Performance of Low Impact Development/Green Infrastructure/Sustainable Urban Drainage Systems/etc.

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Presentation Topics

- Issues of concern affecting infiltration devices
- Modeling green infrastructure compared to large-scale monitoring
- Summary and conclusions

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Dozen Issues of Concern Affecting Infiltration Devices

- Improper Modeling
- 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

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1) Improper Modeling and Poor Selection of Targeted Rain Events

- 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

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

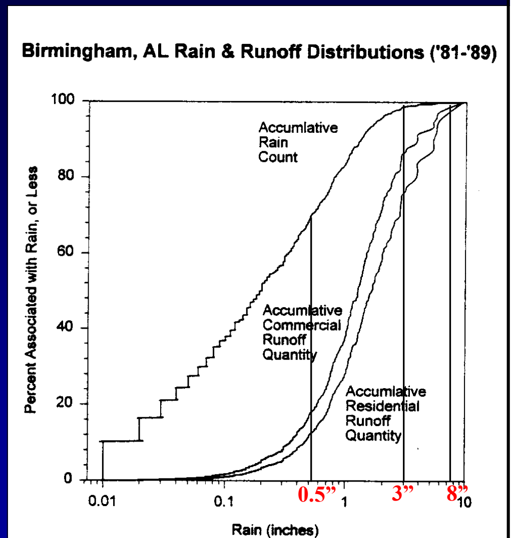
Birmingham Rains:

<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)



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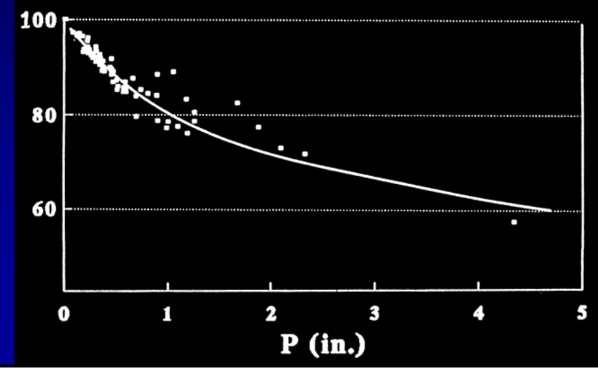
Typical plot of calculated curve numbers for actual site monitoring. This date is from the Univ. of Florida’s rainfall-runoff database that contains historical SCS and COE monitoring data that was used to develop TR-55. Obviously, the CN method is only applicable for the large drainage design storms 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)



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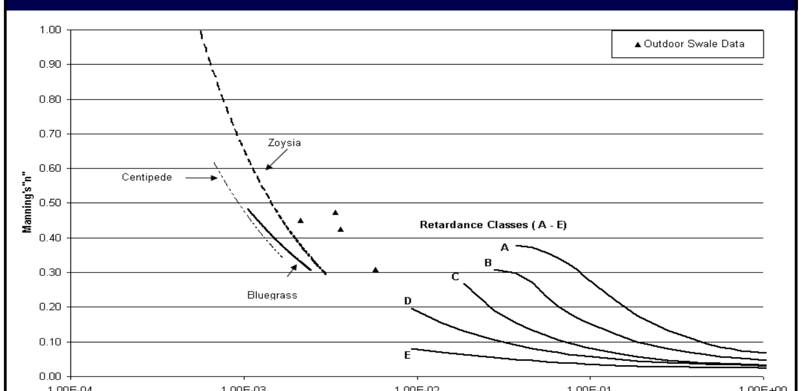
Indoor vs. Historical Stillwater, Oklahoma, Retardance Curves



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.

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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.

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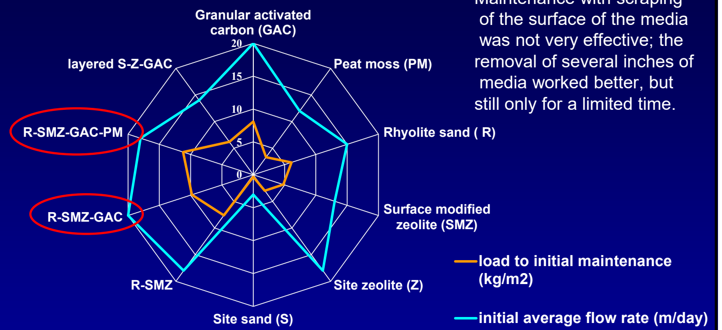
Want media with good clogging and good flow rate characteristics

Maintenance with scraping of the surface of the media was not very effective; the removal of several inches of media worked better, but still only for a limited time.



1. Site sand clogged first and had the lowest flow rate
2. Site zeolite and peat alone were next to clog
3. Biofiltration mixed media combination performed better than current site layered media combination

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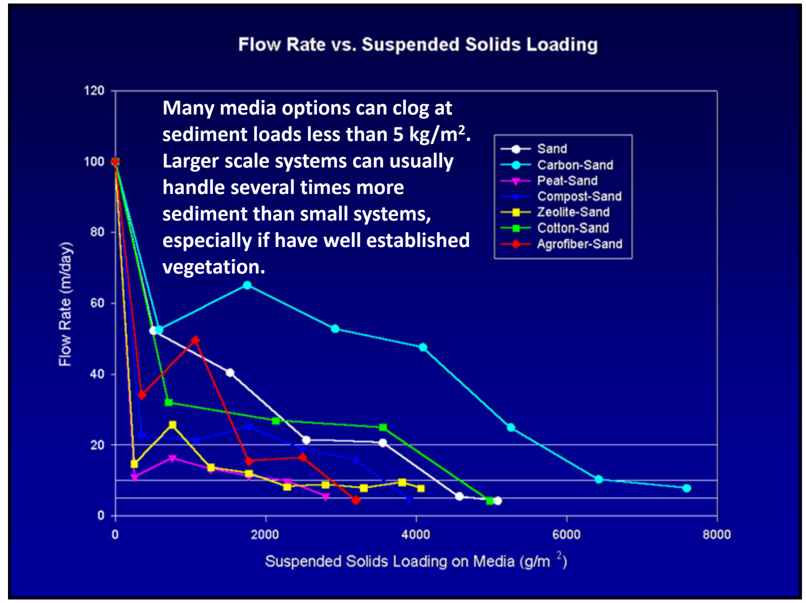

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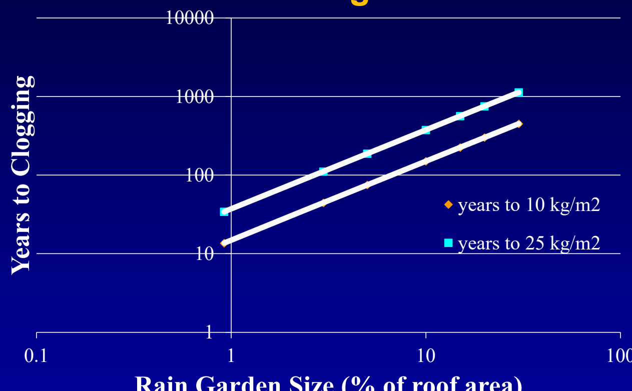
Clogging Potential for Different Sized Rain Gardens Receiving Roof Runoff



Clogging not likely a problem with rain gardens from roofs

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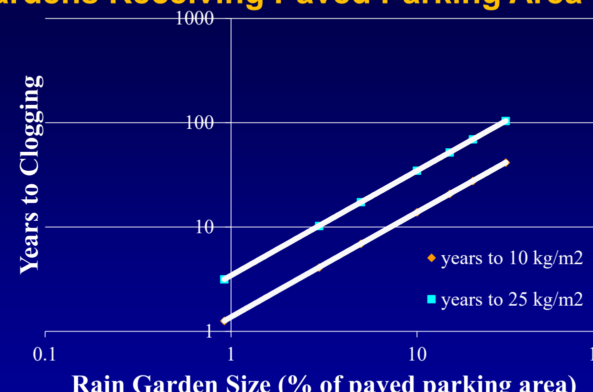
Clogging Potential for Different Sized Rain Gardens Receiving Paved Parking Area Runoff



Rain gardens should be at least 10% of the paved drainage area, or receive significant pre-treatment (such as with long grass filters or swales, or media filters) to prevent premature clogging.

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3) 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.

