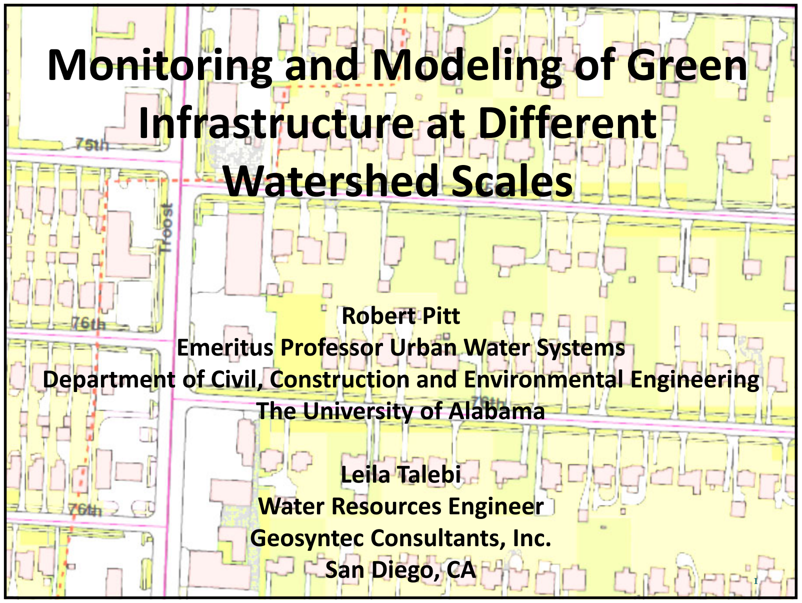

Monitoring and Modeling of Green Infrastructure at Different Watershed Scales

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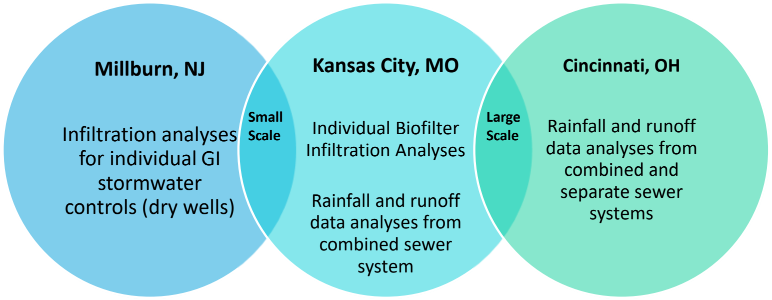
Introduction

- There is great interest in the use of green infrastructure (GI) to mitigate stormwater and combined sewer overflow discharges.
- While there are much data indicating the performance for individual stormwater controls used in GI projects, few data are available describing the performance of multiple GI facilities implemented at large scales, although many modeling studies have been conducted to illustrate the likely results.
- This paper presents monitoring results from three GI monitoring projects conducted at small to large scales, demonstrating expected performance, along with concurrent modeling.
  - Real time rainfall and runoff data from areas served by GI controls were analyzed before and after their construction.
  - The GI controls at these locations were capable of infiltrating most all flows from common small to intermediate rains.
  - Large-scale monitoring confirmed that the overall performance was directly related to the amount of the drainage area flows that were directed to the GI controls.
- High levels of control are challenging and expensive to achieve when retrofitting in existing developed areas, but more effective in institutional areas where greater control of the site runoff is available, and in newly developing areas where GI controls can be integrated into the overall design.

Methodology



Millburn, NJ

Infiltration analyses for individual GI stormwater controls (dry wells)

Small Scale

Kansas City, MO

Individual Biofilter Infiltration Analyses

Rainfall and runoff data analyses from combined sewer system

Large Scale

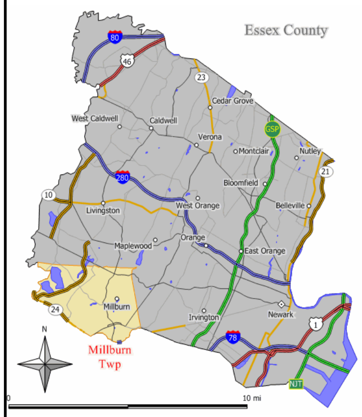
Cincinnati, OH

Rainfall and runoff data analyses from combined and separate sewer systems

Millburn, NJ (Background and Site Descriptions)

- This project was supported by the Wet Weather Flow Research Program of the US EPA and the City of Millburn to investigate whether increased beneficial uses of the runoff would be a more efficient use of the water instead of infiltrating into the shallow groundwaters, and to verify if the use of dry wells are effective in reducing the increased stormwater flows.
- The city of Millburn has required dry wells/cisterns to infiltrate the increased flows from newly developed areas.
- Some water storage tanks are used to store the increased stormwater for later irrigation.
- There are substantial data available for this community, which we supplemented with detailed site information and dry well infiltration measurements to allow a comprehensive review of beneficial stormwater uses.

Geographical Locations and Description – Millburn, NJ

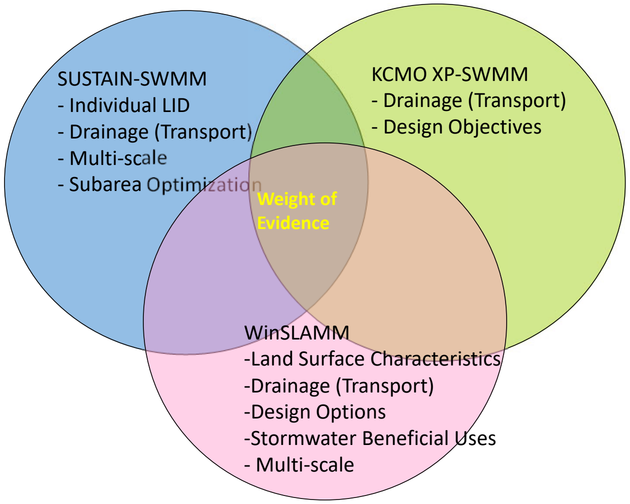


http://upload.wikimedia.org/wikipedia/commons/5/58/Millburn_twp_nj_013.png

Kansas City's CSO Challenge

- Combined sewer area: 58 mi^2 (150 km^2)
- Fully developed
- Rainfall: 37 in./yr (94 cm/yr)
- 36 sewer overflows/yr by rain > 0.6 in (1.5 cm); reduce frequency by 65%.
- 6.4 billion gal (24 million m^3) overflow/yr, reduce to 1.4 billion gal/yr (5.3 million m^3)
- Aging wastewater infrastructure
- Sewer backups
- Poor receiving-water quality

KC's Modeling Connections



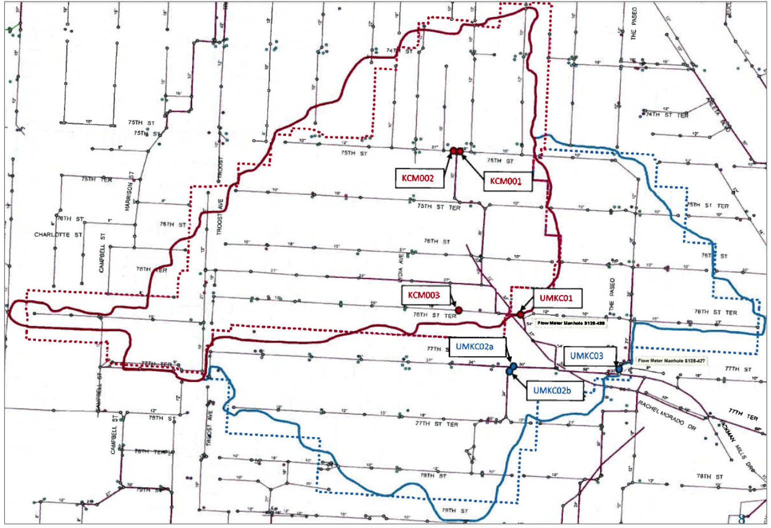
SUSTAIN-SWMM
- Individual LID
- Drainage (Transport)
- Multi-scale
- Subarea Optimization

