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

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The US EPA's Green Infrastructure Demonstration project in Kansas City, MO, is likely the largest area having many infiltration controls that has been monitored. The 40 ha (100 acres) test watershed has a maximum number of individual controls constructed throughout the area, but yard drains and current infrastructure inhibited treating all of the stormwater from the area. The controls include curb-cut biofilters, rain gardens, cascading biofilters, and porous concrete sidewalks. The 35 ha (87 acres) adjacent control area watershed was also monitored for comparison. The monitoring results were used to verify the WinSLAMM stormwater quality model to enable evaluations of specific design options of these stormwater controls and for analyses of green infrastructure alternatives at other areas of the city.

WinSLAMM was used to evaluate the biofilter designs for the test area and was calibrated using the early test and control watershed flow and rainfall data after sewer re-lining in the test watershed, but before the construction of the stormwater controls in the test area. Flow monitoring occurred during four phases: initial baseline; after sewer relining; during construction of the infiltration controls, and after the construction was completed. The control area was compared to the test area for each of these monitoring phases. The "after" construction runoff was significantly reduced (by about 70%) compared to the control area. Monitoring and evaluation of the test area is continuing into the 2013 rain season to obtain additional data.

X.1 Introduction

Site specific rainfall-runoff data were obtained during four years of flow monitoring (from 2009 through 2012) in adjacent test and control watersheds in the green infrastructure study area in the Marlborough neighborhood of Kansas City. Being a combined sewer system, the measured wet weather flows were adjusted by having the expected concurrent dry weather sanitary sewage flows (from adjacent dry period monitoring periods) subtracted from the combined sewer flows. These hydrograph separation analyses were conducted by the TetraTech project team. These flow data were used to verify the regional and site calibration conditions. The site development characteristics for the test and control watershed were used, along with the actual rain history during the flow monitoring period, to show how closely the calibrated model predicted the runoff characteristics that were monitored.

Detailed land development characteristics were obtained for the study area, along the site soil infiltration measurements, by the University of Missouri, Kansas City (UMKC) project team. This allowed the model calibration based on these critical site characteristics to be included. Long-term continuous rain data were also used during the analyses to minimize the effects of any unusual conditions, along with the actual monitored rains.

The sewer rehabilitation project was conducted between the first two monitored years. The data collected prior to the repairs are not suitable for flow calibrations, as the observed wet weather flows were substantially less than the flows observed after the repairs. After the repairs in the test area, the flows were very similar to the control area that did not require repairs. In addition, the two demonstration rain gardens have two to three years of flow data available. Those observations were also used to verify the modeled performance of these controls. Other data now available include the complete area green infrastructure (GI) components (mostly comprised of curb-cut biofilters and porous pavement). Several of the curb-cut biofilters were also constructed to enable localized monitoring, to supplement the large-scale monitoring.

X.2 Site Characterization Data

Land development information corresponding to the different land uses is needed as an initial step in investigating stormwater management options for an area. The Marlborough test area in Kansas City is mostly a medium density residential area, constructed prior to 1960, with a small amount of strip commercial area along Troost Ave., and a small portion of a school. Detailed inventories were made of each of the approximately 600 homes in the area by graduate students from UMKC. Table X.1 shows the breakdown of the surface areas in the medium density residential area portion of the test (pilot) watershed.

Table X.1. Test Area Land Development Characteristics

	Roofs	Driveways	Side-walks	Park-ing/storage	Streets	Lands-caped	Total
Impervious directly con-nected	1.87 (15%)	4.12 (46%)	1.15 (46%)	1.59	9.35		18.1
disconnected	10.57 (85%)	4.03 (45%)	1.34 (54%)				16.0
Pervious unpaved (gravel, severely compacted)		0.81 (9%)					0.81
landscaped						65.13	65.1
isolated (swimming pools)							0.05
total residential area	12.44	8.95	2.49	1.59	9.35	65.13	100

Only about 15% of the residential roofs are directly connected in the test (pilot) area. If all were assumed to be connected, large errors in the roof run-off contribution calculations would occur. Similarly, if roof runoff stormwater controls were located at all roofs, those located where the roofs were already disconnected would have much lower additional benefits in decreasing the area's runoff quantity.

X.3 System Wide Observations and Model Calibration

Runoff monitoring was conducted in the combined sewer system at several locations in the test and control watersheds. Events were monitored after the sewer was rehabilitated and these data were used as the initial baseline condition. WinSLAMM evaluated the test (pilot) and control watershed conditions during the two monitoring periods (post re-lining, as the new baseline vs. after construction of controls) to verify the rainfall-runoff calibration based on site development characteristics and the actual rains monitored.

