Large-Scale Monitoring of Green Infrastructure Controls in Areas Served by Combined Sewers

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The 9th International Conference on Urban Watershed Management
Sustainable Water Technologies and Impact Assessment of Climate Change
Tianjin, China. September 14-17, 2014

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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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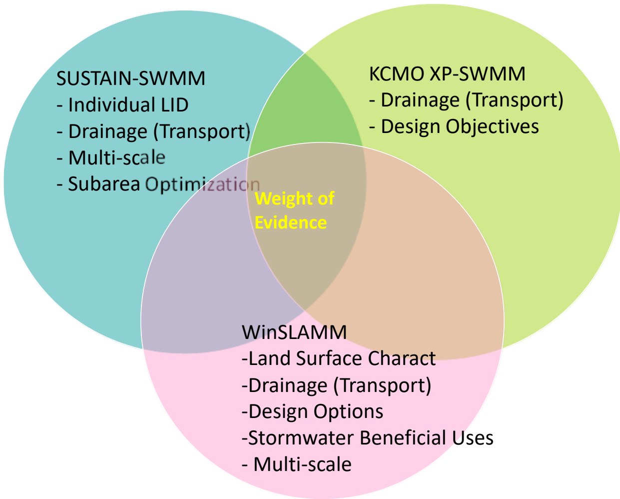
KC's Modeling Connections



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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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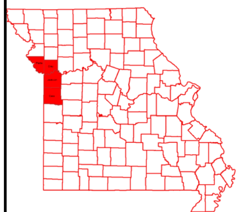
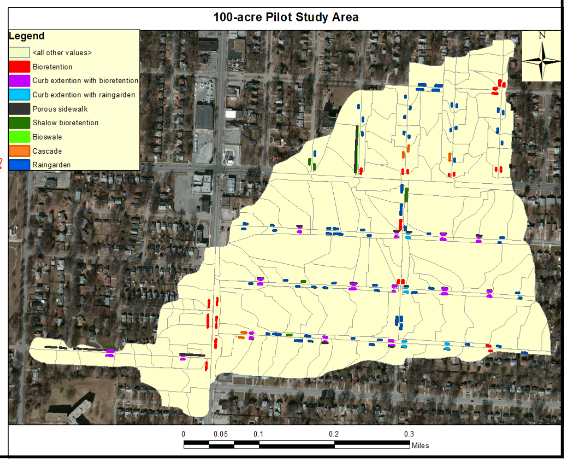
Geographical Locations and Description of project – Kansas City, MO





Many GI controls located in right-of-ways along streets so city could legally maintain the practices as required in their CSO consent decree.

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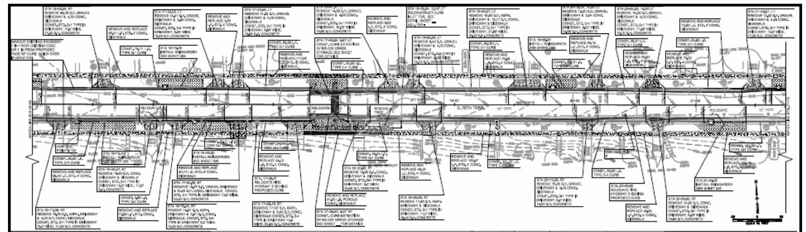
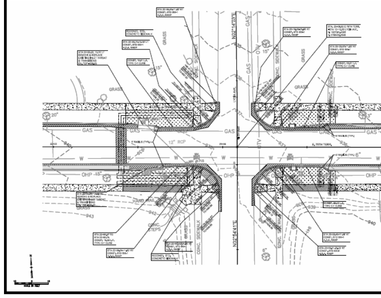
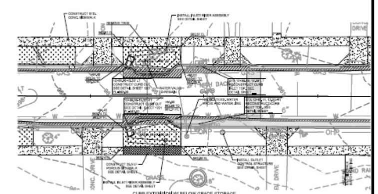


Examples from "95%" plans prepared by URS for project streets. Plans reviewed and modeled by project team, and construction completed in Summer 2012. Monitored until end of 2013.





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About half of runoff from area is not treated by GI controls due to yard drains on private property collecting runoff and some optimal sites not available due to trees and driveways. These are all typical problems when retrofitting stormwater controls in existing areas.

