Integrating Green Infrastructure into a Combined Sewer Service Area Model

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Abstract

The Kansas City demonstration project on the use of green infrastructure to minimize combined sewer overflows (funded by the US EPA and supported by a wide range of national and local agencies) 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 test watershed, and in a parallel control site. 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.

Introduction

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.

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.

Source Area Control Modeling

This paper describes how WinSLAMM, the Source Loading and Management Model, will be used to evaluate the source area control in the watershed, and throughout the city.

WinSLAMM conducts a continuous water mass balance for every storm in the study period. As an example, for water tank cisterns, the model fills the tanks during rains. Between rains, the 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 has elapsed to drain the tank), excess water from the event would be discharged to the drainage system after the tank fills. Curb-cut rain gardens 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.

One of the most important aspects of WinSLAMM is its ability to consider many stormwater controls (affecting source areas, drainage systems, and outfalls) together, for a long series of rains. Another is its ability to accurately describe a drainage area in sufficient detail for water quality investigations, but without requiring a great deal of superfluous information that field studies have shown to be of little value in accurately predicting discharge results. WinSLAMM also applies stochastic analysis procedures to more accurately represent actual uncertainty in model input parameters in order to better predict the actual range of outfall conditions (especially pollutant concentrations). SLAMM uses the water volume and suspended solids concentrations at the outfall to calculate the other pollutant concentrations and loadings. SLAMM keeps track of the portion of the total outfall suspended solids loading and runoff volume that originated from each source area. The suspended solids fractions are then used to develop weighted loading factors associated with each pollutant. In a similar manner, dissolved pollutant concentrations and loadings are calculated based on the percentage of water volume that originates from each of the source areas within the drainage system. SLAMM predicts urban runoff discharge parameters (total storm runoff flow volume, flow-weighted pollutant concentrations, and total storm pollutant yields) for many individual storms and for the complete study period. It has built-in Monte Carlo sampling procedures to consider many of the uncertainties common in model input values. This enables the model output to be expressed in probabilistic terms that more accurately represent the likely range of results expected. The reference list includes some recent chapters and other publications that describe some of the processes included in WinSLAMM.

Initial Watershed Analyses

The performance of the controls is the area is obviously dependent on their design and ability to locate them throughout the area. With a maximum 1500 rain garden 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. 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 5 to 10 hours a year to about half of the flow rates if un-controlled.

The maximum runoff volume control that is expected using 200 large cisterns in the 100 acre area is about 35%. Typical small rain barrels would have very little benefit in reducing the annual discharges to the combined sewers. Levels of runoff volume reductions of about 75% may be achieved with about 500 rain gardens and 250 large cisterns, or alternatively with 1,000 rain gardens and 50 cisterns. Modeling during the project will involve a wide range of potential controls, well beyond the few examples described here.

In many areas, detailed aerial coverage with GIS data sets are becoming available, showing and quantifying the finer elements of an area. Figure 1 is an example from Kansas City, MO, that is being used during this project. This high resolution GIS data shows all of the main elements. Detailed field surveys were conducted by University of Missouri, Kansas City researchers to verify the drainage pattern for each impervious element in the test and control watersheds.

