XX

Simple Hydrograph Shapes for Urban Stormwater Water Quality Continuous Analyses

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Over the years, a number of different approaches have been used to represent hydrographs in urban areas for drainage design. Unit hydrographs are usually used to represent one inch of runoff and are scaled according to calculated total runoff amounts and the hydrograph shapes are based on different drainage area characteristics. An actual complex rain distribution is then used to assemble a set of scaled unit hydrographs to represent the total storm event. As an example, the USDA developed different urban area hydrograph shapes which are dependent on expected rainfall distribution patterns. The simplest hydrograph shape is a triangle, while more complex hydrographs have more detailed recession curves and other features. The need for accurate hydrograph representations have long been recognized for drainage design calculations, for both single event “design storms” and for continuous simulations using long-term rainfall records. The events of most interest in drainage design are obviously large and occur infrequently. Actual rainfall and flow records of these events are therefore rare, with little opportunity for verification of flow modeling tools. Reasonable assumptions based on regional observations of selected large events that have occurred over long periods have therefore been the basis for most drainage design calculations. However, these assumptions and tools may not accurately represent runoff conditions that occur during more frequent rains of most interest for use in water quality evaluations in urban areas (see Burton and Pitt 2002; Pitt 2002 for extensive summaries of the literature). Because these smaller rains are more common, it is likely that significant monitoring rec-

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ords exist that are suitable for calibration and subsequent verification of stormwater models. This paper reviews about 550 urban area hydrographs that have been collected at eight locations in four regions of North America, representing different land uses under widely varying rain conditions. Statistical analyses were conducted to quantify the important shape factors of the observed hydrographs that focus on the small and intermediate-sized rains used for water quality analysis.

11.1 Observed Urban Area Hydrographs

Monitored hydrograph information has been routinely collected during stormwater monitoring projects for many years. This paper reviews about 550 events that have been monitored at four North American locations since the late 1970s that were readily available for these analyses. These data include:

• San Jose, CA (Pitt 1979). Residential and downtown commercial areas (about 50 to 500 acres) monitored as part of EPA-funded project to measure the benefits of street and catchbasin cleaning. Figures XX.1 and XX.2 are examples of a complex and a simple hydrograph recorded during this research project.

• Bellevue, WA (Pitt 1985). Residential and commercial areas (about 100 to 300 acres) monitored as part of the EPA's Nationwide Urban Runoff Project (NURP) (EPA 1983). Detailed flow information obtained through a joint monitoring effort with the USGS.

• Toronto, Ontario (Pitt and McLean 1986). Residential, commercial, and industrial areas (about 100 to 300 acres) monitored as part the Toronto Area Wastewater Management Strategy Study (TAWMS) funded by the Ontario Ministry of the Environment.

• Tuscaloosa, AL (Khambhammettu, *et al.*, 2007; Pitt and Khambhammettu 2006; and Togawa, *et al*. 2010). Small commercial areas (about 1 acre) mostly represented by directly connected parking and roof areas. These areas were monitored as part of EPA and industry funded projects to test critical source area treatment devices. Figure XX.3 is an observed large event hydrograph from the City Hall station.

The San Jose hydrographs are for relatively small rains and typical residential areas, with the rain intensities plotted in hourly increments, while the

Tuscaloosa hydrographs are for larger rains for a small completely paved area, with the rain intensities plotted in 5-minute increments. The San Jose rains were typical relatively low intensity and the areas are relatively large with low fractions of directly connected impervious areas, resulting in hydrographs that are smooth and of “traditional” shape. In contrast, the Tuscaloosa rains included intense summer thunderstorms and one very large hurricane, and because the drainage area was small and paved, the hydrographs are much more complex.

Table XX.1 is a summary of the characteristics of the monitored areas, the rains, and the runoff. The Rv is the ratio of the monitored runoff quantity (represented as the depth of runoff over the complete area) to the rainfall depth. The observed CN is the calculated curve number using the NRCS equations that define the CN values as a function of the runoff depth (Q) and the rain depth (P), both expressed in inches:

$$CN = 1000/[10+5P+10Q-10(Q^2+1.25QP)^{0.5}] \qquad \text{(XX-1)}$$

The observed C is the rational coefficient C factor, or the ratio of the instantaneous peak discharge (Q, in CFS) to the peak rain intensity (I, in inches/hr).

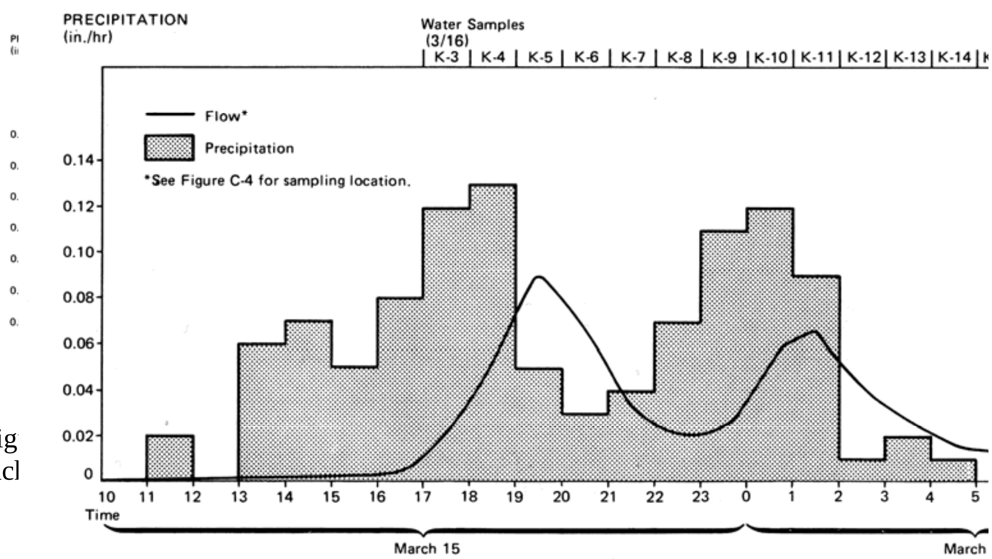
Most of the flow observations used in this analysis are from the Bellevue NURP project, representing mostly residential areas, with some mixed commercial areas. The Toronto Emery site is the only industrial area shown here, while the Tuscaloosa sites are small mostly paved areas. The rains observed ranged from 0.01 in (0.25 mm), which was sufficient to produce runoff at the San Jose study areas, to a 4.5 in (110 mm) rainfall event lasting several days during the Bellevue monitoring. The recent Tuscaloosa locations are much smaller than the other sites, being about 1 ac (0.4 ha), in contrast to the 100 to 200 ac (40 to 80 ha) areas of the other sites. The range of rainfall conditions observed during these projects therefore represented a wide range of expected conditions that are likely to be found throughout North America.

