

Integrated Modeling of Green Infrastructure Components in an Area Served by Combined Sewers

Robert Pitt¹ and John Voorhees²

¹Cudworth Professor of Urban Water Systems, Department of Civil, Construction, and Environmental Engineering, The University of Alabama, Tuscaloosa, AL 35487, e-mail: rpitt@eng.ua.edu

²PV&Assoc., Madison, WI, e-mail: jvoorhees@winslamm.com

ABSTRACT

The EPA's Kansas City, MO demonstration project on the use of green infrastructure to minimize combined sewer overflows will use a variety of integrated practices and modeling approaches. This extensive project will collect data before, during, and after implementation of a variety of control practices in a 100 acre pilot subwatershed, and in a parallel control subwatershed. The reduction of discharges to the drainage system during wet weather will be calculated using models and verified through field monitoring. The continuous models will determine the decreased amount of stormwater discharged for each event as the storage and infiltration facilities dynamically fill and drain over an extended period of time.

WinSLAMM, the Source Loading and Management Model, conducts a continuous water mass balance for every storm in the study period. As an example, for rain barrels, water tanks or cisterns, capturing roof runoff, the model fills the available storage during rains. Between rains, the storage tank is drained according to the water demands for each month. If the tank is almost full from a preceding close rain (and not enough time was available to drain the storage tank), excess water from the event would be discharged to the drainage system after the tank fills. Curb-cut rain gardens/biofilters along a street are basically a cascading swale system where the site runoff is allowed to infiltrate. If the runoff volume is greater than the capacity of the rain gardens, the excessive water is discharged into the combined sewers. When evaluated together, the cisterns treat the roof runoff first, but the excess water is discharged to the curb-cut rain gardens for infiltration. The continuous simulation drains the devices between events, depending on the interevent conditions. As an example, if 200 ft² rain gardens were used for each house in the 100 acre pilot subwatershed, up to about 90% of the annual roof runoff from directly connected roofs may be infiltrated.

The use of a single 35 gallon rain barrel per house is expected to provide about a 24% reduction in directly connected roof runoff through irrigation to match ET. However, more than 25 rain barrels per house would be needed to reduce the roof's contributions by 90%. The use of rain gardens having a total area of 80ft² and two 35 gallon rain barrels per house can collectively reduce the runoff from directly connected roofs by about 90%. Modeling during the project will involve a wide range of potential controls, well beyond the few examples noted here.

INTRODUCTION

The selected 100 acre pilot subwatershed 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, and Mid-America Regional Council (MARC). Critical project leveraging and cooperation is provided by the Kansas City, MO, Water Services Department and EPA Region 7.

Traditional CSO control practices were originally designed for this area. However, several years ago, Kansas City, MO 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 and tunnels. The city is applying the CSO controls required by 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 other presentations at the EWRI World Environmental and Water Resources Congress in Kansas City, MO, presented overviews of this project.

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 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 pervious cover area in the residential land use is 65.1 acres, and with 576 homes, each has about 4,925 ft² of pervious area that could potentially be irrigated.

Figure 1 shows the monthly evapotranspiration (ET) requirements of typical turf grasses based on data from the ET monitoring station closest to Kansas City (at Ottawa, KS, a University of Kansas field station in eastern Kansas, about 50 miles from the study area). 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 is needed during those months.

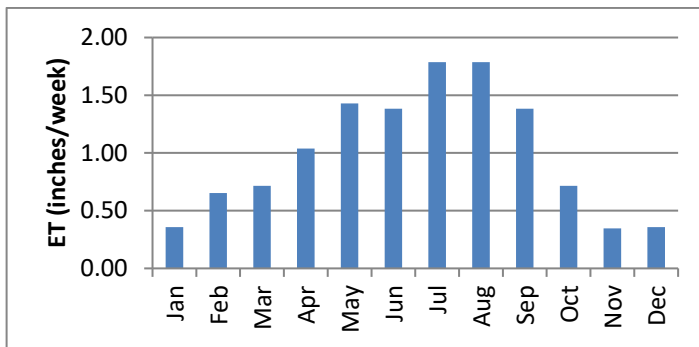


Figure 1. Monthly evapotranspiration at Ottawa, KS (typical turf grass).