KCMO XP-SWMM
- Drainage (Transport)
- Design Objectives

Weight of Evidence

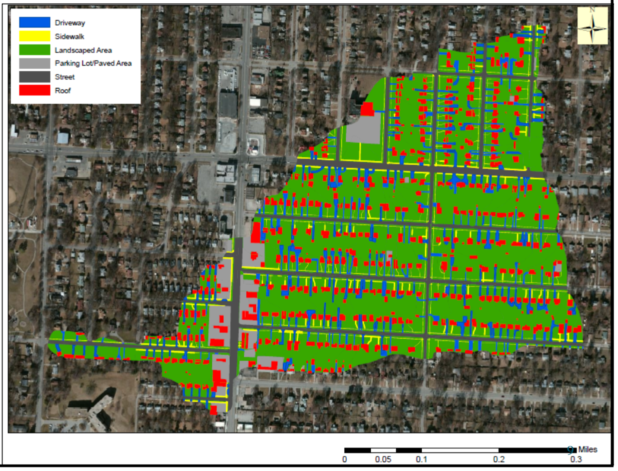
WinSLAMM
-Land Surface Characteristics
-Drainage (Transport)
-Design Options
-Stormwater Beneficial Uses
- Multi-scale

Large-scale performance monitoring at Kansas City, MO (separating test (red) and control (blue) watersheds)



Watershed Analysis and Land Cover Description

- Landscaped areas: 58%
- Roofs: 15%
- Streets: 11%
- Driveways, sidewalks, and parking lots: 16%



Small-scale performance monitoring at Kansas City, MO

1324 76th St. monitoring location, biofilter and adjacent porous concrete sidewalk (one of 10 monitored, along with the large-scale system monitoring of whole drainage areas)

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1. Curb Extension with BR - 1324 E 76th St.

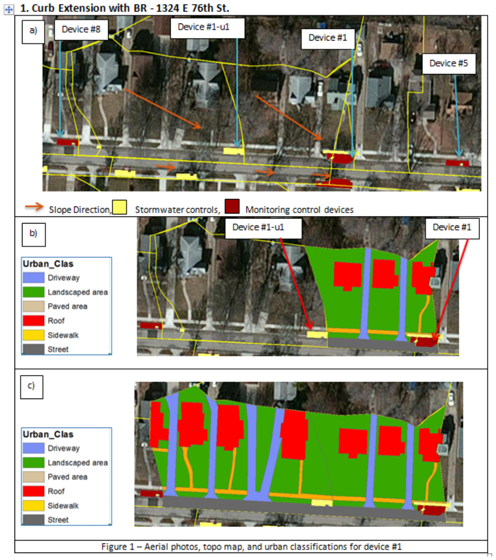


Figure 1 – Aerial photos, topo map, and urban classifications for device #1

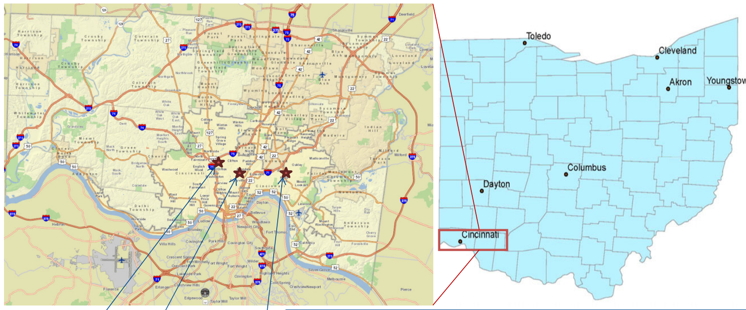
Example micro flow and drainage area analysis for a set of stormwater controls in the test area, examining both direct runoff area to biofilters and overflows from upgradient biofilters.

Summary of Constructed Stormwater Controls in Test Area

Design plan component	Number of this type of stormwater control units in 100 acre (40 ha) 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

Only about 55% of the total area is treated with the green infrastructure components as they had to be located on the public rights-of-way. Other areas flowed to yard drains or treatment locations hindered by trees or structures.

Cincinnati, OH Geographical Locations and Description



Cincinnati State College

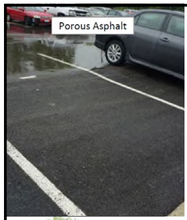
Cincinnati Zoo

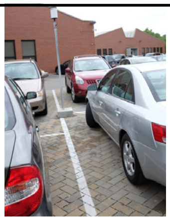
Clark Montessori High School

The Metropolitan Sewer District of Greater Cincinnati is among the top 5 CSO dischargers in the country (14 billion gallons (53 million m^3) of overflows annually)

About 75 million gallons (280,000 m^3) per year of stormwater removed from the combined system from 22 Green Demonstration projects.