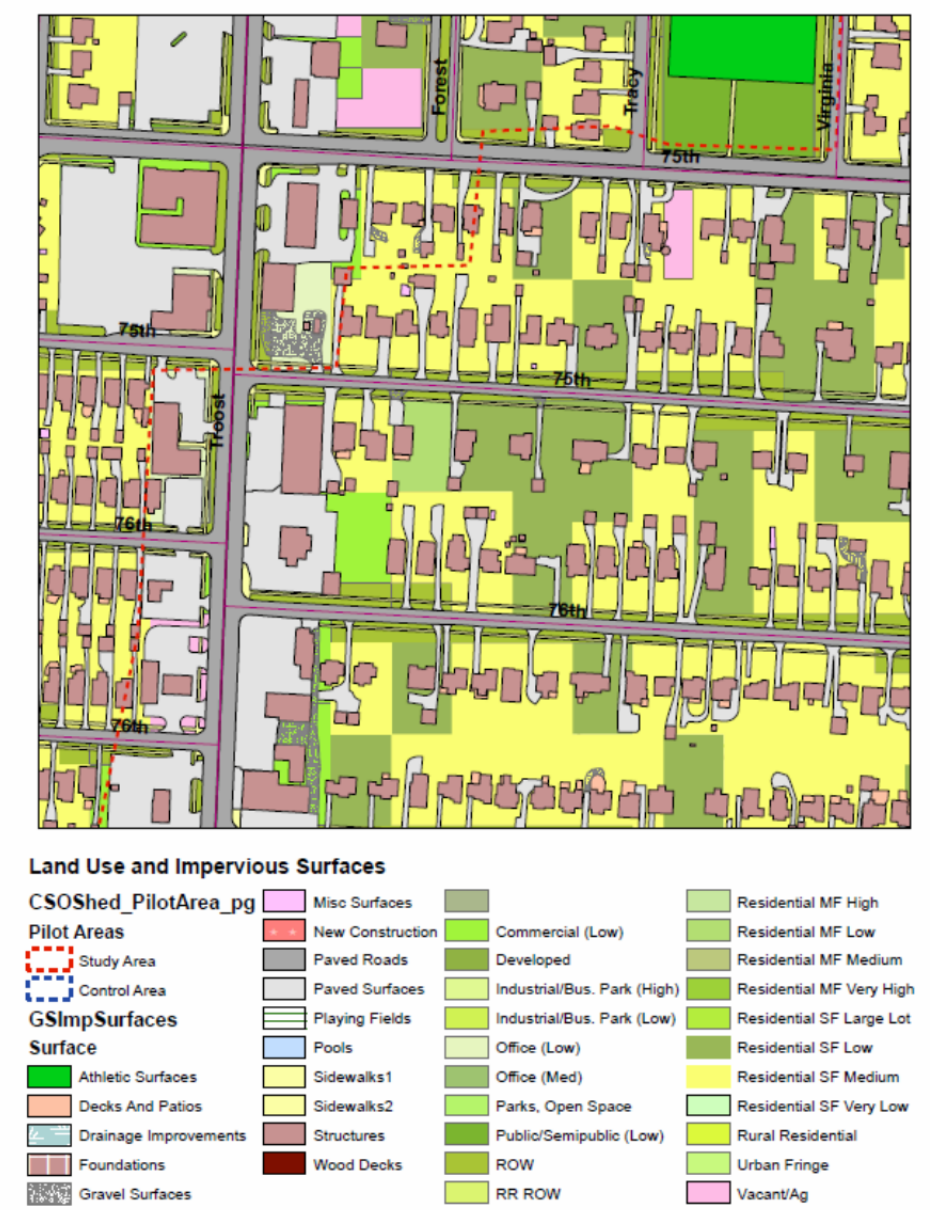


Figure 1. Detailed GIS coverage showing land cover components of different land uses in the Kansas City test watershed.

Land use files have been prepared using the GIS and field data and initial performance calculations for the project have been made. In addition, many infiltration tests have been conducted by the UMKC team. The sites for these infiltration tests were located throughout the study area to represent all of the soil types in the subcatchment. These were all disturbed urban soils and do not correspond to conventional soil map units. Each site was tested using a cluster of three TurfTec infiltrometers spaced about one meter apart to obtain measures of the variation in the infiltration rates. Each test was conducted for two hours to represent typical rain durations. Figure 2 is a composite plot for all of these tests, showing the decrease in the event-average infiltration rates as the duration increases. As an example, a 30 minute rain event would have an average infiltration rate of about 2.7 in/hr, while a 2 hr event has an average infiltration rate of about 0.9 in/hr. An average rate of 0.5 in/hr may occur for rains lasting about 5 hrs. The variation is relatively high for these measurements, with coefficients of variation (the standard deviation divided by the average) ranging from about 1.6 for the shortest events to about 3 for the 2 hr events. Currently, URS, the design contractor for the city, is conducting deep soil infiltration measurements in the areas where the control practices will be located. To date, they have found relatively tight soils and slow infiltration rates. For these reasons, the initial modeling calculations presented here assume a rate of 0.5 in/hr. The recent soil evaluations are using deep infiltration rates of 0.2 in/hr.

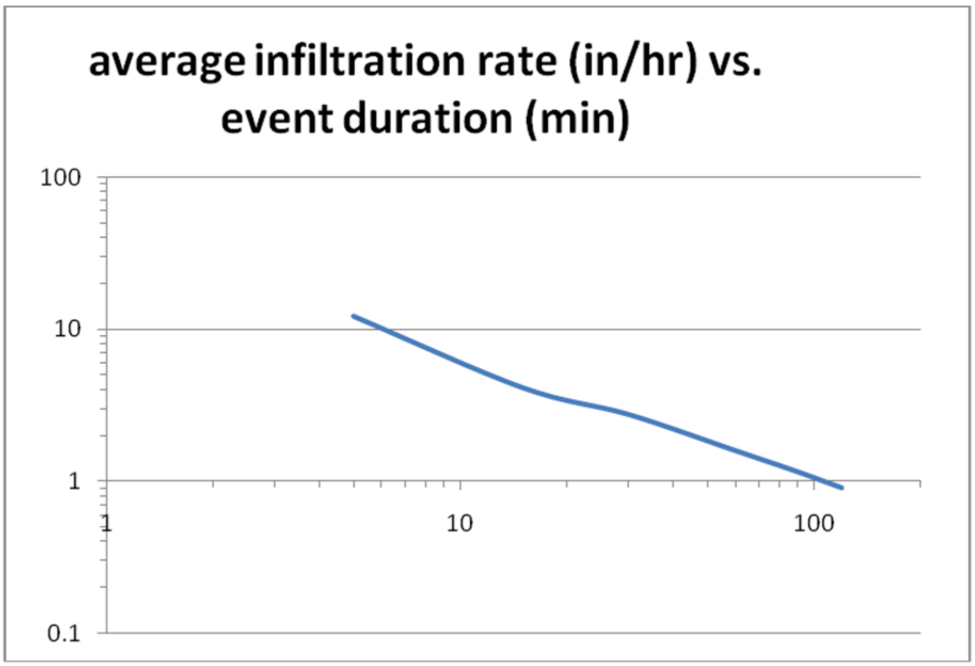
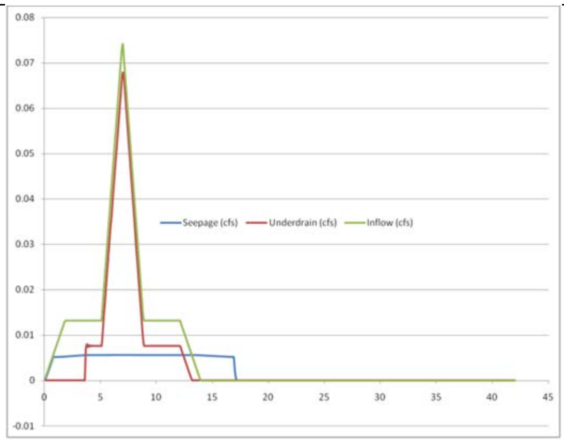


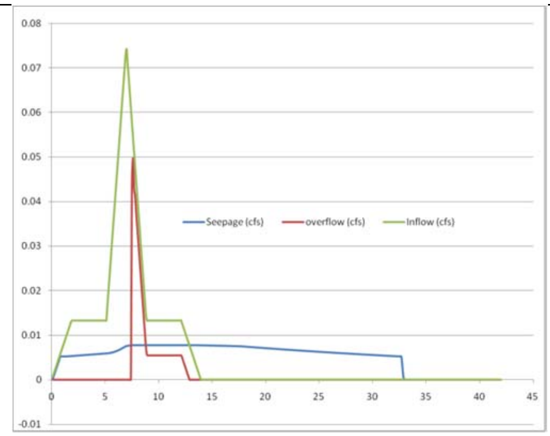
Figure 2. Measured infiltration rates in the test watershed.