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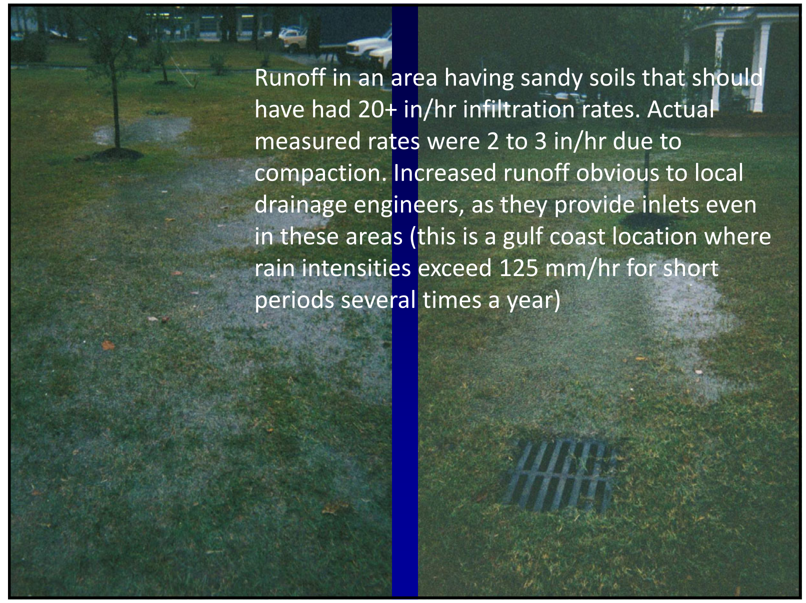

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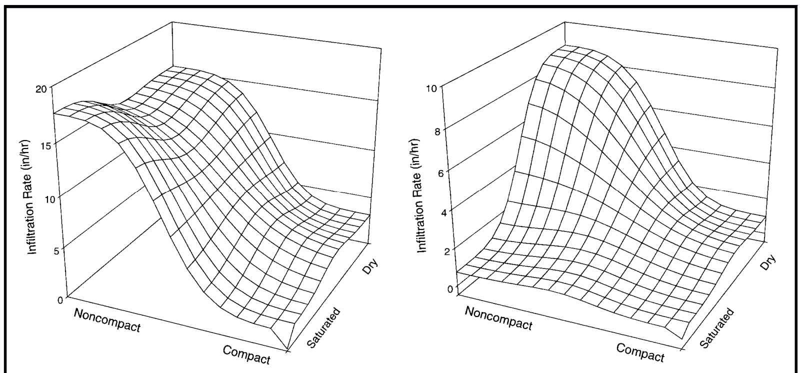

Infiltration Rates in Disturbed Sandy Urban Soils

Infiltration Rates in Disturbed Clayey Urban Soils

Pitt, *et al.* 1999

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In-situ soil density sampling and measurements:

1) Small hole is excavated and soil brought to lab for moisture and dry weight analyses (and usually texture measurements also)
2) The hole is backfilled with a free-flowing sand to measure the volume
3) The soil density is then directly calculated (infiltration rates are also simultaneously measured in the same area)

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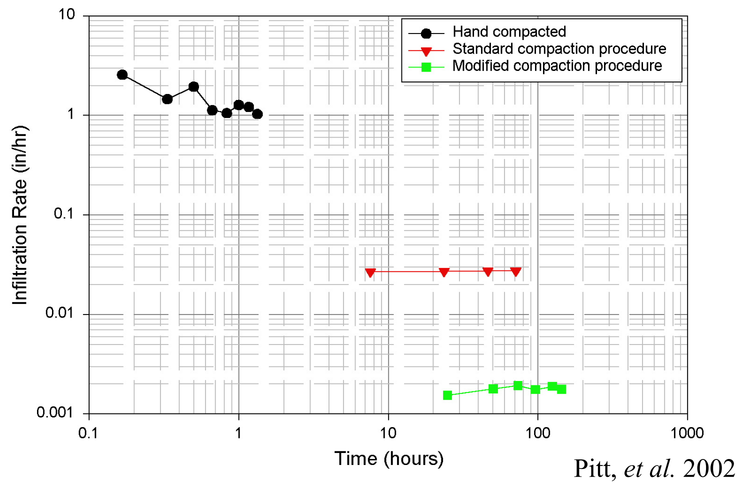
Laboratory Infiltration Tests for Silty Loam Soil
4" Diameter Test Cylinder, 4.5" Depth



Pitt, *et al.* 2002

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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.

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Mostly ionic forms in filtered stormwater (with some notable exceptions); also, several removal processes occur, beyond ion exchange and sorption

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

Morquecho 2005

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Breakthrough Capacity Compared to Clogging Period

Ratios of Media Capacity to Clogging Period	R-SMZ	R-SMZ-GAC	R-SMZ-GAC-PM	Site Sand-GAC-Site Zeolite Layered
Cadmium, Total	>230	>170	>130	>150
Copper, Total	>2.2	>3.4	>1.7	>2.2
Gross Alpha radioactivity	>0.3	>0.3	>0.2	>0.2
Lead, Total	>2.1	>1.6	>0.9	>0.9
Mercury	>250	>230	>130	>140
Oil and Grease	0.1	>0.1	>0.1	<0.1
TCDD	>3.1	>2.5	>1.3	>1.5

Green: will clog before breakthrough (desired, as easier to detect)
Red: breakthrough before clogging

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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 should prohibit clays, focusing on sandy material with stable organic amendments (peat recommended; compost can be a problem).

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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.

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Soils in area of curb-cut biofilters being retrofitted, indicating high clay content, debris, and compaction (these soils will be removed and new media used after the other components (underground storage and new sidewalks) are constructed)

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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.

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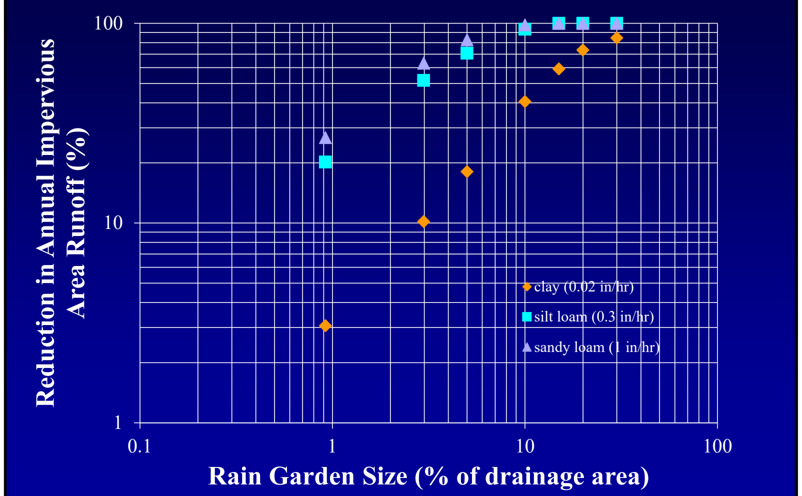
Annual Runoff Reductions from Paved Areas or Roofs for Different Sized Rain Gardens for Various Soils



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Cistern/Storage Tank Sizing vs. Performance

Storage per house (ft^3 per ft^2 of roof area)	Reduction in annual roof runoff (%)	Number of 35 gallon rain barrels for 945 ft^2 roof	Tank height size required if 5 ft D (ft)	Tank height size required if 10 ft D (ft)
0.005	24	1	0.24	0.060
0.010	29	2	0.45	0.12
0.020	39	4	0.96	0.24
0.050	56	10	2.4	0.60
0.12	74	25	6.0	1.5
0.50	99	100	24	6.0

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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 LID components!

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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
- 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).

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Potential Problem Pollutants were Identified by Pitt, *et al.* (1994 and 1996) Based on a Weak-Link Model Having the Following Components:

- Their abundance in stormwater,
- Their mobility through the unsaturated zone above the groundwater, and
- Their treatability before discharge.

