DERIVATION AND CALIBRATION
OF
VOLUME-BASED RUNOFF COEFFICIENTS
FOR DENVER AREA, COLORADO

Prepared by

Dr. James C.Y. Guo, P.E., Professor and Director,
Civil Engineering, U of Colorado Denver
James.Guo@UCDenver.edu

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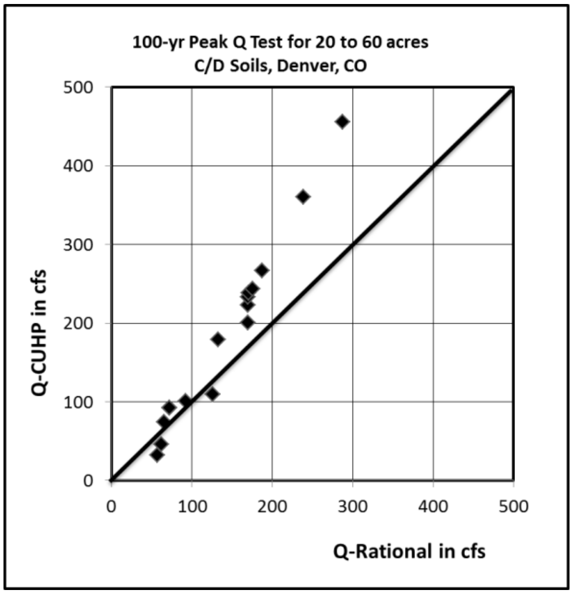
1. INTRODUCTION

During the Urban Stormwater Drainage Criteria Manual (USDCM) update in 2001 sponsored by the Urban Drainage and Flood Control District (UDFCD), a new procedure for calculating the runoff coefficient was developed and adopted (USDCM 2001). In 2005, the Colorado Urban Hydrograph Procedure (CUHP) was enhanced to extend the application of the parameter of time to peak to catchments less than 10 acres. These changes in the methodology have led to inconsistency in peak-flow and runoff-volume predictions among the CUHP, Rational Method, and Modified FAA Procedure. Figure 1.1 is a comparison of 100-yr peak flows predicted by the CUHP and Rational Method for small urban catchments ranging from 20 to 60 acres with Types C or D soils. The difference between the two sets of predicted flows increases as the catchment area increases. A similar pattern is also observed in Figure 1.2 for stormwater detention volumes predicted by the Rational Volumetric Method and UDFCD's regression equation for the 100-yr event under various impervious conditions.



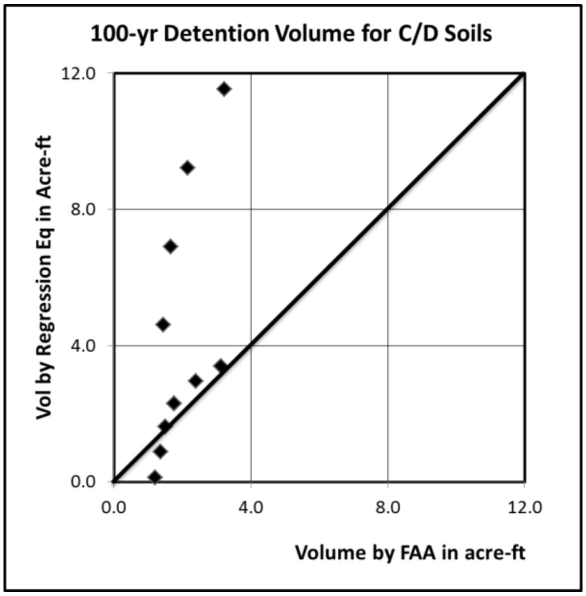


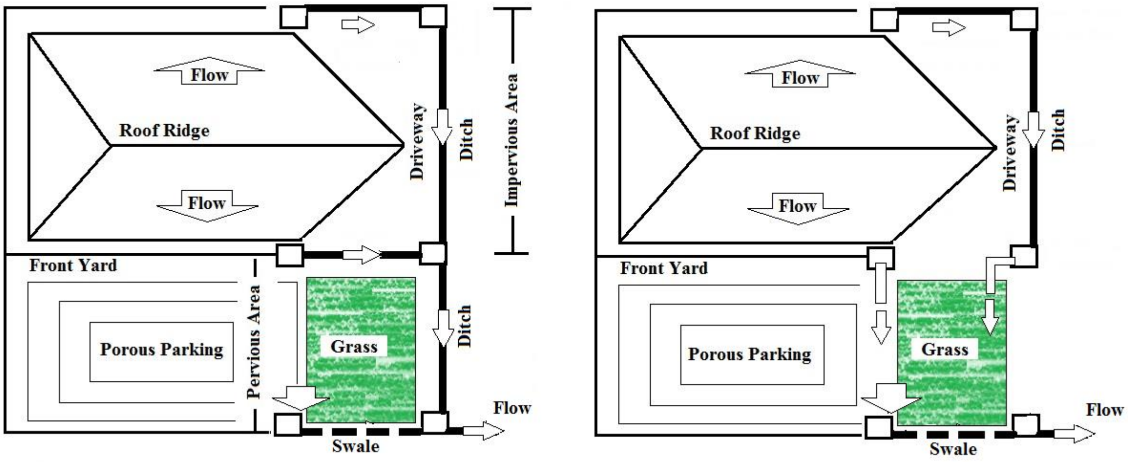
Figure 1.1 Comparison of Peak Flow

Figure 1.2 Comparison of Detention Volume

This report presents a calibration effort to derive a set of new volume-based runoff coefficients that serve as the basis to establish the optimal consistency between the CUHP and the Rational Method for peak flow predictions, and also between UDFCD's regional regression formula and Rational Volumetric Method for storm water detention sizing. It is noted that the Rational Volumetric Method is also termed the Modified FAA Procedure because it was originated from the Federal Aviation Administration technical report for storm water detention designs (FAA 1970, Guo 1999).

2. VOLUME-BASED RUNOFF COEFFICIENT

For a small urban catchment, the land use is divided into impervious and pervious sub-areas. The watershed's response to a rainfall event is very sensitive to how storm drains are networked together. A *distributed flow system* in Fig 2.1 has separate flow paths to drain impervious and pervious areas respectively, while a *cascading flow system* directs stormwater from the upper impervious area onto the lower pervious area.



Distributed Flow System (Two Separated Flows)

Cascading Flow System (One Mixed Flow)

Fig 2.1 Distributed and Cascading Drainage Systems

In this study, two sets of theoretical runoff coefficients are derived for distributed and cascading flow systems separately. The required time of concentration was re-formulated and then calibrated using the CUHP 2005 computer model as the basis. Good agreement has been achieved between the Rational Method and the CUHP with these new sets of runoff coefficients and the new formula for the regional time of concentration for the use in the Denver metro area.