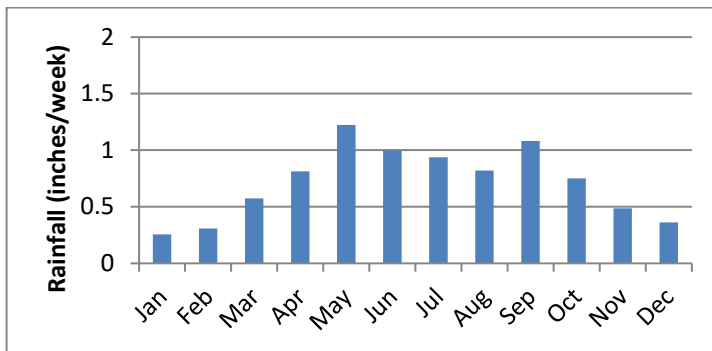


Figure 2. Monthly rainfall at Kansas City (1973 through 1999).

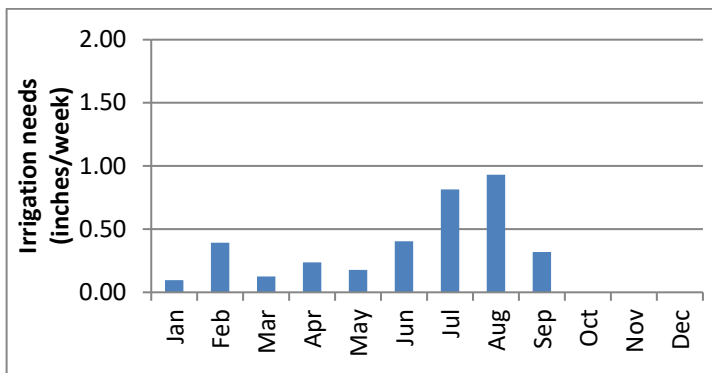


Figure 3. Supplemental irrigation needed to meet ET for typical turfgrass.

The total amount of rainfall harvesting potential for irrigation (to match the ET) is about 46,600 gallons (6,230 ft³) per household per year. With 4,925 ft² 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 ft³) per year for the 100 acre pilot subwatershed 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.

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 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 2. Roof Area Runoff Contributions in Kansas City, MO Pilot Subwatershed

	runoff from the currently directly connected roofs of 1.87 acres	runoff from the currently disconnected roofs of 10.57 acres	land use total runoff from the 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. Runoff from Directly Connected and Disconnected Roofs in Kansas City, MO, Pilot Subwatershed

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

Rain Gardens

Each rain garden used in these analyses has a surface area of 160 ft², being about 10 by 16 ft in area. They are 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 ft² 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 ft² 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 ft² 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 ft² in area).

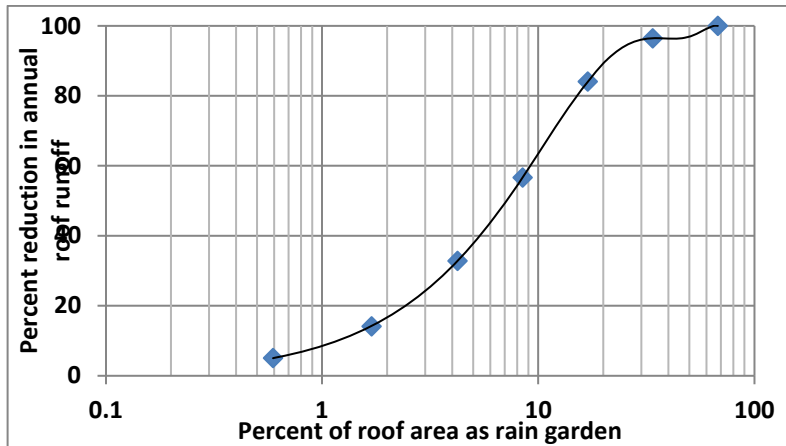


Figure 4. Percentage reduction in annual runoff from directly connected roofs with the use of rain gardens.

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 ET 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 or cisterns were also considered. 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 also more difficult to control.

