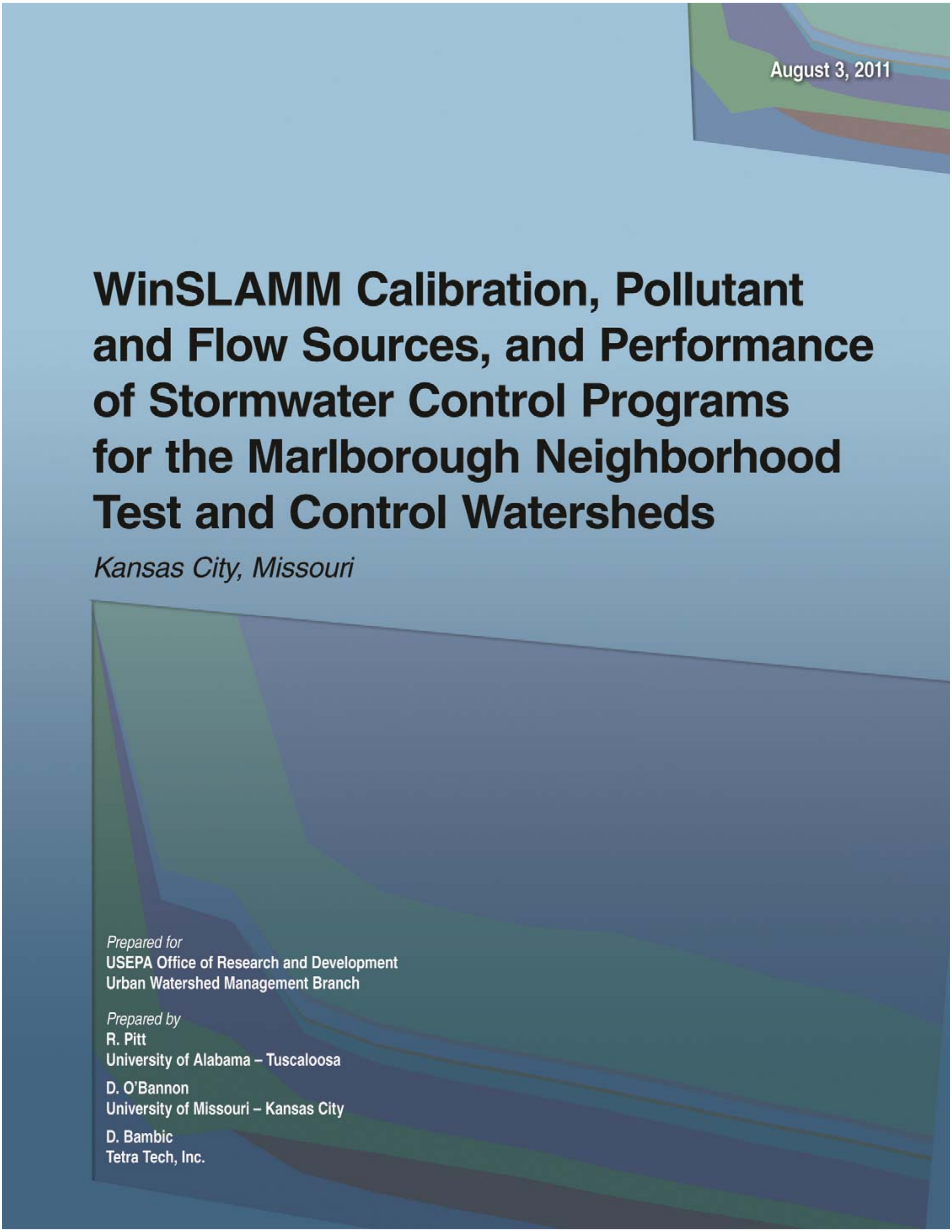

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WinSLAMM Calibration, Pollutant and Flow Sources, and Performance of Stormwater Control Programs for the Marlborough Neighborhood Test and Control Watersheds

Kansas City, Missouri

Prepared for
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1 Introduction

This report describes the WinSLAMM modeling activities carried out to support the green infrastructure (GI) demonstration project in the Marlborough area of Kansas City.

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 will enable direct measurements of the benefits of the GI options. Besides the large-scale monitoring, individual controls will also be monitored to quantify their performance under a variety of runoff conditions. The stormwater management controls in the demonstration area drain to the municipal combined sewer drainage system in the Middle Blue River watershed. The drainage pattern allowed isolation of the benefits of the GI stormwater controls with no flows coming from outside areas. The watershed model (WinSLAMM) and the sewerage model (SWMM) have been calibrated for this area using the pre-construction flow and water quality data. The calibrated models have been used to predict the benefits of the controls, and these predictions will be verified as the controls are installed. The calibrated and verified models can also be used to predict the benefits of wider applications of the upland controls across the city during later project phases. Specifically, the models will predict the decreased runoff volumes and peak runoff rates associated with 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 are being quantified using WinSLAMM. WinSLAMM will be also 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 are being used interactively, emphasizing their respective strengths. As an example, the detailed analyses of site-specific designs of the Marlborough test area stormwater controls conducted using WinSLAMM are being used to optimize the control performance components contained in SUSTAIN-SWMM. The strength of using a combination of models is in increasing the weight of evidence supporting the GI approach, as shown in Figure 1.

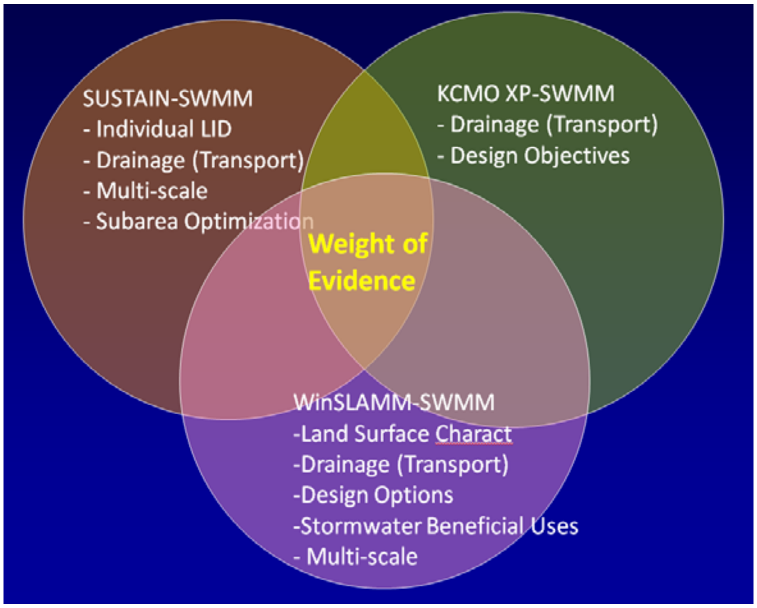


Figure 1. Interactions of different modeling approaches

As described in this report, the calibration and verification of WinSLAMM is a process that occurs in steps, as data becomes available. WinSLAMM was originally calibrated using site-specific data obtained from site measurements (the detailed land development surveys by University of Missouri–Kansas City (UMKC) students where they surveyed each home and lot in the test watershed) and the use of the local rainfall data. Test watershed site soil infiltration data were also used to quantify the soil responses for the modeling. In addition, regional stormwater quality data, as contained in the National Stormwater Quality Database (NSQD), and more recent data from Lincoln, Nebraska, were used to develop calibrated regional parameter modeling files for use in Kansas City. Verification of the model is continuous as additional site monitoring data become available. The test and control watershed flow monitoring and rainfall data obtained by UMKC over the past two years were used to verify the model calculations for current conditions for the complete drainage areas. This activity was completed and is described in this report. In addition, rain garden monitoring data have been collected in the test watershed, and those observations have been used to verify the model predictions on rain garden performance. Additional verification will occur as individual practice data become available during the coming project phase, and the test and control watershed flow (and rain) data will be used to verify the performance of the large-scale implementation of the GI controls throughout the area.

Future use of the calibrated and verified model will be to examine stormwater conditions for other land uses that occur in the Kansas City area, and to calculate the benefits of alternative stormwater control programs for those areas. A preliminary assessment of other land uses is also described in this report, based on recent analyses conducted in Lincoln, Nebraska, a smaller city about 200 miles northwest of Kansas City. Later project phases will involve continued verification, especially for the currently constructed GI components.

1.1 WinSLAMM Background Information

WinSLAMM was developed to evaluate stormwater runoff volume and pollutant loadings in urban areas using continuous, small-storm hydrology, in contrast to single-event hydrology methods that have been traditionally used for much larger drainage design events. WinSLAMM determines the runoff on the basis of local rain records and calculates runoff volumes and pollutant loadings from each individual source area within each land use category for each rain. Examples of source areas include roofs, streets, small landscaped areas, large landscaped areas, sidewalks, and parking lots.

1.1.1 Regional Rainfall and Runoff Distributions

The model can use any length of rainfall record as determined by the user, from single rainfall events to several decades of rains. The rainfall file used in the calculations for Kansas City was developed from hourly data obtained from EarthInfo CDROMs, using the 27 years from 1972 through 1999, as shown in Figure 2. This period had 2,537 rains, with an average of 0.40 inch and a maximum of 6.19 inches.

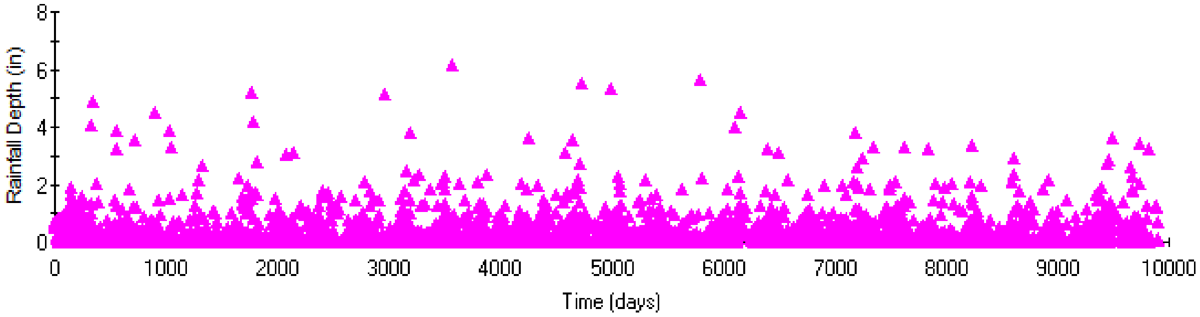


Figure 2. Long-term rain depths for individual Kansas City, MO, rains (1972–1999).

Figure 3 shows that the regional stormwater runoff is heavily influenced by the small to intermediate rains (data for the region shown for St. Louis). Almost all the runoff is associated with rains between about 0.3 to 2 inches, the events for which WinSLAMM is optimized. The rare drainage design events generally compose a very small portion of the typical year's runoff. The 1.4-inch event used in Kansas City is close to the rain depth associated with the median runoff depth.

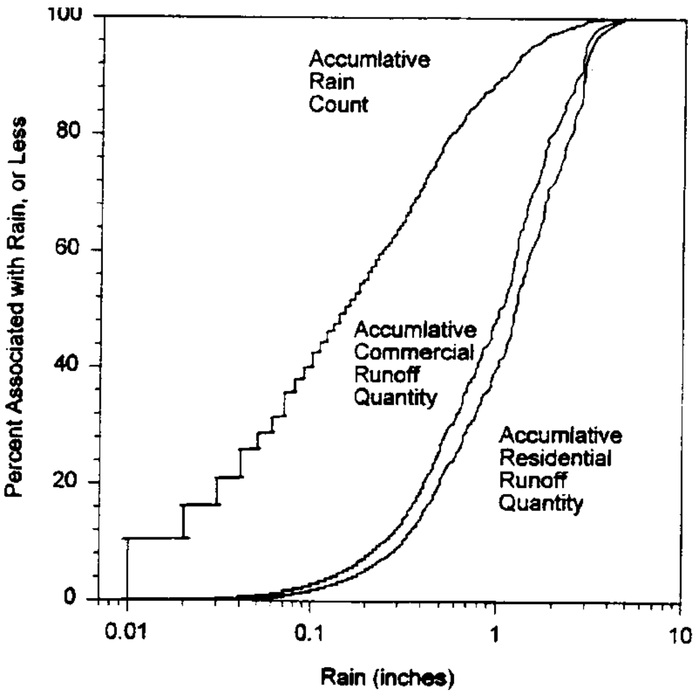


Figure 3. St. Louis, Missouri, rain and runoff distributions (1984 through 1992).

1.1.2 Stormwater Controls in WinSLAMM and Calculation Processes

WinSLAMM was used to examine a series of stormwater control practices, including rain barrels and water tanks for stormwater irrigation, pavement and roof disconnections, roof rain gardens, infiltration/biofiltration in parking lots and as curb-cut biofilters, street cleaning, wet detention ponds, grass swales, porous pavement, catch basins, and selected combinations of these practices for regional land use conditions. The model evaluates the practices through engineering calculations of the unit processes on the basis of the actual design and size of the controls specified and determines how effectively these practices remove runoff volume and pollutants.

WinSLAMM does not use a percent imperviousness or a curve number to general runoff volume or pollutant loadings. The model applies runoff coefficients to each *source area* within a land use category. Each source area has a different runoff coefficient equation on the basis of factors such as slope, type and condition of surface, soil properties, and the like, and it calculates the runoff expected for each rain. The runoff coefficients were developed using monitoring data from typical examples of each site type under a broad range of conditions. The runoff coefficients are continuously updated as new research data become available.

Each source area also has a unique pollutant concentration (event mean concentrations [EMCs] and a probability distribution) assigned to it. The EMCs for a specific source area vary depending on the rain depth. The source area’s EMCs are based on extensive monitoring conducted in North America by the U.S. Geological Survey (USGS), Wisconsin Department of Natural Resources, University of Alabama, and other groups. These monitoring efforts isolated source areas (roofs, lawns, streets, and such) for different land uses and examined long-term data on the runoff quality. The pollutant concentrations are also continuously updated as new research data become available.

For each rainfall in a data set, WinSLAMM calculates the runoff volume and pollutant load (EMC x runoff volume) for each source area. The model then sums the loads from the source areas to generate a land use or drainage basin subtotal load. The model continues this process for the entire rain series described in the rain file. It is important to note that WinSLAMM does not apply a *unit load* to a land use. Each rainfall produces a unique load from a modeled area on the basis of the specific source areas in that modeled area.

The model was used to predict stormwater management practice effectiveness as presented in this project report. The model replicates the physical processes occurring in the practice. For example, for a wet detention pond, the model incorporates the following information for each rain event:

1. Runoff hydrograph, pollution load, and sediment particle size distribution from the drainage basin to the pond
2. Pond geometry (depth, area)
3. Hydraulics of the outlet structure
4. Particle settling time and velocity in the pond based on retention time

Stokes Law and Newton’s settling equations are used in conjunction with conventional surface overflow rate calculations and modified Puls-storage indication hydraulic routing methods to determine the sediment amounts and characteristics that are trapped in the pond. Again, it is important to note that the model does not apply *default* percent efficiency values to a control practice. Each rainfall is analyzed and the pollutant control effectiveness will vary on the basis of each rainfall and the pond’s antecedent condition. This report describes how each stormwater control practice examined in Antelope Creek is evaluated in WinSLAMM.

The model’s output is comprehensive and customizable, and it typically includes

1. Runoff volume, pollutant loadings, and EMCs for a period of record or for each event, or both.
2. The above data pre- and post- for each stormwater management practice.
3. Removal by particle size from stormwater management practices applying particle settling.
4. Other results can be selected related to flow-duration relationships for the study area, impervious cover model expected biological receiving water conditions, and life-cycle costs of the controls.

A full explanation of the model's capabilities, calibration, functions, and applications are at www.winslamm.com. For this project, the parameter files were calibrated using the local Lincoln MS4 monitoring data, supplemented by additional information from regional data from the NSQD, at http://www.unix.eng.ua.edu/~rpitt/Research/ms4/mainms4.shtml

1.2 Summary of Findings

The study area is a 100-acre subcatchment. The selected sewershed contains commercial, medium-density, and some high-density residential land uses. An adjacent 86-acre subcatchment has been selected as a control watershed.

Model calibration requires detailed information pertaining to the areas where monitored data have been collected to compare to the modeled predictions. For this project, calibration of the WinSLAMM model was conducted in several steps:

- Regional calibration using water quality and flow data from the NSQD. This information was used to update and compare the original model calibrations that were mostly associated with Wisconsin and Alabama source data. The regional NSQD data enabled significant amounts of data to be examined for main land use categories for several geographical areas in the United States. The Kansas City area is in the central U.S. region and those data were used for this step of the calibration process.
- Detailed land development characteristics were obtained for the study area, along the site soil infiltration measurements. This allowed use to customize the prior model calibration to the area on the basis of these actual site characteristics. Long-term continuous rain data were also used during the analyses to minimize the effects of any unusual conditions.
- Site-specific rainfall-runoff data were obtained from two years of flow monitoring (2009 and 2010) in the test and control watershed in the Marlborough study of Kansas City. Being a combined sewer system, the measured wet-weather flows were adjusted by having the expected concurrent dry-weather sanitary sewage flows (from adjacent dry period monitoring) subtracted from the combined sewer flows. These flow data are being used to verify the regional and initial site calibrations. The site development characteristics for the test and control watershed were used, along with the actual rain history during the flow monitoring period, to show how closely the calibrated model predicted the runoff characteristics that were monitored.
- As data become available, additional calibration verifications of the model will be possible. As an example, the sewer rehabilitation project was conducted between the two monitored years. The effects of the sewer repairs on the monitored data are obvious. The data collected before the repairs are therefore not suitable for flow calibrations because the observed wet-weather flows are substantially less than the flows observed after the repairs. It seems that large amounts of the sewage were leaking from the collection system, resulting in an artificially reduced runoff yield. After the repairs, the flows were very similar to the other area that did not require repairs. In addition, one of the demonstration rain gardens being monitored had almost full years of flow data available. Those observations were also used to verify the modeled expected conditions. Other data becoming available with further construction includes the manufactured treatment devices, other rain gardens, and the complete area GI components (mostly composed of curb-cut biofilters and porous pavement). Several of the GI components are being constructed to enable localized monitoring, to supplement the large-scale monitoring. Again, as these additional data become available, further and more detailed model calibration/verification will be possible.

1.2.1 Land Development and Urban Soil Characteristics

The Marlborough study area in Kansas City is mostly a medium-density residential, constructed before 1960, with a small amount of strip commercial area along Troost Ave. Detailed inventories were made of each of the approximately 600 homes in the area by graduate students from UMKC. Only about 15 percent of the residential roofs are directly connected. If all were assumed to be connected, large errors in the roof runoff contribution calculations would occur. Similarly, if roof runoff stormwater controls were located at all roofs, those located where the roofs were already disconnected would have much lower effects in decreasing the areas runoff amounts. Even though the detailed GIS information is very helpful, the area still needed site surveys. Table 1 shows the breakdown of the different land surface components in the test watershed for the residential areas.

Table 1. Land development characteristics for residential areas in test watershed

	Roofs	Driveways	Sidewalks	Parking/ storage	Streets	Landscaped	Isolated	Total
Impervious								
directly connected	1.87 (15%)	4.12 (46%)	1.15 (46%)	1.59	9.35			18.07
disconnected	10.57 (85%)	4.03 (45%)	1.34 (54%)					15.95
Pervious								
unpaved (gravel, severely compacted)		0.81 (9%)						0.81
landscaped						65.13		65.13
isolated (swimming pools)							0.05	0.05
Total residential area	12.44	8.95	2.49	1.59	9.35	65.13	0.05	100.00

In addition to the site surveys, site-specific soils information is also needed for the area. Disturbed urban soils have infiltration rates that are usually substantially less than the assumed rates from general county soil maps. For the Kansas City project, small-scale infiltrometers were used to measure infiltration rates in the disturbed urban soils of the test watershed area. UMKC students monitored infiltration rates at several locations near the streets throughout the project area. Figure 4 shows the average infiltration responses from three sets of measurements at six locations, representing 18 infiltration tests. Initial infiltration rates were several inches per hour but were reduced to about 1 inch per hour after about one hour. Initial modeling efforts assumed infiltration rates of about 0.3 inch per hour, but more recent measurements and deeper soil profiles indicated that this might even be too large for the site. Therefore, for the shallow rain gardens considered in this analysis, infiltration rates of 0.2 inch per hour were used.

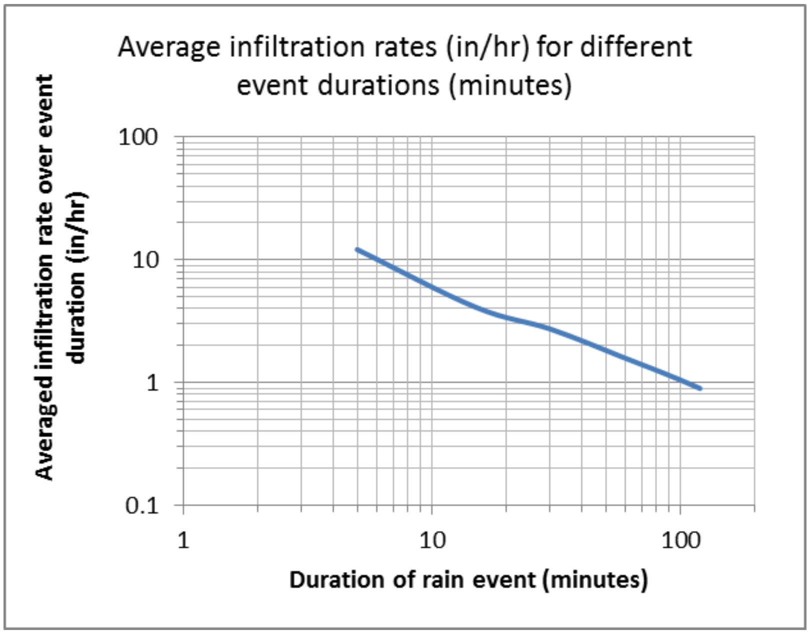


Figure 4. Soil infiltration characteristics for Kansas City test area.

1.2.2 Model Calibration Results

Runoff monitoring was conducted in the combined sewer system at several locations in the test and control watersheds. This sampling arrangement enabled flows to be separated for the test and the control watersheds. Nine complete events were monitored in the area in 2009, and six events were monitored in 2010. These data were used to do an initial verification of the WinSLAMM runoff calculations. Because sewer rehabilitation was occurring during this period in the test watershed, only the control area data were used for these analyses.

The calculated values are slightly lower than the observed values using these initial observations for the control watershed (Figure 5), and substantially lower for the test watershed. The overall average volumetric runoff coefficient (Rv) observed at the control watershed was 0.29, while the calculated average Rv value was 0.28. The slope term in the regression comparing the modeled to the observed flow was highly significant ($p < 0.01$), but the slope of the regression line indicates about a 28 percent bias for the control watershed. Residual analyses were also conducted to identify where the model calibration could be improved. Before making further adjustments in the flow calibrations for the control watershed, further monitoring results are needed to see if these model under-predictions are now consistent with time. The overall calibration at the control watershed was significant, but with a moderate (28 percent) bias, it is somewhat greater than a desirable flow monitoring bias of about 25 percent. Most of the flow residuals in the test area are close to zero, with the notable exception of five residual values that have very large negative values (observed flows much larger than modeled flows). These five events are shown to be related to the large rains. When these rains are removed, the runoff response for the test watershed was very similar to the control watershed. Additional flow data are need to further refine these flow calibrations and to verify the effects of time or large rains.

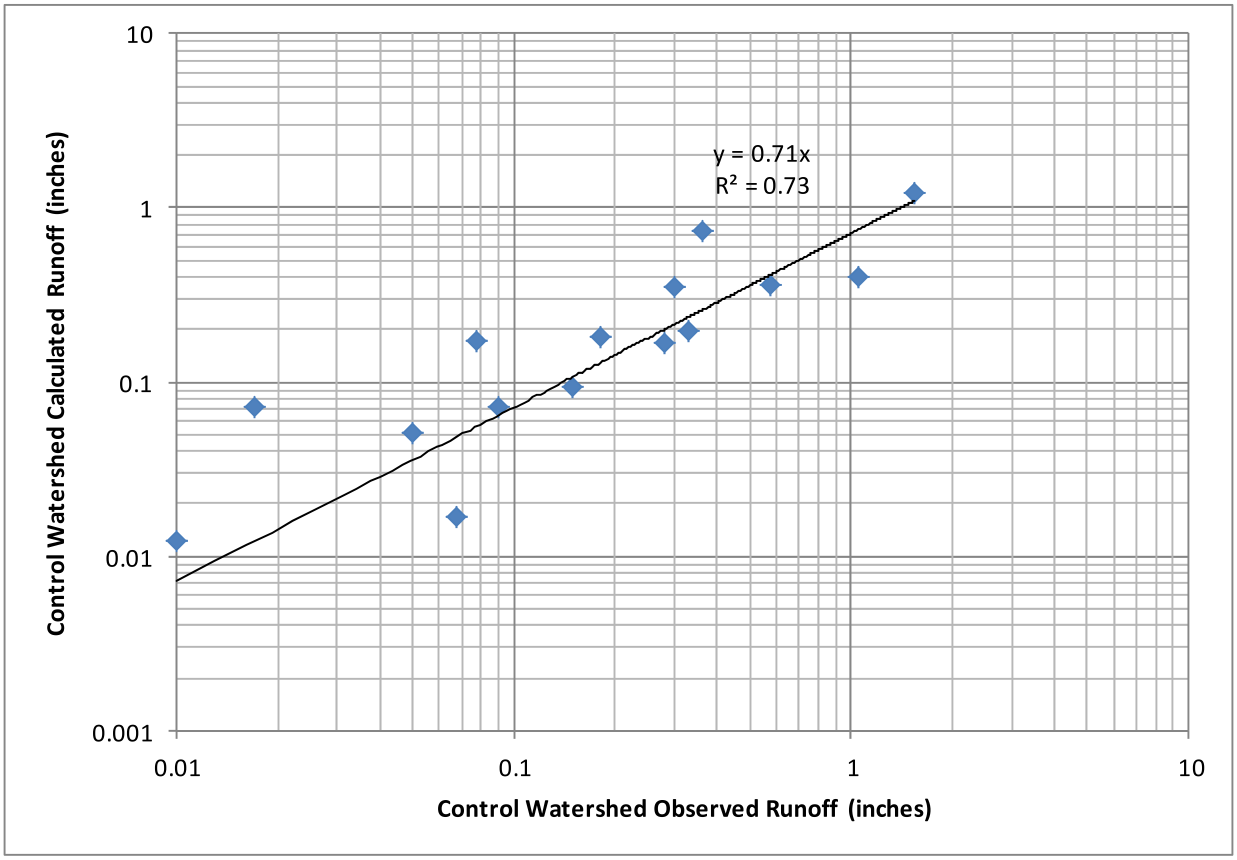


Figure 5. Modeled vs. observed runoff, control watershed.

1.2.3 Sources of Flows and Pollutants

The Marlborough Kansas City test watershed stormwater sources change for different rain depths. For the smallest rains (< 0.25 inch of rain), most of the runoff originates from the directly connected impervious areas (DCIAs; directly connected roofs, paved parking, driveways, sidewalks, and streets). After about 0.25 inch, the small landscaped areas contribute about half of the runoff, a relatively large fraction because of the clayey soils and low infiltration rates. Generally, streets contribute about half of the remaining flows, then driveways and the roofs.

1.2.4 Evaluation of On-Site Controls

Modeling examined the benefits of using rain gardens, rain barrels/tanks, and roof disconnections in the Kansas City test area for controlling combined sewer overflows.

Performance plots were prepared comparing the size of the rain gardens to the size the roof versus percent flow reductions (Figure 6). Rain gardens that are about 20 percent of the roof area are expected to result in about 90 percent reductions in total annual flow compared to directly connected roofs. This area is about 200 ft^2 per house which could be composed of several smaller rain gardens so they can be placed at each downspout. Fifty percent reductions in the total annual flows could be obtained if the total rain garden area per house was about 7 percent of the roof area. The 200 ft^2 rain garden area per house is also expected to completely control the runoff from the regulatory design storm *D* of 1.4 inches.

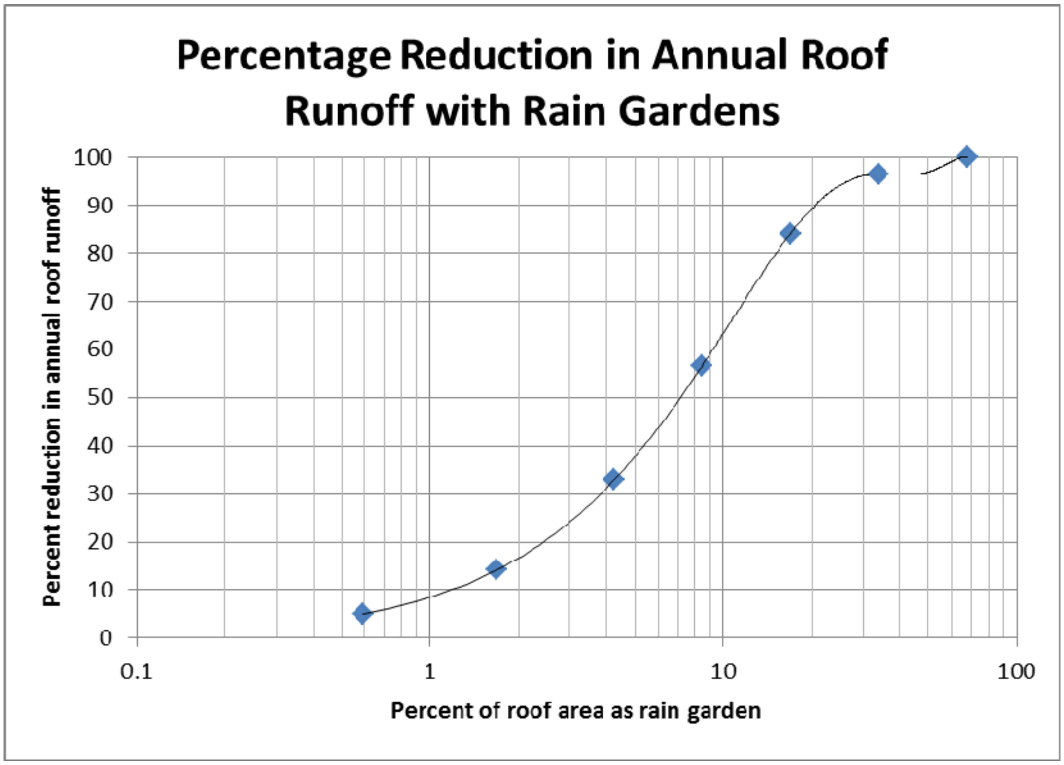


Figure 6. Production function for roof runoff rain gardens.

The water harvesting potential for the retrofitted rain gardens and water tanks was calculated on the basis of supplemental irrigation requirements for the basic landscaped areas. The irrigation needs were determined to be the amount of water needed to satisfy the evapotranspiration (ET) needs of typical turf grasses, after the normal rainfall, as shown in Figure 7.

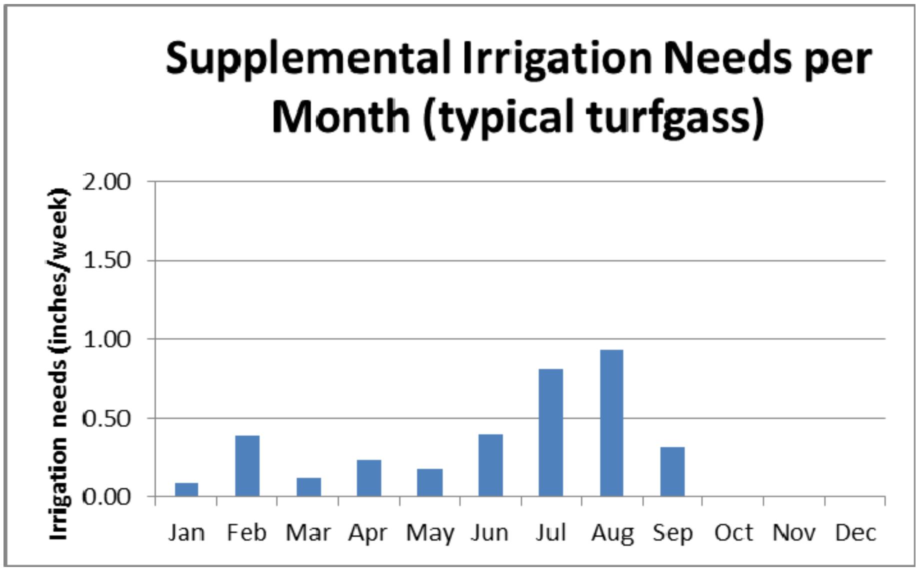


Figure 7. Monthly irrigation requirements to match ET.