Table XX.1a Monitored Area Characteristics.

Location	Land use	area (acres)	directly connected impervious (%)	partially connected impervious (%)	pervious (%)	# of events monitored
Bellevue, WA						
Surrey Downs	residential medium density	95.1	17	19	64	196
Lake Hills	residential medium density	101.7	17	19	64	201
San Jose, CA						
Keyes	residential, medium density	92	30	22	48	6 (drought)
Tropicana	residential, medium density	195	25	19	56	8 (drought)
Toronto, Ontario						
Thistledowns (half swales)	residential, medium density	96.4	21	24	55	35
Emery	industrial	380.5	42	33	25	60
Tuscaloosa, AL						
City Hall	Institution-al/commercial	0.9	100	0	0	31
BamaBelle	commercial	0.89	68	0	32	17 (on-going)

Table XX.1b Monitored Area Characteristics.

Location	monitored rains (in, avg and range)	Observed Rv (avg and range)	Observed CN (avg and range)	Observed C (avg and range)	peak/avg flow ratio (avg and range)
Bellevue, WA					
Surrey Downs	0.35 (0.03 - 4.38)	0.18 (0.01 - 0.60)	95 (64 - 100)	0.17 (0.02 - 0.40)	4.4 (1 - 14)
Lake Hills	0.35 (0.02 - 3.69)	0.21 (0.01 - 0.49)	95 (73 - 100)	0.25 (0.02 - 0.54)	5.4 (1.1 - 19)
San Jose, CA					
Keyes	0.25 (0.01 - 1.06)	0.10 (0.01 - 0.28)	96 (88 - 100)	0.10 (0.01 - 0.37)	3.2 (2.4 - 3.7)
Tropicana	0.22 (0.01 - 1.08)	0.59 (0.17 - 1.6)	99 (95 - 100)	0.67 (0.18 - 1.0)	3.8 (2.7 - 4.9)
Toronto, Ontario					
Thistledowns (half swales)	0.33 (0.03 - 1.01)	0.17 (0.02 - 0.37)	95 (84 - 99)	0.04 (0.01 - 0.12)	4.0 (1.4 - 12)
Emery	0.27 (0.03 - 1.0)	0.23 (0.05 - 0.58)	96 (87 - 99)	0.1 (0.02 - 0.50)	3.1 (1.3 - 8.3)
Tuscaloosa, AL					
City Hall	0.7 (0.02 - 3.2)	0.6 (0.09 - 0.80)	98 (95 - 99)	0.3 (0.09 - 0.80)	4.2 (1.1 - 8)
BamaBelle	0.7 (0.1 - 1.9)	0.8 (0.3 -	99 (94 - 100)	0.6 (0.3 -	5.5 (1.8 -



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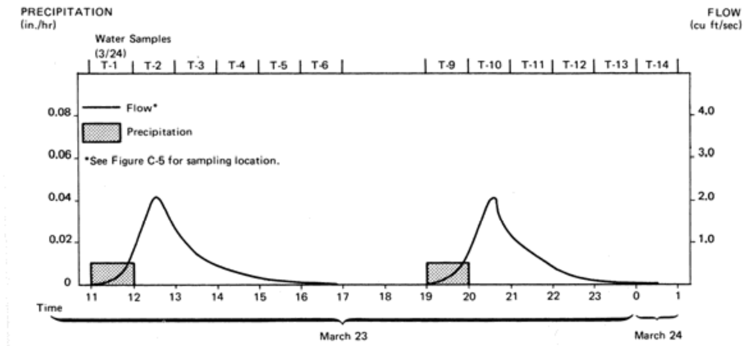


Figure XX.2 7 Tropicana study area, San Jose, CA. March 23, 1977 (0.01 and 0.01 inches) (Pitt 1979).

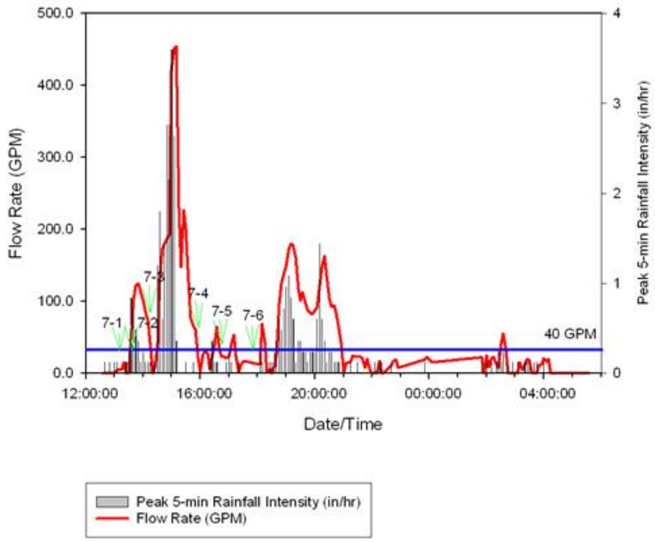


Figure XX.3 Tuscaloosa, AL, City Hall, August 29, 2005 (Hurricane Katrina, 3.2 inches) (Pitt and Khambhammettu 2006).

XX.2 Modeling Hydrographs in Urban Areas

Hydrological models predict flow distributions using a variety of methods. This section is not intended to be a review of these methods, for which extensive literature exists. One method utilizes unit hydrographs which represent the flow distribution associated with one inch of runoff from a specific drainage area. These can be used to produce a complete storm hydrograph by scaling and separating the rain intensity into short time increments, as illustrated in FigureXX.4, while Figure XX.5 defines the dimensions of the individual unit hydrographs.