For these calculations, each rain barrel is assumed to have 35 gallons of storage capacity (4.7 ft³). Each roof has an average area of 945 ft² and receives a total of 3,100 ft³ of rainfall per year. 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 pilot subwatershed.

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 rain barrels per house 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, MO Pilot Subwatershed

# 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

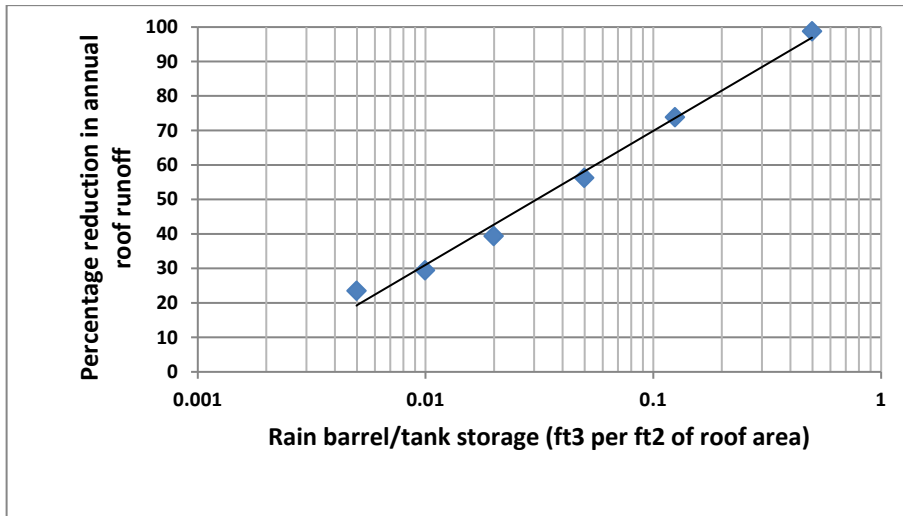


Figure 5. Reduction of annual runoff from directly connected roofs with the use of runoff storage and irrigation.

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.

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

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 ft² 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.

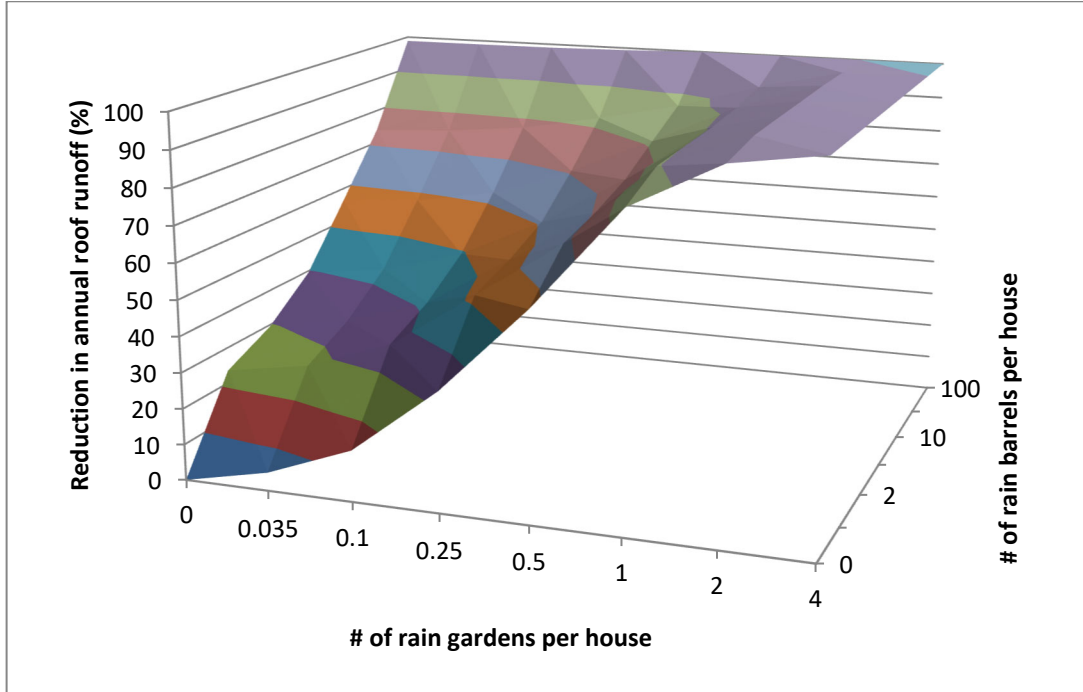


Figure 6. Reduction in annual runoff from directly connected roofs with the use of 160 ft² rain gardens and 35 gallon rain barrels for roof runoff storage and irrigation.