2.1 Distributed Flow System (Option of DCIA=0 in CUHP Model)

A *distributed flow or two-flow system* is equivalent to the Option of *DCIA=0* in the CUHP computer Model (CUHP 2005). Impervious areas are connected together to deliver stormwater directly into manholes. Pervious areas are linked through swales to pass stormwater to the downstream streets. A *two-flow system* is essentially composed of two independent flow paths to drain surface runoff. Under a rainfall event, the total rainfall amount on the catchment is:

$$V_R = PA \qquad (1)$$

where V_R= event rainfall volume on catchment, P= event rainfall depth, and A=catchment area. The runoff volumes produced from the pervious and impervious areas are calculated as:

$$V_m = (P - D_{vi}) I_a A \tag{2}$$

$$V_P = m(P - D_{vp} - F)(1 - I_a) A \qquad m = 1 \; if \; V_p > 0 \, ; otherwise \; m = 0 \tag{3}$$

$$V_F = V_m + V_p \text{ = volume from impervious area + volume from pervious area} \tag{4}$$

Where V_m = runoff volume from impervious area, V_p = runoff volume from pervious area, V_F= total runoff volume, D_{vi} = depression loss on impervious area, I_a = impervious area ratio, D_{vp}=depression loss on pervious area, F=infiltration amount, and m = 1 if $V_p>0$ or 0 if $V_p \leq 0$. By definition, the volume-based runoff coefficient is calculated as:

$$C = \frac{V_F}{V_R} = n[(1 - \frac{D_{vi}}{P}) I_a + m(1 - \frac{D_{vp}}{P} - \frac{F}{P})(1 - I_a)] \tag{5}$$

$$n = 1 \; if \; C > 0; otherwise \;\; n = 0$$

where C= volume-based runoff coefficient, $C \geq 0$. Eq (5) is the sum of two flows, and mostly dominated by the runoff volume from the impervious areas or V_m. The runoff coefficient in Eq (5) is always greater than zero as long as $P>D_{vi}$.

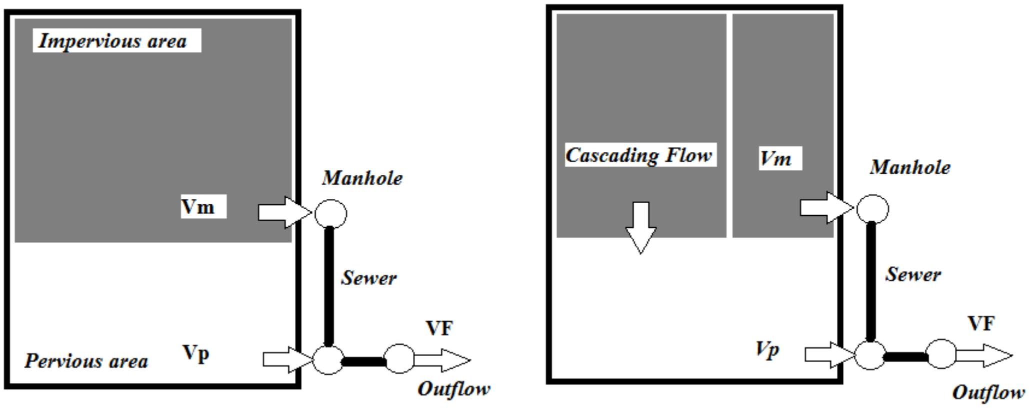
2.2 Cascading Flow System (Option of DCIA= 2 in CUHP Model)

A *lumped system* represents a cascading flow process that drains storm water from impervious onto pervious areas. Mathematically, the intercepted runoff volume is directly added to the lower pervious area for more infiltration benefits. As shown in Fig 2.2, not the entire impervious area can be drained onto the pervious area (SWMM 2005), the flow interception ratio, between zero and one, is introduced to the volume calculation as:

$$V_P = m[r(P - D_{vi}) I_a A + (P - D_{vp} - F)(1 - I_a) A] \tag{6}$$

where r = flow interception ratio of V_m. When r=1, Eq (6) represents a complete flow interception, while r=0, Eq (6) is reduced to Eq (3) for distributed flow system. For 0<r <1, the residual runoff volume from the impervious area is directly released to the street as:

$$V_m = (1 - r)(P - D_{vi}) I_a A \tag{7}$$



Two-Flow System

Cascading Flow System

Fig 2.2 Two-flow and Cascading-flow Systems

The resultant runoff coefficient is calculated as:

$$C = \frac{V_F}{V_R} = n\{(1-r)(1-\frac{D_{vi}}{P})I_a + m[r(1-\frac{D_{vi}}{P})I_a + (1-\frac{D_{vp}}{P}-\frac{F}{P})(1-I_a)]\} \qquad (8)$$

Setting r=0, Eq(8) is reduced to Eq (5). Numerically, Eq (8) can become zero if the catchment is under a low development condition. On the contrary, Eq (8) is converged to Eq (5) for a highly urbanized catchment because the lower pervious area is too small to produce any significant infiltration benefits. More details can be found elsewhere (Guo and MacKenzie in 2013, Guo and Urbonas in 2013).

3. RATIONAL METHOD AND CUHP

The Rational Method is a simplified kinematic wave approach for peak flow estimation (Guo 2001). The major variables in the Rational Method are time of concentration, watershed tributary area, and runoff coefficient. The Rational Method states as (Kuichling 1889):

$$Q_P = C\,I\,A \qquad (9)$$

in which Q_p= peak flow, A= tributary area, and I= average rainfall intensity. By definition, *the peak flow-based runoff coefficient* is determined as:

$$C = \frac{Q_p}{IA} \qquad (10)$$

For the peak flow prediction, the contributing rainfall amount is defined by the Intensity-Duration-Frequency (IDF) curve under the assumption that the period of contributing rainfall amount is equal to the time of concentration of the catchment as:

$$I = \frac{28.5 P_1}{(10 + T_c)^{0.789}} \tag{11}$$

in which P_1= index rainfall event using 1-hr depth in inches, and T_c = time of concentration in minutes. Eq (11) was derived for the metro Denver area, Colorado. As illustrated in Figure 3.1, the Rational Method is expanded from peak flow predictions to hydrograph predictions. The contributing rainfall amount and the corresponding flow rate at t=T, are calculated as:

$$I(T) = \frac{1}{T_c} \sum_{t=T-T_c}^{t=T} \Delta P(t) \quad \text{where } T_c \leq T \leq T_d \tag{12}$$

$$Q(T) = CA\, I(T) \tag{13}$$

in which I(T)= moving average rainfall intensity at time T for a period of T_c prior to T, T_B= based time of runoff hydrograph, Q(T) = runoff rate at time T in runoff hydrograph, t= time variable, T_d= event duration, and $\Delta P(t)$= incremental rainfall depth at time t.