Figure X.1 focuses on the time during construction period and after most of the stormwater control construction was completed. The three month period, between April 1 and July 1, 2012, was therefore separated from the construction period as it represents a period when most of the stormwater controls were functioning. Only eight events are in this last critical category. However, the site monitoring will be continuing into the 2013 rain year for additional observations. All of these last events have a reasonably constant flow volume ratio (test area total runoff volume compared to the control area total runoff volume), except for one of the events that apparently produced more runoff from the test area (or less from the control area) than expected.

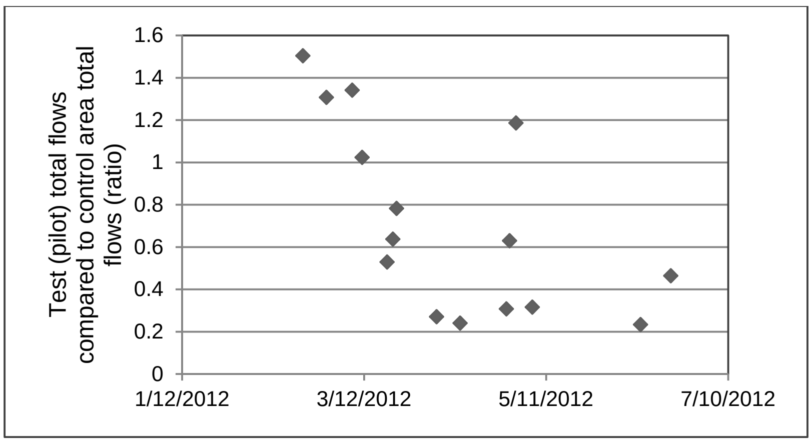

Figure X.1 Decreasing test (pilot) area event flows compared to control area flows during and after construction.

Table X.2 summarizes the average test (pilot) to control area total runoff volume ratios for each of the four monitoring periods and the percentage differences from the appropriate baselines, along with the Wilcoxon Rank-Sum test results indicating if the differences were statistically significant. The after-construction flow ratios were significantly different from the before construction baseline flow ratios. However, the “after re-lining flow ratios” were not shown to be statistically significantly different from the “before re-lining flow ratios,” due to the few data observations after the re-lining and before the start of the green infrastructure stormwater control construction period.

Table X.2. Test (pilot) and Control Watershed Total Runoff Volume Comparisons during Four Monitoring Periods

Monitoring Period	Average test (pilot) to control area runoff volume ratio	% change compared to initial baseline (and p from Wilcoxon Rank-Sum test)	% change compared to final baseline (after re-lining) (and p from Wilcoxon Rank-Sum test)
Initial baseline	1.06	n/a	n/a
After re-lining (final baseline)	1.53	44% increase (p=0.20)	n/a
During construction	1.02	4% decrease (p=0.94)	33% decrease (p=0.26)
After construction (after April 1, 2012)	0.46	55% decrease (***p=0.006***)*	70% decrease (***p=0.004***)*

Figure X.2 is a scatterplot showing the observed vs. the modeled test (pilot) watershed area total flows for each of the events during the "after re-lining" baseline period. As shown, these are all close to the line of equivalent values.

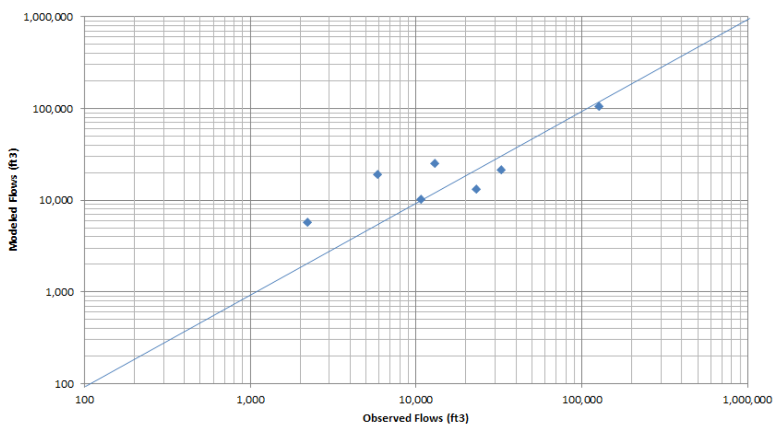

Figure X.2 Observed vs. modeled flows during final baseline conditions (after re-lining).

