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Modeling Green Infrastructure Components in a Combined Sewer Area

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The US EPA’s Office of Research and Development’s National Risk Management Research Laboratory has funded this research element in support of its Water Supply and Water Resources Division’s AWI Research Program. “This project will evaluate, at full-scale, the integration of green infrastructure technology (e.g., engineered bioretention, rain gardens) with conventional CSO control (gray infrastructure) to gain a better understanding and develop guidance on planning, design, costs and implementation.” The intent of this project is to evaluate the water quality and quantity improvement benefits of a large-scale application of green infrastructure control practice retrofits in an entire monitored subcatchment. These green infrastructure controls have been shown to, when implemented and maintained properly, increase retention at the runoff source. This decreases the runoff volume entering the drainage system and the demand on a drainage system. Both developed stormwater and combined sewersheds can benefit from the added storage from areas retrofitted with bioretention cells or rain gardens and other management practices, e.g., inlet retrofits or curb-cuts with tree plantings.

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This project will document an effort by the ORD to demonstrate the efficacy of implementing integrated, green infrastructure-based solutions to support control of wet-weather flow pollution problems in an urban core neighborhood within a combined sewer system. This pilot project is part of a larger adaptive management approach to incorporate Green Solutions into the Kansas City, MO CSO long-term control plan. The project involves local and regional efforts to provide the "basis-for-success" of the implementation of Green Solution infrastructure and stormwater management at the neighborhood, watershed, and regional levels. The project will demonstrate the strategy and methodology, including model support, for identifying where and how Green Solutions will be implemented within Kansas City, MO.

The overall key project objectives are to:

- Demonstrate the integration of green solutions with traditional gray infrastructure in an urban-core neighborhood having a combined sewer system
- Develop a methodology for implementation of Green Solutions
- Measure the changes in the peak flow, total volume and pollutant mass of storm events in the receiving system or the reduction of combined wastewater volumes, pollutant loads and overflows
- Develop a model for predicting the quality and quantity benefits of implementing Green Solutions
- Compare economic costs and benefits of integrated green and gray solutions

Pre and post-control installation monitoring of the combined sewer flows in the drainage area below the area where the stormwater management controls are being installed are critical components to this project. The stormwater management controls in the demonstration area drain to the municipal combined sewer drainage system in the Middle Blue River watershed. This drainage pattern will allow isolation of the benefits of the upland stormwater controls with minimal flows coming from outside areas. The watershed model (WinSLAMM) and the sewerage model (SWMM) will be calibrated for this area using the pre-construction flow and water quality data. Both dry and wet weather flow data will be recorded. The calibrated models will be used early in the project to predict the benefits of the upland controls, and these predictions will be verified as the controls are installed. After the models are calibrated and verified for the demonstration area, they will be used to predict the benefits of wider application of the upland controls across the city. Specifically, the models will predict the decreased runoff volumes and peak runoff rates associated with upland stormwater controls to alleviate problems in the combined sewer system. Water quality benefits associated with stormwater pollutant discharge reductions of wet-weather flow particulates (including particle size distributions), nutrients, bacteria, and heavy metals will be quantified. WinSLAMM will be used to calculate the stormwater contributions to the combined sewerage system during wet-weather by providing a time series of flows and water quality conditions, for various types of upland controls, while SWMM, with its detailed hydraulic modeling capabilities, will focus on the interaction of these time series data with the sewerage flows and detailed hydraulic conditions in the drainage system. Both models will be used interactively emphasizing their respective strengths.

The study area is a 100 acre subcatchment. The selected sewershed contains commercial, medium density, and some high density residential land uses. An adjacent 80 acre subcatchment has been selected as a control watershed.

The project contractor is Tetra Tech, Inc., and associated subcontractors include the University of Alabama, University of Missouri – Kansas City, Mid-America Regional Council (MARC), and Bergmann Associates, Inc. Critical project leveraging and cooperation is provided by the Kansas City Water Services Department, and EPA Region 7.

Traditional CSO control practices were originally designed for this area. However, several years ago, Kansas City municipal officials, in conjunction with local citizen groups, started exploring how “low impact development” concepts could be used in the area instead of traditional very large storage tanks. The city is applying many CSO controls listed on the Nine Minimum Control list, such as by making necessary repairs to the sewerage to minimize I&I (infiltration and inflow). The use of bioretention controls has been shown to be promising in meeting the CSO control requirements, with less cost, while providing needed community benefits. Initial modeling is being conducted in conjunction with the design efforts to illustrate the levels of control that can be achieved. With the monitoring results, the models will be verified and then used throughout the city to identify and investigate other retrofit opportunities. In addition, the long duration project will also accumulate much needed information concerning actual costs and maintenance for these controls. Struck (2009), along with many presentations at the ASCE/EWRI conference in Kansas City, presented overviews of this project.