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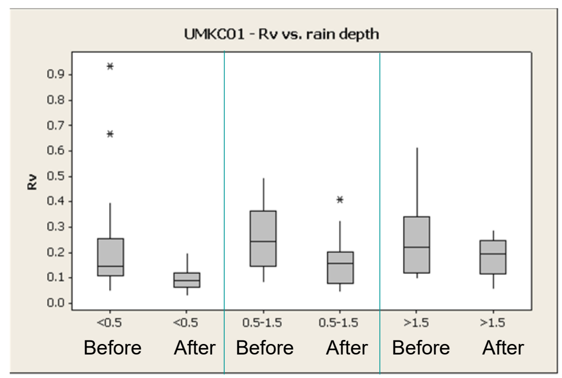
Comparisons of Rv Values at UMKC01 for Before and After GI Facility Construction Monitoring Periods



The GI controls resulted in significant runoff reductions for small and intermediate rains (<1.5 inches), but the few large rains monitored (>1.5 inches) did not indicate significant reductions due to lack of data.

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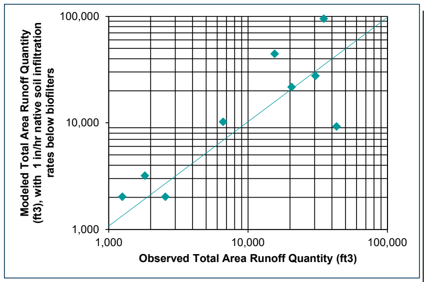
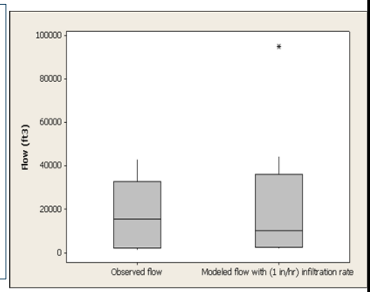
WinSLAMM modeling results – (Kansas City, MO)





WinSLAMM was calibrated using pre-construction runoff observations and verified with post-construction observed flows. Very good agreement for sum of loads over entire monitoring period and for individual events.

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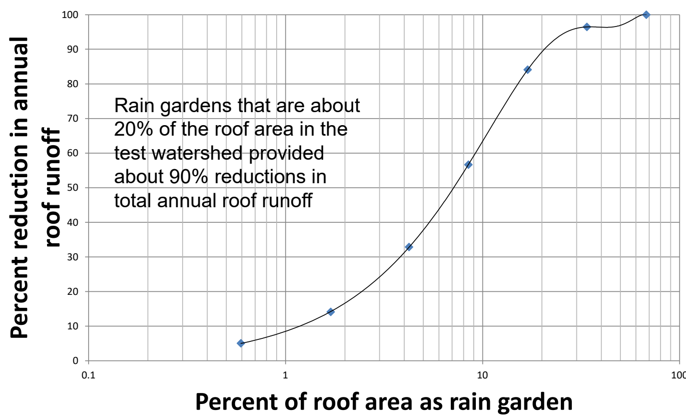
WinSLAMM Production Function: Percentage Reductions of Annual Runoff Flows with Rain Gardens



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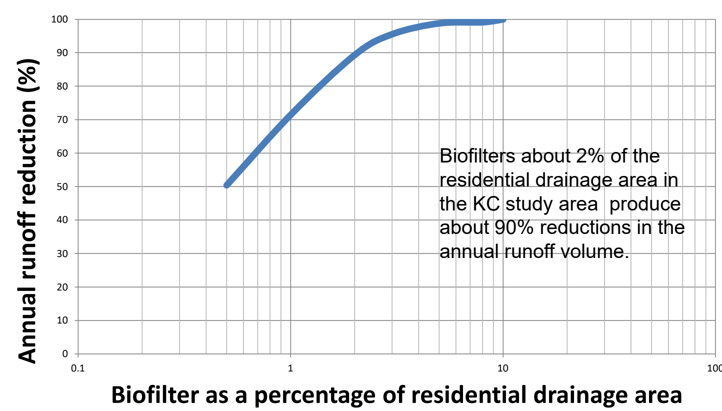
WinSLAMM Production Function (0.5 in/hr subsurface soil infiltration rates)