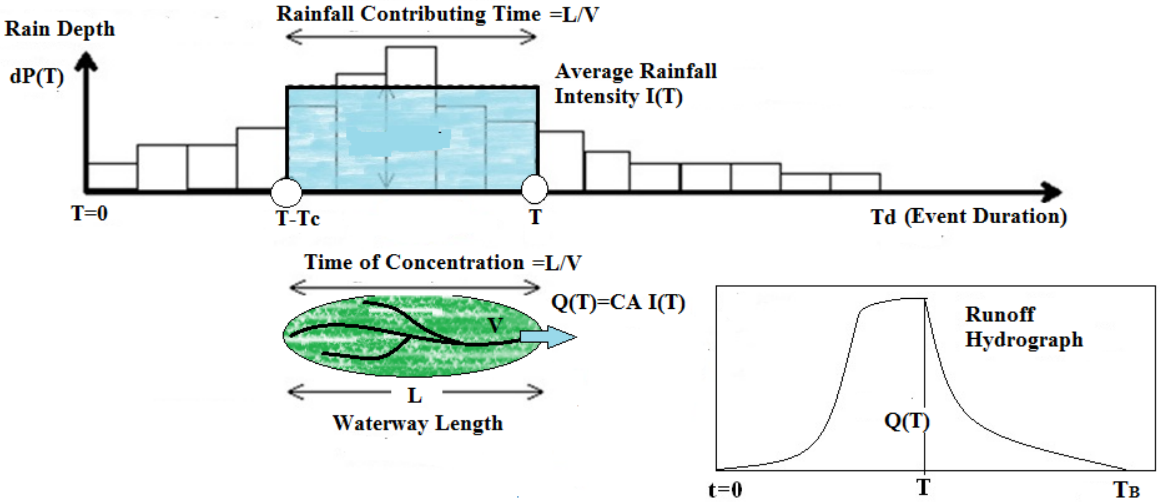


Figure 3.1 Hydrographs for CUHP and Rational Method

Aided with Eq's (12) and (13), the Rational Method is expanded into a convolution process to integrate a series of individual triangular hydrographs to produce the entire runoff hydrograph

(Guo 2001). The *volume-based runoff coefficient* is referred to as the volume ratio of runoff hydrograph to rainfall hyetograph as:

$$C = \frac{V_F}{V_R} = \frac{\sum_{T=0}^{T=T_B} Q(T)\Delta T}{A\sum_{T=0}^{T=T_d} \Delta P(T)} = \frac{Volume\ of\ Runoff\ \ Hydrograph}{Volume\ of\ \ Hyetograph} \tag{14}$$

in which ΔT = incremental time step on runoff hydrograph such as 5 minutes. Although in theory Eq's (10) and (14) should yield identical values for runoff coefficients, in fact, the non-linear nature in runoff flow results in significant gaps between Eq's (10) and (14) (Guo and Urbonas 2013).

In this study, the volume-based runoff coefficient is selected to establish the modeling consistency. The runoff hydrograph in Eq (14) is produced using the CUHP 2005 computer model. CUHP applies the unit hydrograph protocol to predict storm hydrographs using a convolution process (Sherman 1932). The input parameters for CUHP include catchment area, length of waterway, length to centroid, slope for waterway, and soil losses (USDCM 2001). As illustrated in Figure 3.1, the peak flow is the highest point on the storm hydrograph. The hydrograph convolution process using the Rational Method is similar to the unit-graph method, except that the contributing time of rain amount to each triangular hydrograph is set to be the time of concentration.

In this study, the ultimate goal is to calibrate the rational parameters by minimizing the squared differences between the two peak flows predicted by the two methods.

$$E = Min\sum_{j=1}^{j=N}(Q_p - Q_{cuhp})_j^{\ 2} \tag{15}$$

where E= minimized squared error, Q_{cuhp}=peak flow on CUHP hydrograph for j-th case, and N= number of cases used in the test. Eq (15) is involved two unknowns: runoff coefficient and time of concentration. In this study, a data base was established to systematically solve Eq (15).

4. DATA BASE

In this study, the data base was selected from the UDFCD master drainage studies (MacKenzie 2010). It was composed of 295 individual urban small catchments. The ranges of hydrologic parameters are summarized in Table 4.1.

Tributary	Waterway	Length to	Waterway
		Centroid	Slope
Area	Length	LC	S
sq mile	mile	mile	ft/ft
0.0310	0.3980	0.1790	0.0220
0.3300	1.4000	0.6300	0.0343

Table 4.1 Ranges of Hydrologic Parameters used in Data Base

According to the SCS hydrologic guide (NRSCS 1972), the infiltration characteristics of soils are classified into Types A, B, and C/D. These 293 catchments were studied under the combinations of soils A, B, or C/D, catchment's impervious percent varied from 5%, 25%, 45%, 65%, 85%, to 99%, and rainfall depths ranging from 2-, 10-, to 100-yr event.

5. RESULTS FROM DATA ANALYSES

5.1 Runoff Coefficients

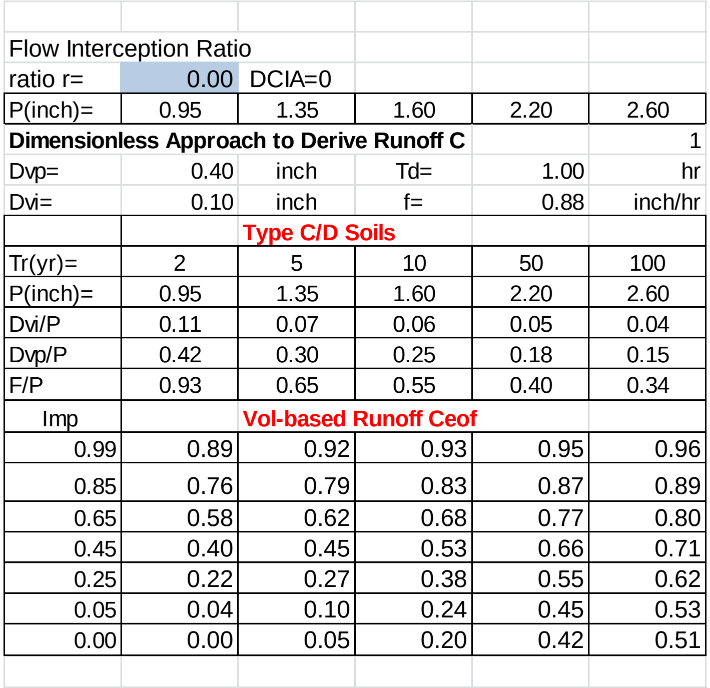
The computer model: CUHP 2005-Version 1.3.3 was used to build a base model for 293 catchments. Soil infiltration rates were modeled with Horton's formula (Horton 1933). Horton's parameters are listed in Table 5.1 as (USDCM 2001):