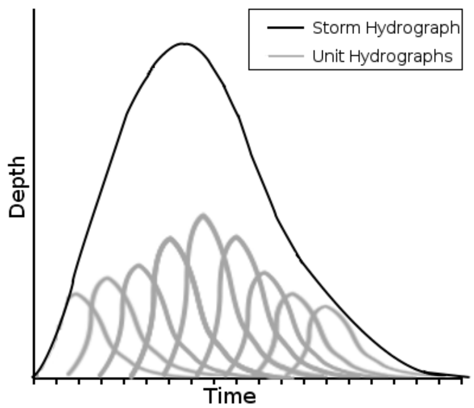


Figure XX.4 Superposition of unit hydrographs to form a storm hydrograph (UDFCD 2010).

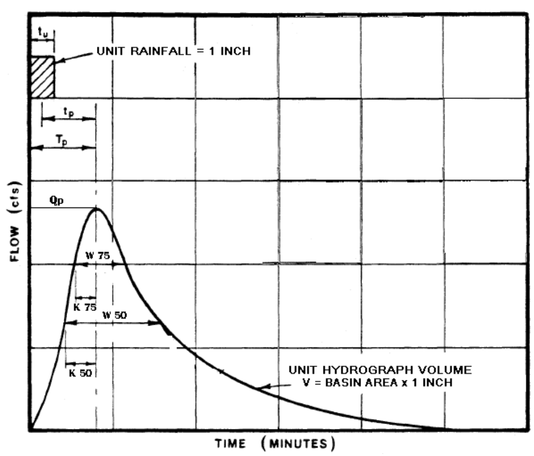


Figure XX.5 Colorado Unit Hydrograph parameters (UDFCD 2010).

The individual unit hydrographs are developed using a variety of methods, including analyzing actual rainfall-runoff records, or by predicting the shape based on watershed characteristics. As an example, HEC-HMS (Feldman 2000) includes a number of unit hydrograph options available to the model user, including: SCS dimensionless unit graph, Clark unit hydrograph, Snyder unit hydrograph, User-defined, and ModClark unit hydrograph. These options each have unique attributes that the model user must evaluate for the best application for their site.

The NRCS (SCS) dimensionless hydrograph and triangular hydrograph is shown in Figure XX.6. It shows how closely the smoothed hydrograph is represented by a simple triangle. The NRCS in TR-55 (SCS 1986) developed storm hydrographs for different hypothetical rainfall distributions that were composite intensity and duration joint data sets representing severe storm conditions commonly used for drainage designs (2 to 100 year storms). These hydrographs were not intended for representing smaller storms of most interest in water quality analyses, but were developed as an efficient tool for drainage design with relatively large rains.

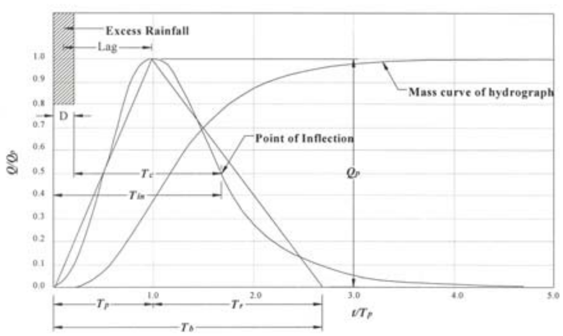


Figure XX.6 NRCS dimensionless unit hydrograph and triangular hydrograph.

XX.2.1 Calculated Unit Hydrographs using WinTR-55

WinTR-55 was used to calculate storm hydrographs for the eight watersheds used for this analysis. Table XX.2 summarizes the basic watershed characteristics from the site information and TR-55 (SCS 1986). The time of concentration values were calculated using the TR-55 methods and ranged from 6 minutes for the small paved areas in Tuscaloosa, to 40 minutes for the large residential area in San Jose. The NRCS rain categories for these four locations represented all four possible rain distribution options, from mild Types I and Ia on the west coast, to more intense, Type III in the southeast, and Type II for most of the country. The soil groups were based on the soil textures observed in the field. The curve number values were selected from the TR-55 tables based on the land use, soil type, and impervious percentages.

Table XX.2 Basis Watershed Characteristics and TR-55 Parameters

Location	Land use	Area (acres)	Time of Concentration, Tc (min)	NRCS rainfall distribution category	Hydrologic Soil Group (HSG)	CN (from TR55)
Bellevue, WA						
Surrey Downs	Resid.	95	28.5	1a	C	81
Lake Hills	Resid.	102	30.5	1a	C	81
San Jose, CA						
Keyes	Resid.	92	30	1	D	87
Tropicana	Resid.	195	40	1	D	87
Toronto, Ontario						
Thistledowns	Resid.	96	19	2	B	75
Emery	Industrial	381	32	2	B	88
Tuscaloosa, AL						
City Hall	Commercial	0.9	6	3	D	98
Bama-Belle	Commercial	0.9	6	3	D	92

Table XX.3 summarizes the actual curve numbers observed at the watersheds during the monitoring. The CN values were calculated using equation XX-1 based on the actual rainfall and runoff quantities and then compared as a function of rain depth (this is a spurious self-correlation, but was used as an expedient method to sort the observed values for different rain ranges). As expected based on data from many locations previously evaluated, the CN values are all very large for the smallest rains and then decrease as the rain depth increases. In most cases, the actual CN values approach the TR-55 table CN values shown in Table XX.2 for rains greater than 1.5 inches.

For smaller rains, the actual runoff amounts are greater than expected if using a constant CN value for all rains.

