

# Potential Groundwater Contamination Associated with Stormwater Infiltration and Recommended Practices

Robert Pitt, University of Alabama

Plus many colleagues, clients, undergraduate and graduate students who assisted in various aspects of this research

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## Introduction

- Scattered information is available addressing groundwater quality impacts in urban areas. Major information sources include:
  - Historically known high chlorides under northern cities
  - EPA 1983 NURP work on groundwater beneath Fresno, CA, and Long Island, NY, infiltration basins
  - NRC 1994 report on groundwater recharge using waters of impaired quality
  - USGS work on groundwater near stormwater management devices in Florida and Long Island
  - A number of communities throughout the world (including Phoenix, AZ; WI; FL; Tokyo; plus areas in France, Denmark, Sweden, Switzerland, and Germany, etc.)

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## Research Elements/Methodology

- Our research on stormwater and groundwater interactions began during an EPA cooperative agreement to identify and control stormwater toxicants, including groundwater impact potential associated with infiltration.
- Our first efforts were based on extensive literature reviews for reported groundwater data beneath urban areas and management options.
- Initial stormwater - groundwater impact report published by EPA (1994) and Lewis Publishers, CRC Press (1996).
- Have since continued to investigate pollutant fates in amended and natural soils and filtration media, plus updated literature reviews and have conducted many modeling and lab/field investigations on the transport of urban pollutants. An updated report was recently prepared for WERF (Clark, *et al.* 2009).

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## Presentation Outline

- Conservation design objectives
- Common infiltration practices
- Targeted flows for infiltration
- Identifying potential infiltration problems
- Recommendations to reduce contamination potential
- Soil characteristics and amendments
- Recent and current research results and applications

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## Conservation Design Objectives

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## Watershed-Based Stormwater Controls

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)

These approaches emphasize infiltration, however, other stormwater treatment approaches will also likely be required to meet the wide range of beneficial use objectives of urban receiving waters.

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## Conservation Design Approach for New Development

- Better site planning to maximize resources of site (natural drainageways, soils, open areas, etc.)
- Emphasize water conservation and stormwater use on site
- Encourage infiltration of runoff at site (after proper treatment)
- Treat stormwater at critical source areas
- Treat and manage stormwater that cannot be infiltrated at the site

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## Common Infiltration Practices

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## Stormwater Infiltration Practices in Urban Areas

- Roof drain (and other impervious area) disconnections
- Bioretention areas
- Rain gardens and amended soils
- Porous pavement and paver blocks
- Grass swales and infiltration trenches
- Percolation ponds
- Dry/injection wells, perforated inlets, bottomless catchbasins, etc.

These controls have varying groundwater impact potentials

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## Rain Gardens can be Designed for Complete Infiltration of Roof Runoff



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Permeable paver blocks have been used in many locations to reduce runoff to combined systems, reducing overflow frequency and volumes (Sweden, Germany, and WI examples here), but should not be used where de-icing salts are applied.

Essen, Germany

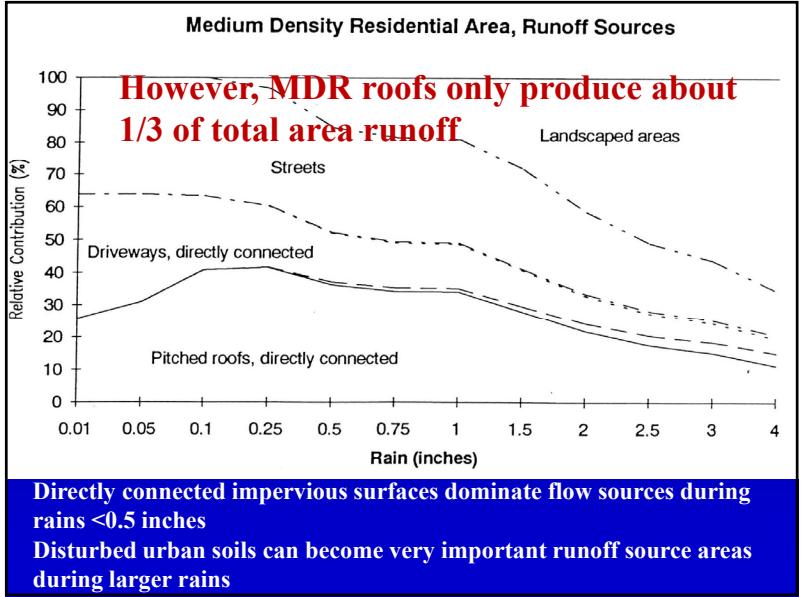
Malmo, Sweden

Madison, WI

### Calculated Benefits of Various Roof Runoff Controls (compared to typical directly connected residential pitched roofs)

Annual roof runoff volume reductions for typical medium density residential 1500 ft <sup>2</sup> roof (modeled using WinSLAMM)	Birmingham, Alabama (55.5 in.)	Seattle, Wash. (33.4 in.)	Phoenix, Arizona (9.6 in.)
Cistern for use of runoff for toilet flushing and irrigation (10 ft. diameter x 5 ft. high)	66	67	88%
Planted green roof (but will need to irrigate during dry periods)	75	77	84%
Disconnect roof drains to loam soils	84	87	91%
Rain garden with amended soils (10 ft. x 6.5 ft.) (4.3% of roof area)	87	100	96%

There are therefore a number of potential controls for roof runoff, from the conventional to the unusual, that can result in large runoff reductions.



## Targeted Flows for Infiltration

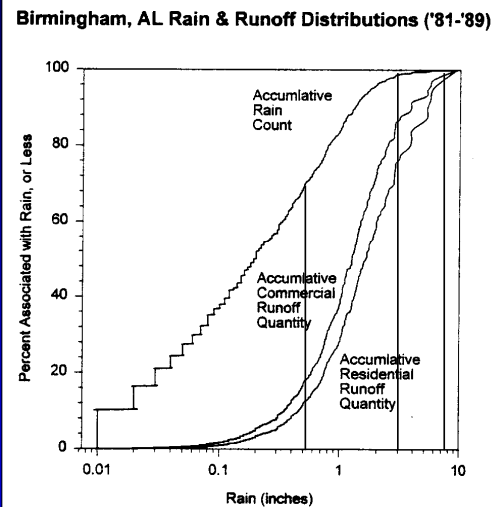
**Probability distribution of typical Alabama rains (by count) and runoff (by depth).**

<0.5": 65% of rains  
(10% of runoff)

0.5 to 3": 30% of rains  
(75% of runoff)

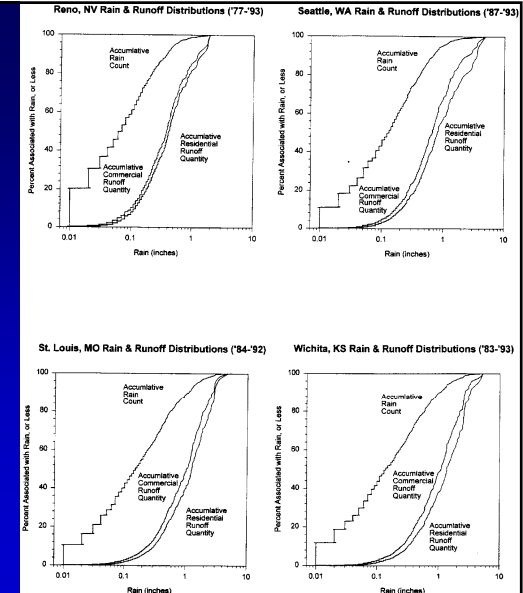
3 to 8": 4% of rains  
(13% of runoff)