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. As shown in Figure 8, one 35-gallon rain barrel is expected to reduce the total annual runoff by about 24 percent, 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 from the roofs could be as high as about 40 percent. Larger storage quantities result in increased beneficial usage but likely require larger water tanks.

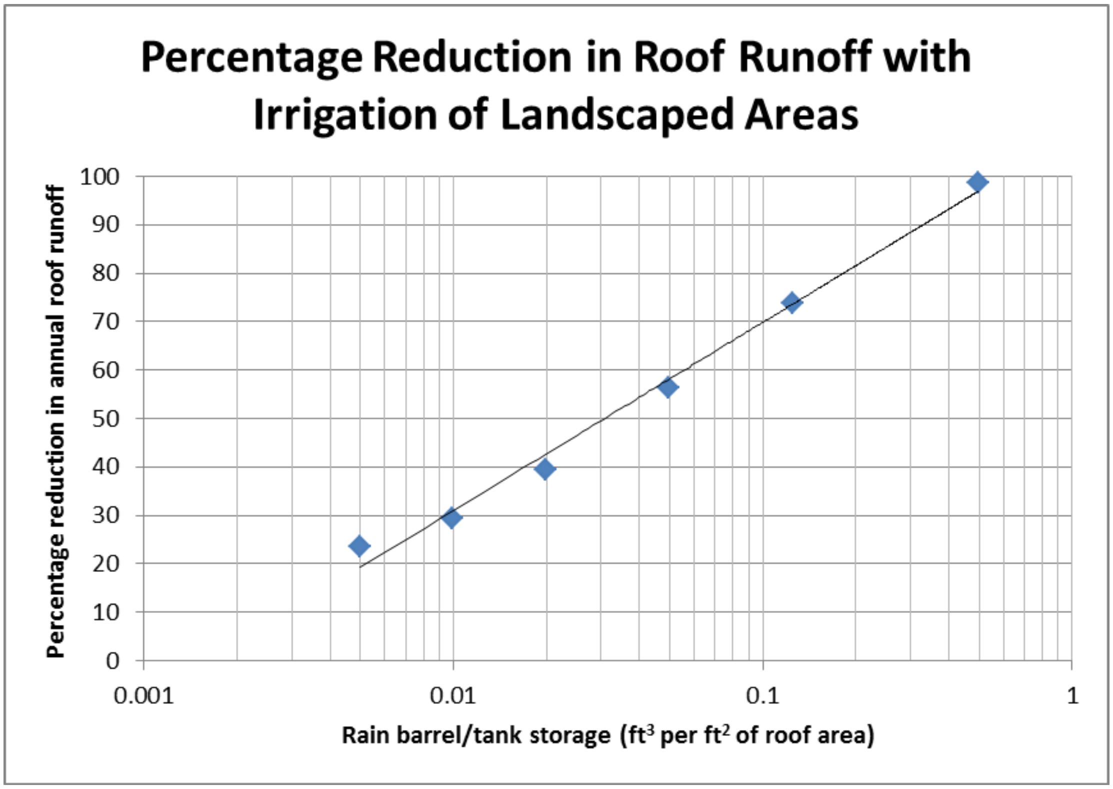


Figure 8. Production function of water cistern/tanks storage for irrigation to meet ET.

Figure 9 illustrates the expected benefits of pavement or roof disconnection practices for different individual rains, up to 4 inches deep. The Rv, the ratio of runoff volume to rainfall volume falling on an area, is seen to increase 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 deep. When disconnected to clayey soils, runoff is not expected until the rain depth is greater than 0.1 inch, and the Rv starts to climb steeply with rains larger than several inches deep. It is expected to be very large for very large and unusual rains that can cause severe flooding, regardless of whether they are disconnected. However, the benefits for small and intermediate rains are large.

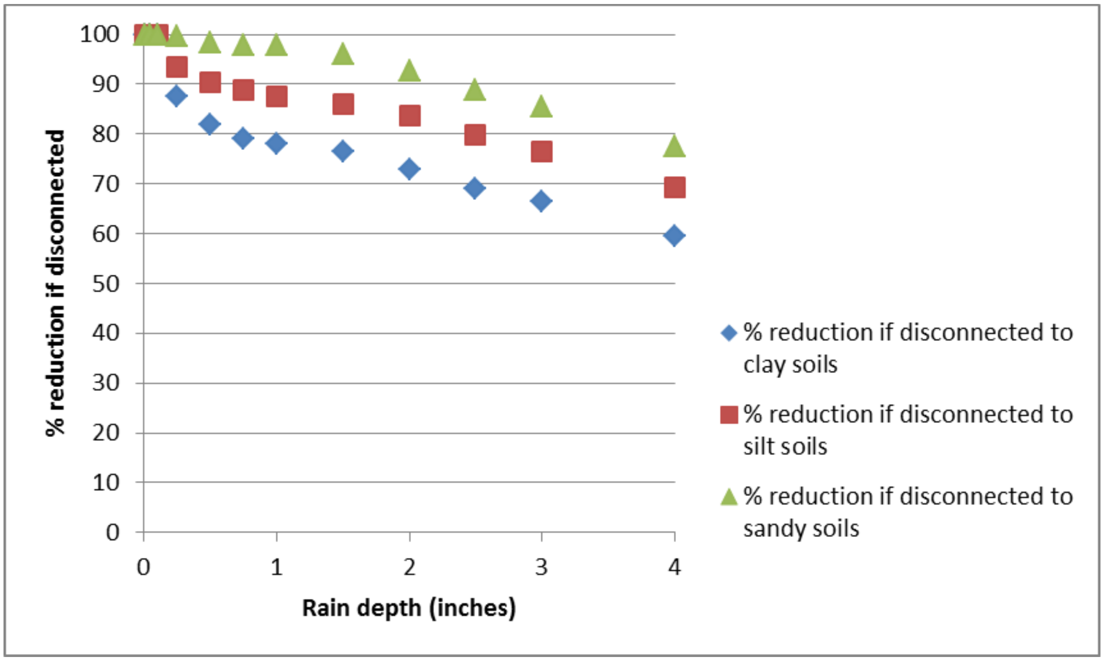


Figure 9. Effectiveness of roof disconnections for different soil characteristics.

1.2.5 Preliminary Evaluation of other Land Use Controls

Recently, a comprehensive evaluation of stormwater controls was conducted for many land use categories in Lincoln, Nebraska, as part of its stormwater management plan (Pitt 2011).

This example is from the Lincoln report and represents conditions similar to the main land use in the Marlborough test watershed in Kansas City. Twenty-eight alternative control options were examined for this medium-density residential area and are compared to the base conditions. Figure 10 uses data from the batch processor in WinSLAMM that enable many attributes about each control alternative to be examined, including life-cycle costs, land requirements, maintenance requirements, expected biological conditions in the receiving waters, and runoff and pollutant characteristics. The performance characteristics and the total annual costs are plotted as scatterplots to enable the most cost-effective alternative to be identified for different levels of performance. The most cost-effective stormwater control programs plotted in the figure (the alternatives with the least cost at the highest potential control benefits) are

- Curb-cut biofilters along 20 percent of curb line (37 percent runoff volume reductions)
- Curb-cut biofilters along 40 percent of curb line (54 percent runoff volume reductions)
- Small wet pond and curb-cut biofilters along 40 percent of curb line (54 percent runoff volume reductions) [same volume reduction as above alternative, but higher cost because of small pond for increased particulate pollutant control]
- Small wet pond, rain gardens (15 percent of roof area), and curb-cut biofilters along 40 percent of curb line (66 percent runoff volume reductions) [increased volume reduction because of rain gardens added to curb-cut biofilters, small pond added for increased particulate pollutant control]
- Curb-cut biofilters along 80 percent of curb line (75 percent runoff volume reductions) [obviously it would be challenging to install this high a level of curb-cut biofilters in an area already developed]

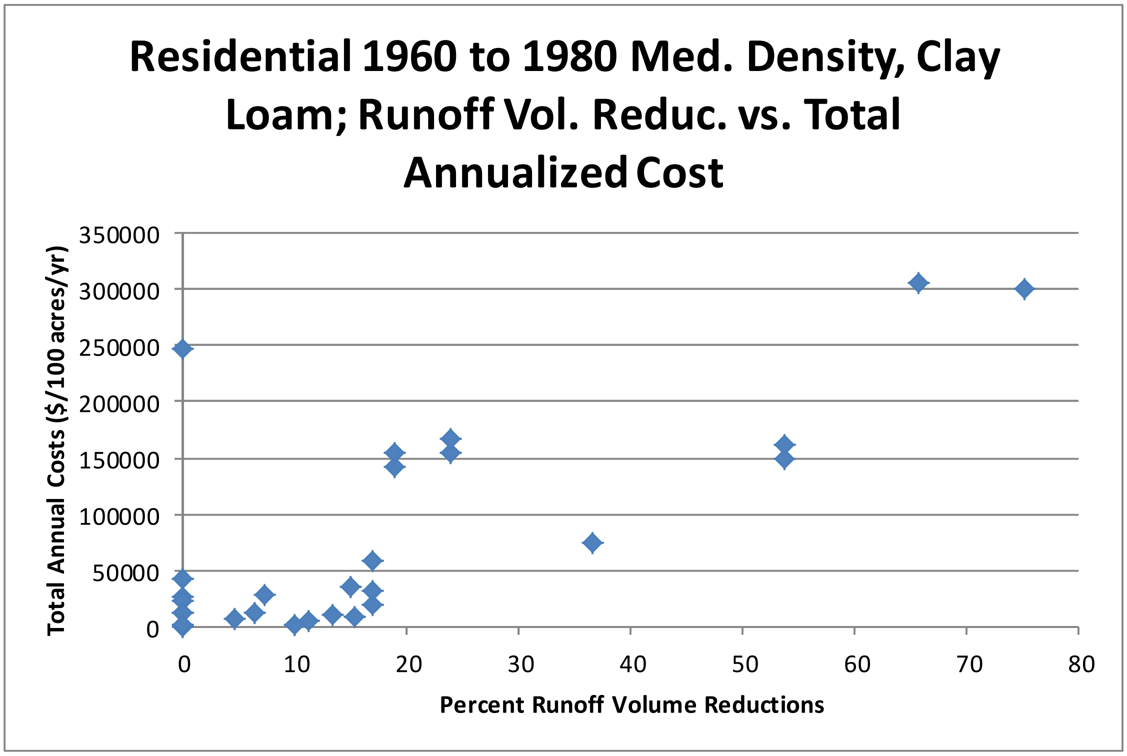


Figure 10. Cost-effectiveness of alternative stormwater management programs.

Besides the above medium-density residential land use analyses, similar analyses were conducted for other Lincoln area land uses that are similar to land uses found in the Kansas City area. The following is a brief discussion of the findings for these areas.

For runoff volume controls, each land use group had similar *most cost-effective* controls, as shown in the following list for the controls having at least 25 percent levels of runoff volume reduction potential in areas having clay loam soils in the infiltration areas. Other control options have similar potential levels of control, but the others are likely more costly. These are listed in order with the first control having the lowest level of maximum control (the approximate percentage of runoff reduction in shown), and with the best unit cost-effectiveness; and the last control listed having the highest level of maximum control, but the worst expected unit cost-effectiveness. Therefore, if low to moderate levels of control are suitable, the first control option might be best, but if maximum control levels are needed, the last control option listed would be needed.

- Strip mall and shopping center areas:
  - Porous pavement (in half of the parking areas), 25 percent volume reductions
  - Curb-cut biofilters (along 80 percent of the curbs) for strip malls or biofilters in parking areas (10 percent of the source area) for shopping centers, 29 percent volume reductions
  - Biofilters in parking areas (10 percent of the source area) and curb-cut biofilters (along 40 percent of the curbs), 42 percent volume reductions

- Light industrial areas:
  - Curb-cut biofilters (along 40 percent of the curbs), 26 percent volume reductions
  - Roofs and parking areas half disconnected, 32 percent volume reductions

  - Roofs and parking areas all disconnected, 61 percent volume reductions

- School, church, and hospital institutional areas:
  - Small rain tank (0.10 ft^3 storage per ft^2 of roof area) for schools and churches; rain tank (0.25 ft^3 storage per ft^2 of roof area) for hospitals, 26 percent volume reductions
  - Roofs and parking areas half disconnected, 31 percent volume reductions
  - Roofs and parking areas all disconnected, 67 percent volume reductions

- Low- and medium-density residential areas:
  - Curb-cut biofilters (along 20 percent of the curbs), 36 percent volume reductions
  - Curb-cut biofilters (along 40 percent of the curbs), 53 percent volume reductions
  - Curb-cut biofilters (along 80 percent of the curbs), 75 percent volume reductions

1.2.6 Other Considerations Affecting Selection and Use of Stormwater Controls

Suitable care is needed in constructing stormwater controls and interpreting modeling results because other critical factors could dramatically affect their success. Certain site conditions might restrict the applicability of some of these controls, as briefly discussed in the following paragraphs (mostly summarized from a prior publication by Pitt et al. (2008) and from research reported by others at recent technical conferences.

- The sodium adsorption ratio (SAR) can radically degrade the performance of an infiltration device, especially when clays are present in the infiltration layers of a device, and snowmelt containing deicing salts enters the device. Soils with an excess of sodium ions, compared to calcium and magnesium ions, remain in a dispersed condition and are almost impermeable to rain or applied water. A *dispersed* soil is extremely sticky when wet, tends to crust, and becomes very hard and cloddy when dry. Such failures occur when snowmelt water is allowed to enter a biofilter that has clay in the soil mixture. To minimize this failure, prevent snowmelt water from entering a biofilter unit. As an example, roof runoff likely has little salt and SAR problems seldom occur for roof runoff rain gardens. The largest problem is associated with curb-cut biofilters or parking lot biofilters in areas with snowmelt entering the devices, especially if clay is present in the engineered backfill soil.
- The designs of infiltration devices need to be checked on the basis of their clogging potential. As an example, a relatively small and efficient biofilter (in an area having a high native infiltrating rate) might capture a large amount of sediment. Having a small surface area, this sediment would accumulate rapidly over the area, possibly reaching a critical clogging load early in its design lifetime. Infiltration and bioretention devices might show significantly reduced infiltration rates after about 2 to 5 lb/ft^2 (10 to 25 kg/m^2) of particulate solids have been loaded, especially in a short several year period.
- The potential for infiltrating stormwaters to contaminate groundwaters is dependent on the concentrations of the contaminants in the infiltrating stormwater and how effective those contaminants might travel through the soils and vadose zone to the groundwater. Source stormwaters from residential areas are not likely to be contaminated with compounds having significant groundwater contaminating potential (with the exception of high salinity snowmelt waters). In contrast, commercial and industrial areas are likely to have greater concentrations of contaminants of concern that could adversely affect the groundwater.
- Most of the control options being considered as GI components in areas served by combined sewers are intended for retrofitting in existing urban areas. Therefore, their increased costs and availability of land will be detrimental in developing highly effective control programs. The range of difficulties and land requirements varies, mostly depending on available opportunities.

2 Standard Land Use Development Characteristics Used for WinSLAMM Calibration

Land development information corresponding to the different land uses in an area is needed as an initial step in investigating stormwater quality for an area. This is especially true when modeling expected stormwater characteristics under a variety of conditions. Detailed land use characteristics for a wide variety of land uses are available from several stormwater research projects. The available data were used in conjunction with the detailed, house-by-house surveys conducted in the study area. The data were used in conjunction with the site soils infiltration and density measurements.

The Marlborough study area in Kansas City is mostly a medium-density residential, constructed before 1960, with a small amount of strip commercial area along Troost Ave. Graduate students from UMKC made detailed inventories of each of the approximately 600 homes in the area. These data, along with initial modeling results, have been summarized recently in the following publications:

- *Modeling green infrastructure components in a combined sewer area* (Pitt and Voorhees 2011)
- *Green infrastructure performance modeling with WinSLAMM* (Pitt and Voorhees 2009)

These Kansas City observations for the one land use were supplemented by extensive land use surveys recently conducted in Lincoln, Nebraska, a city in the same geographical region as the Kansas City study sites, as part of a stormwater management project being conducted by EA Engineering, Science and Technology Inc. (Lincoln, Nebraska) and Wright Waters Engineers, Inc. (Denver, Colorado) (Pitt 2011). The additional land uses surveyed in Lincoln were low-density residential; medium-density residential before 1960; 1960-80; after 1980; light industry; strip malls; shopping centers; schools; churches; hospitals. These land development descriptions are from an ongoing project in Lincoln, Nebraska, examining pollutant sources and controls. About 10 homogeneous neighborhoods representing each land use were studied using both aerial photography and on the ground surveys to develop these additional land use descriptions. Regional National Pollutant Discharge Elimination System stormwater data are also available for the Lincoln area were and used in the initial regional stormwater quality calibration of WinSLAMM.

Appendix A includes detailed descriptions of these individual Kansas City and Lincoln areas, along with average characteristics for similar land uses from throughout the country from other research study areas. The national data for each of the 63 individual land use areas were grouped into six major land use categories: commercial, industrial, institutional, open space, residential, and freeway/highway land uses (neither the Kansas City nor the Lincoln sites included open space areas). To examine geographical variations in stormwater characteristics, these land uses were sorted into six areas: Northwest; Southwest; Central; Southeast; Great Lakes; and East Coast. Model calibration was performed in each of these six geographical areas for all the land uses in each area. Stormwater quality data from the NSQD were sorted into groups representing major land use and geographical categories. The modeled concentrations were compared to the observed concentrations, as described in the following calibration section of this report.

Table 2 summarizes the breakdown of these categories into DCIAs, partially connected impervious areas, and pervious areas. The DCIAs are most closely related to the runoff quantities. The partially connected impervious areas contribute runoff at later portions of larger rains, while the pervious areas might contribute flows only after substantial rain has occurred. As expected, most of the data represent residential areas, with commercial areas next, and the other areas having fewer than 10 detailed area descriptions.

Table 2. Summary of major land ue characteristics: average (and coefficient of variability values)

Land use category (# of example areas)	Total DCIAs	Total partially connected impervious areas	Total pervious areas
Commercial (16)	79.5 (0.3)	1.8 (2.8)	18.6 (1.0)
Industrial (5)	54.3 (0.3)	21.4 (0.4)	24.3 (0.5)
Institutional (8)	50.0 (0.4)	9.1 (0.9)	40.8 (0.3)
Open Space (5)	10.2 (1.2)	10.6 (1.3)	79.1 (0.3)
Residential (25)	24.0 (0.6)	12.1 (0.5)	63.8 (0.2)
Freeway and Highway (4)	31.9 (1.2)	27.4 (1.2)	40.7 (0.3)

The land development data from other areas, besides Kansas City and Lincoln, were obtained from the following research projects and reports:

- Jefferson County, Alabama (high-density residential; medium-density residential before 1960, 1960 to 1980 and after 1980; low density residential; apartments; multi-family; offices; shopping center; schools; churches; light industrial; parks; cemeteries; golf courses; and vacant land). These areas were inventoried as part of regional stormwater research and included about 10 single land use neighborhoods for each land use category. Local National Pollutant Discharge Elimination System data were used to calibrate WinSLAMM for regional conditions using the specific monitored areas. The sites are described in several publications, one of which is
  - *Land development characteristics in Jefferson County, Alabama* (Bochis et al. 2008)
- Bellevue, Washington (medium-density residential before 1960). These data were from test and control watersheds that were extensively monitored as part of the Bellevue project of EPA’s Nationwide Urban Runoff Program. Much monitoring data from these sites were used for calibrating WinSLAMM. These areas are described in
  - *Bellevue Urban Runoff Program Summary Report* (Pitt and Bissonnette 1984)
  - *Characterizing and Controlling Urban Runoff through Street and Sewerage Cleaning* (Pitt 1985)
- Downtown Central Business Districts (Atlanta, Georgia; Chicago, Illinois; Los Angeles, California; New York, New York; and San Francisco, California). These were not monitored locations but were selected because this land use was not well represented in the available research projects. Five example areas in the high-density, downtown areas of each of these five cities were examined in detail using Google Maps. The areas associated with each land cover in a several block area were manually measured and described. No runoff quality or quantity data are available for these areas for model calibration.
- Millburn, New Jersey (medium-density residential 1961–1980). Nine homes are being monitored during this EPA research project investigating the effects of dry-well disposal of stormwater from individual homes, and the potential for irrigation use of this water. Google Maps aerial photographs and site surveys were conducted at each home to determine the land covers and characteristics. Site stormwater data are not available yet for these areas, but dry well infiltration has been extensively used for model calibration for these locations. Preliminary results were presented at the following conferences:
  - *Stormwater Non-potable Beneficial Uses: Modeling Groundwater Recharge at a Stormwater Drywell Installation*. ASCE/EWRI World Environment and Water Resources Congress. Palm Springs, CA, May 22–26, 2011. (Talebi and Pitt 2011a)

  - *Stormwater Non-potable Beneficial Uses and Effects on Urban Infrastructure*. 84th Annual Water Environment Federation Technical Exhibition and Conference (WEFTEC), Los Angeles, CA, October 15–19, 2011 (Talebi and Pitt 2011a).

- San Jose, California (medium-density residential 1961–1980; downtown central business district). Two residential and one downtown area were characterized as part of this early stormwater research project. Stormwater characterization data are available for these areas and used for model calibration. These areas are described in the following report:
  - *Demonstration of Nonpoint Pollution Abatement Through Improved Street Cleaning Practices* (Pitt 1979)

- Toronto, Ontario (medium-density residential 1961–1980; medium industrial). These two areas were characterized and monitored as part of a research project conducted for the Toronto Area Wastewater Management Strategy Study. Stormwater characterization data are also available for these areas and was used for calibration. The areas are described in the following reports:
  - *Humber River Pilot Watershed Project* (Pitt and McLean 1986).
  - *Small Storm Urban Flow and Particulate Washoff Contributions to Outfall Discharges* (Pitt 1987).

- Tuscaloosa, Alabama (parking lot at city park; city hall). These two sites were characterized and monitored as part of the pilot-scale and full-scale monitoring projects of the Up-Flo^{TM} filter. The pilot-scale tests were conducted as part of an EPA SBIR project and were conducted at the Tuscaloosa city hall. The full-scale tests were conducted at the Riverwalk parking lot. Stormwater quality and quantity data are available from both of these sites and used for model calibration. These sites and data are described in the following reports:
  - *Field Verification Tests of the UpFlow^{TM} Filter. Small Business Innovative Research, Phase 2 (SBIR2) Report* (Pitt and Khambhammettu 2006).
  - *UpFlow filtration for the treatment of stormwater at critical source areas* (Khambhammettu et al. 2007)
  - *Field Performance Results of UpFlow Stormwater Treatment Device* (Togawa et al. 2011).

- Wisconsin (downtown central business district; duplex residential; high-density residential with alleys; high-density residential without alleys; high rise residential; hospital; fairgrounds; light industry; low-density residential; medium-density residential; medium industry; mobile homes; multifamily residential; open space; schools; shopping center; strip commercial; and suburban residential). These areas are the standard land use areas studied and described by the Wisconsin Department of Natural Resources and USGS to support WinSLAMM modeling in the state. These area descriptions are based on locations studied throughout the main urban areas in Wisconsin, including Milwaukee, Madison, Green Bay, and others. Generally, about 10 homogeneous areas representing each land use category were examined in each study area to develop these characteristic descriptions. Many stormwater characterization data are available for these areas, and USGS maintains calibrated versions of the WinSLAMM parameter files for use by state stormwater managers and regulators. Descriptions of these projects and the source water quality data are summarized in the following:
  - *Sources of pollutants in urban areas (Part 1)–Older monitoring projects* (Pitt et al. 2005b)
  - *Sources of pollutants in urban areas (Part 2)–Recent sheetflow monitoring results* (Pitt et al. 2005c)
  - *Review of historical street dust and dirt accumulation and washoff data* (Pitt et al. 2005a)

2.1 Land Characteristics Survey in Kansas City Test Watershed

In many areas, detailed aerial coverage with GIS data sets are becoming available, showing and quantifying the finer elements of an area. Figure 11 is an example GIS map from Kansas City, Missouri, showing parts of the study area. This high-resolution GIS data shows all the main elements, but field surveys are still needed to verify the drainage pattern for each impervious element in the test watershed and to identify many other site elements used in stormwater quality modeling.

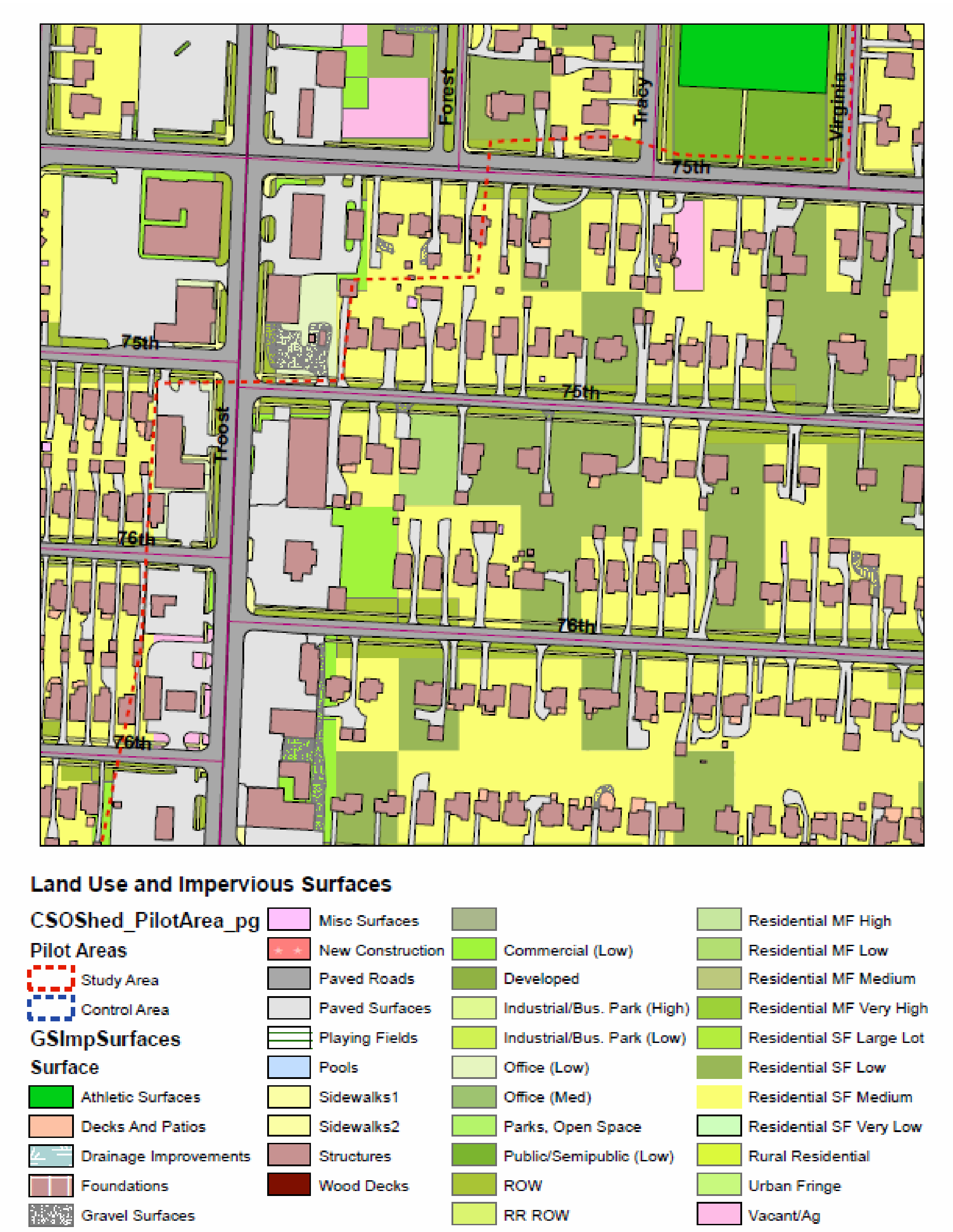


Figure 11. Detailed GIS coverage showing land cover components of different land uses in the Kansas City test watershed.

Dr. Deb O'Bannon and her graduate students at UMKC conducted a detailed survey of the development characteristics in the study area. This information was used in conjunction with the overall GIS information describing each land element to identify the specifics needed for the continuous modeling. They surveyed 576 homes in the 100-acre area (90.6 acres was residential). The housing density is therefore about 6.4 homes per acre. Tables 3 and 4 show the original GIS information for the test watershed provided by the City of Kansas City Water Services Department (KCMO) along with the detailed site data.

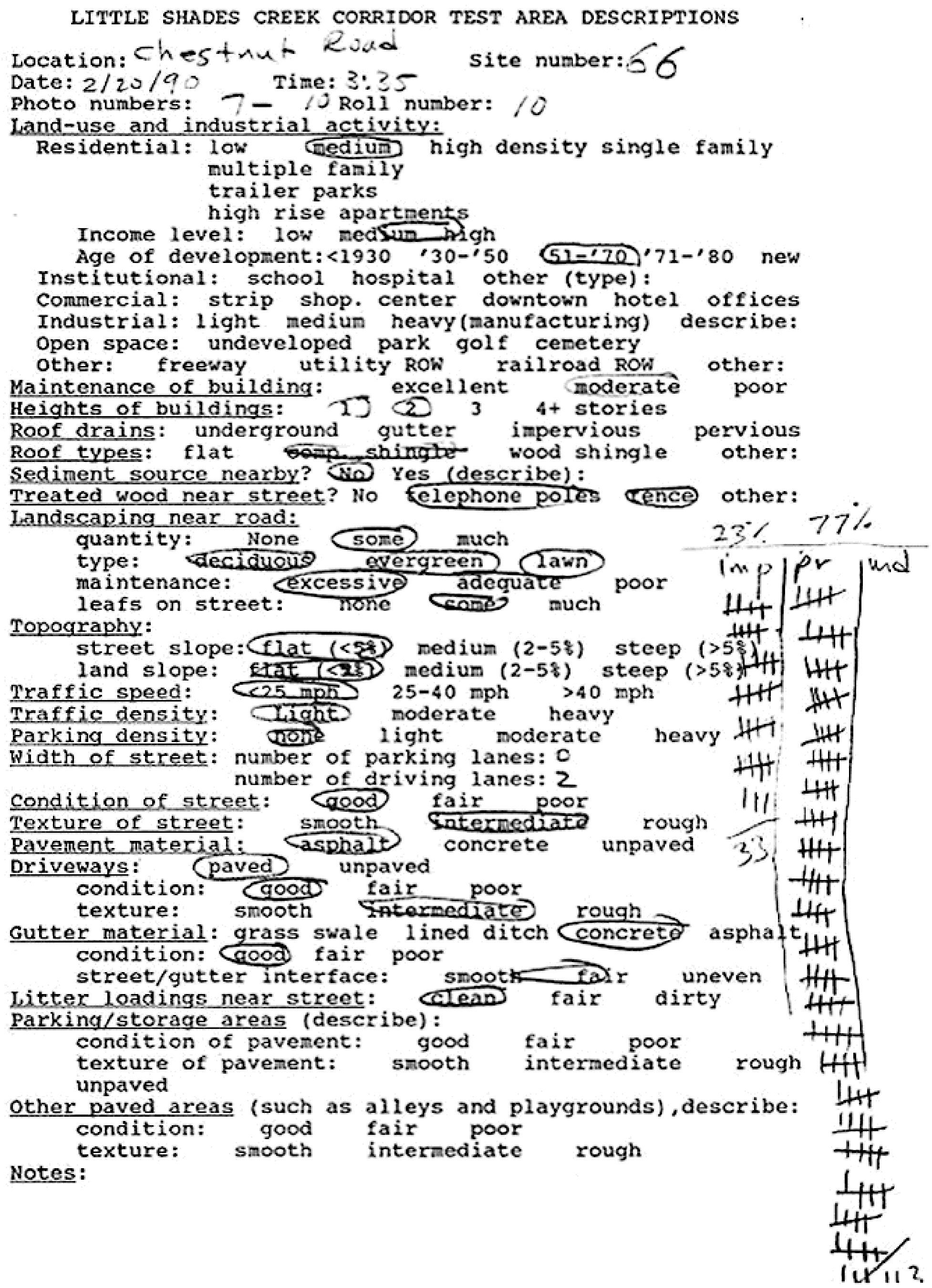
Table 3. Original GIS measurements by KCMO for test watershed

	Decks and patios	Gravel surfaces	Paved roads	Paved parking/ storage	Sidewalks	Roofs	Pools	Pervious areas	Sum
All Commercial:									
acres	0.00	0.14	1.92	3.41	0.24	1.36	0.00	1.25	8.32
%	0.00	1.68	23.10	40.93	2.87	16.37	0.00	15.06	100.00
All Office									
acres	0.00	0.00	0.00	0.26	0.03	0.17	0.00	0.11	0.58
%	0.00	0.00	0.00	45.86	5.80	29.72	0.00	18.63	100.00
All Institutional									
acres	0.00	0.00	0.31	0.01	0.04	0.00	0.00	0.19	0.56
%	0.00	0.00	56.07	2.59	6.36	0.00	0.00	34.98	100.00
All Residential									
acres	0.94	0.25	8.08	8.17	2.03	11.72	0.02	59.35	90.56
%	1.04	0.27	8.93	9.02	2.24	12.94	0.02	65.54	100.00
All Combined									
acres	0.94	0.39	10.32	11.85	2.34	13.25	0.02	60.91	100.02
%	0.94	0.39	10.32	11.85	2.34	13.25	0.02	60.89	100.00

Table 4. Medium-density residential areas

	Roofs	Driveways	Sidewalks	Parking/ storage	Streets	Landscaped	Isolated	Total
Impervious								
directly connected	1.87 (15%)	4.12 (46%)	1.15 (46%)	1.59	9.35			18.07
disconnected	10.57 (85%)	4.03 (45%)	1.34 (54%)					15.95
Pervious								
unpaved (gravel, severely compacted)		0.81 (9%)						0.81
landscaped						65.13		65.13
isolated (swimming pools)							0.05	0.05
Total residential area	12.44	8.95	2.49	1.59	9.35	65.13	0.05	100.00

Even though the major categories for the site agreed between the GIS information and the site surveys, the site surveys were able to distinguish the different categories of pervious surfaces and to quantify how much of the impervious areas were directly connected to the drainage system. This addition information can have dramatic effects on the actual stormwater quality and quantity, especially for the small and intermediate storms that produce most of the annual site runoff, and even for the 1.4-inch design storm used for the combined sewer overflow evaluations. As an example, only about 15 percent of the residential roofs are directly connected. If all were assumed to be connected, large errors in the roof runoff contribution calculations would occur. Similarly, if roof runoff stormwater controls were placed at all roofs, those placed where the roofs were already disconnected would have much lower effects in decreasing the areas runoff amounts. Therefore, even though the detailed GIS information is very helpful, the area still needs site surveys. An *Area Description* field sheet is used to record important characteristics of the homogeneous land use areas during the field surveys (Figure 12).