Table XX.3 Actual Curve Numbers Based on Monitored Rainfall and Runoff

Location	Actual CN for 0.25 in rains	Actual CN for 0.50 in rains	Actual CN for 1.0 in rains	Actual CN for 1.5 in rains	Actual CN for 2.5 in rains
Bellevue, WA					
Surrey Downs	96	93	87	81	72
Lake Hills	96	94	90	86	79
San Jose, CA					
Keyes	93	92	90	89	88
Tropicana	98	97	97	96	96
Toronto, Ontario					
Thistledowns	96	92	86	81	74
Emery	96	94	88	83	75
Tuscaloosa, AL					
City Hall	99	98	97	97	96
BamaBelle	99	99	99	98	97

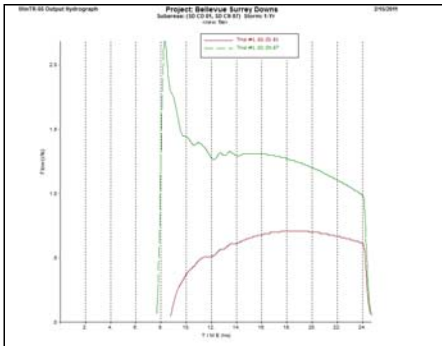
Table XX.4 summarizes the results of the WinTR-55 evaluations of these eight watersheds, using the CN values as obtained from the Tables in TR-55, while Table XX.5 summarize the same hydrograph characteristics using the observed CN values. As noted above, the TR-55 CN values are lower than expected, even for the one inch rain, except for one location. Figures XX.7 and XX.8 are plots of the actual hydrographs for the Bellevue and Tuscaloosa locations and indicate the dramatic differences in the hydrograph shapes when using the two different CN values for the same sites. The hydrograph features summarized on these two tables include the instantaneous peak flow rate and the average flow rate over the event (in CFS), and their ratio, along with the rain duration and runoff duration (both in hours) and the duration ratios. The rain duration values are assumed to be 24 hours based on the TR-55 rainfall distribution characteristics, although most of the rainfall occurs near the middle of the duration. The distortion of the rainfall distribution is greater for the Type II and III distributions than for the Type I and Ia distributions. The ratios of the flows and durations are smaller when using the smaller CN values that when using the larger observed CN values. The shapes of the hydrographs for the Type Ia rainfall distributions are greatly distorted, with the peak flows occurring near the beginning of the event for the higher CN condition; for the smaller CN conditions, the flows are more evenly distributed. In both cases, the flows abruptly end. This is likely associated with the low flows calculated for these conditions.

Table XX.4 Hydrograph Characteristics for 1 inch Rains using Table CN Values from TR-55

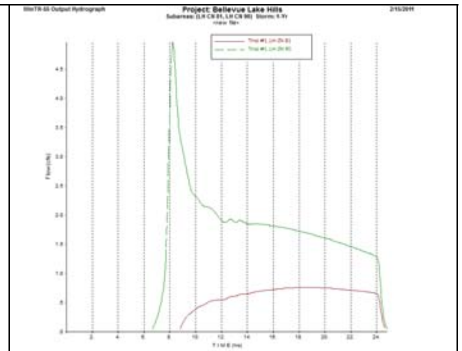
	WinTR55 using TR55 CN values and 1 in rain					
Location	peak flow (CFS)	avg flow (CFS)	peak/avg flow rate ratio	rain duration (hrs)	runoff duration (hrs)	runoff/rain duration ratio
Bellevue, WA						
Surrey Downs	0.71	0.6	1.2	24	16	0.67
Lake Hills	0.76	0.63	1.2	24	16	0.67
San Jose, CA						
Keyes	6	1.32	4.6	24	15	0.63
Tropicana	4.1	2.64	1.6	24	16	0.67
Toronto, Ontario						
Thistledowns	0.36	0.23	1.6	24	13	0.54
Emery	71	7.5	9.5	24	14	0.58
Tuscaloosa, AL						
City Hall	0.69	0.12	5.8	24	2.5	0.1
BamaBelle	0.37	0.12	3.1	24	1.5	0.06

Table XX.5 Hydrograph Characteristics for 1 inch Rains using Observed CN Values during Monitoring

	WinTR55 using actual CN values and 1 in rain					
Location	peak flow (CFS)	avg flow (CFS)	peak/avg flow rate ratio	rain duration (hrs)	runoff duration (hrs)	runoff/rain duration ratio
Bellevue, WA						
Surrey Downs	2.2	1.26	1.7	24	17	0.71
Lake Hills	5.0	1.95	2.5	24	18	0.75
San Jose, CA						
Keyes	11	1.93	5.8	24	16	0.67
Tropicana	56	6.73	8.3	24	22	0.92
Toronto, Ontario						
Thistle-downs	18	1.83	9.7	24	14	0.58
Emery	71	7.5	9.5	24	14	0.58
Tuscaloosa, AL						
City Hall	0.64	0.10	6.4	24	2.2	0.09
BamaBelle	0.68	0.14	4.9	24	2.2	0.09

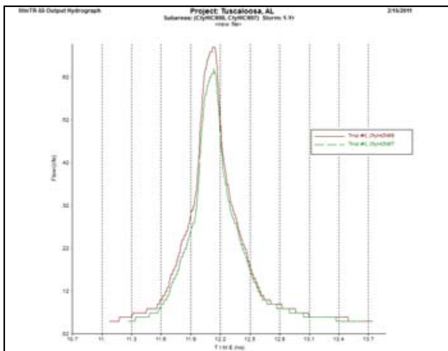


Bellevue, WA, Surrey Downs, medium density residential area, 1 inch rain, TR55CN 81 and observed 87

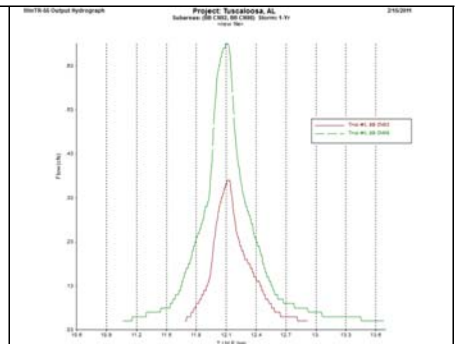


Bellevue, WA, Lake Hills, medium density residential area, 1 inch rain, TR55CN 81 and observed 90

Figure XX.7 WinTR-55 hydrographs for Bellevue, WA, sites (Type Ia rain distributions).



Tuscaloosa, AL, City Hall, institutional/commercial area, 1 inch rain, TR55CN 98 and observed 97



Tuscaloosa, AL, BamaBelle, landscaped parking area, 1 inch rain, TR55CN 92 and observed 98

Figure XX.8 WinTR-55 hydrographs for Tuscaloosa, AL, sites (Type III rain distributions).