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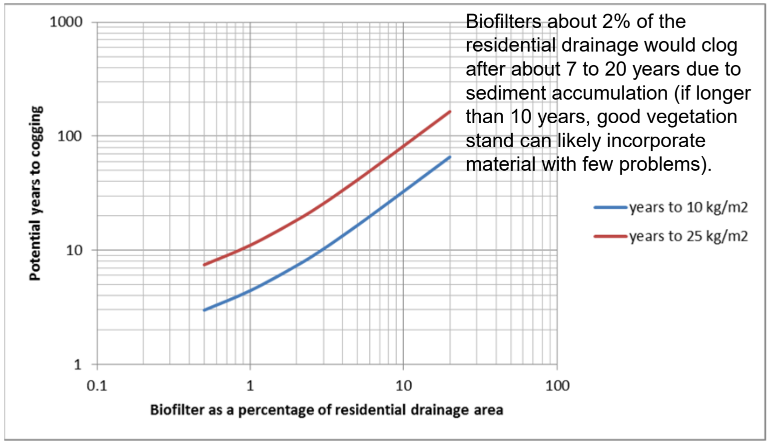
WinSLAMM Production Functions: Clogging Potential for Biofilters in the Kansas City Test Area



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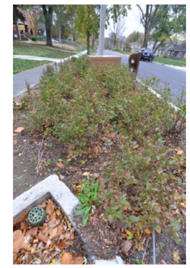


1324 76th St. monitoring location, biofilter and adjacent porous concrete sidewalk (one of 10 monitored, plus system)

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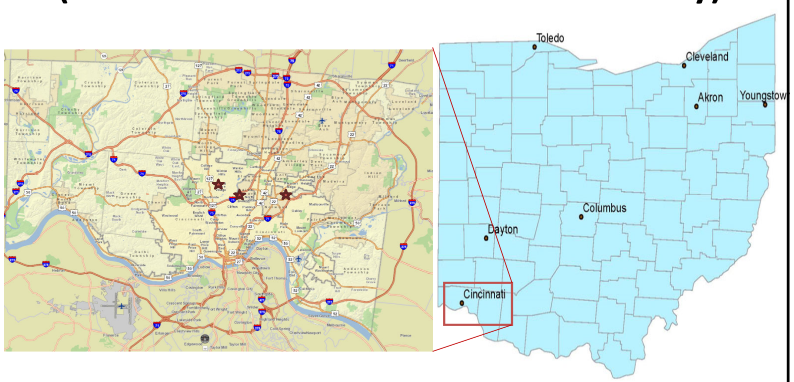
Three Study Areas for Green Infrastructure Effectiveness Monitoring in Cincinnati, OH (more than 20 GI demo areas in the city)



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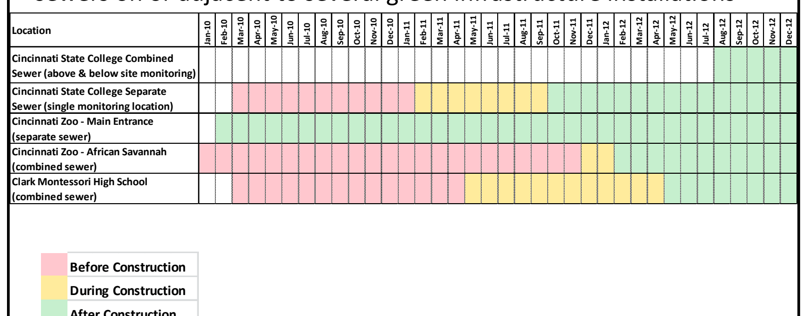
Available Flow Data at GI Demonstration Projects

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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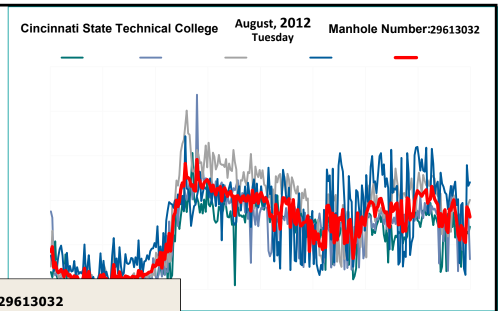
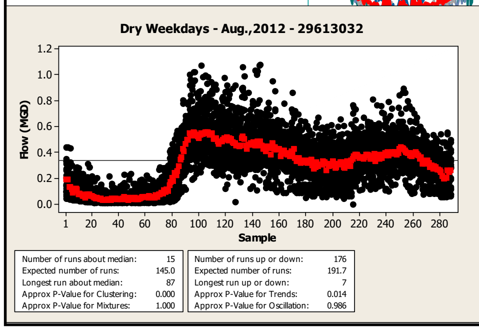
Need to determine the base dry weather flows from the flow time series in sewer lines to subtract from wet weather combined flows.