Operation of the Biofilters

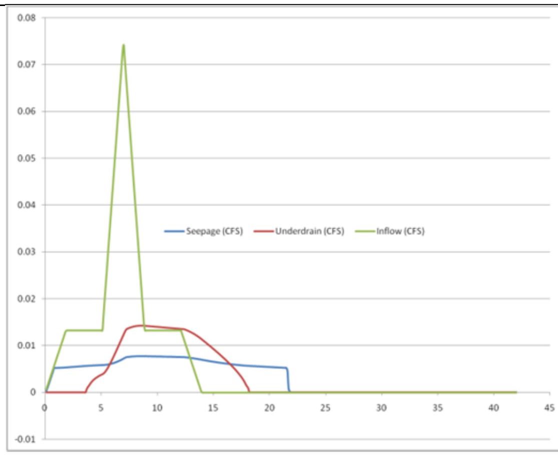
Another preliminary modeling activity being conducted is assisting in the design of the control practices. Figure 3 is an example showing the effects of a small bioretention facility and different underdrain options, for example. Depending on the objectives (peak flow reduction, infiltration, or filtering of the water), different options can be selected. Sizing the controls can also be evaluated using the model based on both short-term and long-term rain records for the area. We are currently investigating a modified underdrain material that may allow significant improvements in the performance of these biofiltration devices.



Conventional underdrain



No underdrain



Restricted underdrain

Example Biofilter Performance and Design using WinSLAMM

0.75 inch rain with complex inflow hydrograph from 1 acre of pavement. 2.2% of paved area is biofilter surface, with natural loam soil (0.5 in/hr infilt. rate) and 2 ft. of modified fill soil for water treatment and to protect groundwater.

Conventional underdrain allows significant short-circuiting and less infiltration and little peak flow attenuation.

Figure 3. Initial design evaluation of alternative bioretention facility designs.

The flow-moderating component of biofilters frequently fail as the usually used orifices are usually very small (<10 mm) and are prone to clogging. A series of tests are being conducted using a newly developed foundation drain material (SmartDrain™) that offers promise as a low flow control device with minimal clogging potential. SmartDrain™ operates using laminar flow conditions and is advertised as having minimal clogging potential by the fines in the stormwater. The smart drain has many micro channels in an 8 inch width. Pilot-scale biofilters, one being a trough 3m long and 0.6 x 0.6m in cross section is being used to test the variables affecting the drainage characteristics of the underdrain material (such as length, slope, hydraulic head, and type of sand media), while a second deeper pilot-scale biofilter is being used to verify performance for deeper water depths, and for clogging potential.

Five replicates for each of the five different lengths of the SmartDrain™ (2.9m, 2.2m, 1. 6m, 0.95m and 0.34m) were conducted to study the variables affecting the drainage characteristics of the material as a function of length, slope, and hydraulic head. Different slopes (0%, 3%, 6%, 9%, and 12%) were also examined. Flowrate measurements were manually taken from the effluent of the biofilter at 25 to 30 minute intervals until the water was completely drained from the trough.

Figure 4 is an example of the stage vs. flow rate relationship for the deep tank during the clogging tests. As in all of the tests, this relationship has a small intercept of stage reflecting the needed head to overcome the resistance in the drainage material. The slope term is the flow rate (L/sec) divided by the head (m). As indicated on Figure 5, this slope term is slowly decreasing with increased sediment load on the filter, but it is about 0.065 L/s per m of head for the one meter long drain for the 1m^2 surface area of the biofilter.

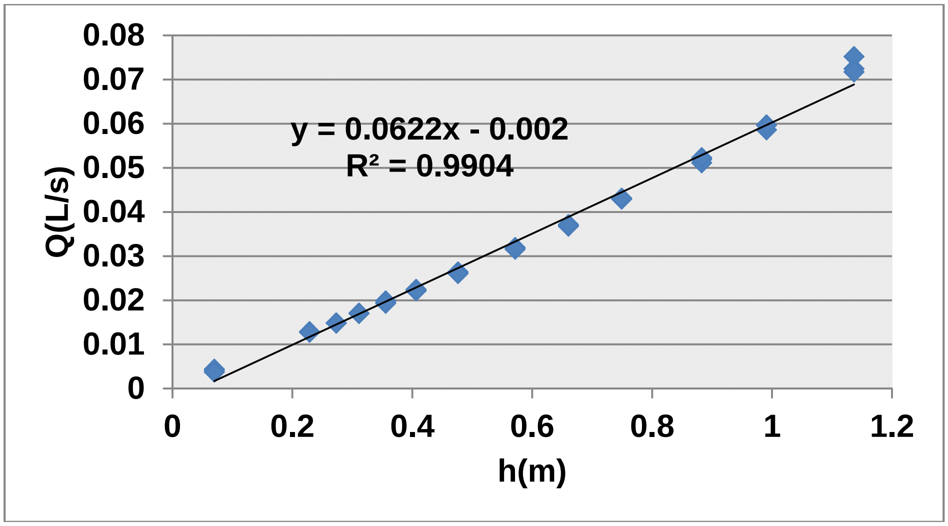


Figure 4. Example Flowrate vs. Head Relationship for Pilot-Scale Biofilter using SmartDrain™ (clogging trial 22)

