R. Pitt
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Flow-Duration Analyses and Stream Stability for Habitat Evaluations and the Design of Stormwater Controls

Receiving Water Impacts Associated with Increased Discharges

Urbanization causes profound changes in the hydrology of the area, specifically the timing of the runoff, the water use, runoff volume and flow rates, channel complexity, and especially pollution in receiving waters. Water quality problems increase with increasing imperviousness of the watershed. Impervious areas cause increased runoff and contaminated discharges from these areas and also contribute to receiving water contamination. Increases in urban population, and associated urban sprawl alters drainage basins and rivers. When watershed areas are urbanized, much of the vegetation and top soil is replaced by impervious surfaces (roads, parking lots, and roof tops) and much of the remaining soils are compacted. Population increases therefore cause increases in impervious areas which means less water will soak into the ground and more water will go directly to urban streams during the rains, along with faster rises in runoff. In addition to the high flows caused by urbanization, the increased runoff also contains increased contaminants. These increased flows are likely one of the major causes of stream degradation in urban areas (Burton and Pitt 2001). Increasing amounts of impervious cover are typically used as an indicator of these increased flows, and have therefore become an indicator in measuring the impact of land development on drainage systems and aquatic life (Schueler 1994). Impervious cover is one of the variables that can be quantified for different types of land development, although there are many different types of impervious surfaces and how they are connected to the drainage system. In urban areas, stream and lake impairment is also due to habitat destruction; but, in addition, physical and chemical contaminant loadings come from runoff from impervious areas (e.g., parking lots, streets) off of construction sites, and industrial, commercial, and residential areas. Numerous studies (such as May 1996) have examined the extent of urbanization with decaying receiving water conditions (Figure 1).

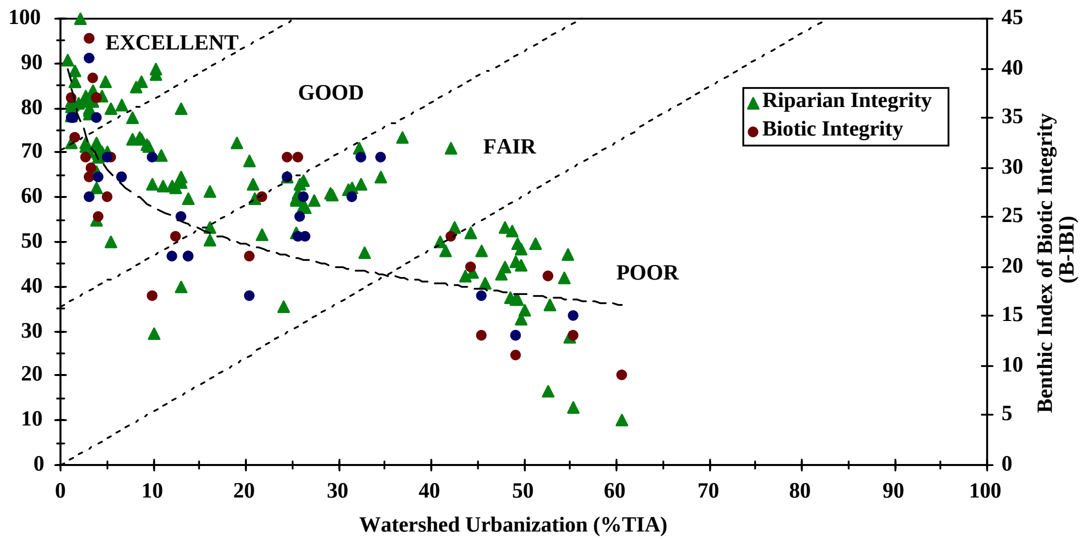


Figure 1. Relationship between basin development, riparian buffer width, and biological integrity in Puget Sound lowland streams (May 1996).

Urban pollutant loads in aquatic systems are directly related to watershed imperviousness. It is generally found that stream degradation occurs at low levels of imperviousness (about 10 to 15%), where sensitive stream elements are lost from the system. There is a second threshold at around 25 to 30% impervious cover, where most indicators of stream quality change to a poor condition (Schueler 1994). Bochis-Micu and Pitt (2005) have extensively examined land development practices in Little Shades Creek watershed in Birmingham, Alabama. Table 1 shows the amounts of impervious cover in these areas, along with the calculated volumetric runoff coefficients determined by WinSLAMM using a 43 year rain period. Overall, the watershed has a total impervious cover of about 35%, of which about 25% is directly connected to the drainage system and 10% drains to pervious areas. As expected, the land use with the least impervious cover is open space (parks, cemeteries, golf course), and the land uses with the largest impervious covers are commercial areas, followed by industrial areas.

Table 1. Little Shade Creek, Birmingham, AL: Average of Source Area Drainage Connections by Land Use (Bochis-Micu and Pitt 2005)

Land Use	Pervious Areas (%)	Directly Connected Impervious Areas (%)	Disconnected Impervious Areas (%) (draining to pervious areas)	Volumetric Runoff Coefficient (Rv) if Sandy Soils	Volumetric Runoff Coefficient (Rv) if Clayey Soils
High Dens. Residential	76.07	13.41	10.52	0.09	0.17
Med. Dens. Residential (<1960)	81.74	9.06	9.20	0.06	0.14
Med. Dens. Residential (1961-80)	81.24	8.80	9.96	0.07	0.15
Med. Dens. Residential (>1980)	81.59	14.09	4.31	0.09	0.17
Low Dens. Residential (drained by swales)	89.84	4.92	5.24	0.05	0.17
Apartments	57.79	15.86	26.36	0.09	0.17
Multi Family	65.19	27.38	7.43	0.13	0.14
Offices	38.67	56.77	4.57	0.41	0.43
Shopping Centers	32.53	63.83	3.64	0.43	0.47

Schools	79.12	16.03	4.86	0.12	0.17
Churches	44.24	53.64	2.12	n/a	n/a
Strip Commercial	7.90	87.80	4.30	0.60	0.61
Industrial	53.61	35.79	10.60	0.46	0.49
Parks	59.32	32.32	8.36	0.29	0.34
Cemeteries (drained by swales)	82.90	0.00	17.10	0.08	0.16
Golf Courses (drained by swales)	94.56	1.93	3.51	0.04	0.15
Freeways (drained by swales)	40.91	0.00	59.09	0.08	0.26
Vacant (drained by swales)	95.23	0.00	4.77	0.06	0.17

Figures 2 and 3 illustrate the relationships between the directly connected impervious area percentages and the calculated volumetric runoff coefficients (Rv) for each land use category (using the average land use characteristics), based on 43 years of local rain data. As expected, there is a strong relationship between these parameters for both sandy and clayey soil conditions. The fitted exponential equations are:

Sandy soils: $y = 0.062e^{0.031x}$ ($R^2 = 0.83$)

Clayey soils: $y = 0.15e^{0.017x}$ ($R^2 = 0.72$)

Where y is the volumetric runoff coefficients (Rv) and x is the directly connected impervious areas (%) for the areas. It is interesting to note that the Rv is relatively constant until the 10 to 15% directly connected impervious cover values are reached (at Rv values of about 0.07 for sandy soil areas and 0.16 for clayey soil areas), the point where receiving water degradation typically is observed to start. The 25 to 30% directly connected impervious levels (where significant degradation is observed), is associated with Rv values of about 0.14 for sandy soil areas and 0.25 for clayey soil areas, and is where the curves start to greatly increase in slope.

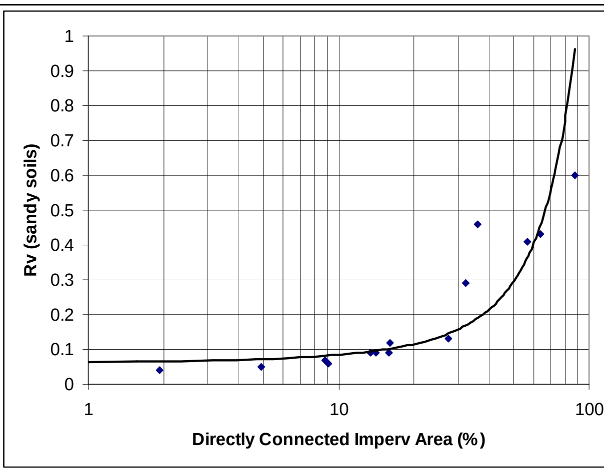


Figure 2. Relationships between the directly connected impervious area (%) and the calculated volumetric runoff coefficients (Rv) for each land use category for sandy soil.

