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Green Infrastructure Performance Modeling with WinSLAMM

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Abstract

The Kansas City demonstration project team will use existing and additional data to make predictions of before and after green infrastructure implementation. Applications of these tools can help better understand sources of urban runoff pollutants and their control, placement for maximum treatment benefit, and optimization based on potential cost savings. The main models that will be used for the project are WinSLAMM and the Storm Water Management Model (SWMM). The reduction of discharges to the drainage system during wet weather will be calculated and considered in the combined sewage flows. The models will determine the decreased amount of stormwater discharged for each event as the storage and infiltration facilities dynamically fill and drain.

Introduction

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

Preliminary Analyses

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, but field surveys are still being conducted to verify the drainage pattern for each impervious element in the test and control watersheds.

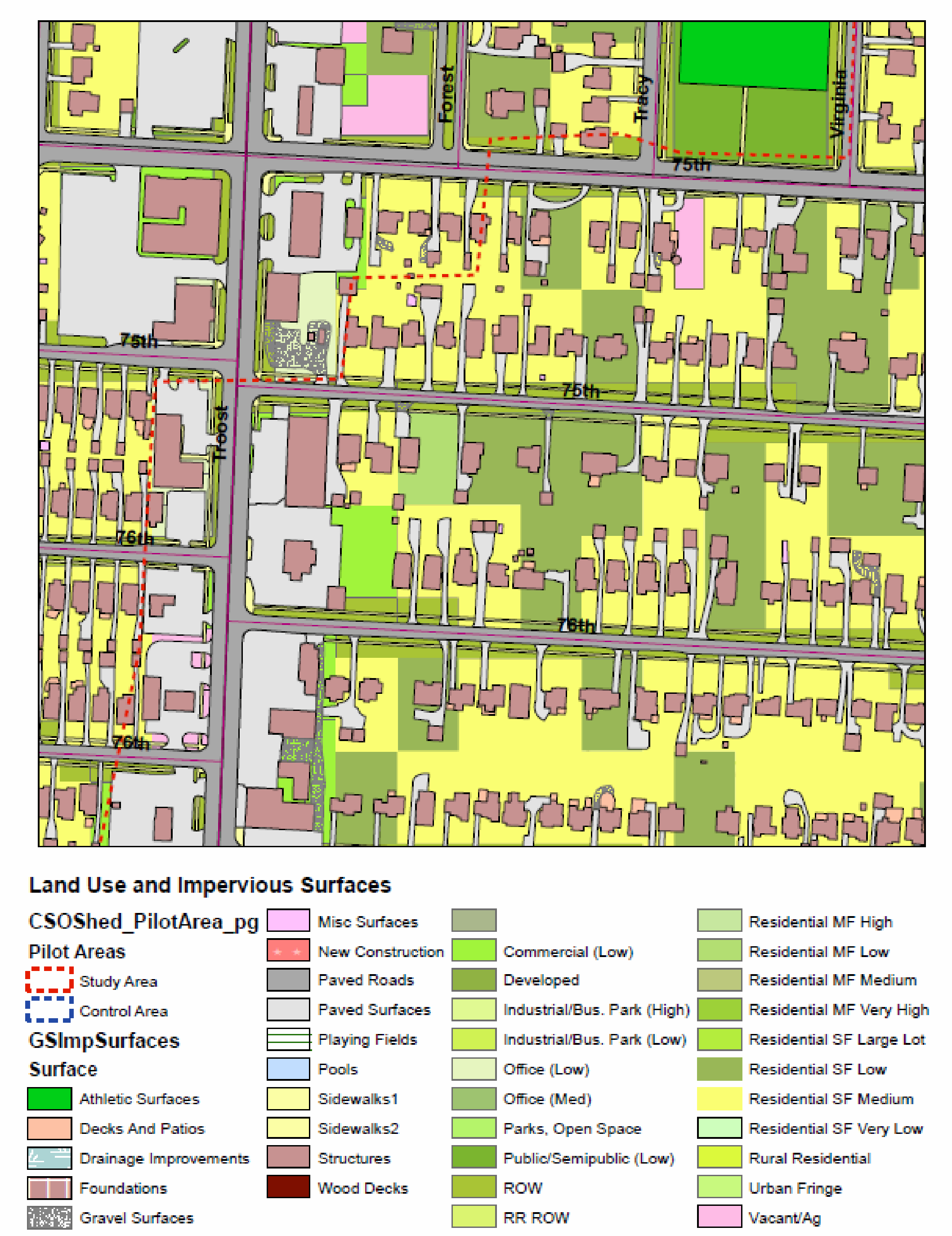
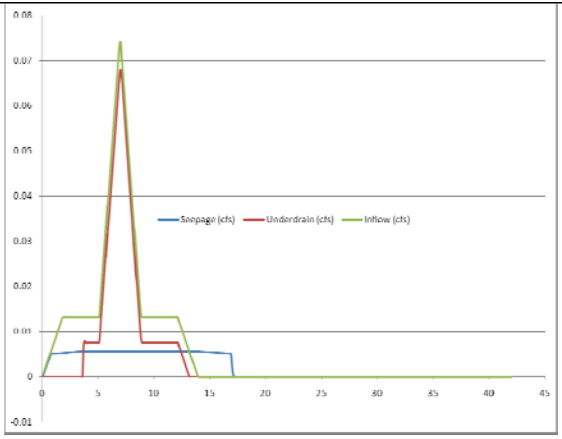
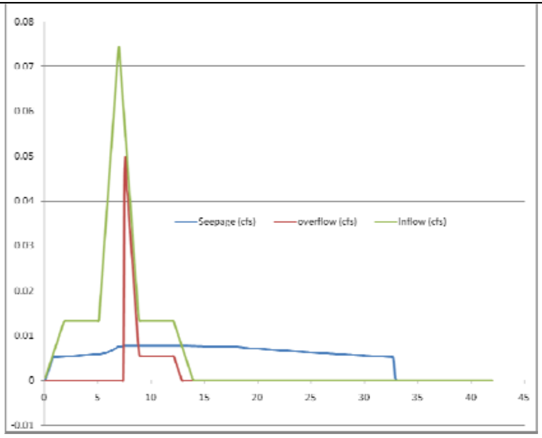