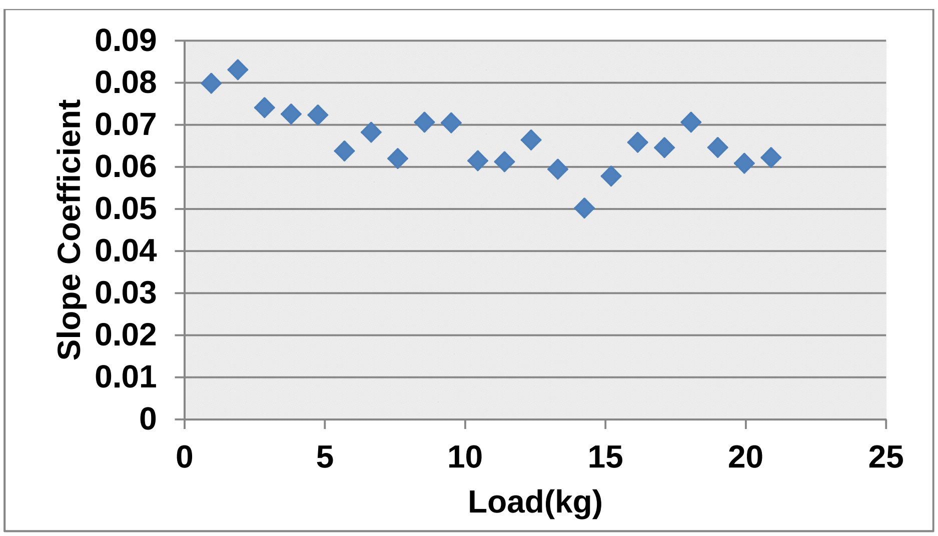


Figure 5. Unit Depth Flow Rate (L/s/m) vs. Sediment Loading on the Biofilter, using Sil-Co-Sil 250 (clogging trials 1 to 22)

Turbidity measurements of the effluent during the clogging tests are also being taken at 25 to 30 minute intervals at the same time as the flowrate measurements until the water completely drains from the tank. We have observed that turbidity (NTUs) decreases with the head of water in the tank (and effluent flow rate). The initial turbidity levels are about 1,000 NTU in the tank at the beginning of the test (and with similar effluent water turbidity at the beginning of the tests), but with significantly decreasing effluent turbidity values as the test progresses and the flow rate decreases (Figure 6).

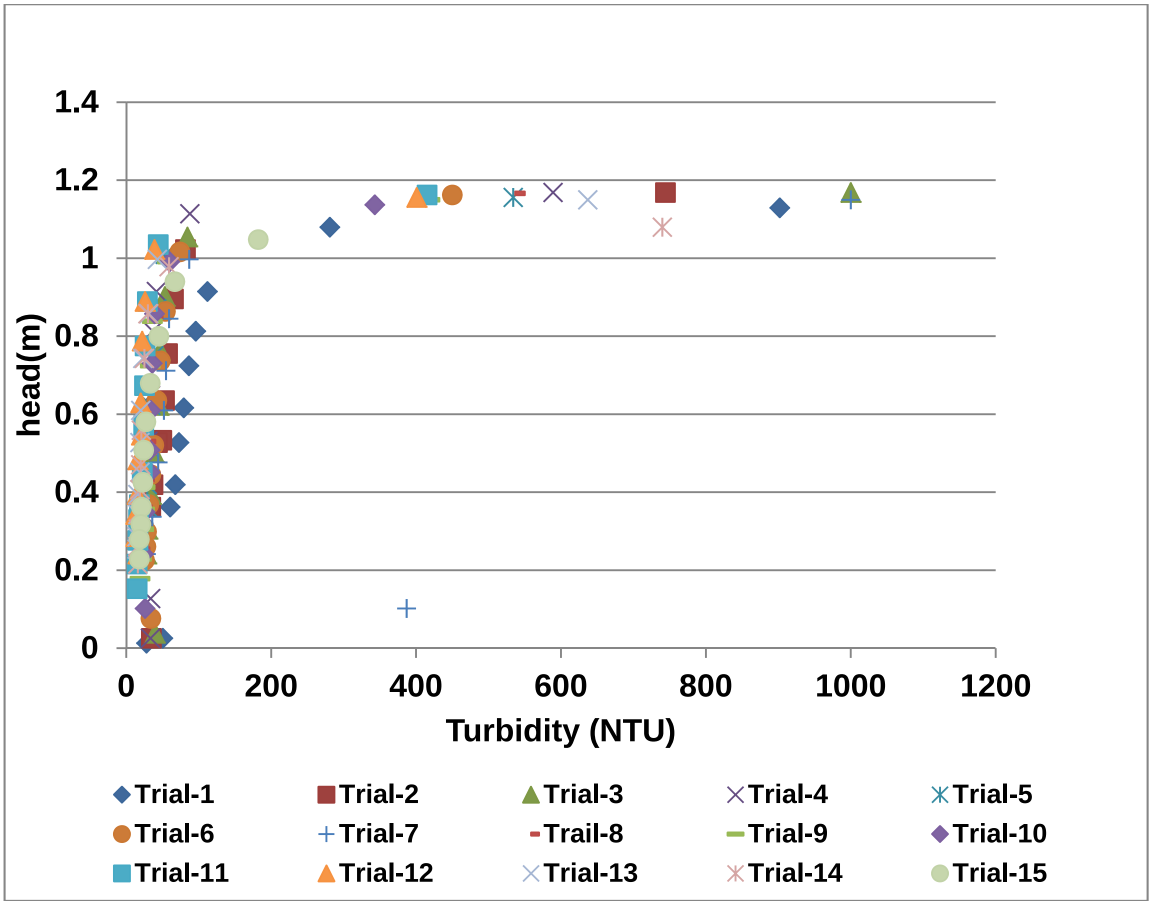


Figure 6. Effluent Turbidity Levels during Clogging Trials

A typical biofilter that is 1 m deep, 1.5 m wide and 5 m long would require about 8 hours to drain using the SmartDrain^{TM} material as the underdrain. This is a substantial residence time in the media to optimize contaminant removal and also provides significant retention of the stormwater before being discharged to a combined sewer system. In addition, this slow drainage time will allow infiltration into the native underlying soil, with minimal short-circuiting to the underdrain.