X.3.1 Biofilter Measurements during Rain Events

A tremendous amount of information was collected during this project, ranging from drainage area characteristics to runoff and flow monitoring that will be published in the final EPA research report after completion of the project. The delayed construction period only resulted in several events being monitored after the construction period for analyses in this paper, but the monitoring period is being extended into the next rainy season to obtain additional information.

The infiltration rates in the biofilters were monitored during actual rains by measuring the rate of drop of the ponded water during large rains (monitored by continuous stage recorders in the biofilters). Statistical analyses identified three distinct groups of these data, as shown on the following list and group box and whisker plot (Figure X.3).

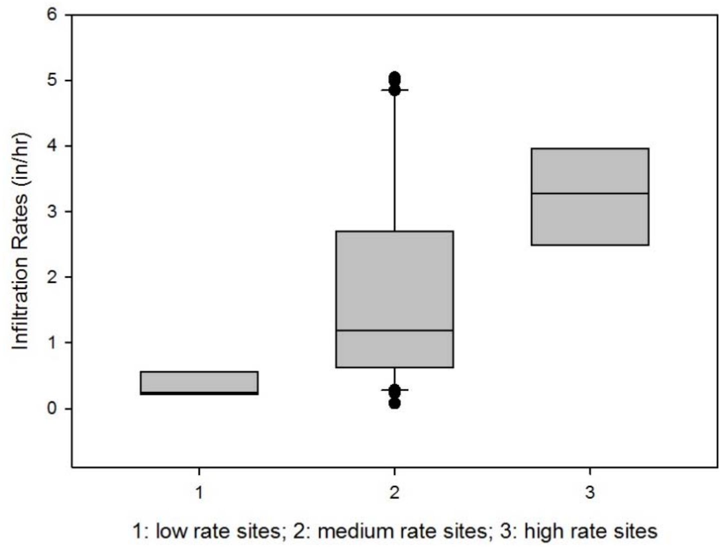

Figure X.3 Measured infiltration rates in biofilters during actual rains.

X.3.2 Monitored and Modeled Performance of Stormwater Control Practices

The Kansas City green infrastructure demonstration project site is unique because a very large portion of the test (pilot) area receives direct treatment from many separate stormwater control devices, and the large area was monitored to demonstrate the actual flow reductions. However, as in all retrofit installations, stormwater controls could not be placed to treat all of the flows from the whole watershed area due to interferences from existing infrastructure, large trees, and surface drainage paths. Figure X.4 is a map showing the subareas receiving stormwater control before being discharged into the combined sewer. The blanked-out areas drain into the combined sewers directly without any surface infiltration or retention control. Some areas are treated by multiple control units, with overflows from upgradient devices flowing into downgradient controls.

The total impervious area for the area being treated is about 45%, while the total impervious area for the untreated area is about 37%, indicating greater flows from the treated areas than indicated than indicated if only based on the total subareas. The calculations and modeling efforts determine the maximum amounts of stormwater control possible, reflecting the different land development characteristics in the treated and untreated subareas, and shows the sensitivity of the native soil conditions on biofilter performance.

Figure X.4 Areas receiving surface stormwater control before being discharged into the combined sewer.

Figure X.5 compares the modeled to the monitored events that occurred after the majority of the site construction was completed. Tables X.3 summarizeS the characteristics for each category of stormwater control used in the test (pilot) area, including the number of each device type and the average areas being treated by each type of control. The device areas as a percentage of drainage area are also shown, and ranges from about 1.5 to 2% for the biofilters to 9% for the bioswale. The porous pavement sidewalks treat 100% of the sidewalk areas as they do not receive runon from adjacent areas.

The calculated runoff volume reductions range from 86 to 100% for a four year continuous simulation period corresponding to the site total monitoring period (September 2008 through October 2012). The predicted maximum water depths in the biofilters ranged from about 2 to 5 inches, similar to the water depths observed. The maximum ponding times for the biofilters ranged from about 60 to 90 hours. Only a single event in the 4 years of simulation had a holding time longer than 3 days, the typical criterion for mosquito control. Only about 1/3 of the events likely have any surface or underdrain discharges, and these amounts would be very small compared to the untreated volumes.