Initial modeling results using WinSLAMM indicate that the use of bioretention facilities in the test area (which has poor soils with very limited infiltration capacities) can still be effective in storage of the peak flows during critical events, significantly decreasing overflows. The use of large water storage tanks to allow on-site beneficial uses of the runoff, in contrast, has limited benefits, and small rain barrels are even less effective. Research is also being conducted showing how newly available drainage controls can be used in the bioretention facilities to maximize their storage potentials.

This paper describes updated modeling results for the use of rain gardens, rain barrels/tanks, and roof disconnections, along with preliminary calculations pertaining to curb-cut biofilters that are being examined for potential application in the Kansas City test area for the control of combined sewer overflows.

1.1 Water Harvesting Potential

The water harvesting potential for the retrofitted rain gardens and water tanks was calculated based on supplemental irrigation requirements for the basic landscaped areas. The irrigation needs were determined to be the amount of water needed to satisfy the evapotranspiration needs of typical turf grasses, after the normal rainfall.

Table 1 shows the monthly average rainfall for the 1973 through 1999 period at the Kansas City airport, a 26 year unbroken continuous rain record. The average total annual rainfall is typically about 37.5 inches, with most falling in the spring to early fall. A much smaller fraction of the annual rain occurs during December through February.

Table 1. 1973 through 1999 Kansas City Airport Rain Records

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Avg.	1.13	1.24	2.54	3.48	5.41	4.27	4.15	3.63	4.63	3.32	2.08	1.60	37.49
COV	0.68	0.57	0.66	0.61	0.54	0.48	0.85	0.67	0.75	0.81	0.59	0.83	0.25
Min.	0.02	0.20	0.32	0.34	1.18	1.73	0.25	0.65	0.57	0.00	0.00	0.00	21.60
Max.	2.81	2.72	9.08	8.43	12.41	8.67	15.47	9.58	11.11	10.16	5.12	5.42	55.26

The total landscaped area in the residential land use is 65.1 acres, and with 576 homes, each has about 4,925 ft^2 of landscaped area that could potentially be irrigated.

Figure 1 shows the monthly evapotranspiration requirements of typical turf grasses for a monitoring station near Kansas City (at Ottawa, KS, a University of Kansas field station in eastern Kansas). The total annual ET is about 52 inches a year, while the annual total rainfall is about 37 inches a year, resulting in a rainfall deficit of about 15 inches per year. Figures 2 and 3 are plots of the monthly rainfall, and supplemental irrigation needs to meet the ET. Most of the supplemental irrigation is needed in July and August, while there is an excess of rainfall in October through December and therefore no supplemental irrigation needed during those months.

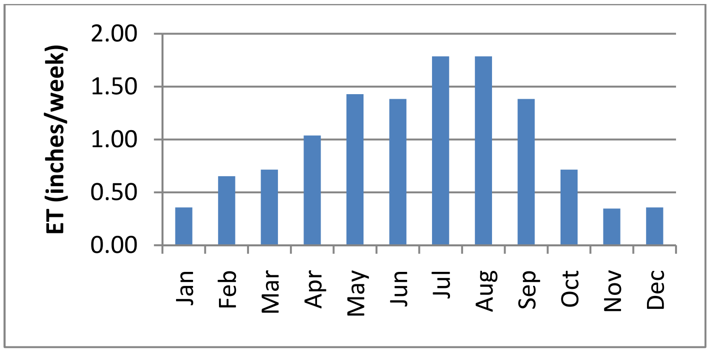

Figure 1. Monthly evapotranspiration at Ottawa, KS (typical turf grass).

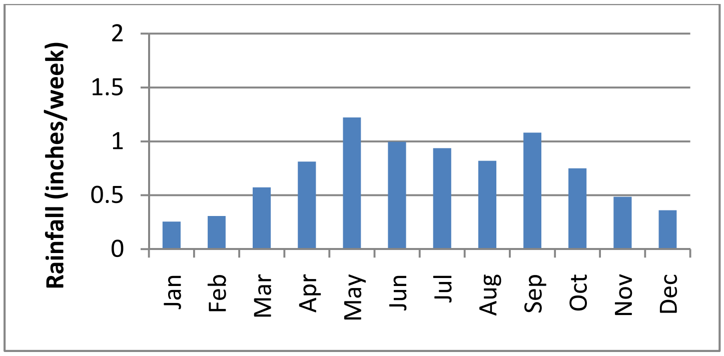

Figure 2. Monthly rainfall at Kansas City (1973 through 1999).