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Moderate to High Contamination Potential

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**

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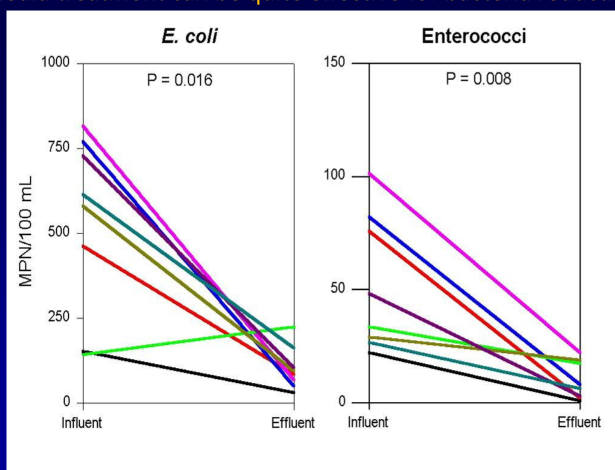
Media treatment can be quite effective for bacteria reductions



PEAT-SAND FILTER: Pilot-Scale Testing, Fall 1999

Clark and Pitt 1999

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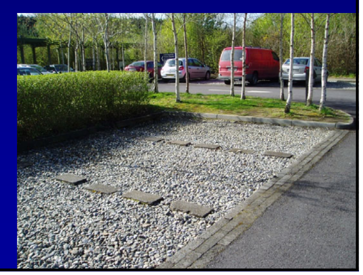
Minimal Pre-treatment before Infiltration Leads to Greater Groundwater Contamination Potential

Early approaches to infiltrating stormwater:



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

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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.

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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.

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

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Obvious short-circuiting flow path and washout of media in over-filled biofilter.

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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.

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Excessive erosion at edges of biofilter.

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

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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.

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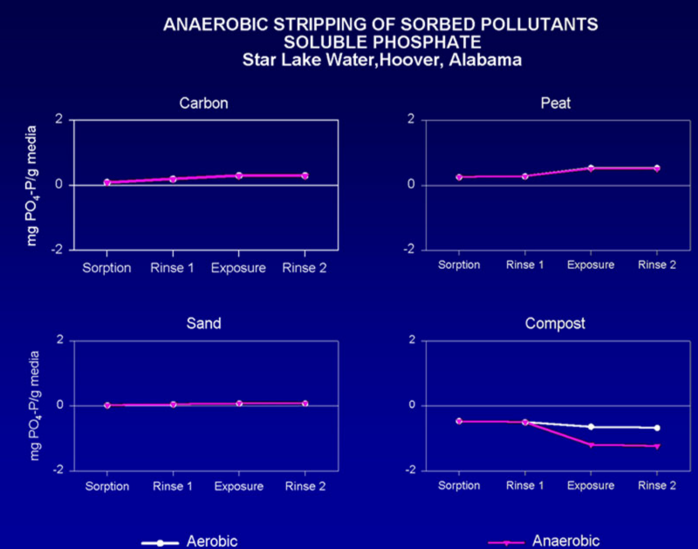

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11) Large Underdrains and Short-Circuiting

- 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.

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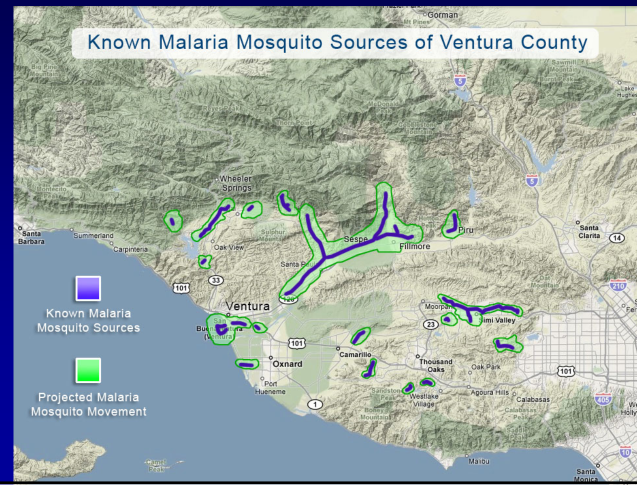
Many Areas Require Biofilter Drainage within 72 hours to Prevent Mosquito Infestation



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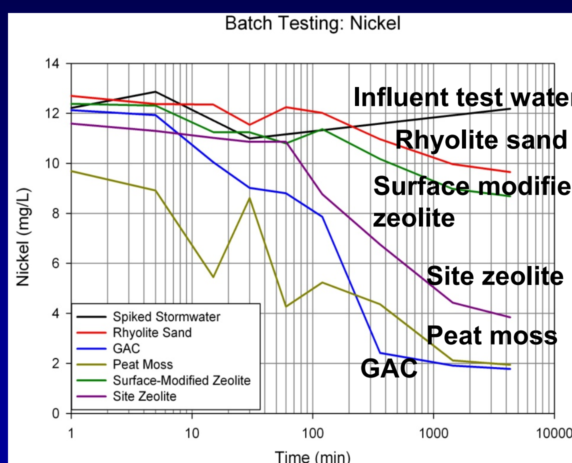
Contact Time Affects Pollutant Removals

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.



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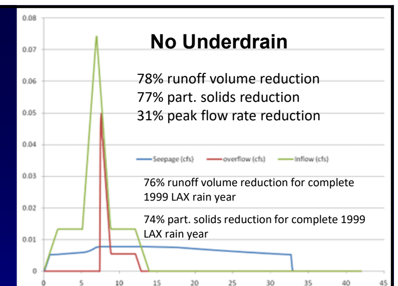
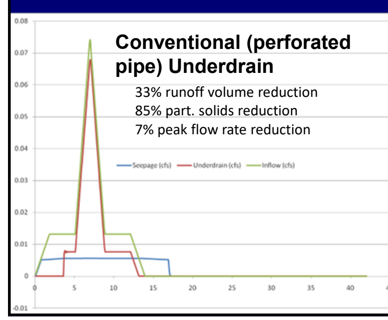
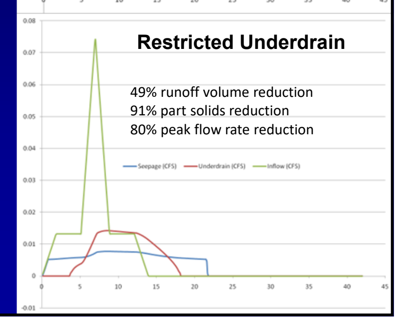
Underdrain Effects on Water Balance

20 mm rain with complex inflow hydrograph from 0.4 ha of pavement. 2.2% of paved area is biofilter surface, with natural loam soil (12 mm/hr infilt. rate) and 0.6 m of modified fill soil for water treatment and to protect groundwater.







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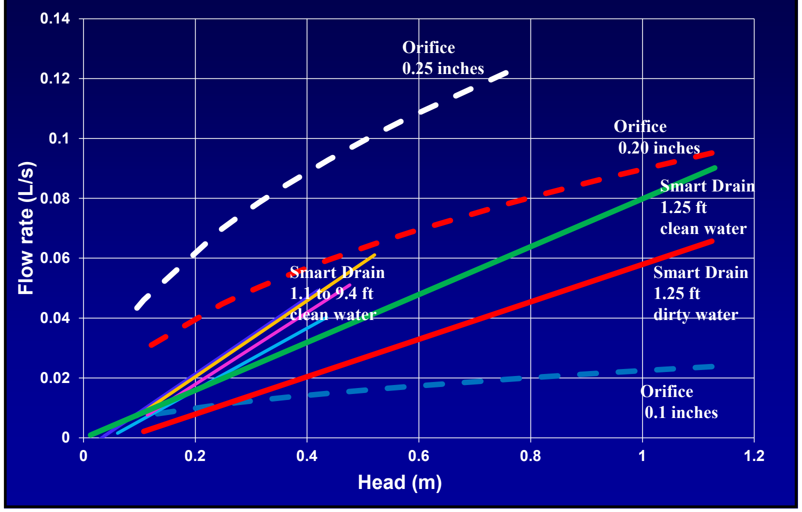
Smart Drain Flow Rates Compared to Very Small Orifices



