Day 4: Emerging green and grey infrastructure for combined sewage control

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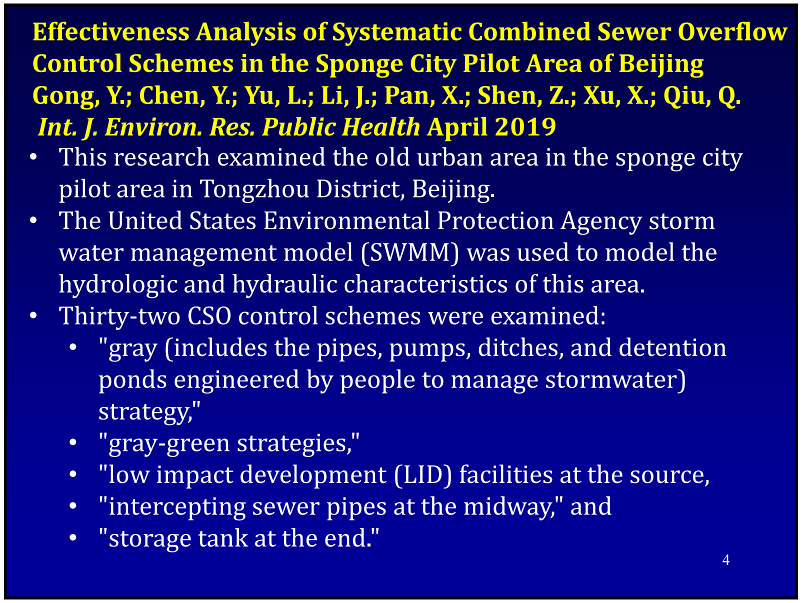
Characterization of Urban Runoff from Combined Sewer and Storm Sewer Catchments in Beijing, China

Che, W, Zhang, W, Liu, D. K., Gan, Y P, Lv, F F
International Conference on Pipelines and Trenchless Technology 2011, Beijing

- Two monitoring systems located in Beijing separate and combined sewer urban catchments have been operating since July 2010.
- COD, TSS, TN, TP, and NH3-N exceeded Class V surface water quality standard developed by Ministry of Environmental Protection (MEP).
- Strong correlation between COD and TSS concentrations, and stronger correlations between TSS and other pollutant cumulative pollutant loads.

Characterization of Urban Runoff from Combined Sewer and Storm Sewer Catchments in Beijing, China (continued)

- First flush was seldom observed in separate stormwater and CSO discharges due to the influence of sewer sediments, sewer system characteristics, catchment characteristics, etc.
- Based on quantitative analysis, urban nonpoint pollution resulting from surface runoff and CSO emissions is recognized as one of the major causes of quality deterioration in the receiving water bodies in Beijing.
- An integrated system, which combines runoff source control and sewer control, will be an effective and economic approach to urban runoff pollution control.



Effectiveness Analysis of Systematic Combined Sewer Overflow Control Schemes in the Sponge City Pilot Area of Beijing

Gong, Y.; Chen, Y.; Yu, L.; Li, J.; Pan, X.; Shen, Z.; Xu, X.; Qiu, Q.
***Int. J. Environ. Res. Public Health* April 2019**

- This research examined the old urban area in the sponge city pilot area in Tongzhou District, Beijing.
- The United States Environmental Protection Agency storm water management model (SWMM) was used to model the hydrologic and hydraulic characteristics of this area.
- Thirty-two CSO control schemes were examined:
  - "gray (includes the pipes, pumps, ditches, and detention ponds engineered by people to manage stormwater) strategy,"
  - "gray-green strategies,"
  - "low impact development (LID) facilities at the source,
  - "intercepting sewer pipes at the midway," and
  - "storage tank at the end."

Effectiveness Analysis of Systematic Combined Sewer Overflow Control Schemes in the Sponge City Pilot Area of Beijing (continued)

- LID resulted in a calculated annual reduction rate of 22% for the CSO frequency and 35% to 49% for the CSO volume.
- The retrofitting of intercepting sewer pipes resulted in a calculated annual reduction rate of 11% for the CSO frequency and 4% to 15% for the CSO volume
- The storage tank resulted in a calculated annual reduction rate from 3% to 36% for the CSO volume;
- A reasonable CSO control target for the study area is not exceeding four overflows per year.

Suggestions for New Sewerage Systems (Richard Field, US EPA)

- Larger diameter sewers to add in-line storage
- Steeper-sloped sewers/more effective bottom cross-sections/sediment traps to reduce sediment deposition
- Treatment plant capacity sized for CSO
- Larger interceptors
- Beneficial use of stormwater
- Blackwater-graywater separation/graywater recycling
- Integrate green & gray infrastructure

What Does EPA Mean by "Green Solutions"?

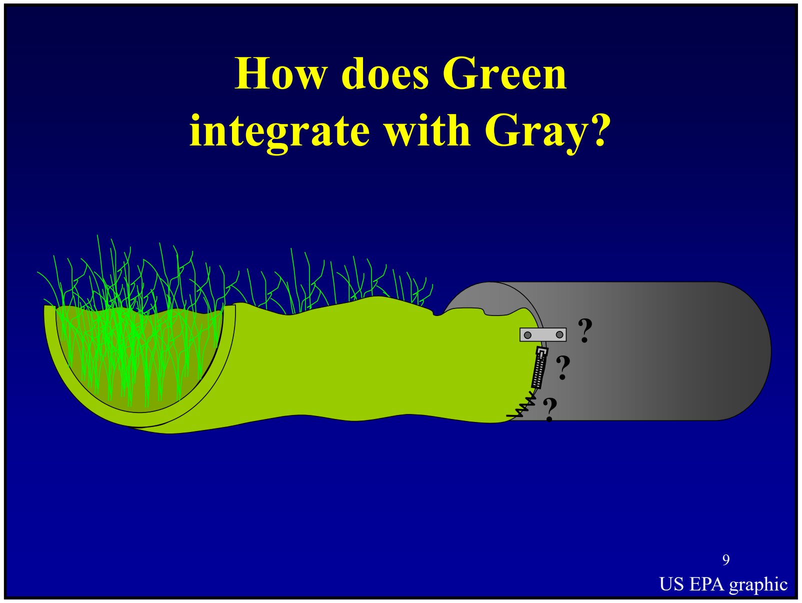
- Green Solutions use natural or engineered systems – e.g., green roofs, bioretention/rain gardens, swales, wetlands, & porous pavement
- These systems mimic natural processes and direct stormwater to areas where it can infiltrate, evapotranspirate, be slowed, and beneficially used
- Green Solutions generally are a subset of sustainable infrastructure
- Green Solutions can provide many environmental benefits

Green Solutions Can Have Multiple Community Benefits

- **Water quality**
- **Flood and hydromodification control**
- **Rainwater capture and use**
- **CSO/SSO control**
- **Increased groundwater recharge and baseflow**
- **Improved air quality**
- **Reduced energy consumption**

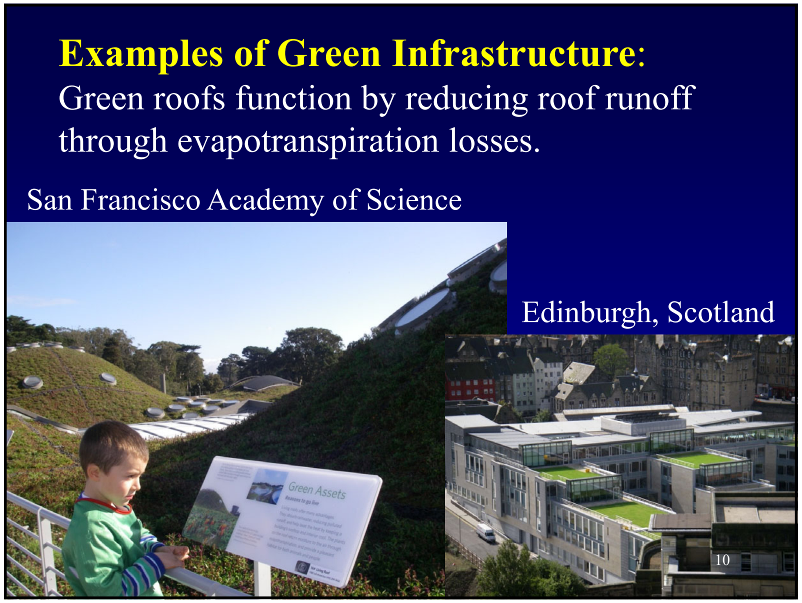
- **Cost savings**
- **Community identity**
- **Recreational greenspace**
- **Reduced urban heat island effect**
- **Wildlife habitat**
- **Enhanced property values**
- **Carbon sequestering**
- **Aesthetics**

(from Ben Grumbles, US EPA March 5, 2007 memo)



How does Green integrate with Gray?

US EPA graphic

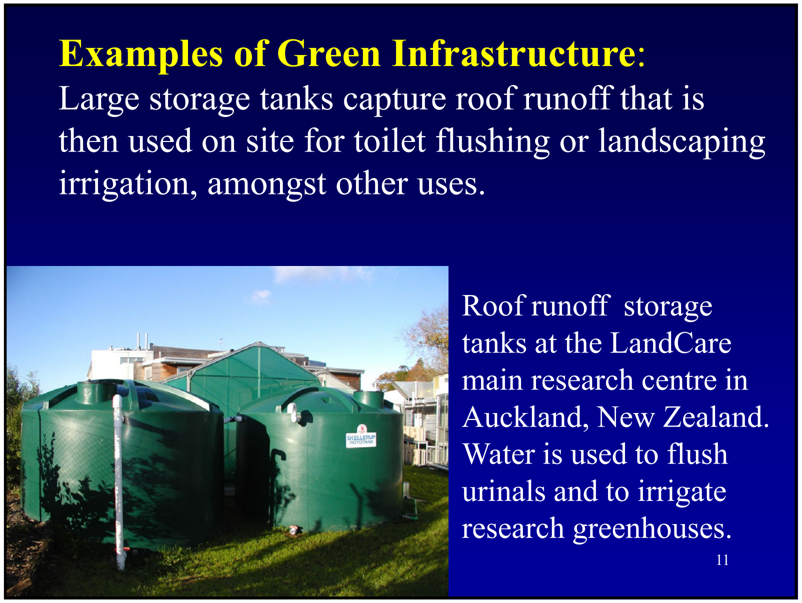


Examples of Green Infrastructure:

Green roofs function by reducing roof runoff through evapotranspiration losses.

San Francisco Academy of Science

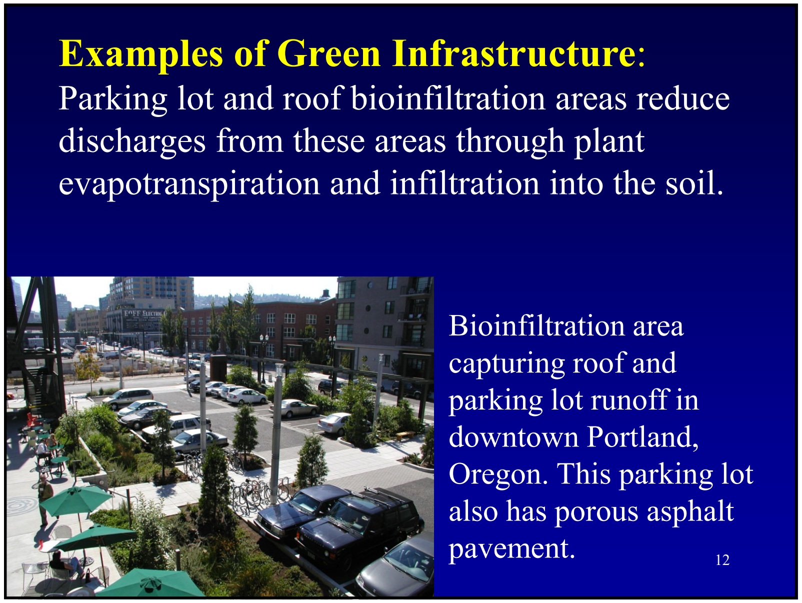
Edinburgh, Scotland



Examples of Green Infrastructure:

Large storage tanks capture roof runoff that is then used on site for toilet flushing or landscaping irrigation, amongst other uses.