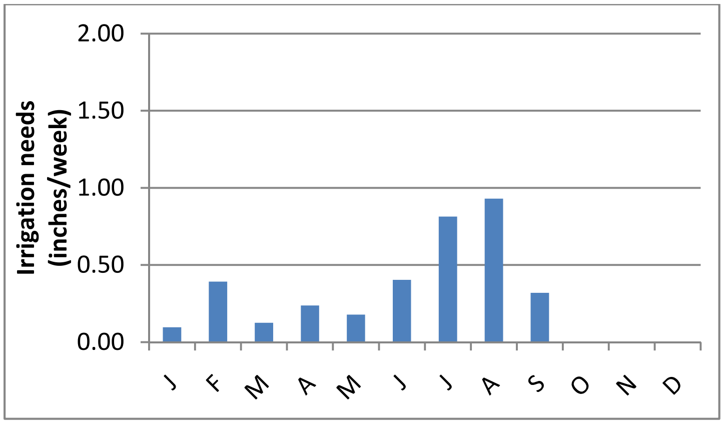

Figure 3. Supplemental irrigation needed to meet ET for typical turfgrass.

The total amount of rainfall harvesting potential for irrigation (to match the ET) is about 46,600 gallons (6,230 ft^3) per household per year. With 4,925 ft^2 of landscaped area per household, the annual irrigation requirement is about 1.3 ft, or 15 inches, or an average of about half an inch of water applied per week during the 9 months when there is an irrigation need. With 576 homes in the watershed, this totals about 27 million gallons (3.6 million ft^3) per year for the 100 acre project area. Continuous simulations are used to see how much of this can actually be used based on the interevent conditions and rain patterns compared to the water need patterns and water storage volume. It may also be possible to use a greater amount of this water for irrigation for certain plants, but that will have to be further investigated. These irrigation values are for typical turf grasses. Any additional irrigation would theoretically not be used by the plants, but would be infiltrated into the soil. The infiltration rates available through the soils at the project site are low, as described in the following section.

1.2 WinSLAMM Modeling of Rain Garden, Rain Barrel/Tanks, and Disconnection Roof Runoff Controls

WinSLAMM modeling processes of importance in calculating the benefits of these controls have been described in several prior recent monographs from this conference series and other sources (Pitt, *et al*. 2008a and b; Pitt and Clark 2008; Pitt, *et al.* 2009 and 2010). These devices are being considered for residential areas in the Kansas City study area. They would be located on private property and receive the runoff from directly connected roofs. Their maximum benefit is dependent on the amount of runoff that is contributed from the source areas where they would be located. Table 2 shows that currently, the directly connected roofs only contribute about 5.8%, 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.

Table 2. Roof Area Runoff Contributions in Kansas City Study Area

	roof 1 areas (currently directly connected) (1.87 acres)	roof 2 areas (currently disconnected) (10.57 acres)	land use total (100 acres)	Rv
base conditions (ft^3/year)	257,200	319,200	4,449,000	0.3
% contributions	5.8	7.2		
% roof contributions	13.0			
if all roofs connected (ft^3/year)	257,200	1,458,000	5,588,000	0.38
% contributions	4.6	26.1		
% roof contributions	30.7			
if all roofs disconnected (ft^3/year)	56,340	319,200	4,248,000	0.29
% contributions	1.3	7.5		
% roof contributions	8.8			

Table 3 shows that 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 pervious 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. If an infiltration or beneficial use control is used to control runoff from disconnected roofs, they would have to be about 4.5 times larger than if used for runoff control from directly connected roofs, in order to have the same benefit on the overall discharge volume from the area.

Table 3. Runoff from Directly Connected and Disconnected Roofs in Kansas City Study Area

	area (acres)	annual runoff (ft^3)	runoff per area (ft^3/acre/year)
roof 1 areas (directly connected)	1.87	257,200	137,500
roof 2 areas (disconnected)	10.57	319,200	30,200
ratio of disconnected to directed connected:	5.65	1.24	0.220

1.2.1 RAIN GARDENS

Each rain garden has a top surface area of 160 ft^2, being about 10 by 16 ft in area. It is excavated to an overall depth of 3 ft, with 2 ft backfilled with a loam soil. The surface 1 ft is left open to provide surface storage 9 inches deep. A native soil infiltration rate of 0.2 inches per hour was used in the calculations, while the loam soil fill only had a 0.15 in/hr infiltration rate. The only outlet used (besides the natural infiltration) is a surface overflow along one edge of the rain garden.

The use of one of these rain gardens per house results in a rain garden that is about 17% of the surface of the typical roof in the study area. Figure 4 summarizes the continuous modeling results for several different sizes and numbers of rain gardens, per house, based on the 1990 rain year (the year that was selected as being representative of the long-term rain record). As noted above, disconnected roofs already experience substantial runoff reductions (about 78%) in the study area, even with the low infiltration rates. Therefore, about 13% of the roof area would have to be served by rain gardens to be equivalent to the current benefits of disconnected roof drainage. This corresponds to a rain garden having about 120 ft^2 in surface area per house, with the rain garden overflow then flowing directly to the combined sewer drainage system.