XX.3 Hydrograph Characteristics used in WinSLAMM

All of the hydraulic routing that is done in WinSLAMM and WinDETPOND is based upon a complex triangular storm hydrograph (see Pitt 1997; 1999; Pitt and Voorhees 2002 for descriptions of WinSLAMM). This hydrograph shape was selected to reflect a typical urban hydrograph, and is flexible enough to represent a range of conditions. The total discharge quantity is calculated for the drainage area while the shape of the hydrograph is a function of the runoff to rainfall duration ratio and the peak flow to average flow ratio. The runoff duration is assumed to be 1.2 times the rainfall duration. The average flow is calculated by dividing the runoff volume WinSLAMM calculates for each event by the runoff duration. This average value is multiplied by the peak to average flow ratio to obtain the peak flow for the event. The model then creates the hydrograph, as shown below, based upon the peak flow, the runoff duration and the inflection points in the hydrograph. This shape provides the flow rates for each time step used to calculate the performance of wet detention ponds, catchbasins and hydrodynamic devices, biofilters, porous pavement and grass swales. WinSLAMM version 10 will also use this hydrograph shape for new controls added to the model, including grass filters and green roofs. Version 10 will also have the ability to route flows (starting with this basic hydrograph shape), and particle size distributions, through series of stormwater controls located at many source area, drainage system, and outfall locations. Figure XX.9 is an example hydrograph that has a typical peak to average flow ratio of 3.8, a rainfall duration of one hour and a runoff volume of 0.25 in (6.4 mm) over one acre (0.4 ha) of land surface.

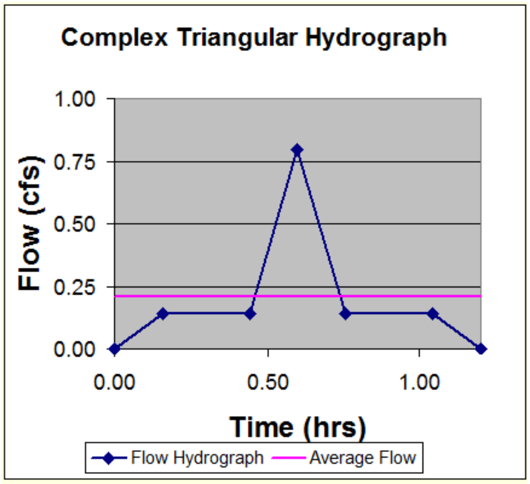


Figure XX.9 Example complex triangular hydrograph used in WinSLAMM for routing flows through stormwater control practices.

XX.4 Analyses of Observed Urban Hydrograph Shapes

In order to determine the most reasonable hydrograph shape parameters (peak to average flow ratios and runoff to rain duration ratios) for the WinSLAMM complex triangular hydrograph, statistical analyses were conducted on the approximate 550 observed urban area hydrographs described above. The rainfall and flow data from the hydrographs were entered into Excel spreadsheets from archived project records and the published reports. The data were then separated by land use and sorted by rain depth, and copied into SigmaPlot (version 11 from SYSTAT.com) for statistical analyses and plotting.

XX.4.1 Peak to Average Flow Ratios

A 2-way ANOVA was initially examined to identify the effects and interactions of the main factors of land use and rain depth on the peak to average flow rate ratios of the approximately 550 hydrographs. Unfortunately, the interactions could not be calculated due to lack of data for some conditions, so a general linear model was used. The data also failed the normality (Shapiro-Wilk test) and the equal variance tests, making any parametric ANOVA analysis improper. Therefore, the following analyses focused on the non-parametric Kruskal-Wallis one way ANOVA test that is based on ranks, examining the land use and rain characteristics separately.

Figure XX.10 is a box and whisker plot illustrating the medians, along with the 25th and 75th percentiles in the grey boxes, and the 5th and 95th percentiles at the end of the whiskers, of the peak to average flow ratios for different rain depth categories. Observations less than, and greater than, these values are shown as dots. These rain range categories were selected to result in a reasonably large number of observations in each group (41 to 191).

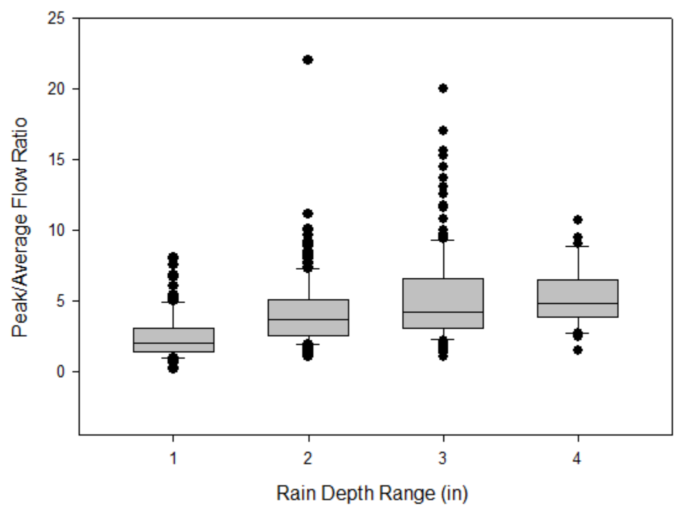


Figure XX.10 Peak to average runoff ratios for all sites combined, separated into four rain depth categories (Rain range 1: 0.01 to 0.09 in (0.25 to 2.3 mm); range 2: 0.1 to 0.29 in (2.5 to 7.4 mm); range 3: 0.3 to 0.99 in (7.6 to 25 mm); and range 4: 1.0 to 4.4 in (25 to 110 mm).

The following is the non-parametric Kruskal-Wallis one way ANOVA (based on ranks), indicating that there is at least one significant difference between the rain groups:

Group	N	Missing	Median	25%	75%
very small	130	0	2.012	1.412	3.071
small	191	0	3.640	2.520	5.029
medium	188	0	4.148	3.026	6.561
large	41	0	4.768	3.800	6.467

H = 121.309 with 3 degrees of freedom. (P = <0.001)

Dunn's method was then used to conduct a pairwise multiple comparison to isolate the group, or groups, that differ from the others:

Comparison	Diff of Ranks	Q	P<0.05
large vs very small	222.38	7.813	Yes
large vs small	89.422	3.269	Yes
large vs medium	39.435	1.440	No
medium vs very small	182.95	10.093	Yes
medium vs small	49.987	3.062	Yes
small vs very small	132.96	7.359	Yes

Therefore, the large and medium rain groups were combined to result in only three rain categories, as shown in Figure XX.11. The Kruskal-Wallis and Dunn's tests indicated that these groupings were significant ($p < 0.001$).