Roof runoff storage tanks at the LandCare main research centre in Auckland, New Zealand. Water is used to flush urinals and to irrigate research greenhouses.



Examples of Green Infrastructure:

Parking lot and roof bioinfiltration areas reduce discharges from these areas through plant evapotranspiration and infiltration into the soil.

Bioinfiltration area capturing roof and parking lot runoff in downtown Portland, Oregon. This parking lot also has porous asphalt pavement.

National Demonstration of Advanced Drainage Concepts Using Green Solutions for CSO Control

Collaborations in Kansas City:

- EPA: National Risk Management Research Laboratory (NRMRL), Region 7, Office of Wastewater Management (OWM), and Office of Enforcement and Compliance Assurance (OECA)
- Kansas City, MO, Water Services Department (KCMO WSD), Tetra Tech, Univ. of Missouri-Kansas City UMKC), Univ. of Alabama (UA), Mid-America Regional Council (MARC), Bergmann Associates
- Partnerships at neighborhood, watershed & regional levels

Project Objectives

Demonstrate value of integrated, green infrastructure-based solutions to WWF pollution problems in a combined sewer system

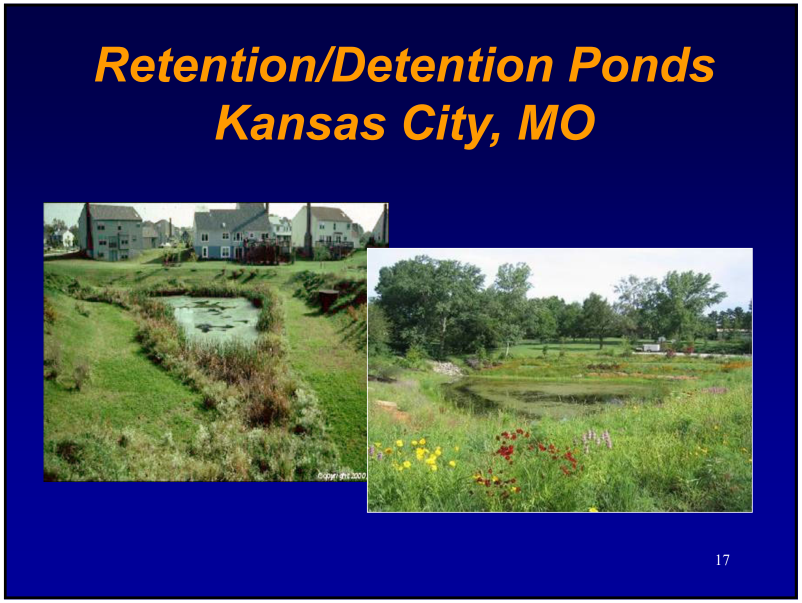
- **Assess multiple Green Infrastructure practices (include planning, designing, and implementing)**
- **Develop approach to identify & prioritize stormwater micro-control projects**
- **Monitor quantity (flow) and quality (pollutant concentrations) of surface and combined system flows**
- **Determine practice performance**
- **Model performance (quantity and quality) at multiple scales of implementation (WinSLAMM, SUSTAIN)**
- **Conduct economic analyses comparing to traditional approaches**
- **Provide community education, outreach and coordination activities**

Economic Viability of Green Infrastructure in Kansas City

	Control Component	Est. Capital Cost ($M)	Storage Provided (M gal)	Unit Capital Cost ($/gal Stored)
Gray Controls Only	Outfall 059: 1 M gal Storage Tank 0.5 MGD Pumping Station 17 MGD Screening 2,000 ft 48-in. Sewer 500 ft 8-in. Force Main Odor Control	20.0	1.0	20.00
Green Solutions	Stormwater Inlet Retrofits	0.7	0.1	2.00-7.00
	Porous Pavement Parking Lots	1.9	0.325	5.50
	Curb Extension Swales	4.1	0.30	11.00
	Porous Pavement in Street Right-of-way	3.6	0.40	11.00
	Green Solution Totals	10.3	1.125	9.00

Preliminary Comparison of Present Worth Costs CSO Control for Kansas City, MO

- Deep-Tunnel Storage: $19-27/gallon stored
- Near-Surface Storage: $17-23/gallon stored
- High-Rate Treatment: $15-25/gallon treated
- Green Solutions: $5-10/gallon stored



Retention/Detention Ponds
Kansas City, MO

Rain Gardens
Kansas City, MO

Bioretention at Catchbasins
Kansas City, MO

Retrofit of Parks & Lakes
Kansas City, MO

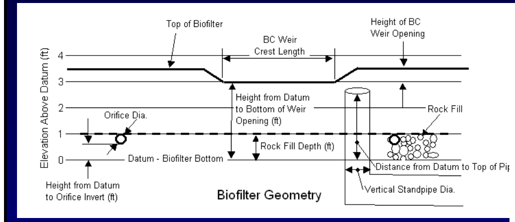
Wetland increases infiltration

Outlet provides CSO control

Stormwater Control Practices Included in WinSLAMM version 10

	wet ponds	hydro-dynamic separator	biofilter	cistern	Benefic. uses	grass filter strip	disconnect pavement	porous pavement	compacted soil restoration	catch-basin	storm-water filter	upflow filter	grass swale	street cleaning
Roofs	x	x	x	x	x	x	x				x	x	x	
Paved parking/storage	x	x	x	x	x	x	x	x		x	x	x	x	
Unpaved parking/storage	x	x	x	x	x	x	x			x	x	x	x	
Driveways	x	x	x	x	x	x	x	x			x	x	x	
Sidewalks	x	x	x	x	x	x	x	x			x	x	x	
Streets		x	x			x		x		x	x	x	x	x
Large landscaped areas	x	x	x	x	x	x			x				x	
Small landscaped areas	x	x	x	x	x	x			x				x	
Undeveloped areas	x	x	x	x	x	x			x				x	
Paved playgrounds	x	x	x	x	x	x	x	x			x	x	x	
Other impervious areas	x	x	x	x	x	x	x	x		x	x	x	x	
Other non-paved areas	x	x	x	x	x	x	x	x	x	x	x	x	x	
Paved lane/shoulders	x	x	x			x	x	x		x	x	x	x	x
High traffic urban highways	x	x	x			x	x	x		x	x	x	x	x
High traffic ruban pervious	x	x	x			x	x	x		x	x	x	x	x
Drainage system	x	x	x			x				x			x	
Outfall	x	x	x											

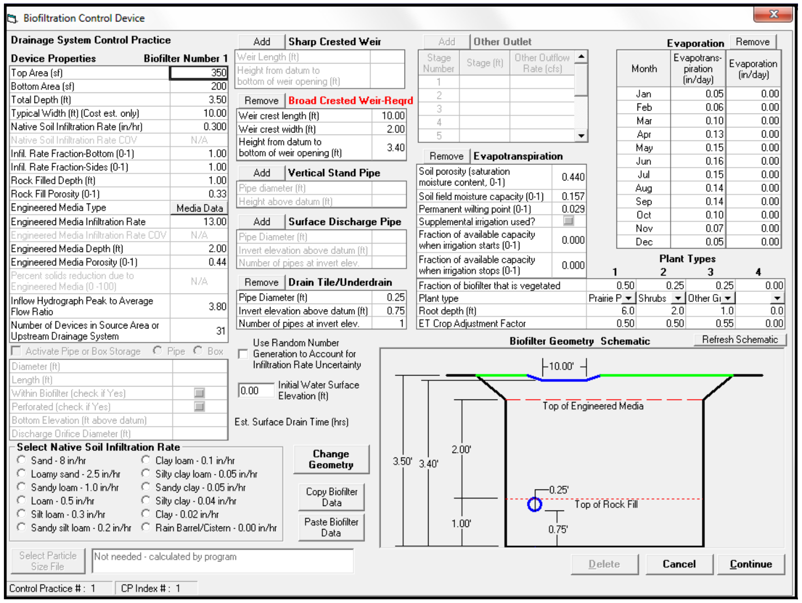
Biofilters in WinSLAMM



Biofilter Geometry

Main Features of Biofilter Calculations in WinSLAMM:

- Full hydraulic routing using modified PULS using total storage components.
- Detailed media performance data (hydraulic and water quality effects (based on lab and field studies).
- Evapotranspiration calculations based on soil and plant selections.
- Hydraulic and water quality performance verified from many field studies at many scales.



Biofiltration Control Device

Drainage System Control Practice

Device Properties	Biofilter Number 1
Top Area (sf)	350
Bottom Area (sf)	200
Total Depth (ft)	3.50
Typical Width (ft) (Cost est. only)	10.00
Native Soil Infiltration Rate (in/hr)	0.300
Native Soil Infiltration Rate COV	N/A
Infil. Rate Fraction-Bottom (0-1)	1.00
Infil. Rate Fraction-Sides (0-1)	1.00
Rock Filled Depth (ft)	1.00
Rock Fill Porosity (0-1)	0.33
Engineered Media Type	Media Data
Engineered Media Infiltration Rate	13.00
Engineered Media Infiltration Rate COV	N/A
Engineered Media Depth (ft)	2.00
Engineered Media Porosity (0-1)	0.44
Percent solids reduction due to Engineered Media (0 -100)	N/A
Inflow Hydrograph Peak to Average Flow Ratio	3.80
Number of Devices in Source Area or Upstream Drainage System	31

☐ Activate Pipe or Box Storage ○ Pipe ○ Box

Diameter (ft)	
Length (ft)	
Within Biofilter (check if Yes)	☐
Perforated (check if Yes)	☐
Bottom Elevation (ft above datum)	
Discharge Orifice Diameter (ft)	

Select Native Soil Infiltration Rate

○ Sand - 8 in/hr
○ Loamy sand - 2.5 in/hr
○ Sandy loam - 1.0 in/hr
○ Loam - 0.5 in/hr
○ Silt loam - 0.3 in/hr
○ Sandy silt loam - 0.2 in/hr
○ Clay loam - 0.1 in/hr
○ Silty clay loam - 0.05 in/hr
○ Sandy clay - 0.05 in/hr
○ Silty clay - 0.04 in/hr
○ Clay - 0.02 in/hr
○ Rain Barrel/Cistern - 0.00 in/hr

Select Particle Size File: Not needed - calculated by program

Sharp Crested Weir (Add)

Weir Length (ft)	
Height from datum to bottom of weir opening (ft)	

Broad Crested Weir-Reqrd (Remove)

Weir crest length (ft)	10.00
Weir crest width (ft)	2.00
Height from datum to bottom of weir opening (ft)	3.40

Vertical Stand Pipe (Add)

Pipe diameter (ft)	
Height above datum (ft)	

Surface Discharge Pipe (Add)

Pipe Diameter (ft)	
Invert elevation above datum (ft)	
Number of pipes at invert elev.	