Cincinnati State Technical College

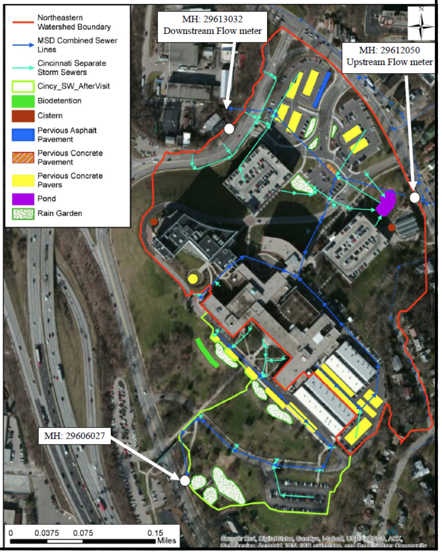

Porous Asphalt

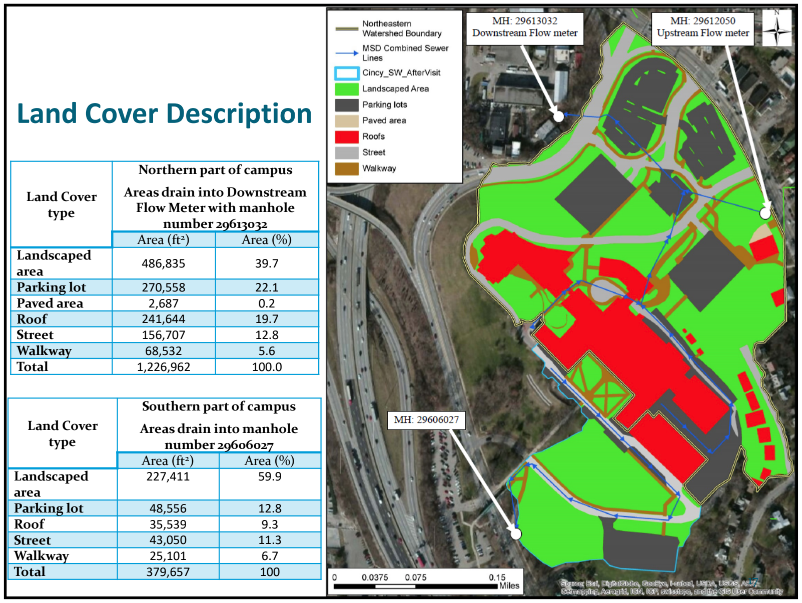



Living Wall


Level Spreader


Rain Gardens

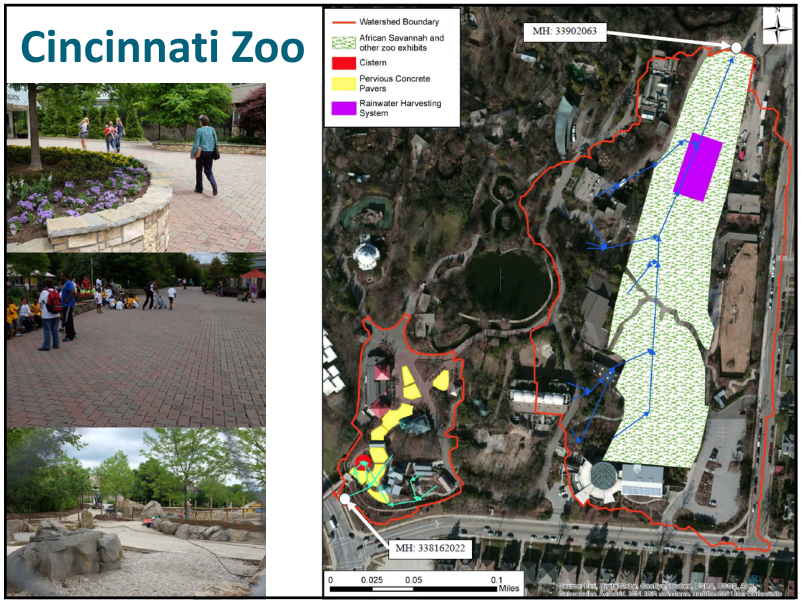




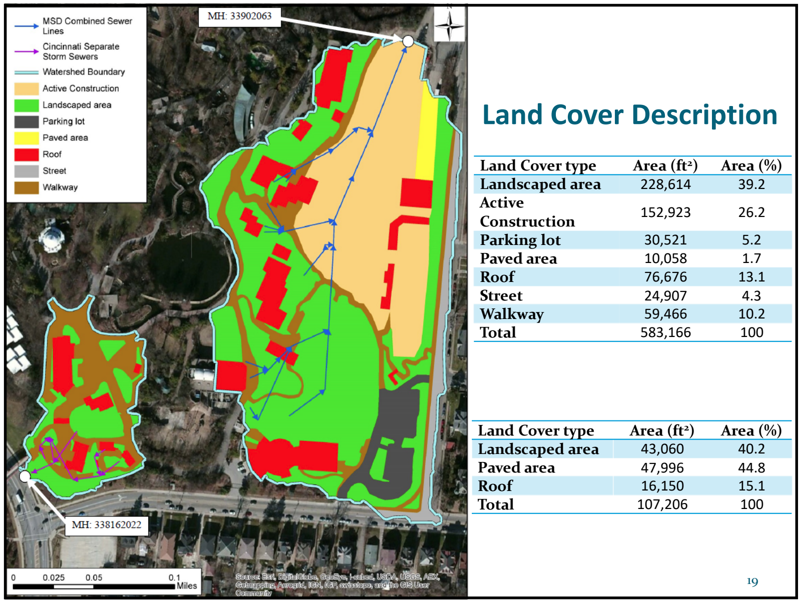
Land Cover Description

Land Cover type	Northern part of campus Areas drain into Downstream Flow Meter with manhole number 29613032	
	Area (ft²)	Area (%)
Landscaped area	486,835	39.7
Parking lot	270,558	22.1
Paved area	2,687	0.2
Roof	241,644	19.7
Street	156,707	12.8
Walkway	68,532	5.6
Total	1,226,962	100.0

Land Cover type	Southern part of campus Areas drain into manhole number 29606027	
	Area (ft²)	Area (%)
Landscaped area	227,411	59.9
Parking lot	48,556	12.8
Roof	35,539	9.3
Street	43,050	11.3
Walkway	25,101	6.7
Total	379,657	100



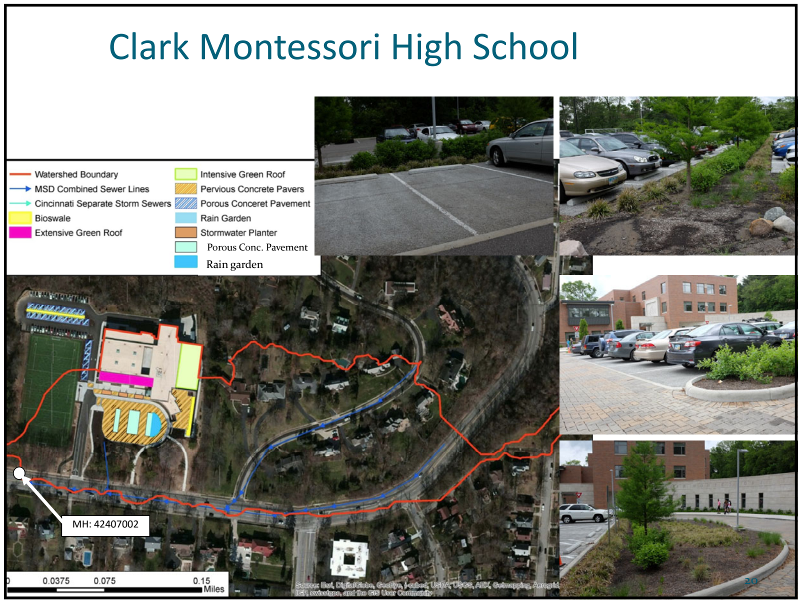
Cincinnati Zoo



Land Cover Description

Land Cover type	Area (ft²)	Area (%)
Landscaped area	228,614	39.2
Active Construction	152,923	26.2
Parking lot	30,521	5.2
Paved area	10,058	1.7
Roof	76,676	13.1
Street	24,907	4.3
Walkway	59,466	10.2
Total	583,166	100

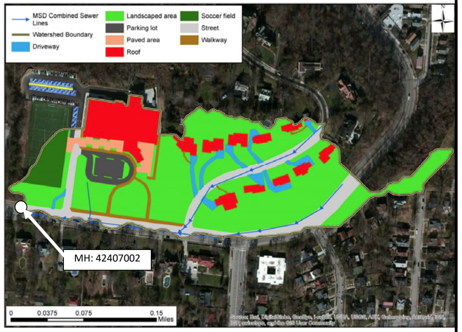
Land Cover type	Area (ft²)	Area (%)
Landscaped area	43,060	40.2
Paved area	47,996	44.8
Roof	16,150	15.1
Total	107,206	100



Clark Montessori High School

Land Cover Description

Land Cover type	Area (ft²)	Area (%)
Driveway	22,842	3.6
Landscaped area	369,455	57.5
Parking lot	22,082	3.4
Paved area	15,026	2.3
Roof	86,624	13.5
Soccer Field	25,867	4.0
Street	86,134	13.4
Walkway	14,956	2.3
Total	642,986	100.0



Sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Data Analyses

Availability of Data for Different Case Studies

- Millburn, NJ
  - 14 dry wells monitored for infiltration purposes
  - Short and long-term periods (ranging from 2 months to one year)
  - Actual rains and controlled tests using township water from fire hydrants.
- Kansas City, MO
  - 100-acre (40 ha) pilot watershed
  - 179 green infrastructure-based stormwater controls
  - 3 curb extension biofilters, 2 curb-cut biofilters, 2 biofilters with smart drains, and a cascade biofilter were monitored for infiltration for several months.
  - Flow data in the combined sewer system for before, during, and after the green infrastructure component construction periods, for both the pilot and control watersheds.