Economic Analysis using WinSLAMM

The economic analyses in WinSLAMM can be used to automatically calculate the capital, maintenance and operation, and financing costs for the stormwater control programs being examined. This information can be used with the model batch processor to develop cost-benefit curves for the different control options. The cost information is entered in the model using the set of forms as shown in Figure 7. Figure 8 shows the cities that currently have inflation data already in the model. Besides the unit cost rates that are already available, it is possible to enter more specific local cost data, based on site costs. Figure 9 is another plot that can be automatically created using WinSLAMM that illustrates flow-duration comparisons for each set of stormwater control being evaluated, compared to base conditions having no controls.

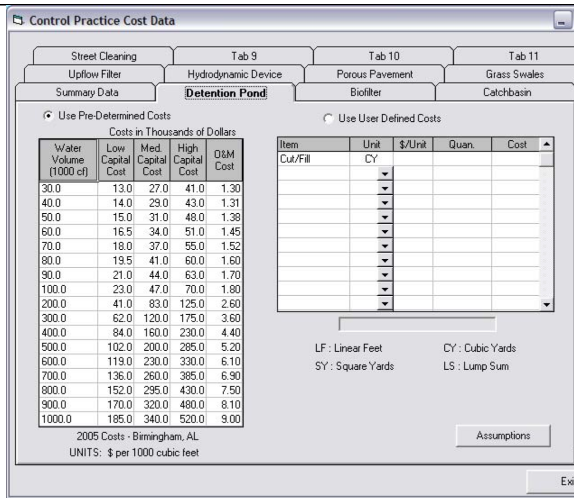


Figure 7. Basic economic analyses input screen

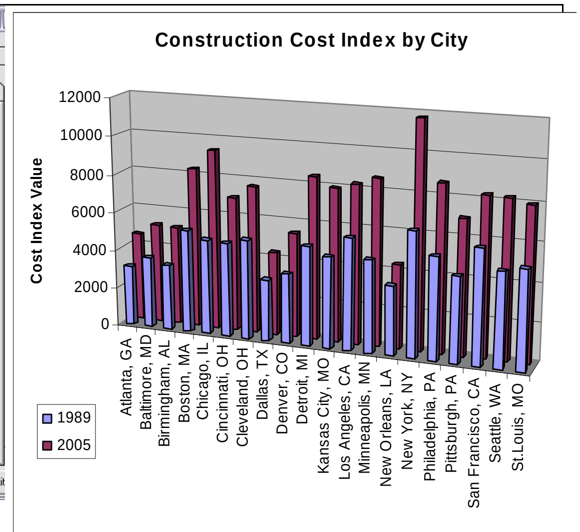


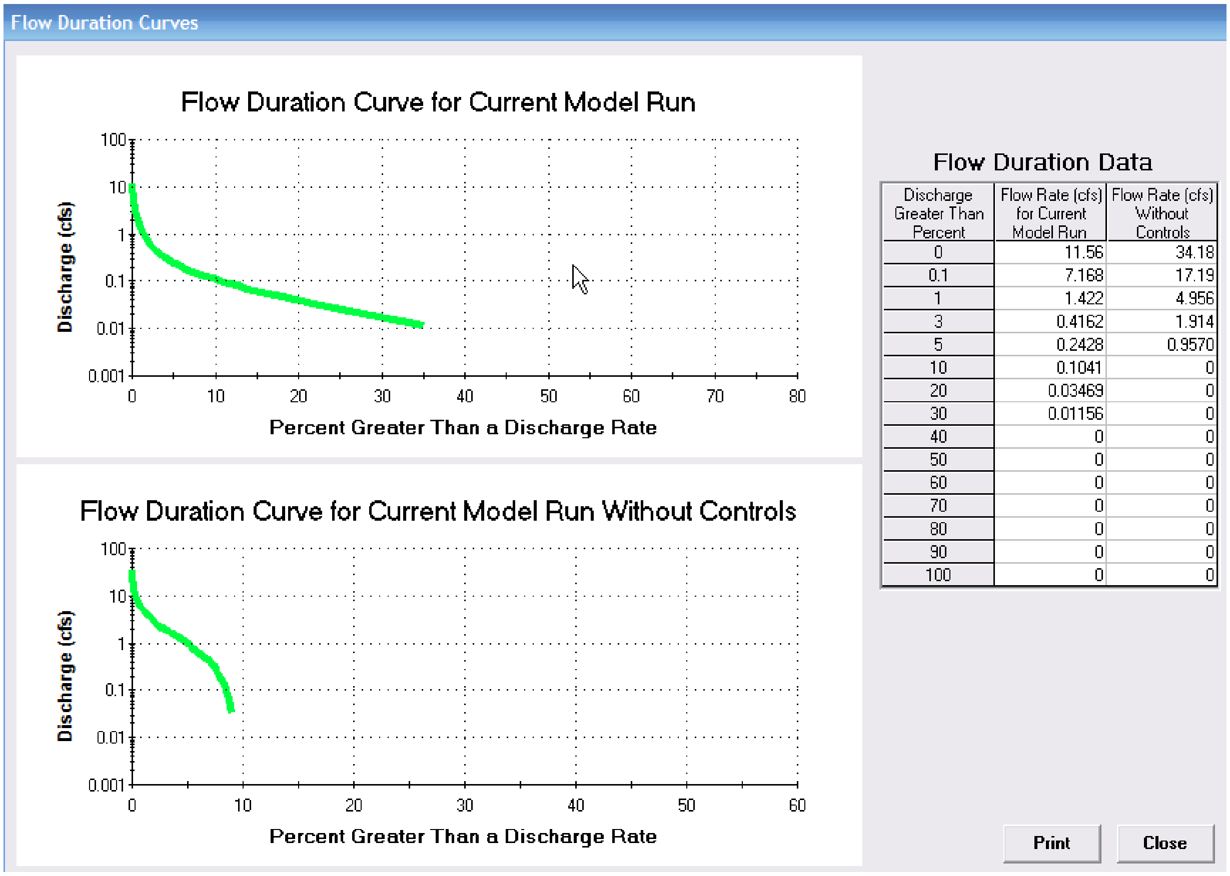
Figure 8. Different US cities currently included in economic model