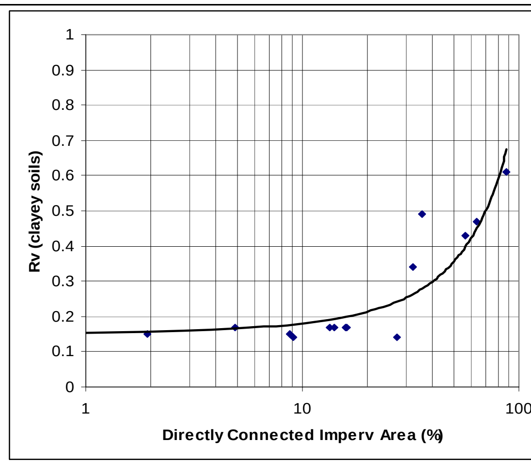


Figure 3. Relationships between the directly connected impervious area (%) and the calculated volumetric runoff coefficients (Rv) for each land use category for clayey soil.

These relationships are used in WinSLAMM to predict the relationship between the amount of impervious cover and the approximate expected receiving water biological condition (by using the calculated Rv values) affected by the study area. WinSLAMM calculates the Rv for the duration of the study period for various conditions, including with and without controls. These values are correlated to the expected biological conditions, weighted by the soil properties in the study area. This enables one to predict the expected benefits that may occur with the use of the stormwater controls, compared to no controls.

Stream Flow Effects and Associated Habitat Modifications

Some of the most serious effects of urban and agricultural runoff are on the aquatic habitat of the receiving waters. A major habitat destruction threat comes from the rapidly changing flows and the absence of refuge areas to protect the biota during these flow changes. The natural changes in stream hydrology will change naturally at a slow, relatively nondetectable rate in most areas where streambanks are stabilized by riparian vegetation. In other areas, however, natural erosion and bank slumping will occur in response to high flow events. This "natural" contribution to stream solids is accelerated by hydromodifications, such as increases in stream power due to upstream channelization, installation of impervious drainage networks, increased impervious areas in the watershed (roof tops, roadways, parking areas), and removal of trees and vegetation. All of these increase the runoff volume and stream power, and decrease the time period for stream peak discharge. The following summary is excerpted from Burton and Pitt (2001) and presents a few case studies describing habitat problems associated with increased urbanization and associated flows.

In moderately developed watersheds, peak discharges are two to five times those of pre-development levels (Leopold 1968, Anderson 1970). These storm events may have 50% greater volume which may result in flooding. The quicker runoff periods reduce infiltration thus interflows and baseflows into the stream from groundwater during drought periods are reduced, as are groundwater levels. As stream power increases, channel morphology will change with an initial widening of the channel to as much as 2 to 4 times their original size (Robinson 1976, Hammer 1972). Floodplains increase in size, stream banks are undercut and riparian vegetation lost. The increased sediment loading from erosion moves through the watershed as bedload, covering sand, gravel, and cobble substrates.

As an example, the aquatic organism differences found during the Bellevue Urban Runoff Program were probably most associated with the increased peak flows in Kelsey Creek caused by urbanization and the resultant increase in sediment carrying capacity and channel instability of the creek (Pedersen 1981; Perkins 1982; Richey, *et al*. 1981; Richey 1982; Scott, *et al*. 1982). Kelsey Creek had much lower flows than Bear Creek during periods between storms. About 30 percent less water was available in Kelsey Creek during the summers. These low flows may also have significantly affected the aquatic habitat and the ability of the urban creek to flush toxic spills or other dry weather pollutants from the creek system (Ebbert, *et al*. 1983; Prych and Ebbert undated). Kelsey Creek had extreme hydrologic responses to storm. Flooding substantially increased in Kelsey Creek during the period of urban development; the peak annual discharges almost doubled in the last 30 years, and the flooding frequency also increased due to urbanization (Ebbert, *et al.* 1983; Prych and Ebbert undated). These increased flows in urbanized Kelsey Creek resulted in greatly increased sediment transport and channel instability. The Bellevue studies (Pitt and Bissonnette 1984) indicated very significant interrelationships between the physical, biological, and chemical characteristics of the urbanized Kelsey Creek system. The aquatic life beneficial uses were found to be impaired and stormwater conveyance was most likely associated with increased flows from the impervious areas in the urban area. Changes in the flow characteristics could radically alter the ability of the stream to carry the polluted sediments into the other receiving waters.

In another study, Stephenson (1996) studied changes in streamflow volumes in South Africa during urbanization. He found increased stormwater runoff, decreases in the groundwater table, and dramatically decreased times of concentration. The peak flow rates increased by about two-fold, about half caused by increased pavement (in an area having only about 5% effective impervious cover), with the remainder caused by decreased times of concentration.

Bhaduri, *et al.* (1997) quantified the changes in streamflow and associated decreases in groundwater recharge associated with urbanization. They point out that the most widely addressed hydrologic effect of urbanization is the peak discharge increases that cause local flooding. However, the increase in surface runoff volume also represents a net loss in groundwater recharge. They point out that urbanization is linked to increased variability in volume of water available for wetlands and small streams, causing "flashy" or "flood-and-drought" conditions. In northern Ohio, urbanization at a study area was found to cause a 195% increase in the annual volume of runoff, while the expected increase in the peak flow for the local 100-yr event was 26% for the same site. Although any increase in severe flooding is problematic and cause for concern, the much larger increase in annual runoff volume, and associated decrease in groundwater recharge, likely has a much greater effect on in-stream biological conditions.

A number of presentations concerning aquatic habitat effects from urbanization were made at the *Effects of Watershed Development and Management on Aquatic Ecosystems* conference held in Snowbird, UT, in August of 1996, sponsored by the Engineering Foundation and the ASCE. MacRae (1997) presented a review of the development of the common zero runoff increase (ZRI) discharge criterion, referring to peak discharges before and after development. This criterion is commonly met using detention ponds for the 2 yr storm. MacRae shows how this criterion has not effectively protected the receiving water habitat. He found that stream bed and bank erosion is controlled by the frequency and duration of the mid-depth flows (generally occurring more often than once a year), not the bank-full condition (approximated by the 2 yr event). During monitoring near Toronto, he found that the duration of the geomorphically significant pre-development mid-bankfull flows increased by a factor of 4.2 times, after 34% of the basin had been urbanized, compared to before development flow conditions. The channel had responded by increasing in cross-sectional area by as much as 3 times in some areas, and was still expanding. Table 2 shows the modeled durations of critical discharges for predevelopment conditions, compared to current and ultimate levels of development with "zero runoff increase" controls in place. At full development and even with full ZRI compliance in this watershed, the hours exceeding the critical mid-bankfull conditions will increase by a factor of 10, with resulting significant effects on channel stability and the physical habitat.

Table 2. Hours of Exceedence of Developed Conditions with Zero Runoff Increase Controls Compared to Predevelopment Conditions (MacRae (1997)

Recurrence Interval (yrs)	Existing Flowrate (m^3/s)	Exceedence for Predevelopment Conditions (hrs per 5 yrs)	Exceedence for Existing Development Conditions, with ZRI Controls (hrs per 5 yrs)	Exceedence for Ultimate Development Conditions, with ZRI Controls (hrs per 5 yrs)
1.01 (critical mid-bankfull conditions)	1.24	90	380	900
1.5 (bankfull conditions)	2.1	30	34	120

MacRae (1997) also reported other studies that found that channel cross-sectional areas began to enlarge after about 20 to 25% of the watershed was developed, corresponding to about a 5% impervious cover in the watershed. When the watersheds are completely developed, the channel enlargements were about 5 to 7 times the original cross-sectional areas. Changes from stable streambed conditions to unstable conditions appear to occur with basin imperviousness of about 10%, similar to the value reported for serious biological degradation. He also summarized a study conducted in British Columbia that examined 30 stream reaches in natural areas, in urbanized areas having peak flow attenuation ponds, and in urbanized areas not having any stormwater controls. The channel widths in the uncontrolled urban streams were about 1.7 times the widths of the natural streams. The streams having the ponds also showed widening, but at a reduced amount compared to the uncontrolled urban streams. He concluded that an effective criterion to protect stream stability (a major component of habitat protection) must address mid-bankfull events, especially by requiring similar durations and frequencies of stream power (the product of shear stress and flow velocity, not just flow velocity alone) at these depths, compared to satisfactory reference conditions.