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

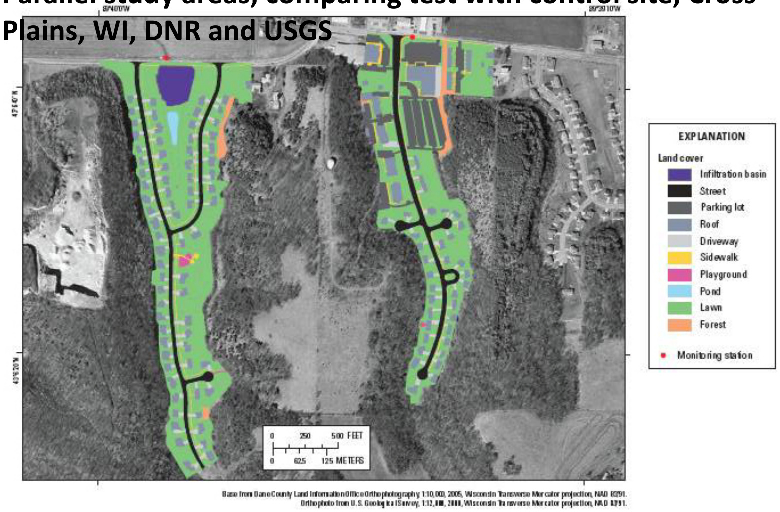
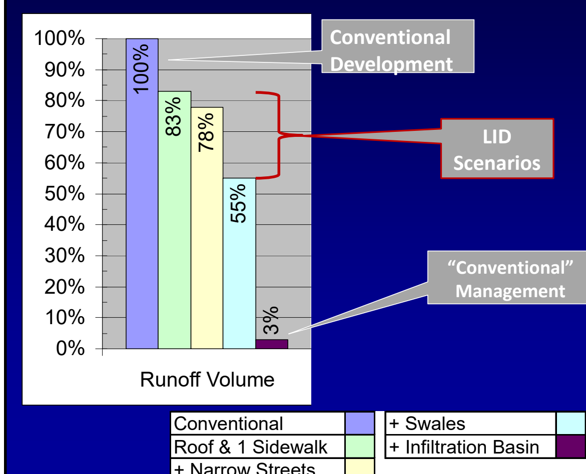
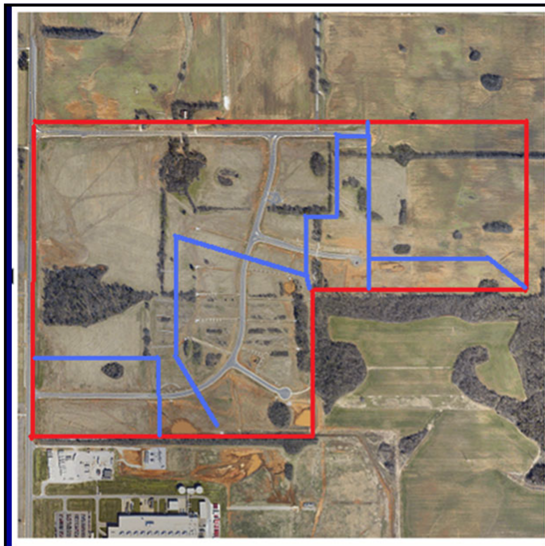


Figure 2. Land use in the low-impact-development (left) and conventional-development (right) basins and location of water-quality monitoring stations, Cross Plains, Wis.

Runoff Reductions by Site Components





North Huntsville (AL) Conservation Design Industrial Park

- On-site bioretention swales
- Level spreaders
- Large regional swales
- Wet detention ponds
- Critical source area controls
- Pollution prevention (no Zn!)
- Buffers around sinkholes
- Extensive trail system linking water features and open space

Aerial Photo of Site under Construction (Google Earth)

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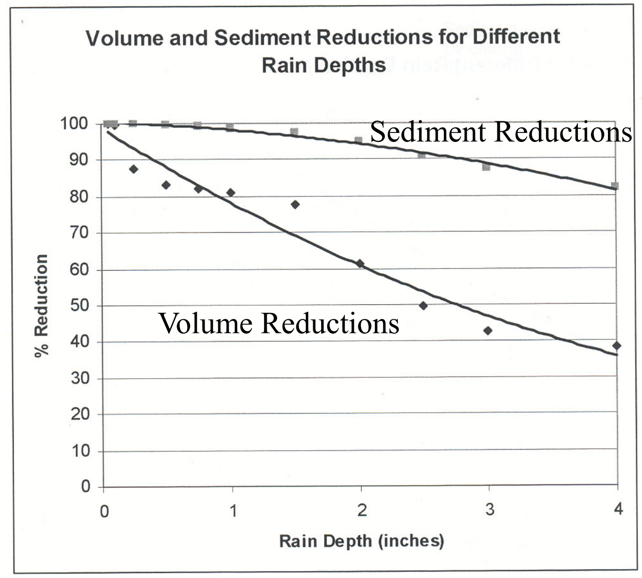

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Modeling Green Infrastructure Compared with Large-Scale Monitoring at Kansas City, MO and Cincinnati, OH

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Kansas City's CSO Challenge

- Combined sewer area: 58 mi^2
- Fully developed
- Rainfall: 37 in./yr
- 36 sewer overflows/yr by rain > 0.6 in; reduce frequency by 65%.
- 6.4 billion gal overflow/yr, reduce to 1.4 billion gal/yr
- Aging wastewater infrastructure
- Sewer backups
- Poor receiving-water quality

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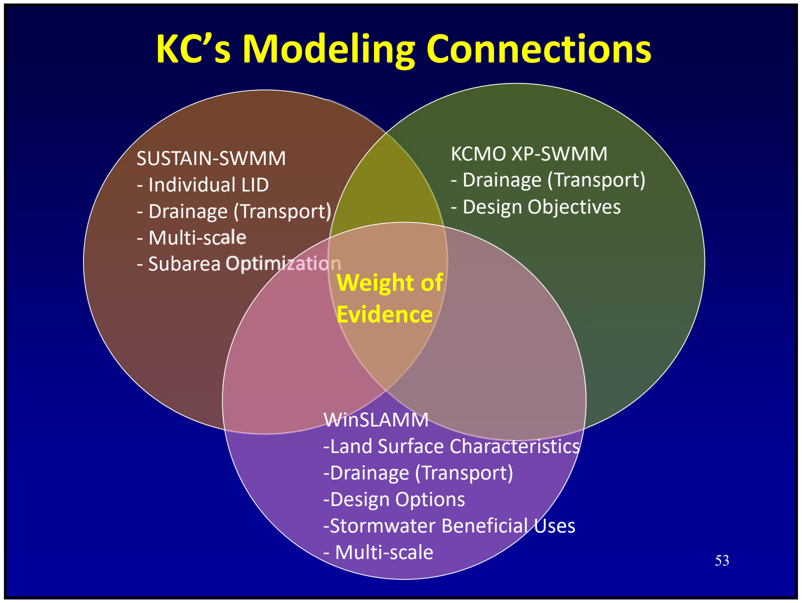
KC's Modeling Connections
SUSTAIN-SWMM
- Individual LID
- Drainage (Transport)
- Multi-scale
- Subarea Optimization
KCMO XP-SWMM
- Drainage (Transport)
- Design Objectives
Weight of Evidence
WinSLAMM
-Land Surface Characteristics
-Drainage (Transport)
-Design Options
-Stormwater Beneficial Uses
- Multi-scale
53

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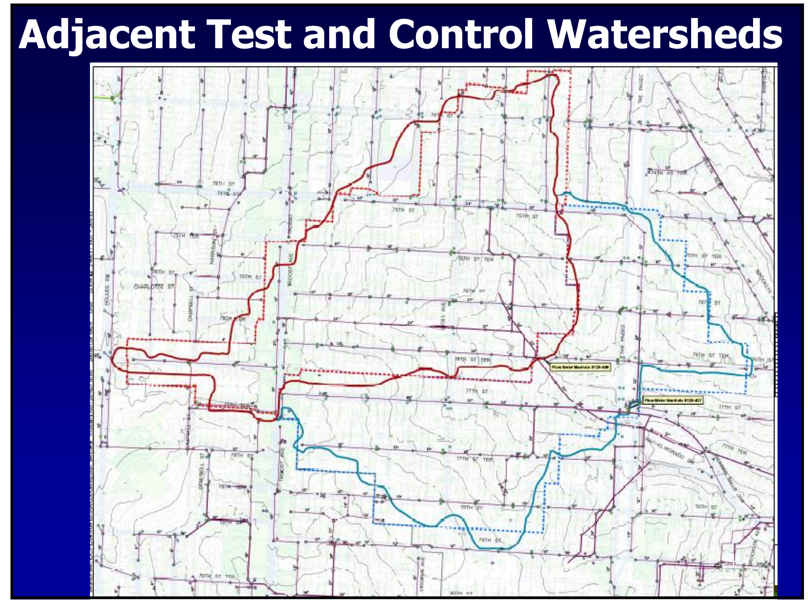
Adjacent Test and Control Watersheds

