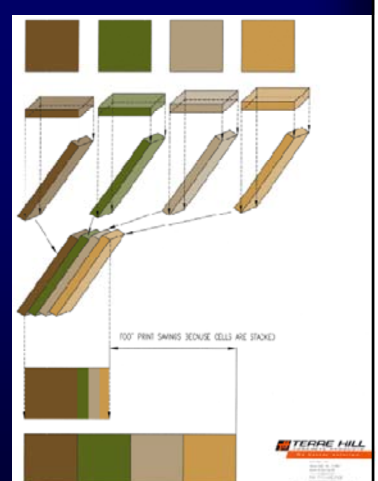
MCTT Cross-Section

(Pitt et al. 1999)



Inclined Plate Settlers

- Common in water treatment industry.
- Reduces settling distance and scour potential.
- Increases effective surface area.
  - Performance Increase based on inclined cells that overlap each other. Each cell forms the ceiling of the next cell, etc.
  - Projected area of each base forms the settling surface of each cell. Horizontal distance between each plate is fraction of horizontal projection of the cell base.
    - If plates relatively flat and close together, increase in performance greater than if plates are steeper and wider apart.
    - Effective increase is usually about 3 to 5 fold, and in the drinking water industry where this technology has been studied and optimized, the increase has been about 10 fold.



New Development or Retrofit

Narrow streets with angled parking draining to bioretention

Green = green roof

Blue = bioretention

Red = rejuvenated detention basin/ballfields

Orange = pervious pavement

The Stormwater Design Train of Thought

Pollution Prevention

- **Public Education**
- **Spill Prevention**
- **Used Oil Recycling**
- **Lawn Chemical Mgt.**
- **Construction Mtl. Selection**

Infiltration and Rainwater Harvesting

- **Rainwater Capture**
- **Bioretention**
- **Filter Strips and Swales**
- **Porous Pavement**
- **Infiltration**

Pre-treatment/Treating Critical Source Area Runoff

- **Sediment Forebays**
- **Ponds**
- **In-line, High-rate Treatment**
- **WWTP**