LITTLE SHADES CREEK CORRIDOR TEST AREA DESCRIPTIONS

Location: Chestnut Road Site number: 56
Date: 2/20/90 Time: 3:35
Photo numbers: 7 – 10 Roll number: 10
Land-use and industrial activity:
Residential: low [✓ medium] high density single family
multiple family
trailer parks
high rise apartments
Income level: low [✓ medium] high
Age of development: <1930 '30-'50 [✓ '51-'70] '71-'80 new
Institutional: school hospital other (type):
Commercial: strip shop. center downtown hotel offices
Industrial: light medium heavy(manufacturing) describe:
Open space: undeveloped park golf cemetery
Other: freeway utility ROW railroad ROW other:
Maintenance of building: excellent [✓ moderate] poor
Heights of buildings: [✓ 1] [✓ 2] 3 4+ stories
Roof drains: underground gutter impervious pervious
Roof types: flat ~~comp. shingle~~ wood shingle other:
Sediment source nearby? [✓ No] Yes (describe):
Treated wood near street? No [✓ telephone poles] [✓ fence] other:
Landscaping near road:
quantity: None [✓ some] much
type: [✓ deciduous] [✓ evergreen] [✓ lawn]
maintenance: [✓ excessive] adequate poor
leafs on street: none [✓ some] much
Topography:
street slope: [✓ flat (<2%)] medium (2-5%) steep (>5%)
land slope: [✓ flat (<2%)] medium (2-5%) steep (>5%)
Traffic speed: [✓ <25 mph] 25-40 mph >40 mph
Traffic density: [✓ Light] moderate heavy
Parking density: [✓ none] light moderate heavy
Width of street: number of parking lanes: 0
number of driving lanes: 2
Condition of street: [✓ good] fair poor
Texture of street: smooth [✓ intermediate] rough
Pavement material: [✓ asphalt] concrete unpaved
Driveways: [✓ paved] unpaved
condition: [✓ good] fair poor
texture: smooth [✓ intermediate] rough
Gutter material: grass swale lined ditch [✓ concrete] asphalt
condition: [✓ good] fair poor
street/gutter interface: smooth [✓ fair] uneven
Litter loadings near street: [✓ clean] fair dirty
Parking/storage areas (describe):
condition of pavement: good fair poor
texture of pavement: smooth intermediate rough
unpaved
Other paved areas (such as alleys and playgrounds), describe:
condition: good fair poor
texture: smooth intermediate rough
Notes:

23% 77%
imp | pr | ind
33
112

Figure 12. Example Area description field sheet.

The tallies shown on the field sheet above are counts of the roof drain connection types. The first colum is the counts of roof drains directly to impervious areas, the second column is roof drains to pervious areas (mostly lawns and some landscaped areas), while the third column (none observed) is indirectly connected roof drains (to small pervious areas with close by impervious areas connected to the drainage system).

2.2 Infiltration Rate Monitoring

In addition to the site surveys described above, site-specific soils information is also needed for the area. Disturbed urban soils have infiltration rates that are usually substantially less than the assumed rates from general county soil maps. For the Kansas City project, small-scale infiltrometers were used to measure infiltration rates in the disturbed urban soils of the test watershed area, as shown in Figure 13. Using several of these units simultaneously and in relatively close proximity also enables measurements of variability to be determined. Any standard or small double-ring infiltrometer likely overestimates the actual infiltration rates for a specific site. The relatively small areas being tested, even with the larger traditional units, have substantial edge effects, especially if the area's soils are not saturated. Also, double-ring infiltrometer measurements do not use large amounts of water that would be needed to cause groundwater mounding, and then saturated flow conditions, and resultant highly reduced infiltration rates. The most precise measurements of infiltration, and that should be used in areas where large infiltration units are being designed, should rely on full-scale tests. These are typically large trenches or boreholes, constructed to penetrate the depths of soil that the final units will use for infiltration, and use large volumes of water over extended periods. For small stormwater biofiltration units, this approach is usually not warranted, while it would be for infiltration galleries that are critical for drainage in enclosed areas. In the Kansas City study area, the constructed rain gardens undergo full-scale inundation tests to supplement the smaller scale tests.

Figure 13. Three Turf-Tec infiltrometers for infiltration measurements in pre-development soils.

Infiltration rates are strongly affected by the soil density. In fact, for sandy soils, Pitt et al. (1999, 2008) show that soil density has a greater effect on infiltration rates than soil moisture, while for clayey soils, soil density has about the same effect on infiltration as does soil moisture. Unfortunately, most stormwater models effectively track soil moisture, but they ignore soil density. It is important to also measure soil density with the infiltration rates. WinSLAMM has a MonteCarlo component that can describe the highly variable infiltration rates actually observed.

The UMKC students monitored infiltration rates at several locations near the streets throughout the project area. Figure 14 shows the average infiltration responses from three sets of measurements at six locations, representing 18 infiltration tests. Initial infiltration rates were several inches per hour, but were reduced to about 1 inch per hour after about one hour.

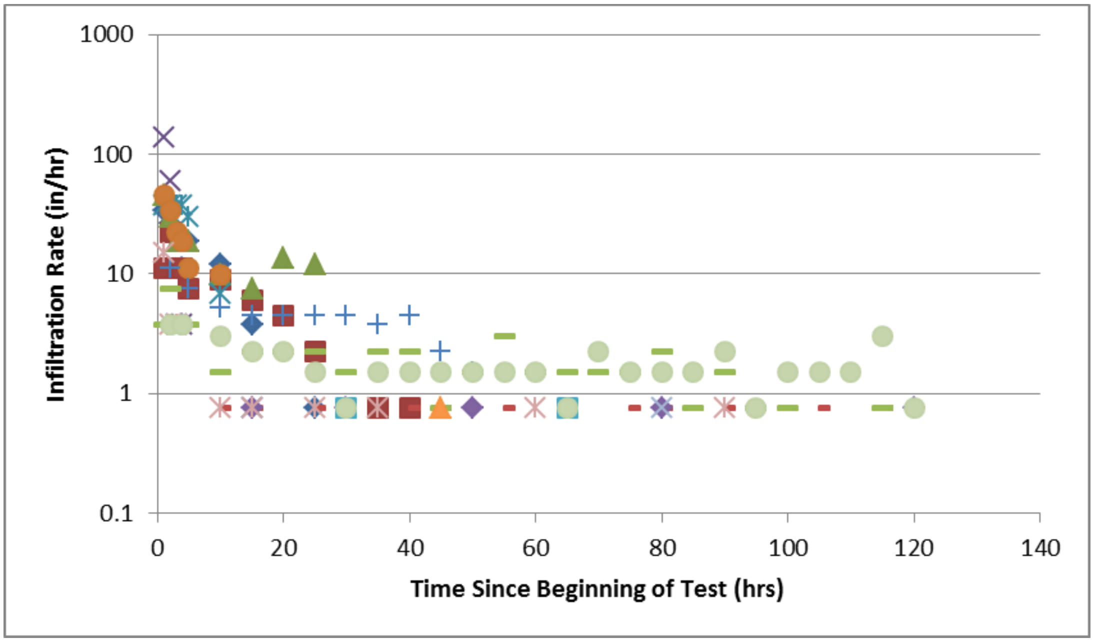


Figure 14. Soil infiltration rates (in/hr) vs. time of test (hr).

Table 5 shows the observed infiltration rates, averaged for different event durations (in/hr). These values are also plotted in Figure 15.

Table 5. Infiltration rates for different event durations (in/hr)

	5-min event	15-min event	30-min event	60-min event	90-min event	120-min event
Average	12.15	4.12	2.73	1.58	1.15	0.90
Std dev	20.42	6.28	5.04	3.79	3.17	2.78
COV	1.68	1.52	1.84	2.39	2.76	3.10
Min	0.00	0.00	0.00	0.00	0.00	0.00
Max	138.75	30.00	30.00	30.00	30.00	30.00

Figure 15 indicates that the infiltration rate would be between 1 and 10 inches per hour for rains that lasted up to about 2 hours, with likely decreasing infiltration rates for the long rains of interest for the critical combined sewer overflow event design storm. Initial modeling efforts assumed infiltration rates of about 0.3 inch per hour, but more recent measurements and deeper soil profiles indicated that this might even be too large for the site. Therefore, for the shallow rain gardens considered in this analysis, infiltration rates of 0.2 inch per hour were used.

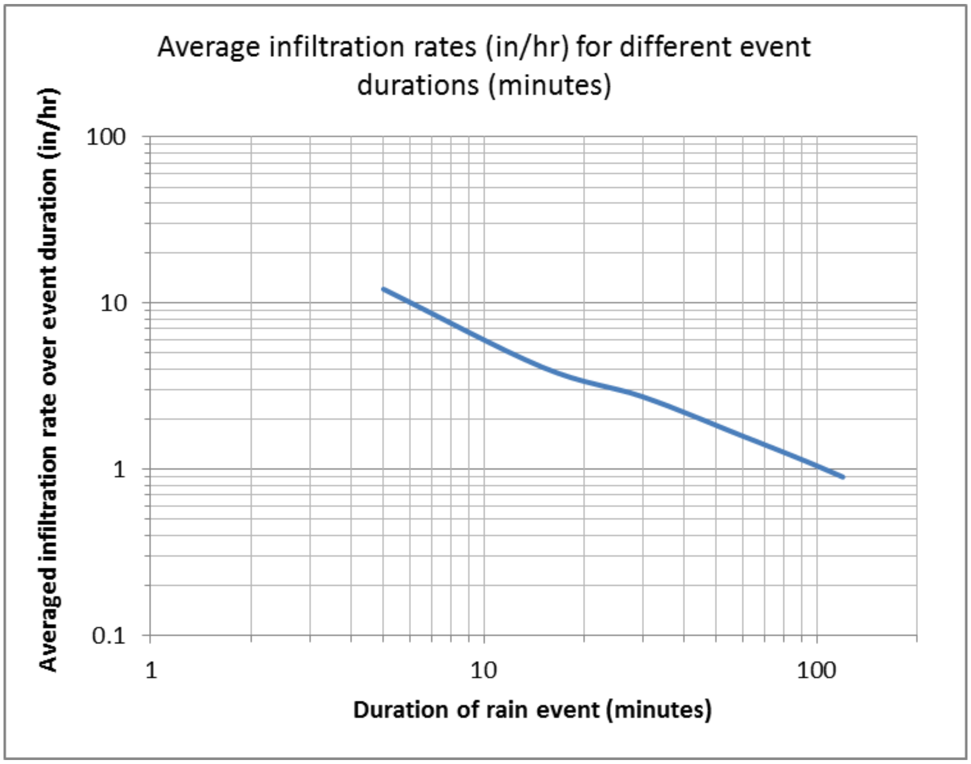


Figure 15. Averaged infiltration rates for different rain event durations.

3 Modeled Stormwater Characteristics Compared to Observed Data

As noted above, the land use characteristics were used to create a range of standard land use files for evaluation with WinSLAMM. Six geographical areas and six major land use categories were examined. Many of the locations where the site characteristics were available also had stormwater monitoring data available that were used for regional calibration. If sites did not have site-specific data, NSQD regional data were used instead.

The first task was to sort all the land use files into these six major land use categories. Table 6 lists the number of sites that were available for each group. As noted, most of the data were available for residential, then commercial areas, with less data available for institutional, industrial, open space, and highway/freeway areas. A total of 114 files with concurrent stormwater quality and quantity data were used, with most in the residential and commercial areas, as previously noted, and with most of the files in the Great Lakes region (because of the large number of Wisconsin observations), in the Southeast (because of the large number of Birmingham, Alabama, area observations), and in the Central region (because of the Lincoln, Nebraska, observations).

Table 6. Number of land use files used for each category

Region	Commercial	Industrial	Institutional	Open space	Residential	Freeways/ highways	Total by location
Central	4	2	4	1	5	3	19
East Coast	3	1	1	1	2	3	11
Great Lakes	6	4	4	2	11	4	31
Northwest	2	1	1	1	3	3	11
Southeast	7	2	3	5	8	4	29
Southwest	5	1	1	1	2	3	13
Total by land use	27	11	14	11	31	20	114

The calculated long-term modeled concentrations were compared to the monitored concentrations for each site and for the land use category combined. Appendix B shows the scatterplots of the 114 land use conditions, comparing the calibrated modeled with the observed concentrations. Table 7 summarizes the results of the comparisons of the modeled to the observed values for all 114 files (91 for Rv, because some areas did not have suitable comparison data) for each constituent. As noted in this summary table, the regression statistics are all excellent (the P-values of the regression equations and for the slope terms are all highly significant), and the regression slope terms are close to 1.0, with a few exceptions. The 95 percent confidence intervals included 1, or were within 10 percent, for all cases except TDS, NO_3, Cu, and fecal coliforms. The residual behaviors were all very good, except for phosphorus with modeled concentrations being too high for small observed concentrations. All the other constituents had random variations about the best fit lines with small variabilities. The biases for some of the constituents will be further examined when additional site becomes available. Therefore, the following lists the performance of the calibrations using the available data:

- Excellent: Slope term (modeled = observed conditions) included 1 in the 95 percent confidence interval and residual behavior was good: COD, TKN, Pb, and Zn
- Very Good: Slope term < 10 percent low: Runoff volume (by 7 percent), total suspended solids (TSS) (by 10 percent)
- Good: Slope term 11 to 40 percent low: TDS (by 38 percent), NO_3+NO_2 (by 30 percent), Cu (by 41 percent), and fecal coliforms (by 26 percent)

- Needs further adjustments: Residual behavior indicates bias for small values: total and filtered phosphorus (moderate level of bias)

Table 7. Summary of observed vs. modeled concentrations

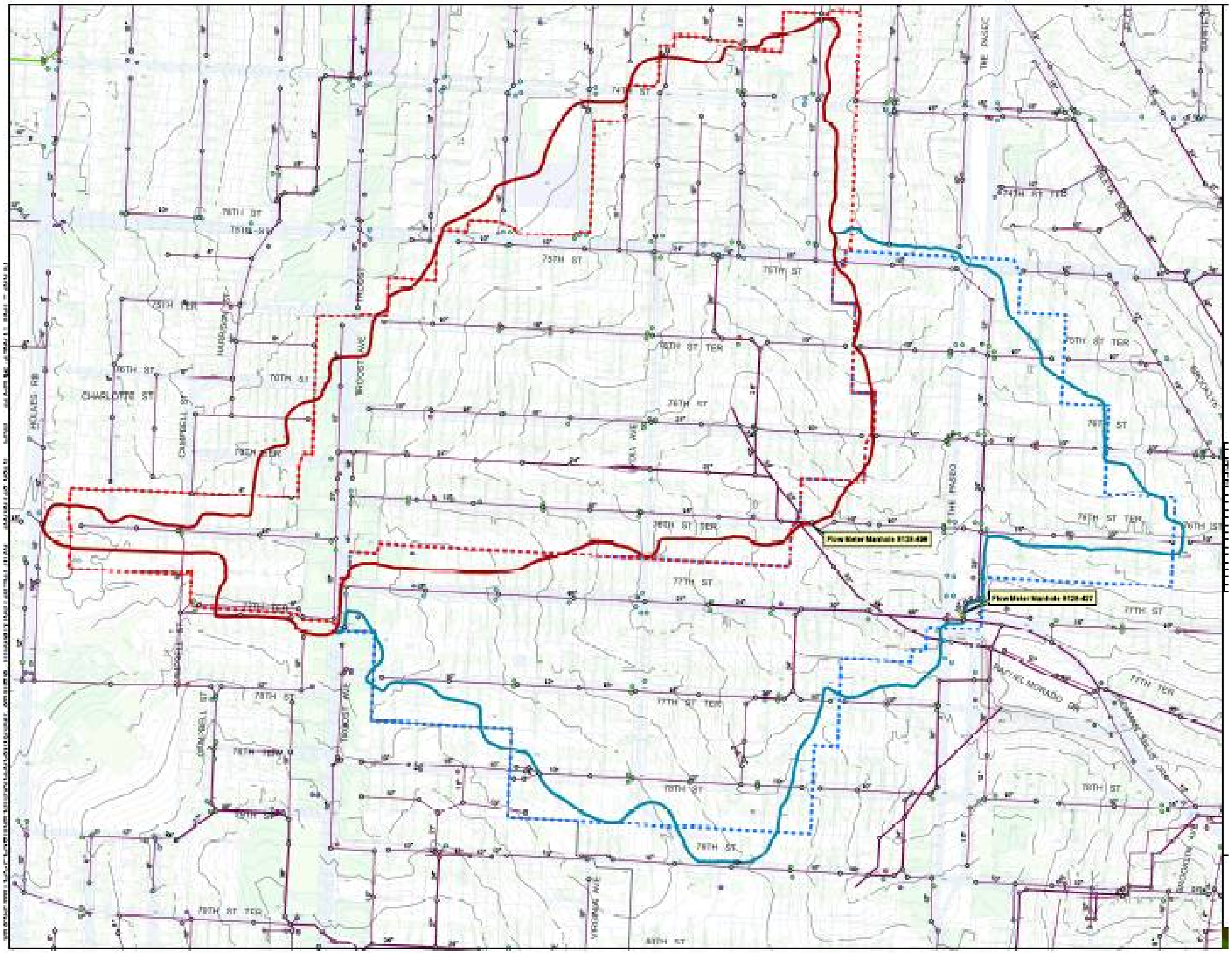
	Regression slope (intercept = 0) and 95% CI	P-value of slope term	P-value of regression	Adjusted R^2	Number of observations	Residual behavior comments
Volumetric runoff coefficients	0.93 (0.87, 0.99)	< 0.0001	< 0.0001	0.90	91	Good
Total suspended solids	0.90 (0.83, 0.97)	< 0.0001	< 0.0001	0.85	114	Good
Total dissolved solids	0.62 (0.53, 0.70)	< 0.0001	< 0.0001	0.63	114	Good
Chemical oxygen demand	1.00 (0.92, 1.04)	< 0.0001	< 0.0001	0.93	114	Good
Total phosphorus	0.88 (0.68, 1.08)	< 0.0001	< 0.0001	0.40	114	Most modeled values high for small observed TP concentrations
Filterable phosphorus	0.95 (0.81, 1.09)	< 0.0001	< 0.0001	0.61	114	Most modeled values high for small observed filterable P concentrations
Total Kjeldahl nitrogen	1.06 (0.96, 1.15)	< 0.0001	< 0.0001	0.80	114	Good
Nitrites plus nitrates	0.70 (0.62, 0.78)	< 0.0001	< 0.0001	0.71	114	Good
Total copper	0.59 (0.50, 0.67)	< 0.0001	< 0.0001	0.60	114	Good
Total lead	0.99 (0.93, 1.05)	< 0.0001	< 0.0001	0.90	114	Good
Total zinc	0.96 (0.92, 1.00)	< 0.0001	< 0.0001	0.95	114	Good
Fecal coliform bacteria	0.74 (0.65, 0.83)	< 0.0001	< 0.0001	0.68	114	Good

CI – Confidence interval

4 Runoff Calibration for Test and Control Watersheds

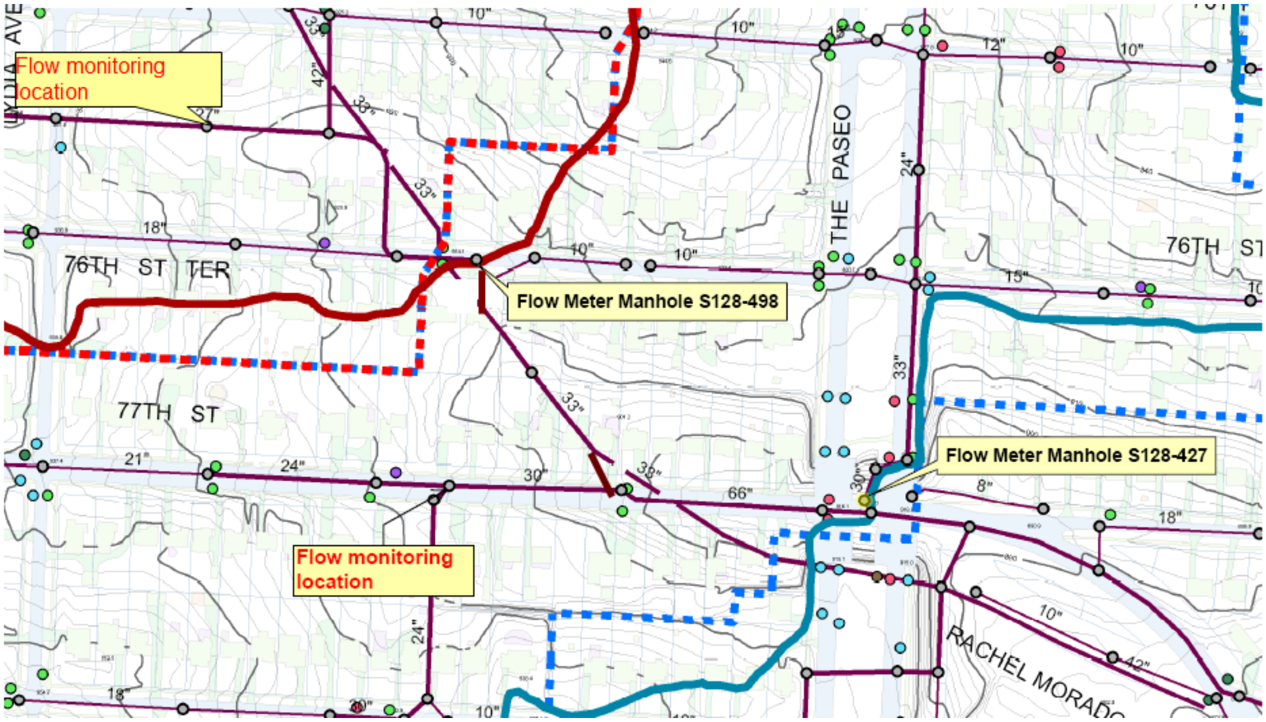
Runoff monitoring was conducted in the combined sewer system at several locations in the test and control watersheds. This sampling arrangement enabled flows to be separated for the test and the control watersheds. Nine complete events were monitored in the area during 2009, and six events were monitored during 2010. These data were used to do an initial verification of the WinSLAMM runoff calculations. Because sewer rehabilitation was occurring during this period in the test watershed, only the control area data were used for these analyses. The following describes the data collected and its formatting.

As noted previously, the detailed land development and land use information for the test and control watersheds will enable the verification of the water quantity portion of WinSLAMM, using this site rainfall and runoff data. Figures 16 and 17 (from Tetra Tech) show the test and control watershed boundaries and the locations of the flow monitoring stations. Monitoring station S128-427 measures the flows from both areas combined, and station S128-498 measures the flows from the test watershed alone. Therefore, the station 498 flows are subtracted from the combined station 427 flows to obtain the control watershed flows portion. This was the best arrangement to determine the separate flows from each area and enables flow characteristics to be quantified for each area for each event.



Source: Tetra Tech and KCMO

Figure 16. Test (100 acres) and control (86 acres) watersheds in the Marlborough area of Kansas City, Missouri



Source: Tetra Tech and KCMO

Figure 17. Flow monitoring locations at test and control area boundaries

Tables 8 and 10 (flow data summaries provided by Tetra Tech) contain the flow data observed during the monitoring period. These tables contain the observed values, with the values shown in Tables 9 and 11 calculated on the basis of the observed data. The raw flow data represents both the dry- and wet-weather flows together in the monitored combined sewers. However, because we are interested in only the wet-weather flows, the flow values in the wet-weather flow tables below have had the dry-weather sanitary sewage flows subtracted. The preceding dry-weather period (showing the diurnal flow fluctuations that vary by day of the week and time of day) were subtracted from the combined flows to result in the separate rainfall-runoff contributions. The resulting data were used in the model calibration efforts.

Table 8. Observed rainfall and runoff conditions for the test and control watersheds (2009 monitoring period)

Site	Area (acres)	Event #	Rain start date	Rain start time	Rain end date	Rain end time	Total rain[a] (in)	5-minute peak rain intensity[a] (in/hr)	Pipeflow start date	Pipeflow start time	Pipeflow end date	Pipeflow end time	Total pipeflow discharge volume[b] (ft^3)	Peak pipeflow discharge rate[b] (cfs)
Test watershed	100	1	9/4/2009	10:30	9/5/2009	2:45	0.4	0.48	9/4/2009	10:30	9/5/2009	6:00	51,050	7.51
Control watershed	86	1	9/4/2009	10:30	9/5/2009	2:45	0.4	0.48	9/4/2009	12:15	9/4/2009	18:15	5,314	2.67
Test watershed	100	2	9/8/2009	16:00	9/9/2009	17:30	0.32	0.48	9/8/2009	16:30	9/10/2009	9:30	54,665	4.1
Control watershed	86	2	9/8/2009	16:00	9/9/2009	17:30	0.32	0.48	9/8/2009	16:00	9/9/2009	19:00	15,787	3.69
Test watershed	100	3	9/21/2009	10:00	9/22/2009	14:45	0.77	0.48	9/21/2009	10:15	9/23/2009	1:30	113,380	5.25
Control watershed	86	3	9/21/2009	10:00	9/22/2009	14:45	0.77	0.48	9/21/2009	10:00	9/22/2009	2:00	56,618	4.35
Test watershed	100	4	9/26/2009	0:30	9/26/2009	4:30	0.4	0.36	9/26/2009	0:45	9/27/2009	0:00	56,550	8.94
Control watershed	86	4	9/26/2009	0:30	9/26/2009	4:30	0.4	0.36	9/26/2009	1:00	9/26/2009	19:30	28,793	5.02
Test watershed	100	5	9/30/2009	16:15	10/1/2009	11:15	0.14	0.24	10/1/2009	5:00	10/1/2009	8:00	5,586	1.04
Control watershed	86	5	9/30/2009	16:15	10/1/2009	11:15	0.14	0.24	9/30/2009	16:30	10/1/2009	23:45	21,442	1.96
Test watershed	100	6	10/6/2009	2:15	10/9/2009	5:30	2.09	1.56	10/8/2009	2:30	10/11/2009	4:15	320,319	16.77
Control watershed	86	6	10/6/2009	2:15	10/9/2009	5:30	2.09	1.56	10/6/2009	2:30	10/9/2009	1:30	112,689	7.29
Test watershed	100	7	10/11/2009	23:30	10/15/2009	0:15	0.48	0.36	10/11/2009	23:30	10/15/2009	10:15	102,782	6.02
Control watershed	86	7	10/11/2009	23:30	10/15/2009	0:15	0.48	0.36	10/11/2009	23:30	10/15/2009	2:30	47,355	4.62
Test watershed	100	8	10/20/2009	5:30	10/22/2009	15:00	1.32	1.32	10/20/2009	5:45	10/25/2009	13:00	327,772	11.57
Control watershed	86	8	10/20/2009	5:30	10/22/2009	15:00	1.32	1.32	10/20/2009	5:30	10/24/2009	3:00	94,243	8
Test watershed	100	9	10/25/2009	14:00	10/27/2009	13:00	0.73	0.48	10/25/2009	14:00	10/29/2009	5:00	230,809	12.67
Control watershed	86	9	10/25/2009	14:00	10/27/2009	13:00	0.73	0.48	10/25/2009	14:00	10/28/2009	3:00	86,870	6.03

Source: Tetra Tech

Notes:

Event 10 is not included because of missing rain fall data. Events 11 and 12 are excluded since it seems to be an improper measurement from flow meter for Site 1.

a. the rainfall data are obtained from a rain gauge at the site location;

b. the discharge volumes and flow rates have dry-weather base flow value subtracted

Table 9. Calculated rainfall and runoff conditions (based on observed 2009 conditions)

Site	Event #	Rain start date	Antecedent dry days	Rain dur. (hrs)	Pipeflow duration (hrs)	Avg rain int. (in/hr)	Total discharge (in)	Rv	Pipeflow/rain duration ratio	Peak/avg. pipeflow rate ratio
Test watershed	1	9/4/2009	n/a	16.25	19.5	0.024	0.14	0.35	1.2	10.46
Control watershed	1	9/4/2009	n/a	16.25	6	0.024	0.017	0.04	0.37	11.31
Test watershed	2	9/8/2009	3.55	25.5	41	0.0125	0.15	0.47	1.61	11
Control watershed	2	9/8/2009	3.55	25.5	27	0.0125	0.05	0.15	1.06	23
Test watershed	3	9/21/2009	11.68	28.75	39.25	0.027	0.31	0.40	1.36	6.6
Control watershed	3	9/21/2009	11.68	28.75	16	0.027	0.18	0.23	0.55	4.5
Test watershed	4	9/26/2009	3.4	4	23.25	0.1	0.15	0.375	5.81	13.5
Control watershed	4	9/26/2009	3.4	4	18.5	0.1	0.09	0.225	4.62	12.1
Test watershed	5	9/30/2009	4.5	19	3	0.007	0.015	0.1	0.16	2.18
Control watershed	5	9/30/2009	4.5	19	31.25	0.007	0.068	0.48	1.64	10.48
Test watershed	6	10/6/2009	4.6	75.25	73.75	0.028	0.88	0.42	0.98	14.2
Control watershed	6	10/6/2009	4.6	75.25	71	0.028	0.36	0.17	0.94	16.6
Test watershed	7	10/11/2009	2.75	72.75	82.75	0.006	0.28	0.58	1.13	17.7
Control watershed	7	10/11/2009	2.75	72.75	75	0.006	0.15	0.31	1.03	26.4
Test watershed	8	10/20/2009	5.22	57.5	127.25	0.023	0.9	0.68	2.21	16.23
Control watershed	8	10/20/2009	5.22	57.5	93.5	0.023	0.3	0.23	1.62	28.7
Test watershed	9	10/25/2009	2.96	47	87	0.015	0.63	0.86	0.85	17.24
Control watershed	9	10/25/2009	2.96	47	61	0.015	0.28	0.38	1.29	15.3

Source: Tetra Tech

Table 10. Observed rainfall and runoff conditions for the test and control watersheds (2010 monitoring period)

Site	Area (acres)	Event #	Rain start date	Rain start time	Rain end date	Rain end time	Total rain[a] (in)	5-minute peak rain intensity[a] (in/hr)	Pipeflow start date	Pipeflow start time	Pipeflow end date	Pipeflow end time	Total pipeflow discharge volume[b] (ft^3)	Peak pipeflow discharge rate[b] (cfs)	Notes
Test watershed	100	1	4/5/2010	7:25	4/7/2010	19:40	1.46	2.64	4/5/2010	7:30	4/11/2010	5:15	638,316	39.5	
Control watershed	86	1	4/5/2010	7:25	4/7/2010	19:40	1.46	2.64	4/5/2010	7:30	4/11/2010	5:30	329,237	33.7	
Test watershed	100	2	4/16/2010	5:15	4/16/2010	9:15	0.11	0.12	4/16/2010	6:00	4/16/2010	7:30	1,844	0.68	A
Control watershed	86	2	4/16/2010	5:15	4/16/2010	9:15	0.11	0.12	4/16/2010	6:30	4/16/2010	8:30	3,203	0.89	A
Test watershed	100	3	4/22/2010	10:15	4/27/2010	5:45	3.36	1.08	4/22/2010	10:30	4/29/2010	0:00	1,016,906	19.1	
Control watershed	86	3	4/22/2010	10:15	4/27/2010	5:45	3.36	1.08	4/22/2010	10:30	4/29/2010	9:30	485,674	9.8	
Test watershed	100	4	4/29/2010	10:00	5/3/2010	11:00	0.82	1.2	4/30/2010	7:00	5/3/2010	4:45	123,915	23.1	
Control watershed	86	4	4/29/2010	10:00	5/3/2010	11:00	0.82	1.2	4/29/2010	10:00	5/3/2010	11:15	102,261	10.99	
Test watershed	100	6	5/19/2010	11:30	5/21/2010	2:00	1.34	0.96	5/19/2010	11:30	5/24/2010	0:00	532,394	19.61	
Control watershed	86	6	5/19/2010	11:30	5/21/2010	2:00	1.34	0.96	5/19/2010	14:15	5/21/10	1:30	182,745	10.68	
Test watershed	100	7	6/1/2010	13:00	6/2/2010	7:45	0.75	1.92	6/2/2010	6:45	6/2/2010	9:45	58,305	16.12	
Control watershed	86	7	6/1/2010	13:00	6/2/2010	7:45	0.75	1.92	6/2/2010	6:30	6/2/2010	8:30	23,959	8.27	

Source: Tetra Tech

Notes:

Events 5 and several other events after event 7 were not included because of missing flow data for Site 1.