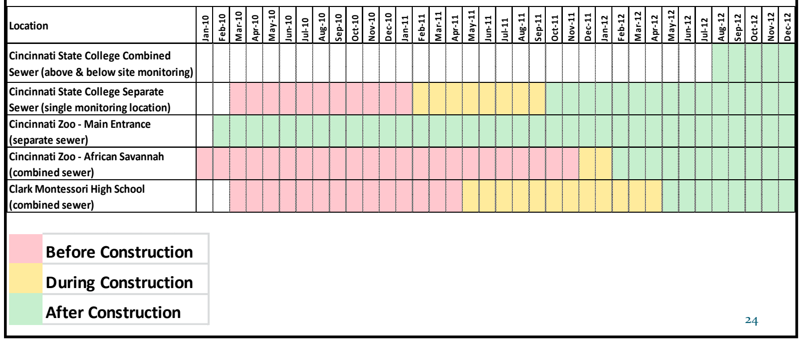
Monitoring Periods in Test/Pilot and Control Area Watersheds (Kansas City, MO)

Monitoring period	Dates corresponding to monitoring period	Number of monitored storms in each monitoring period*
Initial baseline	03/23/09 – 06/19/10	69 events
After re-lining	01/22/11 – 03/19/11	7 events
After construction	04/07/13 – 10/30/13	37 events

Availability of Data for Different Case Studies

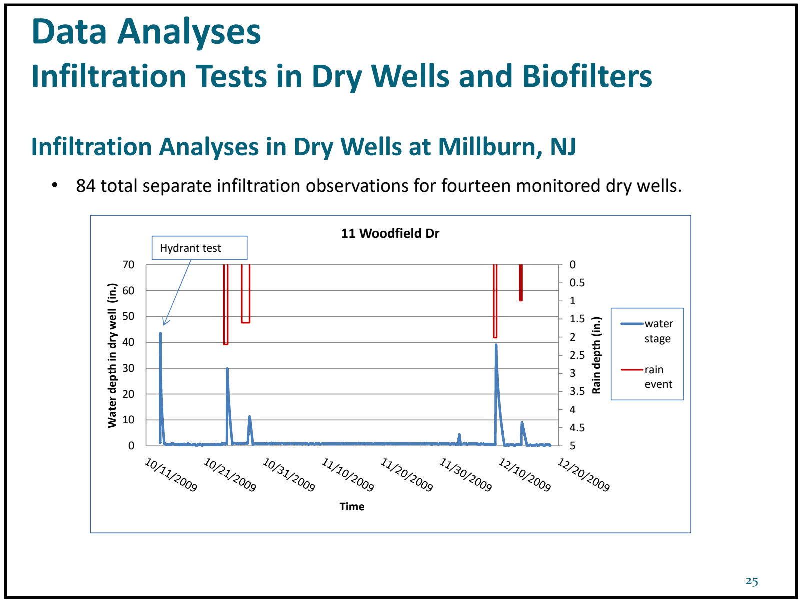
Cincinnati, OH

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



Location	Jan-10	Feb-10	Mar-10	Apr-10	May-10	Jun-10	Jul-10	Aug-10	Sep-10	Oct-10	Nov-10	Dec-10	Jan-11	Feb-11	Mar-11	Apr-11	May-11	Jun-11	Jul-11	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11	Jan-12	Feb-12	Mar-12	Apr-12	May-12	Jun-12	Jul-12	Aug-12	Sep-12	Oct-12	Nov-12	Dec-12
Cincinnati State College Combined Sewer (above & below site monitoring)																																🟩	🟩	🟩	🟩	🟩
Cincinnati State College Separate Sewer (single monitoring location)			🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Cincinnati Zoo - Main Entrance (separate sewer)		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Cincinnati Zoo - African Savannah (combined sewer)	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Clark Montessori High School (combined sewer)			🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

🟥 **Before Construction**
🟨 **During Construction**
🟩 **After Construction**

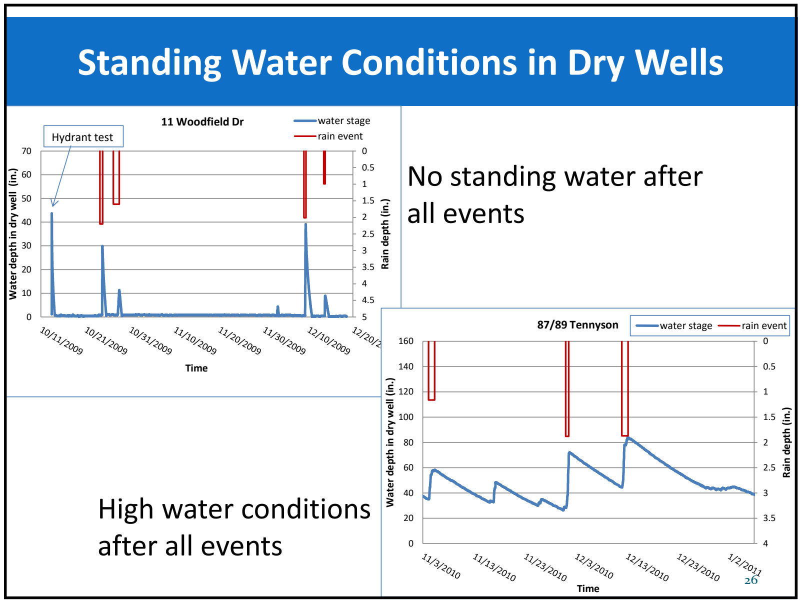


Data Analyses

Infiltration Tests in Dry Wells and Biofilters

Infiltration Analyses in Dry Wells at Millburn, NJ

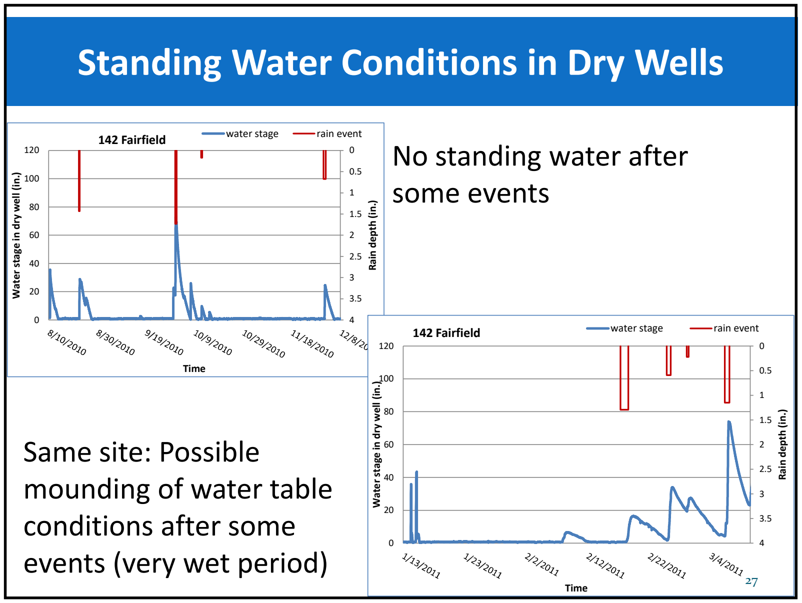
- 84 total separate infiltration observations for fourteen monitored dry wells.