A goal of reducing 90% of the runoff from directly connected roofs in the study area would require rain gardens that are about 20% of the roof areas, or a total area of slightly less than 200 ft^2 per house. In most cases, this area would be made of two to four separate smaller rain gardens per house, depending on the locations of the roof gutter downspouts. With a peaked roof that all drains to one end of the house, two would be needed (each about 100 ft^2 in area), while for a more common peaked roof that drains to each corner separately, then four separate smaller rain gardens would be needed (each about 50 ft^2 in area).

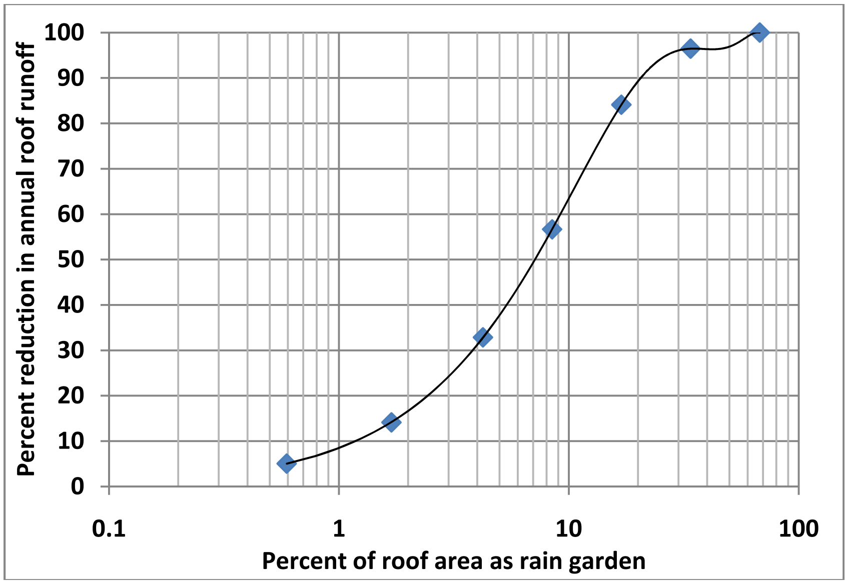

Figure 4. Percentage reduction in annual runoff from directly connected roofs with the use of rain gardens.

1.2.2 RAIN BARRELS AND WATER TANKS

Rain barrels are a very simple method for collecting roof runoff for later beneficial uses. In these analyses, irrigation of typical turf grass landscaping around the homes in the study area is the use provided. This irrigation requirement was described previously and is the additional water needed to supplement the long-term monthly average rainfall in order to match the evapotranspiration requirements of turf grass for the area. As will be shown in these analyses, small rain barrels provide limited direct benefits, so larger water tanks were also considered. Also, in order to be most beneficial, these calculations assume that the irrigation rates are controlled by soil moisture conditions in order to match the ET requirements closely. This level of control is usually most effectively achieved with a single large storage tank connected to an automatic irrigation system. Numerous smaller rain barrels are more difficult to control optimally.

For these calculations, each rain barrel is assumed to have 35 gallons of storage capacity (4.7 ft^3). Each roof has an average area of 945 ft^2 and receives a total of 3,100 ft^3 of rainfall. As noted above, these analyses are only for the directly connected roofs in the area, which only comprise about 15% of the total roof area in the study watershed.

Table 4 and Figure 5 show the benefits of storage and irrigation use of runoff collected from directly connected roofs. The use of a single rain barrel per house is expected to provide about a 24% reduction in runoff through irrigation to match ET. However, more than 25 would be needed to reduce the roof's contributions by 90%. In order to match the benefits of disconnection of the connected downspouts (about 78% reductions), about 25 rain barrels would be needed. Twenty-five rain barrels correspond to a total storage quantity about equal to 0.12 ft (1.4 inches).

As the storage volume increases, it obviously becomes impractical to meet the total storage volume with small rain barrels. Table 5 shows the equivalent size of larger water tanks or cisterns when the number of rain barrels is greater than four. As an example, a moderately-sized water tank 5 ft in diameter and 6 ft tall has a similar storage capacity as 25 rain barrels, and if the 6 ft tall tank was expanded to 10 ft in diameter, this larger tank would have a similar capacity as 100 rain barrels.