Figure 1. Detailed GIS coverage showing land cover components of different land uses in the Kansas City test watershed.

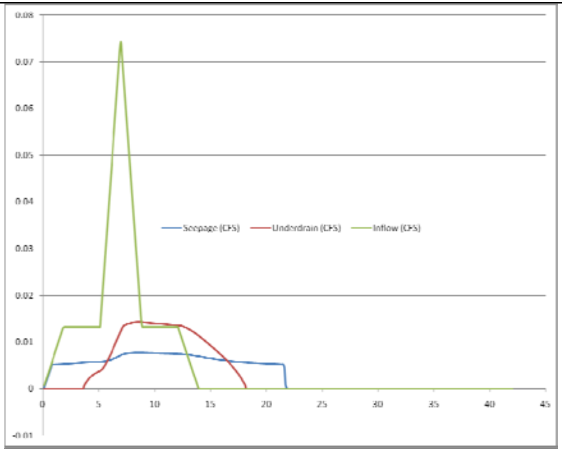
Land use files are being prepared using the GIS and field data and preliminary performance calculations are being made. Another preliminary modeling activity being conducted is assisting in the design of the control practices. Figure 2 is an example showing the effects of a small bioretention facility 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 of the controls can also be evaluated using the model based on both short-term and long-term rain records for the area.



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 2. Preliminary design evaluation of alternative bioretention facility designs.