>8": <0.1% of rains  
(2% of runoff)

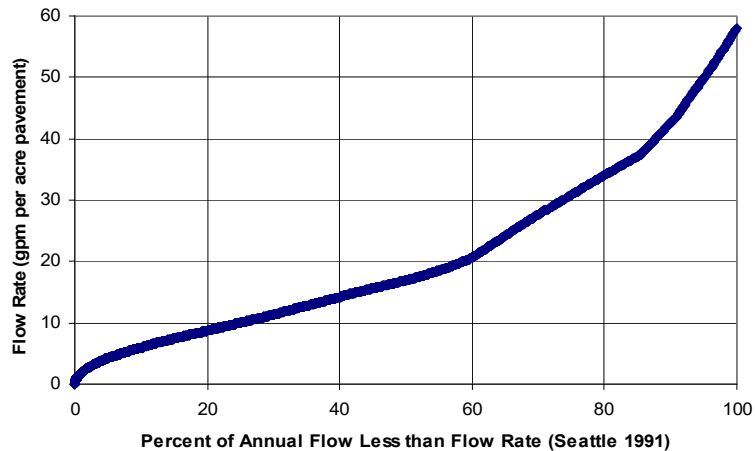


EPA report on wet weather flows, Pitt, *et al.* 1999

Same general distribution pattern in other parts of the country, just shifted.



Pitt, *et al.* (1999)



Runoff flow rate distribution for Seattle paved area for a typical rain year (without extreme events). The highest flows shown here are about 1/3 to 1/2 of the flow rates for the southeastern US.

**Identifying Potential Infiltration Problems**

## Areas of Concern Affecting Groundwater Contamination Potential (weak-link model):

- **Presence of constituent in stormwater** (function of flow phase and source area/land use)
- **Mobility of constituent in vadose zone** (function of soil and constituent properties)
- **Treatability of constituent** (mostly a function of constituent association with particulates and infiltration device design)

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## EPA Research Efforts

- Sources of pollutants were monitored
- Classes of stormwater constituents that may adversely affect groundwater quality were evaluated:
  - Nutrients
  - Pesticides
  - Other organics
  - Microorganisms
  - Metals
  - Salts

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## Nutrients

- Nitrates are one of the most frequently encountered contaminants in groundwater, mostly in agricultural areas and where septic tanks are used (very mobile, but relatively low stormwater concentrations).
- Phosphorus contamination of groundwater has not been as widespread, or as severe, as that of nitrogen compounds (less mobile, but in higher concentrations in stormwater).

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## Heavy Metals

- Studies of recharge basins receiving large metal loads found that most of the heavy metals are removed by sedimentation, or in the first few inches of soil.
- Order of attenuation in the vadose zone from infiltrating stormwater varies, but generally is: zinc (most mobile) > lead > cadmium > magnesium > copper > iron > chromium > nickel > aluminum (least mobile)

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## Pesticides

- The greatest pesticide mobility occurs in areas with coarse-grained or sandy soils, without a hardpan layer.
- Pesticides decompose in soil and water, but the total decomposition time can range from days to years.
- Pesticide mobility can be retarded or enhanced depending on soil conditions (Henry's Law and soil adsorption constants).

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## Microorganisms

- Viruses have been detected in groundwater where stormwater recharge basins were located short distances above the aquifer.
- Factors affecting survival of bacteria and viruses in soil include pH, antagonism, moisture, temperature, sunlight, and organic matter.
- The major bacterial removal mechanisms in soil are straining at the soil surface and at intergrain contacts, sedimentation, sorption by soil particles, and inactivation.

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## Salts

- Sodium and chloride travel down through the vadose zone to the groundwater with little attenuation.
- Studies of depth of penetration in soil have shown that sulfate and potassium concentrations decrease with depth, whereas sodium, calcium, bicarbonate, and chloride concentrations increase with depth.

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## Example Weak-Link Model Influencing Factors

Constituent	Abundance in Stormwater	Mobility (sandy/low organic soils)	Filterable Fraction (problems with treatability)
Nitrates	low/moderate	mobile	high
Chlordane	moderate	intermediate	very low
Anthracene	low	intermediate	moderate
Pyrene	high	intermediate	high
Lead	low/moderate	very low	very low

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### **Links Depend on Infiltration Method (contamination potential is the lowest rating of the influencing factors)**

- Surface infiltration with no pretreatment (pavement or roof disconnections)
  - **Mobility and abundance** most critical
- Surface infiltration with sedimentation pretreatment (treatment train: bioretention area after wet detention pond; or effective grass swale)
  - **Mobility, abundance, and treatability** all important
- Subsurface injection with minimal pretreatment (infiltration trench in parking lot or dry well)
  - **Abundance** most critical (if present, then a problem!)

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### **Example Applications: Low Abundance**

- Abundance is important for all cases, therefore if a constituent is in low abundance in stormwater, the groundwater contamination potential will “always” be low, irrespective of infiltration method.
- Examples for most areas include: 2-4-D, VOCs, anthracene, naphthalene, and cadmium; some areas may have higher concentrations of these constituents, with an increased contamination potential.

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### **Example Application: No Pretreatment Before Infiltration through Surface Soils (such as for pavement disconnection)**

- Mobility also considered.
- If a compound is mobile, but in low abundance in the stormwater (such as for nitrates in most urban areas), the contamination potential is low.
- If compound is mobile and also in high abundance (such as chlorides in cold regions that use salt de-icers), the contamination potential would be high.

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### **Example Application: Sedimentation Pretreatment Before Biofiltration (treatment train)**

- All three factors considered
- Chlordane would have low contamination potential with sedimentation pretreatment (because much of the chlordane would be removed), even though it has moderate abundance and intermediate mobility.
- If no pretreatment, the chlordane contamination potential would be moderate.

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## Moderate to High Contamination Potential

Surface Infiltration with no Pretreatment	Surface Infiltration after Sedimentation	Injection after Minimal Pretreatment
Lindane, chlordane		Lindane, chlordane
Benzo (a) anthracene, bis (2-ethylhexyl phthalate), fluoranthene, pentachlorophenol, phenanthrene, pyrene	Fluoranthene, pyrene	<b>1,3-dichlorobenzene</b> , benzo (a) anthracene, bis (2-ethylhexyl phthalate), <b>fluoranthene</b> , pentachlorophenol, phenanthrene, <b>pyrene</b>
<b>Enteroviruses</b>	<b>Enteroviruses</b>	<b>Enteroviruses, some bacteria and protozoa</b>
		<b>Nickel</b> , chromium, lead, <b>zinc</b>
<b>Chloride</b>	<b>Chloride</b>	<b>Chloride</b>

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## Modeling of Pollutant Movement in the Subsurface Below Infiltration Devices

- Mass Balance (Conservation of Mass):  
Input = Output - Storage



- If difference calculated between the vadose zone inflow and outflow, then the pollutants are trapped in the vadose zone media or water pore space.
- Various groundwater and seepage models were used to determine likely movement of stormwater constituents and to identify the removal processes of most importance.