Urbanization radically affects many natural stream characteristics. Pitt and Bissonnette (1984) reported that the coho and cutthroat were affected by the increased nutrients and elevated temperatures of the urbanized streams in Bellevue, as studied by the University of Washington as part of the U.S. EPA's NURP project (EPA 1983). These conditions were probably responsible for accelerated growth of the fry which were observed to migrate to Puget Sound and the Pacific Ocean sooner than their counterparts in the control forested watershed that was also studied. However, the degradation of sediments, mainly the decreased particle sizes, adversely affected their spawning areas in streams that had become urbanized. Sovern and

Washington (1997) reported that, in Western Washington, frequent high flow rates can be 10 to 100 times the predevelopment flows in urbanized areas, but that the low flows in the urban streams are commonly lower than the predevelopment low flows. They have concluded that the effects of urbanization on western Washington streams are dramatic, in most cases permanently changing the stream hydrologic balance by: increasing the annual water volume in the stream, increasing the volume and rate of storm flows, decreasing the low flows during dry periods, and increasing the sediment and pollutant discharges from the watershed. With urbanization, the streams increase in cross-sectional area to accommodate these increased flows and headwater downcutting occurs to decrease the channel gradient. The gradients of stable urban streams are often only about 1 to 2 percent, compared to 2 to 10 percent gradients in natural areas. These changes in width and the downcutting result in very different and changing stream conditions. The common pool/drop habitats are generally replaced by pool/riffle habitats, and the stream bed material is comprised of much finer material, for example. Along urban streams, fewer than 50 aquatic plant and animal species are usually found. They have concluded that once urbanization begins, the effects on stream shape are not completely reversible. Developing and maintaining quality aquatic life habitat, however, is possible under urban conditions, but it requires human intervention and it will not be the same as for forested watersheds.

Increased flows due to urban and agricultural modification obviously cause aquatic life impacts due to destroyed habitat (unstable channel linings, scour of sediments, enlarging stream cross-sections, changes in stream gradient, collapsing of riparian stands of mature vegetation, siltation, embeddedness, etc.) plus physical flushing of aquatic life from refuge areas downstream. The increases in peak flows, annual runoff amounts, and associated decreases in groundwater recharge obviously cause decreased dry weather flows in receiving streams. Many small and moderate-sized streams become intermittent after urbanization, causing extreme aquatic life impacts. Even with less severe decreased flows, aquatic like impacts can be significant. Lower flows are associated with increased temperatures, increased pollutant concentrations (due to decreased mixing and transport), and decreased mobility and forage opportunities.

WinSLAMM presents a cumulative summary of all flows predicted over the complete study period. These are presented in graphical and tabular form and show the resultant conditions at the discharge from the study area for all the controls in place, and if the controls were not present. This comparison enables one to examine the benefits of the stormwater controls on the distribution and magnitude of the flows.

Flow-Duration Analyses for Different Treatment Scenarios

The following is a summary discussion showing how WinSLAMM can be used to produce basic flow-duration analyses for different treatment options. Most of these figures are from Bochis, *et al.* (2007) and show how flow information can be used compare treatment alternatives and different land development scenarios.

Table 3 is a summary of stream conditions affected by impervious areas in a watershed, assembled by the Center for Watershed Protection based on many studies from throughout the country. Figure 4 was calculated using WinSLAMM from more than 150 land use areas in Alabama, for three different soil characteristics. The sensitive conditions up to 10% impervious are related to a flat portion of the curves. The impacted portion (between 10 and 25%) is where the curves start to rise, while the damaged portion (>25%) is associated with a very steep portion of the curve. In this region, substantial reductions in imperviousness would be needed to improve damaged streams. Figure 5 is a copy of the WinSLAMM summary screen that shows the expected receiving water conditions, optional annualized stormwater control costs, and discharge conditions for the modeled conditions, and if all controls are ignored. Figure 6 is the flow-duration calculation screen from WinSLAMM that is selected from the summary screen. This shows two plots, one for the modeled conditions, and another if all controls are ignored. A table is also available showing the actual flows associated with different probability values.

Table 3. Summary of Stream Habitat Effects Associated with Imperviousness

Urban Steam Classification	Sensitive 0 – 10% Imperviousness	Impacted 11– 25% Imperviousness	Damaged 26–100% Imperviousness
Channel Stability	Stable	Unstable	Highly Unstable
Aquatic Life Biodiversity	Good/Excellent	Fair/Good	Poor

Source: the Center for Watershed Protection

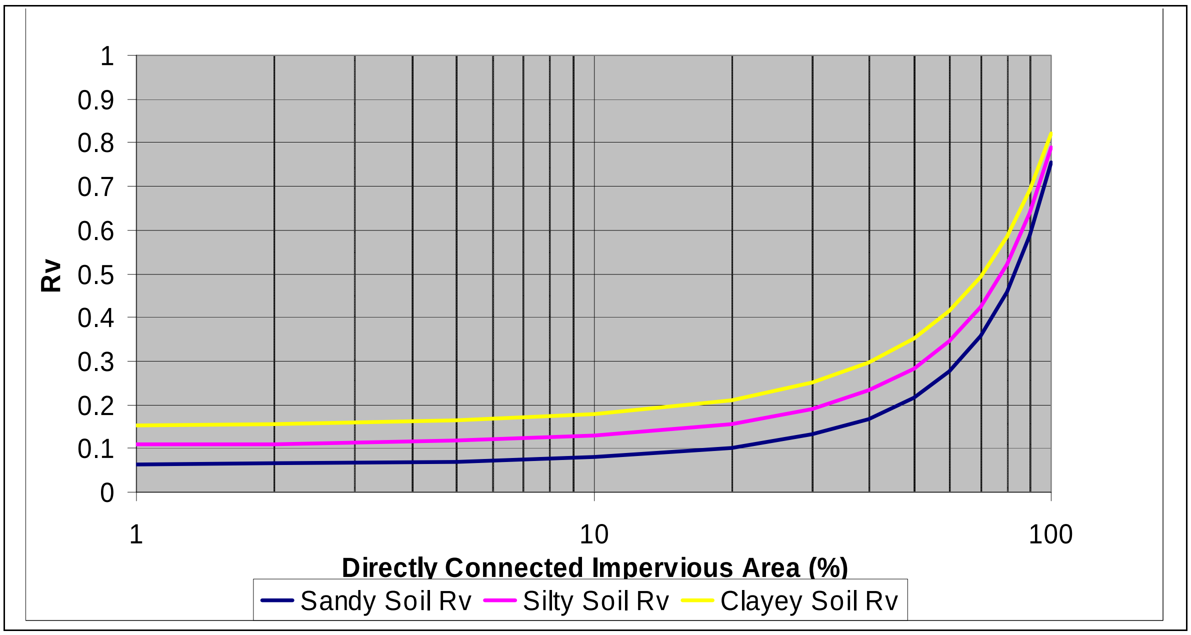


Figure 4. Calculated Rv responses associated with different measured imperviousness values for different soil characteristics