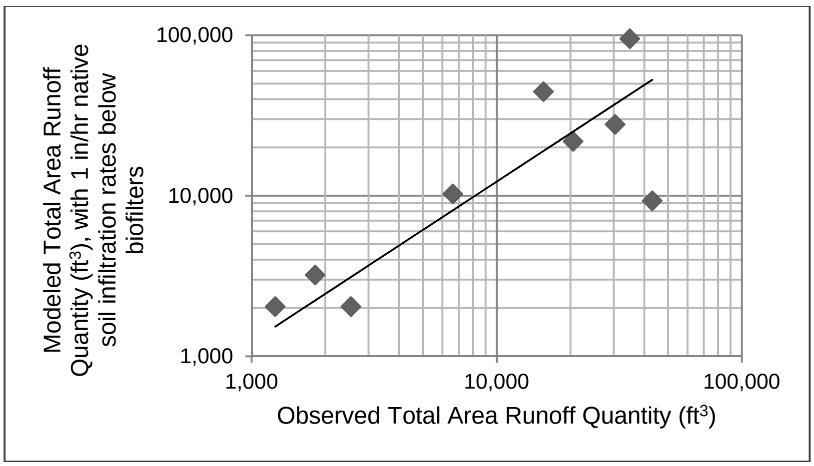

Figure X.5 Modeled vs. observed flows in the test (pilot) area after construction of stormwater controls.

X.3.3 Performance Production Functions for the Design and Analysis of Selected Stormwater Infiltration Controls

The first stormwater control that should be considered in an area is disconnecting the currently directly connected impervious areas, such as roofs and paved parking lots. The directly connected roofs in the test area only contribute about 5.8% of the total area flows, while the much greater area of disconnected roofs contribute about 7.2% of the annual runoff from the whole 100 acre area. The current flow contributions of all roofs in the area total about 13%. If all the roofs were directly connected, the roofs would contribute about 31% of the total area runoff, and the runoff from the total area would increase by about 25%, a significant increase. In contrast, if the currently directly connected roofs were disconnected through a downspout disconnection program, the total roof contribution would decrease to about 9%, and the total area runoff would decrease by about 5%. Since about 85% of the existing roofs in the area are already disconnected, the benefits of controlling the remaining directly connected roofs are therefore limited for this area. Directly connected roofs in the study area contribute about 4.5 times the amount of runoff per unit area as the disconnected roofs. This indicates that about 78% of the annual runoff from the disconnected roofs is infiltrated as it passes over previous areas on the way to the drainage system. Therefore, it is much less cost-effective to use roof runoff controls for the runoff from the disconnected roofs compared to runoff controls for the directly connected roofs. The benefits of disconnecting currently connected paved parking or storage areas are similar to the benefits shown above for roofs.

Table X.3 Summary of the Stormwater Controls Constructed in the Test (Pilot) Watershed

Design plan component	Structural description	Number of this type of stormwater control units in test (pilot) area	drainage area to device area ratio	device as a % of the drainage area	Average drainage area for each unit (ac)	total area treated by these devices (ac)
Bioretention	Bioretention without curb extension	24	61.8	1.6	0.40	9.6
	Curb extensions with bioretention	28	66.1	1.5	0.40	11.2
	Shallow bioretention	5	61.8	1.6	0.40	2.0
Bioswale	Vegetated swale infiltrates to background soil	1	11.2	8.9	0.50	0.5
Cascade	Terraced bioretention cells in series	5	53.0	1.9	0.40	2.0
Porous sidewalk or pavement	With underdrain	18	1.0	100.0	0.015	0.3
	With underground storage cubes	5	1.0	99.9	0.015	0.1
Rain garden	Rain garden without curb extension	64	35.8	2.8	0.40	25.6
	Curb extensions with rain gardens	8	66.0	1.5	0.40	3.2
	total number of control units:	157			total area treated:	54.4
	total area treated (acres):	54.4				
	area per unit:	0.40				