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## Fate and Transport Reactions and Factorial Analysis

- Ion-exchange
- Hydrolysis
- Complexation
- Adsorption
- Absorption
- Precipitation
- Volatilization
- Microbial Degradation

### Factors

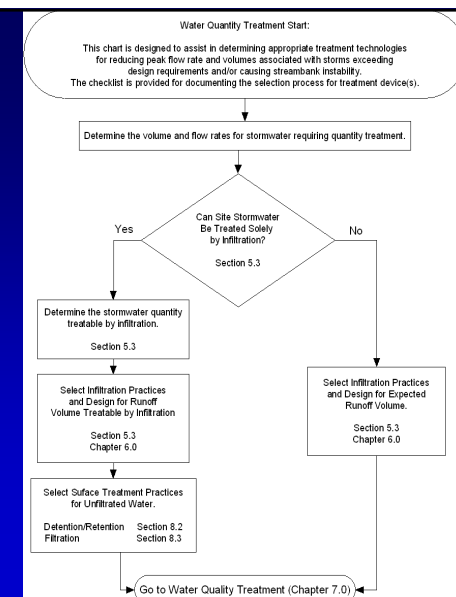
- Intrinsic Permeability
- Soil pH
- Soil Organic Matter
- Rainfall
- Pollutant Concentration
- Vadose Zone Thickness

Factor	High	Low
<b>Concentration (mg/L)</b>		
Zinc	2.1	0.032
Sodium	1360	28
Chloride	2040	42
<b>Rainfall Location and Depth (cm)</b>		
West Palm Beach 154	Phoenix 6.7	
<b>Vadose Zone Thickness (cm)</b>		
1200	300	
Intrinsic Permeability (cm <sup>2</sup> )		
1.00E-07	1.00E-10	
Organic Content (%)		
3	0.5	
pH		
7.2 - 8.0	4.3 - 5.0	

Clark, et al. 2009 (for WERF)

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## Developing Guidance for Selecting Infiltration vs. Surface Treatment Practices (Clark, et al. 2009 WERF report)



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## Recommendations to Reduce Infiltration Problems

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## Recommendations to Reduce Groundwater Contamination Potential when using Infiltration Controls in Urban Areas

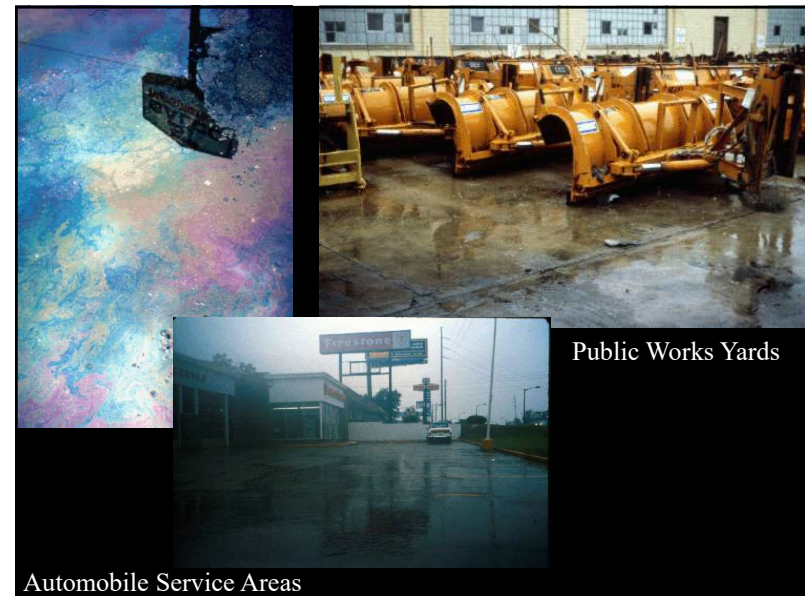
- Combined sewer overflows should be diverted from infiltration devices because of poor water quality.
- Snowmelt runoff should be diverted from infiltration devices because of high concentrations of salts.
- Construction site runoff must be diverted from infiltration devices due to rapid clogging.

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## Recommendations to Reduce Groundwater Contamination Potential when using Infiltration in Urban Areas (cont.)

- Infiltration devices should not be used in most industrial areas without adequate treatment.
- Runoff from critical source areas (mostly in commercial areas) need to receive adequate treatment prior to infiltration.
- Runoff from residential areas (the largest component of urban runoff in most cities) is generally the least polluted and should be considered for infiltration.

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Junkyards and Scrap Metal Storage Areas

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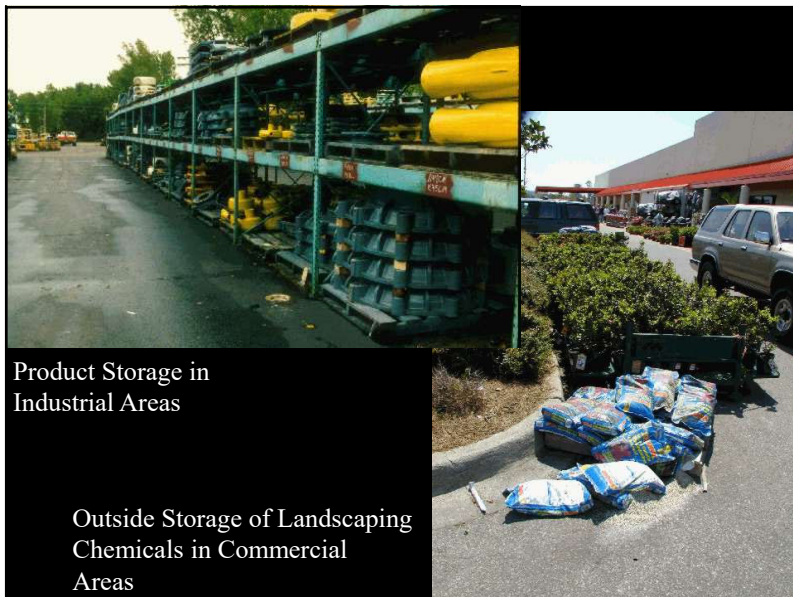


Rapid Turnover Automobile Parking

Utility Storage Areas

Outdoor Treated Wood Storage Areas

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Product Storage in Industrial Areas

Outside Storage of Landscaping Chemicals in Commercial Areas

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Combined Sewer Overflows

Construction Site Runoff

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## Recommended Stormwater Monitoring to Evaluate Potential Groundwater Contamination

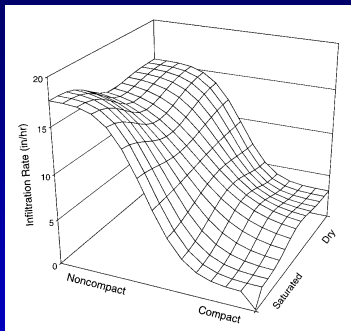
- Most stormwater quality monitoring efforts have not adequately evaluated stormwater's potential for contaminating groundwater.
- Urban runoff contaminates with the potential to adversely affect groundwater:
  - Nutrients (especially nitrates)
  - Salts (especially chlorides), VOCs, Pathogens
  - Bromide and TOC (if considering disinfection)
  - Pesticides, and other organics
  - Heavy metals (especially filterable forms)
- Other stormwater and soil constituents that affect long-term performance of infiltration devices:
  - sediment and psd, SAR, CEC, alkalinity, etc.