A. This event might had an improper measurement from the flow meter for Site 1

a. The rainfall data are obtained from a rain gauge at the site location

b. The discharge volumes and flow rates have dry-weather base flow value subtracted

Table 11. Calculated rainfall and runoff conditions (based on observed 2010 conditions)

Site	Event #	Rain start date	Antecedent dry days	Rain dur (hrs)	Pipeflow duration (hrs)	Avg rain int (in/hr)	Total discharge (in)	Rv	Pipeflow/rain duration ratio	Peak/avg pipeflow rate ratio	Notes
Test watershed	1	4/5/2010	n/a	60.25	141.75	0.024	1.75	1.19	2.35	31.6	
Control watershed	1	4/5/2010	n/a	60.25	142	0.024	1.05	0.72	2.35	51.9	
Test watershed	2	4/16/2010	8.4	4	1.5	0.027	0.005	0.04	0.375	2.34	A
Control watershed	2	4/16/2010	8.4	4	2	0.027	0.01	0.09	0.5	2.26	A
Test watershed	3	4/22/2010	6.04	115.5	157.5	0.029	2.8	0.83	1.36	10.68	
Control watershed	3	4/22/2010	6.04	115.5	167	0.029	1.55	0.46	1.44	12.18	
Test watershed	4	4/29/2010	2.18	97	69.75	0.0085	0.34	0.41	0.72	47	
Control watershed	4	4/29/2010	2.18	97	97.25	0.0085	0.33	0.40	1.00	37.7	
Test watershed	6	5/19/2010	2.03	38.5	108.5	0.034	1.46	1.09	2.82	14.43	
Control watershed	6	5/19/2010	2.03	38.5	35.25	0.034	0.58	0.43	0.91	7.47	
Test watershed	7	6/1/2010	11.46	18.75	3	0.04	0.16	0.21	0.16	3.23	
Control watershed	7	6/1/2010	11.46	18.75	2	0.04	0.077	0.10	0.10	2.8	

Source: Tetra Tech

Notes:

A. This event seems to have an improper measurement from the flow meter for Site 1

WinSLAMM was used to evaluate the test and control watershed conditions during these two monitoring periods to verify the rainfall-runoff calibration on the basis of site development characteristics and the actual rains monitored. Figures 18 to 21 are scatterplots of the observed versus calculated runoff amounts for these 15 separate events for the control and the test watersheds, plus residual plots showing the calibration performance as a function of different rain characteristics. As shown, the calculated values are slightly lower than the observed values using these initial observations for the control watershed (Figure 18), and substantially lower for the test watershed (Figure 20). The overall average Rv observed at the control watershed was 0.29, and the calculated average Rv value was 0.28. The slope term in the regression comparing the modeled to the observed flow was highly significant ($p < 0.01$), but the slope of the regression line indicates about a 28 percent bias for the control watershed. In contrast, the overall average Rv observed at the test watershed was much higher, at 0.53, and the calculated average Rv was only 0.23. The slope term in the regression comparing the modeled to the observed flow in the test watershed was also highly significant ($p < 0.01$); however, the slope value of the regression indicated a much larger bias (61 percent) than for the control watershed.

Residual analyses were also conducted to identify where the model calibration could be improved. Figure 19 and 21 scatterplots show the residual (modeled minus observed flow depths, inches) versus, 5-minute peak rain intensity (in/hr), antecedent dry period (days), rain duration (hrs), rain depth (in), and sampling date for both the control and the test watersheds. The desired residual behavior is for the residuals to be small and to be evenly distributed over the range of the factor being compared. However, in most cases, the residuals have a general fan shape, with small residuals corresponding to *small* rains (low peak intensities, short rain durations, and small rain depths). For the control watershed (Figure 19), this classical behavior is seen for all the plots, but with a possible visual trend with the sample date. The largest positive residual (model over-prediction of runoff) occurred during the 2009 monitoring period, and the largest negative residual (model under-prediction of runoff) occurred during the 2010 monitoring period. Smaller positive and negative residuals also seem to have this same pattern, with an overall visually apparent downward trend in residual behavior between the two monitoring years. A regression analysis with time since the first monitored rain also resulted in a significant downward trend ($p = 0.04$). However, because there was a large gap between the two monitoring periods, an unequal variance t-Test was also conducted to detect any significance in the residuals between the two monitoring periods. With an assumed downward trend, the difference was significant ($p = 0.04$). Therefore, before making further adjustments in the flow calibrations for the control watershed, further monitoring results are needed to see if these model under-predictions are now consistent with time. As noted, the overall calibration at the control watershed was significant but with a moderate (28 percent) bias, somewhat greater than a desirable flow monitoring bias of about 25 percent.

Residual analyses were also conducted for the test watershed data to identify how the calibration could be improved to reduce the calculated larger than desired flow bias. As shown in Figure 21, most of the flow residuals are close to zero, with the notable exception of five residual values that have very large negative values (observed flows much larger than modeled flows). These five events are shown to be related to the large rains. In fact, when examined as a function of rain depth, the residuals have a very significant negative slope term (–0.43 per inch of rain; $p << 0.01$; $R^2 = 0.74$). However, the largest three negative residuals also all occur during the second rain year, resulting in a visually apparent decreasing trend. The slope term of this trend is significant ($p < 0.01$), but again because of the large gap between the two monitoring years, this regression analysis is problematic. An unequal variance t-Test was therefore used to examine the variances between the two monitoring years, but there was not sufficient data to indicate a significant difference ($p = 0.08$ assuming larger negative residuals in 2010). Therefore, a trend might exist with time in the residuals, and more data would be needed to verify the continued residuals. The strong and significant trend with rain depth is more straightforward and indicates that the model is under-predicting runoff from sources that contribute runoff during these larger rains, mainly the landscaped areas and the disconnected impervious areas. The problem with this solution, however, is that the very similar control watershed did not display the same residual behavior with rain depth, even though the monitoring data were obtained for the same events. All the available rainfall information was obtained from a single rain gage. It is possible that rainfall varied significantly across the two watersheds. This is much more likely during the larger events. Additional data are therefore warranted to confirm these observations. As an interim examination, these five larger events were removed from the test watershed data set. Figures 22 and 23 show this much better behaved rainfall-runoff response, which is very similar to the observations from the paired control watershed. The regression shows a bias of about 27 percent, and the slope coefficient is highly significant (p<<0.01).

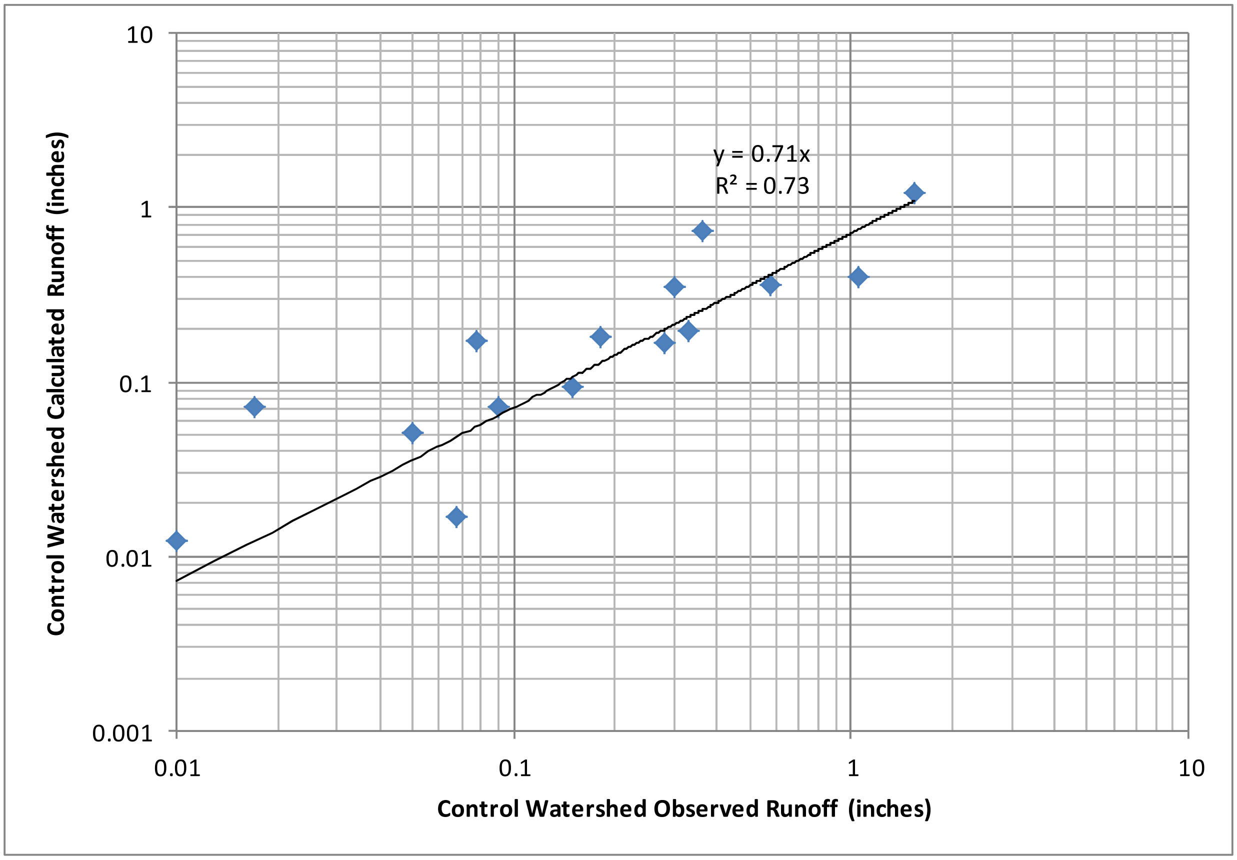
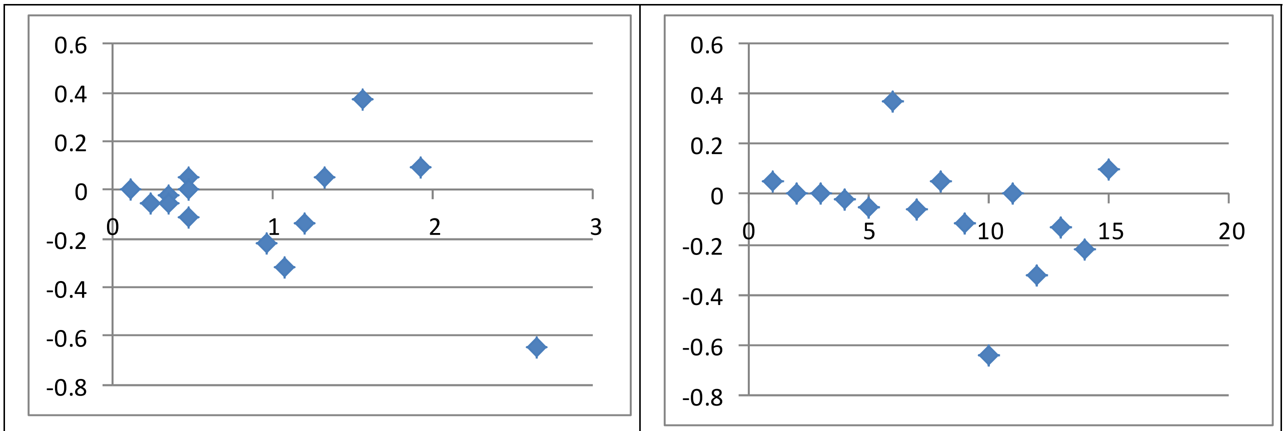
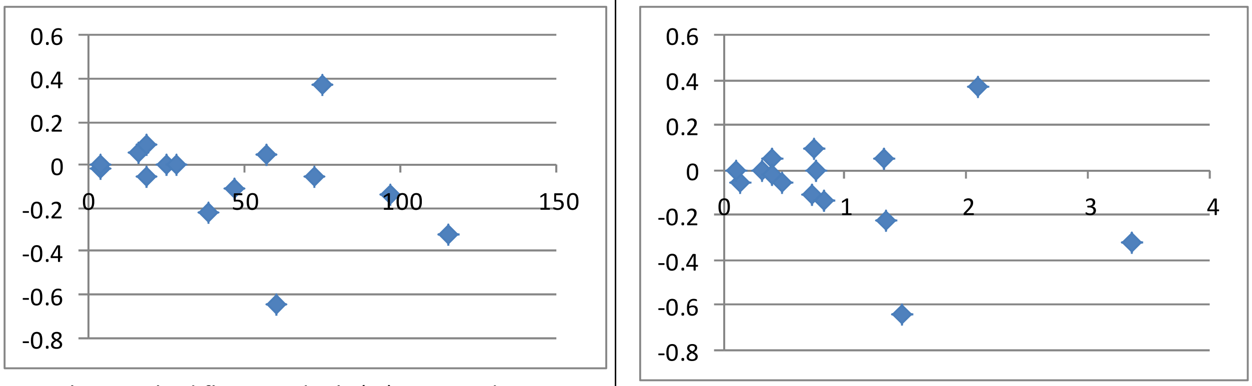


Figure 18. Modeled vs. observed runoff, control watershed.



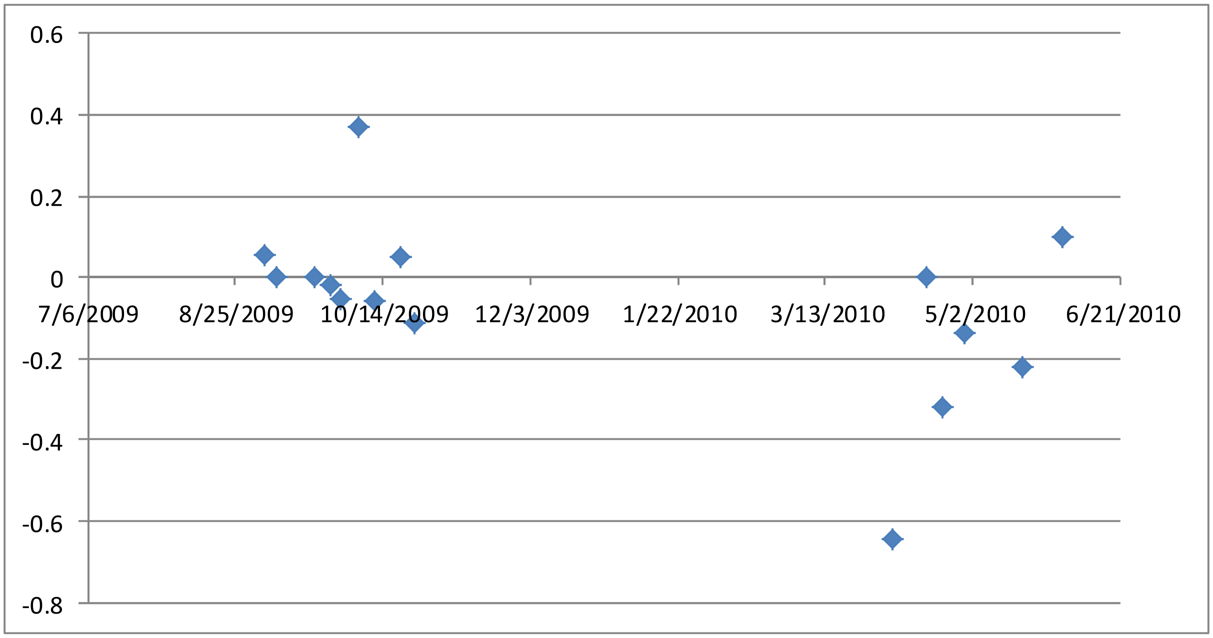
Control watershed flow residuals (in) vs. 5-min. peak rain intensity (in/hr)

Control watershed flow residuals (in) vs. antecedent dry period (days)



Control watershed flow residuals (in) vs. rain duration (hrs)

Control watershed flow residuals (in) vs. rain depth (in)



Control watershed flow residuals (in) vs. sample date

Figure 19. Residual analyses for control watershed.

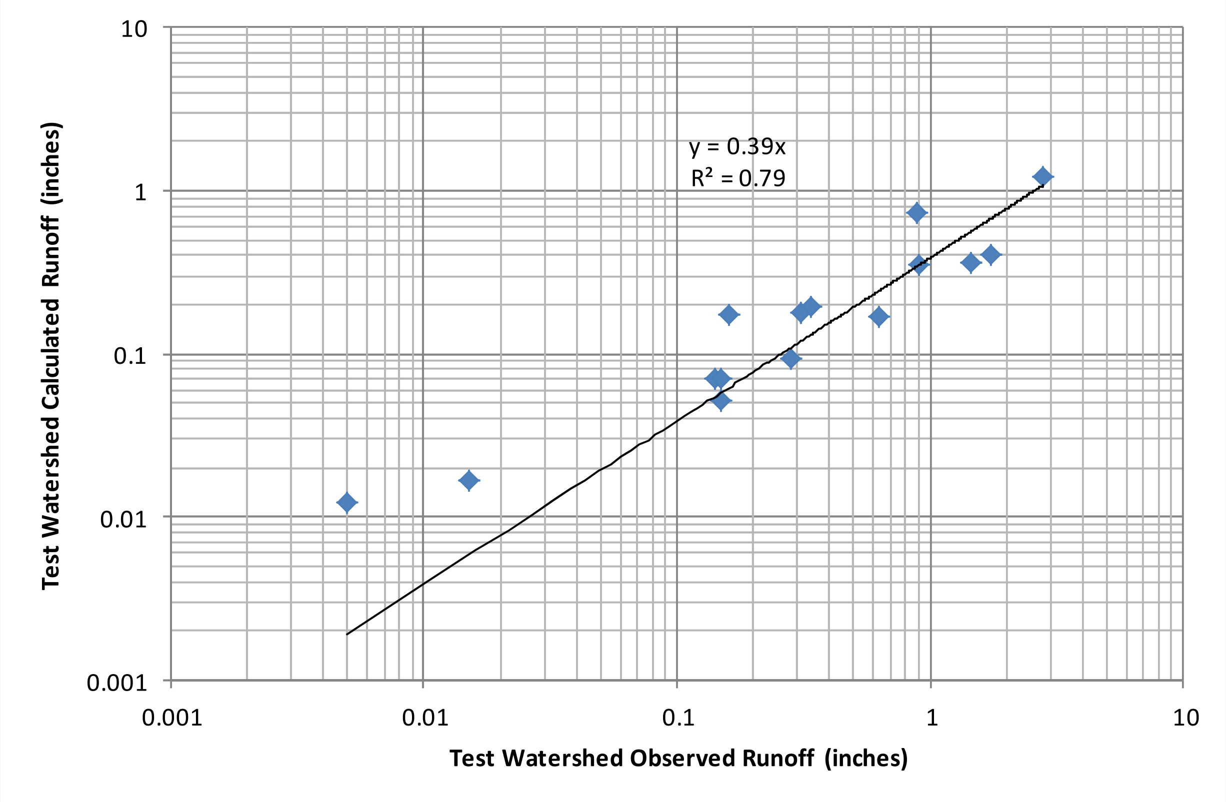
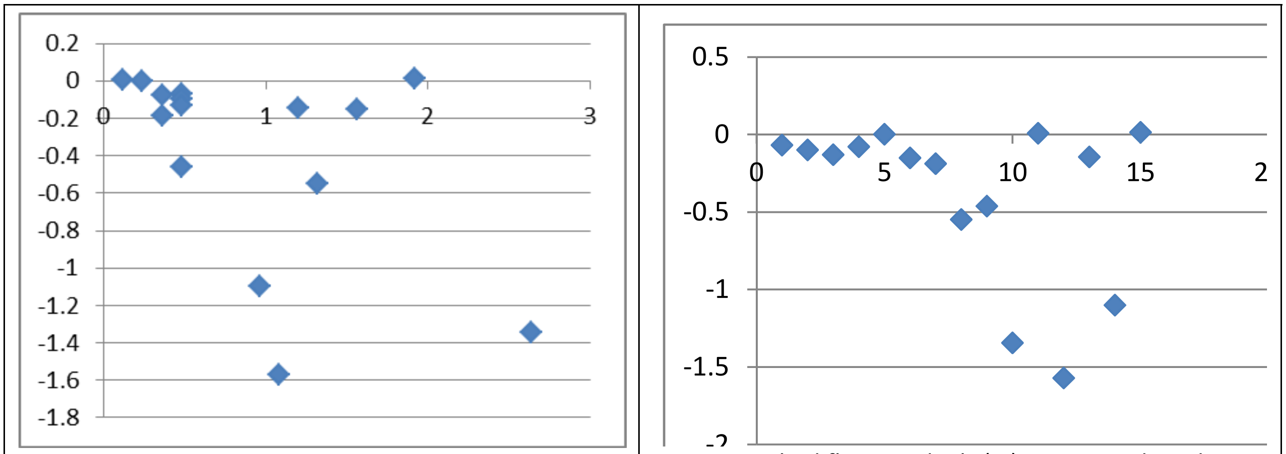
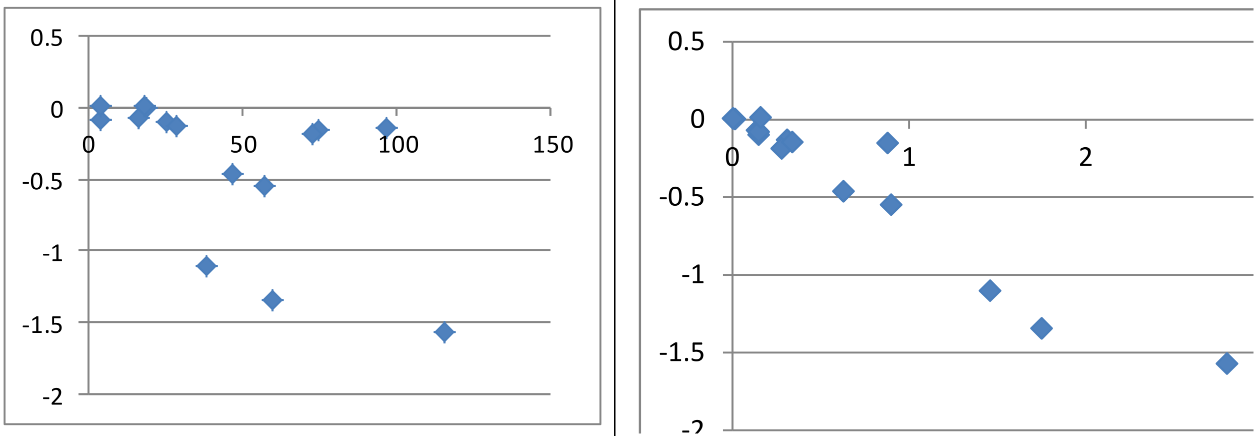


Figure 20. Observed and calculated runoff rates for test watershed.



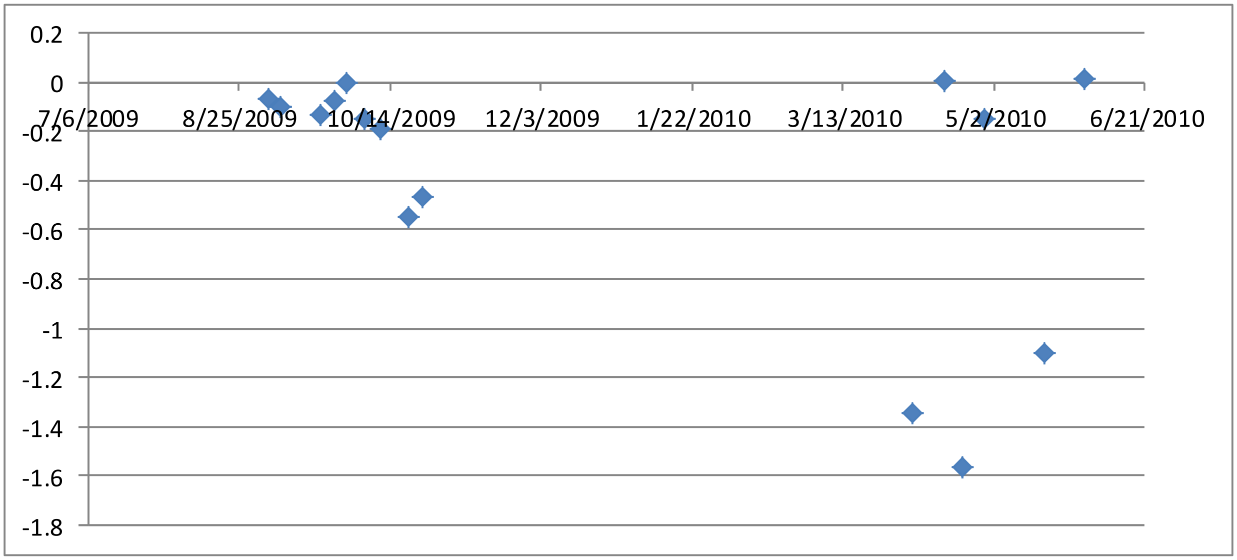
Test watershed flow residuals (in) vs. 5-min. peak rain intensity (in/hr)

Test watershed flow residuals (in) vs. antecedent dry period (days)



Test watershed flow residuals (in) vs. rain duration (hrs)

Test watershed flow residuals (in) vs. rain depth (in)



Test watershed flow residuals vs. sample data

Figure 21. Residual plots for test watershed modeling.

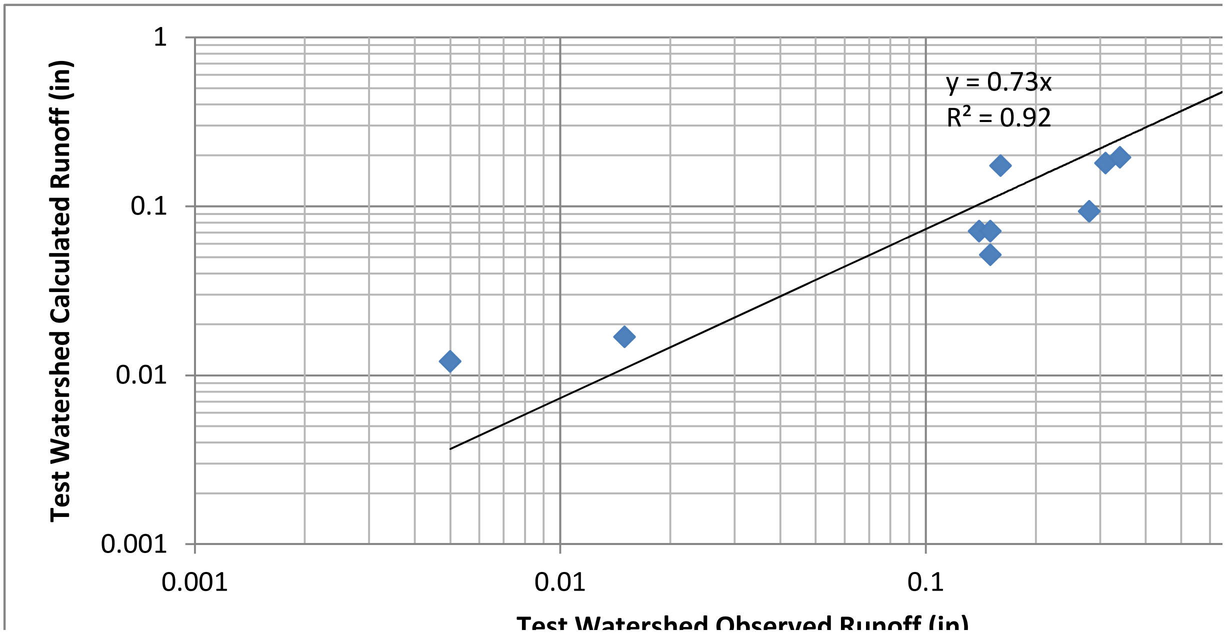
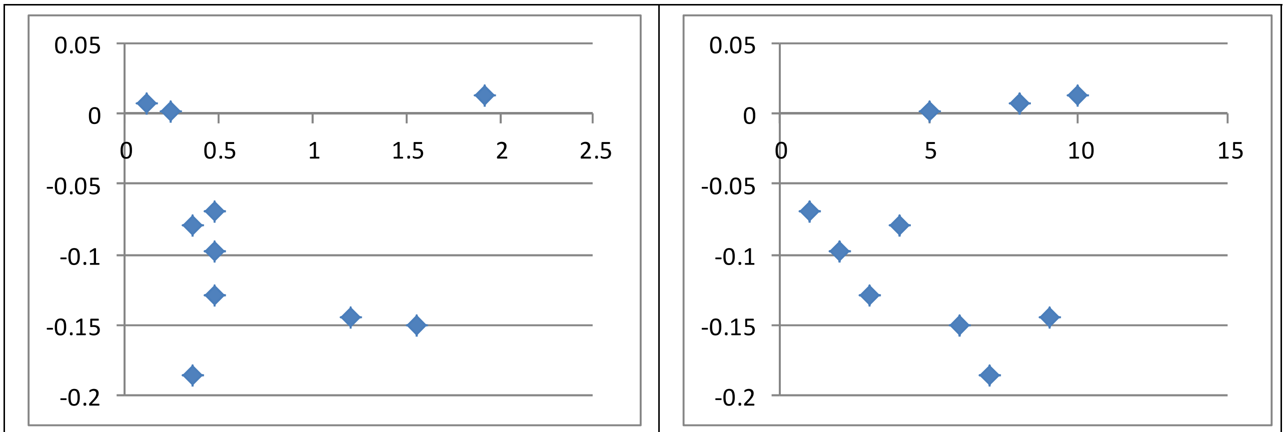
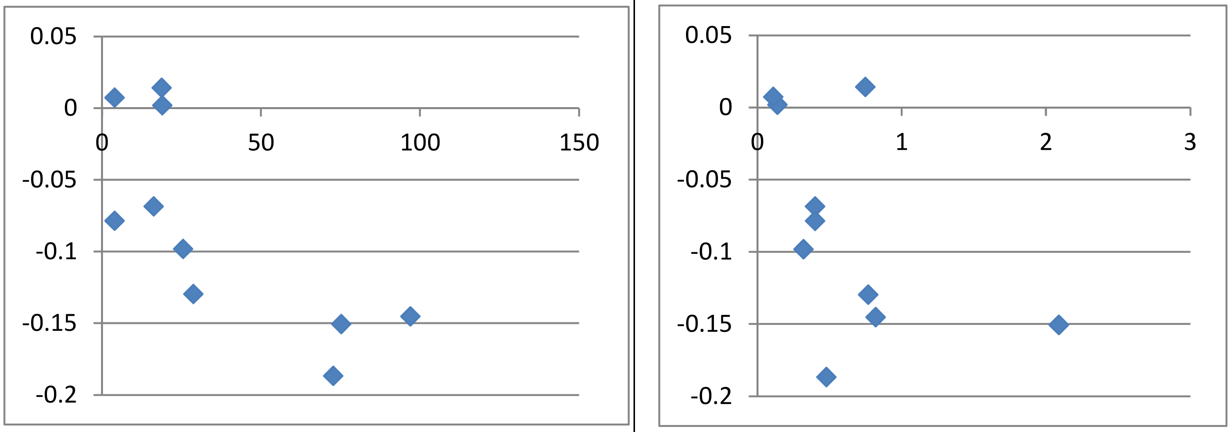


Figure 22. Test watershed observed vs. calculated runoff (in), without five events.