Initial Evaluations of Simple Curb-Cut Rain Gardens and Large Cisterns

Table 1 lists the major land uses, and surface covers for the 100 acre test watershed in Kansas City. About 90% of the area is a single family low and medium density residential land use. About 40% is also comprised of impervious (mostly roofs, driveways, and roads).

Table 1. Major Land Uses and Surfaces in 100 Acre Test Watershed (ft^2)

Land Uses in Test Watershed	Major Surface Components					
	Roads	Driveways	Sidewalks	Roofs	Pervious Areas	Sum
Commercial (High)	80,300	41,900	8,400	5,800	25,600	162,000
Commercial (Low)	3,400	106,500	2,000	53,500	29,000	200,500
Residential MF Low-Med	15,300	4,600	2,200		17,990	40,500
Residential MF Low		5,400	70	8,000	39,200	53,000
Residential SF Medium	330,000	260,900	71,700	340,500	1,611,000	2,645,000
Residential SF Low	4,200	77,200	14,400	157,200	865,500	1,143,000
Residential SF Very Low	2,600	4,300		4,700	48,600	60,300
Sum	449,500	513,100	100,300	577,200	2,653,000	4,356,900



Discharge Greater Than Percent	Flow Rate (cfs) for Current Model Run	Flow Rate (cfs) Without Controls
0	11.56	34.18
0.1	7.168	17.19
1	1.422	4.956
3	0.4162	1.914
5	0.2428	0.9570
10	0.1041	0
20	0.03469	0
30	0.01156	0
40	0	0
50	0	0
60	0	0
70	0	0
80	0	0
90	0	0
100	0	0

Figure 9. Quick flow-duration plots automatically calculated by WinSLAMM

Initial analyses were conducted using WinSLAMM to estimate the amount of runoff from a typical rain year that would not be discharged to the combined sewer. The year 1990 was selected as a typical rain year, even though it had about 3 inches more rain than the long-term average (about 40 inches) because the distribution of events per month was much closer to the average distribution than the few years that had annual rain depth totals closer to the average conditions.

The example described below was for the medium density single family residential area and examined simple curb-cut rain gardens and large cisterns, both individually and in combination. The curb-cut rain gardens were assumed to be simple excavations 20 ft long and 5 ft wide, located in the terrace between the sidewalk and the street. Their depth was limited to 1 ft maximum to minimize 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. The native soil is assumed to be a silty-loam with a typical infiltration rate of about 0.3 in/hr. 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. The water tank cisterns were sized to be about 10 ft in diameter and 5 ft tall. It is assumed that up to about 600 cisterns could be used in the 100 acre test watershed. The assumed monthly water use from these cisterns for toilet flushing and outside irrigation per household is shown in Table 2.

Table 2. Maximum per Household Water Use (gallons/day) from Cisterns for Toilet Flushing and Outside Irrigation

January	300	April	1000	July	2500	October	300
February	300	May	1500	August	1000	November	300
March	500	June	1500	September	1000	December	300

As noted before, WinSLAMM conducts a continuous water mass balance for every storm in the study period, and the overall performance of the combination of controls is based on their actual designs and uses. As an example, Figure 10 shows the general input screen for biofiltration devices. This same screen is used to describe water tanks/cisterns and smaller rain barrels.