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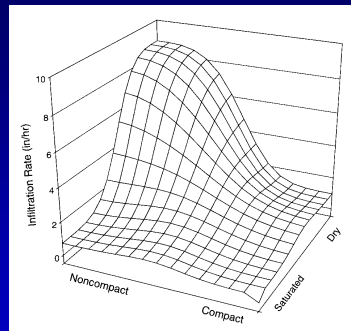
## Soil Characteristics and the use of Amendments to Minimize Groundwater Contamination Potential

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### Infiltration Rates in Disturbed Urban Soils (AL tests)



Sandy Soils



Clayey Soils

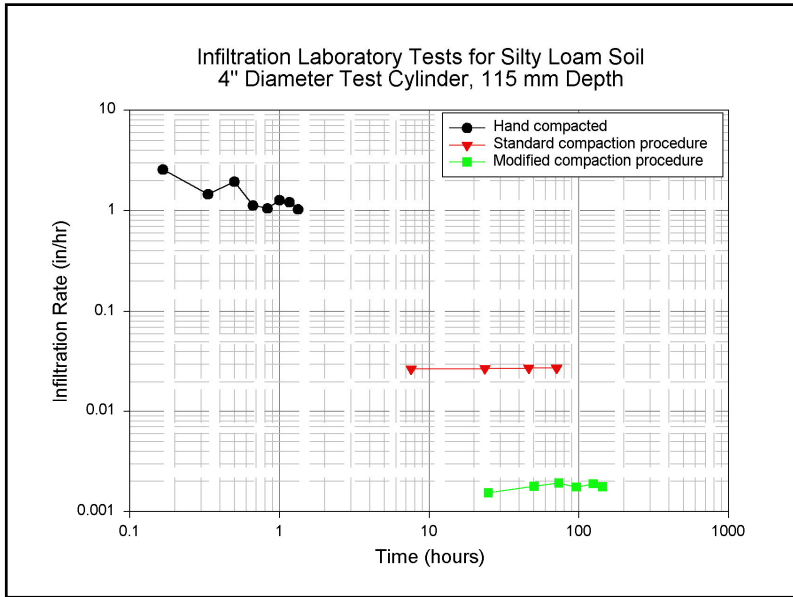
Field measurements have shown that the infiltration rates of urban soils are strongly influenced by compacted, probably more than by moisture levels.

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### Disturbed Urban Soils during Land Development



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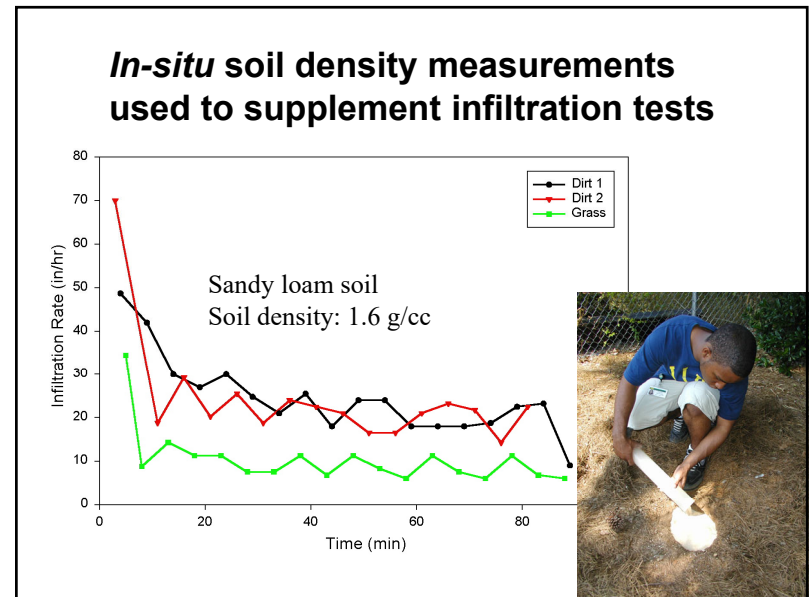
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## Long-Term Sustainable Average Infiltration Rates

Soil Texture	Compaction Method	Dry Bulk Density (g/cc)	Effects on Root Growth (per NRCS)	Long-term Average Infiltr. Rate (in/hr)
Sandy Loam	Hand	1.595	May Affect	35
	Standard	1.653	May Affect	9
	Modified	1.992	Restrict	1.5
Silt Loam	Hand	1.504	May Affect	1.3
	Standard	1.593	May Affect	0.027
	Modified	1.690	May Affect +	0.0017
Clay Loam	Hand	1.502	May Affect	0.29
	Standard	1.703	Restrict	0.015
	Modified	1.911	Restrict	0

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## Effects of Compost-Amendments on Runoff Properties

- Another portion of the EPA research was conducted by Dr. Rob Harrison, of the University of Washington
- They examined the benefits of adding large amounts of compost to glacial till soils at the time of land development

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## Soil Modifications and Rain Gardens



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## Amended Soil Compared to Unamended Soil

Constituent	Surface Runoff Mass Discharges	Subsurface Flow Mass Discharges
Runoff Volume	0.09	0.29 (losses due to ET)
Phosphate	0.62	3.0
Ammonia	0.56	4.4
Nitrate	0.28	1.5
Copper	0.33	1.2
Zinc	0.061	0.18

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## Water Quality and Quantity Effects of Amending Urban Soils with Compost

- Surface runoff rates and volumes decreased by five to ten times after amending the soils with compost, compared to unamended sites.
- Unfortunately, the concentrations of many pollutants increased in surface runoff from amended soils, especially nutrients which were leached from the fresh compost.
- However, the several year old test sites had less, but still elevated concentrations, compared to unamended soil only test plots.

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## Many soil processes reduce the mobility of stormwater pollutants

- Ion exchange, sorption, precipitation, surface complex ion formation, chelation, volatilization, microbial processes, lattice penetration, etc.
- If soil is lacking in these properties, then soil amendments can be added to improve the soil characteristics.
- Cation exchange capacity (CEC) and sodium adsorption ratio (SAR) are two soil factors that can be directly measured and water characteristics compared. Other soil processes (especially in complex mixtures) need to be evaluated using controlled experiments.