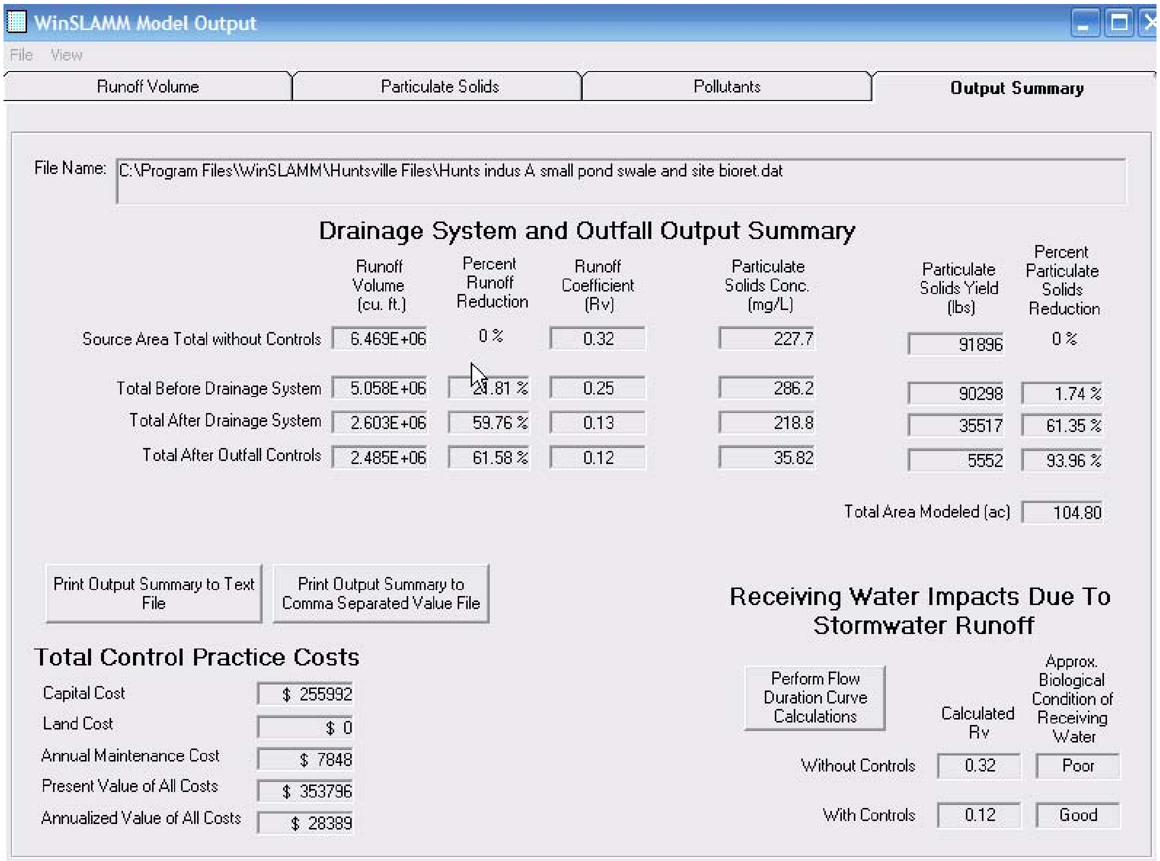
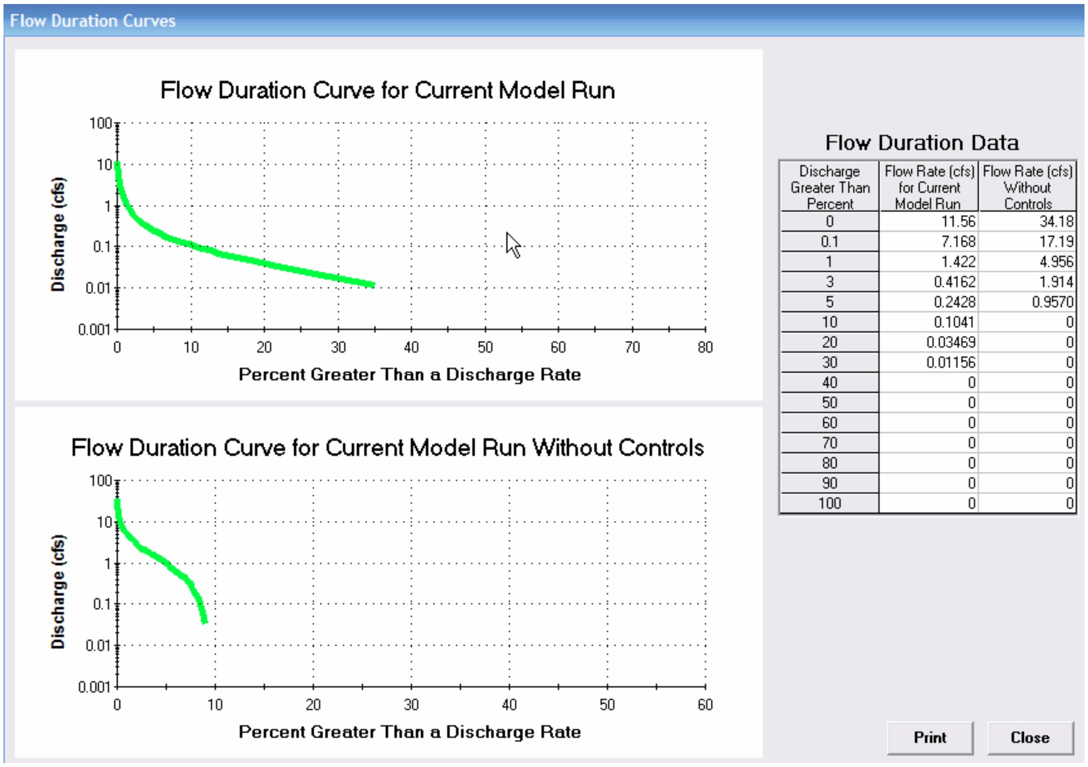


Figure 5. WinSLAMM summary screen showing expected receiving water conditions, annualized stormwater control costs, and discharge conditions.



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

Figure 6. Flow-duration calculation screen from WinSLAMM.

Table 4 summarizes the development conditions for the MS4 monitored watersheds in Jefferson County, AL. The Rv and expected biological conditions were calculated using WInSLAMM after calibration and verification for regional conditions. The expected biological conditions were verified by Stormwater Management Authority biologists. Although all of the expected stream conditions are poor, the residential areas are much closer to the critical flow conditions than the industrial and commercial sites. One of the watersheds is high-lighted and is used in the following example. Figure 6 contains flow-duration plots for alternative treatment scenarios for this watershed. There are three distinct groups of data shown. The top set is for the base conditions and for swales. Since the soils in this area are clayey and the land use is a heavily developed area, the swales are not as effective as they would normally be in more suitable areas. The middle set of flow plots correspond to alternatives that have wet detention ponds. The reduced peak flows are associated with hydraulic routing of the inflow hydrographs, and no volume reductions are associated with these alternatives. The bottom set of flow plots show the most significant reductions in flows and all the alternatives have bioretention systems. These devices were designed with amended soils and had substantial storage capacity and moderate infiltration rates. Figure 7 is a plot showing the comparative and cost-effectiveness values for runoff volume reductions for the different control alternatives. This plot shows the greatest reductions at the least costs by the dashed line connecting the most cost-effective controls. If 50% volume reductions are desired, then bioretention options alone would be sufficient, at almost $40 per 1,000 ft^3 of water reduction. Higher levels of control are possible (to maybe 70% in this example), but at higher unit costs. Table 5 summarizes the expected stormwater control implementation costs and the expected performance for this example. Only the most expensive option is expected to improve the receiving water conditions to fair, from the base level poor conditions. The annual cost for this option would be about $2,400 per acre per year in the watershed. Similar analyses could be conducted for stormwater costs and benefits for controls established at the time of development which would be much more cost effective than these retro-fitted program costs.

Table 4. MS4 Monitoring Watersheds in Jefferson County, AL.

Watershed ID	Major Land Use	Area (ac)	Pervious Areas (%)	Directly Connected Impervious Areas (%)	Disconnected Impervious Areas (%)	Vol. Runoff Coeff. (Rv)	Expected Biological Conditions of Receiving Waters
ALJC 001	IND	341	25	72	2.8	0.67	Poor
ALJC 002	IND	721	40	53	7.3	0.51	Poor
ALJC 009	Resid. High Dens.	102	54	34	12	0.37	Poor
ALJC 010	Resid. Med. Dens.	133	64	28	7.9	0.30	Poor
ALJC 012	COM	228	36	61	3.4	0.61	Poor
Little Shades Creek	RES	5120	67	21	12	0.29	Poor