SCS Soil Type	Initial infiltration *fi* in/hr	Final Infiltration *fo* in/hr	Decay Factor *K* 1/hr	Impervious Depression *Dvi* in	Pervious Depression *Dvp* in	Potential F *t= 1 hr* inch	Actual F *t=1-hr* inch
A	5.0	1.0	0.0007	0.1	0.4	5.00	1.80
B	4.5	0.6	0.0018	0.1	0.4	4.50	1.00
C/D	3.0	0.5	0.0018	0.1	0.4	3.00	0.88

Table 5.1 Soil Infiltration Parameters

The task begins with the assumption that all 293 catchments were covered with Type C/D soils. The storms for this study include 2-, 10- and 100-yr events. Under a selected storm event, all catchments were then tested for imperviousness of 5, 25, 45, 65, 85, or 99%. As a result, a total of 18 combinations, or 18x293 cases, were developed for Type C/D soils. Repeat the same process for Type B and A soils to generate a total of 15822 cases. This data base was further used to produce the volume-based runoff coefficients using Eq (14) for Type A, B, and C/D soils under various catchment imperviousness ratios. Since the one-hr rainfall events are the default index depths to generate the design rainfall distributions in CUHP 2005, the corresponding soil infiltration amount is then determined from CUHP runs using t= 1 hour. In the numerical procedure, the actual infiltration rate is the smaller one between the soil infiltration potential determined by the Horton's formula and the design rainfall intensity available. From the aforementioned data base, the average one-hr infiltration amounts are found to be 1.8 inches for

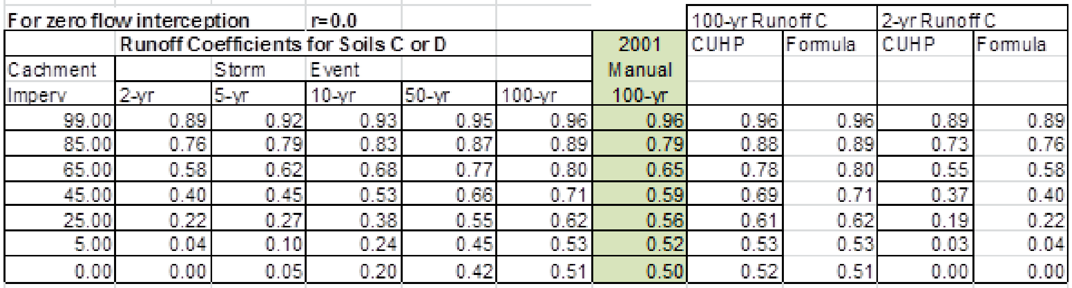
Type A soils, 1.0 inch for Type B soils, and 0.88 inch for Type C soils. As an example, Table 5.2 presents the computational procedure to populate the theoretical runoff coefficients for Type C/D soils:



Flow Interception Ratio					
ratio r=	0.00	DCIA=0			
P(inch)=	0.95	1.35	1.60	2.20	2.60
Dimensionless Approach to Derive Runoff C					1
Dvp=	0.40	inch	Td=	1.00	hr
Dvi=	0.10	inch	f=	0.88	inch/hr
		Type C/D Soils			
Tr(yr)=	2	5	10	50	100
P(inch)=	0.95	1.35	1.60	2.20	2.60
Dvi/P	0.11	0.07	0.06	0.05	0.04
Dvp/P	0.42	0.30	0.25	0.18	0.15
F/P	0.93	0.65	0.55	0.40	0.34
Imp		**Vol-based Runoff Ceof**			
0.99	0.89	0.92	0.93	0.95	0.96
0.85	0.76	0.79	0.83	0.87	0.89
0.65	0.58	0.62	0.68	0.77	0.80
0.45	0.40	0.45	0.53	0.66	0.71
0.25	0.22	0.27	0.38	0.55	0.62
0.05	0.04	0.10	0.24	0.45	0.53
0.00	0.00	0.05	0.20	0.42	0.51

Table 5.2 Theoretical Runoff Coefficients for Type C/D Soils

For a distributed flow system, Figures 5.1 to 5.3 present the comparisons between Eq (5) for theoretical runoff coefficients and Eq (14) for CUHP's volume ratio under the Option of DCIA=0. For all Type of soils, the differences are negligible for engineering practice.



For zero flow interception		r=0.0					100-yr Runoff C		2-yr Runoff C	
	Runoff Coefficients for Soils C or D					2001 Manual 100-yr	CUHP	Formula	CUHP	Formula
Cachment Imperv	2-yr	Storm 5-yr	Event 10-yr	50-yr	100-yr					
99.00	0.89	0.92	0.93	0.95	0.96	0.96	0.96	0.96	0.89	0.89
85.00	0.76	0.79	0.83	0.87	0.89	0.79	0.88	0.89	0.73	0.76
65.00	0.58	0.62	0.68	0.77	0.80	0.65	0.78	0.80	0.55	0.58
45.00	0.40	0.45	0.53	0.66	0.71	0.59	0.69	0.71	0.37	0.40
25.00	0.22	0.27	0.38	0.55	0.62	0.56	0.61	0.62	0.19	0.22
5.00	0.04	0.10	0.24	0.45	0.53	0.52	0.53	0.53	0.03	0.04
0.00	0.00	0.05	0.20	0.42	0.51	0.50	0.52	0.51	0.00	0.00