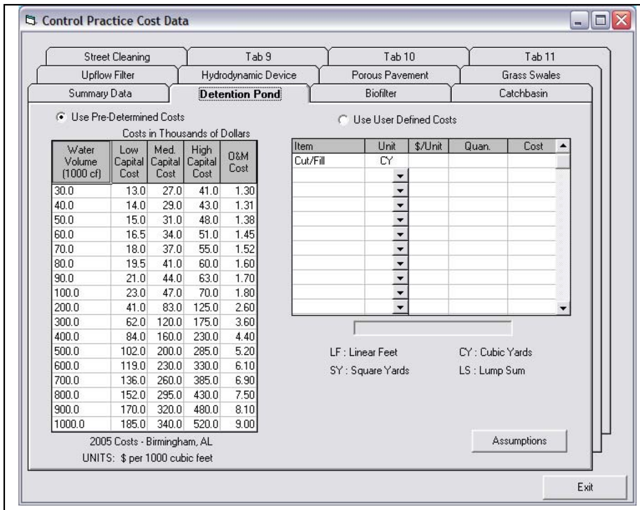
WinSLAMM and SWMM Interface Program

The purpose of the WinSLAMM-SWMM Interface Program (SSIP) is to allow the user to replace SWMM's RUNOFF Block (version 4) with SLAMM. This allows SLAMM to provide the runoff and pollutant loads for input into the TRANSPORT or EXTRAN Blocks of SWMM, instead of using results from the RUNOFF Block. Using SLAMM better accounts for small storm processes and adds greater flexibility in evaluating source area flow and pollutant controls. The interface program manipulates the output from SLAMM so that it is acceptable for SWMM. The principal manipulation is to convert the event volumes and loads into event hydrographs and pollutographs.

The current version of the WinSLAMM-SWMM Interface Program is Version 1. 1 and was developed before the current Windows version of SWMM (version 5) was available. This Kansas City demonstration project will update this interface program to function with the SWMM version used in Kansas City. An early version of the SLAMM-SWMM Integration Program was developed to work with SWMM Windows provided by the US Environmental Protection Agency (based on SWMM Version 4.3, USEPA, 1995). This was used to create SSIP Version 1.1, which is designed for use with all SWMM 4 sub-versions. SSIP Version 1.1 takes hydrographs and pollutographs from WinSLAMM and partially prepares input hydrographs for use in the SWMM EXTRAN Block and input hydrographs and pollutographs for the SWMM TRANSPORT Block. WinSLAMM currently has the option of producing source area hydrographs and pollutographs over long continuous periods.

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 3. Figure 4 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 5 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.



● Use Pre-Determined Costs

○ Use User Defined Costs

Costs in Thousands of Dollars

Water Volume (1000 cf)	Low Capital Cost	Med. Capital Cost	High Capital Cost	O&M Cost
30.0	13.0	27.0	41.0	1.30
40.0	14.0	29.0	43.0	1.31
50.0	15.0	31.0	48.0	1.38
60.0	16.5	34.0	51.0	1.45
70.0	18.0	37.0	55.0	1.52
80.0	19.5	41.0	60.0	1.60
90.0	21.0	44.0	63.0	1.70
100.0	23.0	47.0	70.0	1.80
200.0	41.0	83.0	125.0	2.60
300.0	62.0	120.0	175.0	3.60
400.0	84.0	160.0	230.0	4.40
500.0	102.0	200.0	285.0	5.20
600.0	119.0	230.0	330.0	6.10
700.0	136.0	260.0	385.0	6.90
800.0	152.0	295.0	430.0	7.50
900.0	170.0	320.0	480.0	8.10
1000.0	185.0	340.0	520.0	9.00