Trend Analysis

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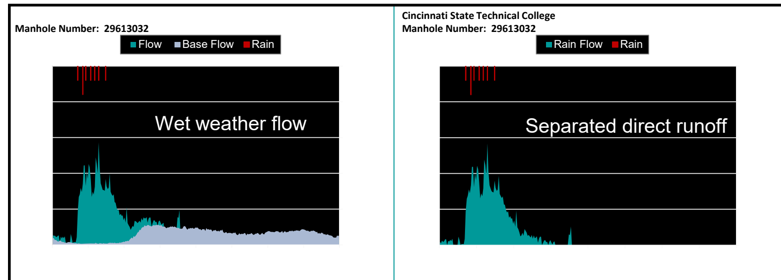

Prepare individual storm event data summaries that are coordinated with the rain data for each monitoring point, including:

- 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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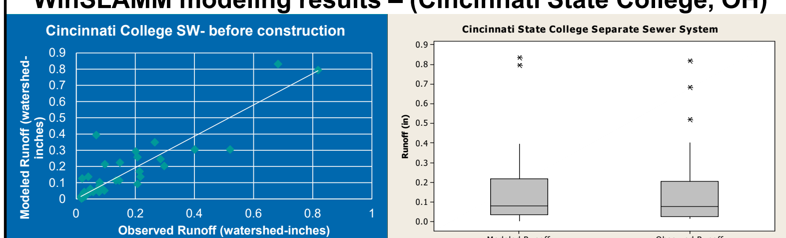
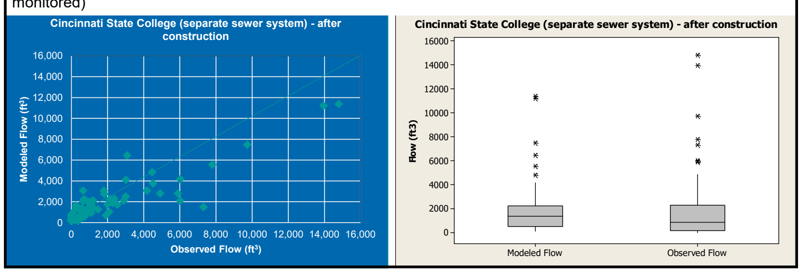
WinSLAMM modeling results – (Cincinnati State College, OH)



Statistical analyses did not identify significant differences between observed and modeled flows (would have detected significant differences greater than about 15 to 30% based on variability and numbers of events monitored)



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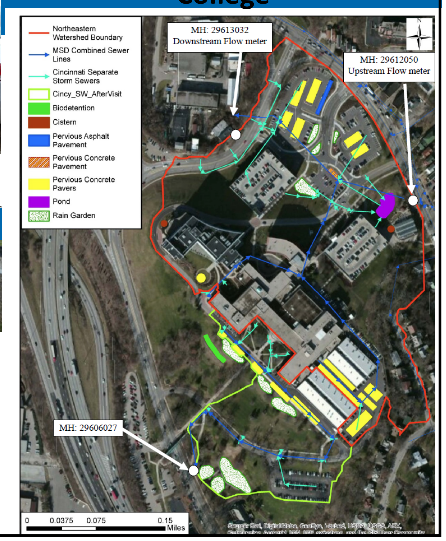
Cincinnati State Technical College



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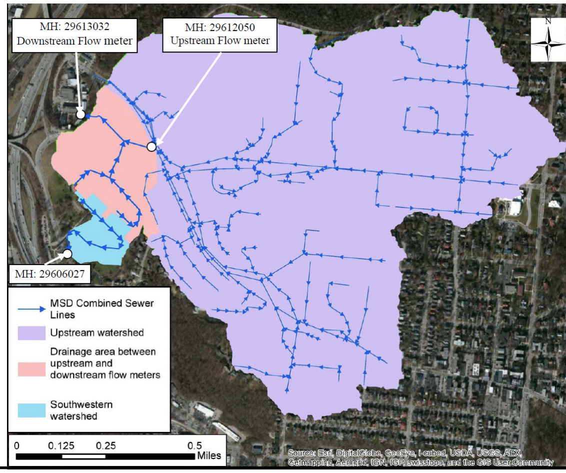
Cincinnati State Technical College Watershed Analysis



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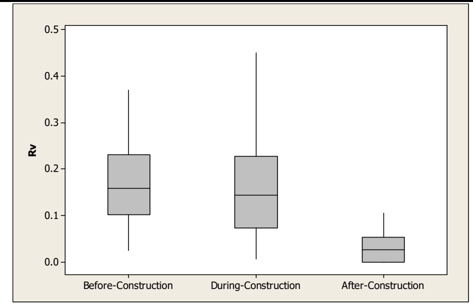
Cincinnati State College

(southern drainage with extensive bioinfiltration and rain gardens)

R_v values for different study periods for Cincinnati State College separate sewer system. No significant differences between before and during construction, but after construction significantly reduced.