Drain Tile/Underdrain (Remove)

Pipe Diameter (ft)	0.25
Invert elevation above datum (ft)	0.75
Number of pipes at invert elev.	1

☐ Use Random Number Generation to Account for Infiltration Rate Uncertainty

0.00 Initial Water Surface Elevation (ft)

Est. Surface Drain Time (hrs)

Other Outlet (Add)

Stage Number	Stage (ft)	Other Outflow Rate (cfs)
1		
2		
3		
4		
5		

Evapotranspiration (Remove)

Soil porosity (saturation moisture content, 0-1)	0.440
Soil field moisture capacity (0-1)	0.157
Permanent wilting point (0-1)	0.029
Supplemental irrigation used?	☐
Fraction of available capacity when irrigation starts (0-1)	0.000
Fraction of available capacity when irrigation stops (0-1)	0.000

Evaporation (Remove)

Month	Evapotrans-piration (in/day)	Evaporation (in/day)
Jan	0.05	0.00
Feb	0.06	0.00
Mar	0.10	0.00
Apr	0.13	0.00
May	0.15	0.00
Jun	0.16	0.00
Jul	0.15	0.00
Aug	0.14	0.00
Sep	0.14	0.00
Oct	0.10	0.00
Nov	0.07	0.00
Dec	0.05	0.00

Plant Types

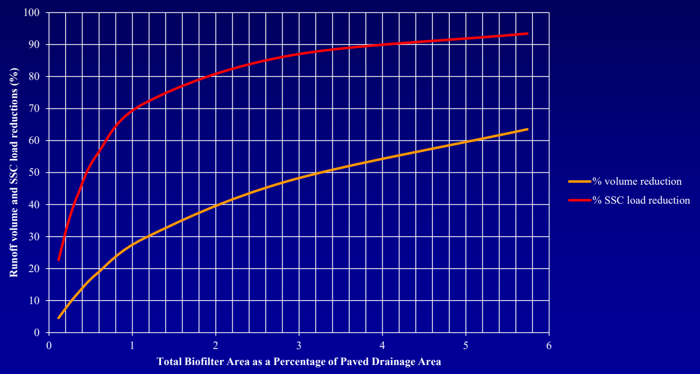
	1	2	3	4
Fraction of biofilter that is vegetated	0.50	0.25	0.25	0.00
Plant type	Prairie P	Shrubs	Other Gı	
Root depth (ft)	6.0	2.0	1.0	0.0
ET Crop Adjustment Factor	0.50	0.50	0.55	0.00

Biofilter Geometry Schematic

Control Practice # : 1 CP Index # : 1

Example Production Function for Parking Lot Biofilters, Long Creek Watershed, So. Portland, ME

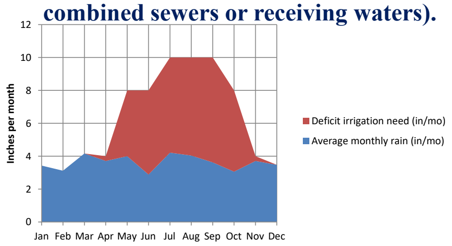
Runoff Volume and SSC Load Reductions with Biofilters in Paved Areas

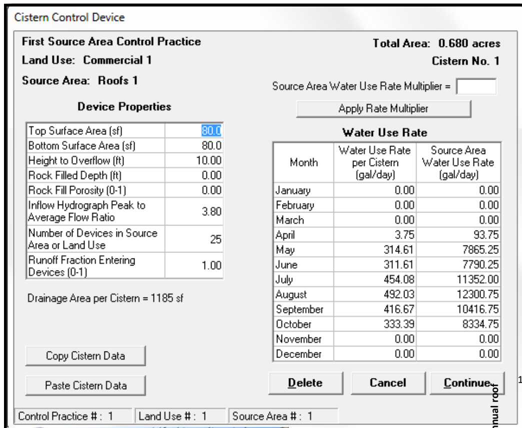


Cisterns and Beneficial Uses in WinSLAMM

Main Features of Cisterns/Water Tank Storage and Beneficial Use Calculations in WinSLAMM:

- **Mass balance calculations for demand series compared to long-term rainfall data.**
- **Calculations for different tank volumes and source areas.**
- **Geographical location affects water needs (conservation approach to meet evapotranspiration (ET) requirements or maximum use to minimize discharges to combined sewers or receiving waters).**





Cistern Control Device

First Source Area Control Practice
Land Use: Commercial 1
Source Area: Roofs 1
Total Area: 0.680 acres
Cistern No. 1

Source Area Water Use Rate Multiplier =

Device Properties

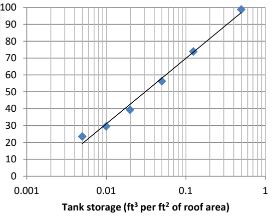
Top Surface Area (sf)	80.0
Bottom Surface Area (sf)	80.0
Height to Overflow (ft)	10.00
Rock Filled Depth (ft)	0.00
Rock Fill Porosity (0-1)	0.00
Inflow Hydrograph Peak to Average Flow Ratio	3.80
Number of Devices in Source Area or Land Use	25
Runoff Fraction Entering Devices (0-1)	1.00

Drainage Area per Cistern = 1185 sf

Water Use Rate

Month	Water Use Rate per Cistern (gal/day)	Source Area Water Use Rate (gal/day)
January	0.00	0.00
February	0.00	0.00
March	0.00	0.00
April	3.75	93.75
May	314.61	7865.25
June	311.61	7790.25
July	454.08	11352.00
August	492.03	12300.75
September	416.67	10416.75
October	333.39	8334.75
November	0.00	0.00
December	0.00	0.00

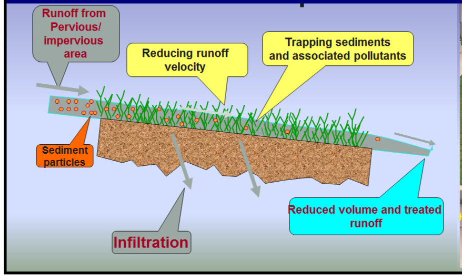
Control Practice # : 1 Land Use # : 1 Source Area # : 1

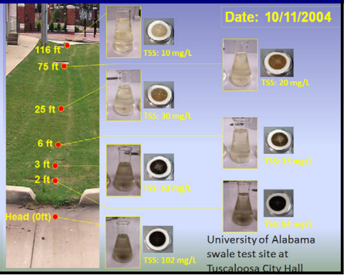


Grass Swales and Grass Filters in WinSLAMM

Main Features of Grass Swale and Grass Filter Calculations in WinSLAMM:

- Unique hydraulic calculations considering shallow flows in grass.
- Settling by particle size and infiltration as stormwater flows over grass.
- Developed calculation procedures in controlled laboratory experiments and verified with field measurements.





University of Alabama swale test site at Tuscaloosa City Hall

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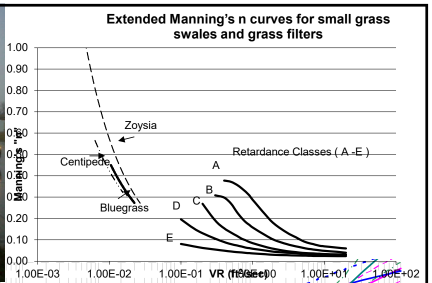
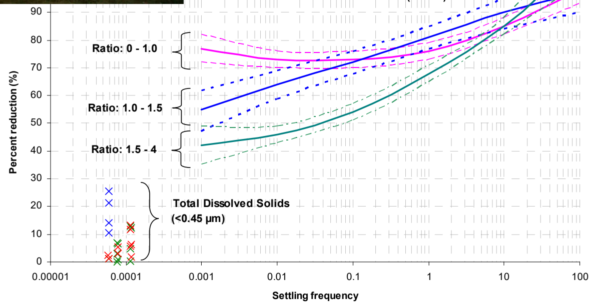
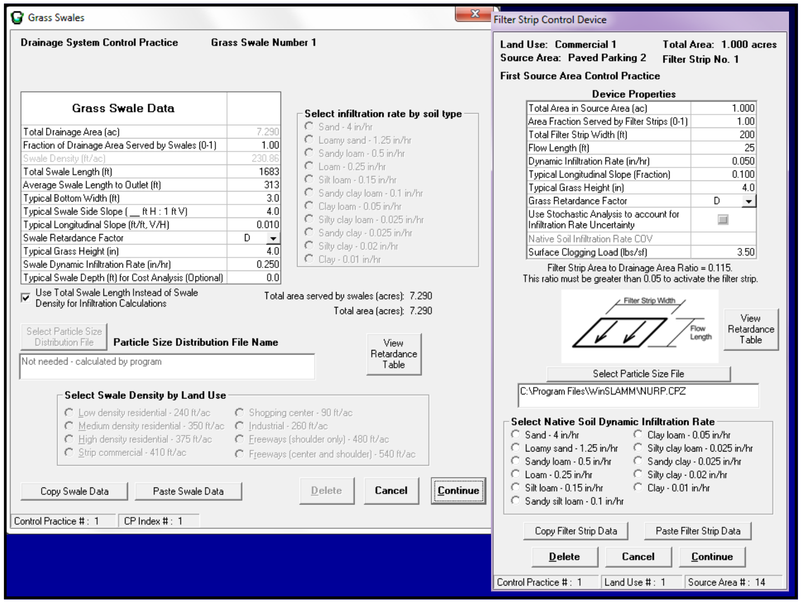






Grass Swales

Drainage System Control Practice **Grass Swale Number 1**

Grass Swale Data	
Total Drainage Area (ac)	7.290
Fraction of Drainage Area Served by Swales (0-1)	1.00
Swale Density (ft/ac)	230.86
Total Swale Length (ft)	1683
Average Swale Length to Outlet (ft)	313
Typical Bottom Width (ft)	3.0
Typical Swale Side Slope (__ ft H : 1 ft V)	4.0
Typical Longitudinal Slope (ft/ft, V/H)	0.010
Swale Retardance Factor	D
Typical Grass Height (in)	4.0
Swale Dynamic Infiltration Rate (in/hr)	0.250
Typical Swale Depth (ft) for Cost Analysis (Optional)	0.0

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 clay 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

☑ Use Total Swale Length Instead of Swale Density for Infiltration Calculations

Total area served by swales (acres): 7.290
Total area (acres): 7.290

Particle Size Distribution File Name
Not needed - calculated by program

Select Swale Density by Land Use
- ○ Low density residential - 240 ft/ac
- ○ Medium density residential - 350 ft/ac
- ○ High density residential - 375 ft/ac
- ○ Strip commercial - 410 ft/ac
- ○ Shopping center - 90 ft/ac
- ○ Industrial - 260 ft/ac
- ○ Freeways (shoulder only) - 480 ft/ac
- ○ Freeways (center and shoulder) - 540 ft/ac

Control Practice # : 1 | CP Index # : 1

Filter Strip Control Device

Land Use: Commercial 1 **Total Area: 1.000 acres**
Source Area: Paved Parking 2 **Filter Strip No. 1**

First Source Area Control Practice

Device Properties

Total Area in Source Area (ac)	1.000
Area Fraction Served by Filter Strips (0-1)	1.00
Total Filter Strip Width (ft)	200
Flow Length (ft)	25
Dynamic Infiltration Rate (in/hr)	0.050
Typical Longitudinal Slope (Fraction)	0.100
Typical Grass Height (in)	4.0
Grass Retardance Factor	D
Use Stochastic Analysis to account for Infiltration Rate Uncertainty	☐
Native Soil Infiltration Rate COV	
Surface Clogging Load (lbs/sf)	3.50

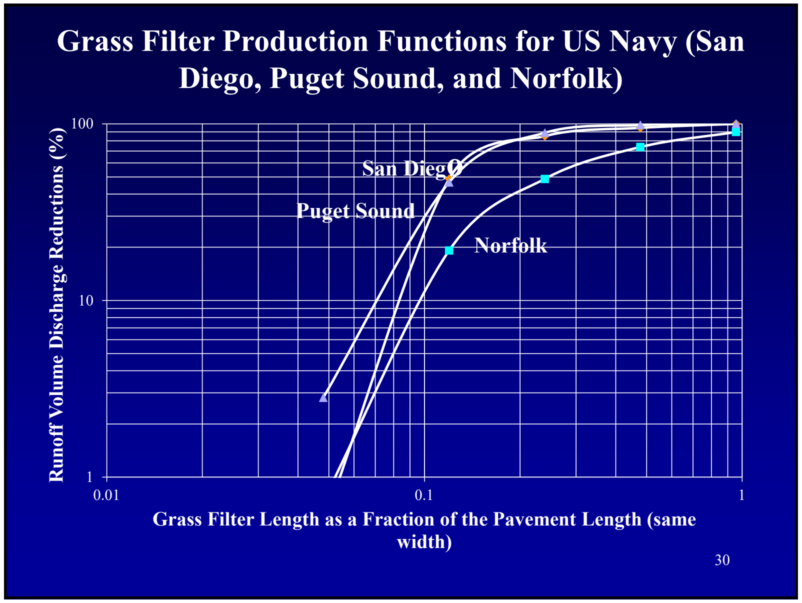
Filter Strip Area to Drainage Area Ratio = 0.115.
This ratio must be greater than 0.05 to activate the filter strip.