Table 4. Benefits of Storage and Irrigation Use of Roof Runoff at Kansas City Study Area

# of rain 35 gal. barrels per house	rain barrel storage per house (ft^3) per roof area (ft^2, or ft depth over the roof)	total annual roof runoff for 86 houses (ft^3)	total annual roof runoff per house (ft^3)	% reduction in roof runoff
0	0	257,200	2990	0
1	0.0050	196,700	2290	24
2	0.010	181,400	2110	29
4	0.020	155,800	1810	39
10	0.050	112,400	1310	56
25	0.12	67,200	780	74
100	0.50	3,160	37	99

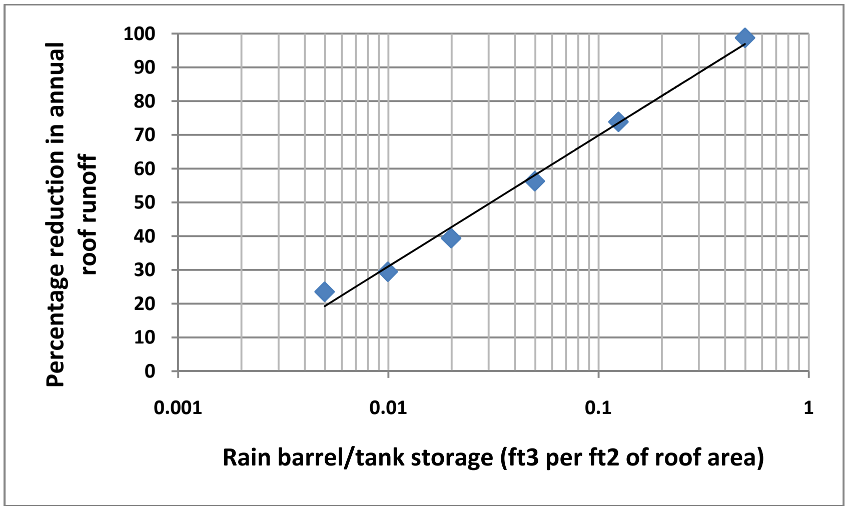

Figure 5. Reduction of annual runoff from directly connected roofs with the use of runoff storage and irrigation.

Table 5. Roof Runoff Storage Options

Runoff storage per house (ft^3)	# of 35 gal rain barrels	tank height size required if 5 ft D (ft)	tank height size required if 10 ft D (ft)
0	0	0	0
4.7	1	0.24	0.060
9.4	2	0.45	0.12
19	4	0.96	0.24
47	10	2.4	0.60
118	25	6.0	1.5
470	100	24	6.0

The use of about 25 rain barrels, or a small tank 5 ft in diameter and 6 ft tall, is the recommended amount of storage for the currently directly connected roofs in the study area. This would provide about 74% reductions in the total annual runoff discharges.

1.2.3 COMBINATIONS OF RAIN GARDENS AND RAIN BARRELS

It may be most efficient to use rain barrels and rain gardens together at the same houses that have directly connected roofs. Figure 6 shows the reductions in the annual runoff for the range of these controls that have been previously examined separately. In order to obtain reductions of about 90% in the total annual runoff, it will be necessary to have at least one rain garden per house, unless the number of rain barrels exceeds about 25 (or 1 small water tank) per house. In that case, the rain gardens can be reduced to about 80 ft^2 per house, or less. This area for the rain gardens can be divided into multiple rain gardens with smaller units near each roof drain downspout. The rain barrels are 35 gallons each and the total volume associated with multiple rain barrels can be combined when using a larger water tank, as noted above.

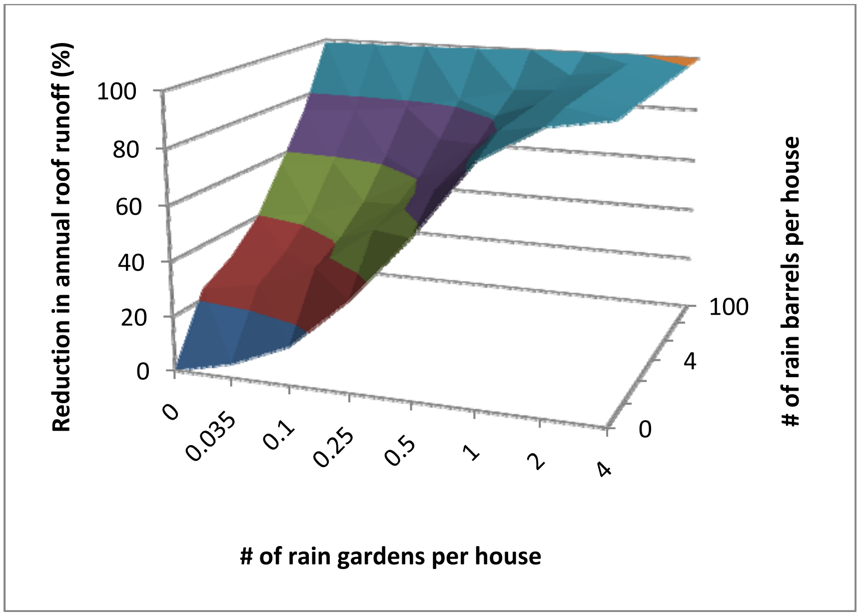

Figure 6. Reduction in annual runoff from directly connected roofs with the use of rain gardens and roof runoff storage and irrigation.