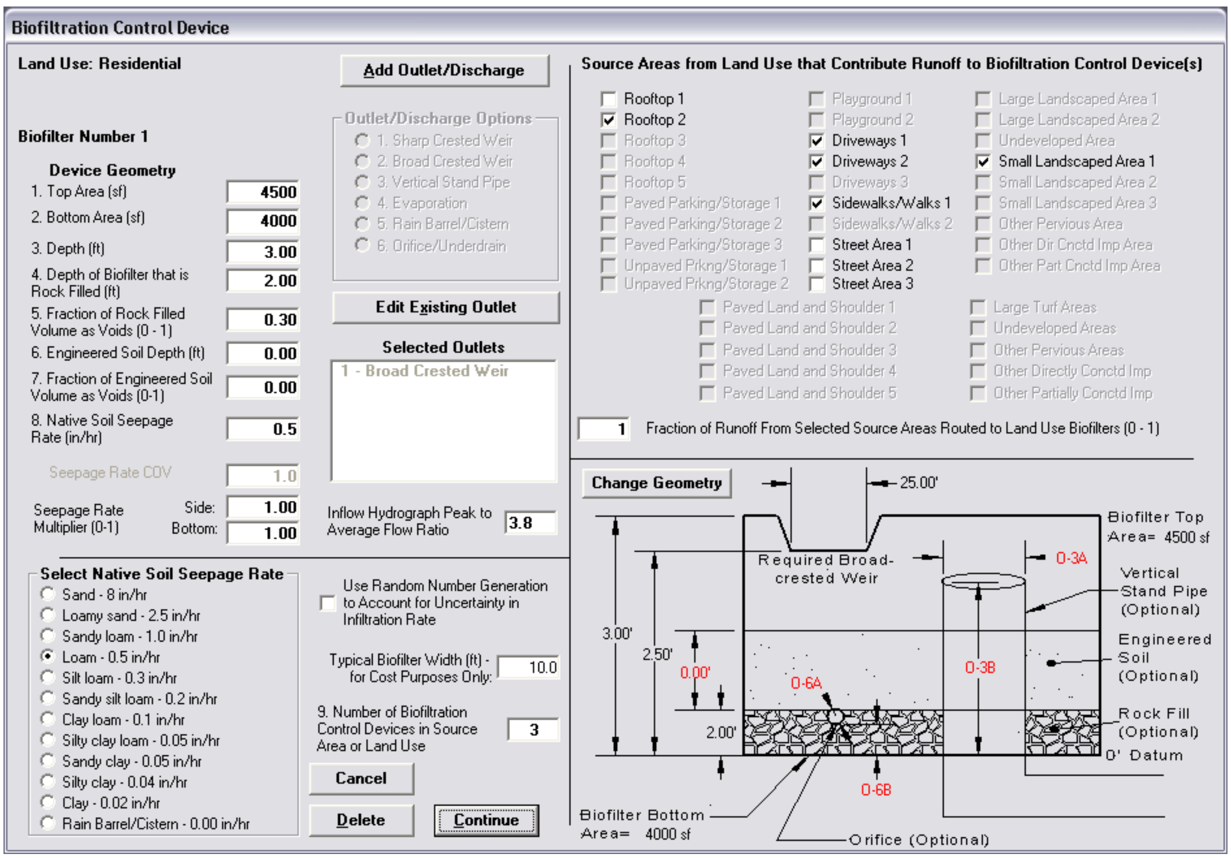


Figure 10. Bioretention input screen for WinSLAMM

Figure 11 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. 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 12 plots some preliminary cost estimates for these devices (this cost estimate does not consider aesthetic landscaping, but only basic excavation and simple curb cuts). The basic total capital cost for these devices is expected to be about $1,000 each, and the annualized total cost to be about $150 each. Again, the actual costs are likely to be greater due to the planting and plant maintenance, and the cost component will be calibrated using local data. Figure 13 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 also likely to reduce the peak flow rates that occur about 5 to 10 hours a year to about half of the flow rates that would occur if un-controlled.

Figure 14 is a plot of the annual roof runoff removals that would occur for different numbers of large cisterns in the area. The maximum control that is expected is about 35%, as that is the fraction of the annual flow that is expected to originate from the roofs. This level of control would occur with about 200 large cisterns in the 100 acre area. Very small rain barrels would have very little benefit in reducing the annual discharges to the combined sewer.

Table 3 shows the expected level of control for various combinations of large cisterns and curb-cut rain gardens. The largest level of control expected is about 90% of the annual runoff, but that would require a maximum application of these controls. However, levels of runoff reduction of about 75% may be achieved with a more reasonable effort (about 500 rain gardens and 250 cisterns, or 1,000 rain gardens and 50 cisterns). The expected cost of this high level of control is likely to be more than $1million for the 100 acres. Controls established at the time of development can be much less, and in many cases can be less than conventional development options.

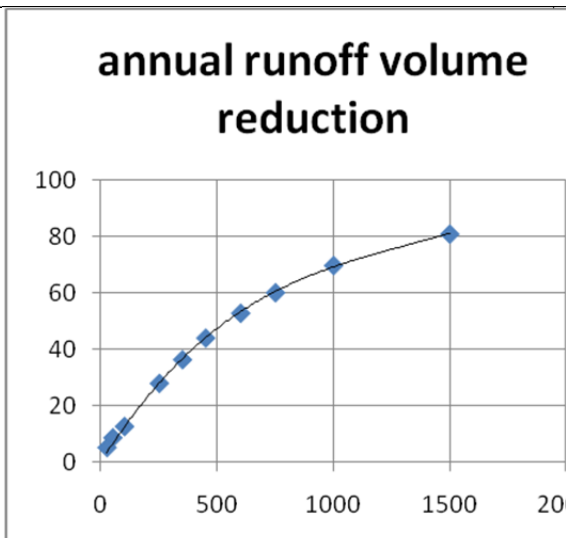


Figure 11. Annual runoff volume reduction (%) for typical rain year (1990) for different numbers of simple curb-cut rain gardens per 100 acre watershed.

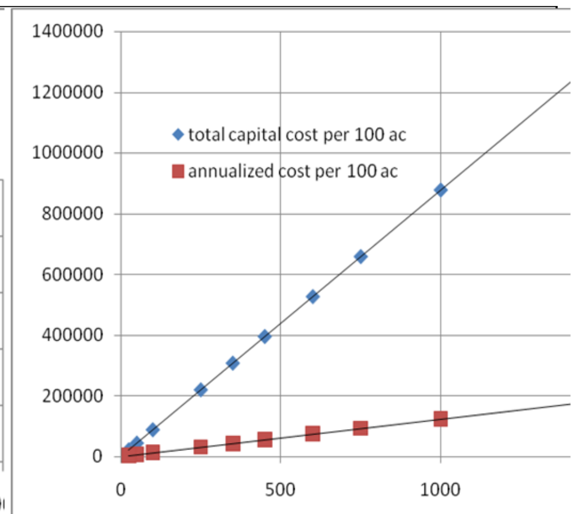


Figure 12. Total capital costs and total annualized costs for different numbers of simple curb-cut rain gardens per 100 acre watershed.

Table 3. Approximate Annual Flow Reductions for Combinations of Large Cisterns and Simple Curb-Cut Rain Gardens, per 100 acres.