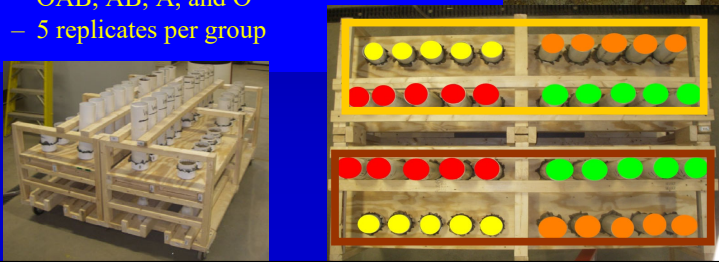
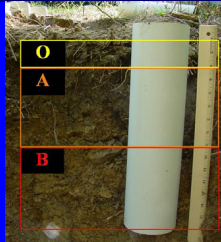
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## Recent and Current Research Results and Applications

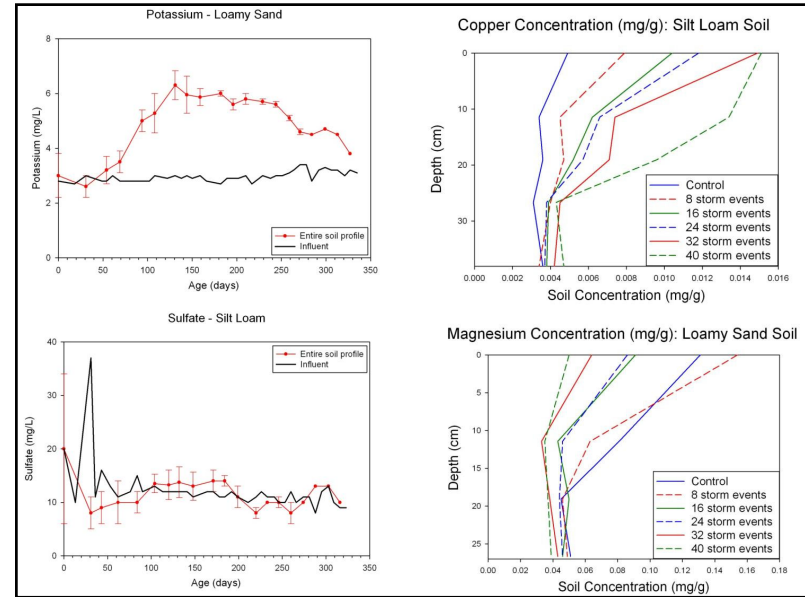
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## Recent Research Conducted at Penn State – Harrisburg to Examine Regional Soil Profiles

- 4-inch PVC drainage pipe used to encase and remove intact soil columns
- 2 soil types
  - Wharton Silt Loam
  - Leetonia Loamy Sand
- each with 20 study columns:
  - 4 test groups of soil horizons OAB, AB, A, and O
  - 5 replicates per group



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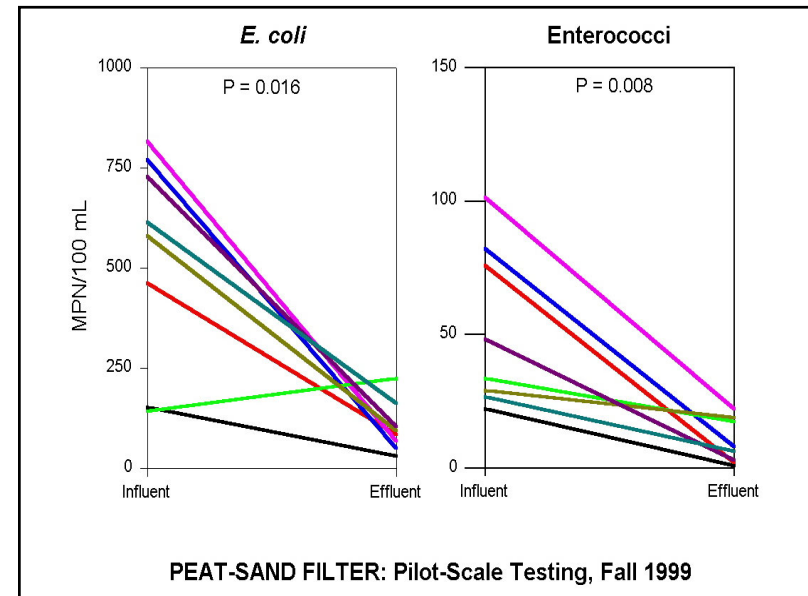


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Controlled column experiments conducted in the field to investigate various soil amendments, filtration media, and soils, with different stormwaters.



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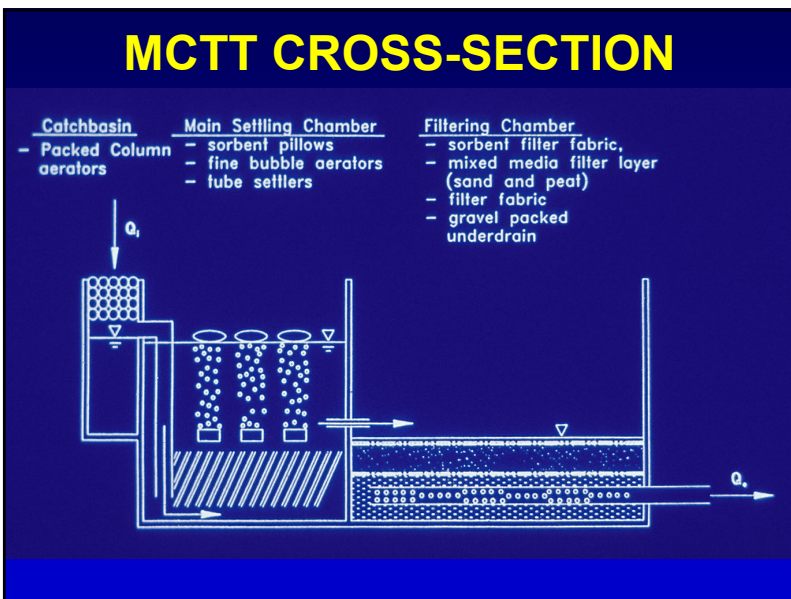


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### The Multi-Chambered Treatment Train (MCTT) was developed to treat stormwater from critical source areas before infiltration

- Developed to abate toxicants in stormwater from critical source areas (vehicle service/parking, storage/maintenance, salvage yards)
- Reductions of > 90% for toxicity, Pb, Zn, organic toxicants
- SS/COD reduced 83%/60%, respectively
- Reductions confirmed at pilot- and full-scale
- Underground device
  - most suited for small areas, 0.1 to 1.0 ha
  - typically sized 0.5 to 1.5 % of paved drainage area
  - sizing requires long-term continuous simulation for specific toxicant reduction based on local hydrology

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## Minocqua, WI, MCTT Installation



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## MCTT Installation, Minocqua, WI :