Biofilter performance is based upon the characteristics of the flow entering the device, the infiltration rate into the native soil, the filtering capacity and infiltration rate of the engineered media fill if used, the amount of rock fill storage, the size of the device and the outlet structures for the device. WinSLAMM was used with the calibration files prepared for the Kansas City demonstration project to examine alternative biofilter and bioinfiltration device designs for the residential test (pilot) area. Four different infiltration rates for the native subsurface soil were examined: 0.2, 0.5, 1.0, and 2.5 in/hr (corresponding to sandy silt loam, loam, sandy loam, and loamy sand soils, respectively). The lowest rate (0.2 in/hr) was the assumed early infiltration rate used by the design consultants for the original designs. Site surface soil measurements in the test watershed indicated 1 in/hr, or greater, infiltration rates for rains lasting 2 hours or less. Site measurements of the biofilters during storms indicated infiltration rates of the media and device at 1.8 in/hr, and modeling indicated likely subsurface rates of about 1 in/hr (or greater) to result in the observed performance during the rains (almost complete infiltration with very little overflow or subsurface underdrain discharges). The use of gravel storage is only important for the low infiltration rate conditions: once the infiltration rate is about 1 inch/hr, or larger, this additional storage is not needed, as far as benefiting the long-term infiltration conditions. As shown in Figure X.6, for the low infiltration rates, the use of underdrains degrades the performance of the biofilters because the underdrains discharge subsurface ponding water before it can completely infiltrate (but underdrains do decrease surface ponding, a desired objective). The use of a slow underdrain (as indicated here by the SmartDrainTM), results in an intermediate effect, while also decreasing periods of long surface ponding. As with the gravel storage, underdrains have very little effect on performance when the native subsurface native infiltration rate is about 1 inch/hr, or greater.

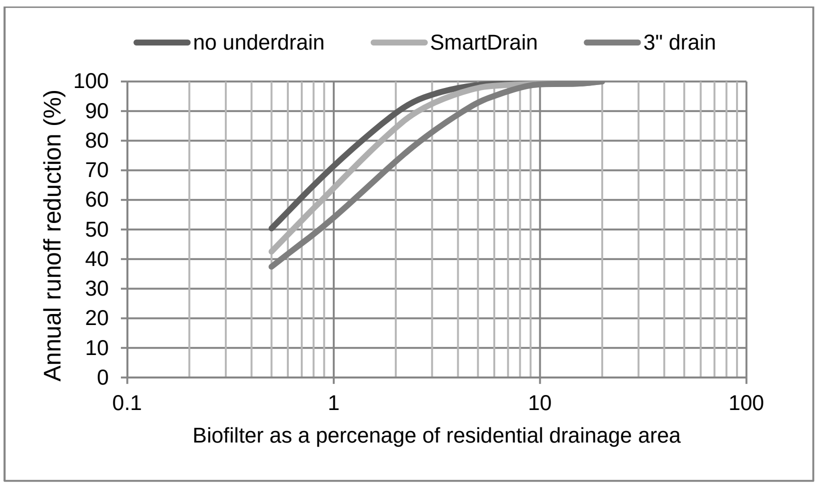

Figure X.6 Effects of underdrains in biofilters on annual runoff reductions for subsurface native soil infiltration rates of 0.5 in/hr.

X.4 Conclusions

A detailed land survey found that most of the homes in the test watershed already have disconnected roofs (85% of all roof areas), and that the total roof areas account for 13% of the total study area. The directly connected roofs, which make up only 2% of the study area, contribute 6% of the total annual flows. The disconnected roofs, which constitute 11% of the area, contribute 7% of the total flows. Thus complete control of the runoff from the remaining directly connected roofs would only reduce the total area run-off volume by a very small amount, less than can be reliably detected by monitoring the total runoff from the area.

Cost-effective designs of biofilters for the area can be identified by examining the production functions provided during this research. For slowly infiltrating native subsoils (<1 in/hr), the use of additional subsurface storage and restricted underdrains can be very beneficial. For higher rate soils, these features have minimal benefit on performance. The biofilters being about 1.5 to 2% of the drainage area in the residential area are expected to provide about 90% long-term reductions in stormwater runoff to the combined sewer for the areas treated. However, only about half of the test (pilot) watershed received runoff control, so the overall runoff volume reduction benefit is less than complete.

X.5 Acknowledgements

The results presented in this paper are a small portion of the full project activities associated with the National Demonstration of Advanced Drainage Concepts Using Green Solutions for CSO Control Project in Kansas City, funded by the USEPA Office of Research and Development, Urban Watershed Management Branch. The direction and support of the EPA Project Officers, Michelle Simon and Richard Field, are gratefully acknowledged. Other project participants, including TetraTech personnel (Dustin Bambic, Jason Hall, and Scott Struck, plus others), University of Missouri, Kansas City faculty and student researchers (under the direction of Dr. Deb O'Bannon), University of Alabama graduate students, the Kansas City Water Services Department, Dr. Michael Ports, and Mid-America Regional Council (MARC), were all instrumental in planning and carrying out this project and are also gratefully acknowledged.

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