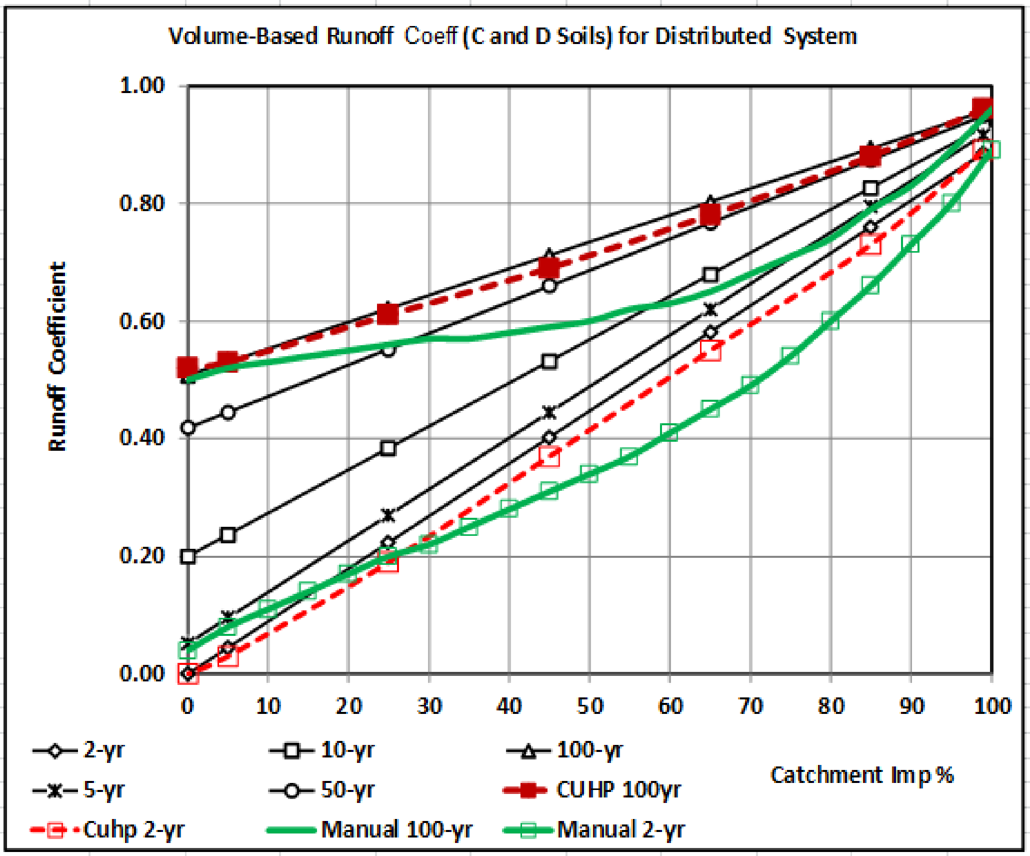
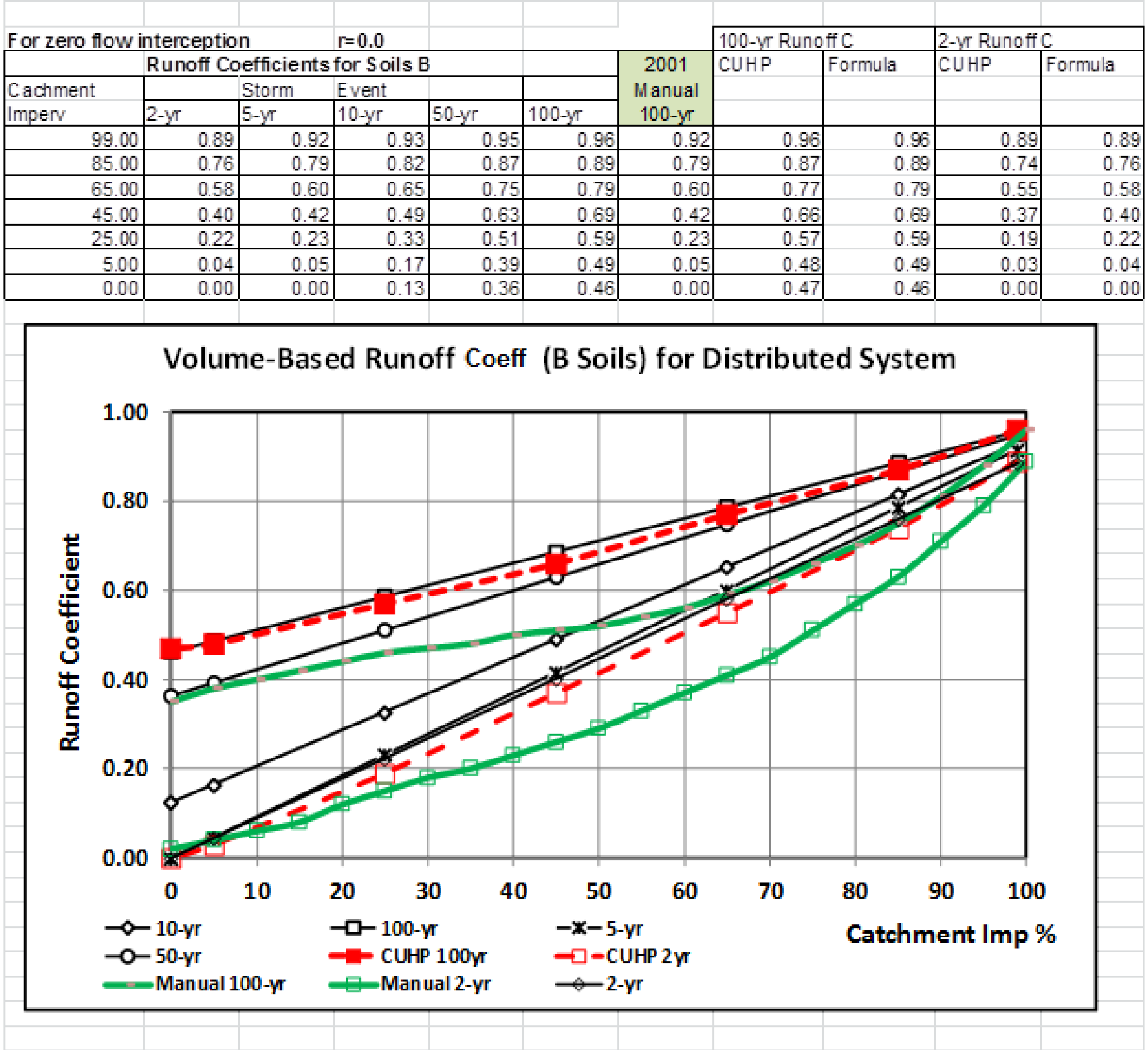
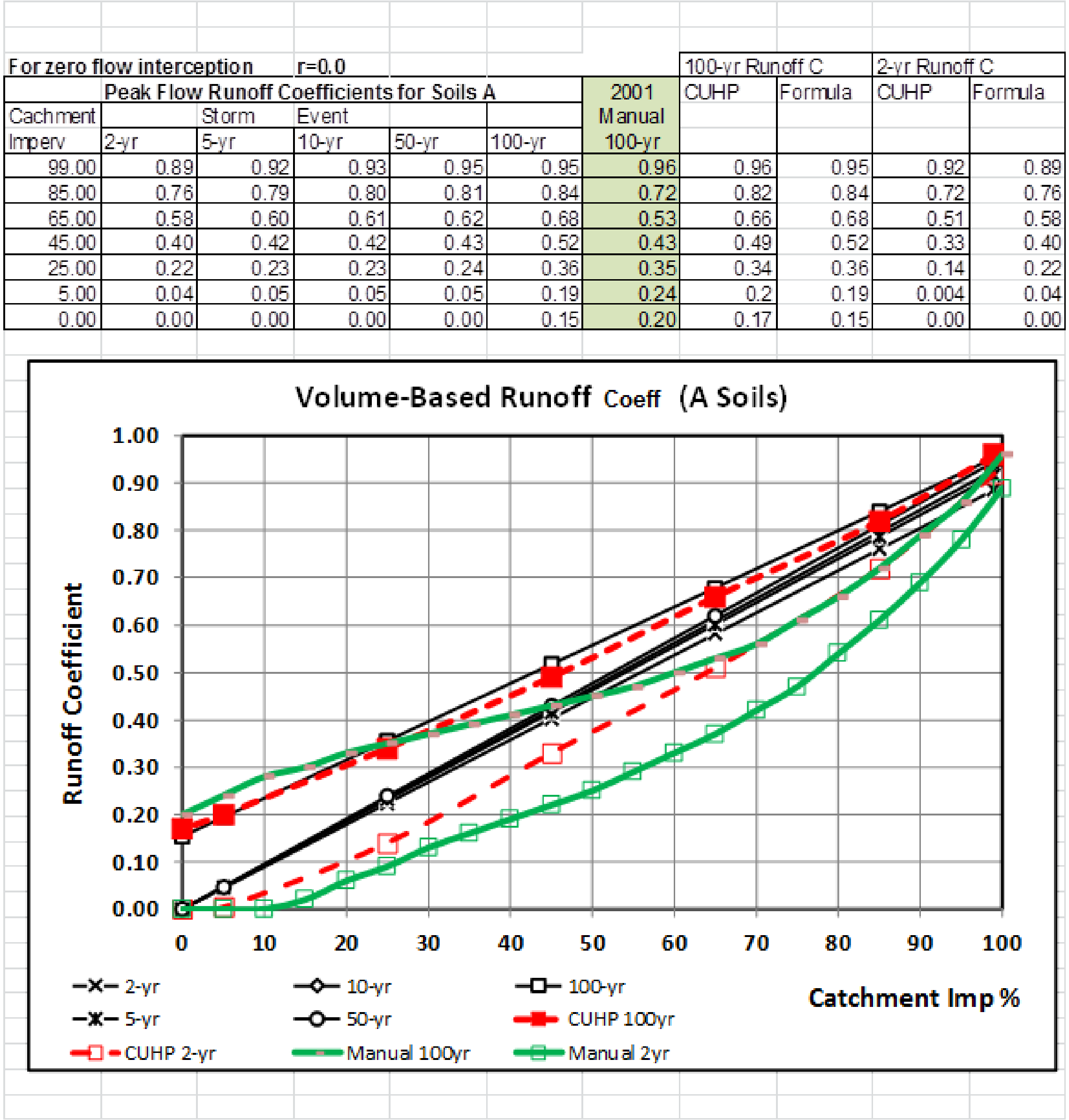