Inlet chamber



Filter chamber



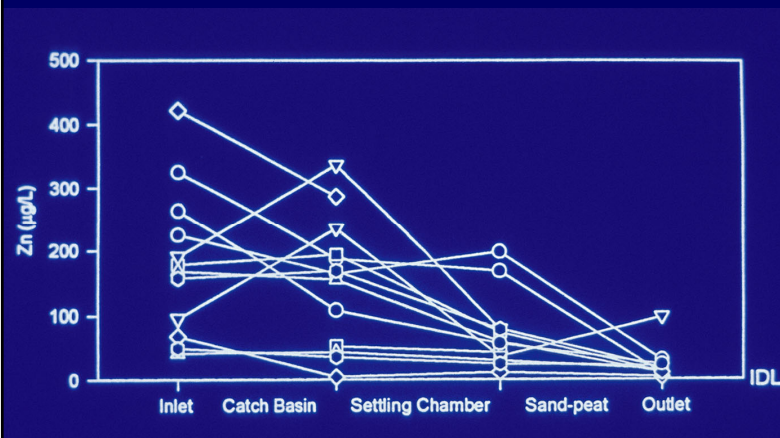
Sedimentation chamber



- Drainage area: 1 ha
- Parking lot: park/commercial area
- Retrofit existing storm drainage
- Settling chamber: 3.0m x 4.6m concrete culverts, 13m long
- Filter chamber: 7.3m long
- Cost: \$95 K

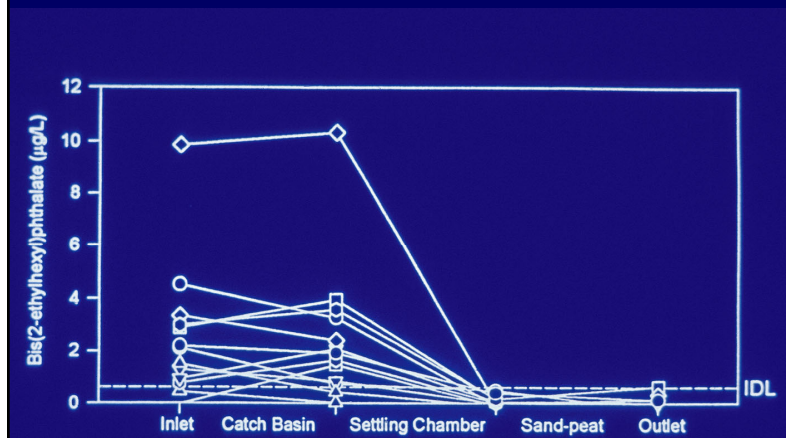
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## Pilot-Scale Test Results



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## Pilot-Scale Test Results



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## MCTT Wisconsin: Median % reductions and median effluent quality

	Milwaukee (15 events)	Minocqua (7 events)
Suspended Solids	98 (<5 mg/L)	85 (10 mg/L)
Phosphorus	88 (0.02 mg/L)	>80 (<0.1 mg/L)
Copper	90 (3 µg/L)	65 (15 µg/L)
Lead	96 (1.8 µg/L)	nd (<3 µg/L)
Zinc	91 (<20 µg/L)	90 (15 µg/L)
Benzo (b) fluoranthene	>95 (<0.1 µg/L)	>75 (<0.1 µg/L)
Phenanthrene	99 (<0.05 µg/L)	>65 (<0.2 µg/L)
Pyrene	98 (<0.05 µg/L)	>75 (<0.2 µg/L)

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## Caltrans Full-Scale MCTT Test Results

	Mean % reductions and mean effluent quality
Suspended solids	80 (6 mg/L)
TKN	35 (0.82 mg/L)
Total Phosphorus	39 (0.11 mg/L)
Copper	38 (5 µg/L)
Lead	50 (3 µg/L)
Zinc	85 (13 µg/L)
Total petroleum hydrocarbons	85 (210 µg/L)
Fecal coliforms	82 (171 MPN/100 mL)

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## Current Milburn, NJ, Monitoring Project to Evaluate Performance and Groundwater Problems Associated with Required Dry Wells



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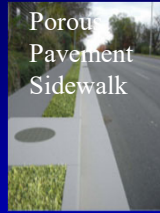
## Preliminary WinSLAMM Modeling for Milburn

	Rv	Runoff volume (ft <sup>3</sup> /year)	Particulate Solids (mg/L)	Particulate Solids (lbs/year)
Base conditions	0.28	28,209	152	268
With drywell for roof and driveway runoff	0.21	21,413	175	234
With above drywell, plus roof cistern for irrigation stormwater use	0.21	21,269	176	233
With above drywell, plus large roof cistern for irrigation stormwater use	0.20	19,914	182	226

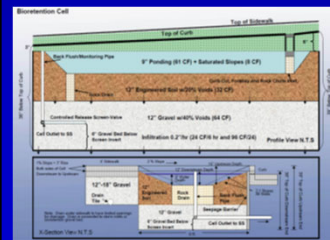
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## Current Kansas City National Demonstration Project: Green Infrastructure for CSO Control

- Conventional CSO evaluations were conducted using XP\_SWMM in order to identify the design storm for the demonstration area that will comply with the discharge permits. XP\_SWMM was also used by KCMO Water Services Department, Overflow Control Program, to examine different biofiltration and porous pavement locations and storage options in the test watershed.



Porous Pavement Sidewalk



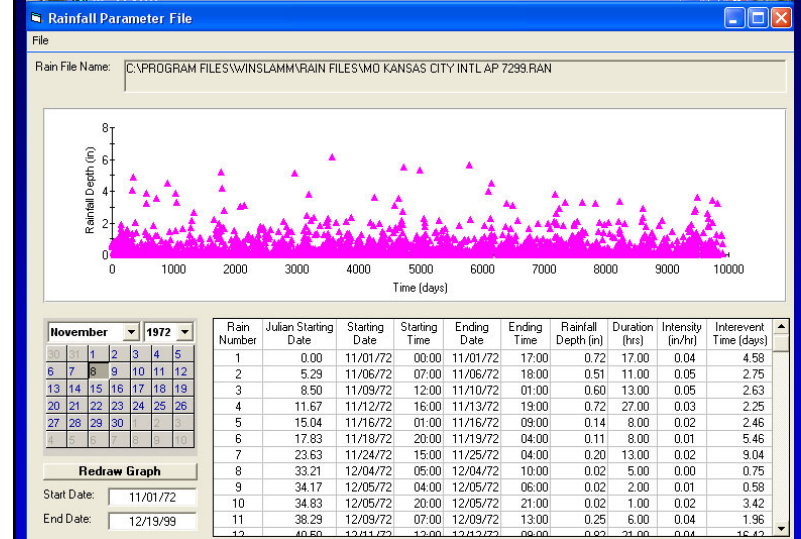
Rain Garden



Bioretention Cell

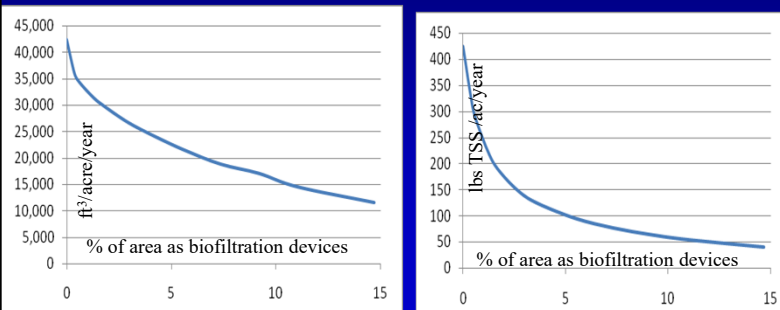
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## Kansas City 1972 to 1999 Rain Series