	0 rain gardens	100 rain gardens	500 rain gardens	1000 rain gardens	1500 rain gardens
0 cisterns	0	12	47	70	81
25 cisterns	12	23	52	73	82
50 cisterns	20	32	58	76	83
100 cisterns	29	40	66	80	85
250 cisterns	36	47	73	86	90
600 cisterns	37	48	74	87	91

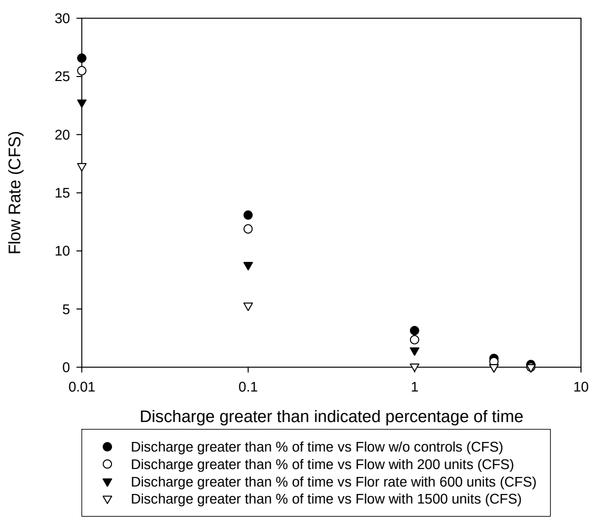


Figure 13. Durations of flows (% of time) for different numbers of simple curb-cut rain gardens.

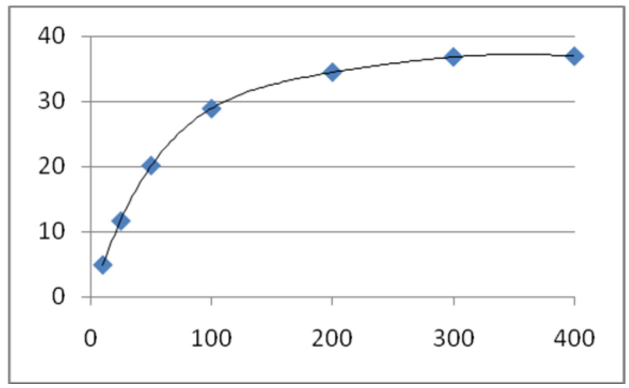


Figure 14. Percentage reduction of annual flows with 10ft diameter X 5 ft tall cisterns (numbers per 100 acres)

Conclusions

The on-going Kansas City demonstration project is showing how retrofitted “green infrastructure” components can be used in an existing area drained by combined sewers to reduce the volumes and frequencies of overflows. 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 biofiltration controls has been shown to be promising in meeting the CSO control requirements, with less cost, while providing needed community benefits. This demonstration project, funded by the EPA, will quantify these benefits through extensive monitoring in the test and adjacent control watersheds. Initial modeling is being conducted in conjunction with the design efforts to illustrate the levels of control that can be achieved, as shown in Figure

15. 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.

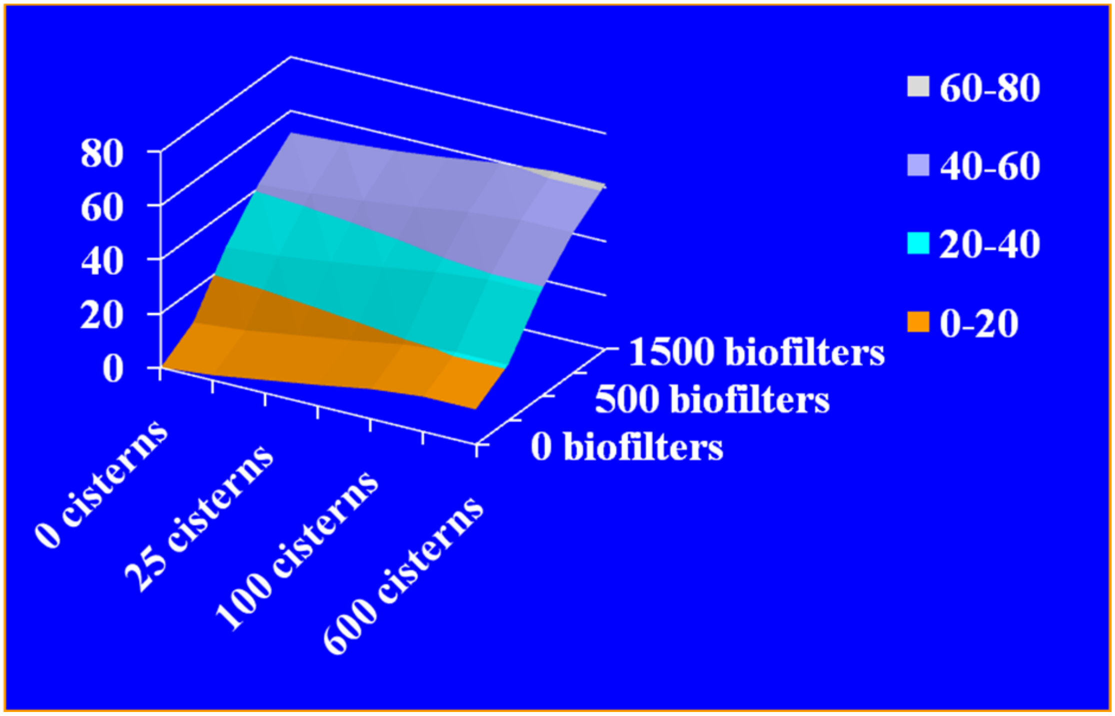


Figure 15. Infiltration benefits (% of annual runoff volume reduced) from combinations of biofilters and cisterns in 100 acre test watershed.