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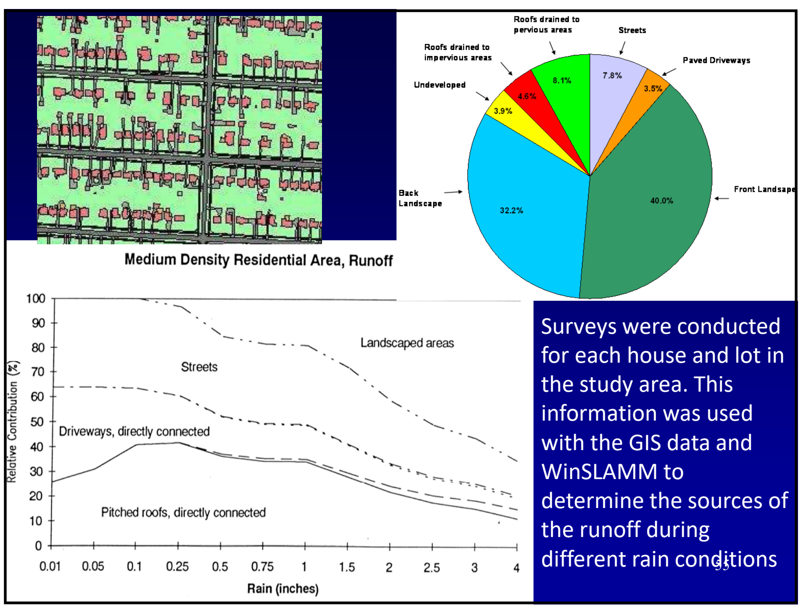
Roofs drained to pervious areas
Streets
Roofs drained to impervious areas
Paved Driveways
Undeveloped
8.1%
7.8%
4.6%
3.5%
3.9%
Back Landscape
Front Landsape
32.2%
40.0%
Medium Density Residential Area, Runoff
Landscaped areas
Streets
Driveways, directly connected
Pitched roofs, directly connected
Relative Contribution (%)
Rain (inches)
Surveys were conducted for each house and lot in the study area. This information was used with the GIS data and WinSLAMM to determine the sources of the runoff during different rain conditions

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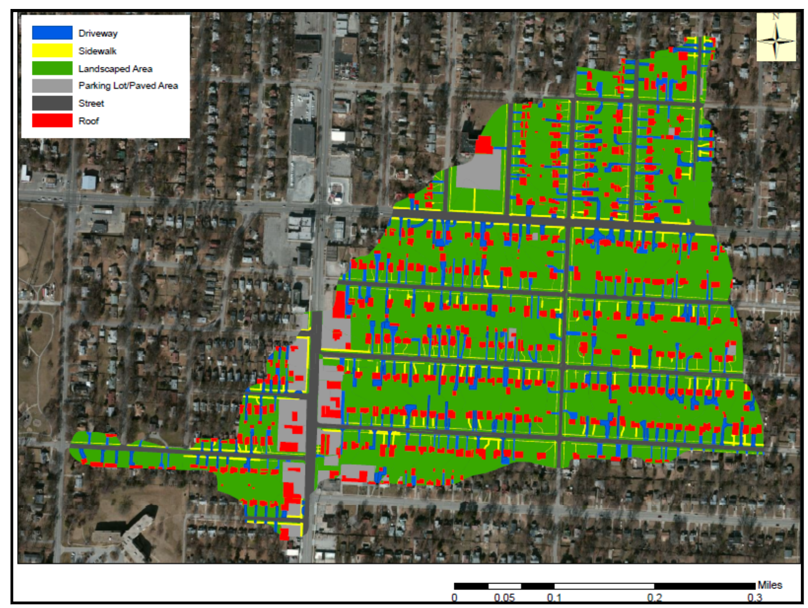
Driveway
Sidewalk
Landscaped Area
Parking Lot/Paved Area
Street
Roof
Miles

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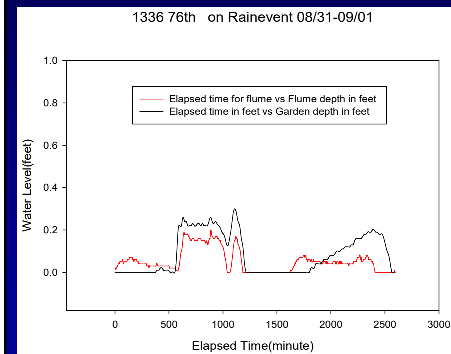
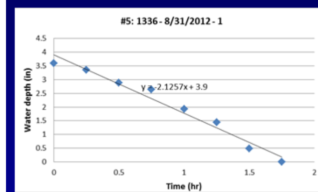
Major Land Use Components in Residential Portion of Study Area (% of area and % of total annual flow contributions)

	Roofs	Drive-ways	Side-walks	Park-ing	Streets	Land-scaped	Total
Directly connected	2 (6)	4 (9)	1 (3)	2 (5)	9 (21)		18 (44)
Disconnected	11 (7)	4 (3)	1 (1)				16 (11)
Landscaped						66 (45)	66 (45)
Total area	13 (13)	8 (12)	2 (4)	2 (5)	9 (21)	66 (45)	100

Based on KCMO GIS mapping and detailed site surveys, along with WinSLAMM calculations.

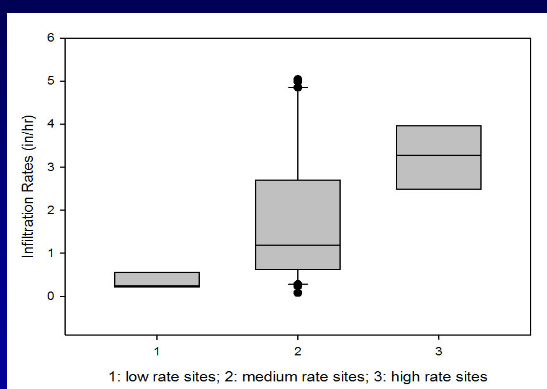
Example Water Level in Influent Flume and Water Stage Recordings in Biofilter used for Calculating Infiltration Rates during Rains

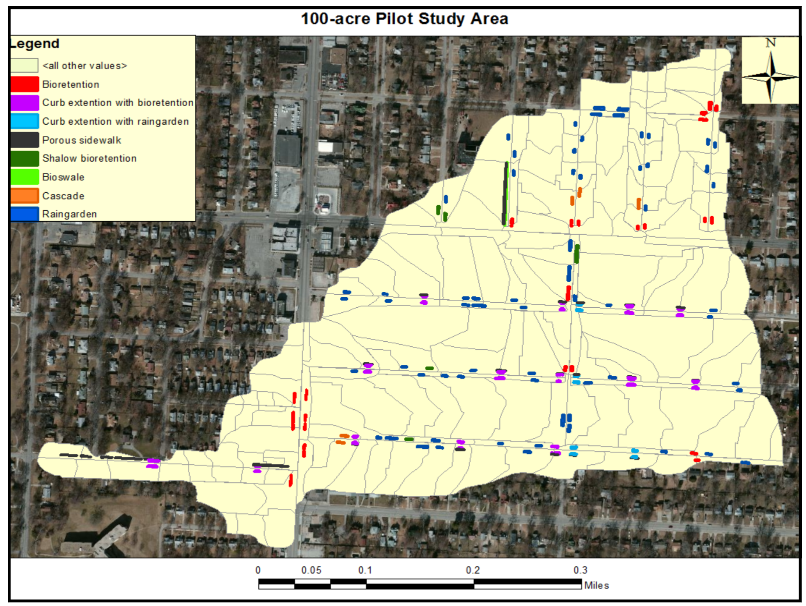




Example plot of recession limbs and infiltration rate calculation (after influent flows ceased).

Measured Biofilter Infiltration Rates During Actual Rains, Separated into Three Categories





Summary of Constructed Stormwater Controls in Test Area

Design plan component	Number of this type of stormwater control units in 100 acre test (pilot) area	Device as a % of the drainage area	Average drainage area for each unit (ac)	Total area treated by these devices (ac)
Bioretention	24 (no curb extensions)	1.6	0.40	9.6
	28 (with curb extension)	1.5	0.40	11.2
	5 (shallow)	1.6	0.40	2.0
Bioswale	1 (vegetated swale)	8.9	0.50	0.5
Cascade	5 (terraced bioretention cells in series)	1.9	0.40	2.0
Porous sidewalk or pavement	18 (with underdrains)	100.0	0.015	0.3
	5 (with underground storage cubes)	99.9	0.015	0.1
Rain garden	64 (no curb extensions)	2.8	0.40	25.6
	8 (with curb extension)	1.5	0.40	3.2