1.2.4 ROOF DRAIN DOWNSPOUT DISCONNECTIONS

Another option for the control of runoff from directly connected roofs is to disconnect the roof drain downspouts that are currently directed towards pavement that in turn are directly connect to the drainage system. When disconnecting downspouts, the water needs to be redirected over pervious ground, most commonly regular turf grass. This is most effective if the water is discharged to relatively flat lawns in good conditions that have flow path lengths of at least 10 feet for small residential roofs. In the study area, the soils have poor infiltration characteristics, but the amount of water that can be infiltrated is still relatively high, mostly because the roofs only comprise about 12% of the lot area and the landscaped areas comprise about 65% of the total area. The available flow paths are therefore relatively long, increasing the infiltration potential.

WinSLAMM version 9.5 was used to make a preliminary analysis of the benefits of disconnecting the directly connected roofs to allow the runoff to flow across the pervious areas. The new version 10 being completed will be able to more directly calculate these benefits through grass filtering processes. The following tables and plots illustrate these results. When additional site details are evaluated, along with the planned model enhancements, these calculations will be re-evaluated. However, these results can be roughly compared to the previous benefits associated with rain gardens and rain barrels. Disconnecting these roofs in areas having clay soils is expected to result in annual runoff reductions of about 78%. This would increase to about 87% and 95% for areas having silty and sandy soils, respectively.

The volumetric runoff coefficient (Rv), the ratio of runoff volume to rainfall volume falling on an area, increases with increasing rain depths. For directly connected pitched roofs, the Rv is about 0.7 for 0.1 inch rains, and is quite close to 1.0 for rains larger than about 2 inches in depth. When disconnected to clayey soils, runoff is not expected until the rain depth is greater than 0.1 inches and the Rv starts to climb steeply with rains larger than several inches in depth. It is expected to be very large for very large and unusual rains that can cause severe flooding, irrespective if they are disconnected or not. However, the benefits for small and intermediate rains are large. Figure 7 illustrates the percentage reductions associated with disconnecting the directly connected roofs for the three main soil categories.

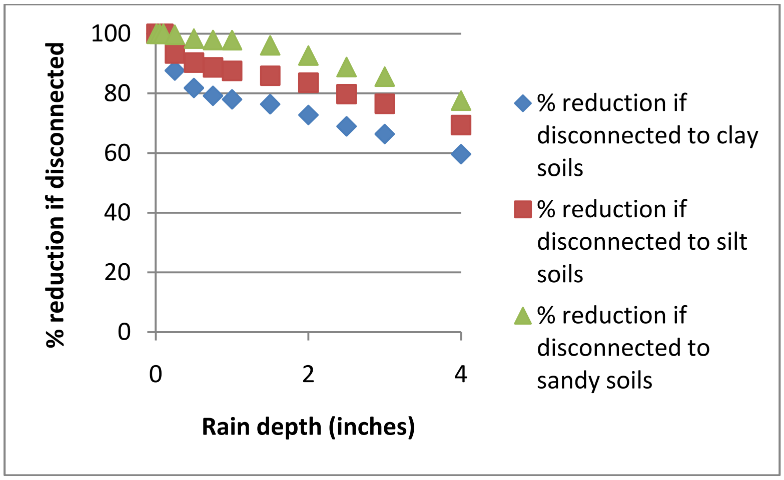

Figure 7. Runoff reductions when directly connected roofs are disconnected.

1.3. Preliminary Evaluations of Curb-Cut Biofilters

The final designs of the curb-cut biofilters are still being completed, but a preliminary analysis of simple curb-cut rain gardens was conducted using WinSLAMM. The curb-cut biofilters were assumed to be simple excavations 20 ft long and 5 ft wide, located in the terrace between the sidewalk and the street. Their surface depth was limited to 1 ft to decrease uneven steep slopes and other hazardous conditions. It is assumed that the subsoil would be loosened after the excavation and a minimum amount of organic material would be added to the soil. There is a little less than 6 miles of street-side drainage systems in the 100 acre test watershed. Therefore, a maximum of about 1500 rain gardens were assumed to be possible in the area. However, a more reasonable maximum number would be about half of this amount due to the presence of large trees and other interferences.

Figure 8 is a plot of the percentage of the typical annual runoff amount that can be infiltrated by the curb-cut rain gardens, based on the number of units used, and with no other controls in the area. With a maximum 1500 units possible, up to about 80% of the annual runoff may be infiltrated. With 400 units, about 40% of the annual flows would be diverted from the combined sewers.