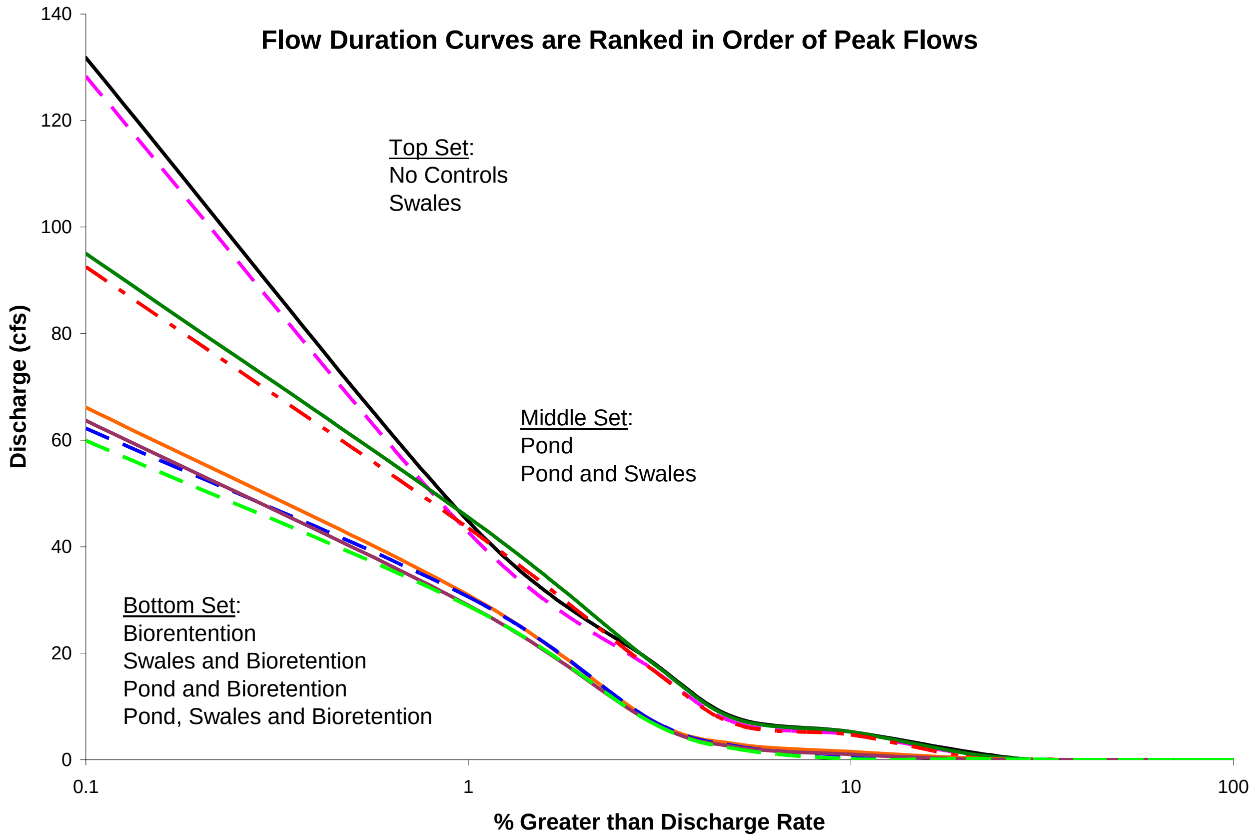


Figure 6. Flow-duration plots for alternative treatment scenarios.

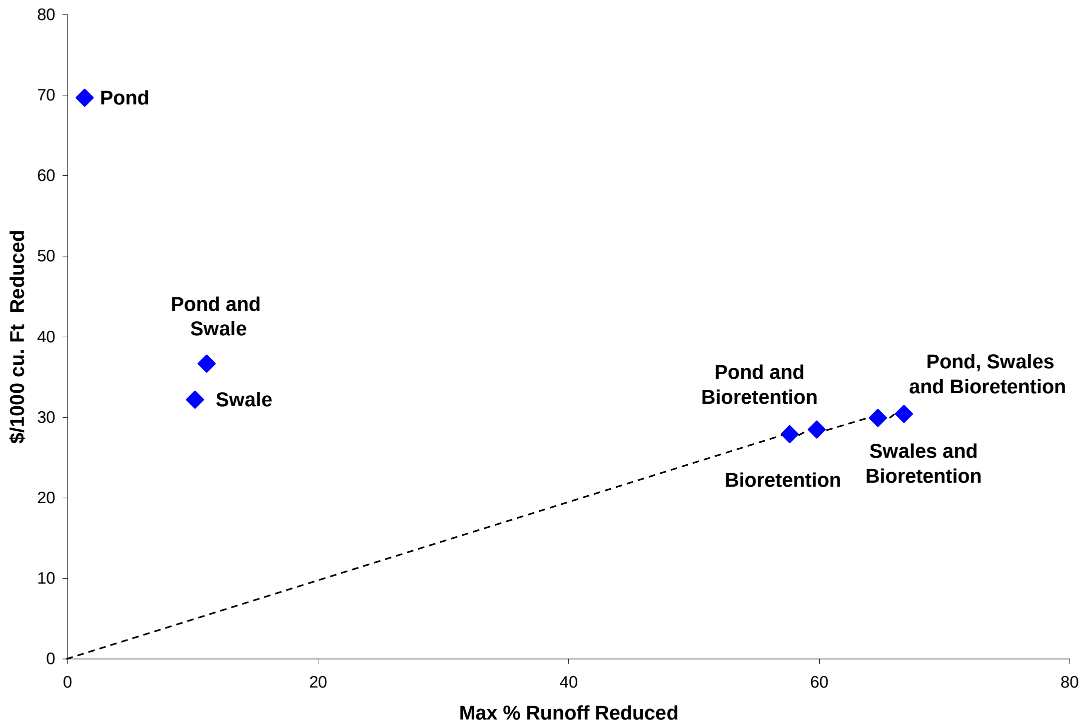


Figure 7. Cost-effectiveness for runoff volume reduction for different control alternatives.

Table 5. Example of Stormwater Control Implementation Costs and Expected Performance

	No controls	**Pond Only**	**Swales Only**	**Bioretention Only**	**Pond, Swales and Bioretention**
Annualized Total Costs ($/year/ac)	0	118	404	1974	2456
Runoff Coefficient (Rv)	0.61	0.60	0.54	0.26	0.20
% Reduction of Total Runoff Volume Discharges	n/a	1.4%	10%	**58%**	67%
Unit Removal Costs for Runoff Volume ($/ft^3)	n/a	0.07	0.03	0.03	0.03
Expected biological conditions in receiving waters (based on Rv)	poor	poor	poor	poor	**fair**

Flow-Duration Analyses to Size Stormwater Filters

The performance of stormwater filters is highly dependent on the amount of the annual runoff that is treated by the unit, and how much is bypassed untreated. Bypassing of the filter occurs when the instantaneous flow rate exceeds the filtration capacity. This can be caused by a filter that is improperly sized, and by a filter that is partially clogged.

Over a long period, obviously some peak flows exceed the design capacity of the filter. Therefore, a series of flow calculations can be made using WinSLAMM to determine the distribution of flows that could be expected for several sets of conditions. Figures 8 to 18 are sizing plots for one acre paved parking or storage areas for five locations in the US having very different rainfall conditions (Seattle, WA; Phoenix, AZ; Atlanta, GA; Milwaukee, WI; and Portland, ME). The first of each pair of plots shows the annual runoff distributions calculated using WinSLAMM for January through September of each of the years noted. The largest flows are likely underpredicted due to the simplifying assumptions made in the design of the complex hydrograph, but the bulk of the probability distributions should be reasonable. This 9 month period was used because of file size limitations in Excel which restricted the number of time increments to about 64,000 (the maximum number of rows in Excel), as there are about 87,600 six minute increments in one year. Excel 2007 does not have this limitation and can handle 1,000,000 rows of data, enabling more that 11 years of rains to be analyzed at one time. WinSLAMM is typically used for continuous simulations using several decades of rain data. These plots were made using calculated flows every 6 minutes, corresponding to the expected time of concentration for these small areas. The second plot of each pair shows the calculated percentage of the annual flows that would be treated at different treatment flow rates.

Table 6 summarizes these plots showing several treatment objectives. It is interesting to note that Seattle, typically known as a wet and rainy city, has the lowest flow rates for the probability points shown, and the smallest required treatment flow rates for the different treatment objectives. In contrast, Phoenix, a desert city, is shown to have some of the highest flow rates and largest treatment flow rates needed. The total rainfall in Phoenix is small, but when it does rain, the rain intensities and associated flow rates are large. In this sampling of cities, the needed treatment flow rates for the same treatment objectives are seen to range by a factor of about three or four: it would require four filter modules per acre of paved drainage area to treat about 90% of the runoff in Atlanta (similar to what was found for the Tuscaloosa test site during the monitoring period), while only one or two modules would be needed for the same area and treatment level objective for Seattle, if each module has a capacity of about 25 gpm.