Standing Water Conditions in Dry Wells

No standing water after all events

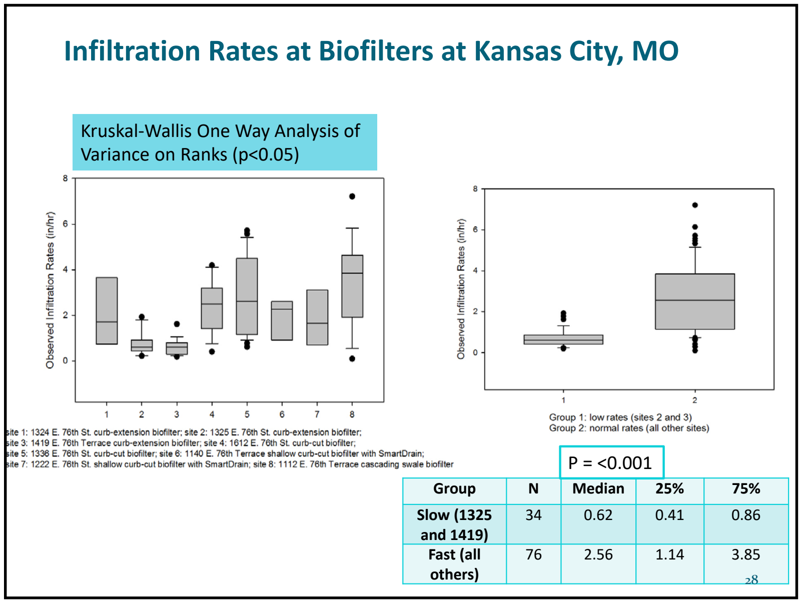
High water conditions after all events



Standing Water Conditions in Dry Wells

No standing water after some events

Same site: Possible mounding of water table conditions after some events (very wet period)



Infiltration Rates at Biofilters at Kansas City, MO

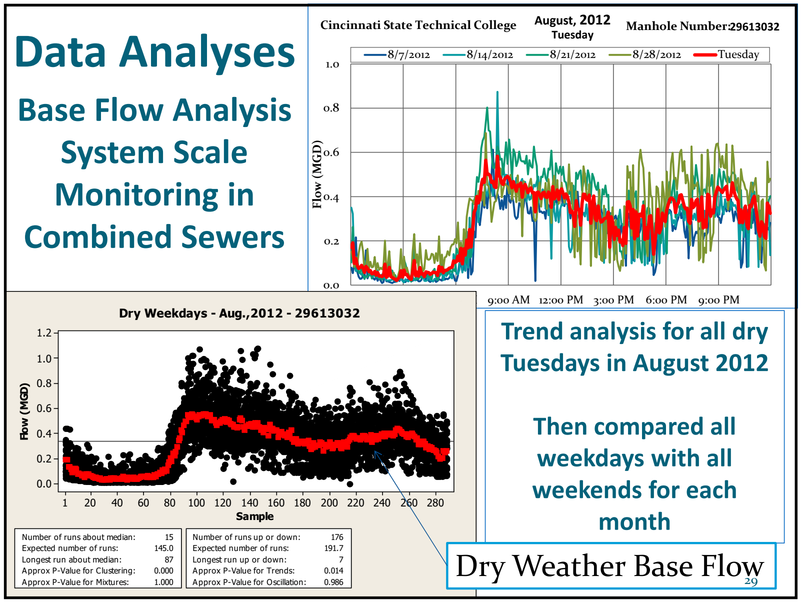
Kruskal-Wallis One Way Analysis of Variance on Ranks (p<0.05)

site 1: 1324 E. 76th St. curb-extension biofilter; site 2: 1325 E. 76th St. curb-extension biofilter;
site 3: 1419 E. 76th Terrace curb-extension biofilter; site 4: 1612 E. 76th St. curb-cut biofilter;
site 5: 1336 E. 76th St. curb-cut biofilter; site 6: 1140 E. 76th Terrace shallow curb-cut biofilter with SmartDrain;
site 7: 1222 E. 76th St. shallow curb-cut biofilter with SmartDrain; site 8: 1112 E. 76th Terrace cascading swale biofilter

Group 1: low rates (sites 2 and 3)
Group 2: normal rates (all other sites)

P = <0.001

Group	N	Median	25%	75%
Slow (1325 and 1419)	34	0.62	0.41	0.86
Fast (all others)	76	2.56	1.14	3.85



Data Analyses

Base Flow Analysis System Scale Monitoring in Combined Sewers

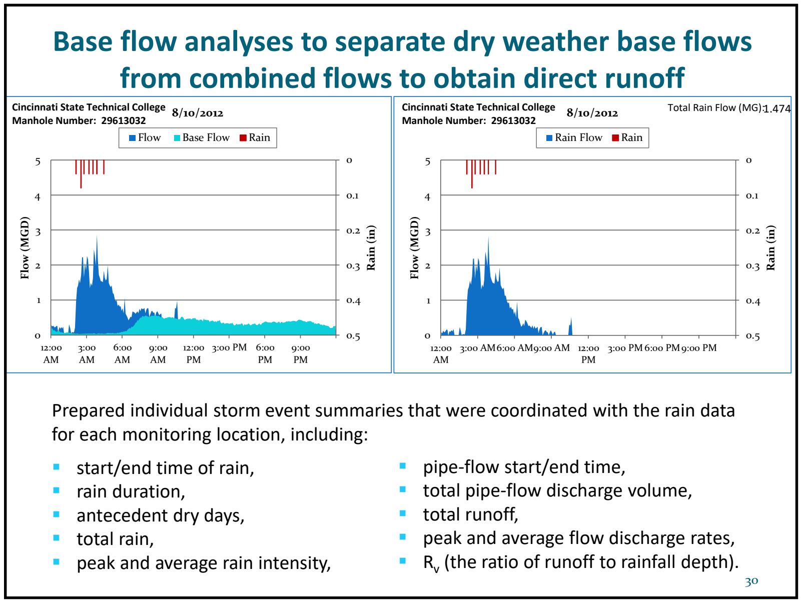
Number of runs about median:	15
Expected number of runs:	145.0
Longest run about median:	87
Approx P-Value for Clustering:	0.000
Approx P-Value for Mixtures:	1.000

Number of runs up or down:	176
Expected number of runs:	191.7
Longest run up or down:	7
Approx P-Value for Trends:	0.014
Approx P-Value for Oscillation:	0.986

Trend analysis for all dry Tuesdays in August 2012

Then compared all weekdays with all weekends for each month

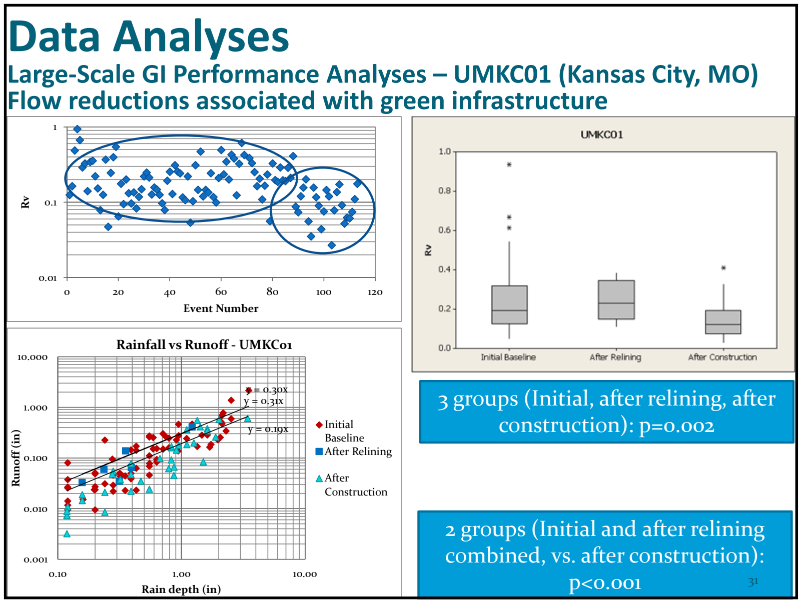
Dry Weather Base Flow



Base flow analyses to separate dry weather base flows from combined flows to obtain direct runoff

Prepared individual storm event summaries that were coordinated with the rain data for each monitoring location, 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).