2005 Costs - Birmingham, AL
UNITS: $ per 1000 cubic feet

Item	Unit	$/Unit	Quan.	Cost
Cut/Fill	CY			

LF : Linear Feet
CY : Cubic Yards
SY : Square Yards
LS : Lump Sum

Figure 3. Basic economic analyses input screen

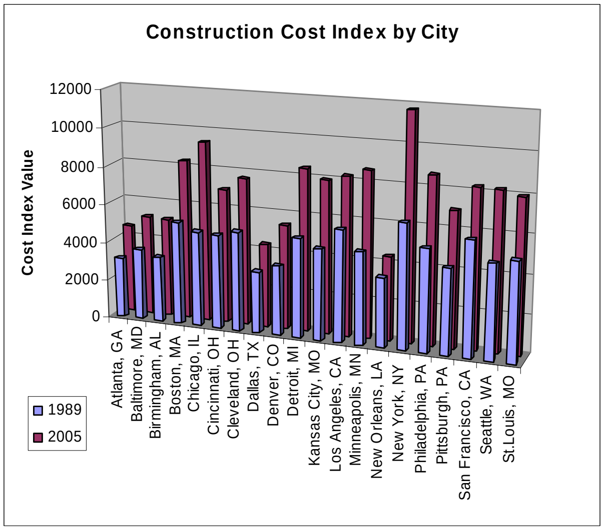


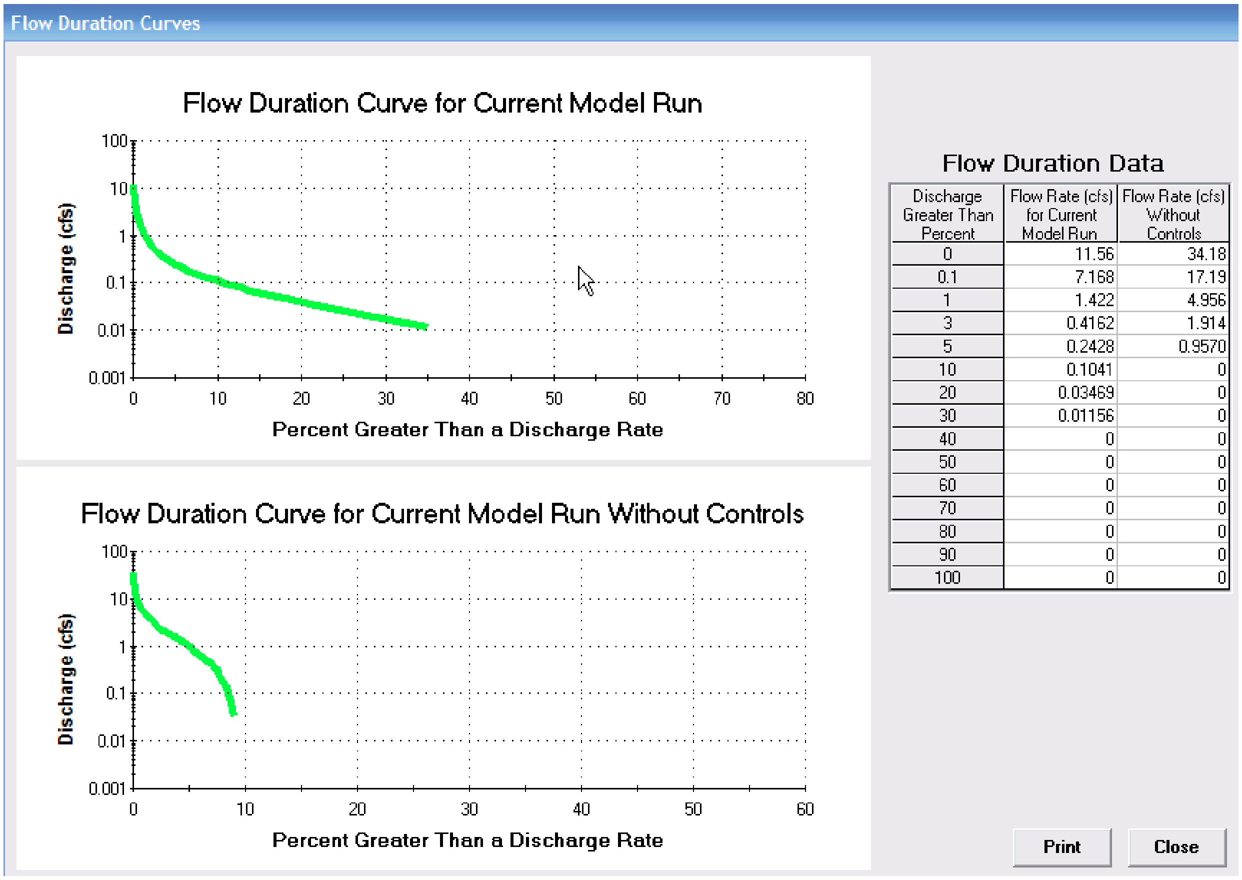
Figure 4. Different US cities currently included in economic model

Preliminary 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



Flow Duration Data

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 5. Quick flow-duration plots automatically calculated by WinSLAMM

Preliminary 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.