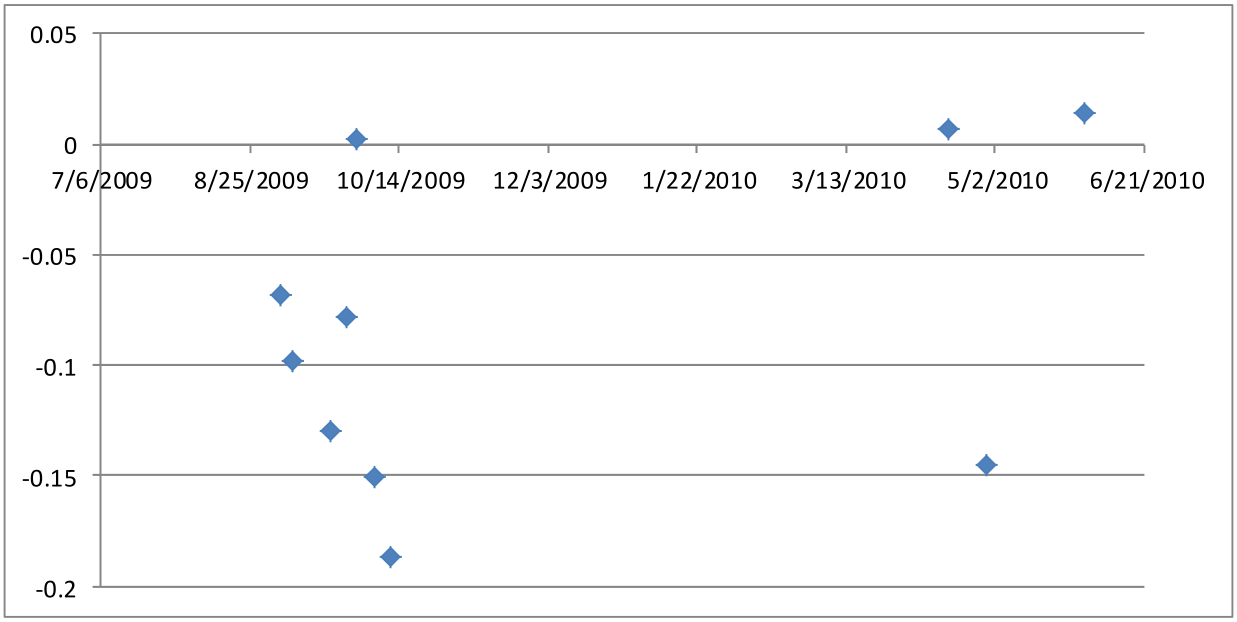
Test watershed flow residuals (in) vs. 5-min. peak rain intensity (in/hr), without five events

Test watershed flow residuals (in) vs. antecedent dry period (days), without five events



Test watershed flow residuals (in) vs. rain duration (hrs), without five events

Test watershed flow residuals (in) vs. rain depth (in), without five events



Test watershed flow residuals vs. sample data, without five events

Figure 23. Residual analyses for test watershed, excluding five large rains.

The sewer rehabilitation projects in the Marlborough area are also affecting the monitoring data, further precluding further modifications to the initial flow calibration until additional data are obtained. Therefore, the flow calibration is judged to be acceptable even though the bias is slightly more than the goal of a 25 percent agreement. The variability of the observed flow conditions might be somewhat larger than typical because of the indirect monitoring strategy (subtracting the flows from the adjacent monitoring locations to obtain the desired flows to isolate the study and test areas), and the use of one rain gage. However, the dual test and control watershed observations help increase the confidence in the data. There appears to be a larger than desired bias between the observed and calculated flows, but it is not excessive. As more data becomes available during the next project phases, additional WinSLAMM flow calibration and verification will be conducted for reevaluations. The calculations shown in this report are therefore suitable for initial project phase evaluations.

4.1 Variability and Uncertainty with WinSLAMM Modeling

WinSLAMM contains various Monte Carlo components that enable one to evaluate uncertainty during the model runs. These are available for the infiltration rates for the various infiltration and biofiltration devices, and for the pollutant concentrations. During field investigations, these model parameters have been recognized as having the greatest variabilities that are not explained by the model. The Monte Carlo elements are described by probability distributions, with average and coefficient of variability values (COV) provided, and assumes log-normal distributions of the actual values. If these uncertainty options are selected, the model randomly selects a value of the parameter from this distribution for each rain event. The long-term simulations therefore result in calculated concentrations and loadings of the constituents and the runoff volumes that vary in a similar manner as observed during monitoring. For the calculations in this report, when different options are being directly compared, the Monte Carlo option was not used because that could affect the average ordering of the different options. However, several different scenarios were repeatedly analyzed, and the different concentrations and loads were examined to estimate the likely variability in the relative model outcomes. The absolute errors are described above in the calibration and verification discussions. As noted, the flow calculations might have a low to moderate bias by underreporting the expected runoff quantities; this bias will be further reduced by additional calibration in later project phases when additional data become available.

Table 12 summarizes these Monte Carlo results by showing the groups of constituents associated with different ranges of variability and uncertainty. As an example, when fully calibrated, WinSLAMM is able to predict the runoff volumes and particulate solids loads more accurately than the other constituents. With COV (the relative standard deviations compared to the average values) of about 5 percent of the average values, the 95 percent confidence range of these constituents would be within about 10 percent of the average (for normal distributions, about 95 percent of the data is obtained within ± 2 times the standard deviation values). However, for zinc concentrations, the 95 percent confidence interval is about ± 20 to 30 percent of the average values. The bacteria data has an even wider range for the confidence interval, as expected (± 60 to 70 percent for *Escherichia coli* and even wider for fecal coliforms). The relative runoff volume (the primary stormwater characteristic of interest in the Kansas City project) and TSS mass load reduction predictions for the alternative stormwater control programs are expected to be more precise and it might be possible to distinguish control programs that are much closer.

Table 12. Uncertainty of modeled constituents

COV (standard deviation as a percentage of average concentration)	
< 5%	runoff volume Rv total and filterable TKN TSS
5% to 10%	total and filterable copper total and filterable lead nitrates
10% to 15%	total and filterable zinc total and filterable COD TDS
30% to 35%	*E. coli* bacteria total and filterable phosphorus
65%	fecal coliform bacteria

5 Sources of Stormwater Flows and Pollutants

Tables 13 to 15 show the calculated sources of stormwater from different source areas in the Marlborough Kansas City test watershed. Table 13 shows how these sources change for different rain depths. Figure 24 also graphs this information. For the smallest rains (< 0.25 inch of rain), most of the runoff originates from the DCIAs (directly connected roofs, paved parking, driveways, sidewalks, and streets). After about 0.25 inch, the small landscaped areas contribute about half of the runoff, a relatively large fraction because of the clayey soils and low infiltration rates. Generally, streets contribute about half of the remaining flows, then driveways and the roofs.

Also shown in Table 14 are the flow contributions during design storm *D*, which is 1.4 inches deep and the basis for the design efforts in the test watershed to meet the regulatory requirements for the combined sewer overflow program. During this critical event, the landscaped areas contribute about 45 percent of the flows, the streets about 22 percent, and the driveways about 13 percent. The roofs combined also contribute about 13 percent of the total flows. Slightly less that 2 percent of the area is composed of the directly connected roofs, but they contributed more than 5 percent of the flows during this event. In contrast, the disconnected roofs that drain to pervious areas compose about 10 percent of the area and contribute about 7 percent of the runoff quantity.

Table 15 summarizes the flow contributions from all the rain events that occurred during the 26-year period from 1973 through 1999. The largest rain during this period was slightly more than 6 inches deep. Interestingly, the flow-weighted average contributions are similar to what is shown for the design storm event.

Table 13. Relative sources of flows for different rain conditions

Rain total (in)	Roofs 1 (directly connected) (1.87%)	Roofs 2 (drains to pervious) (10.57%)	Paved Parking/ Storage 1 (directly connected) (1.59%)	Driveways 1 (directly connected) (4.12%)	Driveways 2 (drains to pervious) (4.03%)	Driveways 3 (gravel) (0.81%)	Sidewalks/ Walks 1 (directly connected) (1.15%)	Sidewalks/ Walks 2 (drains to pervious) (1.34%)	Street Area 1 (inter. Texture) (9.35%)	Small Landscaped Area 1 (clayey soils) (65.13%)	Land use totals
0.01	24	0	76	0	0	0	0	0	0	0	100
0.05	9.9	0	22.5	19	0	0	5.3	0	43.2	0	100
0.1	13.5	0	15.9	19.9	0	0	5.5	0	45.1	0	100
0.25	7.9	5.5	7.5	11.2	2.3	0.5	3.1	0.8	25.5	35.8	100
0.5	6.6	6.8	5.8	9.7	2.7	0.5	2.7	0.9	22	42.2	100
0.75	6.1	7.2	5.3	9.3	2.8	0.6	2.6	0.9	21.2	44	100
1	5.9	7.4	5.1	9.1	2.8	0.6	2.5	0.9	20.7	45	100
1.5	5.4	7.3	4.6	9.6	2.8	0.6	2.7	0.9	21.9	44.2	100
2	4.9	7.6	4.2	9.3	2.9	0.6	2.6	1	21.1	45.8	100
2.5	4.5	8	3.9	8.7	3	0.6	2.4	1	19.9	48	100
3	4.3	8.1	3.6	8.5	3.1	0.6	2.4	1	19.3	49	100
4	3.8	8.6	3.2	7.7	3.3	0.7	2.1	1.1	17.5	52.2	100

Table 14. Residential - source area percentage contribution of runoff volume for design storm *D*

Rain total (in)	Roofs 1 (directly connected) (1.87%)	Roofs 2 (drains to pervious) (10.57%)	Paved Parking/ Storage 1 (directly connected) (1.59%)	Driveways 1 (directly connected) (4.12%)	Driveways 2 (drains to pervious) (4.03%)	Driveways 3 (gravel) (0.81%)	Sidewalks/ Walks 1 (directly connected) (1.15%)	Sidewalks/ Walks 2 (drains to pervious) (1.34%)	Street Area 1 (inter. Texture) (9.35%)	Small Landscaped Area 1 (clayey soils) (65.13%)	Land use totals
1.4	5.5	7.2	4.7	9.6	2.8	0.6	2.7	0.9	21.7	44.4	100

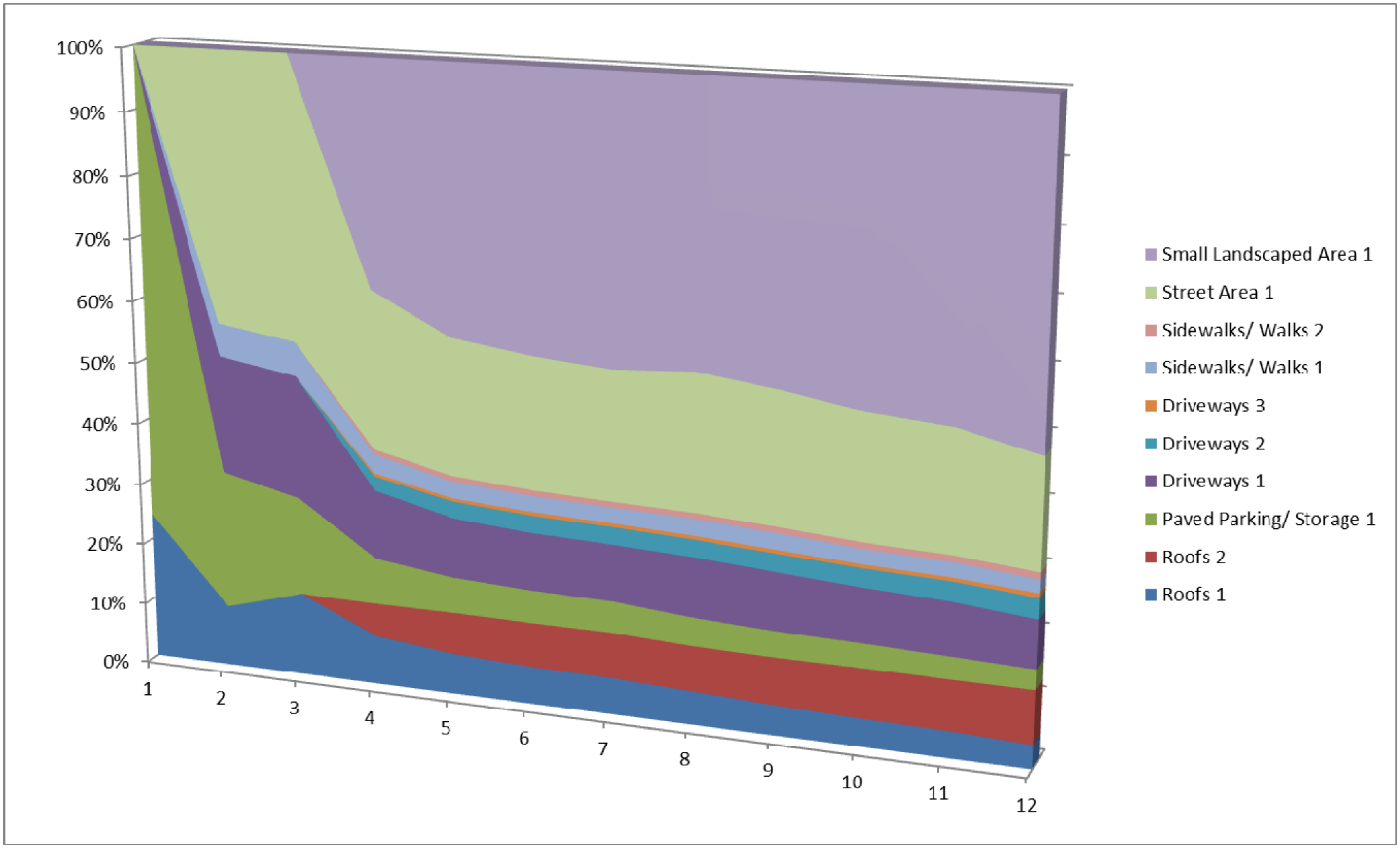


Figure 24. Flow sources by rain depth.

Rain event number	Rain total (in)
1	0.01
2	0.05
3	0.1
4	0.25
5	0.5
6	0.75
7	1
8	1.5
9	2
10	2.5
11	3
12	4

Table 15. Summary for runoff producing events for 26 year rain period (1973–1999)

	Rain total (in)	Roofs 1 (directly connected) (1.87%)	Roofs 2 (drains to pervious) (10.57%)	Paved Parking/ Storage 1 (directly connected) (1.59%)	Driveways 1 (directly connected) (4.12%)	Driveways 2 (drains to pervious) (4.03%)	Driveways 3 (gravel) (0.81%)	Sidewalks/ Walks 1 (directly connected) (1.15%)	Sidewalks/ Walks 2 (drains to pervious) (1.34%)	Street Area 1 (inter. texture) (9.35%)	Small Landscaped Area 1 (clayey soils) (65.13%)	Land use totals
Minimum:	0.01	3.4	0.2	2.9	7.1	0.1	0.1	2	0.2	16.1	1.6	100
Maximum:	6.19	24	8.9	76	19.9	3.4	0.7	5.5	1.1	45.3	54.5	100
Fl Wt Ave:	0.4	5.6	7.3	5	9.3	2.8	0.6	2.6	0.9	21.2	44.6	100

The calibrated WinSLAMM parameter files and local rains along with the land use files were also used to identify the major source areas of each pollutant and flow for a range of land uses. As noted above, only the medium-density residential area (pre-1960 construction) was available from the Marlborough test area in Kansas City, whereas the other land use descriptions were based on regional observations (mainly Lincoln, Nebraska) and other national data. The information for the other land uses is needed when examining potential stormwater flow and pollutant sources, and alternative stormwater control programs for other areas in the community having a more diverse land use makeup. Table 16 summarizes the details presented in Appendix C. This table includes summaries of the major flows and pollutant sources for each of eight land use categories (the urban freeway and rural highway were split, and an office technology park category was added to the original set of land use categories). The major sources are shown for each flow and constituent, for three different rain event categories: small (< 0.5 inch), intermediate (0.5 to 2 inches), and large (> 2 inches).

The small category generally includes most of the rain and runoff events by number, but produces a small fraction of the annual runoff mass. This category of events is therefore of greatest interest when the number of events is of concern. If regulatory limits have numeric effluent standards, the number of runoff events is of the greatest concern, and stormwater control strategies would focus on eliminating as many of the runoff events as possible. Relatively small rains are associated with most of the runoff events, by number (although the total runoff volume from these rains is relatively small). For many locations, typical numeric standards for bacteria and total recoverable heavy metals would be frequently exceeded. Therefore, runoff volume, bacteria, and heavy metals would be of the greatest interest for removal from the small rain category.

The intermediate category generally includes most of the runoff pollutant discharges by mass; frequently more than 75 percent of the annual pollutant discharges, by mass, occur during these rains. It is therefore greatly desired to remove as much of the runoff from this rain category. However, site soil and development conditions will likely prevent the elimination of all runoff from this category. Therefore, stormwater treatment will be needed for the constituents of concern for runoff that cannot be totally eliminated by site beneficial use or infiltration. Flow, as noted, will always be of interest, but further treatment of stormwater to reduce bacteria, nutrient, or heavy metal discharges will also likely be a suitable goal.

The largest rain category includes channel-forming events with dramatic effects on habitat conditions. Therefore, volume reductions during some portions of these large rains will provide some benefit, but reductions in runoff energy discharges will also need to be considered. Runoff energy reductions are most effectively associated with flow-duration modifications of the discharge hydrographs. The largest rains in this category (likely not included in the several year rainfall periods examined) are associated with drainage design and public safety. Flow sources are therefore of the greatest concern, and like for energy reductions, basinwide hydraulic analyses would be needed to result in the most effective stormwater management and drainage options. It is unlikely that pollutant discharges would be of great concern during these large events because they contribute relatively small fractions of the amortized annual flows, and any treatment method that could manage these large flows would be extremely costly and inefficient.

As shown in Table 16, most of the flows originate from the DCIAs, except when undeveloped or landscaped portions of the areas are very large (residential, open space, rural highways). For these areas, the landscaped/undeveloped areas can produce significant flows during the large rains (also during the intermediate rains for the office technology park and open space land uses). The goal of any stormwater management program should therefore be to reduce/eliminate runoff from the DCIAs. However, many conditions exist where large-scale infiltration of stormwater might not be desirable (mainly in areas having severely limited soils hindering infiltration, shallow groundwater, or other factors that would not adequately mitigate pollutant movement to the groundwater). In most cases, roof runoff, being the least contaminated DCIA source water, should be preferentially infiltrated or used on-site for beneficial uses.

In residential areas, roof runoff composes about 20 to 30 percent of the total annual runoff amount. However, streets (along with driveways and landscaped areas) can compose the majority of the total flows. A typical strategy in residential areas would therefore apply rain gardens or otherwise disconnect the roof drainage, for roof runoff control (for currently directly connected roofs). If possible, soil amendments and other strategies to reduce soil compaction to improve infiltration in the landscaped areas could eliminate much of the runoff from those areas. Street and driveway runoff would remain. If the area is drained using grass swales, it is likely that most of the total area runoff would be eliminated. If drained by conventional curbs and gutters, curb-cut bioinfiltration areas could be retrofitted to eliminate almost all the runoff (and associated pollutants). In residential areas having loamy soils that are not compacted and are drained by grass swales, especially if most of the impervious areas are disconnected and drain to pervious areas, additional stormwater controls might not be needed in residential areas. High-density residential areas having larger amounts of impervious areas would, obviously, require additional effort.

Commercial areas have most of their runoff originating from paved parking areas, streets, and roofs. These are also the main sources for most of the pollutants examined. Few opportunities exist to use rain gardens for roof runoff control in most commercial areas, so bioinfiltration areas that collect runoff from mixed sources might be an appropriate approach. In many parking areas, islands or landscaped edges can be retrofitted with infiltration devices for significant runoff volume reductions. Curb-cut biofilters would need to extend into the street in most cases because of a lack of suitable space near the street edge in most commercial areas. Treatment of commercial area stormwater runoff would therefore be needed because complete infiltration is not likely to be achieved. Critical source area treatments in areas of major automobile activity plus pollution prevention to reduce the use of galvanized metals are other strategies. Because of the lack of space in most commercial areas, stormwater treatment might need to be placed in adjacent areas or in underground chambers.

Industrial areas have most of their flows and pollutants originating from paved parking and storage areas. Roofs and streets are lesser but still important sources. Infiltration in these areas is of greater concern because the runoff from industrial areas is more likely to lead to groundwater contamination. Critical source area controls (such as media filtration and biofilters using specialized media as part of treatment trains) will likely be necessary, along with pollution prevention to reduce the exposure of metals (especially galvanized) and other materials. In some industrial areas, stormwater can be used for dust suppression. If a relatively large site, wet detention ponds could also be placed on available land to collect and further treat any remaining surface runoff.

Many institutional, office technology park, and open space areas are predominately landscaped, with fewer DCIAs and larger landscaped or undeveloped areas for stormwater management. Designing stormwater management features that take advantage of the topography in these areas can result in significant runoff discharge reductions. Some of these areas have large parking areas with long-term parking that can also benefit from parking lot island or perimeter bioinfiltration areas.

Rural highways usually have substantial undeveloped land within the rights of way that can be used for stormwater management, especially grass swales. A typical two- or four-lane rural highway could likely be totally controlled with moderately sized grass swales along both roadway edges. Urban freeways from four to eight (or more) traffic lanes might not have adequate space in the medians or along the roadway edges for grass swales. If the space is available, the swales can result in significant runoff reductions. However, significant excess runoff is likely because of the larger paved areas. Freeway intersections or exit/entrance ramps usually have substantial land contained within the rights of way at these locations. This land could be suitable for infiltration controls or wet detention ponds.

The summaries in Table 16 and Appendix C illustrate the likely maximum level of control for different stormwater management approaches applied to source areas. If substantial attention were applied to roof rain gardens in residential areas, it is obvious, for example, that significant runoff will still occur from other sources. Modeling of the different scenarios can be used to quantify how the different control approaches can (or cannot) meet desired objectives. Howerver, these summary tables and the figures can be used to indicate where management strategies should be focused.

Table 16. Summary of major sources of flows and pollutants

Constituents and rain categories	Residential	Commercial	Industrial	Institutional
Flows				
Small	Streets (50%) Roofs (25%)	Paved parking (40%) Streets (35%) Roofs (20%)	Paved park/stor (55%) Roofs (25%) Streets (17%)	Paved parking (50%) Roofs (20%) Streets (20%)
Intermediate	Streets (40%) Roofs (25%) Driveways (10%)	Paved parking (36%) Roofs (35%) Streets (30%)	Paved park/stor (48%) Roofs (28%) Streets (15%)	Paved parking (35%) Roofs (32%) Streets (18%)
Large	Landscaped (33%) Streets (28%) Roofs (20%)	Paved parking (35%) Roofs (30%) Streets (23%)	Paved park/stor (47%) Roofs (25%) Streets (12%)	Paved parking (33%) Roofs (27%) Streets (15%)
Total Suspended Solids				
Small	Streets (80%)	Streets (50%) Paved parking (20%)	Paved park/stor (60%) Streets (30%)	Streets (50%) Paved parking (25%)
Intermediate	Streets (60%) Small Landscaped (20%)	Paved parking (50%) Streets (30%) Roofs (12%)	Paved park/stor (75%) Streets (15%)	Streets (40%) Paved parking (34%)
Large	Small Landscaped (50%) Streets (30%) Driveways (10%)	Paved parking (62%) Roofs (14%) Streets (12%)	Paved park/stor (73%) Landscaping (10%)	Paved parking (38%) Landscaping (25%) Streets (17%)
Total Dissolved Solids				
Small	Streets (55%) Driveways (15%) Roofs (15%)	Streets (40%) Paved parking (30%) Roofs (10%)	Paved park/stor (65%) Streets (15%) Roofs (11%)	Streets (30%) Paved parking (30%) Roofs (25%)
Intermediate	Streets (44%) Landscaping (18%) Driveways (14%) Roofs (14%)	Roofs (37%) Streets (32%) Paved parking (24%)	Paved park/stor (66%) Streets (15%) Roofs (13%)	Roofs (33%) Paved parking (23%) Streets (22%)
Large	Landscaping (47%) Streets (26%)	Roofs (35%) Streets 28%) Paved parking (24%)	Paved park/stor (62%) Streets (12%) Roofs (11%)	Roofs (29%) Paved parking (20%) Streets (17%) Landscaped (12%)

Table 16. Continued

Constituents and rain categories	Residential	Commercial	Industrial	Institutional
Chemical Oxygen Demand				
Small	Streets (60%) Roofs (15%) Paved parking (10%)	Streets (50%) Paved parking (35%) Roofs (12%)	Paved park/stor (45%) Streets (40%)	Streets (50%) Paved parking (20%) Roofs (17%)
Intermediate	Streets (56%) Landscaping (13%) Roofs (12%) Driveways (10%)	Paved parking (36%) Roofs (35%) Streets (25%)	Paved park/stor (60%) Streets (21%) Roofs (12%)	Roofs (41%) Paved parking (25%) Streets (20%)
Large	Landscaping (44%) Streets (24%) Roofs (13%)	Paved parking (38%) Roofs (36%) Streets (19%)	Paved park/stor (60%) Streets (15%) Roofs (10%)	Roofs (37%) Paved parking (24%) Landscaping (18%) Streets (11%)
Total Phosphorus				
Small	Streets (75%) Driveways (12%)	Streets (50%) Paved parking (25%) Roofs (13%)	Streets (40%) Paved park/stor (40%)	Streets (55%) Paved parking (20%) Roofs (9%)
Intermediate	Streets (57%) Landscaped (25%)	Paved parking (30%) Roofs (30%) Streets (20%)	Paved park/stor (47%) Streets (23%) Landscaping (11%) Roofs (9%)	Landscaping (24%) Paved parking (21%) Streets (20%) Roofs (19%)
Large	Landscaped (70%) Streets (17%)	Landscaped (30%) Paved parking (28%) Roofs (23%) Streets (11%)	Paved park/stor (39%) Landscaping (31%) Streets (13)	Landscaping (60%) Paved parking (14%) Roofs (11%)
Filterable Phosphorus				
Small	Streets (60%) Driveways (15%) Roofs (10%)	Paved parking (35%) Streets (26%) Sidewalks (17%) Roofs (16%)	Streets (68%) Paved park/stor (15%)	Paved parking (35%) Streets (20%) Driveways (12%) Playgrounds (11%)
Intermediate	Landscaping (46%) Streets (33%) Driveways (10%)	Paved parking (27%) Roofs (25%) Streets (19%) Landscaping (15%)	Streets (56%) Paved park/stor (15%) Landscaping (12%)	Landscaping (34%) Paved parking (20%) Roofs (18%) Streets (11%)
Large	Landscaping (77%) Streets (13%)	Landscaping (33%) Paved parking (20%) Roofs (17%) Streets (13%)	Street (37%) Landscaping (34%) Paved park/stor (12%)	Landscaping (60%) Paved parking 10%)
Total Kjeldahl Nitrogen				
Small	Streets (58%) Roofs (15%) Driveways (14%)	Streets (55%) Paved parking (20%) Roofs (12%)	Paved park/stor (50%) Streets (35%) Roofs (17%)	Streets (50%) Paved parking (25%) Roofs (18%)
Intermediate	Streets (36%) Landscaping (38%)	Roofs (38%) Paved parking (28%) Streets (23%)	Paved park/stor (46%) Roofs (26%) Streets (12%) Landscaping (10%)	Roofs (34%) Streets (21%) Paved parking (21%) Landscaping (15%)
Large	Landscaping (77%) Streets (9%)	Roofs (35%) Paved parking (28%) Landscaping (19%) Streets (15%)	Paved park/stor (36%) Landscaping (31%) Roofs (20%)	Landscaping (44%) Roofs (23%) Paved parking (16%) Streets (10%)

Table 16. Continued

Constituents and rain categories	Residential	Commercial	Industrial	Institutional
Nitrites + nitrates				
Small	Streets (45%) Roofs (25%) Driveways (10%)	Paved parking (37%) Streets (35%) Roofs (25%)	Paved park/stor (45%) Roofs (25%) Streets (20%)	Paved parking (40%) Roofs (25%) Streets (25%)
Intermediate	Streets (38%) Roofs (30%) Landscaping (11%) Driveways (9%)	Roofs (41%) Paved parking (29%) Streets (27%)	Paved park/stor (40%) Roofs (37%) Streets (16%)	Roofs (39%) Paved parking (29%) Streets (20%)
Large	Landscaping (33%) Streets (26%) Roofs (24%)	Roofs (39%) Paved parking (30%) Streets (24%)	Paved park/stor (40%) Roofs (34%) Streets (13%)	Roofs (34%) Paved parking (28%) Streets (16%) Landscaping (13%)
Total Copper				
Small	Streets (50%) Paved parking (13%) Roofs (10%)	Streets (50%) Paved parking (30%)	Paved park/stor (40%) Streets (35%) Roofs (20%)	Streets (50%) Paved parking (20%)
Intermediate	Streets (49%) Driveways (14%) Roofs (14%) Paved parking (13%)	Paved parking (46%) Streets (31%) Roofs (19%)	Paved park/stor (46%) Roofs (34%) Streets (14%)	Paved parking (37%) Streets (33%) Roofs (18%)
Large	Landscaping (26%) Streets (25%) Roofs (17%) Driveways (15%) Paved parking (15%)	Paved parking (52%) Roofs (21%) Streets (20%)	Paved park/stor (49%) Roofs (34%) Streets (10%)	Paved parking (42%) Streets (20%) Roofs (19%)
Total Lead				
Small	Streets (45%) Roofs (18%) Paved parking (15%) Driveways (15%)	Streets (50%) Paved parking (35%) Roofs (10%)	Paved park/stor (53%) Streets (30%)	Streets (65%) Paved parking (20%)
Intermediate	Streets (40%) Roofs (20%) Paved parking (13%) Landscaping (12%) Driveways (11%)	Paved parking (50%) Roofs (28%) Streets (18%)	Paved park/stor (75%) Streets (10%)	Paved parking (38%) Streets (28%) Roofs (21%)
Large	Landscaping (41%) Roofs (21%) Streets (13%) Paved parking (13%)	Paved parking (56%) Roofs (29%)	Paved park/stor (70%) Landscaping (10%)	Paved parking (42%) Roofs (22%) Landscaping (14%) Streets (12%)
Total Zinc				
Small	Streets (50%) Roofs (19%) Paved parking (15%)	Streets (55%) Paved parking (35%) Roofs (16%)	Paved park/stor (55%) Streets (25%) Roofs (13%)	Streets (55%) Paved parking (25%) Roofs (15%)
Intermediate	Streets (48%) Roofs (16%) Paved parking (14%)	Roofs (40%) Paved parking (38%) Streets (20%)	Paved park/stor (59%) Roofs (14%) Streets (13%)	Roofs (38%) Paved parking (33%) Streets (23%)
Large	Streets (25%) Landscaping (23%) Paved parking (17%) Roofs (16%)	Paved parking (43%) Roofs (42%) Streets (12%)	Paved park/stor (60%) Roofs (33%)	Roofs (40%) Paved parking (38%) Streets (13%)