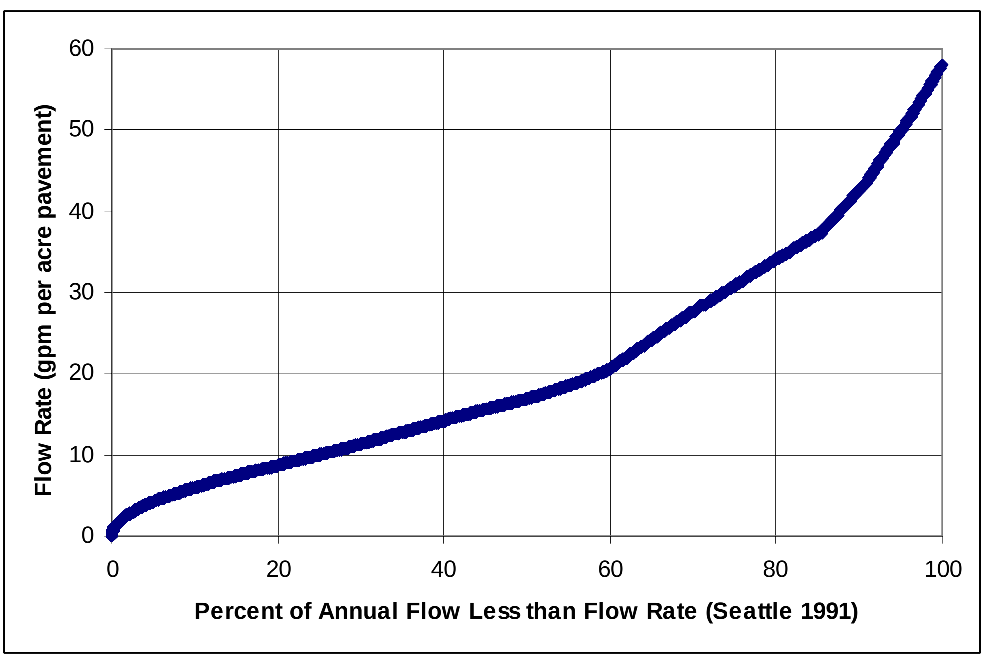


Figure 8. Treatment flow rates needed for Seattle, WA.

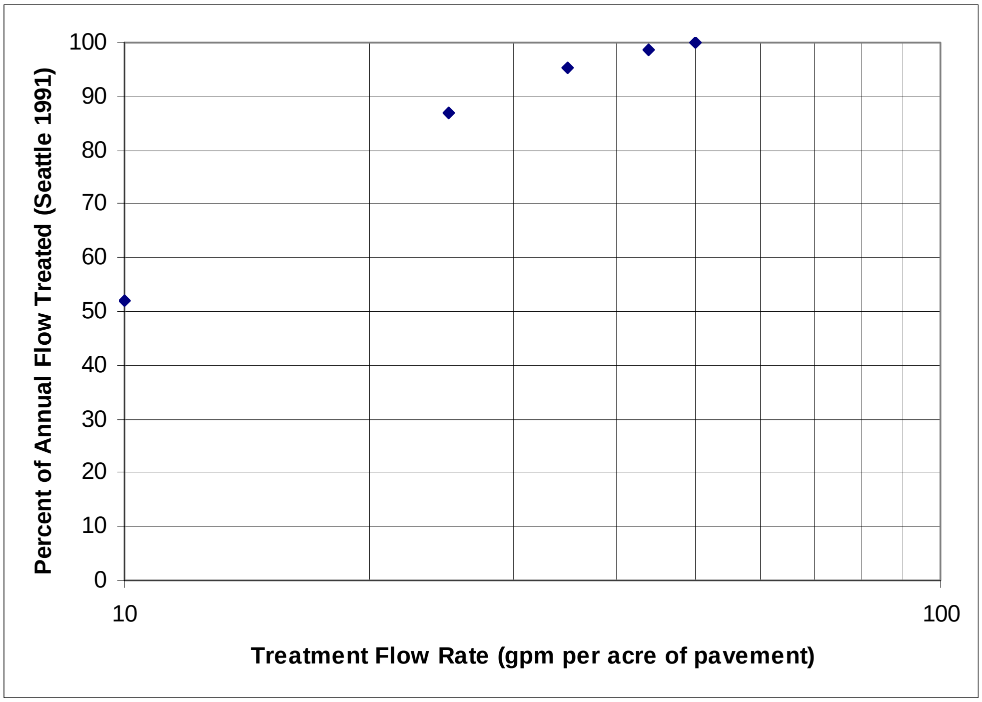


Figure 9. Treatment flow rates needed for Seattle, WA.

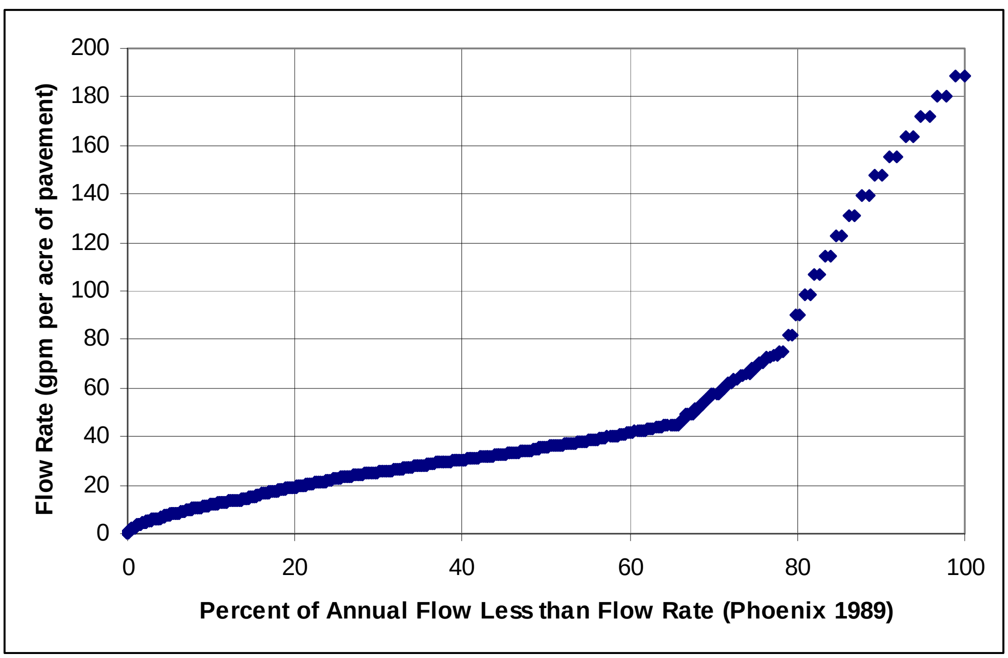


Figure 10. Treatment flow rates needed for Phoenix, AZ.

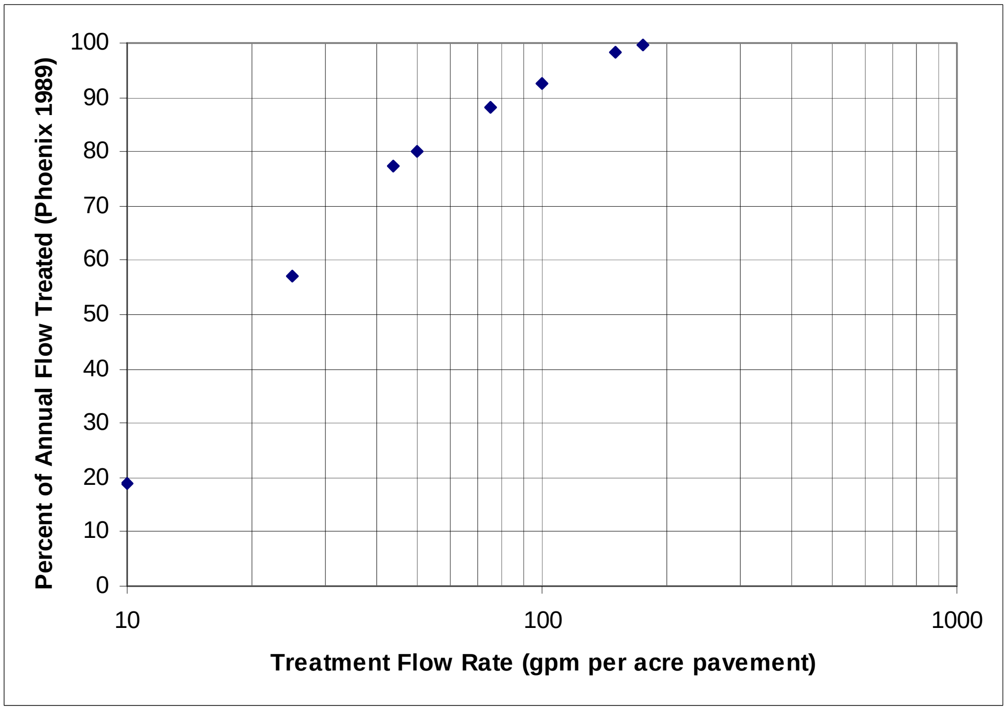


Figure 11. Treatment flow rates needed for Phoenix, AZ.