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.

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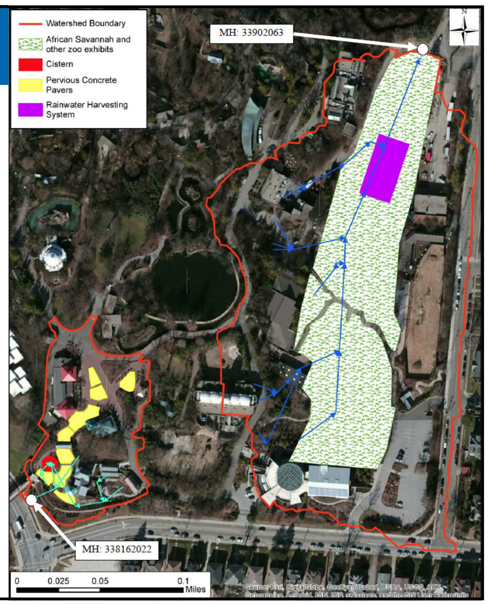
Cincinnati Zoo



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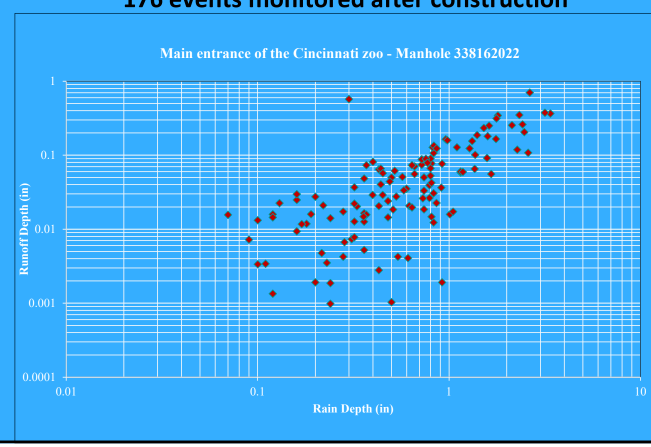
Cincinnati Zoo – Main Entrance with Extensive Paver Block Use (only about 10% of the rain resulted in runoff for this "paved" area)

176 events monitored after construction



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African Savannah at Cincinnati Zoo

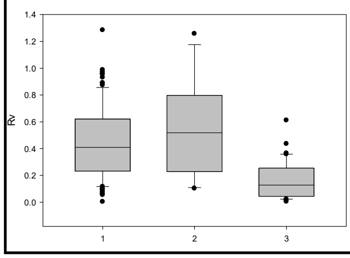
No significant difference between before and during construction period flows, but after construction flows are significantly reduced.

Kruskal-Wallis One Way Analysis of Variance on Ranks of 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 (P = <0.001)

All Pairwise Multiple Comparison Procedures (Dunn's Method):



Comparison	P<0.05
During vs After	Yes
During vs Before	No
Before vs After	Yes

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Clark Montessori High School

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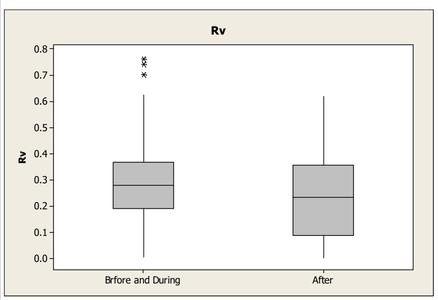
Clark Montessori High School



Grouping Information Using Tukey Method for Rv Values

	N	Mean	Grouping
Before & During	127	0.29	A
After	39	0.23	B

Significant difference between before/during and after construction periods, but only about 20% of the site flows were treated by the GI facilities so the reduction was small.

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Performance Monitoring at Cincinnati 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

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

- Most monitored flows from common rains may only result in shallow water 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 and use weirs.**
  - **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.**

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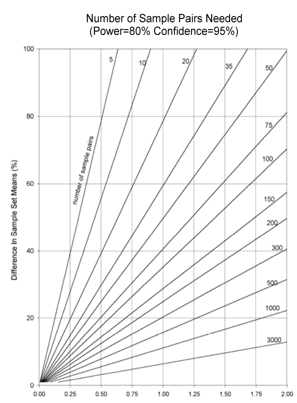
Conclusions and Recommendations for Flow Monitoring for Green Infrastructure Performance (Cont.)

- 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).**



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