Table 16. Continued

Constituents and rain categories	Residential	Commercial	Industrial	Institutional
Fecal Coliform Bacteria				
Small	Streets (48%) Paved parking (25%)	Paved parking (45%) Streets (31%) Sidewalks (15%)	Streets (75%) Paved park/stor (14%)	Paved parking (70%) Streets (15%)
Intermediate	Streets (42%) Paved parking (22%) Sidewalks (13%) Landscaping (12%)	Paved parking (44%) Streets (28%) Sidewalks (18%)	Streets (74%) Paved park/stor (14%)	Paved parking (67%) Streets (15%)
Large	Landscaping (33%) Streets (28%) Paved parking (20%)	Paved parking (38%) Streets (23%) Landscaping (19%) Sidewalks (15%)	Streets (68%) Paved park/stor (14%)	Paved parking (64%) Streets (13%)

Notes:
Small events: < 0.5 inch of rain
Intermediate events: 0.5 to < 2.5 inches of rain
Large events: 2.5 and greater inches of rain

Table 17. Summary of major sources of flows and pollutants

	Office Technology Park	Open Space	Urban Freeway	Rural Highway
Flows				
Small	Streets (90%)	Streets (60%) Paved parking (30%)	Paved lane and shoulder (100%)	Paved lane and shoulder (100%)
Intermediate	Streets (55%) Landscaped (35%)	Streets (50%) Landscaped (25%) Paved parking (20%)	Paved lane and shoulder (98%)	Paved lane and shoulder (96%)
Large	Streets (55%) Landscaped (34%) Roofs (10%)	Landscaped (60%) Streets (22%) Paved parking (14%)	Paved lane and shoulder (93%)	Paved lane and shoulder (84%) Large turf area (16%)
Total Suspended Solids				
Small	Streets (95%)	Streets (85%) Paved parking (10%)	Paved lane and shoulder (100%)	Paved lane and shoulder (100%)
Intermediate	Landscaping (50%) Streets (46%)	Streets (65%) Landscaping (28%)	Paved lane and shoulder (99%)	Paved lane and shoulder (98%)
Large	Landscaping (85%)	Landscaping (83%) Streets (12%)	Paved lane and shoulder (94%)	Paved lane and shoulder (81%) Large turf area (19%)
Total Dissolved Solids				
Small	Streets (95%)	Streets (60%) Paved parking (20%)	Paved lane and shoulder (100%)	Paved lane and shoulder (100%)
Intermediate	Streets (50%) Landscaping (43%)	Landscaping (45%) Streets (42%) Paved parking (10%)	Paved lane and shoulder (97%)	Paved lane and shoulder (93%)
Large	Landscaping (70%) Streets (19%)	Landscaping (75%) Streets (16%)	Paved lane and shoulder (91%)	Paved lane and shoulder (79%) Large turf area (21%)

Table 17. Continued

	Office Technology Park	Open Space	Urban Freeway	Rural Highway
Chemical Oxygen Demand				
Small	Streets (95%)	Streets (75%) Paved parking (10%)	Paved lane and shoulder (100%)	Paved lane and shoulder (100%)
Intermediate	Landscaping (57%) Streets (38%)	Streets (45%) Landscaping (41%) Paved parking (10%)	Paved lane and shoulder (98%)	Paved lane and shoulder (97%)
Large	Landscaping (80%) Streets (10%)	Landscaping (84%)	Paved lane and shoulder (91%)	Paved lane and shoulder (77%) Large turf area (23%)
Total Phosphorus				
Small	Streets (80%)	Streets (90%) Paved parking (10%)	Paved lane and shoulder (100%)	Paved lane and shoulder (100%)
Intermediate	Landscaping (85%) Streets (13%)	Streets (50%) Landscaping (46%)	Paved lane and shoulder (98%)	Paved lane and shoulder (92%)
Large	Landscaping (95%)	Landscaping (89%)	Paved lane and shoulder (81%) Large turf (19%)	Paved lane and shoulder (57%) Large turf area (43%)
Filterable Phosphorus				
Small	Streets (80%) Landscaped (20%)	Streets (87%) Paved parking (12%)	Paved lane and shoulder (100%)	Paved lane and shoulder (100%)
Intermediate	Landscaped (90%)	Landscaping (71%) Streets (23%)	Paved lane and shoulder (90%) Large turf (10%)	Paved lane and shoulder (77%) Large turf (23%)
Large	Landscaped (95%)	Landscaping (86%)	Paved lane and shoulder (72%) Large turf (28%)	Large turf area (52%) Paved lane and shoulder (58%)
Total Kjeldahl Nitrogen				
Small	Streets (95%)	Streets (75%) Paved parking (20%)	Paved lane and shoulder (100%)	Paved lane and shoulder (100%)
Intermediate	Landscaping (78%) Streets (18%)	Landscaping (63%) Streets (29%)	Paved lane and shoulder (90%) Large turf (10%)	Paved lane and shoulder (77%) Large turf (23%)
Large	Landscaping (92%)	Landscaping (93%)	Paved lane and shoulder (72%) Large turf (28%)	Large turf area (52%) Paved lane and shoulder (58%)
Nitrites + nitrates				
Small	Streets (95%)	Streets (65%) Paved parking (26%)	Paved lane and shoulder (100%)	Paved lane and shoulder (100%)
Intermediate	Streets (58%) Landscaping (31%) Roofs (10%)	Streets (55%) Paved parking (21%) Landscaping (20%)	Paved lane and shoulder (99%)	Paved lane and shoulder (97%)
Large	Landscaping (56%) Streets (24%) Roofs (15%)	Landscaping (48%) Streets (30%) Paved parking (15%)	Paved lane and shoulder (96%)	Paved lane and shoulder (89%) Large turf area (11%)

Table 17. Continued

	Office Technology Park	Open Space	Urban Freeway	Rural Highway
Total Copper				
Small	Streets (99%)	Streets (65%) Paved parking (33%)	Paved lane and shoulder (100%)	Paved lane and shoulder (100%)
Intermediate	Streets (76%) Landscaping (16)	Streets (55%) Paved parking (24%) Landscaping (18%)	Paved lane and shoulder (99%)	Paved lane and shoulder (99%)
Large	Landscaping (46%) Streets (31%) Roofs (11%)	Landscaping (53%) Streets (19%) Paved parking (19%)	Paved lane and shoulder (99%)	Paved lane and shoulder (96%)
Total Lead				
Small	Streets (100%)	Streets (65%) Paved parking (33%)	Paved lane and shoulder (100%)	Paved lane and shoulder (100%)
Intermediate	Streets (50%) Landscaping (40%)	Streets (43%) Landscaping (30%) Paved parking (21%)	Paved lane and shoulder (100%)	Paved lane and shoulder (99%)
Large	Landscaping (73%) Roofs (11%) Streets (10%)	Landscaping (70%) Paved parking (10%)	Paved lane and shoulder (96%)	Paved lane and shoulder (86%) Turf areas (14%)
Total Zinc				
Small	Streets (95%)	Streets (60%) Paved parking (35%)	Paved lane and shoulder (100%)	Paved lane and shoulder (100%)
Intermediate	Streets (71%) Landscaping (14%) Roofs (11%)	Streets (55%) Paved parking (28%) Landscaping (16%)	Paved lane and shoulder (100%)	Paved lane and shoulder (99%)
Large	Landscaping (36%) Roofs (28%) Streets (25%)	Landscaping (49%) Paved parking (26%) Streets (22%)	Paved lane and shoulder (98%)	Paved lane and shoulder (93%)
Fecal Coliform Bacteria				
Small	Streets (95%)	Streets (90%)	Paved lane and shoulder (100%)	Paved lane and shoulder (100%)
Intermediate	Streets (59%) Landscaping (38%)	Streets (81%)	Paved lane and shoulder (92%)	Paved lane and shoulder (80%) Turf area (20%)
Large	Landscaping (66%) Streets (25%)	Streets (56%) Landscaping (25%) Unpaved parking (12%)	Paved lane and shoulder (74%) Turf area (26%)	Paved lane and shoulder (51%) Turf area (49%)

6 Evaluation of Performance of Stormwater Control Practices

This section describes updated modeling results for the use of rain gardens, rain barrels/tanks, and roof disconnections that are being used in the Kansas City test area for controlling combined sewer overflows.

The land development characteristics and evaluating flow and pollutant sources in the area determine the maximum effectiveness of different types of controls. The land survey found that most of the homes in the test watershed already have disconnected roofs (85 percent of all roof areas) and that the total roof areas compose about 13 percent of the total area. These will severely hinder the ability to detect any total area benefits of controls practiced at the directly connected roofs because they are expected to contribute only a small portion of the total site runoff. The land survey also found that about 65 percent 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 in July and August, and excess rainfall occurs in October through December (compared to ET requirements during these relatively dormant months). Soil infiltration monitoring, along with soil profile surveys, has indicated relatively poorly draining soil in the test area. Surface infiltration rates during several hour rains might have infiltration rates of about 1 in/hr or greater, but these rates continue to decrease with increasing rain depths. For conservative modeling calculations, soil infiltration rates of 0.2 in/hr were used.

The expected major sources of runoff from the test area vary for different rain depth categories. DCIAs are the major runoff sources only for rains less than about 0.25 inch deep. The large landscaped areas contribute about half of the runoff for rains larger than about 0.5 inch deep. The directly connected roofs, which make up only about 2 percent of the study area, contribute about 6 percent of the total annual flows. The disconnected roofs, which compose about 11 percent of the area, contribute about 7 percent of the total flows. Therefore, complete control of the runoff from the directly connected roofs would reduce the total area runoff by only a very small amount—less than can be reliably detected by monitoring the total runoff from the area. However, source area monitoring at selected individual lots that have directly connected roofs should 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 percent. If all the roofs were directly connected, they would contribute about 30 percent 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 versus percent flow reductions. Rain gardens about 20 percent of the roof area are expected to result in about 90 percent reductions in total annual flow compared to directly connected roofs. This area is about 200 ft^2 per house, which could be composed of several smaller rain gardens so they can be placed at each downspout. Fifty percent reductions in the total annual flows could be obtained if the total rain garden area per house was about 7 percent of the roof area. The 200 ft^2 rain garden area per house is also expected to completely control the runoff from the regulatory design storm *D* of 1.4 inches.

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 percent, 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 from the roofs could be as high as about 40 percent. 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 of about 5 feet wide and 6 feet high is expected to result in about 75 percent total annual runoff reductions, and a larger tank that is 10 feet wide by 6 feet tall could approach complete roof runoff control. The 5-foot diameter tank is also expected to provide almost complete control of runoff from the regulatory design storm *D*.

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. To obtain reductions of about 90 percent 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 one small water tank) per house. In such a case, the rain gardens can be reduced to about 0.5 per house.

Simple disconnections of the directly connected roofs can provide significant reductions in the annual flows from the roofs for expected less cost. A reduction of about 80 percent is expected in the total flows with disconnections, even with the site's clayey soils, with most occurring during small rains, and the benefits decreasing as the rains increase in depth. This flow volume reduction is enhanced because of 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.

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 combined sewer overflow control program (288,000 gallons). As an example, storage provided at directly connected roofs need to be discounted by about 1.3 to 1.4 times because not all 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 the flows in the area, so their storage volumes are more effectively used. More significantly, if storage was provided at roofs that are already disconnected, their storage volumes would need to be discounted by about 4.5 times when compared to the total site storage goals, because of the existing infiltration occurring with the disconnected roof runoff.

6.1 Water Harvesting Potential

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

Table 18 shows the monthly average rainfall for the 1973 through 1999 period at the Kansas City airport, a 26-year 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 18. 1973 through 1999 Kansas City Airport rain records

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Average	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
Minimum	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
Maximum	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 be irrigated.

Tables 19 and 20 along with Figures 25 through 27 show the monthly ET requirements of typical turf grasses for a monitoring station near Kansas City (Ottawa, Kansas, at a University of Kansas field station). 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.

Table 19. Monthly irrigation requirements

Month	In/day ET*	ET (in/month)	Rainfall (in/month)	Irrigation deficit (in/month)	Irrigation deficit (gal/day/house)
Jan	0.05	1.55	1.13	0.42	42
Feb	0.10	2.83	1.24	1.59	172
Mar	0.10	3.10	2.54	0.56	55
Apr	0.15	4.50	3.48	1.02	104
May	0.20	6.20	5.41	0.79	78
Jun	0.20	6.00	4.27	1.73	177
Jul	0.25	7.75	4.15	3.60	357
Aug	0.25	7.75	3.63	4.12	408
Sep	0.20	6.00	4.63	1.37	140
Oct	0.10	3.10	3.32	n/a	0
Nov	0.05	1.50	2.08	n/a	0
Dec	0.05	1.55	1.60	n/a	0

* These ET values are for eastern Kansas (Ottawa, Kansas) and are for typical turf grasses.

Table 20. Monthly irrigation per household

Month	Irrigation needs per month (gal/house)	Irrigation needs per month (ft^3/house)	Irrigation needs per month (ft depth/house)	Irrigation needs per month (in. depth/month)	Irrigation needs per month (in. depth/week)
Jan	1,302	174	0.04	0.42	0.10
Feb	4,859	650	0.13	1.58	0.39
Mar	1,705	228	0.05	0.56	0.13
Apr	3,120	417	0.08	1.02	0.24
May	2,418	323	0.07	0.79	0.18
Jun	5,310	710	0.14	1.73	0.40
Jul	11,067	1,480	0.30	3.60	0.81
Aug	12,648	1,691	0.34	4.12	0.93
Sep	4,200	561	0.11	1.37	0.32
Oct	0	0	0.00	0.00	0.00
Nov	0	0	0.00	0.00	0.00
Dec	0	0	0.00	0.00	0.00
Totals:	46,629	6,234	1.27	15.19	

Figures 25 through 27 plot the monthly ET, rainfall, and supplemental irrigation needs. Most of the supplemental irrigation is needed in July and August, whereas an excess of rain falls in October through December and, therefore, no supplemental irrigation is needed then.

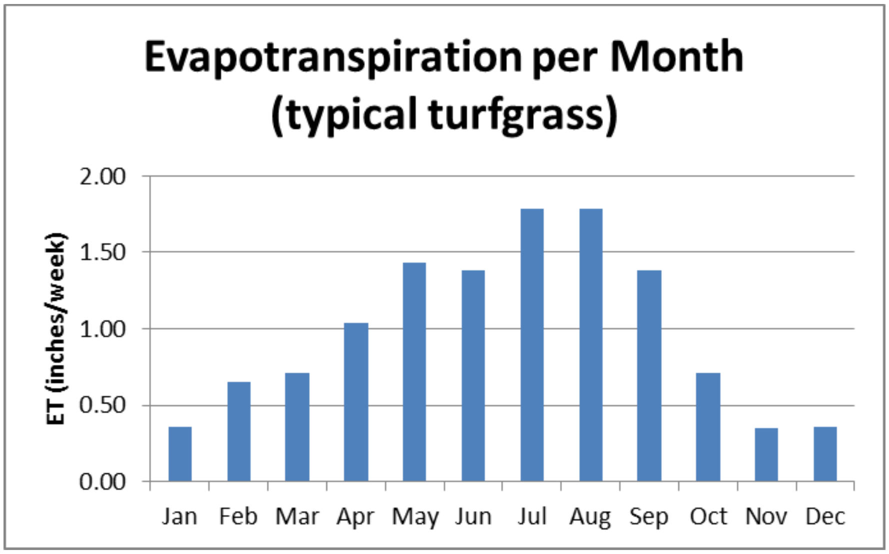


Figure 25. ET by month.

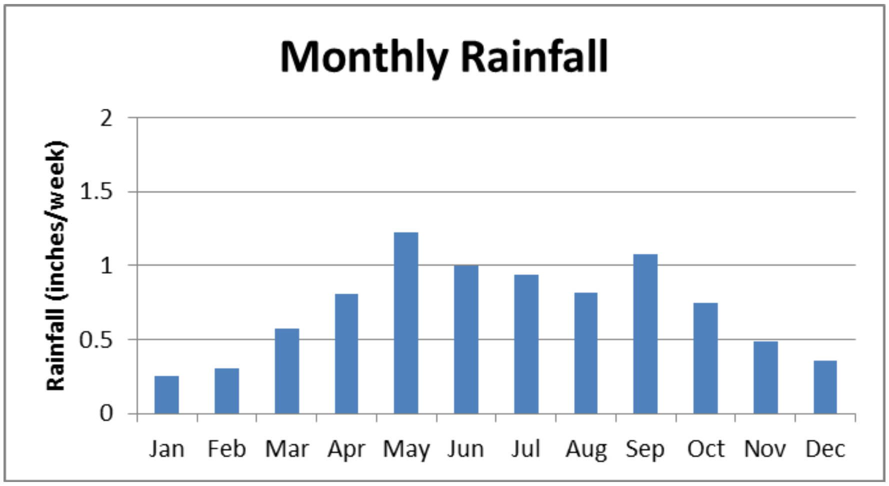


Figure 26. Monthly rainfall.

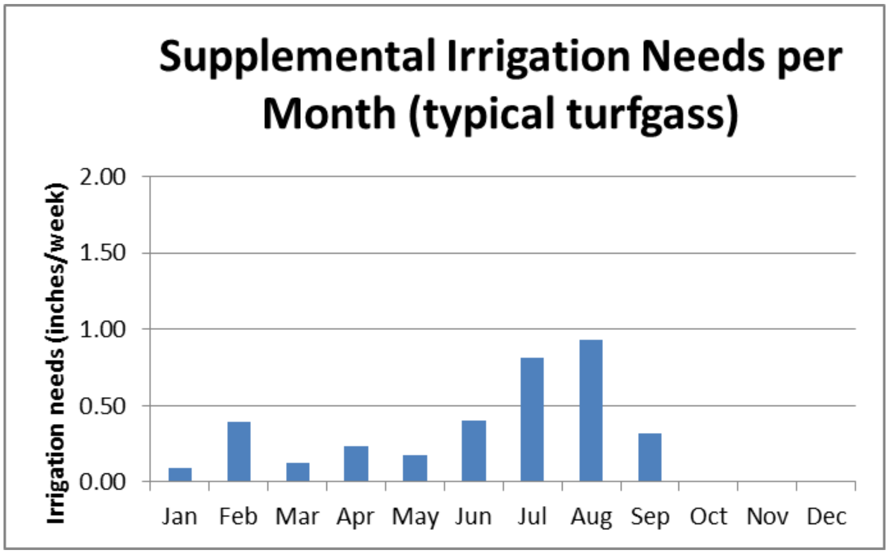


Figure 27. Monthly irrigation requirements to meet ET.

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 irrigation is needed. 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 according to the inter-event conditions and rain patterns compared to the water need patterns and water storage volume. It might 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 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 next section.

6.2 WinSLAMM Modeling of Rain Gardens, Rain Barrel/Tanks, and Disconnection Roof Runoff Controls

Rain gardens, rain barrel/tanks, and disconnection of roof runoff are controls being used in the residential areas in the Kansas City Marlborough study area. They are 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 placed. Table 21 shows that the directly connected roofs only contribute about 5.8 percent, whereas the much greater area of disconnected roofs contribute about 7.2 percent of the annual runoff from the whole 100-acre area. The current flow contributions of all roofs in the area total about 13 percent. If all the roofs were directly connected, they would contribute about 31 percent of the total area runoff, and the runoff from the total area would increase by about 25 percent, a significant increase. In contrast, if the directly connected roofs were disconnected through a downspout disconnection program, the total roof contribution would decrease to about 9 percent, and the total area runoff would decrease by about 5 percent. Because about 85 percent of the existing roofs in the area are already disconnected, the benefits of controlling the remaining directly connected roofs are therefore limited.

Table 21. Effectiveness of roof area disconnections

	Roof 1 areas (currently directly connected) (1.87 acres)	Roof 2 areas (currently disconnected) (10.57 acres)	Land use total (100 acres)	Whole area Rv
Base conditions (ft^3/year)	257,200	319,200	4,449,000	0.30
% contributions	5.8%	7.2%		
% roof contributions	13.0%			
If all roofs were 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 were disconnected (ft^3/year)	56,340	319,200	4,248,000	0.29
% contributions	1.3%	7.5%		
% roof contributions	8.8%			

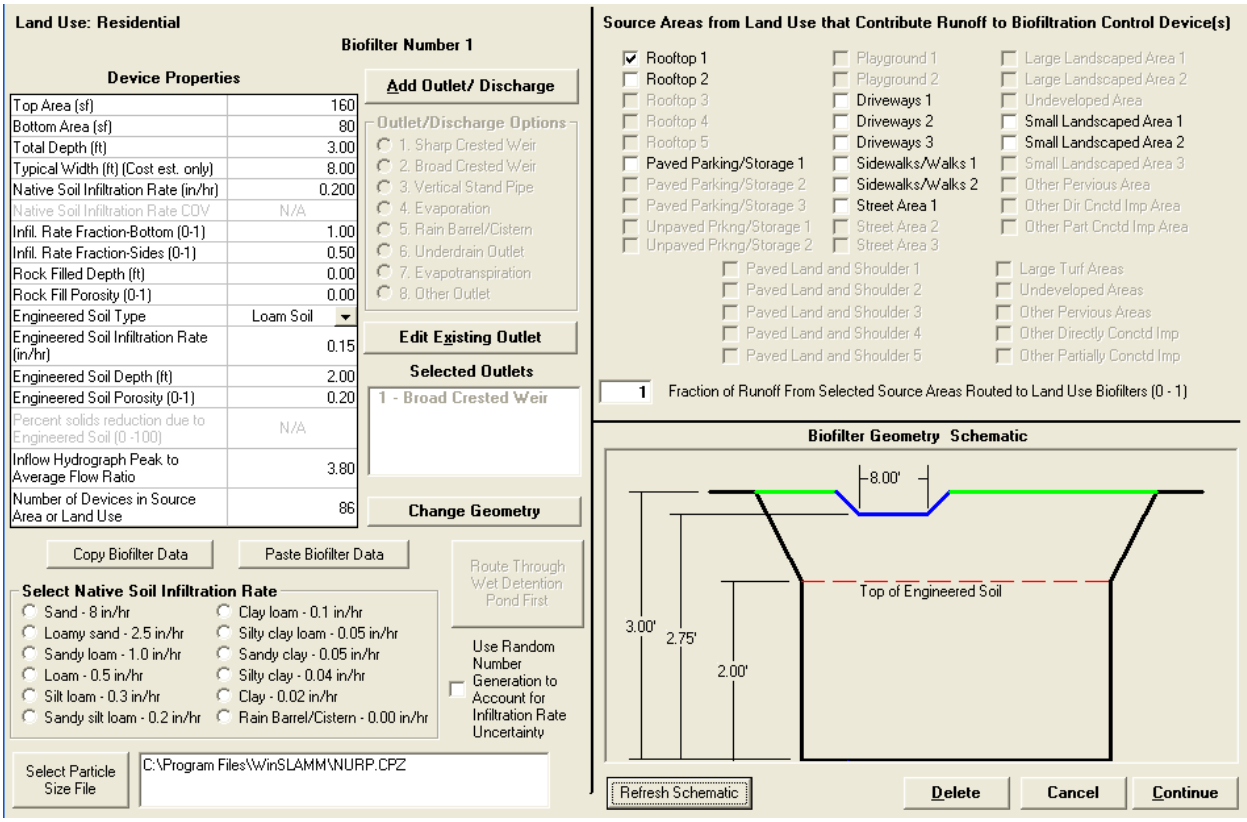
Table 22 shows that directly connected roofs in the study area contribute about 4.5 times the amount of runoff per unit area as the disconnected roofs. This indicates that about 78 percent of the annual runoff from the disconnected roofs is infiltrated as it passes over previous areas on the way to the drainage system. Therefore, it is much less cost-effective to use roof runoff controls for the runoff from the disconnected roofs compared to runoff controls for the directly connected roofs. 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 to have the same benefit on the overall discharge volume from the area.

Table 22. Disconnected and directly roof runoff differences

	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 directly connected:	5.65	1.24	0.220

6.2.1 Rain Gardens

Rain gardens are simple bioretention devices adjacent to roofs. Figure 28 is an input biofilter information screen in WinSLAMM, which describes the rain gardens that were used in this analysis. Each rain garden has a top surface area of 160 ft^2, having an area of about 10 by 16 feet. It is excavated to 3 feet deep, with 2 feet backfilled with a loam soil. The surface 1 foot is left open to provide surface storage of 9 inches deep. A native soil infiltration rate of 0.2 in/hr was used in the calculations, whereas the loam soil fill had only 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.


Land Use: Residential

Biofilter Number 1

Device Properties

Top Area (sf)	160
Bottom Area (sf)	80
Total Depth (ft)	3.00
Typical Width (ft) (Cost est. only)	8.00
Native Soil Infiltration Rate (in/hr)	0.200
Native Soil Infiltration Rate COV	N/A
Infil. Rate Fraction-Bottom (0-1)	1.00
Infil. Rate Fraction-Sides (0-1)	0.50
Rock Filled Depth (ft)	0.00
Rock Fill Porosity (0-1)	0.00
Engineered Soil Type	Loam Soil
Engineered Soil Infiltration Rate (in/hr)	0.15
Engineered Soil Depth (ft)	2.00
Engineered Soil Porosity (0-1)	0.20
Percent solids reduction due to Engineered Soil (0 -100)	N/A
Inflow Hydrograph Peak to Average Flow Ratio	3.80
Number of Devices in Source Area or Land Use	86

Outlet/Discharge Options

○ 1. Sharp Crested Weir
○ 2. Broad Crested Weir
○ 3. Vertical Stand Pipe
○ 4. Evaporation
○ 5. Rain Barrel/Cistern
○ 6. Underdrain Outlet
○ 7. Evapotranspiration
○ 8. Other Outlet

Selected Outlets

1 - Broad Crested Weir

Select Native Soil Infiltration 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

☐ Use Random Number Generation to Account for Infiltration Rate Uncertainty

Select Particle Size File: C:\Program Files\WinSLAMM\NURP.CPZ

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

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

Biofilter Geometry Schematic

Figure 28. Example rain garden WinSLAMM input screen.

The use of one of these rain gardens per house results in a rain garden that is about 17 percent of the surface of the typical roof in the study area. Table 23 and Figure 29 summarize 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 percent) in the study area, even with the low infiltration rates. Therefore, about 13 percent 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 drainage system.

Table 23. Rain garden storage

# rain gardens per house	Ft^2 of rain gardens per house	% of roof area as rain garden	% reduction in roof runoff	Total number of rain gardens if usage rate applied to all 576 homes	Total storage in rain gardens if applied to all 576 homes (ft^3)	Total storage in rain gardens if all 576 homes used them (gal)	Total storage in rain gardens if only used for 86 directly connected roofs (gal)
0	0	0%	0%	0	0	0	0
0.035	5.6	1%	5%	20	2460	18,400	2760
0.1	16	2%	14%	58	7030	52,600	7890
0.25	40	4%	33%	144	17600	131,500	19,700
0.5	80	8%	57%	288	35140	263,000	39,400
1	160	17%	84%	576	70300	526,000	78,900
2	320	34%	96%	1150	140500	1,052,000	158,000
4	640	68%	100%	2300	281100	2,104,000	316,000

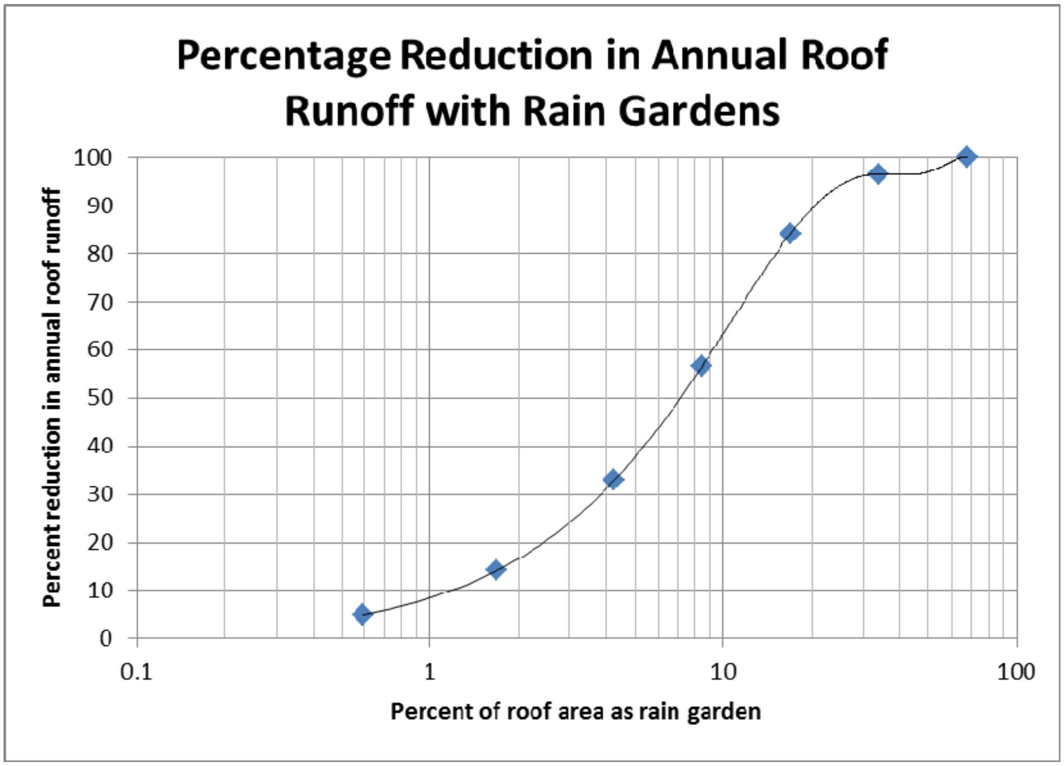


Figure 29. Rain garden production function.

The continuous simulations examined all 98 rain events that occurred during the typical 1990 rain year. In that year, the six rains closest to 1.4 inches in total depth are shown on Tables 24 and 25. In that year, three rains were larger than the six rains listed here: 3.23, 3.11, and 2.18 inches deep. These six rains' depth ranged from 1.21 to 1.76 inches and lasted from 8 to 28 hours. Antecedent dry periods ranged from 8 hours to about 4 days, and the total rain depth that occurred in the week before these rains ranged from 0.02 to 1.24 inches.

Table 24. 1.4-inch class rains in 1990

Date	Rain fall (in)	Event duration (hrs)	Average rain intensity (in/hr)	Prior event interevent period (days)	Prior event rain depths for at least a week before (in, and its prior interevent periods in days)	Total rain fall in week before event (in)
3/14/1990	1.28	28	0.05	0.33	0.14 (0.67); 0.52 (1.1); 0.08 (0.25); 0.19 (3.0)	0.93
4/26/1990	1.76	26	0.07	0.92	0.03(5.0); 0.01 (5.0)	0.04
6/6/1990	1.22	8	0.15	3.8	0.01 (3.1); 0.01 (5.2)	0.02
6/8/1990	1.22	12	0.1	2.1	1.22 (3.8); 0.01 (3.1); 0.01 (5.2)	1.24
7/21/1990	1.67	13	0.13	0.58	0.39 (0.33); 0.08 (6.5)	0.47
10/2/1990	1.21	15	0.08	3	0.12 (8.5)	0.12
Average	1.39	17	0.10			0.47
Standard deviation	0.25	8.1	0.038			0.51
COV	0.18	0.48	0.38			1.1

Table 25. Runoff characteristics during 1.4-inch class rains

Date	Rain fall (in)	Base conditions, total runoff (ft^3/100 ac)	Base conditions, Rv at outfall	Directly con. roof (ft^3 for 86 of 576 total homes)
3/14/1990	1.28	151,000	0.32	8,497
4/26/1990	1.76	227,000	0.35	11,739
6/6/1990	1.22	143,000	0.32	8,098
6/8/1990	1.22	143,000	0.32	8,098
7/21/1990	1.67	211,000	0.35	11,113
10/2/1990	1.21	141,000	0.32	8,032
Average	1.39	169,000	0.33	9,260
Standard deviation	0.25	38,800	0.015	1,700
COV	0.18	0.23	0.047	0.18

The storage provided in the rain gardens is somewhat larger than the amount of runoff removed during the design storm *D* of 1.4 inches deep. Continuous simulations of this year's rains considers antecedent conditions in the rain garden, specifically, some of the storage capacity might not be available because some of the water from a prior event might not have completely drained. This is especially true in areas of poorly draining soils. The total drainage time in this general rain garden design is about 4 days, with about 1.5 to 2 days needed to drain the maximum ponding on the surface of the rain garden. Any rain that might occur before the rain garden could completely drain will lengthen the overall drainage time and reduce the amount of effective storage available for a subsequent event.