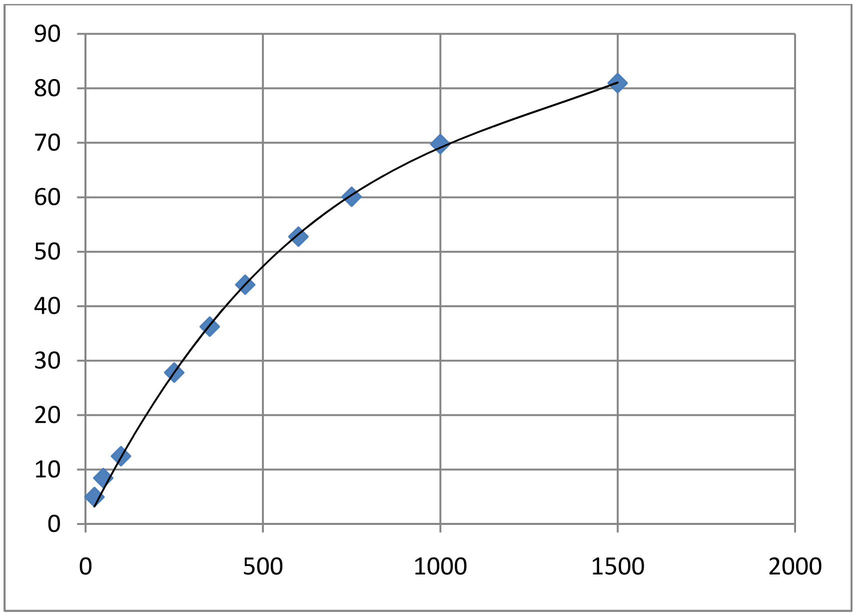

Figure 8. Annual runoff volume reduction (%) for typical rain year (1990) for different numbers of simple curb-cut rain gardens per 100 acre watershed.

Figure 9 shows the durations of flows at different rates for several different curb-cut rain garden applications. The maximum peak flow for the typical rain year is expected to be between 25 and 30 CFS for this area. The use of 600 rain gardens is likely to reduce the flow rates that occur about 0.1% of the annual hours (about 5 to 10 hours a year) to about half of the value if un-controlled.

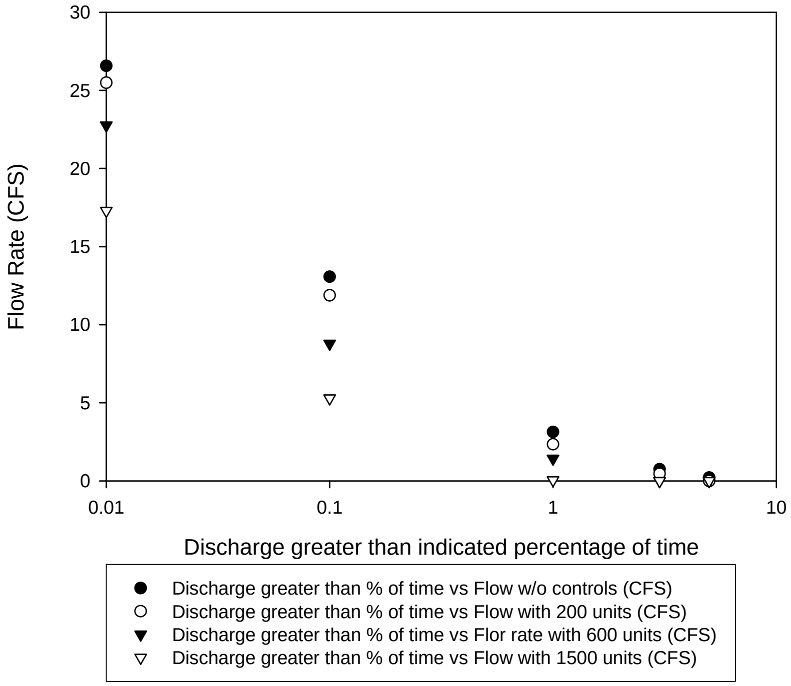

Figure 9. Durations of flows (% of time) for different numbers of simple curb-cut rain gardens.

1.4 Conclusions

The detailed land survey, based on procedures described by Bochis, *et al.* (2009) conducted in the study area by Dr. Deb O'Bannon and her students at UMKC, in conjunction with KCMO GIS information, 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 comprise about 13% of the total area. This severely hinders the ability to detect any total area benefits of controls practiced at the directly connected roofs, as they are expected to contribute only small portions of the total site runoff. The land survey also found that about 65% of the area is landscaped, with most being in turf grass in poor to good condition. This information was used in conjunction with regional

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evapotranspiration data to calculate the amount of supplemental irrigation needed to meet the ET requirements of typical turf grass, considering the long-term rainfall patterns. Most of the supplemental irrigation would be needed during the months of July and August, while excess rainfall occurs in October through December (compared to ET requirements during these relatively dormant months). Soil infiltration monitoring in the area, also by the UMKC researchers, along with recent soil profile surveys, has indicated relatively poorly draining soil in the test area. Surface infiltration rates during several hour rains may have infiltration rates of about 0.5 inches or greater, but these rates continue to decrease with increasing rain depths. For conservative modeling calculations, soil infiltration rates of 0.2 inches per hour were used.