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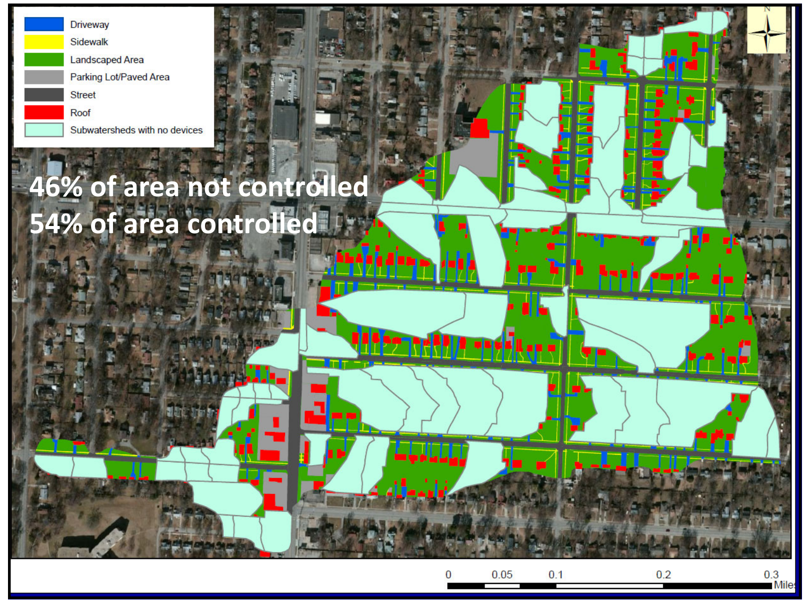

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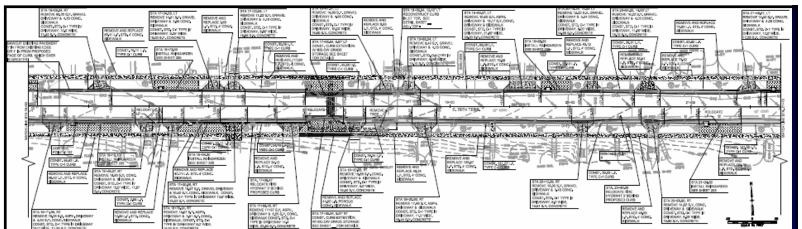

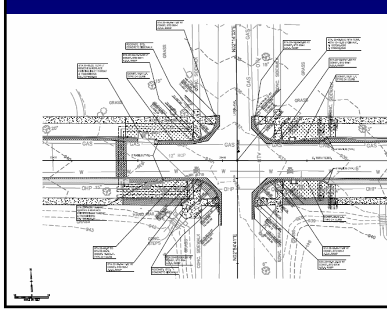

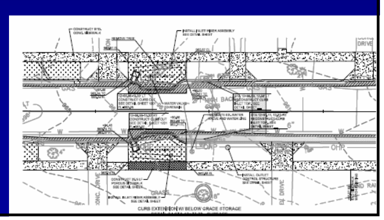

Examples plans prepared by URS for project streets.

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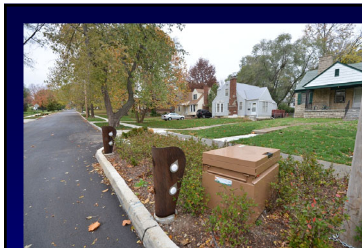

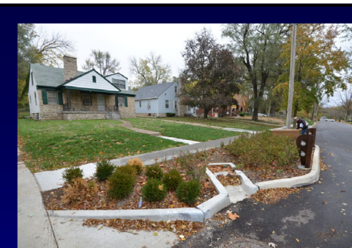

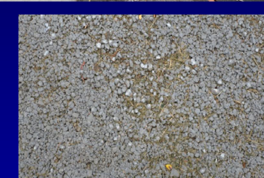

1324 76th St. monitoring location, biofilter and adjacent porous concrete sidewalk

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Other Stormwater Controls in Test Area

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Other Stormwater Controls in Test Area

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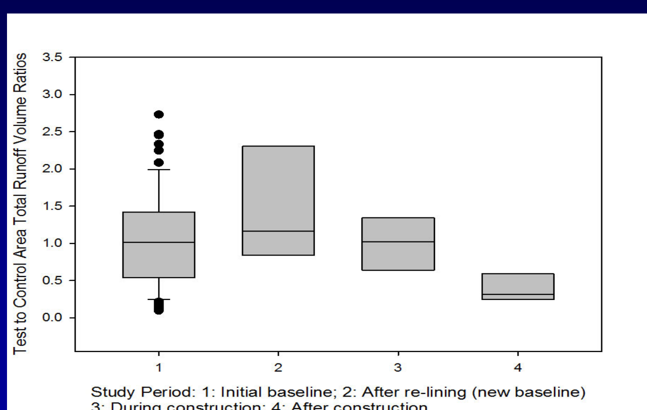
Test to Control Area Runoff Flow Ratios during Different Monitoring Periods



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Test and Control Watershed Flow Comparisons

Monitoring Period	% change compared to initial baseline (and p from Wilcoxon Rank-Sum test)
Initial baseline	n/a
After re-lining	44% increase (p=0.20)
During construction	4% decrease (p=0.94)
After construction (after April 1, 2012)	55% decrease (p=0.006)

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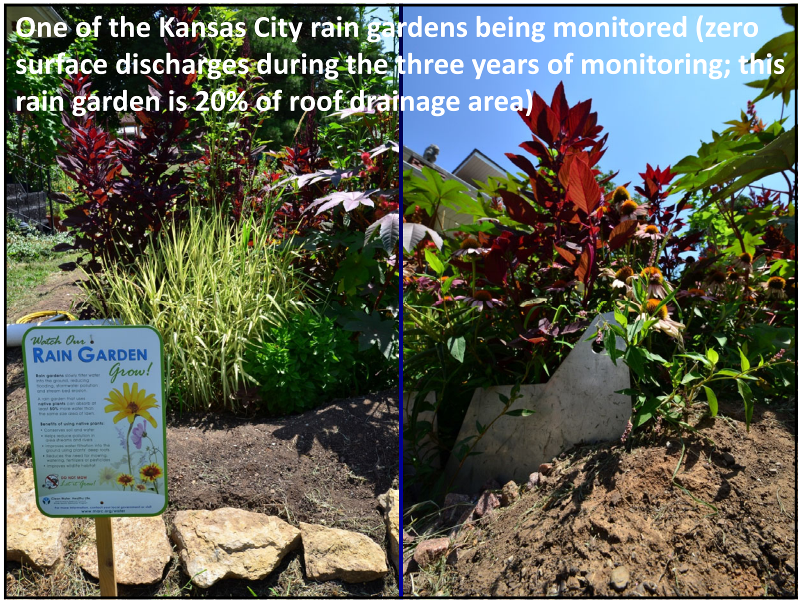
One of the Kansas City rain gardens being monitored (zero surface discharges during the three years of monitoring; this rain garden is 20% of roof drainage area)



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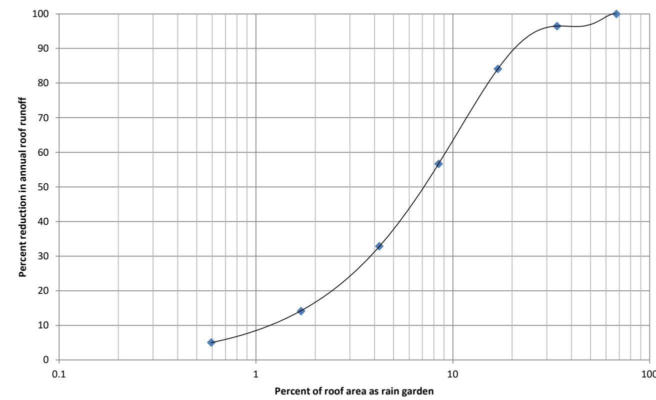
Percentage Reductions of Annual Runoff Flows with Rain Gardens



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Cincinnati Demonstration Projects Background

- The Metropolitan Sewer District of Greater Cincinnati (MSD) is among the top 5 Combined Sewer Overflow (CSO) dischargers in the country, discharging approximately 14 billion gallons of overflows during a typical year of rainfall.
- About 75 million gallons per year of stormwater removed from the combined system from 22 Green Demonstration projects which include:
  - 290,000 square feet of bioinfiltration practices,
  - 168,000 square feet of vegetative (green) roofs,
  - 155,000 square feet of porous/pervious pavement,
  - 125,000 gallons of rainwater storage for reuse,
  - 2,040 linear feet of storm sewer separation, and
  - 5 large capacity stormwater dry wells.