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 of these curb-cut rain gardens would 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 7 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.

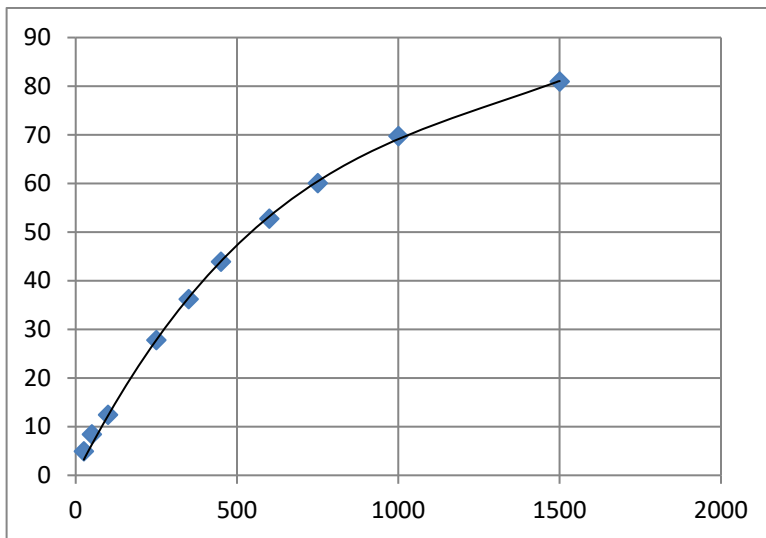


Figure 7. Annual runoff volume reduction (%) for typical rain year (1990) for different numbers of simple curb-cut rain gardens per 100 acre watershed.

Figure 8 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 ft³/sec 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.

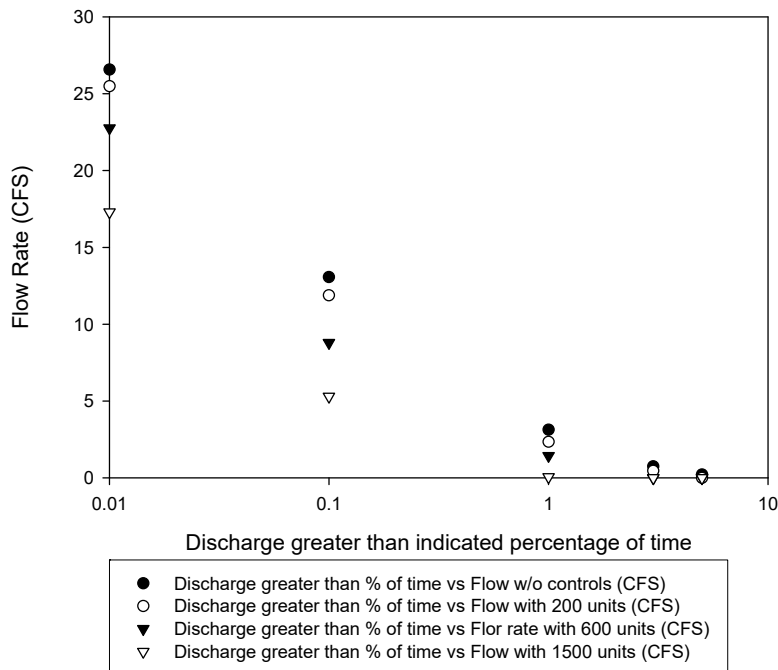


Figure 8. Durations of flows (% of time) for different numbers of simple curb-cut rain gardens.

DISCUSSION AND 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 ET 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, obtained by the UMKC researchers, along with recent soil profile surveys, has indicated relatively poor draining soil in the test area. Surface infiltration rates during several hour rains 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.

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 ft² 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 ft² per house.

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