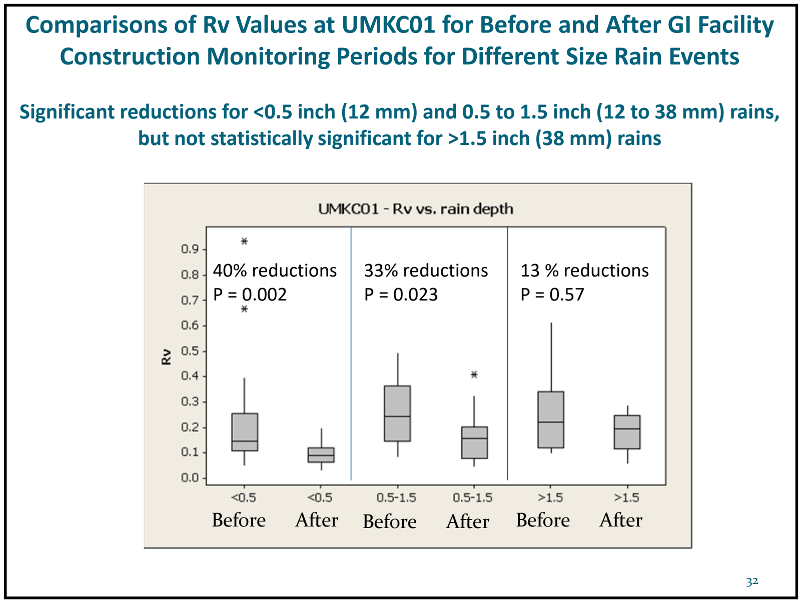
Data Analyses

Large-Scale GI Performance Analyses – UMKC01 (Kansas City, MO)

Flow reductions associated with green infrastructure

3 groups (Initial, after relining, after construction): p=0.002

2 groups (Initial and after relining combined, vs. after construction): p<0.001



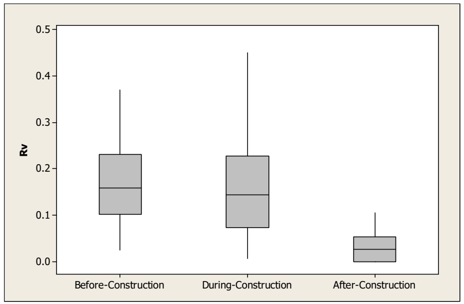
Comparisons of Rv Values at UMKC01 for Before and After GI Facility Construction Monitoring Periods for Different Size Rain Events

Significant reductions for <0.5 inch (12 mm) and 0.5 to 1.5 inch (12 to 38 mm) rains, but not statistically significant for >1.5 inch (38 mm) rains

Cincinnati State College, Cincinnati, OH

(Southwestern drainage in separate storm sewer)

R_v values for different study periods for Cincinnati State College separate sewer system (manhole number 29606027)



Kruskal-Wallis One Way Analysis of Variance on Ranks test

Group	N	Missing	Median	25%	75%
Before Construction	41	0	0.160	0.1000	0.230
During Construction	51	0	0.140	0.0700	0.230
After Construction	78	25	0.0300	0.000	0.0550

H = 73.412 with 2 degrees of freedom. (P = <0.001)

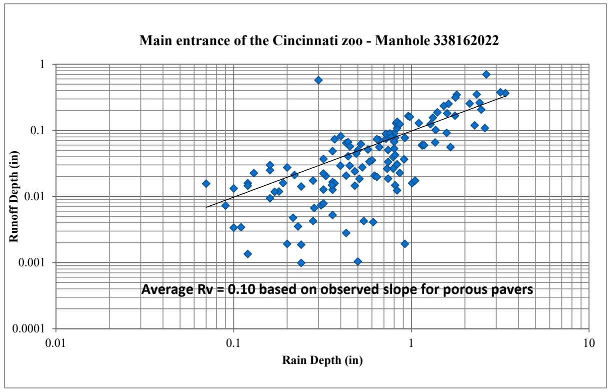
post-hoc comparison test (Tukey's test)

	N	Mean	Grouping
Before Construction	41	0.16919	A
During Construction	51	0.16242	A
After Construction	77	0.03266	B

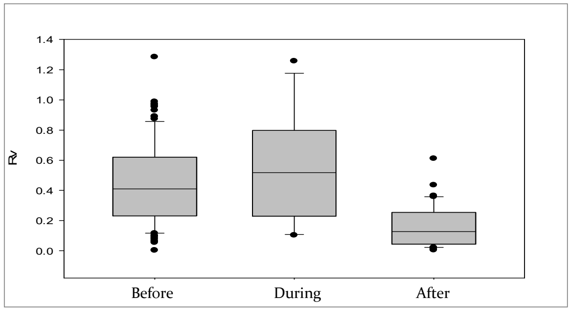
Means that do not share a letter are significantly different.

Cincinnati Zoo – Main Entrance (Cincinnati, OH)

176 after construction events



African Savannah Zoo (Cincinnati, OH)



Kruskal-Wallis for Rv Values

Group	**N**	**Missing**	**Median**	**25%**	**75%**
Before	**111**	**4**	**0.41**	**0.23**	**0.62**
During	**15**	**0**	**0.52**	**0.23**	**0.80**
After	**40**	**0**	**0.13**	**0.044**	**0.25**

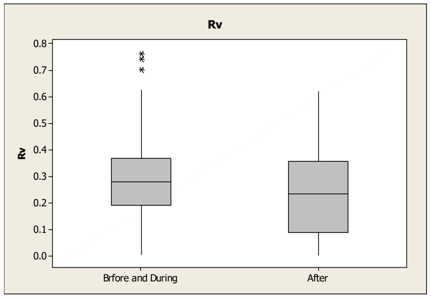
There is a statistically significant difference for at least one data set (P = <0.001)

Dunn's Method:

Comparison	**Diff of Ranks**	**Q**	**P<0.05**
During vs After	61	4.3	Yes
During vs Before	7.9	0.61	No
Before vs After	53	6.1	Yes

Therefore, combine before and during monitoring data

Clark Montessori High School (Cincinnati, OH)



Kruskal-Wallis One Way Analysis of Variance on Ranks

Group	N	Missing	Median	25%	75%
Before and During	127	0	0.280	0.190	0.370
After	39	0	0.230	0.090	0.360

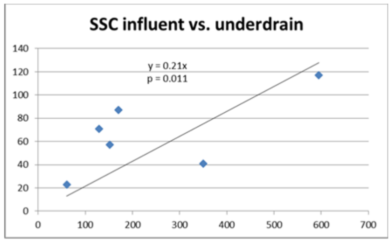
H = 4.918 with 1 degrees of freedom. (P = 0.027)

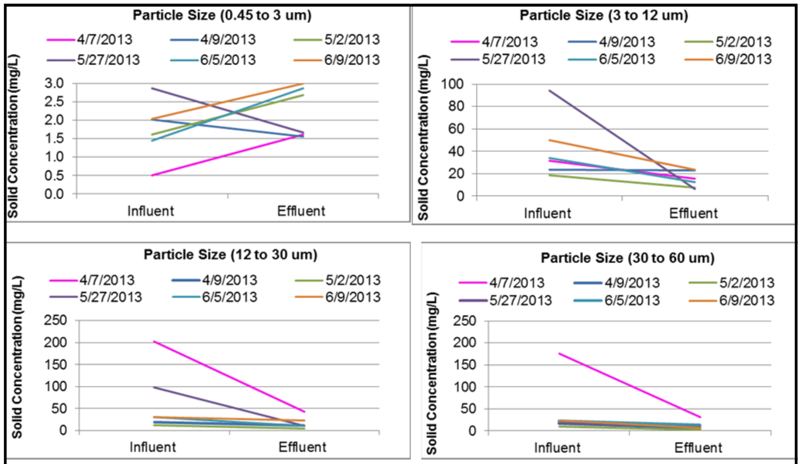
Performance from Cincinnati Monitoring at Green Infrastructure Sites