The expected major sources of runoff from the test area vary for different rain depth categories. Directly connected impervious areas are the major runoff sources only for rains less than about 0.25 inches in depth. The large landscaped areas contribute about half of the runoff for rains larger than about 0.5 inches in depth. The directly connected roofs, which make up only about 2% of the study area, contribute about 6% of the total annual flows. The disconnected roofs, which comprise about 11% of the area, contribute about 7% of the total flows. Therefore, complete control of the runoff from the directly connected roofs would only reduce the total area runoff by a very small amount; less than can be reliably detected by monitoring the total runoff from the area. However, the source area monitoring that will be conducted at selected individual lots that currently have directly connected roofs is expected to result in very useable information that can then be used to accurately predict runoff reduction benefits using these control options in other areas that have greater flow contributions from directly connected roofs.

The modeling calculations illustrate the benefits of using rain gardens, rain barrels/tanks, or simple disconnections of the directly connected roofs. The results are presented on the basis of the benefits for the directly connected roofs alone; if calculated for the whole drainage area, the benefits would be <5%. If all of the roofs were directly connected, they would then contribute about 30% of the annual flows, and the outfall benefits for the whole area from these roof controls would be substantially larger.

Performance plots were prepared comparing the size of the rain gardens to the size the roof vs. percent flow reductions. Rain gardens about 20% of the roof area are expected to result in about 90% reductions in total annual flow compared to directly connected roofs. This area is about 200 ft^2 per house which could be comprised of several smaller rain gardens so they can be located at each downspout. Fifty percent reductions in the total annual flows could be obtained if the total rain garden area per house was about seven percent of the roof area.

Rain barrel effectiveness is related to the need for supplemental irrigation and how that matches the rains for each season. The continuous simulations used a typical one-year rain series and average monthly ET values for varying amounts of roof runoff storage. A single 35 gallon rain barrel is expected to reduce the total annual runoff by about 24% from the directly connected roofs, if the water use could be closely regulated to match the irrigation requirements. If four rain barrels were used (such as one on each corner of a house receiving runoff from separate roof downspouts), the total annual volume reductions could be as high as about 40%. Larger storage quantities result in increased beneficial usage, but likely require larger water tanks. Water use from a single water tank is also easier to control through soil moisture sensors and can be integrated with landscaping irrigation systems for almost automatic operation. A small tank about 5 ft in diameter and 6 ft in height is expected to result in about 75% total annual runoff reductions, while a larger 10ft diameter tank 6 ft tall could approach complete roof runoff control.

The use of rain barrels and rain gardens together at a home is more robust than using either method alone: the rain barrels would overflow into the rain gardens, so their irrigation use is not quite as critical. In order to obtain reductions of about 90% in the total annual runoff, it is necessary to have at least one rain garden per house, unless the number of rain barrels exceeds about 25 (or 1 small water tank) per house. In that case, the rain gardens can be reduced to about 80 ft^2 per house.

Simple disconnections of the currently directly connected roofs can provide significant reductions in the annual flows from the roofs for expected less cost. A reduction of about 80% is expected in the total flows from the directly connected roofs, with disconnections, even with the site's clayey soils, with most runoff flow reductions occurring during small rains, and the benefits decreasing as the rains increase in depth. This flow volume reduction is enhanced due to the relatively small roof areas and large landscaped areas which provide long flow paths. With steep slopes and poor grass, this reduction will be less.

The "best" combination of control options is not necessarily obvious. The CSO program must meet their permit requirements that specify certain amounts of upland storage in the watershed. Other elements, including costs, aesthetics, improvements to street-side infrastructure, and other benefits, also need to be considered in a decision analysis framework, such as described by Pitt and Voorhees (2007). Caution is needed when comparing the amount of site runoff storage provided by these upland controls to the total storage goals to meet the objectives of the CSO control program (288,000 gallons). As an example, storage provided at directly connected roofs need to be discounted by about 1.3 to 1.4X as not all of the storage is available during all rains, and their drainage is controlled by low infiltration rates through the native soils, compared to flow controls directly connected to the combined sewers. In addition, the curb-cut biofilters also have "access" to almost all of the flows in the area, so their storage volumes are more effectively utilized. More significantly, if storage was provided at roofs that are already disconnected, their storage volumes would need to be discounted by about 4.5X when compared to the total site storage goals, due to the existing infiltration already occurring by the disconnected roofs.

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