C:\Program Files\WinSLAMM\NURP.CPZ

Select Native Soil Dynamic Infiltration Rate
- ○ 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

Control Practice # : 1 | Land Use # : 1 | Source Area # : 14

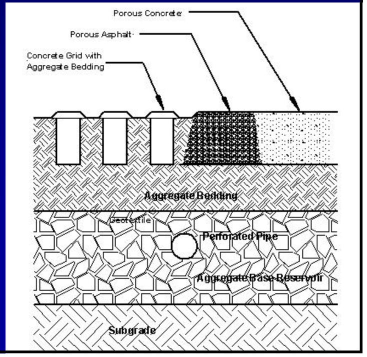
Grass Filter Production Functions for US Navy (San Diego, Puget Sound, and Norfolk)

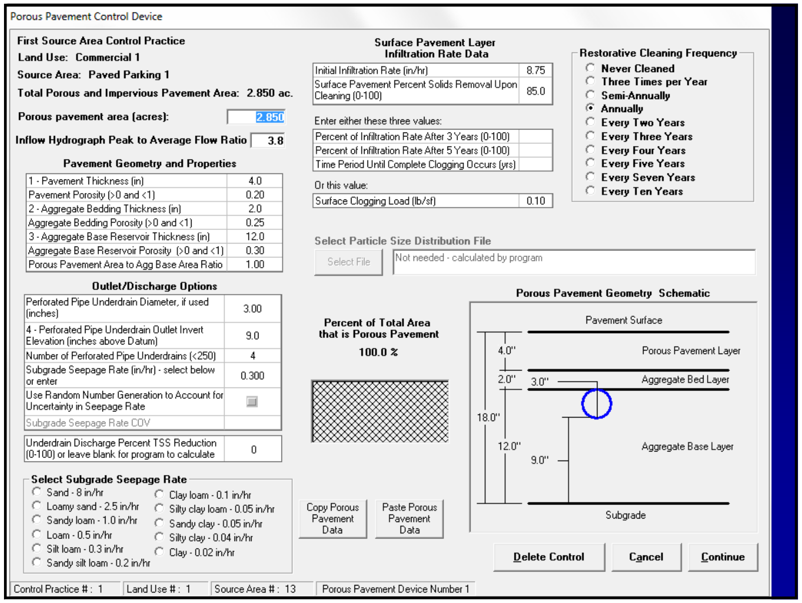


Porous Pavement in WinSLAMM

Main Features of Porous Pavement Performance Calculations in WinSLAMM:

- **Particulate retention and clogging continuously calculated along with hydraulic effects.**
- **Processes modeled in each layer.**
- **Pavement restorative cleaning modeled.**





Porous Pavement Control Device

First Source Area Control Practice
Land Use: Commercial 1
Source Area: Paved Parking 1
Total Porous and Impervious Pavement Area: 2.850 ac.

Porous pavement area (acres): 2.850

Inflow Hydrograph Peak to Average Flow Ratio 3.8

Pavement Geometry and Properties

1 - Pavement Thickness (in)	4.0
Pavement Porosity (>0 and <1)	0.20
2 - Aggregate Bedding Thickness (in)	2.0
Aggregate Bedding Porosity (>0 and <1)	0.25
3 - Aggregate Base Reservoir Thickness (in)	12.0
Aggregate Base Reservoir Porosity (>0 and <1)	0.30
Porous Pavement Area to Agg Base Area Ratio	1.00

Outlet/Discharge Options

Perforated Pipe Underdrain Diameter, if used (inches)	3.00
4 - Perforated Pipe Underdrain Outlet Invert Elevation (inches above Datum)	9.0
Number of Perforated Pipe Underdrains (<250)	4
Subgrade Seepage Rate (in/hr) - select below or enter	0.300
Use Random Number Generation to Account for Uncertainty in Seepage Rate	☐
Subgrade Seepage Rate COV	

Underdrain Discharge Percent TSS Reduction (0-100) or leave blank for program to calculate	0

Select Subgrade Seepage Rate
- ○ Sand - 8 in/hr
- ○ Loamy sand - 2.5 in/hr
- ○ Sandy loam - 1.0 in/hr
- ○ Loam - 0.5 in/hr
- ○ Silt loam - 0.3 in/hr
- ○ Sandy silt loam - 0.2 in/hr
- ○ Clay loam - 0.1 in/hr
- ○ Silty clay loam - 0.05 in/hr
- ○ Sandy clay - 0.05 in/hr
- ○ Silty clay - 0.04 in/hr
- ○ Clay - 0.02 in/hr

Surface Pavement Layer Infiltration Rate Data

Initial Infiltration Rate (in/hr)	8.75
Surface Pavement Percent Solids Removal Upon Cleaning (0-100)	85.0

Enter either these three values:

Percent of Infiltration Rate After 3 Years (0-100)	
Percent of Infiltration Rate After 5 Years (0-100)	
Time Period Until Complete Clogging Occurs (yrs)	

Or this value:

Surface Clogging Load (lb/sf)	0.10

Restorative Cleaning Frequency
- ○ Never Cleaned
- ○ Three Times per Year
- ○ Semi-Annually
- ● Annually
- ○ Every Two Years
- ○ Every Three Years
- ○ Every Four Years
- ○ Every Five Years
- ○ Every Seven Years
- ○ Every Ten Years

Select Particle Size Distribution File
Not needed - calculated by program

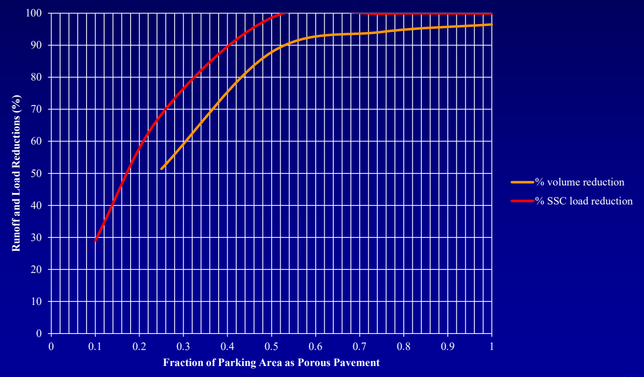
Percent of Total Area that is Porous Pavement
100.0 %

Porous Pavement Geometry Schematic

Control Practice # : 1 | Land Use # : 1 | Source Area # : 13 | Porous Pavement Device Number 1

Example Porous Pavement Production Function, Long Creek Watershed, So. Portland, ME

Runoff Volume and SSC Load Reductions due to Porous Pavement



Challenges in Green Infrastructure Design and Associated Failure Modes, or how to get the most out of planned stormwater controls

Dozen Issues of Concern

- Poor Assumptions
- Clogging
- Compaction
- Chemical Breakthrough
- Sodium Adsorption Ratio
- Improper Sizing and Locations
- Groundwater Interactions
- Improper Construction
- Poor Maintenance
- Anaerobic Conditions
- Large Underdrains and Short-Circuiting
- Need Combinations of Controls and Unit Processes

1) Real Data May Not Support Traditional Urban Hydrology Assumptions

- Many agencies and stormwater managers focus on single design storms that do not adequately represent the long-term discharges of water and pollutants during wet weather
- Legacy of drainage design approaches

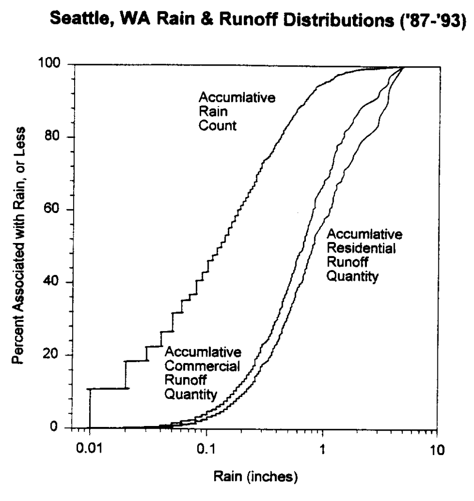
Probability distribution of rains (by count) and runoff (by depth):

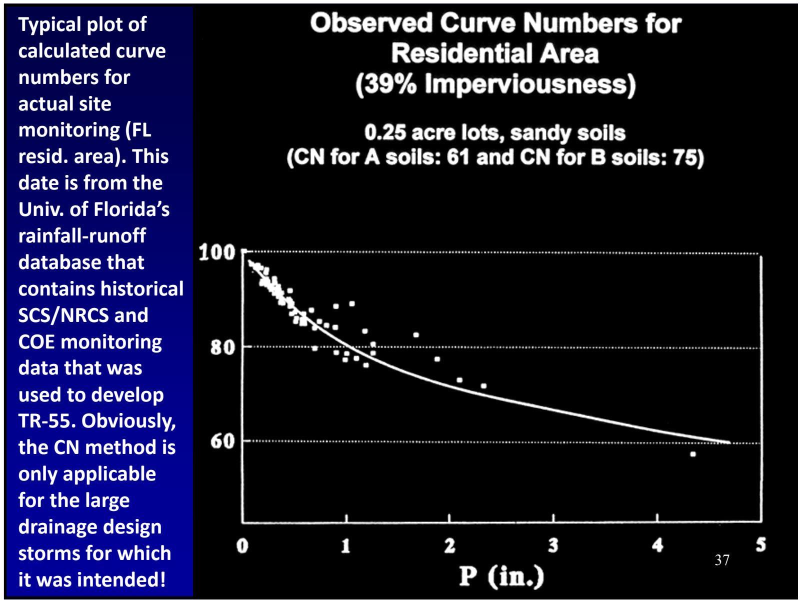
Seattle Rains:
<0.15”: 50% of rains (7% of runoff)

0.15 to 1”: 42% of rains (51% of runoff)

1 to 3”: 8% of rains (26% of runoff)

3 to 8”: <1% of rains (16% of runoff)

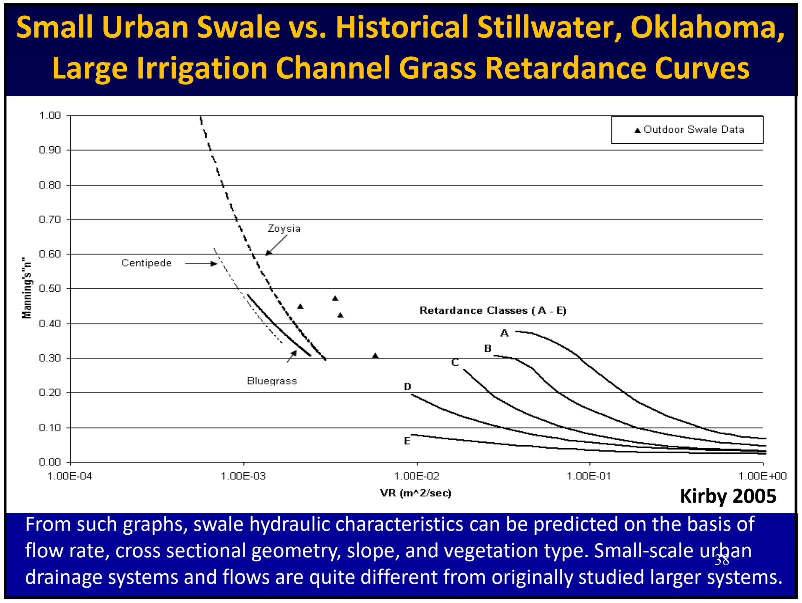




Typical plot of calculated curve numbers for actual site monitoring (FL resid. area). This date is from the Univ. of Florida's rainfall-runoff database that contains historical SCS/NRCS and COE monitoring data that was used to develop TR-55. Obviously, the CN method is only applicable for the large drainage design storms for which it was intended!