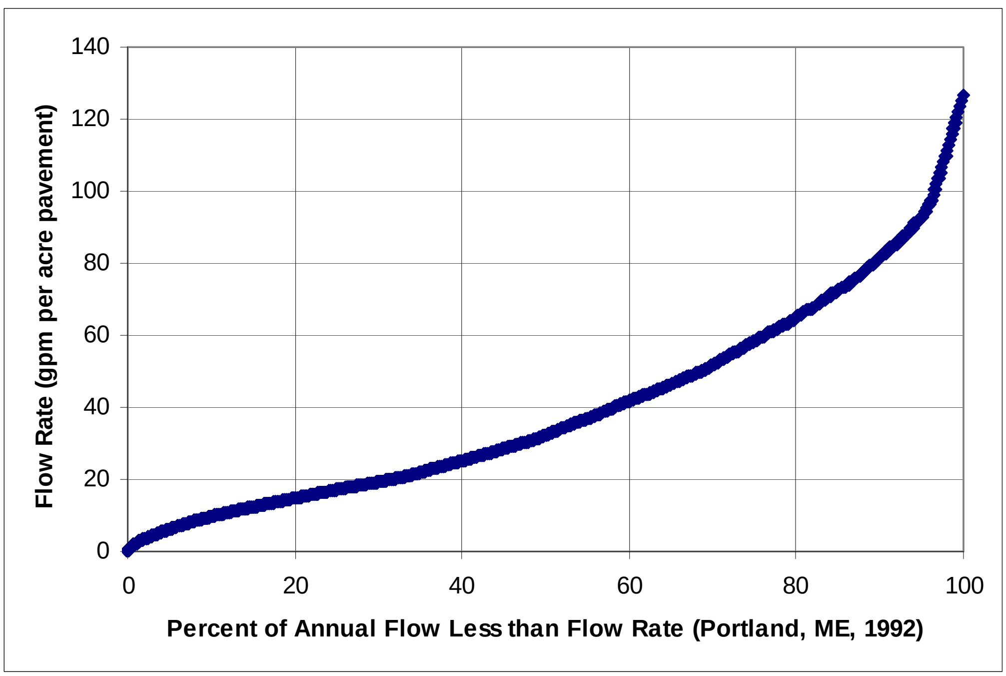


Figure 12. Treatment flow rates needed for Portland, ME.

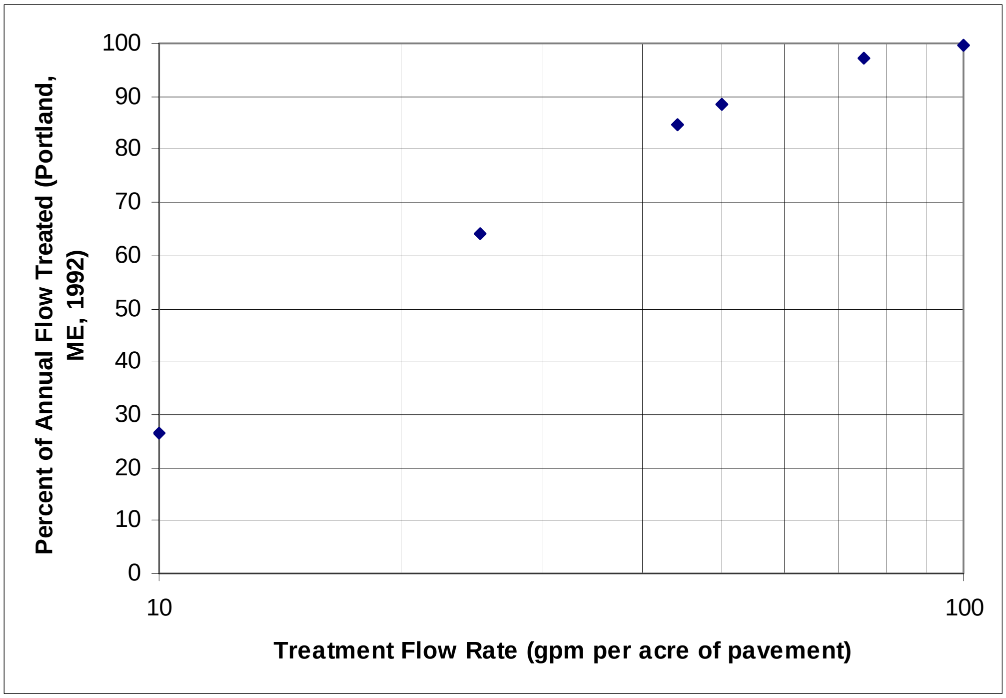


Figure 13. Treatment flow rates needed for Portland, ME.

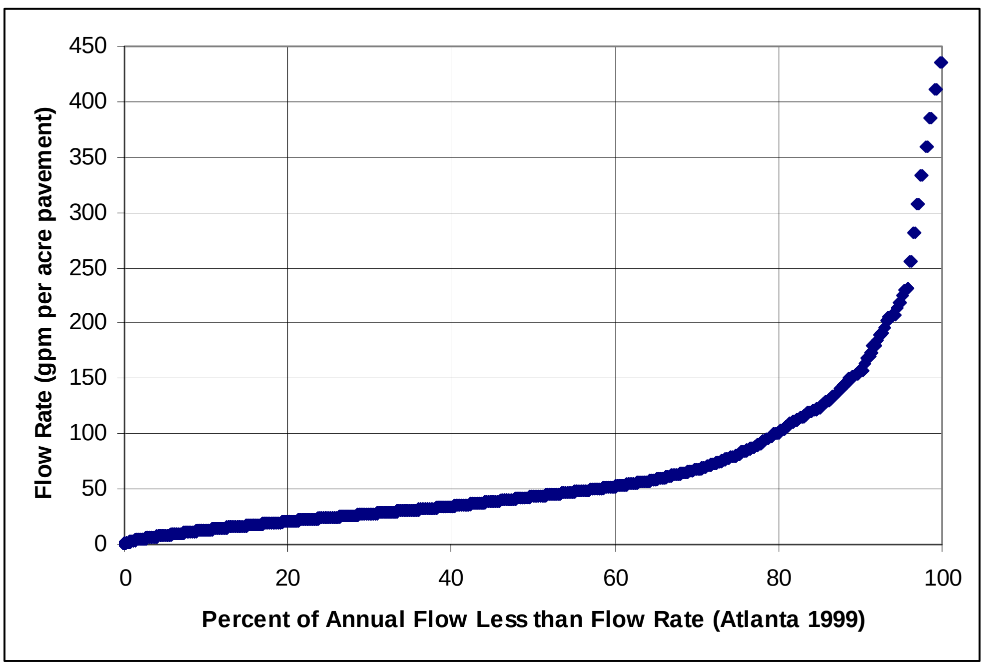


Figure 14. Treatment flow rates needed for Atlanta, GA.