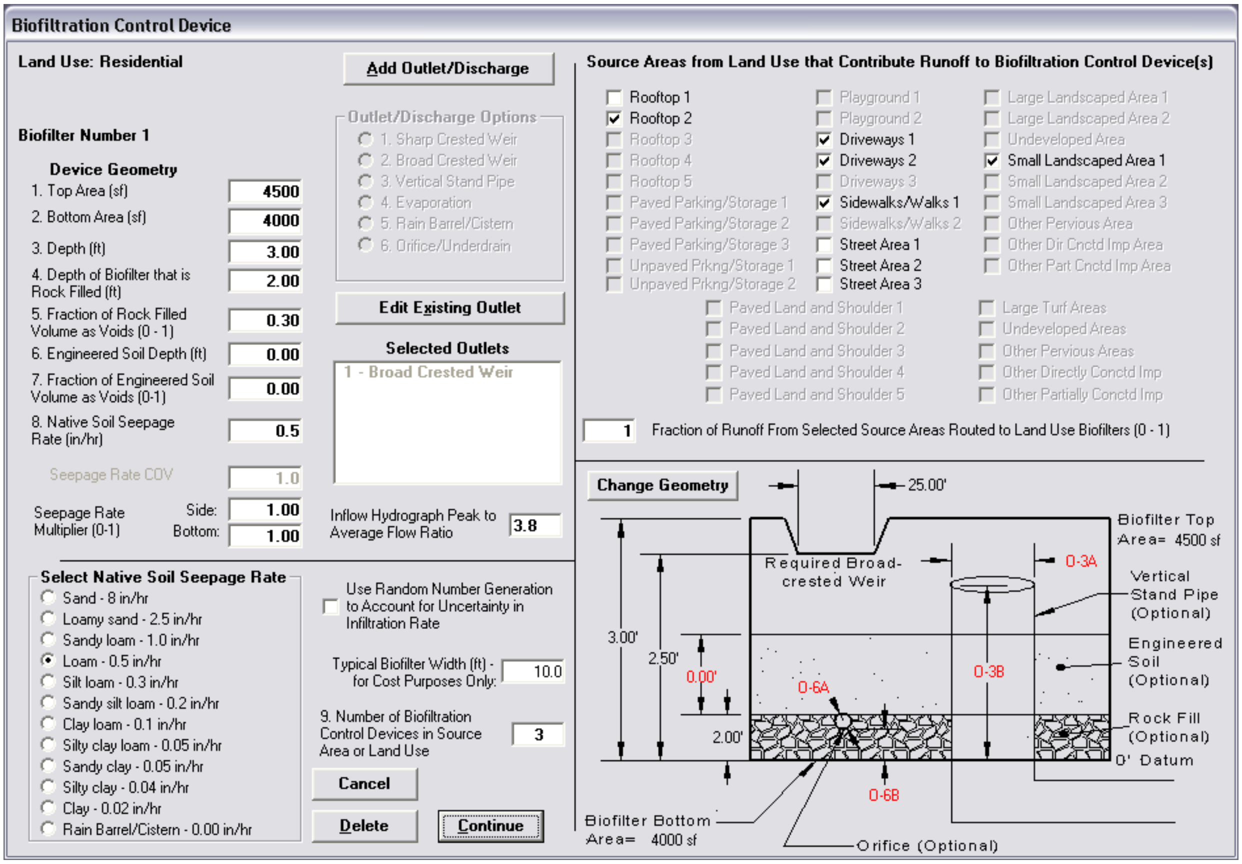
This example was for the medium density single family residential area and examined simple curb-cut rain gardens and large cisterns, both individually and in combination. The curb-cut rain gardens were assumed to be simple excavations 20 ft long and 5 ft wide, located in the terrace between the sidewalk 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

WinSLAMM conducts a continuous water mass balance for every storm in the study period. For the water tank cisterns, the model fills the tanks during rains (up to the maximum amount of runoff designated to be directed to the tanks, from the roofs in this case, or to the maximum available volume of the tank). 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 was available to drain the tank), excess water from the event would be discharged to the drainage system after the tank fills. The 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 (they have ¾ ft of storage above the natural soils), the excessive water is discharged into the combined sewer. 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.