Observed Curve Numbers for Residential Area (39% Imperviousness)

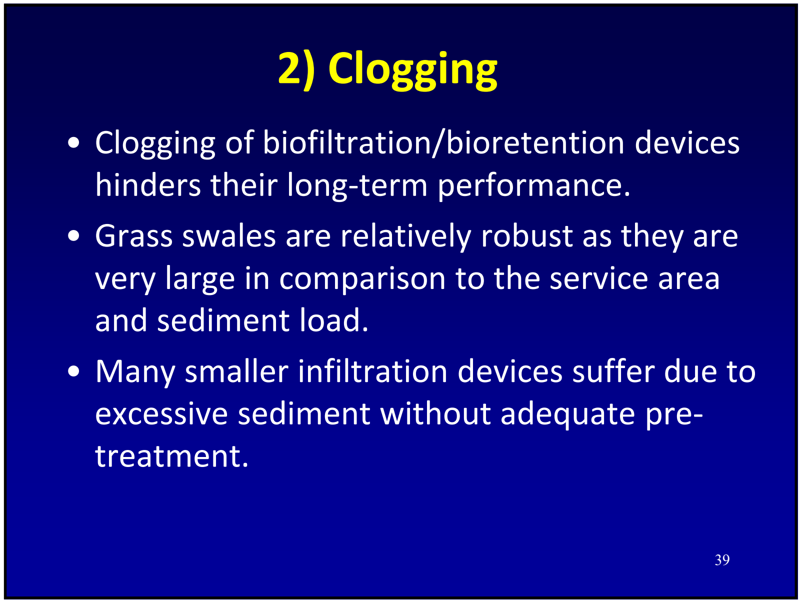
0.25 acre lots, sandy soils
(CN for A soils: 61 and CN for B soils: 75)



Small Urban Swale vs. Historical Stillwater, Oklahoma, Large Irrigation Channel Grass Retardance Curves

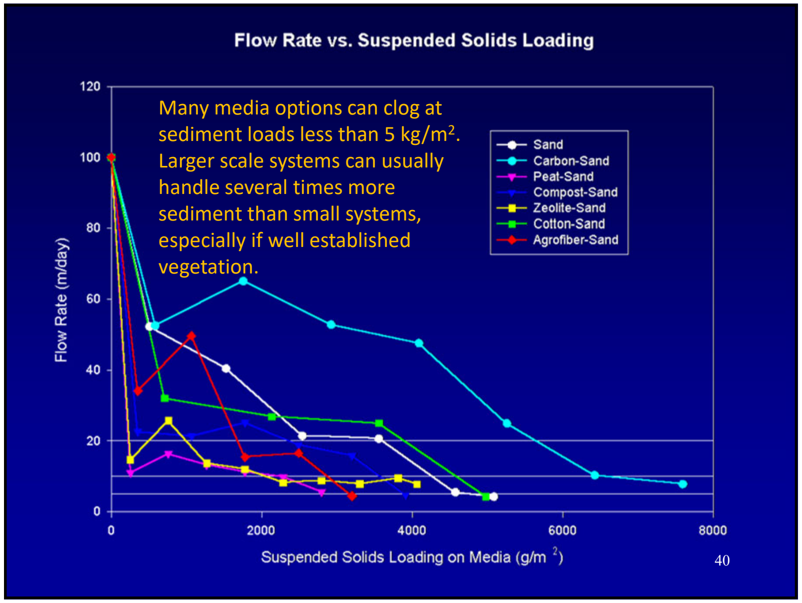
Kirby 2005

From such graphs, swale hydraulic characteristics can be predicted on the basis of flow rate, cross sectional geometry, slope, and vegetation type. Small-scale urban drainage systems and flows are quite different from originally studied larger systems.



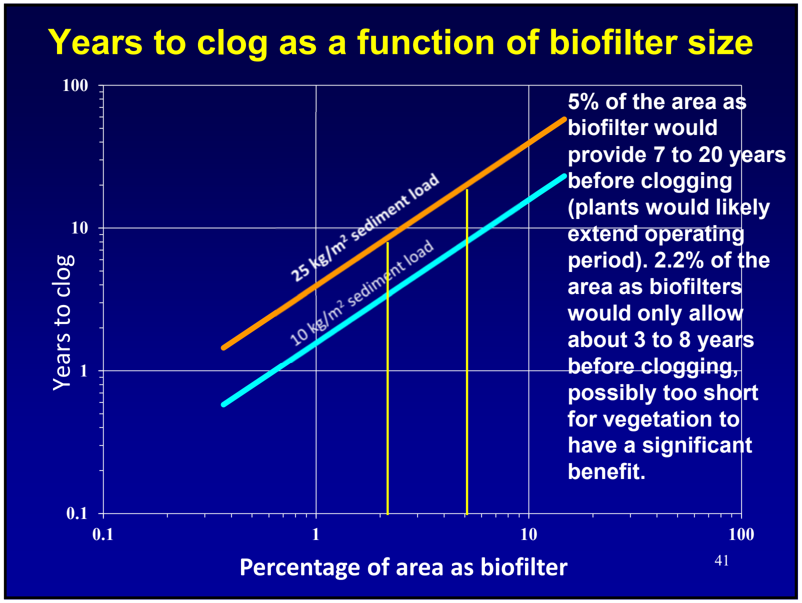
2) Clogging

- Clogging of biofiltration/bioretention devices hinders their long-term performance.
- Grass swales are relatively robust as they are very large in comparison to the service area and sediment load.
- Many smaller infiltration devices suffer due to excessive sediment without adequate pre-treatment.



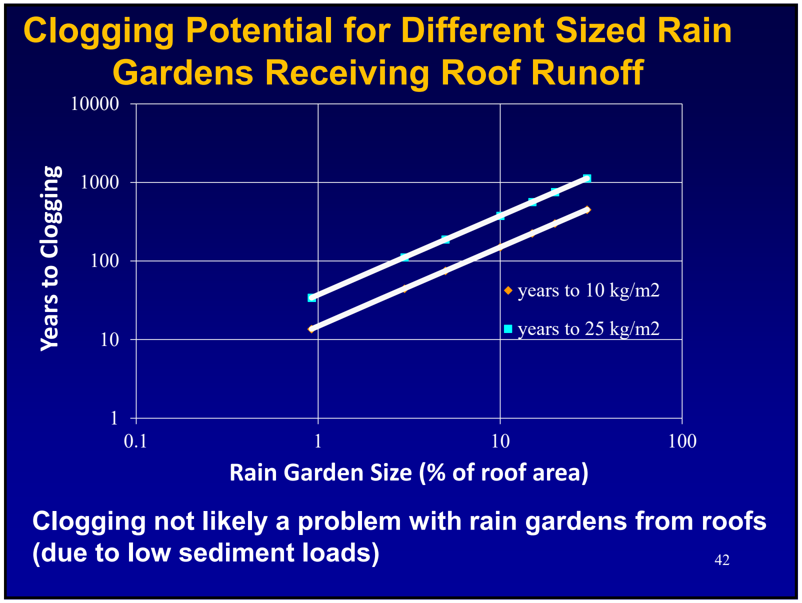
Flow Rate vs. Suspended Solids Loading

Many media options can clog at sediment loads less than 5 kg/m^2. Larger scale systems can usually handle several times more sediment than small systems, especially if well established vegetation.



Years to clog as a function of biofilter size

5% of the area as biofilter would provide 7 to 20 years before clogging (plants would likely extend operating period). 2.2% of the area as biofilters would only allow about 3 to 8 years before clogging, possibly too short for vegetation to have a significant benefit.

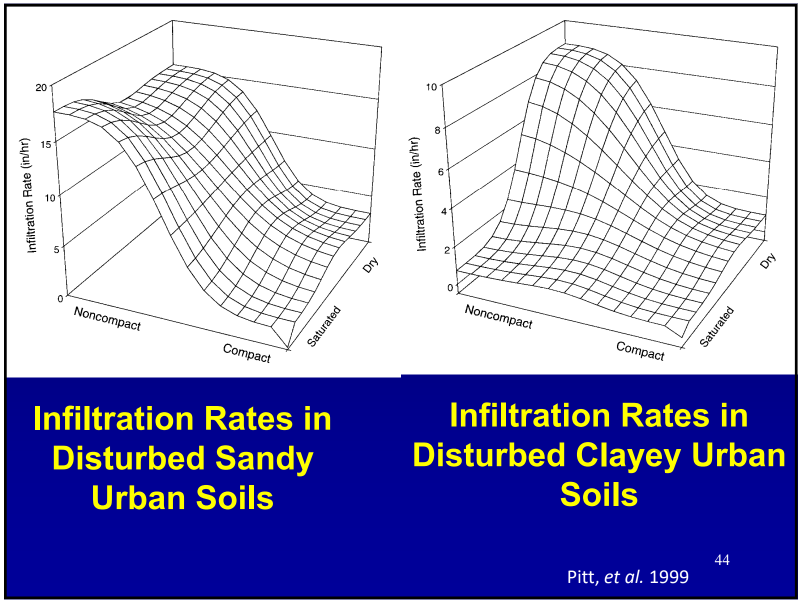


Clogging Potential for Different Sized Rain Gardens Receiving Roof Runoff

Clogging not likely a problem with rain gardens from roofs (due to low sediment loads)

3) Soil and Media Compaction

- Compaction of soils or media in an infiltration area (let alone in all pervious areas!) severely hinders infiltration capacity.
- Difficult to recover from compaction, so care is needed during construction and use.

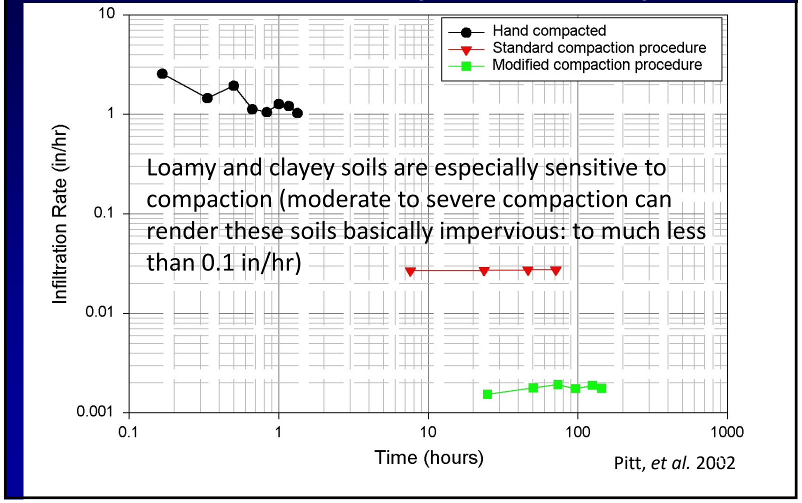


Infiltration Rates in Disturbed Sandy Urban Soils

Infiltration Rates in Disturbed Clayey Urban Soils

Pitt, *et al.* 1999

Laboratory Infiltration Tests for Silty Loam Soil 4" Diameter Test Cylinder, 4.5" Depth



Loamy and clayey soils are especially sensitive to compaction (moderate to severe compaction can render these soils basically impervious: to much less than 0.1 in/hr)

Pitt, *et al.* 2002

4) Breakthrough of Chemical Capacity

- Besides sediment clogging, media can fail due to exceeding chemical treatment capacity of the media.
- Long-term column tests more reliable indicators of chemical capacity than short-term batch tests.
- Need to use actual stormwater to represent the wide range of competing chemicals in the water, compared to tests using artificially high concentrations of single pollutant.

Mostly ionic forms of metals in filtered stormwater (with some notable exceptions); also, several removal processes occur, including precipitation, ion exchange, sorption, etc.