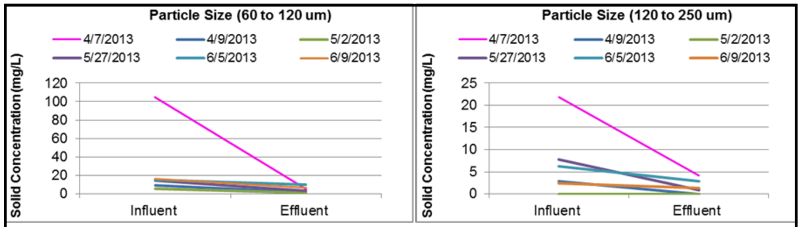
Location	Runoff Volume Reduction (%) Compared to Pre-Construction Data
Cincinnati State College – Southern Area (bioinfiltration and rain gardens)	80
Cincinnati Zoo – Main Entrance (extensive paver blocks)	Average Rv values after construction: 0.1 (compared to about 0.8 for conventional pavement in area)
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

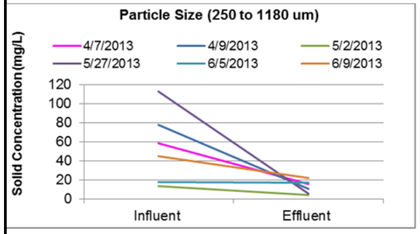
Water Quality Improvements Associated with Green Infrastructure

- Most of the monitored Kansas City biofilters completely infiltrated the stormwater. Only 6 out of 79 monitored events resulted in under drain flows. The influent median particle size ranged from about 13 to 50 µm.
- The SSC influent concentrations ranged from about 50 to 600 mg/L, while the effluent concentrations ranged from about 20 to 120 mg/L.


SSC influent vs. underdrain

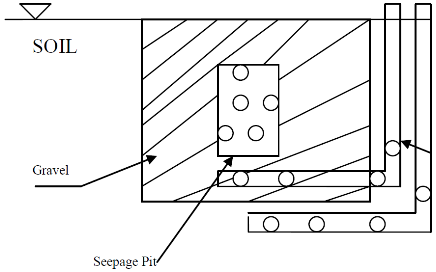

Particle Size (0.45 to 3 um)
Particle Size (3 to 12 um)
Particle Size (12 to 30 um)
Particle Size (30 to 60 um)


Particle Size (60 to 120 um)
Particle Size (120 to 250 um)

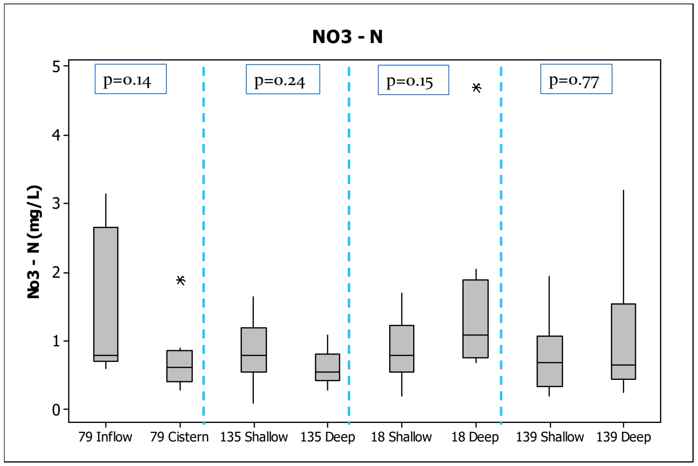

Particle Size (250 to 1180 um)

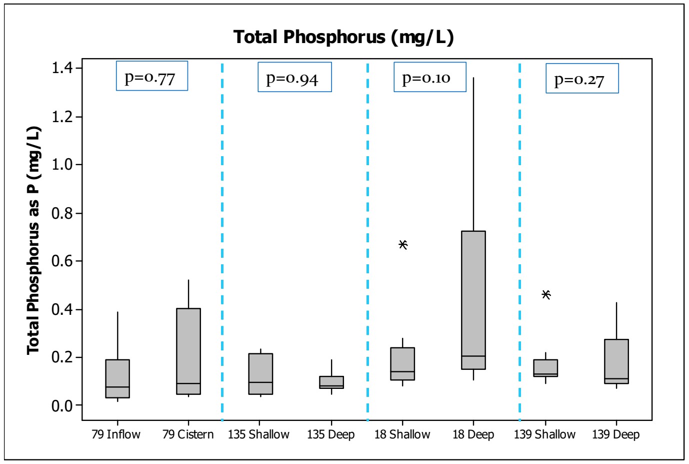
- The biofilters effectively removed a broad range of particle sizes, from 3 µm and larger, along with associated particulate bound pollutants (especially heavy metals). However, phosphorus and nitrogen concentrations increased in the effluent due to the large amount of compost in the media mixture.
- Overall, the pollutant mass reductions were very large, mostly due to the infiltration of the stormwater, but also assisted with the effective reduction in most pollutant concentrations.

Water Quality below Dry Wells



- Three dry wells: a shallow monitoring well immediately below the dry well and a deep monitoring well 2 to 5 ft (60 to 150 cm) below the gravel
- 8 to 10 storms were sampled at each of the three dry wells (all samples were analyzed in duplicate.)





Summary of Paired Sign Test for Metal analysis

Metal	79 Inflow vs. 79 Cistern	135 Shallow vs. 135 Deep	18 Shallow vs. 18 Deep	139 Shallow vs. 139 Deep
Lead	> 0.06	> 0.06	0.18	> 0.06
Copper	0.125	*	>0.06	*
Zinc	0.45	0.45	>0.06	>0.06

***** All the results are below the detection limit (BDL), therefore it is not possible to do a statistical comparison test

Groundwater Quality Criteria for the State of New Jersey Compared to Observed Water Quality from Dry Wells (mg/L)

Constituent	Groundwater Quality Criterion	Observed Range	Fraction of samples that exceed the criteria
Microbiological criteria	Standards promulgated in the Safe Drinking Water Act Regulations (N.J.A.C. 7:10-1 et seq.): 50 MPN/100 mL	Total coliform: 1 to 36,294 MPN/100 mL *E. coli*: 1 to 8,469 MPN/100 mL	Total coliform: 63 of 71 samples exceeded the criterion for total coliforms *E. coli*: 45 of 71 samples exceeded the criterion for *E. coli*
Nitrate and Nitrite	10	BDL to 16.5 (one sample had a concentration of 16.5 mg/L)	1 of 71 samples exceeded the criterion for nitrates plus nitrites
Nitrate	10	0.1 to 4.7	0
Phosphorus	n/a	0.02 to 1.36	n/a
COD	n/a	5.0 to 148	n/a
Lead	0.005	BDL to 0.38	33 of 71 samples exceeded the criterion for lead
Copper	1.3	BDL to 1.1	0
Zinc	2.0	BDL to 0.14	0

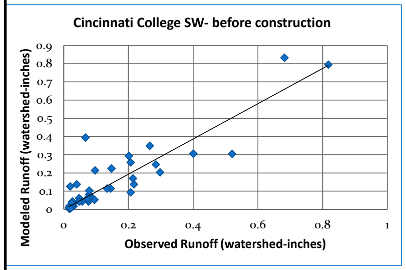
There were no significant reductions identified for any stormwater pollutant below the dry wells.