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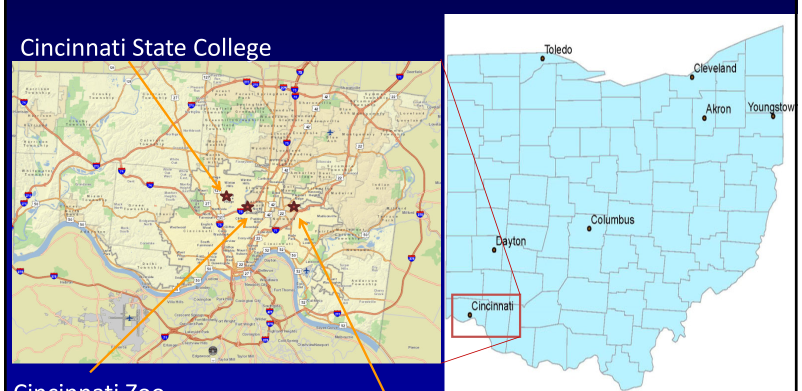
Geographical Locations and Description – Cincinnati, OH

Cincinnati State College



Cincinnati Zoo

Clark Montessori High School

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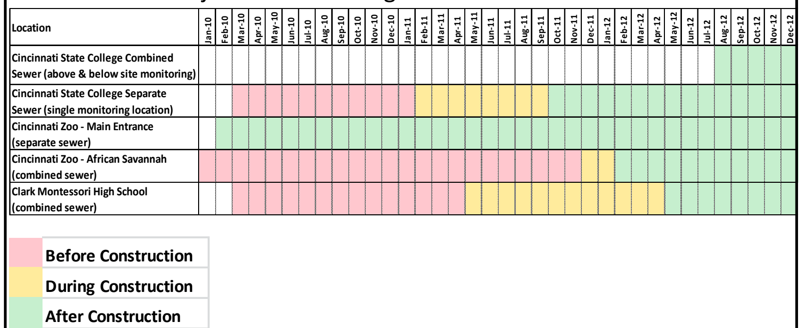
Availability of Flow Monitoring Data for Different Green Infrastructure Evaluation Locations

About 3 years of high-resolution (5-minute) flow measurements from in-system flow monitors located in combined and separate sewers on or adjacent to several green infrastructure installations



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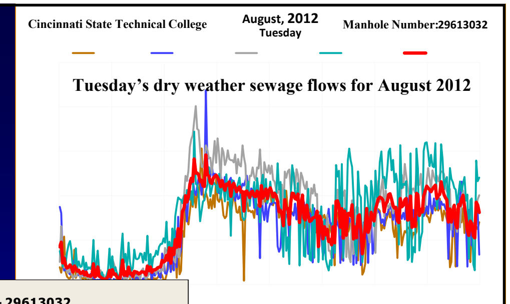
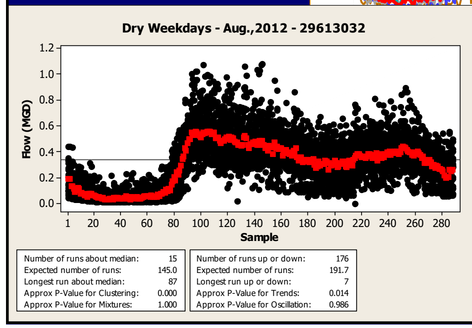
- The first data analysis effort was to separate the base flows (dry weather flows) from the combined wet weather flows to obtain the direct runoff time series associated with each rain.





Combined Time Series of All Weekday's Dry Weather Flows for August 2012

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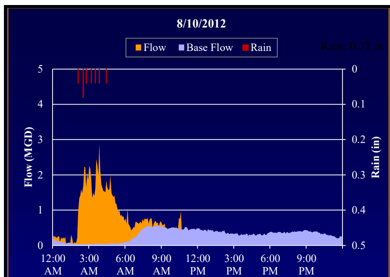

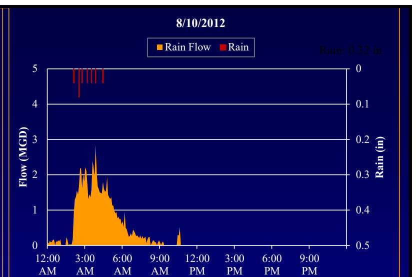

Prepared individual storm event data summaries that coordinated with the rain data for each monitoring point, including:

- start/end time of rain,
- rain duration,
- antecedent dry days,
- total rain,
- peak and average rain intensity,
- pipe-flow start/end time,
- total pipe-flow discharge volume,
- total runoff,
- peak and average flow discharge rates,
- R_v (the ratio of runoff to rainfall depth).

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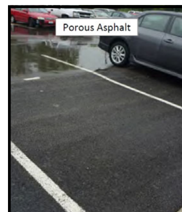
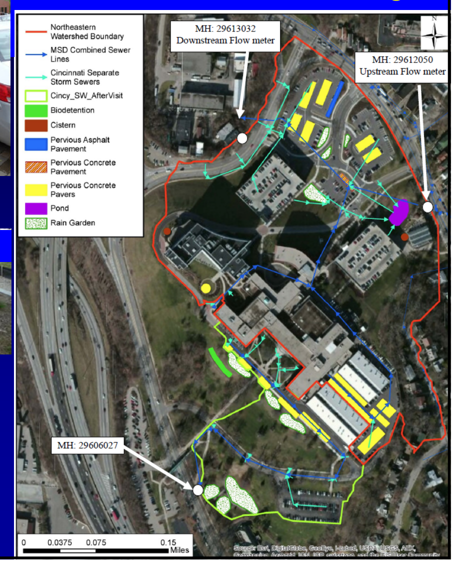
Cincinnati State Technical College





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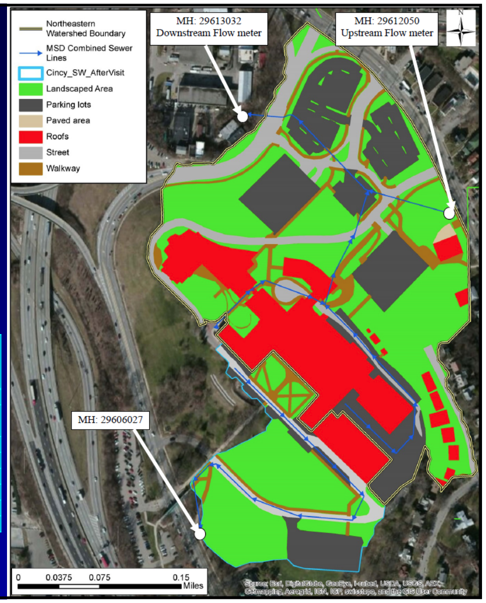
Land Cover Description

Land Cover type	Northeastern part of campus Areas drain into Downstream Flow Meter with manhole number 29613032	
	Area (ft²)	Area (%)
Landscaped area	486,840	39.7
Parking lot	270,560	22.1
Paved area	2,690	0.2
Roof	241,640	19.7
Street	156,700	12.8
Walkway	68,530	5.6
Total	1,226,960 (28 ac)	100.0

Land Cover type	Southwestern part of campus Areas drain into manhole number 29606027	
	Area (ft²)	Area (%)
Landscaped area	360,250	58.3
Parking lot	89,990	14.6
Paved area	0	0
Roof	62,000	10.0
Street	70,340	11.4
Walkway	35,490	5.7
Total	618,070 (14 ac)	100



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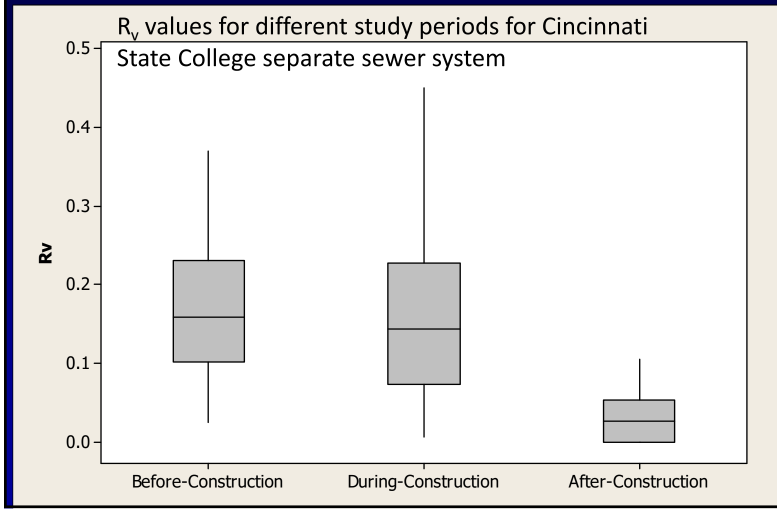
Cincinnati State College (Southwestern drainage in separate storm sewer)