Analyte	% Ionic	% Colloidal
Magnesium	100	0
Calcium	99.1	0.9
Zinc	98.7	1.3
Iron	97	3
Chromium	94.5	5.5
Potassium	86.7	13.3
Lead	78.4	21.6
Copper	77.4	22.6
Cadmium	10	90

Controlled batch tests using "artificial" or simulated stormwater do not represent these chemical characteristics, nor include competing ions.

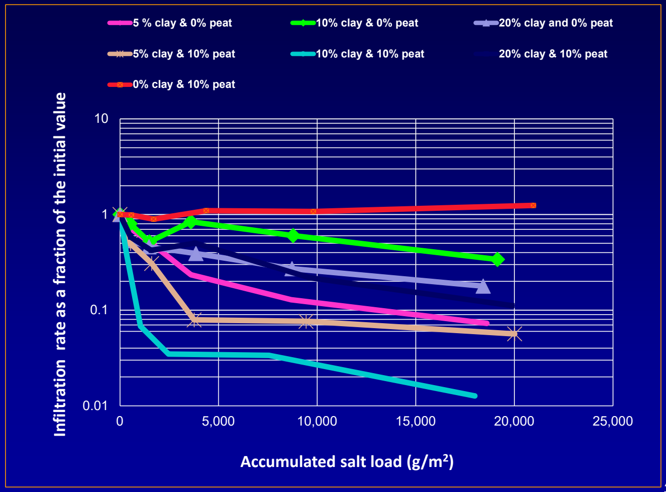
Morquecho 2005

5) Sodium Adsorption Ratio (SAR)

- Excessive amounts of sodium in relation to calcium and magnesium causes the dispersion of clays in a soil, severely restricting infiltration capacity.
- Problem when deicing salts and snowmelt entering infiltration devices that have even small amounts of clay in the soil or media mixture.
- Not much of an issue for roof runoff rain gardens (as long as heavily salted walks or driveways do not drain towards them).
- Acceptable media and soil mixtures in cold climates should prohibit clays, focusing on sandy material with small amounts of organic amendments.

A new infiltration pond after first winter; receives snowmelt from adjacent salted parking areas (plus sediment from area construction); lost almost all of the infiltration capacity and is rapidly becoming a (poorly designed) wet pond. [was subsequently restored]

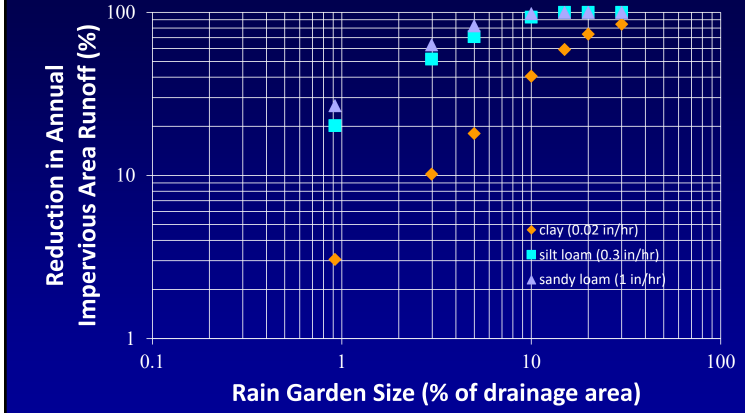
Flow Rate as a Function of Salt Loading



6) Improper Sizing and Poor Locations

- Improper modeling and design storm use can result in (usually) overly-optimistic performance expectations.
- Long-term simulations needed to access likely failures and maintenance issues.
- Over-sizing is usually needed (especially in northern climates) to overcome many uncertainties in infiltration behavior.

Annual Runoff Reductions from Paved Areas or Roofs for Different Sized Rain Gardens for Various Soils



Sandy and silty loam soils can achieve about 90% annual runoff reductions for this area (Kansas City example), if biofilter is at least 8% of the paved drainage area
Clayey soils would need about 30+% of the area for the same performance level.

Unlikely suitable performance of grass pavement in heavily used parking area, with severely compacted soil and no vegetation. At least the table tops in the adjacent hotel had flourishing LID components!

7) Groundwater Interactions

- Groundwater contamination potential from infiltrating stormwater is decreased with treatment before discharge to the groundwater, proper media selection, or located in an area having little contamination potential.
- Mounding below infiltration sites can severely reduce infiltration rates if shallow groundwater table.
- Increased groundwater recharge may increase groundwater flows to adjacent urban streams (usually a positive outcome, but if groundwater is contaminated, then this is a potential problem).

Moderate to High Contamination Potential (worst case sandy soil conditions, with limited organic matter content)

Surface Infiltration after Sedimentation plus sorption/ion-exchange (MCTT and bioretention)	**Surface Infiltration with minimal Pretreatment (biofiltration and marginal soils)**	**Injection after Minimal Pretreatment (dry wells, gravel trenches, and most porous pavements)**
	Lindane, chlordane	Lindane, chlordane
Fluoranthene, pyrene	Benzo (a) anthracene, bis (2-ethylhexl phthalate), fluoranthene, pentachlorophenol, phenanthrene, pyrene	**1,3-dichlorobenzene**, benzo (a) anthracene, bis (2-ethylhexl phthalate), **fluoranthene**, pentachlorophenol, phenanthrene, **pyrene**
Enteroviruses	**Enteroviruses**	**Enteroviruses, some bacteria and protozoa**
		Nickel, chromium, lead, **zinc**
Chloride	**Chloride**	**Chloride**

Minimal Pre-treatment before Infiltration Leads to Greater Groundwater Contamination Potential

Early approaches to infiltrating stormwater:

(also, filter fabric liners are usually not recommended anymore as many have failed due to clogging from silts)

8) Improper Construction and Poor Selection of Components

- Problems with media materials (did I mention clay before?)
- Over-filling biofilters (a surprisingly common problem), reducing storage capacity, usually with overflows set at too low of an elevation further decreasing storage.
- Difficult for water to enter device (not in flow path, no gradient, blocked entrances, and no drop off to top of media, allowing build-up of debris.

Red southern clay turned these terraced biofilters into something else. Constant flooding killed the vegetation and they are attempting to break up the surface clay layers.

Over-filled biofilter allowing short-circuiting of surface flows to slot drain inlet that is set slightly below top of media

9) Poor Maintenance

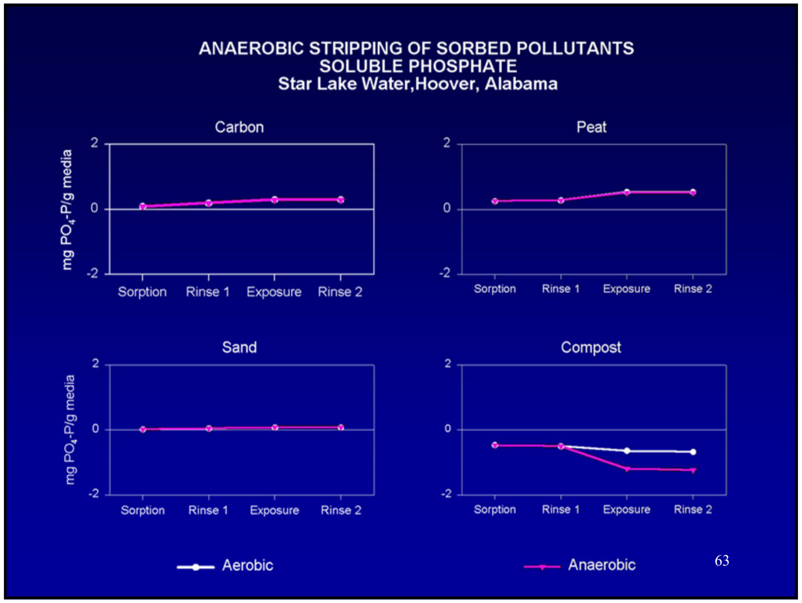
- Proper maintenance is necessary to ensure expected performance.
- Excessive erosion of surrounding areas and at the device itself can lead to excessive sediment loads and clogging in a short period of time.
- Irrigation is needed during periods of low rainfall to keep biofilter plants alive and active. Similar needs for green roof plants during seasonal dry periods. Plants need to be selected to withstand a wide range of dry to flooding conditions.

Excessive erosion at edges of biofilter.

Lack of irrigation resulted in complete loss of these biofilter plants during extended drought.

10) Anaerobic Conditions

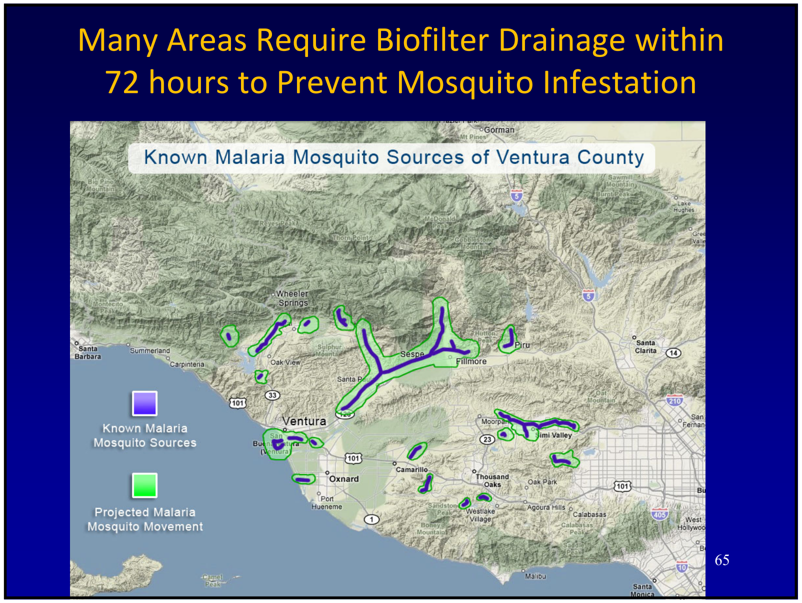
- Anaerobic conditions in biofilter media can enhance nitrate removals, if used in conjunction with other properly designed attributes (media selection and underdrain design).
- Many organic media can loose previously captured pollutants, especially nutrients, under anaerobic conditions. Metal retention is usually more secure, but degradation of the media results in losses of all materials.
- “First-flushes” of retained water from biofilters that have gone anaerobic contain very high pollutant concentrations.
- Free-draining media that remain aerobic during interevent periods exhibit fewer of these problems.



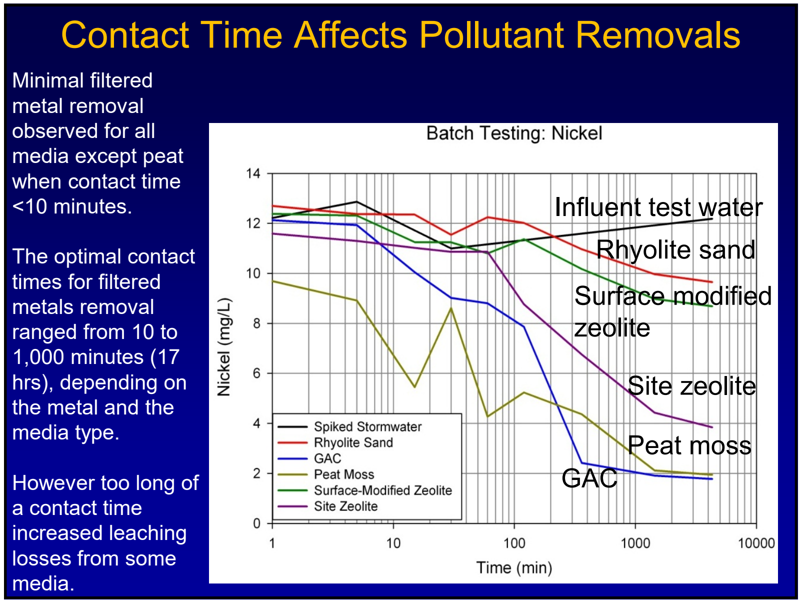
ANAEROBIC STRIPPING OF SORBED POLLUTANTS
SOLUBLE PHOSPHATE
Star Lake Water,Hoover, Alabama

11) Large Underdrains and Short-Circuiting

- Underdrains are needed in areas where standing water for extended periods of time causes problems, and to reduce anaerobic conditions in biofilter media.
- Conventional large underdrains provide too large of a drainage flow rate causing short-circuiting and short residence times.
- Flow restrictions are causes of clogging or maintenance problems.
- Modified underdrains can provide a good solution.