Figure 5.1 Volume-Based Runoff Coefficients for Distributed System (DCIA=0) and C/D Soils



For zero flow interception			r=0.0				100-yr Runoff C		2-yr Runoff C	
	Runoff Coefficients for Soils B					2001	CUHP	Formula	CUHP	Formula
Cachment		Storm	Event			Manual				
Imperv	2-yr	5-yr	10-yr	50-yr	100-yr	100-yr				
99.00	0.89	0.92	0.93	0.95	0.96	0.92	0.96	0.96	0.89	0.89
85.00	0.76	0.79	0.82	0.87	0.89	0.79	0.87	0.89	0.74	0.76
65.00	0.58	0.60	0.65	0.75	0.79	0.60	0.77	0.79	0.55	0.58
45.00	0.40	0.42	0.49	0.63	0.69	0.42	0.66	0.69	0.37	0.40
25.00	0.22	0.23	0.33	0.51	0.59	0.23	0.57	0.59	0.19	0.22
5.00	0.04	0.05	0.17	0.39	0.49	0.05	0.48	0.49	0.03	0.04
0.00	0.00	0.00	0.13	0.36	0.46	0.00	0.47	0.46	0.00	0.00

Figure 5.2 Volume-Based Runoff Coefficients for Distributed System (DCIA=0) and B Soils



For zero flow interception		r=0.0					100-yr Runoff C		2-yr Runoff C	
	Peak Flow Runoff Coefficients for Soils A					2001	CUHP	Formula	CUHP	Formula
Cachment		Storm	Event			Manual				
Imperv	2-yr	5-yr	10-yr	50-yr	100-yr	100-yr				
99.00	0.89	0.92	0.93	0.95	0.95	0.96	0.96	0.95	0.92	0.89
85.00	0.76	0.79	0.80	0.81	0.84	0.72	0.82	0.84	0.72	0.76
65.00	0.58	0.60	0.61	0.62	0.68	0.53	0.66	0.68	0.51	0.58
45.00	0.40	0.42	0.42	0.43	0.52	0.43	0.49	0.52	0.33	0.40
25.00	0.22	0.23	0.23	0.24	0.36	0.35	0.34	0.36	0.14	0.22
5.00	0.04	0.05	0.05	0.05	0.19	0.24	0.2	0.19	0.004	0.04
0.00	0.00	0.00	0.00	0.00	0.15	0.20	0.17	0.15	0.00	0.00

Figure 5.3 Volume-Based Runoff Coefficients for Distributed System (DCIA=0) and A Soils

6. TIME OF CONCENTRATION

Time of concentration is defined as the flow time required through the watershed, or the contributing time of rainfall amount to the peak flow. It is the most sensitive time parameter in catchment hydrology analyses (Kirpitch 1941). To be conservative, the computed time of concentration based on its overland flow and gutter flow is further examined with the regional formula. With reference to USDCM 2001, the procedure for calculating the time of concentration is stated as:

$$T_{comp} = T_o + T_f \tag{16}$$

$$T_o = \frac{0.395(1.1 - C_5)\sqrt{L_o}}{S_o^{\;0.33}} \quad \text{for overland flow where } L_o \le L_*$$

(17)

$$T_f = \frac{L - L_o}{60(2\sqrt{S_o})} \quad \text{for street gutter flows} \tag{18}$$

$$T_{reg} = T_* + \frac{L}{60V_*} = T_* + \frac{L}{60K_*\sqrt{S_o}} \tag{19}$$

$$T_c = \min(T_{reg}, T_{comp}) \tag{20}$$

in which L= waterway length in feet, L_o = overland flow length in feet, C_5=5-yr runoff coeff, S_o = waterway slope in percent, T_o = overland flow time in minutes, T_f= gutter flow time in minutes, T_{reg}= regional time of concentration in minutes, T_{comp}= computed time of concentration in minutes, T_c= design time of concentration in minutes, T_*= initial overland flow time in minutes, V_*= concentrated flow velocity in feet/second, K_*= conveyance factor for concentrated flow in feet/sec.