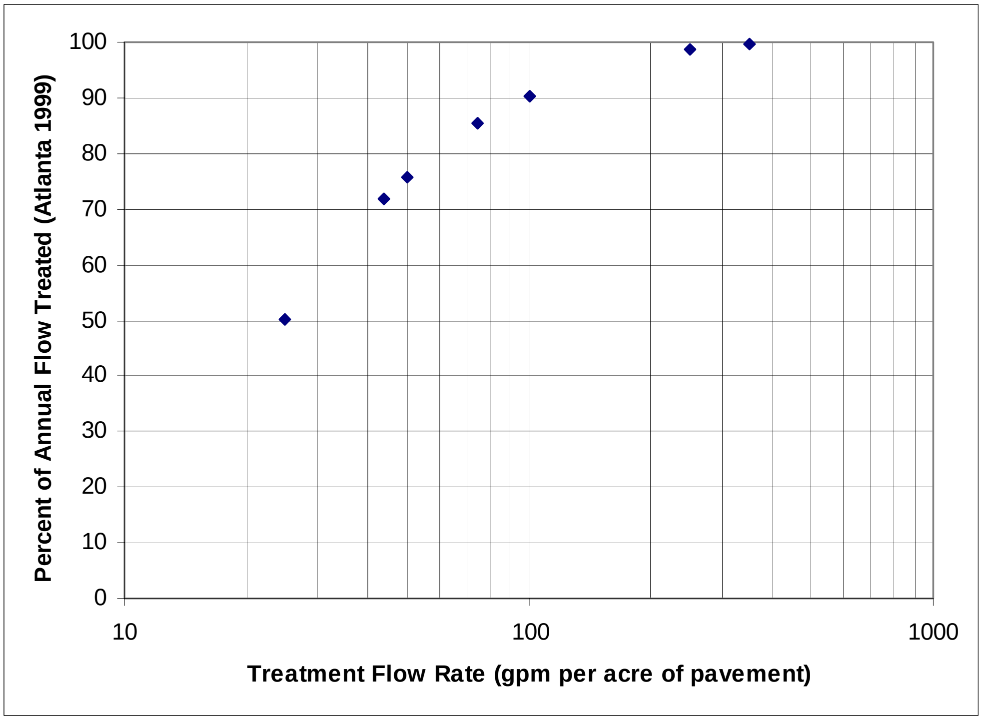


Figure 15. Treatment flow rates needed for Atlanta, GA.

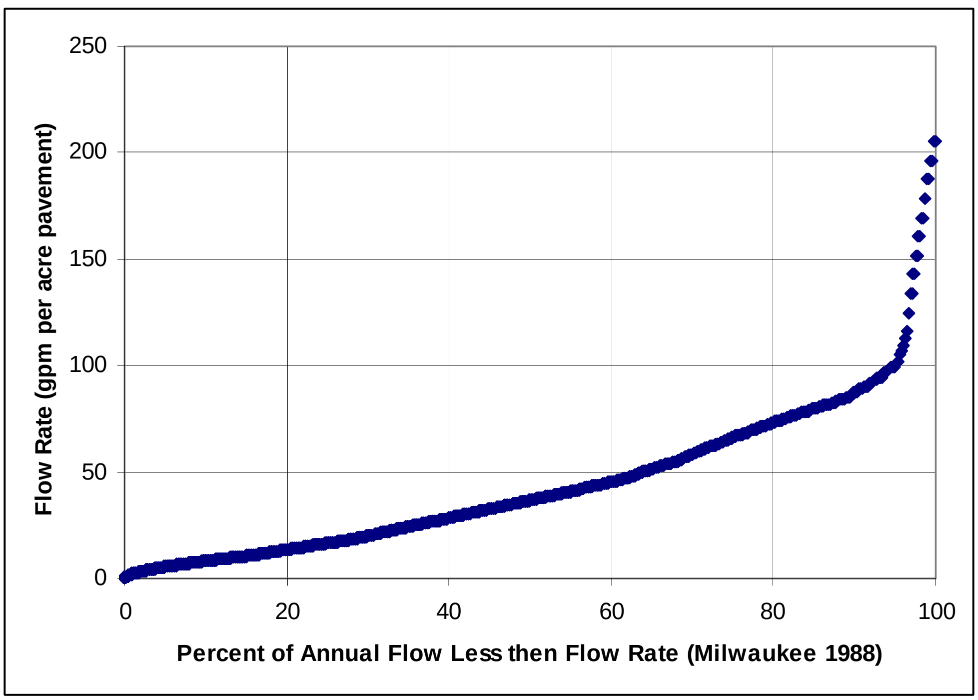


Figure 16. Treatment flow rates needed for Milwaukee, WI.

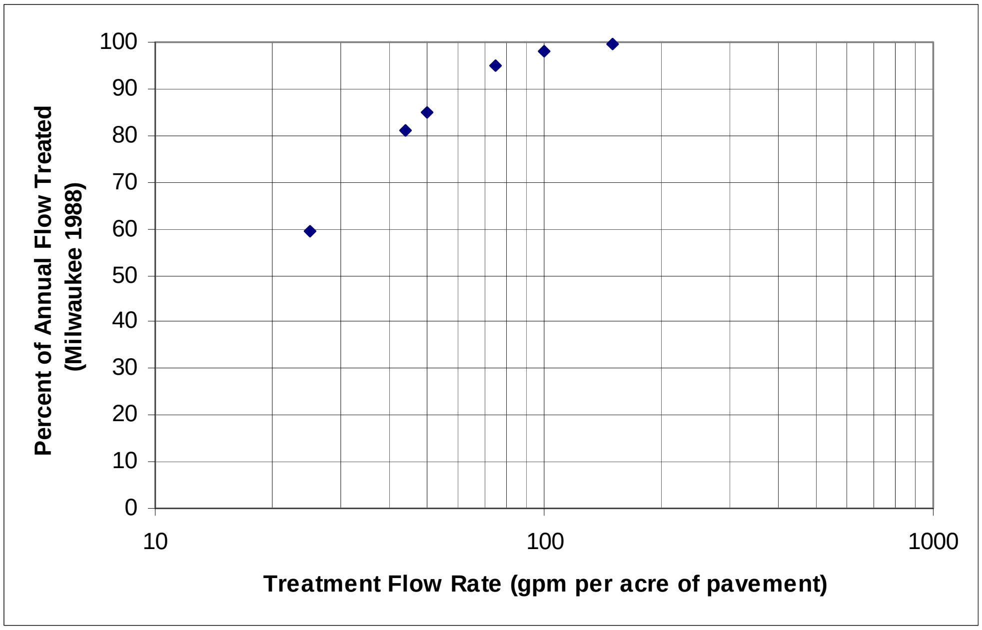


Figure 17. Treatment flow rates needed for Milwaukee, WI.

Table 6. Example Flow Rates and Treatment Rates Needed for Different Treatment Objectives

	Annual Flow Rate Distributaries (gpm/acre pavement)			Flow Rate Needed for Different Levels of Annual Flow Treatment (gpm/acre pavement)		
Location	**50th Percentile**	**70th Percentile**	**90th Percentile**	**50%**	**70%**	**90%**
Seattle, WA	16	28	44	10	18	30
Portland, ME	31	52	80	18	30	53
Milwaukee, WI	35	60	83	20	35	65
Phoenix, AZ	38	60	150	20	35	90
Atlanta, GA	45	65	160	25	40	100

Creating Flow-Duration Probability Plots with WinSLAMM

These plots are created by exporting 6 minute flow increment data (a WinSLAMM output option used to interface with drainage models) into Excel. As noted above, until Office 2007, Excel was limited to about 65,000 rows, restricting the period of analysis to about 9 months (the wet weather season in northern areas). The new Excel 2007 allows 1,000,000 rows, enabling about 11 years of rain data to be analyzed. The selection of the appropriate rain period can be made with the WinSLAMM rain utility. This utility examines a rain file, summing the total rain depth and the number of events for each month, and for each year. These are arranged in a table that can be sorted based on the calculated annual deviations from the long-term average conditions. The top few rain years should then be examined on a month-to-month basis to make sure that there were no unusual months in the selected period.

The six minute flow increments for the selected rain period are exported to Excel and sorted by runoff rate, from highest to lowest. The zero values (most of the periods would have zero runoff) are removed. If desired, further rain period increments can be analyzed and the non-zero values appended to the spreadsheet file. In this way, relatively lengthy rain periods can be analyzed within the size limitations of Excel. A probability plot is then created using these sorted values.

If a treatment flow rate plot is desired, then a candidate treatment flow rate (such as 25 gpm) is subtracted from each incremental flow observation. The excess flow that cannot be treated is then calculated by subtracting the 25 gpm (for example) from each individual value. All negative values are removed (these correspond to periods when the treatment flow rate is greater than the flow, and all is treated). These excess flows are then summed to result in the total flow that is not treated during the rain period. This bypass volume is then compared to the total flow volume to determine the percentage treated and the percentage of flow bypassed. This value is plotted as a function of the treatment flow rate that was examined. Several different treatment flow rates should be examined for the area so a proper selection can be made.

Of course, if coarser data is all that is needed (such as for the basic flow-duration comparisons for different treatment scenarios), then the direct model output option can be used. The above example is only needed when evaluating high-resolution data, such as for determining the treatment flow rates for a site.

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