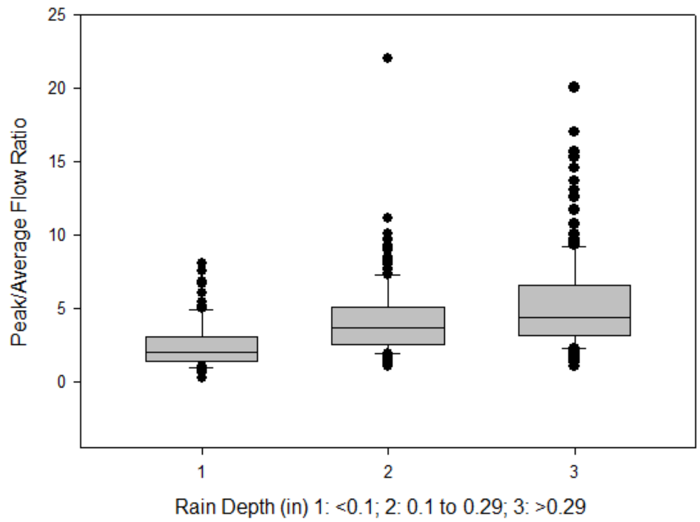


Figure XX.11 Three rain groups representing the range of observed peak to average flow ratios.

The next step was to examine the effects of land use on the peak to average flow rate ratios, as shown in Figure XX.12. The statistical tests indicated that the commercial and residential area data should be combined, while the industrial area peak to flow rate values were significantly less than for this combined category. Figure XX.13 therefore shows the plot of these two main land use categories. The Mann-Whitney U statistical test indicated that the medians values between the two resulting groups is much greater than would be expected by chance (p <0.001).

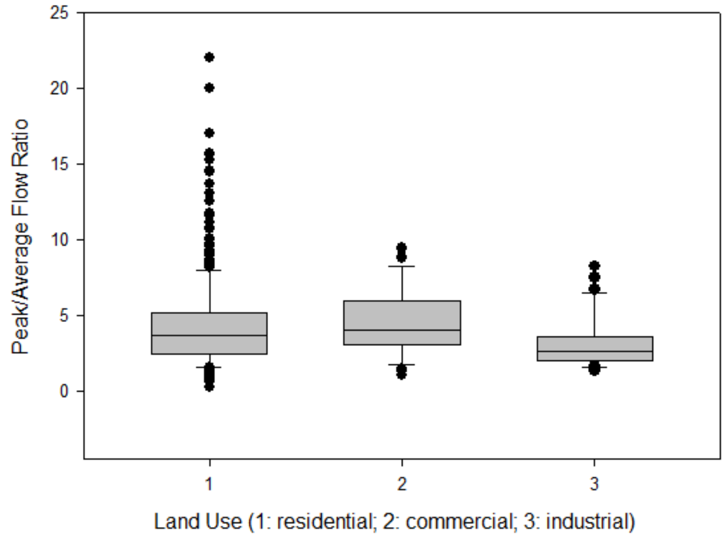


Figure XX.12 Land use effects on the observed peak to average flow rate ratios.

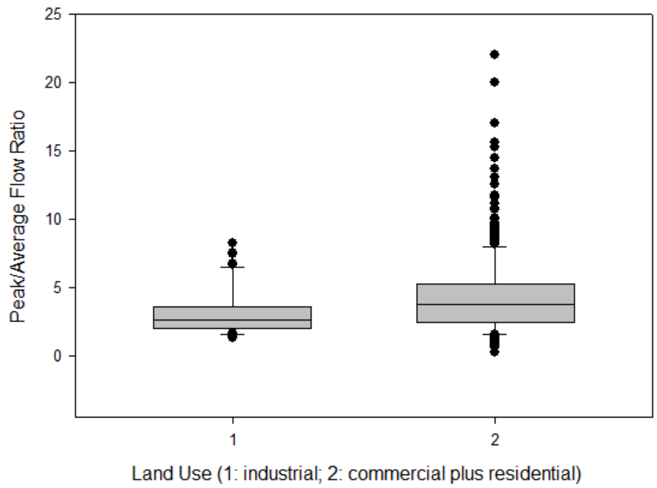


Figure XX.13 Combined land use effects on the peak to average flow ratios.

The next step was to examine these two land use group individually to indicate it they should be separated according to rain groupings. The industrial group did not have sufficient data to indicate that grouping was necessary, based on the Kruskal-Wallis tests (p = 0.054). The industrial data were therefore combined into one group, irrespective of rain depth. When the combined residential plus commercial data were examined by rain groups, the Kruskal-Wallis and Dunn's tests indicated that they should remain separated in the three rain groupings.

The last tests examined these four groups (1 industrial and 3 commercial plus residential) to determine of further data groupings were appropriate. These tests indicated that the industrial data should be combined with the very small rain category of the commercial plus residential observations, as indicated below:

Kruskal-Wallis One Way Analysis of Variance on Ranks

Group	N	Missing	Median	25%	75%
C + R very small +I	172	0	2.283	1.597	3.189
C + R small	172	0	3.792	2.539	5.110
C + R medium + large	206	0	4.652	3.373	6.710

H = 131.502 with 2 degrees of freedom. (P = <0.001)

The differences in the median values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = <0.001)

All Pairwise Multiple Comparison Procedures (Dunn's Method):

Comparison	Diff of Ranks	Q	P<0.05
C + R medium vs C + R very small	186.882	11.386	Yes
C + R medium vs C + R small	65.051	3.963	Yes
C + R small vs C + R very small	121.831	7.110	Yes

Figure XX.14 therefore presents the final three categories of land use and rain categories representing significantly different peak to average flow ratios.