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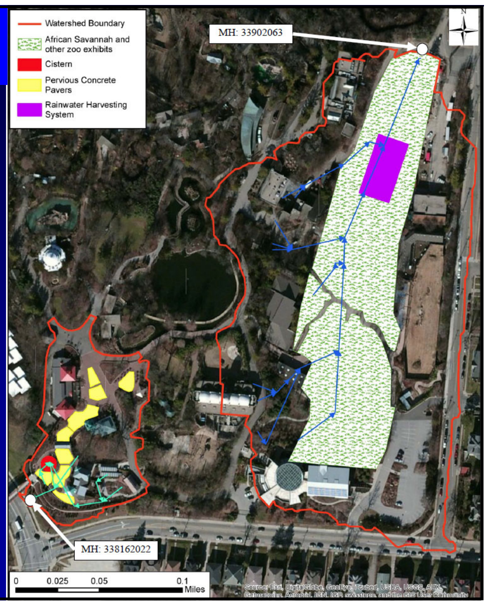
Cincinnati Zoo



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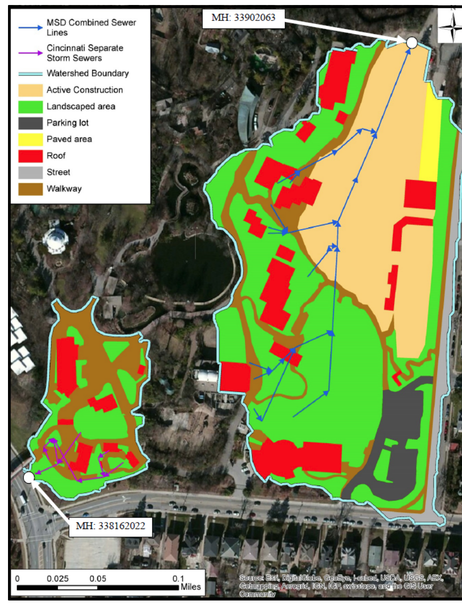

Land Cover Description

African Savannah Zoo

Land Cover type	Area (ft²)	Area (%)
Landscaped area	228,610	39.2
Active Construction	152,920	26.2
Parking lot	30,520	5.2
Paved area	10,060	1.7
Roof	76,680	13.1
Street	24,910	4.3
Walkway	59,470	10.2
Total	583,170 (12 ac)	100

Main Entrance

Land Cover type	Area (ft²)	Area (%)
Landscaped area	43,060	40.2
Paved area	47,990	44.8
Roof	16,150	15.1
Total	107,200 (2.5 ac)	100

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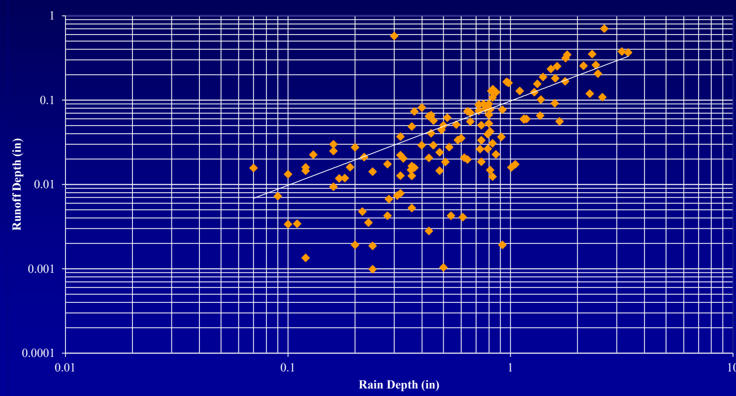
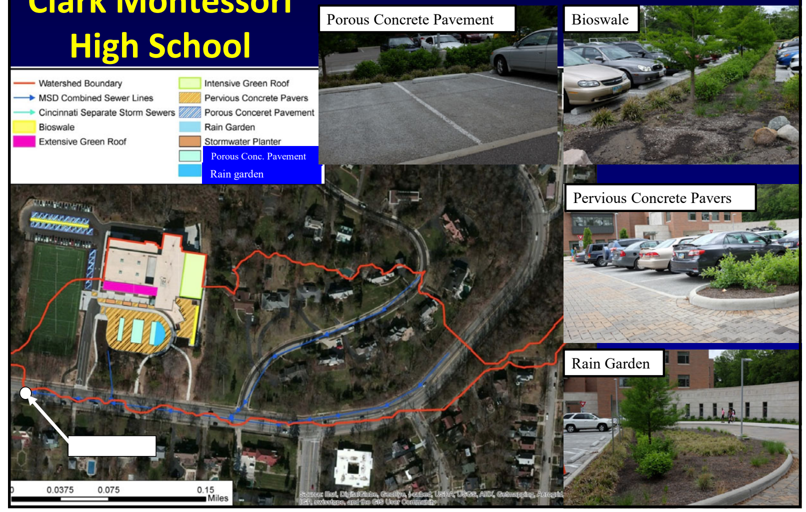
Cincinnati Zoo – Main Entrance (Paver blocks)

176 after construction events

Average Rv = 0.10 based on observed slope

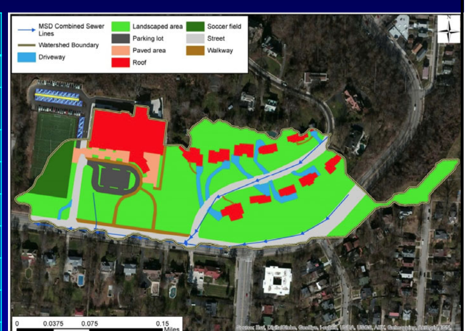


Clark Montessori High School

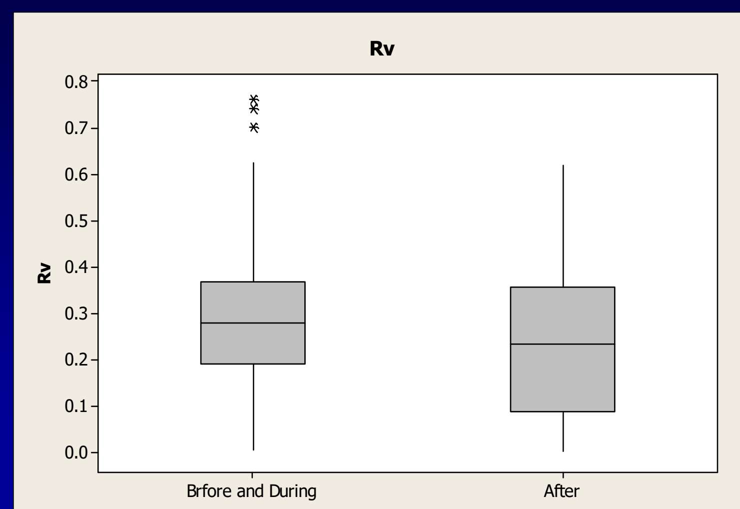


Land Cover Description

Land Cover type	Area (ft²)	Area (%)
Driveway	22,840	3.6
Landscaped area	369,450	57.5
Parking lot	22,080	3.4
Paved area	15,030	2.3
Roof	86,620	13.5
Soccer Field	25,870	4.0
Street	86,130	13.4
Walkway	14,960	2.3
Total	642,980 (15 ac)	100.0



Clark Montessori High School



Summary

Location	Runoff Volume Reduction (%) Compared to Pre-Construction Data
Cincinnati State College – Southern Area (bioinfiltration and rain gardens)	80
Cincinnati Zoo – Main Entrance (extensive paver blocks)	Average Rv values after construction: 0.1 (compared to about 0.8 for conventional pavement in area)
Cincinnati Zoo – African Savannah (rainwater harvesting system and pavement removal)	70
Clark Montessori High School (green roofs and parking lot biofilters on small portion of watershed)	21

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Conclusions and Recommendations for Flow Monitoring for Green Infrastructure Performance

- Monitor both test and control areas both before and after construction of stormwater controls, if possible, for the greatest reliability (to account for typical year-to-year rainfall variations and to detect sensor problems early).
- Test areas should have most of their flows treated by the control practices to maximize measurable reductions.
  - **Any untreated upgradient areas should be very small in comparison to the test areas. Difficult to subtract two large numbers (each having measurement errors and other sources of variability), such as above and down gradient monitoring stations, and have confidence on the targeted flows.**

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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.

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