For up to one rain garden per house (17 percent of roof area), the storage provided is about 30 to 40 percent greater than the actual amount of runoff removed during storms that are close to the 1.4 inches deep. This additional storage volume is related to the typical antecedent conditions before these rains, especially considering the low natural infiltration rates in the area. When the desired level of performance increases, this over-design volume also increases. When two rain gardens are used per house (34 percent of roof area), the actual storage in the rain garden is about 2.3 times the volume removed, and when the rain garden usage is further increased to four per house (64 percent of roof area), the actual storage is about 4.6 times the roof runoff removed. This is evidenced by the non-linear plot in Figure 30, which flattens out considerably for the largest removal rates. The use of two rain gardens per house results in complete removal of the runoff from directly connected roofs from the drainage system during this 1.4 inch site design storm, so that is the practical upper limit when considering only the design storm regulatory objectives. When the number of rain gardens is increased above one, the rain gardens do not always fill completely during all the rains in this size category. However, additional rain garden area might be used to increase the total amount of runoff reduction when the complete annual rain series is considered, as shown above. The use of the two rain gardens per house provides 100 percent control of the regulatory design storm and results in an expected 96 percent reduction in the total annual runoff from the directly connected roofs.

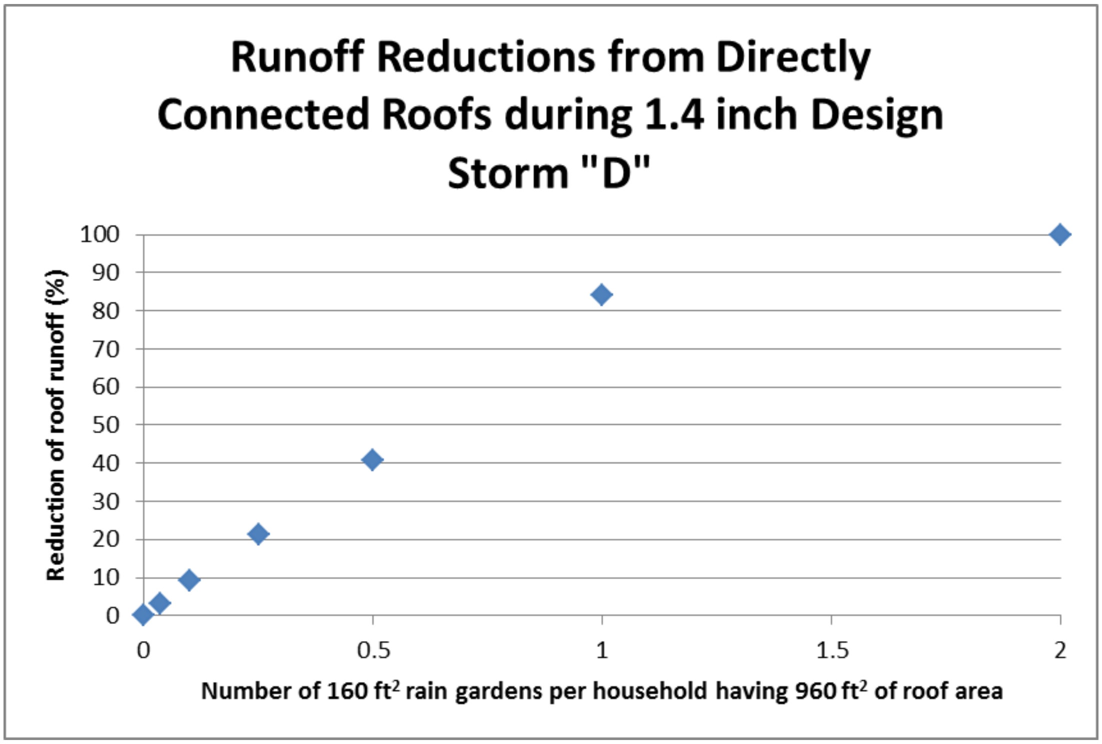


Figure 30. Rain garden production function for a 1.4-inch rain.

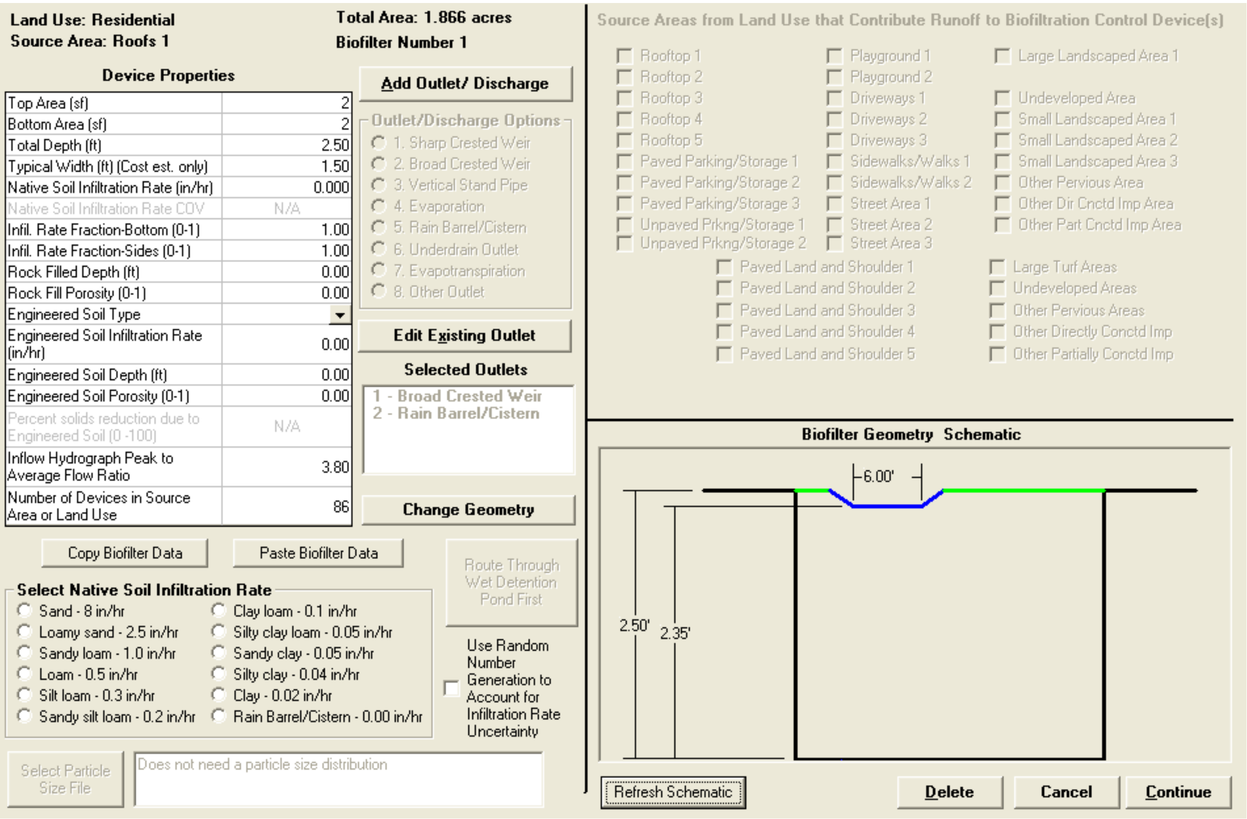
In conclusion, a goal of reducing 90 percent of the runoff from directly connected roofs in the study area would require using rain gardens that are about 20 percent of the roof areas, or a total area of slightly less than 200 ft^2 per house. This would also provide about 90 percent runoff reductions from the directly connected roofs during the 1.4-inch regulatory design storm *D*. 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). But for a more common peaked roof that drains to each corner separately, four separate smaller rain gardens would be needed (each about 50 ft^2).

6.2.2 Rain Barrels and Water Tanks

Rain barrels are a very simple method for collecting roof runoff for 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 to match the ET requirements 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, to be most beneficial, these calculations assume that the irrigation rates are controlled by soil moisture conditions to match the ET requirements closely. This level of control is usually most effectively achieved with one 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 compose about 15 percent of the total roof area in the study watershed.

Figures 31 and 32 are input screens used for rain barrels or cisterns in WinSLAMM version 9.5 (version 10 currently being completed has a more streamlined water beneficial use/water barrels input screen). As noted, it is the same form used for the biofilters, but conditions relevant to rain barrels and water beneficial use are selected (top and bottom area the same, no native soil infiltration, and no fill material needed). The two discharges include the required overflow (just the tank upper rim) and the monthly water use requirements (the irrigation demands).



Land Use: Residential
Source Area: Roofs 1
Total Area: 1.866 acres
Biofilter Number 1

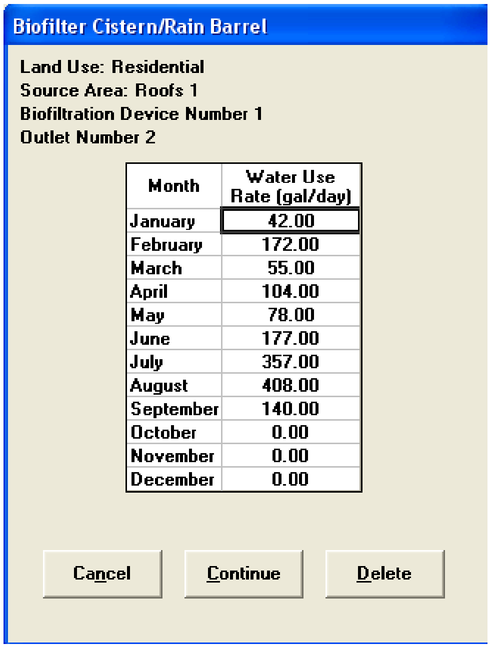
Device Properties

Top Area (sf)	2
Bottom Area (sf)	2
Total Depth (ft)	2.50
Typical Width (ft) (Cost est. only)	1.50
Native Soil Infiltration Rate (in/hr)	0.000
Native Soil Infiltration Rate COV	N/A
Infil. Rate Fraction-Bottom (0-1)	1.00
Infil. Rate Fraction-Sides (0-1)	1.00
Rock Filled Depth (ft)	0.00
Rock Fill Porosity (0-1)	0.00
Engineered Soil Type	
Engineered Soil Infiltration Rate (in/hr)	0.00
Engineered Soil Depth (ft)	0.00
Engineered Soil Porosity (0-1)	0.00
Percent solids reduction due to Engineered Soil (0 -100)	N/A
Inflow Hydrograph Peak to Average Flow Ratio	3.80
Number of Devices in Source Area or Land Use	86

Selected Outlets
1 - Broad Crested Weir
2 - Rain Barrel/Cistern

Does not need a particle size distribution

Figure 31. Cistern/water tank WinSLAMM input screen.



Land Use: Residential
Source Area: Roofs 1
Biofiltration Device Number 1
Outlet Number 2

Month	Water Use Rate (gal/day)
January	42.00
February	172.00
March	55.00
April	104.00
May	78.00
June	177.00
July	357.00
August	408.00
September	140.00
October	0.00
November	0.00
December	0.00

Figure 32. Water use WinSLAMM input screen.

Tables 26 through 28 and Figures 33 through 35 summarize the benefits of storage and irrigation use of runoff collected from directly connected roofs. The use of a single rain barrel is expected to provide about a 24 percent reduction in runoff through irrigation to match ET. However, more than 25 would be needed to reduce the roof's contributions by 90 percent. To match the benefits of disconnecting the connected downspouts (about 78 percent reductions), about 25 rain barrels would be needed. That corresponds to a total storage quantity about equal to 0.12 ft (1.4 inches).

Table 26. Rain barrel use and roof runoff reductions

# of rain 35-gal. barrels per house	Rain barrel storage per house (ft^3)	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)	Rv for roof area	% reduction in roof runoff
0	0	0	257,200	2,990	0.97	0%
1	4.7	0.0050	196,700	2,290	0.74	24%
2	9.4	0.010	181,400	2,110	0.68	29%
4	19	0.020	155,800	1,810	0.58	39%
10	47	0.050	112,400	1,310	0.42	56%
25	118	0.12	67,200	780	0.25	74%
100	470	0.50	3,160	37	0.01	99%

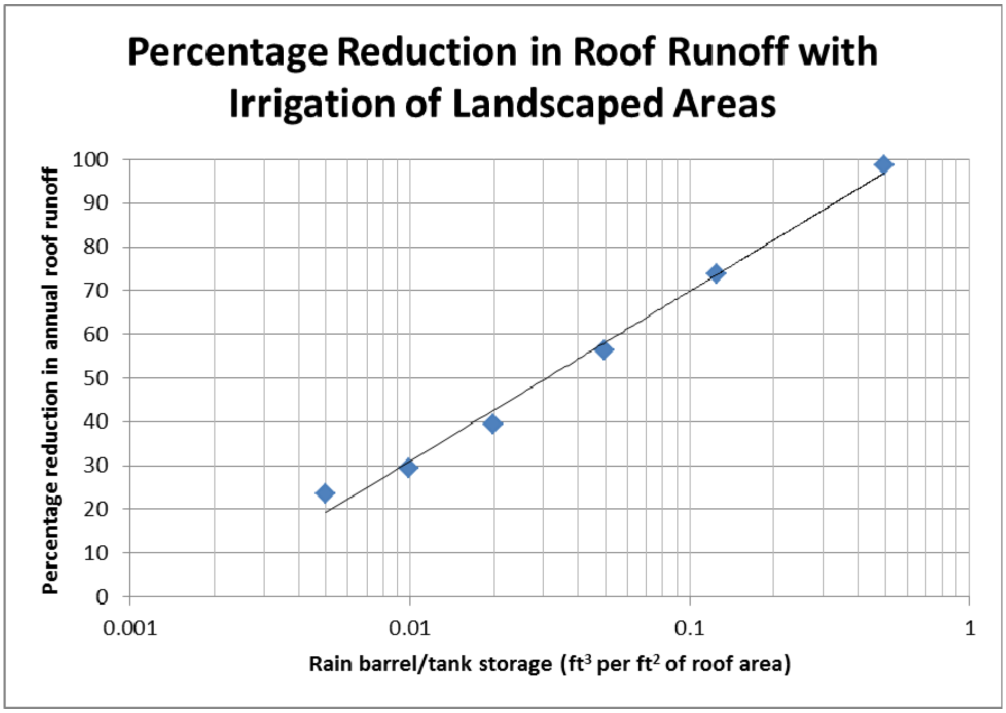


Figure 33. Irrigation storage requirements production function.

Figure 34 illustrates the runoff reductions calculated from directly connected roofs during the 1.4-inch regulatory design storm *D*. Like the performance plot for the reuse benefits during the total annual rain series shown above, the benefits of using additional rain barrels are linear. The maximum benefit for this single rain, however, tops out with the use of about 25 rain barrels (118 ft^3 of total storage) per house. Additional storage would not provide any additional benefit for this rain event.

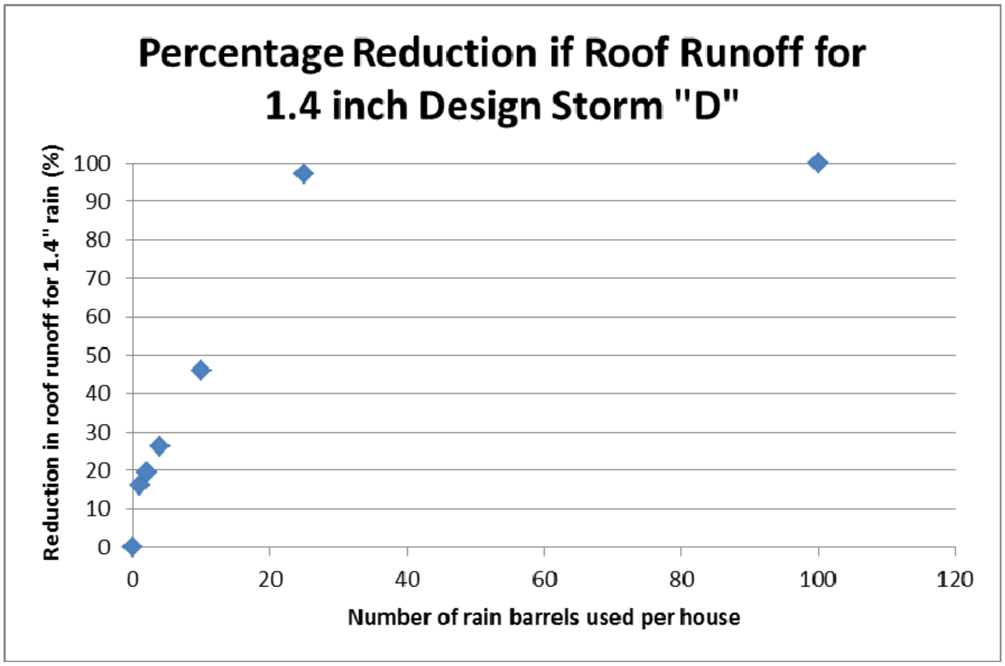


Figure 34. Rain barrel production function for a 1.4-inch rain.

As the storage volume increases, it likely becomes impractical to meet the total storage volume with small rain barrels. Table 27 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 that is 5 feet wide and 6 feet tall has a similar storage capacity as 25 rain barrels, and if the 6-foot tall tank was expanded to 10 feet wide, the larger tank would have a similar capacity as 100 rain barrels.

Table 27. Rain barrels and water tank equivalents

Storage per house (ft depth over the roof)	Storage per house having 945 ft^2 roof area (ft^3 and gallons)	Reduction in roof runoff for 1.4 inch rain (%)	Reduction in annual roof runoff (%)	# 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%	0%	0	0	0
0.0050	4.7 (35)	16%	24%	*1*	0.24	0.060
0.010	9.4 (70)	19%	29%	*2*	0.45	0.12
0.020	19 (140)	27%	39%	*4*	0.96	0.24
0.050	47 (350)	46%	56%	10	*2.4*	0.60
0.12	118 (880)	96%	74%	25	*6.0*	1.5
0.50	470 (3,500)	100%	99%	100	24	*6.0*

Using about 25 rain barrels, or a small tank 5 feet wide and 6 feet tall, is the recommended amount of storage for the directly connected roofs in the study area. This would provide about 74 percent reduction in the total annual runoff discharges, and almost complete control for the 1.4 inch regulatory design storm *D*.

6.2.3 Combinations of Rain Gardens and Rain Barrels

It is possible to use rain barrels and rain gardens together at the same houses that have directly connected roofs. Table 28 and Figure 35 show the reductions in the annual runoff for the range of these controls that have been previously examined separately. To obtain reductions of about 90 percent 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 one small water tank) per house. In that case, the rain gardens can be reduced to about 0.5 per house, or less.

Table 28. Reductions in annual runoff quantities from a combination of rain barrels and rain gardens

		Number of rain gardens* per house							
		0	0.035	0.1	0.25	0.5	1	2	4
Number of rain barrels** per house	0	0	5	14	33	57	84	96	100
	1	24	27	36	52	68	89	99	100
	2	29	33	41	55	71	90	99	100
	4	39	43	49	61	75	91	99	100
	10	56	58	62	71	81	92	100	100
	25	74	75	78	82	87	94	100	100
	100	99	99	99	99	100	100	100	100

Notes

* Each rain garden has a surface area of about 160 ft^2. This area 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.

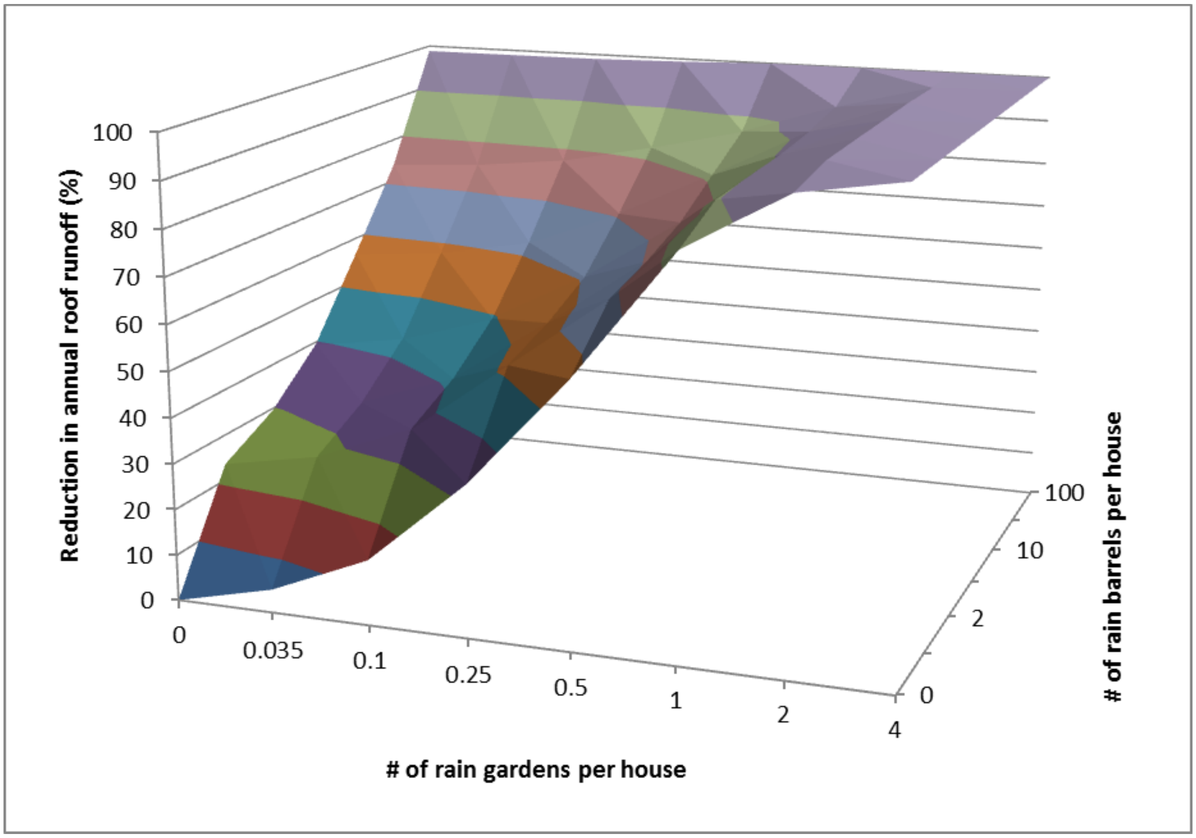


Figure 35. Combined effect of rain gardens and rain barrels.

6.2.4 Roof Drain Downspout Disconnections

Another option for controlling runoff from directly connected roofs is to disconnect the roof drain downspouts that are directed toward pavement that, in turn, is directly connected 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 compose only about 12 percent of the lot area and the landscaped areas compose about 65 percent 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. Table 29 and Figures 36 and 37 illustrate these results. Table 29 provides the expected runoff quantities associated with the roof disconnections for the site’s clayey soils, along with potential benefits for other soil conditions for comparison. As indicated previously, disconnecting these roofs in areas having clay soils is expected to result in annual runoff reductions of about 78 percent. This would increase to about 87 percent and 95 percent for areas having silty and sandy soils, respectively.

Table 29. Effects of disconnecting roofs

	annual runoff (ft^3)	% reduction for 1990 rain year
Clayey soils, medium to high density, no alleys		
Connected roofs (1.866 acres)	257,200	
Disconnected roofs (1.866 acres)	56,300	78
Silty soils		
Connected roofs (1.866 acres)	257,200	
Disconnected roofs (1.866 acres)	34,200	87
Sandy soils		
Connected roofs (1.866 acres)	257,200	
Disconnected roofs (1.866 acres)	12,200	95

The plot in Figure 36 illustrates the expected benefits of these disconnection practices for different individual rains, up to 4 inches deep. The Rv, the ratio of runoff volume to rainfall volume falling on an area, is seen to increase 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 deep. When disconnected to clayey soils, runoff is not expected until the rain depth is greater than 0.1 inch, and the Rv starts to climb steeply with rains larger than several inches deep. Runoff is expected to be very large for very large and unusual rains that can cause severe flooding, whether the roofs and pavement are disconnected or not. However, the benefits for small and intermediate rains are large.

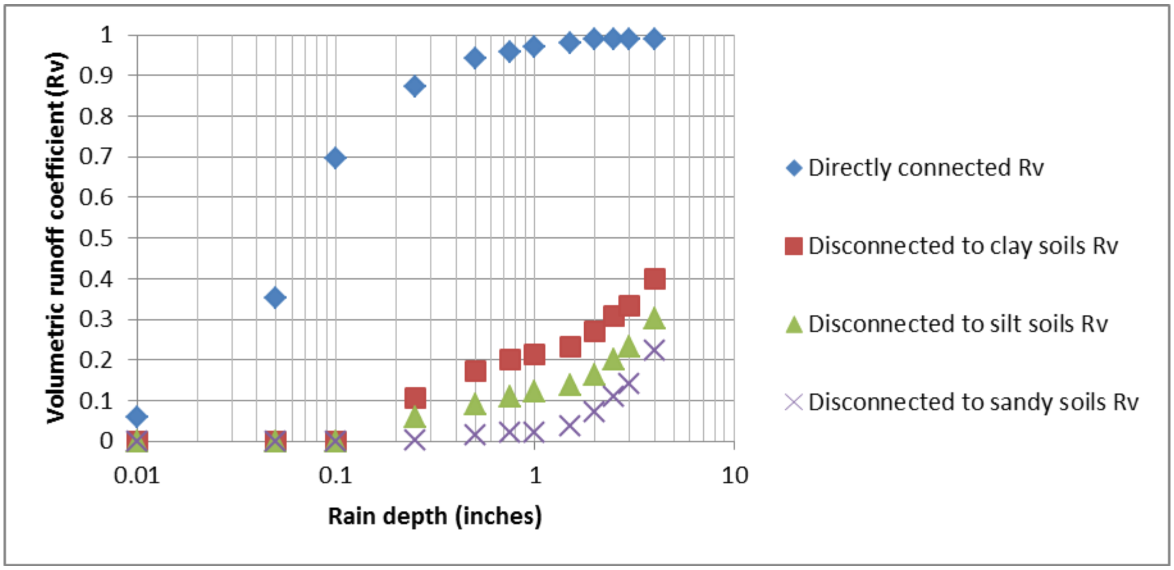


Figure 36. Resulting Rv for disconnecting roofs and pavement.

The graph in Figure 37 illustrates the percentage reductions associated with disconnecting the directly connected roofs for the three main soil categories. The percentage reduction is about 75 percent for 1.5-inch rains, being greater for smaller rains.

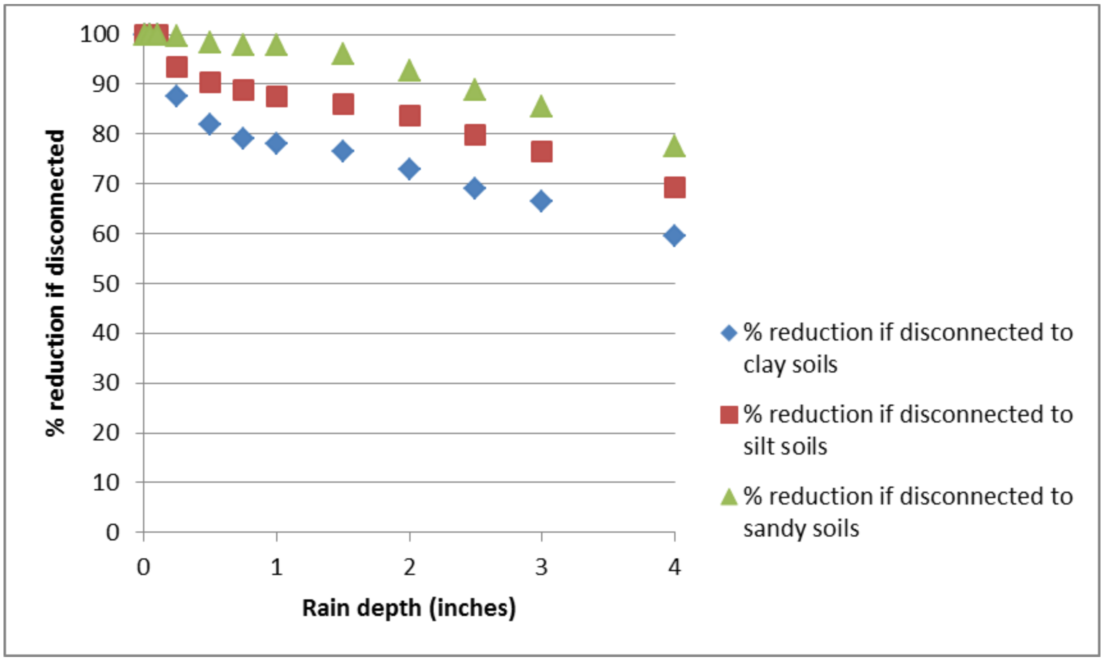


Figure 37. Production functions for disconnected roofs and paved areas.

6.3 Additional Controls

Recently, a comprehensive evaluation of stormwater controls was conducted for many land use categories in Lincoln, Nebraska, as part of its stormwater management plan (Pitt 2011). The following section briefly summarizes some of the findings from this resent work because it covers a broad range of land uses common to both Lincoln and Kansas City. These analyses were also based on regionally calibrated model analyses for the region. They also examined a wider range of stormwater controls that have been evaluated so far in Kansas City as an indication of how other GI controls can be integrated with the household controls described in this report and evaluated for the Marlborough test area in Kansas City.

6.3.1 Detailed Example of Many Alternative Control Program Options for a Medium-Density Residential Area (constructed before 1960)

This example is from the Lincoln report and represents conditions similar to the main land use in the Marlborough test watershed in Kansas City. Twenty-eight alternative control options were examined for this area and are compared to the base conditions. Table 30 was produced by the batch processor in WinSLAMM that enable many attributes about each control alternative to be examined, including life-cycle costs, land requirements, maintenance requirements, expected biological conditions in the receiving waters, and runoff and pollutant characteristics. The performance characteristics and the total annual costs are plotted as scatterplots in Figures 38 and 39 to enable the most cost-effective alternative to be identified for different levels of performance.