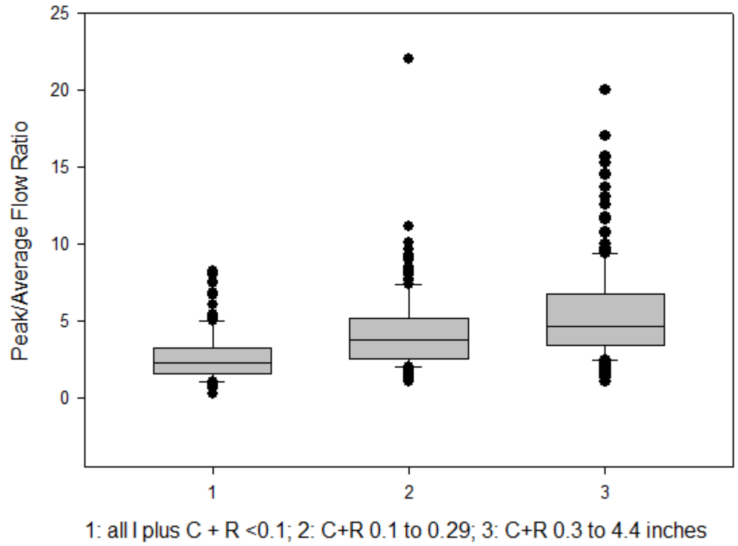


Figure XX.14 Final three categories of land uses and rain groupings for peak to average flow ratios for urban areas.

Because of the small number of industrial site observations (and they only represent a single location), these data should probably be combined for all of the basic land uses, with the different categories representing the rain ranges only.

XX.4.2 Runoff to Rain Duration Ratios

A 2-way ANOVA was also initially used for these analyses to examine the effects and interactions of the main factors of land use and rain depth on the runoff to rain duration ratios. Unfortunately, the normality and equal variance test failed with these data also. As there are no equivalent nonparametric 2-way ANOVA tests, these initial results are only used to help structure more robust analyses. These initial results indicated that the land use and rain category interactions were likely significant, and that the rain categories should be combined into two groups, the very small group (<0.1 inch) and the other rains, resulting in four possible categories: very small rains in industrial areas; other rains in industrial areas; very small rains in commercial and residential areas, and other rains in commercial and residential areas.

A one-way ANOVA was then used to examine these four categories. Because the normality test also failed for these groups, the Kurskal-Wallis One-Way ANOVA on ranks test was used on the following four groups:

Group	**N**	**Missing**	**Median**	**25%**	**75%**
indus very small	20	0	3.008	2.208	4.920
indus larger	40	1	1.202	1.047	1.633
resid very small	114	6	0.900	0.547	1.498
resid larger	333	2	0.905	0.719	1.143

H = 70.987 with 3 degrees of freedom. (P = <0.001)

The differences in the median values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = <0.001)

To isolate the group or groups that differ from the others, the all Pairwise Multiple Comparison Procedure (Dunn's Method) was used:

Comparison	**Diff of Ranks**	**Q**	**P<0.05**
indus very sm vs resid very sm	217.531	6.210	Yes
indus very sm vs resid larger	215.741	6.511	Yes
indus very sm vs indus larger	80.196	2.026	No
indus larger vs resid very sm	137.334	5.108	Yes
indus larger vs resid larger	135.545	5.564	Yes
resid larger vs resid very sm	1.789	0.112	No

Therefore, combine land uses: Residential/Commercial vs. Industrial. The Mann-Whitney Rank Sum Test was therefore used to confirm that these two groups are significantly different:

Group	**N**	**Missing**	**Median**	**25%**	**75%**
resid	447	8	0.905	0.693	1.167
indus	60	1	1.421	1.098	3.170

Mann-Whitney U Statistic= 4464.000

T = 23207.000 n(small)= 59 n(big)= 439 (P = <0.001)

The difference in the median values between the two groups is greater than would be expected by chance; there is a statistically significant difference ($P = <0.001$)

Figure XX.15 illustrates the range and medians of the flow to rainfall duration ratios.

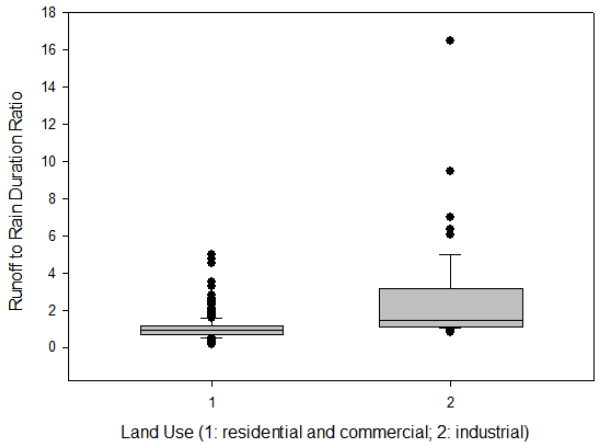


Figure XX.15 Final two categories representing runoff to rain duration ratios.

XX.5 Conclusions

Table XX.6 summarizes the characteristics of the three land use and rain categories that were found to be significantly different in their peak to average flow ratios. This table also shows the characteristics of the combined data set. As expected, there is a slight, but significant, increase in the peak/average flow ratio as the rain depth increases. Analyses (not reported here) were also conducted to attempt to further explain the variability left in these groups. No significant patterns were observed for rain intensity or duration, antecedent dry period, season, or other factors. Therefore, it is suggested that these average ratio values be adjusted according to these significant categories when conducting long-term continuous simulations, and that Monte Carlo stochastic components of runoff models vary the average values according to the coefficient of variation values, for different rains in each category. Applying these shape factors to urban hydrographs when examining small and intermediate-sized rains, which are of greatest interest to stormwater quality managers, will improve sizing and designs of stormwater quality control practices. It is likely that similar data are available for many locations and that all stormwater quality models be compared to the locally available data during model calibration activities. As an example, the ratio values observed and presented here for these events are about half of the values that are be traditionally used for drainage design calculations when considering large events.

Table XX.7 summarizes the flow duration to rain duration ratios that are used to calculate the baseline duration for the urban hydrographs. The statistical analyses indicated that the land use categories were significantly different in these ratios, with residential and commercial areas having flow durations about equal to the rain durations on the average; however, the variation is relatively large. The flow to rain duration ratios for the industrial areas are much larger, being about 2.5 on the average, and with even larger variations. The rain categories were examined in an attempt to explain some of this variability, but with minimal success. As for the peak to average flow rate ratios, it is recommended that a Monte Carlo routine be used in continuous modeling to randomly vary the duration ratios with the land use categories.