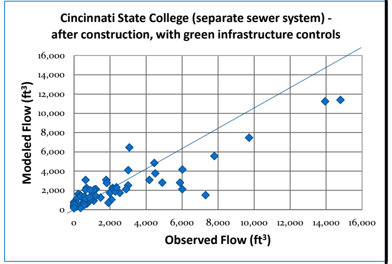
WinSLAMM (Source Loading and Management Model)

- Using the local continuous rain records, WinSLAMM evaluates the runoff volume as well as pollutant loadings from each individual source area within each land use category and for the whole watershed area considering the individual microsites and how they are connected.
- In this research, WinSLAMM calculated:
  - the effectiveness of GI stormwater controls, based upon long series of rainfalls, the source area characteristics, and the characteristics of stormwater control (such as size and location).
  - the stormwater contributions from the source areas in the watersheds to assist in locating the most effective controls.
  - production functions to illustrate the magnitude of runoff and pollutant controls for different applications of different green infrastructure controls.
  - likely maintenance intervals associated with clogging and breakthrough.
  - life-cycle costs of different green infrastructure controls, based on different design attributes.

Production Function Modeling

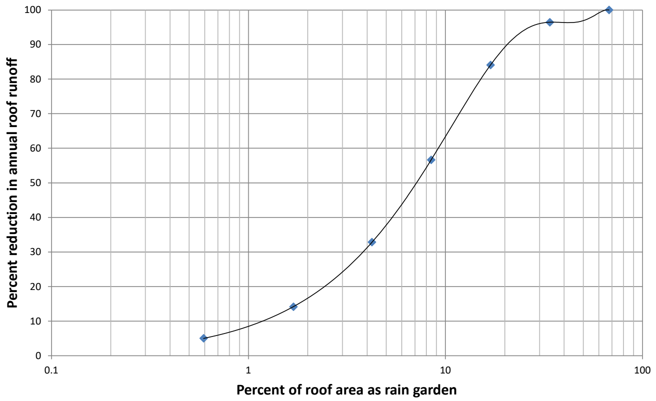
- WinSLAMM was calibrated and verified using these monitoring results to better understand the limitations and usefulness of the green infrastructure controls and to extrapolate the measured performance to other sites and conditions.





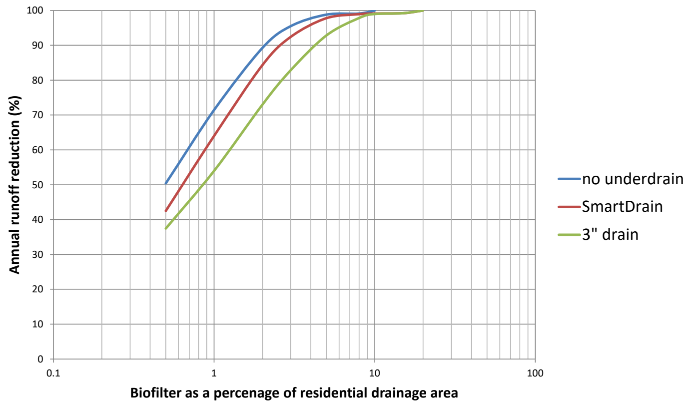
No statistically significant differences between observed and modeled runoff amounts

Example WinSLAMM Production Function: Percentage Reductions of Annual Runoff Flows with Rain Gardens



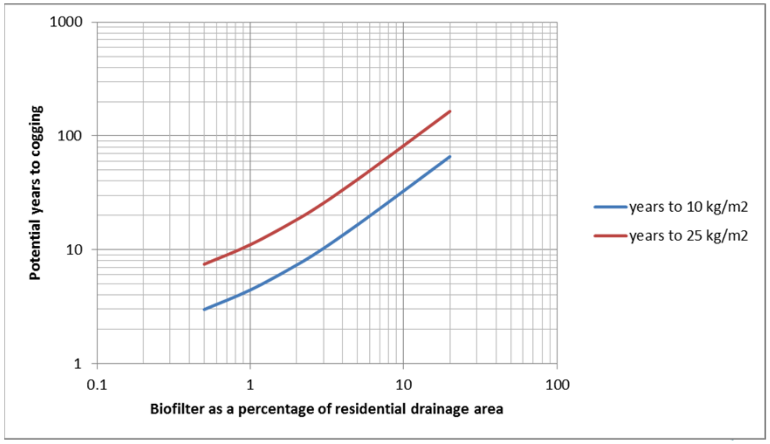
Not as effective on a same area comparison as a biofilter due to lack of large amounts of runoff storage in rain gardens.

Example WinSLAMM Production Functions: Effects of Underdrains in Biofilters on Annual Runoff Reductions (0.5 in/hr subsurface soil infiltration rates)



Unrestricted underdrains result in short-circuiting of infiltration, reducing their performance; design restrictions as needed to reduce standing water problems.

Example WinSLAMM Production Functions: Clogging Potential for Biofilters in the Kansas City Test Area



Conclusions and Recommendations for Flow Monitoring for Green Infrastructure Performance

- Groundwater table information is needed in the study area, especially if promoting recharge of groundwater and development of local water supplies as beneficial uses. This is also needed to evaluate the potential of groundwater interfering with the subsurface structures and infiltration processes, and also affects potential groundwater intrusion into the drainage systems.
- Soil surveys at pilot-scales are needed to identify site selection of GI stormwater controls in order to maximize their benefits.
- It is essential to have adequate rain gauges (at least several) near the flow sensors in the study area.

Conclusions and Recommendations for Flow Monitoring for Green Infrastructure Performance (Cont.)

- Monitor both test and control areas 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).

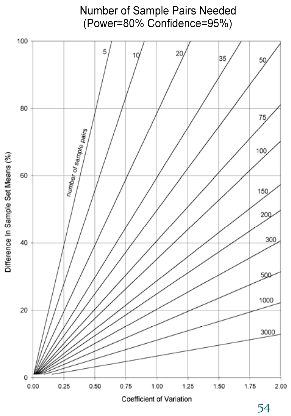
- Test areas should have most of their flows treated by the control practices to maximize measurable reductions.
  - **Any untreated upgradient areas should be very small in comparison to the test areas. Difficult to subtract two large numbers (each having measurement errors and other sources of variability), such as above and down gradient monitoring stations, and have confidence on the targeted flows.**

Conclusions and Recommendations for Flow Monitoring for Green Infrastructure Performance (Cont.)

- Most monitored flows from common rains may only result in shallow depths in the sewerage, a flow condition that is difficult to accurately monitor.
- Flow sensors may fail more often than expected.
- Costs of flow monitoring is small compared to green infrastructure investment.
  - **Use redundant sensors, such as an area-velocity sensor (or bubbler) in addition to an acoustic depth sensor mounted on the crown.**
  - **Calibrate the flow sensors at the beginning and periodically throughout the project period.**
  - **Review flow data frequently and completely to identify sensor failures or other issues.**
  - **Supplement the flow sensors with adequate numbers and placement of rain gages in the watersheds.**

Conclusions and Recommendations for Flow Monitoring for Green Infrastructure Performance (Cont.)

- Monitor sufficient numbers of events to have statistically valid results for the performance expectations.
  - **As an example, with a COV of 1 (a typical value for stormwater), 50 pairs of samples would enable differences of about 50% or greater to be detected with 95% confidence and 80% power.**
  - **It is very difficult to detect small differences with suitable confidence and power (the reason why most of the runoff needs to be treated).**



Acknowledgements

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