Figure 6 shows the general input screen for biofiltration devices. This same screen is used to describe water tanks/cisterns and smaller rain barrels.



Biofiltration Control Device

Land Use: Residential

Biofilter Number 1

Device Geometry

1. Top Area (sf) 4500
2. Bottom Area (sf) 4000
3. Depth (ft) 3.00
4. Depth of Biofilter that is Rock Filled (ft) 2.00
5. Fraction of Rock Filled Volume as Voids (0 - 1) 0.30
6. Engineered Soil Depth (ft) 0.00
7. Fraction of Engineered Soil Volume as Voids (0-1) 0.00
8. Native Soil Seepage Rate (in/hr) 0.5

Seepage Rate COV 1.0

Seepage Rate Multiplier (0-1) Side: 1.00 Bottom: 1.00

Select Native Soil Seepage Rate

- ○ Sand - 8 in/hr
- ○ Loamy sand - 2.5 in/hr
- ○ Sandy loam - 1.0 in/hr
- ● Loam - 0.5 in/hr
- ○ Silt loam - 0.3 in/hr
- ○ Sandy silt loam - 0.2 in/hr
- ○ Clay loam - 0.1 in/hr
- ○ Silty clay loam - 0.05 in/hr
- ○ Sandy clay - 0.05 in/hr
- ○ Silty clay - 0.04 in/hr
- ○ Clay - 0.02 in/hr
- ○ Rain Barrel/Cistern - 0.00 in/hr

Outlet/Discharge Options

- ○ 1. Sharp Crested Weir
- ○ 2. Broad Crested Weir
- ○ 3. Vertical Stand Pipe
- ○ 4. Evaporation
- ○ 5. Rain Barrel/Cistern
- ○ 6. Orifice/Underdrain

Selected Outlets

1 - Broad Crested Weir

Inflow Hydrograph Peak to Average Flow Ratio 3.8

☐ Use Random Number Generation to Account for Uncertainty in Infiltration Rate

Typical Biofilter Width (ft) - for Cost Purposes Only: 10.0

9. Number of Biofiltration Control Devices in Source Area or Land Use 3

Source Areas from Land Use that Contribute Runoff to Biofiltration Control Device(s)

- ☐ Rooftop 1
- ☑ Rooftop 2
- ☐ Rooftop 3
- ☐ Rooftop 4
- ☐ Rooftop 5
- ☐ Paved Parking/Storage 1
- ☐ Paved Parking/Storage 2
- ☐ Paved Parking/Storage 3
- ☐ Unpaved Prkng/Storage 1
- ☐ Unpaved Prkng/Storage 2
- ☐ Playground 1
- ☐ Playground 2
- ☑ Driveways 1
- ☑ Driveways 2
- ☐ Driveways 3
- ☑ Sidewalks/Walks 1
- ☐ Sidewalks/Walks 2
- ☐ Street Area 1
- ☐ Street Area 2
- ☐ Street Area 3
- ☐ Large Landscaped Area 1
- ☐ Large Landscaped Area 2
- ☐ Undeveloped Area
- ☑ Small Landscaped Area 1
- ☐ Small Landscaped Area 2
- ☐ Small Landscaped Area 3
- ☐ Other Pervious Area
- ☐ Other Dir Cnctd Imp Area
- ☐ Other Part Cnctd Imp Area
- ☐ Paved Land and Shoulder 1
- ☐ Paved Land and Shoulder 2
- ☐ Paved Land and Shoulder 3
- ☐ Paved Land and Shoulder 4
- ☐ Paved Land and Shoulder 5
- ☐ Large Turf Areas
- ☐ Undeveloped Areas
- ☐ Other Pervious Areas
- ☐ Other Directly Conctd Imp
- ☐ Other Partially Conctd Imp

1 Fraction of Runoff From Selected Source Areas Routed to Land Use Biofilters (0 - 1)

Figure 6. Bioretention input screen for WinSLAMM

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. 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 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. 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 10 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 expected 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.