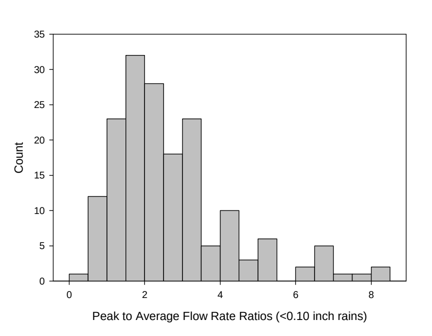
Table XX.6 Peak to Average Flow Rate Ratios for Urban Areas

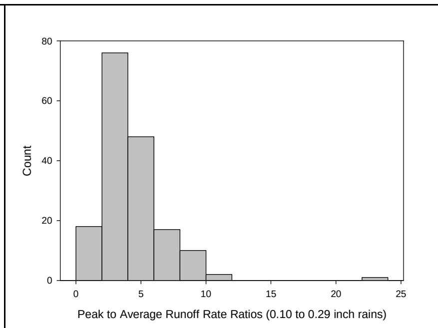
	All Industrial; plus Commercial and Residential areas for <0.10 in (<2.5 mm) rains	Commercial and Residential areas for 0.10 to 0.29 in (2.5 to 7.4 mm) rains	Commercial and Residential areas for 0.30 to 4.4 in (7.5 to 120 mm) rains	All Data Combined (all land uses and all rain depths)
Number of Observations	172	172	206	550
Minimum	1.00	1.00	1.05	1.00
Maximum	8.3	22	20	22
Average	2.67	4.22	5.42	4.18
Median	2.28	3.79	4.65	3.54
Standard deviation	1.57	2.45	3.06	2.72
COV	0.55	0.65	0.66	0.65

Table XX.7 Runoff Duration to Rain Duration Ratios for Urban Areas

	Runoff Duration to Rain Duration Ratios			
	Residential and Commercial Areas	Industrial Areas	All data combined (all land uses and all rain depths	Rain Depth (inches)
Number of observations	447	60	507	507
Minimum	0.16	0.78	0.16	0.01
Maximum	5.0	16	16	4.34
Average	1.0	2.5	1.2	0.34
Median	0.91	1.4	0.97	0.20
Standard deviation	0.63	2.6	1.2	0.40
COV	0.63	1.0	1.0	1.2

These analyses examined a set of about 550 different monitored rainfall and runoff events from four areas in North America, each paired with another site. These eight monitored areas represent each of the four rainfall distribution types, and represent typical ranges of drainage areas, land uses, and rain depths. Obviously, with the variations observed for these urban hydrographs, other locations may have hydrograph characteristics within a relatively wide range. However, as shown in the following histograms (Figures XX.16 and XX.17), most of the observations are within a relatively narrow range, and indicate log-normal distributions.





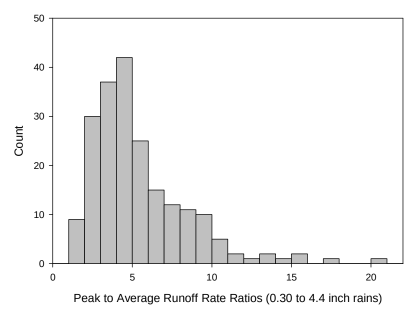


Figure XX.16 Histograms of observed peak to average runoff rate ratios.

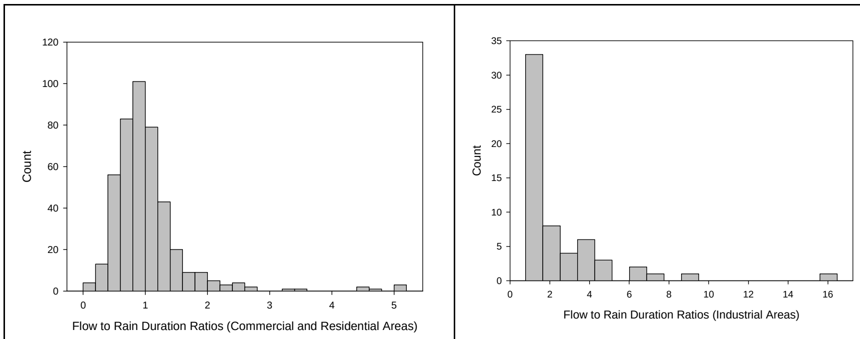


Figure XX.17 Histograms for observed runoff flow to rain duration ratios.

Uncalibrated, or partially calibrated (such as only for runoff quantity) runoff models likely greatly distort the actual hydrograph shapes that occur in urban areas. This dramatically affects the flow-duration calculations needed for receiving water habitat evaluations. Simple models, such as WinTR-55, cannot be adequately and completed calibrated for an area for a wide range of rain conditions because of the curve number variation with respect to rainfall depth? It is possible to calculate the correct total runoff volume for an area over an extended period of time by adjusting the curve number value, but small rains would be under-reported and large rains would be over-reported to compensate for the non-constant actual curve numbers. It is not possible to calibrate TR-55 methods for peak flows, as the storm hydrographs are based on a composite highly distorted rainfall distribution that includes combined features of a number of large rains. The TR-55 methods were originally developed for single event analyses to examine relatively rare and large drainage design storms, a very worthwhile objective. However, the many simplifying assumptions used in its development preclude its accurate use for a wide range of continuous events of interest in either water quality or habitat stability analyses.

In contrast, complex hydrologic models can be appropriately calibrated to accurately represent a wide range of rain and watershed conditions. Both runoff volumes and flow distributions can be reasonably well matched with observed conditions. However, if uncalibrated and "traditional" model parameters are used without checking with observed data for similar conditions (an unfortunately common occurrence), distorted flow conditions are likely, especially for unfamiliarly modeled smaller events. As an example, typical peak to average flow ratios are likely greatly over-predicted when using uncalibrated models in urban areas. [provide a specific example?]

WinSLAMM uses a hydrograph generation approach intermediate to these examples. The complex triangular storm hydrograph can be modified in shape for site conditions based on relatively simple data evaluations (the peak to flow rate ratios and the runoff to rain duration ratios). Currently, a single set of these ratios are used for all of the rains in an analysis, usually a ratio of 3.8 for the flow ratio value and 1.2 for the duration ratio value, which are shown to be close to the overall average observed. Future model changes are planned that will enable these ratios to vary based on both the site and storm factors identified in this paper, and will include Monte Carlo type stochastic methods to account for the remaining uncertainty in the model calculations.

X.6 Acknowledgment

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