Many Areas Require Biofilter Drainage within 72 hours to Prevent Mosquito Infestation

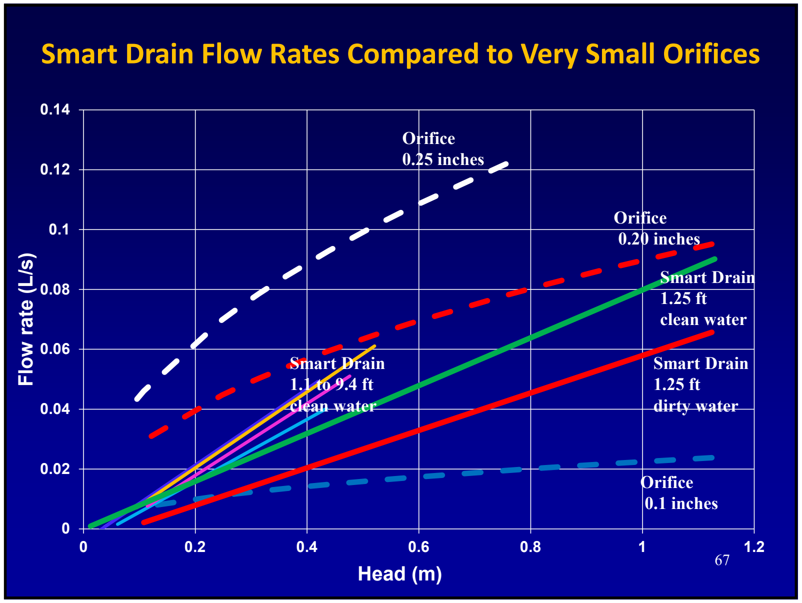


Contact Time Affects Pollutant Removals

Minimal filtered metal removal observed for all media except peat when contact time <10 minutes.

The optimal contact times for filtered metals removal ranged from 10 to 1,000 minutes (17 hrs), depending on the metal and the media type.

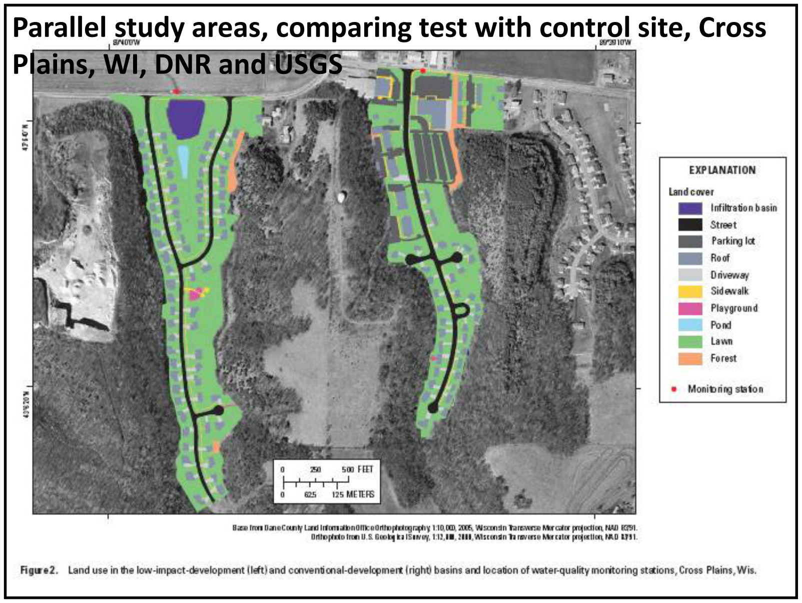
However too long of a contact time increased leaching losses from some media.



Smart Drain Flow Rates Compared to Very Small Orifices

12) Need Combinations of Controls (storage, sedimentation and infiltration)

- Infiltration alone can be effective in reducing most stormwater pollutants and flows.
- Sedimentation before infiltration offers advantages of pre-treatment and better sediment control.
- Storage before infiltration enhances treatment at low treatment flow rates.



Parallel study areas, comparing test with control site, Cross Plains, WI, DNR and USGS

Base from Dane County Land Information Office Orthophotography 1:10,000, 2005, Wisconsin Transverse Mercator projection, NAD 83/91.
Orthophoto from U.S. Geological Survey, 1:12,000, 2000, Wisconsin Transverse Mercator projection, NAD 83/91.

Figure 2. Land use in the low-impact-development (left) and conventional-development (right) basins and location of water-quality monitoring stations, Cross Plains, Wis.

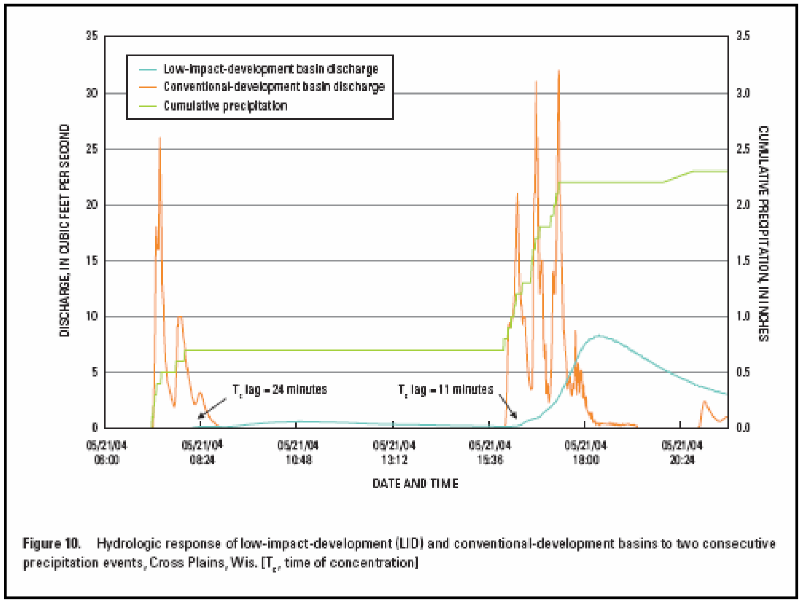
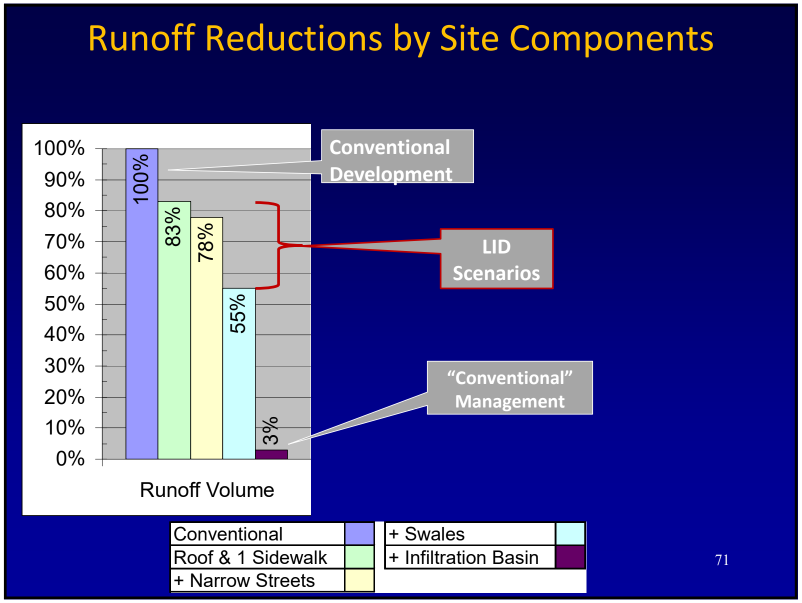
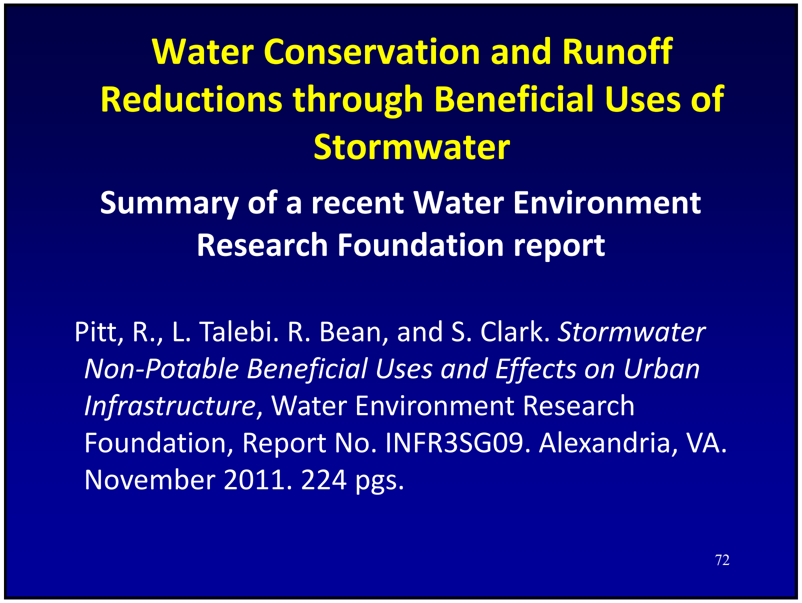


Figure 10. Hydrologic response of low-impact-development (LID) and conventional-development basins to two consecutive precipitation events, Cross Plains, Wis. [T_c, time of concentration]



Runoff Reductions by Site Components

Conventional	▨	+ Swales	▨
Roof & 1 Sidewalk	▨	+ Infiltration Basin	▨
+ Narrow Streets	▨		

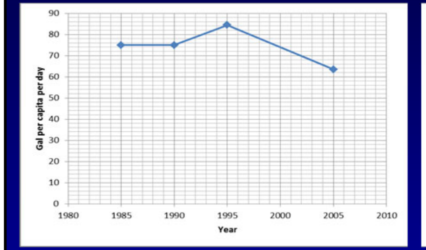


Water Conservation and Runoff Reductions through Beneficial Uses of Stormwater

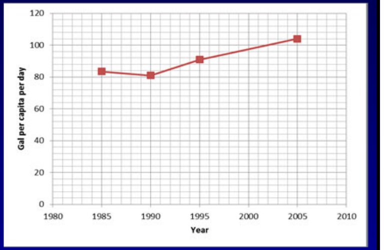
Summary of a recent Water Environment Research Foundation report

Pitt, R., L. Talebi. R. Bean, and S. Clark. *Stormwater Non-Potable Beneficial Uses and Effects on Urban Infrastructure*, Water Environment Research Foundation, Report No. INFR3SG09. Alexandria, VA. November 2011. 224 pgs.

Domestic Water Use Trends in the US



Essex County NJ daily per capita Water Use.



Per capita daily Water Usage in the Kansas City MO Metropolitan Area.

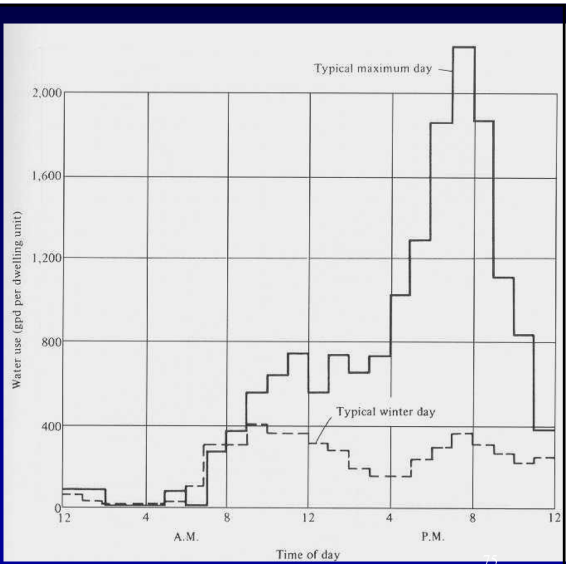
These data are available from the Census Bureau and the USGS for all counties in the US as a valuable resource for studying trends in populations and water use.