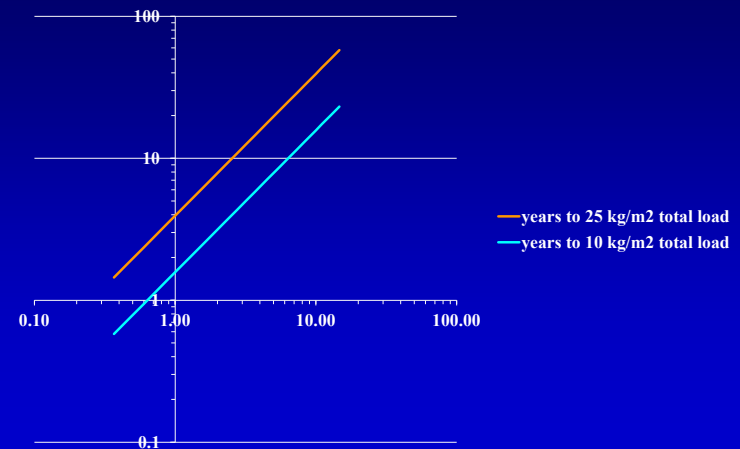
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## Long-Term Continuous WinSLAMM Simulations (28 years) to Examine the Benefits of the Biofiltration Controls for Long-Term Performance



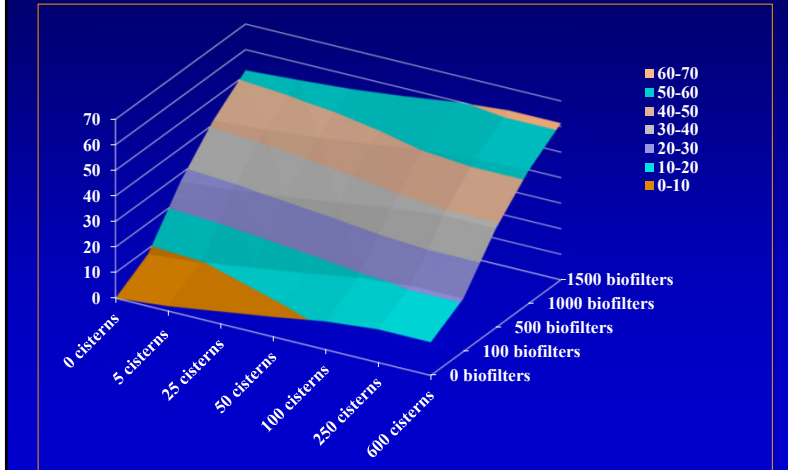
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## Years to clog (10 to 25 kg/m<sup>2</sup> total load) vs. % of area as a biofilter



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## Simultaneous use of cisterns and biofilters in 100 acre site (% annual flow discharge reductions)

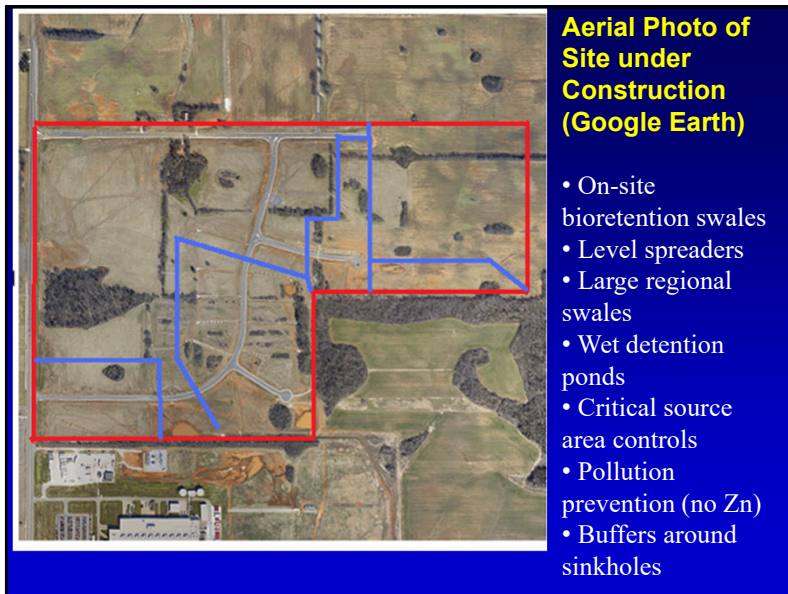


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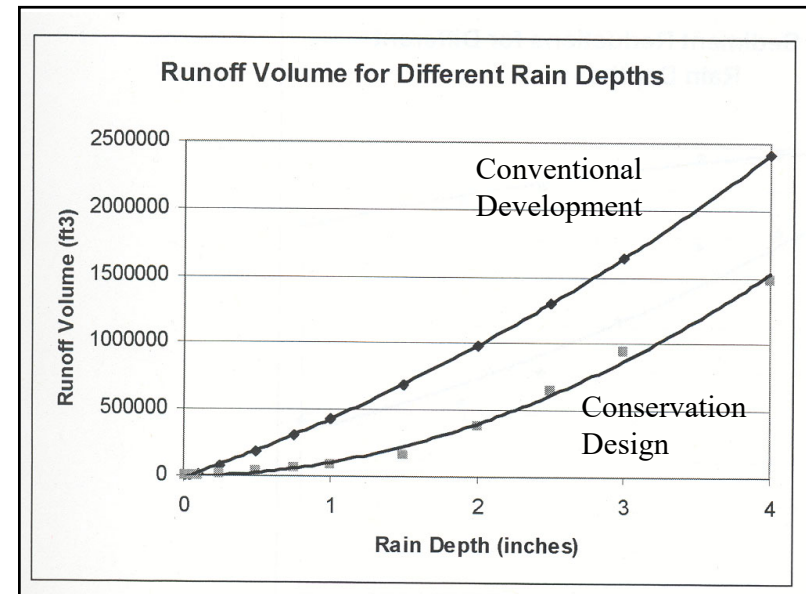
## North Huntsville Industrial Park showing conservation design elements