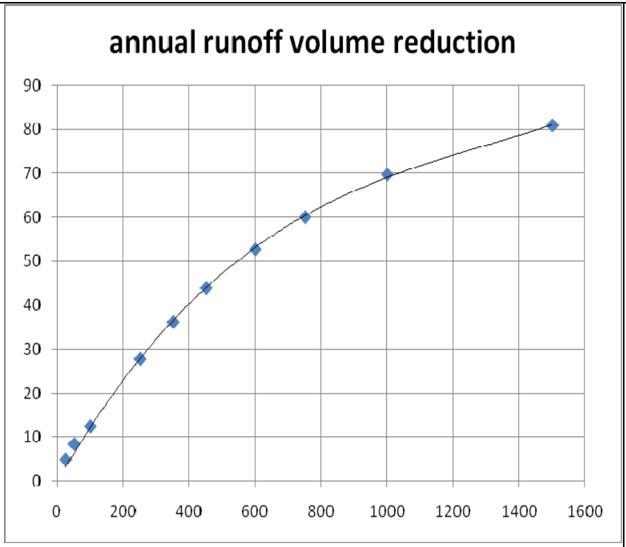


Figure 7. Annual runoff volume reduction (%) for typical rain year (1990) for different numbers of simple curb-cut rain gardens per 100 acre watershed.

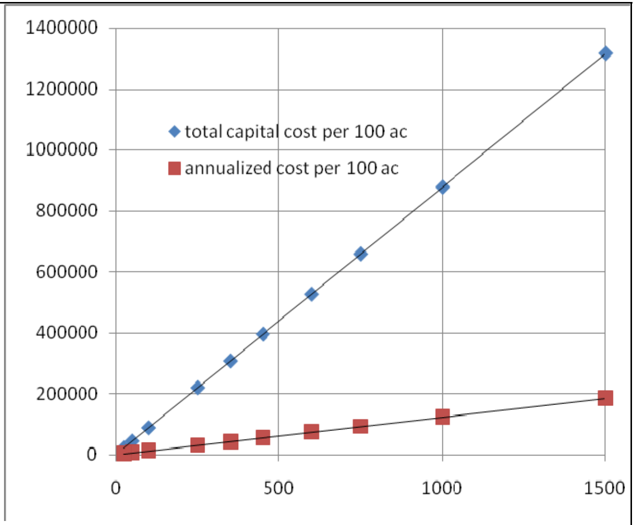


Figure 8. Total capital costs and total annualized costs for different numbers of simple curb-cut rain gardens per 100 acre watershed.

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

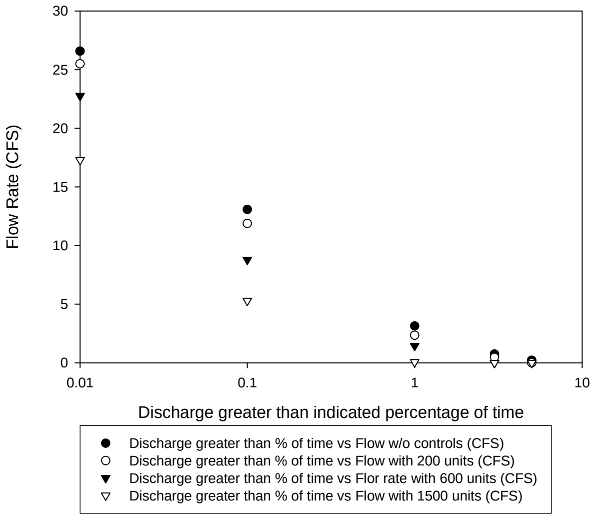


Figure 9. Durations of flows (% of time) for different numbers of simple curb-cut rain gardens.