Example Domestic Indoor Water Use in the US

Home Uses	Daily Water Use Per Person	
	Gallons	Percent
Toilet	32	45
Bathing/Personal Hygiene	21	30
Laundry/Dishes	14	20
Drinking/Cooking	3	5
TOTAL	70	100

Daily Water-Use Patterns in Residential Area: Maximum Day (with irrigation) and Minimum Day

From: *Water Supply and Pollution Control, Sixth Edition*. Warren Viessman, Jr. and Mark J. Hammer, Addison-Wesley. 1998.



On-Site Building-Scale Beneficial Uses of Stormwater

Decorated rain barrels as part of EPA/Kansas City public education program for Green Infrastructure controls.

Large water storage tank at Heathcote, Australia winery.

Water storage tank at Washington, D.C. fire station storing roof runoff.

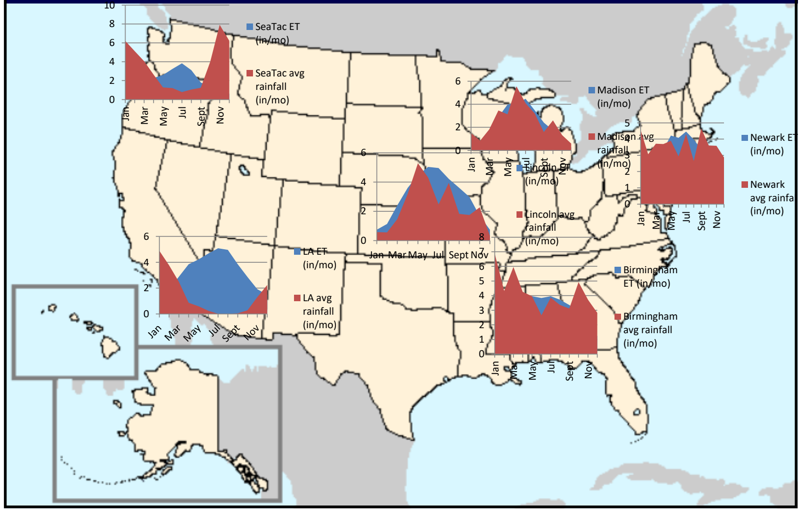
On-site stormwater harvesting for small-scale beneficial uses include several categories of opportunities that result in reductions in domestic water use, depending on the land use and size of buildings.

- **toilet flushing**
- **irrigation of landscaped areas**
- **storage and later controlled releases**
- **HVAC make-up water**
- **vehicle/equipment washing**
- **firefighting water**
- **shallow aquifer recharge**
- **aesthetics and water features**

Irrigation Calculations

- For most irrigation calculations, minimum application of water to meet the evapotranspiration (ET) deficit is used (Et minus soil moisture from rainfall).
- For maximum use of stormwater, it is desired to irrigate at the highest rate possible, without causing harm to the plants.
- For a “healthy” lawn, total water applied (including rain) is generally about 1" of water per week, or 4" per month.
- However, Kentucky Bluegrass, the most common lawn grass in the US, needs about 2.5 in/week, or more, during the heat of the summer, and should also receive some moisture during the winter

Maximum Water use by Plants (red rainfall and blue excess irrigation demand)



Storage Tank Sizes for Different Ranges of Captured Runoff

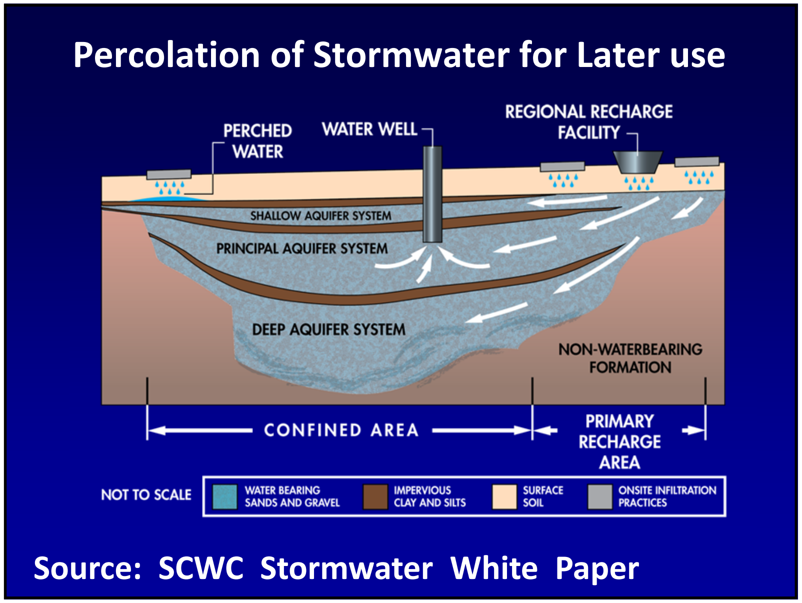
storage tank volume (ft³)	Approximate runoff removal range (% of long-term runoff for 1,000 ft² impervious area at six US regions)	number of 35 gal rain barrels per 1,000 ft² impervious area	number of 5 ft D, 5 ft tall tanks (730 gallons) per 1,000 ft² impervious area	number of 10 ft D, 10 ft tall tanks (5,900 gallons) per 1,000 ft² impervious area
10	20 to 30	2.1	0.1	
100	80 to 90	21.4	1.0	0.1
1,000	100	214	10.2	1.3

Retrofitted curb-cut biofilters in commercial areas in Kansas City.

Large stormwater park at 18th and Broadway in downtown Kansas City integrating underground storage for beneficial irrigation use along with surface water features and infiltration.

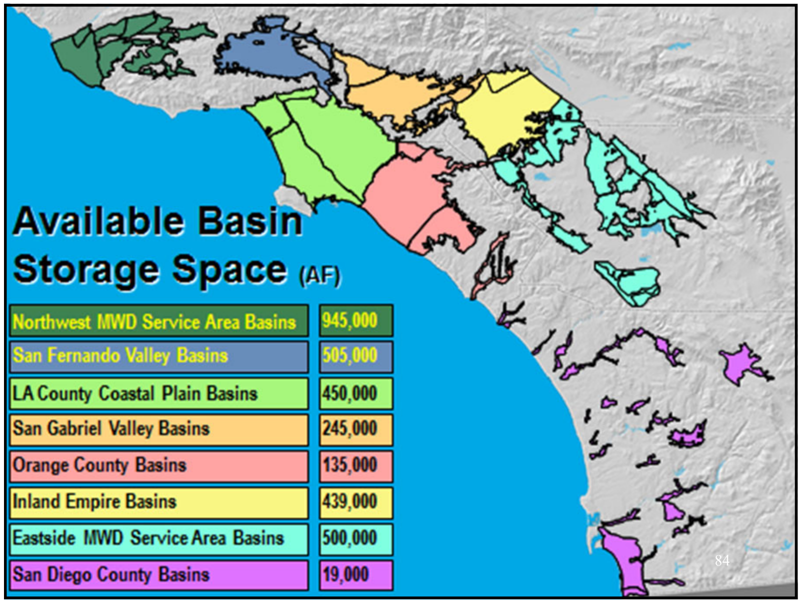
Docklands, downtown Melbourne, Australia showing public sculpture garden in wetland area near large underground tanks.

An example of a large stormwater storage facility for later beneficial uses is at the Docklands Park in Melbourne, Australia. Docklands Park is a downtown open space with an area of 2.7 ha. The park collects stormwater from the adjacent ultra-urban catchment of downtown Melbourne, providing water for park irrigation. Treated stormwater is stored in the underground storage tanks and the captured stormwater is also treated using UV prior to use. The three underground storage tanks have a combined capacity of 500 m^3.



Percolation of Stormwater for Later use

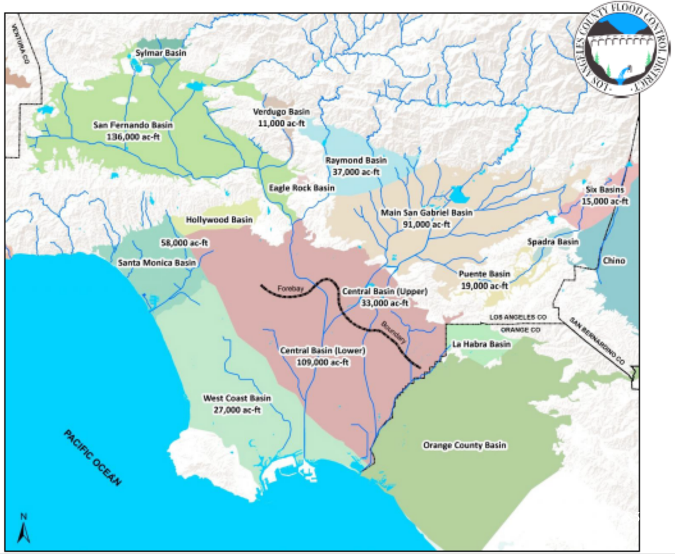
Source: SCWC Stormwater White Paper



Available Basin Storage Space (AF)

Northwest MWD Service Area Basins	945,000
San Fernando Valley Basins	505,000
LA County Coastal Plain Basins	450,000
San Gabriel Valley Basins	245,000
Orange County Basins	135,000
Inland Empire Basins	439,000
Eastside MWD Service Area Basins	500,000
San Diego County Basins	19,000

Los Angeles Basin: 25 Year Annual Average Stormwater Capture Potential



Conclusions

- Public water supplies are being stressed with increasing populations and diminishing available supplies.
- Beneficial uses of stormwater can replace some of the non-consumptive used of the domestic water supply (especially irrigation and toilet flushing)
- With suitable storage, stormwater can supply most/all of these non-consumptive needs, reducing water demands from the public water supply by significant amounts.
- Availability vs. demand time-series, water quality, necessary treatment, and costs currently restrict the wide-spread use of beneficial use of stormwater.

Summary

- Learn from others (and yourselves)! Evaluate and monitor installations and modify approaches.
- Site conditions and local rains dramatically affect performance.
- Northern areas and locations using deicing salts are an extreme example that require special approaches to stormwater management.
- Groundwater issues need to be considered.
- Combinations of unit processes almost always result in the most robust, most cost-effective, and best water quality.

Acknowledgements

- Many research sponsors have supported our research in recent years addressing stormwater treatment, including:
  - US EPA
  - US Navy
  - NSF
  - National Research Council of the National Academy of Sciences
  - American Society of Civil Engineers
  - Water Environment Research Foundation
  - Metropolitan Sewer District of Greater Cincinnati
  - Kansas City
  - City of Tuscaloosa
  - TetraTech
  - Geosyntec
  - HydroInternational
  - Institute of Scrap Recycling Industries
  - The Boeing Co.

Many of our research reports, students theses, and dissertations are available at my teaching and research web site at: http://rpitt.eng.ua.edu/index.shtml

- Most importantly, many students have contributed to our recent research during their graduate studies, including but not limited to:
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  - Dr. Vijay Eppakayala
  - Dr. Kenya Goodson
  - Dr. Alex Maestre
  - Dr. Renee Morquecho
  - Yukio Nara
  - Dr. Olga Ogburn
  - Dr. Radahegn Sileshi
  - Dr. Noburo Togawa
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  - University of Missouri, Kansas City (Dr. Deborah O'Bannon)
  - Universidad de los Andes (Dr. Mario Diazganados Ortiz)