The best fitted values for the two parameters, K_* and T_* in Eq 19, are determined using the least squared error method as:

$$E = Min\sum_{j=1}^{j=N}(T_{reg} - T_{comp})_j^{\;2} = Min\sum_{j=1}^{j=N}[(\frac{L}{60K_*\sqrt{S_o}} + T^*) - T_{comp}]_j^{\;2} \quad \text{where N= 293} \tag{21}$$

Fig 6.1 is the summary of the best-fitted equation for the value of K_*. As expected, a concentrated flow through an urbanized watershed is highly correlated to catchment's imperviousness. Eq 22 was derived for Types A, B, and C/D soils with various imperviousness ratios between 5 and 85%.

$$K_* \,(fps) = 0.24 I_a + 12 \quad I_a \text{ in percent} \qquad (22)$$

	Flow Conveuence K* (ft/sec)		
Imp %	Soil C/D	Soil B	Soil A
99.00	30.00	30.00	32.00
85.00	30.00	30.00	32.00
65.00	29.00	37.00	40.00
45.00	28.00	25.00	32.00
25.00	12.00	13.00	17.00
5.00	8.00	9.00	19.00
1.00	8.00	10.00	16.00

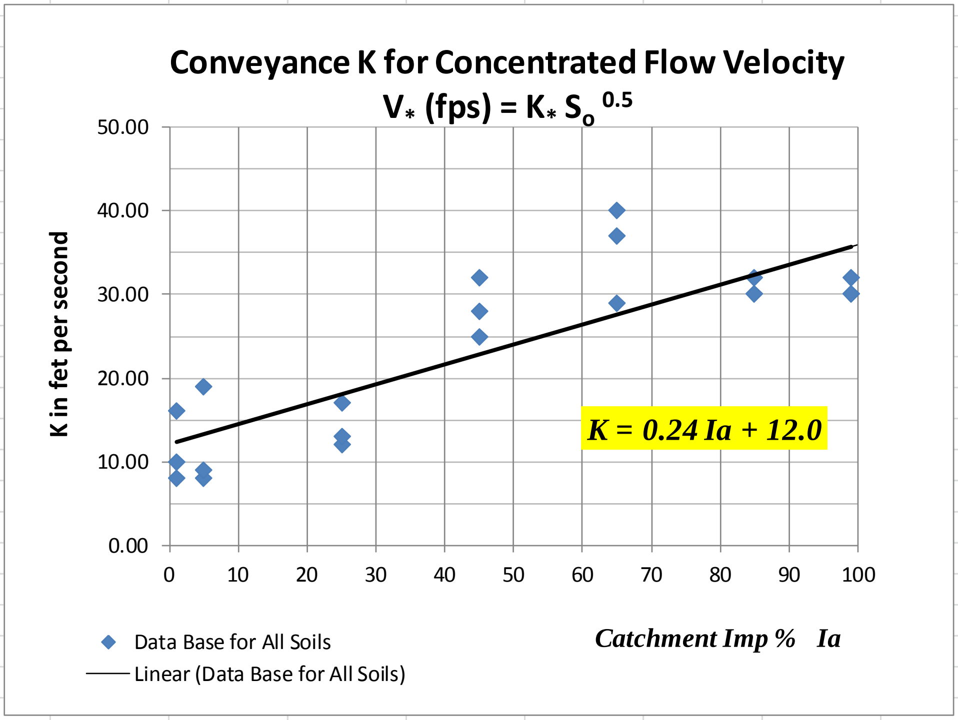


Figure 6.1 Conveyance Parameters for Concentrated Flow

The conveyance factor is varied between 12 cfs for *Ia*=0% to 36 fps for *Ia*=100%. It is noted that the conveyance factor of 20 cfs is recommended by the SCS upland method for paved surfaces. The value of 20 cfs is approximately the average for the range of Eq 22.

An initial time represents the average overland flow time. Repeat the above process to analyze the best fitted values for initial times. Fig. 6.2 presents the analysis for the value of T* in minutes. The imbedded initial time in the CUHP/Rational Method is found to be 18 minutes under I_a=0%, and it becomes shortened as the catchment development increases. Under I_a=100%, the initial time is reduced to 3 minutes.

$$T_*\ (\text{min}) = 18 - 0.15 I_a \quad I_a \text{ in percent} \tag{23}$$

		Initial Time (min)	
Imp %	Soil C/D	Soil B	Soil A
99.00	5.00	5.00	5.00
85.00	5.00	5.00	6.00
65.00	6.00	9.00	8.00
45.00	10.00	10.00	10.00
25.00	14.00	15.00	15.00
5.00	17.00	19.00	17.00
1.00	15.00	21.00	20.00