Table 30. Medium-density residential before 1960 land use, sandy loam soil (costs are per 100 acres)

File name	Rv	Biological condition	Runoff volume percent reduction	Particulate solids yield percent reduction	Particulate solids concentration (mg/L)	Capital cost	Land cost	Maintenance cost	Total annual cost	Total present value cost	Cost per cubic foot runoff volume reduced ($/cf)	Cost per pound particulate solids reduced ($/lb)
08 Med dens resid bfr 1960 Linc base	0.22	Poor	n/a	n/a	89	n/a	n/a	n/a	n/a	n/a	n/a	n/a
08 Med dens resid bfr 1960 Linc CB	0.22	Poor	0%	15%	75	$236,094	0	$8,175	$27,120	$337,973	-	$14.37
08 Med dens resid bfr 1960 Linc pond 04 perct	0.22	Poor	0%	65%	31	$107,544	5,100	$3,583	$12,622	$157,292	-	$1.56
08 Med dens resid bfr 1960 Linc pond 08 perct	0.22	Poor	0%	82%	16	$200,509	10,200	$5,899	$22,807	$284,223	-	$2.26
08 Med dens resid bfr 1960 Linc pond 16 perct	0.22	Poor	0%	93%	6	$379,468	20,400	$10,069	$42,155	$525,348	-	$3.66
08 Med dens resid bfr 1960 Linc street cleaning daily	0.22	Poor	0%	59%	37	$55,333	0	$290,441	$294,881	$3,674,864	-	$40.57
08 Med dens resid bfr 1960 Linc street cleaning monthly	0.22	Poor	0%	22%	69	$2,564	0	$13,457	$13,662	$170,264	-	$4.97
08 Med dens resid bfr 1960 Linc street cleaning sp fl	0.22	Poor	0%	8%	81	$481	0	$2,523	$2,562	$31,924	-	$2.52
08 Med dens resid bfr 1960 Linc street cleaning weekly	0.22	Poor	0%	44%	50	$9,667	0	$50,743	$51,519	$642,037	-	$9.54
08 Med dens resid bfr 1960 Linc connt roof rain garden 3 perct sandy loam	0.21	Poor	6%	0%	94	$31,923	901	$2,092	$4,726	$58,892	$0.04	$116.47
08 Med dens resid bfr 1960 Linc rain barrels few	0.21	Poor	6%	0%	94	$9,912	112	$590	$1,395	$17,382	$0.01	$31.55
08 Med dens resid bfr 1960 Linc rain barrels	0.21	Poor	7%	0%	95	$19,823	224	$1,181	$2,790	$34,764	$0.02	$57.36
08 Med dens resid bfr 1960 Linc rain barrels many	0.20	Poor	8%	0%	96	$49,538	560	$2,951	$6,971	$86,873	$0.04	$125.10
08 Med dens resid bfr 1960 Linc connt roof rain garden 15 perct sandy loam	0.20	Poor	8%	0%	96	$148,973	4,204	$9,762	$22,053	$274,831	$0.12	$376.67
08 Med dens resid bfr 1960 Linc rain tanks few	0.20	Poor	9%	1%	97	$32,996	467	$2,234	$4,919	$61,300	$0.02	$78.87
08 Med dens resid bfr 1960 Linc all roof rain garden 3 perct sandy loam	0.20	Poor	9%	1%	97	$180,896	5,105	$11,854	$26,779	$333,723	$0.13	$412.85
08 Med dens resid bfr 1960 Linc rain tanks large	0.20	Poor	10%	1%	97	$247,448	3,500	$16,751	$36,888	$459,703	$0.17	$555.23
08 Med dens resid bfr 1960 Linc rain tanks	0.20	Poor	10%	1%	97	$82,483	1,167	$5,584	$12,296	$153,235	$0.06	$185.07

File name	Rv	Biological condition	Runoff volume percent reduction	Particulate solids yield percent reduction	Particulate solids concentration (mg/L)	Capital cost	Land cost	Maintenance cost	Total annual cost	Total present value cost	Cost per cubic foot runoff volume reduced ($/cf)	Cost per pound particulate solids reduced ($/lb)
08 Med dens resid bfr 1960 Linc sml pnd and rain tanks	0.20	Poor	10%	67%	32	$190,027	6,267	$9,166	$24,917	$310,527	$0.12	$2.99
08 Med dens resid bfr 1960 Linc all roof rain garden 15 perct sandy loam	0.19	Poor	15%	1%	103	$929,310	26,224	$60,895	$137,570	$1,714,420	$0.42	$1,345.08
08 Med dens resid bfr 1960 Linc small pnd and all roof rain garden 15 perct sandy loam	0.19	Poor	15%	69%	33	$1,036,854	31,324	$64,478	$150,191	$1,871,712	$0.46	$17.71
08 Med dens resid bfr 1960 Linc porous pvt driveways sandy loam	0.21	Poor	6%	2%	93	$165,285	0	$553	$13,816	$172,179	$0.10	$67.20
08 Med dens resid bfr 1960 Linc curb biofilters 20 sandy loam	0.05	Good	77%	77%	89	$595,175	7,231	$39,062	$87,401	$1,089,206	$0.05	$9.18
08 Med dens resid bfr 1960 Linc sml pnd and swale sandy loam	0.04	Good	80%	95%	24	$1,484,988	5,100	$46,845	$166,413	$2,073,877	$0.09	$14.23
08 Med dens resid bfr 1960 Linc swale sandy loam	0.04	Good	80%	81%	83	$1,377,444	0	$43,262	$153,792	$1,916,585	$0.09	$15.26
08 Med dens resid bfr 1960 Linc curb biofilters 40 sandy loam	0.02	Good	92%	94%	70	$1,190,349	14,463	$78,124	$174,801	$2,178,412	$0.09	$15.10
08 Med dens resid bfr 1960 Linc sml pnd and curb biofilters 40 sandy loam	0.02	Good	92%	97%	28	$1,297,893	19,563	$81,707	$187,423	$2,335,704	$0.09	$15.55
08 Med dens resid bfr 1960 Linc sml pnd and rain grdn 15 prct and curb biofilters 40 sandy loam	0.01	Good	95%	98%	29	$2,227,203	45,787	$142,602	$324,992	$4,050,124	$0.15	$26.73
08 Med dens resid bfr 1960 Linc curb biofilters 80 sandy loam	0.00	Good	99%	99%	62	$2,380,699	28,926	$156,248	$349,603	$4,356,823	$0.16	$28.52

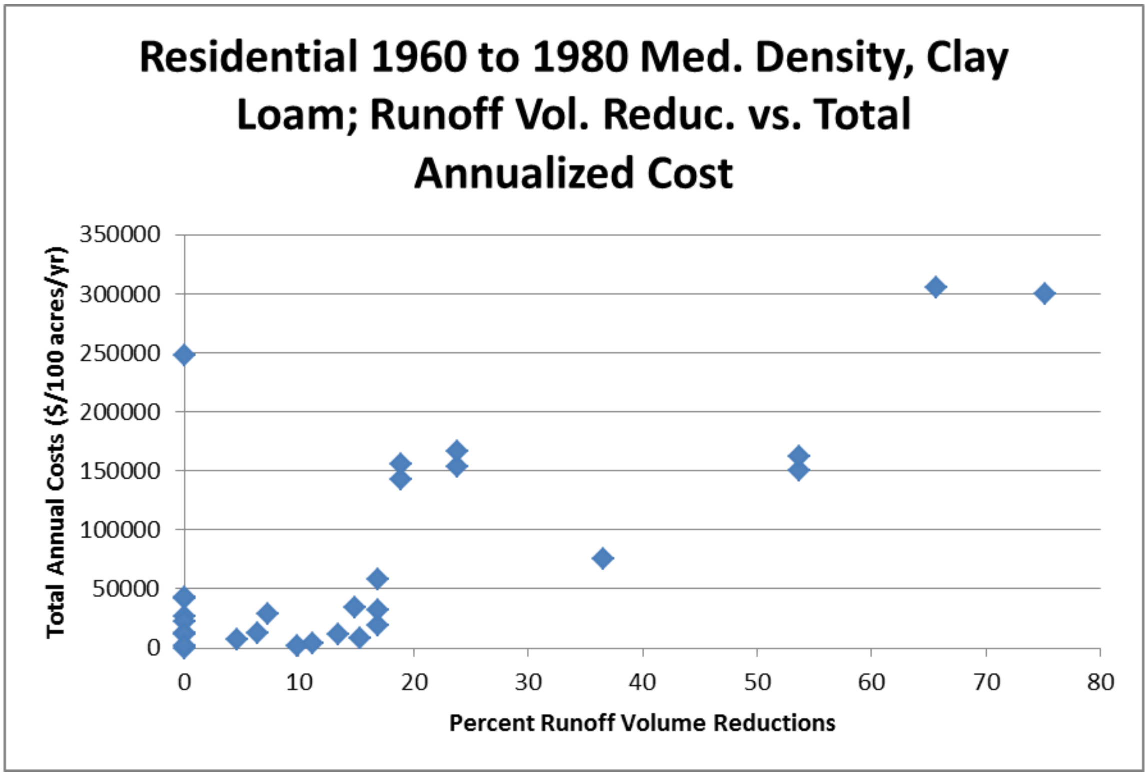


Figure 38. Cost-effectiveness for various runoff volume controls.

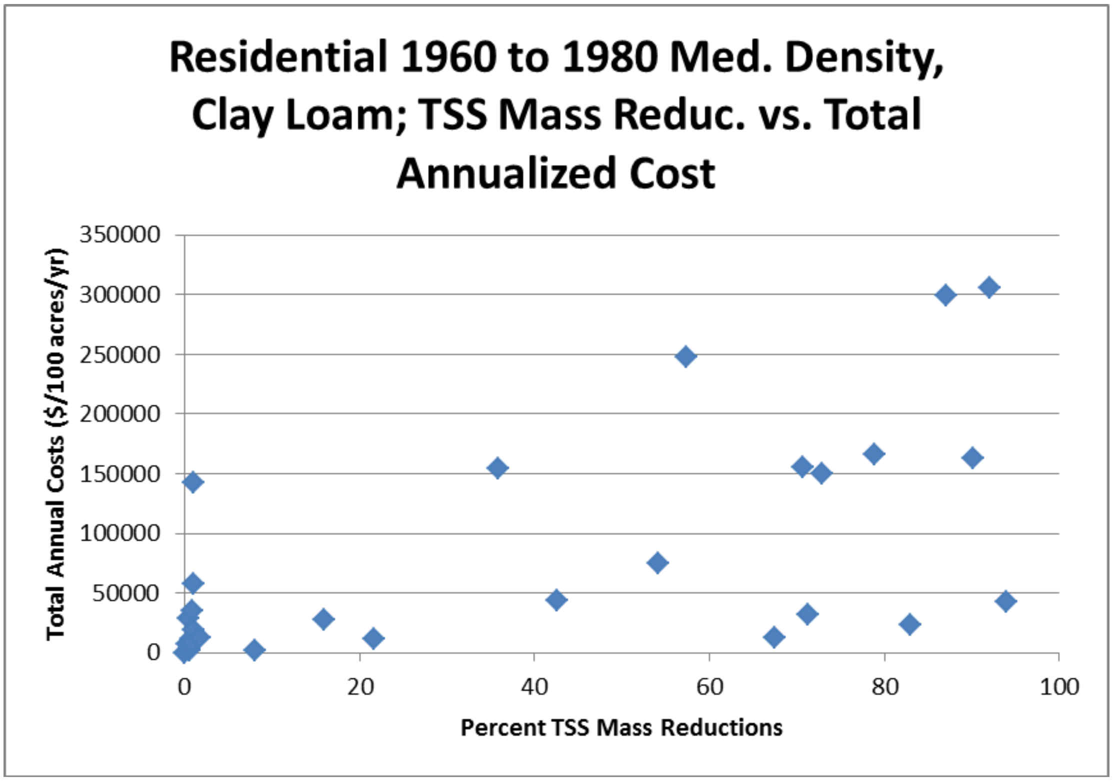


Figure 39. Cost-effectiveness for various TSS reduction controls

6.3.2 Stormwater Control Performance Alternatives for other Land Uses

Besides the above older medium-density residential land use analyses, similar analyses were conducted for other Lincoln area land uses that are similar to land uses found in the Kansas City area. The following is a brief discussion of the findings for these areas.

For runoff volume controls, each land use group had similar *most cost-effective* controls, as shown on the following list for the controls having at least 25 percent levels of runoff volume reduction potential in areas having clay loam soils in the infiltration areas. Other control options have similar potential levels of control, but the others are likely more costly. These are listed in order with the first control having the lowest level of maximum control (the approximate percentage of runoff reduction in shown) and with the best unit cost-effectiveness; and the last control listed having the highest level of maximum control but the worst expected unit cost-effectiveness. Therefore, if low to moderate levels of control are suitable, the first control option might be best, but if maximum control levels are needed, the last control option listed would be needed.

- Strip mall and shopping center areas:
  - Porous pavement (in half of the parking areas), 25 percent volume reductions
  - Curb-cut biofilters (along 80 percent of the curbs) for strip malls or biofilters in parking areas (10 percent of the source area) for shopping centers, 29 percent volume reductions
  - Biofilters in parking areas (10 percent of the source area) and curb-cut biofilters (along 40 percent of the curbs), 42 percent volume reductions

- Light industrial areas:
  - Curb-cut biofilters (along 40 percent of the curbs), 26 percent volume reductions
  - Roofs and parking areas half disconnected, 32 percent volume reductions
  - Roofs and parking areas all disconnected, 61 percent volume reductions

- School, church, and hospital institutional areas:
  - Small rain tank (0.10 ft^3 storage per ft^2 of roof area) for schools and churches; rain tank (0.25 ft^3 storage per ft^2 of roof area) for hospitals, 26 percent volume reductions
  - Roofs and parking areas half disconnected, 31 percent volume reductions
  - Roofs and parking areas all disconnected, 67 percent volume reductions

- Low and medium density residential areas:
  - Curb-cut biofilters (along 20 percent of the curbs), 36 percent volume reductions
  - Curb-cut biofilters (along 40 percent of the curbs), 53 percent volume reductions
  - Curb-cut biofilters (along 80 percent of the curbs), 75 percent volume reductions

However, selecting the *best* stormwater control program for an area is not just dependent on the highest level of performance at the least cost. Other program attributes must also frequently be considered. The following sections describe a simple and a more comprehensive decision analysis approach that is suitable for these decisions (again, the data used are from the Lincoln area analyses but are expected to be similar to conditions in the Kansas City study areas).

6.3.3 Filtering Simple Attributes and Selecting Least Costly Acceptable Alternatives

In the simplest case, selecting the most suitable control can be done by examining the calculated outcomes and filtering them according to set objectives, and then choosing the least costly alternative. As an example, if the runoff reduction objectives were expressed in expected biological conditions of *good* and the required particulate solids (TSS) mass discharge reductions needed were at least 75 percent, 7 of these 29 control programs for the medium-density residential area (built between 1960 and 1980) would be satisfactory. This combination of high runoff volume reductions (the *good* biological conditions occur with about 75 percent runoff volume reductions) and particulate solids reductions will also provide high reductions of all the other pollutants. If only particulate solids reductions were targeted, the wet detention ponds would be the least costly choice, but they alone would not reduce the discharges of the filterable pollutants. But they provide excellent particulate pollutant reductions. The seven alternative programs meeting these two simple (but relatively robust) control objectives, along with their estimated annual unit area costs, are shown in Table 31.

Table 31. Attributes of acceptable stormwater control programs (examples)

Stormwater control programs for medium-density residential land use (1960-1980)	Subbasin total annual cost ($/ac/yr)	Biological condition	Particulate solids yield percent reduction
Curb-cut biofilters 20%	$187	Good	76%
Curb-cut biofilters 40%	$375	Good	93%
Curb-cut biofilters 80%	$749	Good	99%
Grass swale drainage	$384	Good	83%
Small wet pond and swale	$416	Good	95%
Small wet pond and curb biofilters 40%	$406	Good	97%
Small wet pond, grdn 15% and curb biofilters 40%	$763	Good	98%

The least costly alternative involves the use of curb-cut biofilters along at least 20 percent of the total curb length. If this control program meets other objectives—mainly the approval of the residents living in the area, and design specifics to overcome possible problems associated with snowmelt and clogging can be developed—this would be a good choice. Retrofitting grass swales is not a very suitable choice but can be an excellent option for new development (especially when their moderate costs are compared to the high costs associated with conventional curb and gutter drainages). The combination control options listed all have small wet detention ponds that could be difficult to site in a previously developed area, and they are not that necessary in this land use, even with new development, if proper design and use of a swale or biofilter drainage system is possible.

The main issues, especially for a city that uses deicing salts (as in both Lincoln, Nebraska, and Kansas City, Missouri), is the potential problem of failure from excessive sodium discharges with snowmelt and clogging from high particulate loads into the biofilter area. The sodium and associated SAR problems occur if the biofilter media contains clay. Therefore, the media specified should be sand alone, with a shallow layer of mixed (very low clay content) topsoil on the surface to support plant growth.

The problem of clogging can be overcome with pretreatment by using grass swales between the biofilters to act as grass filters or to increase the surface area of the biofilters to decrease the unit area sediment loading. If 20 percent of the curb has biofilters, the approximate biofilter area is about 0.6 percent of the total drainage area. For 100 acres, the total biofilter area would therefore be 0.6 acres (about 26,000 ft^2). For this example, the total particulate loading expected to be trapped by the curb-cut biofilters during 4 years over 100 acres is about 32,000 lbs. That corresponds to about 0.3 lb/ft^2/year (or about 1.5 kg/m^2/year) of operation. Biofilter clogging could occur with sediment loads of about 10 to 25 kg/m^2, especially if that cumulative load occurs over just a few years. The predicted maximum loading before clogging would therefore occur between about 6 and 15 years. The shortest period before potential clogging might be problematic, but vigorous plants also tend to help reduce clogging. It is likely, if care is taken in selecting materials and plants and in construction and maintenance, these biofilters would function for a long time.

6.3.4 Utility Functions and Tradeoffs in Selecting the Most Suitable Stormwater Control Program

Formal decision analysis methods can be used when conflicting and complex attributes and objectives make the simpler filtering method described above impractical. One example used for stormwater programs was described with examples by Pitt and Voorhees (2007). The method uses utility curves and tradeoffs between the different attributes. The utility curves should be based on data and technical interpretations and not reflect personal attitudes or objectives, while the tradeoffs between the attributes reflect different viewpoints of the stakeholder groups. This decision analysis method is, therefore, a powerful tool that can be used to compare the rankings of alternative stormwater management programs for different groups. In many cases, final rankings might be similar among the interested parties, although their specific reasons vary. This tool also completely documents the decision-making process, enabling full disclosure. This feature is probably more important for site-selection projects for power plants than for small public works projects, but this level of documentation is still critical when public policy and taxes are concerned.

The detail and depth of understanding needed to fully use this decision analysis methodology forces the user to acquire a deeper understanding of the problem being solved. This can be both an advantage and a disadvantage. Multiple experts are usually needed to develop the utility curves. The tradeoffs are dependent on the mix of decision makers and stakeholders involved in the process and are expected to change with time. The depth of knowledge obtained and full documentation always is a positive aspect of these methods, but the required resources to fully implement the system can be an insurmountable obstacle to smaller communities. However, sensitivity analyses can be used to focus resources only on those aspects of greatest importance.

The first step in applying decision analysis techniques consists of defining the alternatives and quantitative measures (attributes) for the objectives. How well each of the alternative stormwater programs in this example achieves the objective is also determined. In this example for the medium-density residential (1960 to 1980) land use, five attributes (total annual cost, Rv, TSS reductions, TP reductions, and *E. coli* reductions) are chosen to reflect the different considerations in deciding which stormwater management program to select. Obviously, these would vary depending on the local goals and objectives. These are selected here as examples and illustrate how WinSLAMM can be used to help describe many attributes of stormwater programs, beyond just costs. These attributes, their units of measurement, and the associated ranges are shown in Table 32.

Table 32. Selected characteristics and attributes of alternative stormwater management programs for medium-density residential area (1960–1980)

Program ID number	Stormwater control programs	Subbasin total annual cost ($/ac/yr)	Rv	Particulate solids yield percent reduction	Phos. yield percent reduction	*E. coli* yield percent reduction
1	Roof rain garden 3% of connected roofs only	$17	0.18	1%	1%	1%
2	Roof rain garden 15% of connected roofs only	$87	0.16	1%	2%	1%
3	Rain garden 3% of all roofs	$71	0.17	1%	1%	1%
4	Rain garden 15% of all roofs	$357	0.15	1%	3%	1%
5	Rain barrels few	$5	0.18	1%	1%	1%
6	Rain barrels	$11	0.17	1%	1%	1%
7	Rain barrels many	$27	0.17	1%	1%	1%
8	Rain tanks small	$19	0.17	1%	2%	1%
9	Rain tanks	$48	0.16	1%	2%	1%
10	Rain tanks large	$145	0.16	1%	2%	1%
11	Porous pavement on driveways	$31	0.18	2%	2%	28%
12	Curb-cut biofilters 20%	$187	0.05	76%	66%	77%
13	Curb-cut biofilters 40%	$375	0.02	93%	86%	91%
14	Curb-cut biofilters 80%	$749	0.00	99%	97%	98%
15	Street cleaning daily	$619	0.20	57%	13%	0%
16	Street cleaning monthly	$29	0.20	22%	5%	0%
17	Street cleaning weekly	$108	0.20	43%	9%	0%
18	Street cleaning once in spring and fall	$5	0.20	8%	2%	0%
19	Catchbasin cleaning	$68	0.20	16%	4%	0%
20	Grass swale drainage	$384	0.04	83%	78%	83%
21	Wet pond 0.4%	$32	0.20	67%	16%	0%
22	Wet pond 0.8%	$57	0.20	83%	19%	0%
23	Wet pond 1.6%	$105	0.20	94%	22%	0%
24	Small wet pond and rain tanks	$80	0.16	71%	18%	1%
25	Small wet pond and all roof rain garden 15%	$389	0.15	72%	19%	1%
26	Small wet pond and swale	$416	0.04	95%	81%	83%
27	Small wet pond and curb biofilters 40%	$406	0.02	97%	87%	91%
28	Small wet pond, grdn 15% and curb biofilters 40%	$763	0.01	98%	91%	94%
	minimum	$5	< 0.01	1%	1%	0%
	maximum	$763	0.20	99%	97%	98%

The next step consists of quantifying the preferences and tradeoffs for the various attribute levels using utility curves and attribute weighting factors. The concepts of utility theory, such as described in Keeney and Raiffa (1976), provide a consistent scale to quantify how much one gives up when choosing one attribute over another. Utility curves are first assessed for the individual attributes. These curves quantify the preferences that exist for the total range of each attribute. They also quantify attitudes toward risk. This is important when alternatives yield uncertain consequences. The curves are defined on the basis of technical information and are usually developed by experts. The most preferred point is defined as having a utility value of 1.00 and the least preferred point a utility value of 0.00. The utility assessments establish where the intermediate points fall on the utility scale. The utility curves can take many shapes, from step functions, simple curves to straight lines. The five attributes listed in the table have the following assumed utility curves and associated values:

- Total annual cost: straight line, with \$763/acre/yr = 0 and \$5/acre/yr = 1.0.
- Rv as an indicator of habitat quality and aquatic biology stress:

Attribute value	Expected Habitat Condition	Utility value
< 0.1	Good	1.0
0.1 to 0.17	Fair	0.75
0.18 to 0.50	Poor	0.25
0.51 to 1.0	Very poor	0

- Particulate solids yield reduction:

% reduction	Utility value
> 90%	1.0
75% to 89%	0.75
50% to 74%	0.25
< 50%	0

- Phosphorus yield reduction:

% reduction	Utility value
> 75%	1.0
50% to 74%	0.75
25% to 49%	0.25
< 25%	0

- *E. coli* yield reduction:

% reduction	Utility value
> 95%	1.0
90% to 94%	0.75
75% to 89%	0.25
< 75%	0

Tradeoffs between attributes are determined by each group of stakeholders. The sum of the tradeoffs for all attributes must equal one for each set. There would likely be several sets of these, and each would have a different set of tradeoff values, depending on the stakeholders' goals. Table 33 summarizes some example tradeoff values for different stakeholder groups.

Table 33. Tradeoff values for different stakeholder groups

	Regulatory agency	Municipal government	Local residents
Annual cost	0.05	0.40	0.50
Rv	0.25	0.20	0.20
TSS reductions	0.10	0.20	0.10
TP reductions	0.10	0.10	0.10
E. coli reductions	0.50	0.10	0.10
Sum of tradeoff values:	1.00	1.00	1.00

The next step is to calculate the utilities associated with each attribute for each alternative control program. The tradeoff values are then used as weighting factors to sum the total score for each alternative. The total scores are then used to rank the alternatives, with the highest total score the most desirable for that stakeholder group. Table 34 shows these calculations, with the final total scores and ranks, for each stakeholder group.

Table 34. Calculated utility values, weighted sum of factors, and ranks for different stakeholder groups (top five ranks highlighted for each group)

Program ID number	Stormwater control programs	Cost utility	Rv utility	TSS utility	TP utility	*E. coli* utility	Regulatory agency weighted sum of factors	Regulatory agency rank	Munic. govt. weighted sum of factors	Munic. govt. rank	Local resid. weighted sum of factors	Local resid. rank
1	Roof rain garden 3% of connected roofs only	0.98	0.25	0.00	0.00	0.00	0.11	23	0.44	21	0.54	19
2	Roof rain garden 15% of connected roofs only	0.89	0.75	0.00	0.00	0.00	0.23	15	0.51	16	0.60	12
3	Rain garden 3% of all roofs	0.91	0.75	0.00	0.00	0.00	0.23	14	0.52	15	0.61	11
4	Rain garden 15% of all roofs	0.54	0.75	0.00	0.00	0.00	0.21	17	0.36	27	0.42	27
5	Rain barrels few	1.00	0.25	0.00	0.00	0.00	0.11	21	0.45	19	0.55	17
6	Rain barrels	0.99	0.75	0.00	0.00	0.00	0.24	10	0.55	11	0.65	6
7	Rain barrels many	0.97	0.75	0.00	0.00	0.00	0.24	12	0.54	13	0.64	8
8	Rain tanks small	0.98	0.75	0.00	0.00	0.00	0.24	11	0.54	12	0.64	7
9	Rain tanks	0.94	0.75	0.00	0.00	0.00	0.23	13	0.53	14	0.62	10
10	Rain tanks large	0.82	0.75	0.00	0.00	0.00	0.23	16	0.48	18	0.56	15
11	Porous pavement on driveways	0.97	0.25	0.00	0.00	0.00	0.11	25	0.44	23	0.53	21
12	Curb-cut biofilters 20%	0.76	1.00	0.75	0.75	0.00	0.44	7	0.73	*3*	0.73	*2*
13	Curb-cut biofilters 40%	0.51	1.00	1.00	1.00	0.75	0.85	*2*	0.78	*1*	0.73	*1*
14	Curb-cut biofilters 80%	0.02	1.00	1.00	1.00	1.00	0.95	*1*	0.61	6	0.51	22
15	Street cleaning daily	0.19	0.25	0.25	0.00	0.00	0.10	28	0.18	28	0.17	28
16	Street cleaning monthly	0.97	0.25	0.00	0.00	0.00	0.11	24	0.44	22	0.53	20
17	Street cleaning weekly	0.86	0.25	0.00	0.00	0.00	0.11	27	0.40	26	0.48	24
18	Street cleaning once in spring and fall	1.00	0.25	0.00	0.00	0.00	0.11	22	0.45	20	0.55	18
19	Catchbasin cleaning	0.92	0.25	0.00	0.00	0.00	0.11	26	0.42	24	0.51	23
20	Grass swale drainage	0.50	1.00	0.75	1.00	0.25	0.58	6	0.68	*5*	0.65	*5*
21	Wet pond 0.4%	0.96	0.25	0.25	0.00	0.00	0.14	20	0.49	17	0.56	16
22	Wet pond 0.8%	0.93	0.25	0.75	0.00	0.00	0.18	19	0.57	9	0.59	13
23	Wet pond 1.6%	0.87	0.25	1.00	0.00	0.00	0.21	18	0.60	7	0.58	14
24	Small wet pond and rain tanks	0.90	0.75	0.25	0.00	0.00	0.26	8	0.56	10	0.63	9
25	Small wet pond and all roof rain garden 15%	0.49	0.75	0.25	0.00	0.00	0.24	9	0.40	25	0.42	26
26	Small wet pond and swale	0.46	1.00	1.00	1.00	0.25	0.60	*5*	0.71	*4*	0.65	*4*
27	Small wet pond and curb biofilters 40%	0.47	1.00	1.00	1.00	0.75	0.85	*3*	0.76	*2*	0.71	*3*
28	Small wet pond, grdn 15% and curb biofilters 40%	0.00	1.00	1.00	1.00	0.75	0.83	*4*	0.58	8	0.48	25
	Regulatory agency tradeoffs	0.05	0.25	0.10	0.10	0.50						
	Municipal government tradeoffs	0.40	0.20	0.20	0.10	0.10						
	Local residents tradeoffs	0.50	0.20	0.10	0.10	0.10						

It is interesting to note that the top-ranked alternatives are generally similar for each stakeholder group, even with very different tradeoff values. The municipal government and local resident tradeoffs are quite similar, but they are quite different from the regulatory agency's tradeoff values. The overall top-ranked alternative is the curb-cut biofilters at 40 percent of the curb line. This alternative ranked first for the municipal government and local resident stakeholder groups and second for the regulatory agency. The top-ranked alternative for the regulatory agency (the curb-cut biofilters at 80 percent of the curb line) ranked much lower for the other two stakeholder groups because of its much higher costs. The small wet pond plus the curb-cut biofilters at 40 percent of the curb line ranked second for the municipal government stakeholders and third for the regulatory agency and the local government stakeholder groups. As stated previously, one of the great values of the multiple/conflicting objectives decision analysis procedure is being clear in the process, while showing how diverse stakeholder groups might be closer to agreement than realized.

The decision analysis approach outlined in this section has the flexibility of allowing for variable levels of analytical depth, depending on the problem requirements. The preliminary level of defining the problem explicitly in terms of attributes often serves to make the most preferred alternatives clear. The next level of analysis might consist of a first-cut assessment and ranking as described in this example. Spreadsheet calculations with the model are easily performed, as was done here, making it possible to conduct several decision analysis evaluations using different tradeoff values, representing different viewpoints, at one time. A small set of options could exist that everyone agrees are the best choices, as in this example. Also, this procedure documents the process for later discussion and review. Sensitivity analyses can also be conducted to identify the most significant factors that affect the decisions. The deepest level of analysis can use all the analytical information one collects, such as probabilistic forecasts for each of the alternatives and the preferences of experts over the range of individual attributes. Monte Carlo options available in WinSLAMM can also be used that consider the uncertainties in the calculated attributes for each option.

6.4 Other Considerations Affecting Selection and Use of Stormwater Controls

Suitable care is needed in constructing stormwater controls and interpreting modeling results because other critical factors could dramatically affect their success. Certain site conditions could restrict the applicability of some of these controls, as briefly discussed in the next paragraphs (mostly summarized from a prior publication by Pitt et al. (2008) and from research reported by others at recent technical conferences.

- The SAR can radically degrade the performance of an infiltration device, especially when clays are present in the infiltration layers of a device and snowmelt containing deicing salts enters the device. Soils with an excess of sodium ions, compared to calcium and magnesium ions, remain in a dispersed condition, and are almost impermeable to rain or applied water. A *dispersed* soil is extremely sticky when wet, tends to crust, and becomes very hard and cloddy when dry. Water infiltration is therefore severely restricted. SAR has been documented to be causing premature failures of biofiltration devices in northern communities. These failures occur when snowmelt water enters a biofilter that has clay in the soil mixture. To minimize this failure, prevent snowmelt water from entering a biofilter unit. As an example, roof runoff likely has little salt and SAR problems seldom occur for roof runoff rain gardens. The largest problem is associated with curb-cut biofilters or parking lot biofilters in areas with snowmelt entering these devices, especially if clay is present in the engineered backfill soil. The biofilter fill soil should not have any clay. It appears that even a few percent clay can cause a problem, but little information is available on the tolerable clay content of biofilter soils. The most robust engineered soil mixtures used in biofilters should be mixtures of sand and an organic material (such as compost if nutrient leaching is not an issue, or Canadian peat for a more stable material having little nutrient leaching potential).

- The designs of infiltration devices must be checked according to their clogging potential. As an example, a relatively small and efficient biofilter (in an area having a high native infiltrating rate) might capture a large amount of sediment. Having a small surface area, this sediment would accumulate rapidly over the area, possibly reaching a critical clogging load early in its design lifetime. Infiltration and bioretention devices might show significantly reduced infiltration rates after about 2 to 5 lb/ft^2 (10 to 25 kg/m^2) of particulate solids have been loaded, especially in a short, several year period.
- The potential for infiltrating stormwaters to contaminate groundwaters is dependent on the concentrations of the contaminants in the infiltrating stormwater and how effectively those contaminants might travel through the soils and vadose zone to the groundwater. Source stormwaters from residential areas are not likely to be contaminated with compounds having significant contaminating potential (with the exception of high salinity snowmelt waters). In contrast, commercial and industrial areas are likely to have greater concentrations of contaminants of concern that could adversely affect the groundwater. Therefore, pretreatment of the stormwater before infiltration might be necessary, or using specially selected media in the biofilter.
- Most of the control options being considered as GI components in areas served by combined sewers are intended for retrofitting in existing urban areas. Therefore, their increased costs and availability of land will be detrimental in developing highly effective control programs. The range of difficulties and land requirements varies, mostly depending on available opportunities.

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