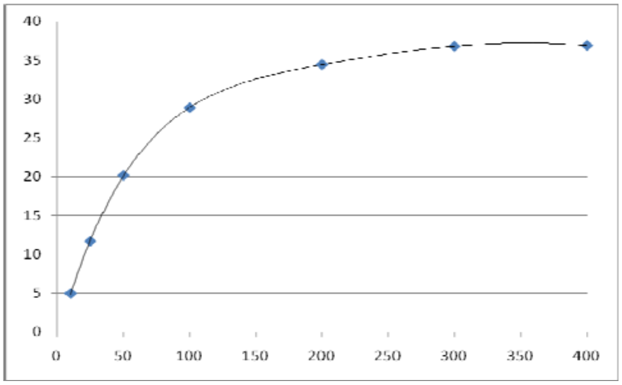


Figure 10. Percentage reduction of annual flows with 10ft diameter X 5 ft tall cisterns (numbers per 100 acres)

References Describing WinSLAMM Processes

Avila, H., R. Pitt, and S.R. Durrans. “Factors affecting scour of previously captured sediment from stormwater catchbasin sumps.” In: *Stormwater and Urban Water Systems Modeling*, Monograph 16. (edited by W. James, E.A. McBean, R.E. Pitt and S.J. Wright). CHI. Guelph, Ontario, pp. 197 – 218. 2008.

Bochis, C., R. Pitt, and P. Johnson. “Land development characteristics in Jefferson County, Alabama.” In: *Stormwater and Urban Water Systems Modeling*, Monograph 16. (edited by W. James, E.A. McBean, R.E. Pitt and S.J. Wright). CHI. Guelph, Ontario, pp. 249 – 282. 2008.

Pitt, R. and J. Voorhees. “Using decision analyses to select an urban runoff control program” Chapter 4 in: *Contemporary Modeling of Urban Water Systems*, ISBN 0-9736716-3-7, Monograph 15. (edited by W. James, E.A. McBean, R.E. Pitt, and S.J. Wright). CHI. Guelph, Ontario. pp 71 – 107. 2007.

Pitt, R. J. Voorhees, and S. Clark. “Evapotranspiration and related calculations for stormwater biofiltration devices: Proposed calculation scenario and data.” In: *Stormwater and Urban Water Systems Modeling*, Monograph 16. (edited by W. James, E.A. McBean, R.E. Pitt and S.J. Wright). CHI. Guelph, Ontario, pp. 309 – 340. 2008.

Pitt, R., D. Williamson, and J. Voorhees. “Review of historical street dust and dirt accumulation and washoff data.” *Effective Modeling of Urban Water Systems*, Monograph 13. (edited by W. James, K.N. Irvine, E.A. McBean, and R.E. Pitt). CHI. Guelph, Ontario, pp 203 – 246. 2005.

Pitt, R., R. Bannerman, S. Clark, and D. Williamson. “Sources of pollutants in urban areas (Part 1) – Older monitoring projects.” In: *Effective Modeling of Urban Water Systems*, Monograph 13. (edited by W. James, K.N. Irvine, E.A. McBean, and R.E. Pitt). CHI. Guelph, Ontario, pp. 465 – 484 and 507 – 530. 2005.

Pitt, R., R. Bannerman, S. Clark, and D. Williamson. "Sources of pollutants in urban areas (Part 2) – Recent sheetflow monitoring results." In: *Effective Modeling of Urban Water Systems*, Monograph 13. (edited by W. James, K.N. Irvine, E.A. McBean, and R.E. Pitt). CHI. Guelph, Ontario, pp. 485 – 530. 2005.

Pitt, R., S.-E. Chen, S.E. Clark, J. Lantrip, C.K. Ong. "Compaction's impacts on urban stormwater infiltration." *Journal of Irrigation and Drainage Engineering*. Vol. 134, no. 5, pp. 652-658. October 2008.

Pitt, R., S.E. Clark. "Integrated stormwater management for watershed sustainability." *Journal of Irrigation and Drainage Engineering*. Vol. 134, no. 5, pp. 548-555. October 2008.

Pitt, R., Y. Nara, J. Kirby, and S.R. Durrans. "Particulate transport in grass swales." in: *Low Impact Development; New and Continuing Applications*. ISBN 978-0-7844-1007-3. Edited by Michael Clar. ASCE, Reston, VA. pp. 191 – 204. 2009.