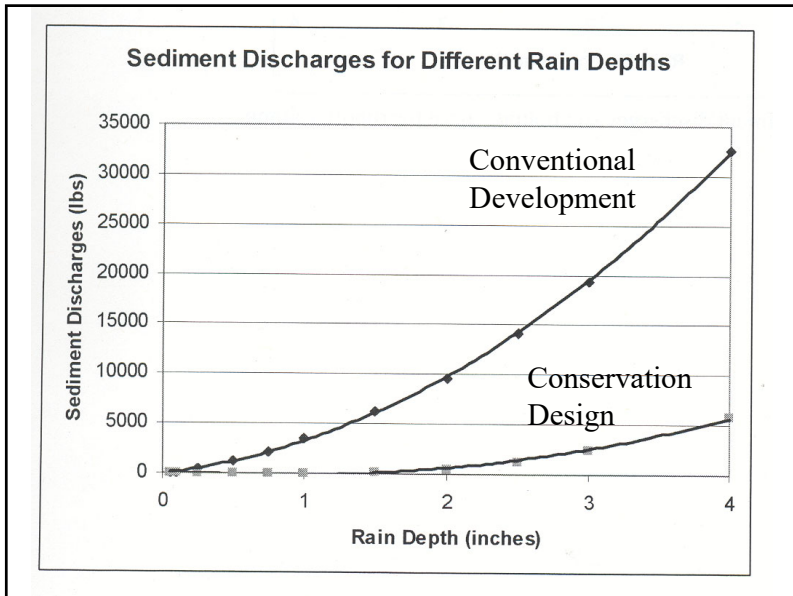
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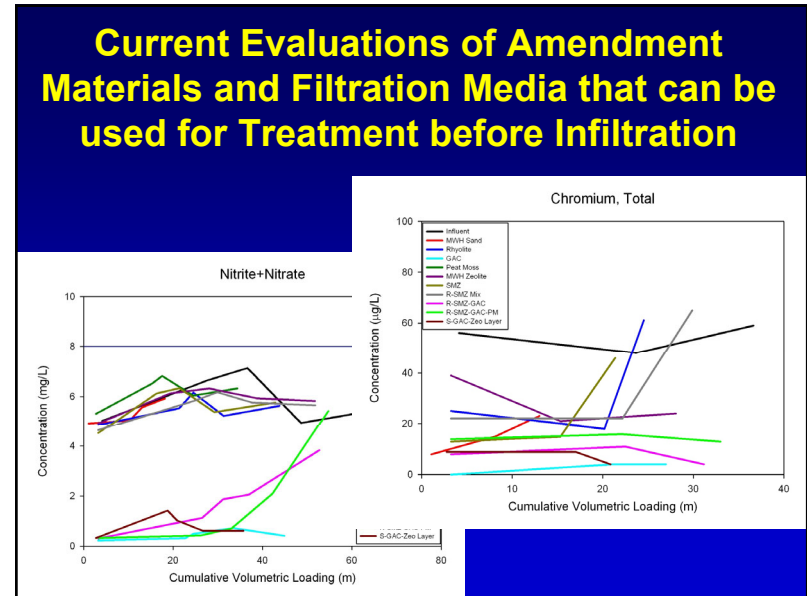
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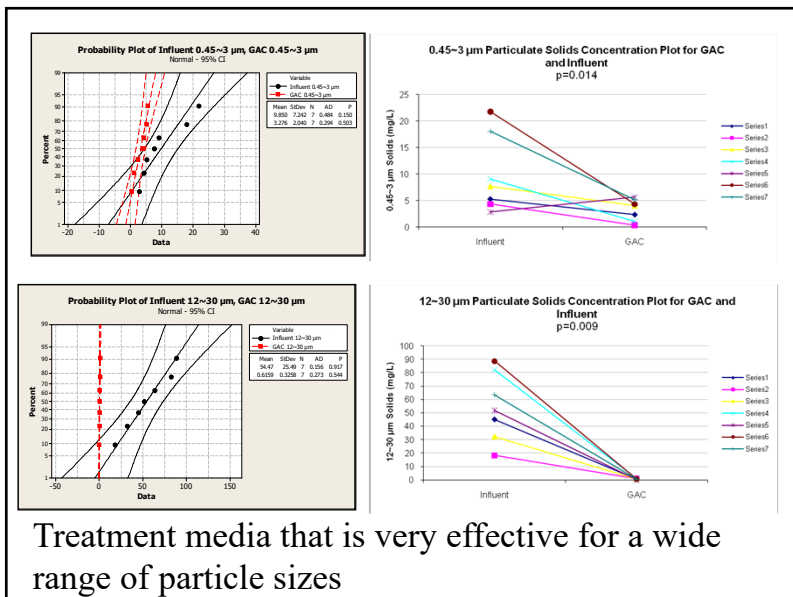
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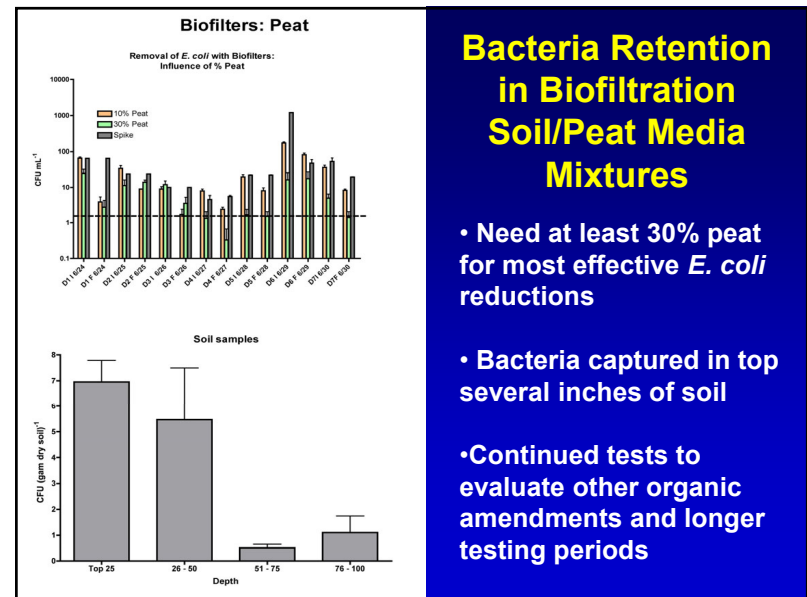


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Treatment media that is very effective for a wide range of particle sizes

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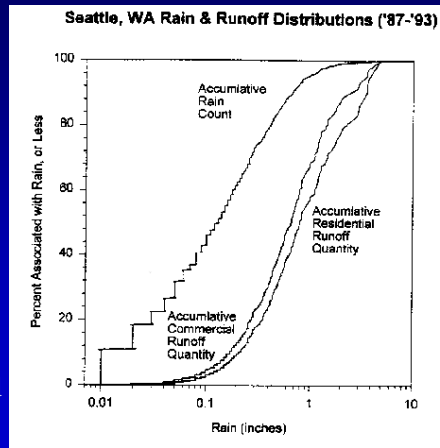
### Bacteria Retention in Biofiltration Soil/Peat Media Mixtures

- Need at least 30% peat for most effective *E. coli* reductions
- Bacteria captured in top several inches of soil
- Continued tests to evaluate other organic amendments and longer testing periods

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## Combinations of Controls Needed to Meet Many Stormwater Management Objectives

- Smallest storms should be captured on-site for use, or infiltrated
- Design controls to treat runoff that cannot be infiltrated on site
- Provide controls to reduce energy of large events that would otherwise affect habitat
- Provide conventional flood and drainage controls



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## Conclusions

- Most of the stormwater toxic organics and metals are associated with the nonfilterable fraction, and are easiest to remove using conventional sedimentation practices.
- Pollutants in filterable forms have a greater potential of affecting groundwater.
- Sorption and ion exchange mechanisms can be used to capture filterable toxicants. These can be enhanced by amending soils in the infiltration area, or by using media filtration as pretreatment.
- "Treatment trains" having multiple components and processes (especially sedimentation and infiltration) offer good solutions in most areas.

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