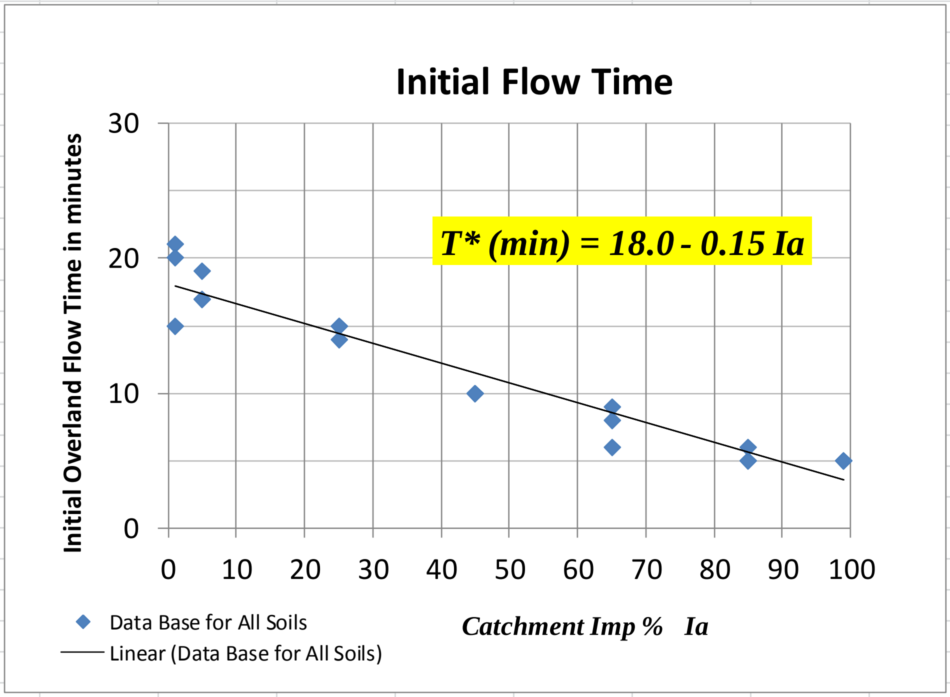


Figure 6.2 Initial Times for Concentrated Flow

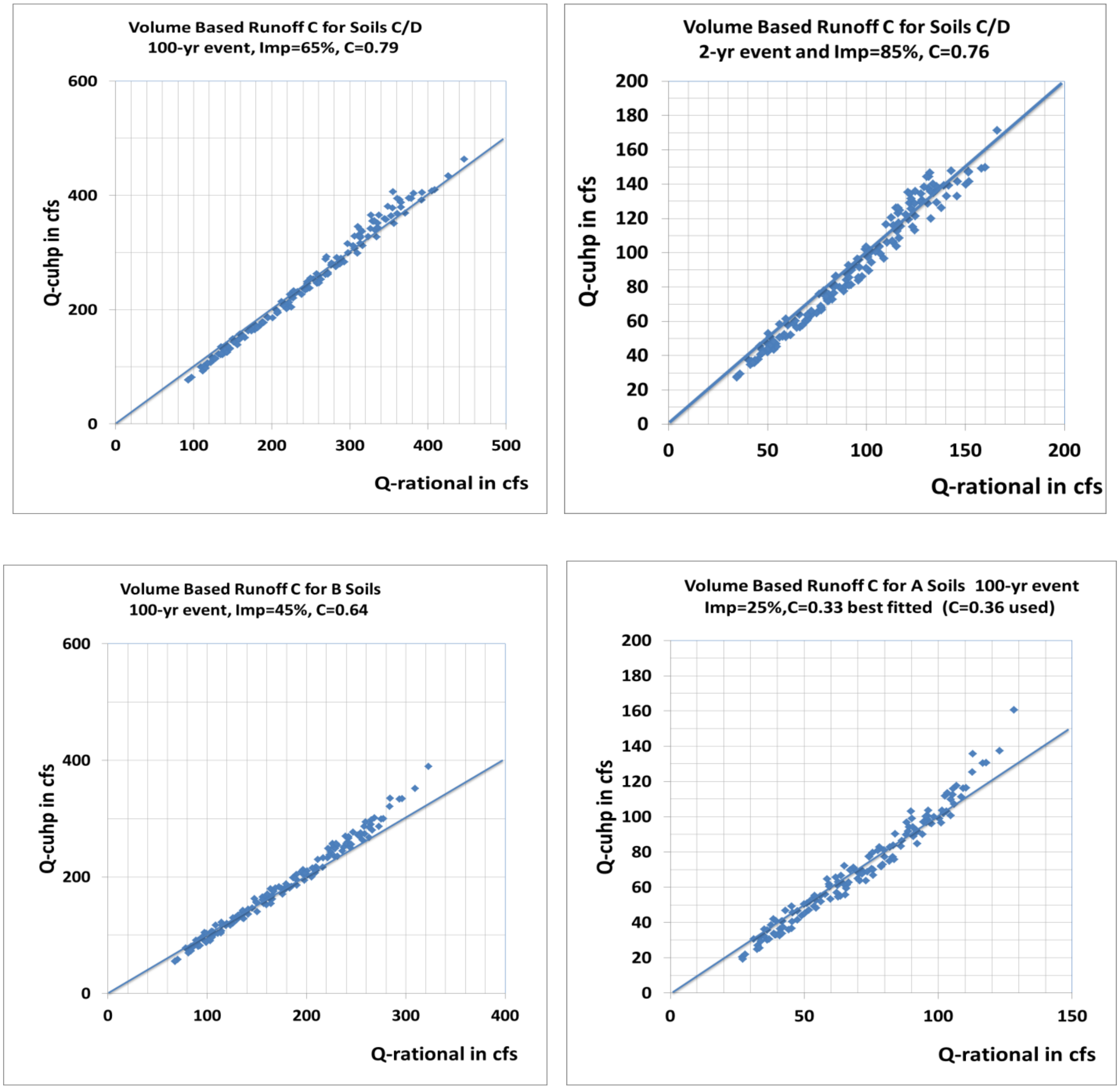
All empirical formulas are subject to application limits. The overland flow length in Eq 17 is recommended not to exceed 300 feet in urban areas because the average distance between two adjacent street inlets is approximately 300 feet. Similarly, a distance of 500 feet was recommended as the maximum overland flow length in a rural area because of the nature of surface soil erosion. Using the 5-yr event as the basis, the initial time in Eq 23 is further converted into its corresponding overland flow lengths as shown in Table 6.1. In this study, Eq 23 reveals that the limits on overland flow length for the practice of CUHP/Rational Method for small catchments are varied from approximately 80 to 90 feet on a slope of 1% to 185 to 190 feet on a slope of 3% etc. The range of these flow lengths agrees with the conventional approach recommended for the Rational Method.

Catchment		Overland Flow Length			
Imperv	Runoff	Overland To			Initial T*
	Coef	Slope	Length	Time	Time
%	Soil B	%	ft	min	min
	C5	So	Lo	To	Ti
99.0	0.917	1.00	90.1	3.15	3.15
85.0	0.787	1.00	85.9	5.25	5.25
65.0	0.602	1.00	83.7	8.25	8.25
45.0	0.417	1.00	82.7	11.25	11.25
25.0	0.231	1.00	82.2	14.25	14.25
5.0	0.046	1.00	81.8	17.25	17.25
	Soil C/D				
99.0	0.92	3.00	187.2	3.15	3.15
85.0	0.79	3.00	186.5	5.25	5.25
65.0	0.62	3.00	186.2	8.25	8.25
45.0	0.45	3.00	186.0	11.25	11.25
25.0	0.27	3.00	185.9	14.25	14.25
5.0	0.10	3.00	185.9	17.25	17.25
1.0	0.05	3.00	182.8	17.85	17.85

Table 6.1 Limits on Overland Flow Lengths Defined by Initial Times

7. VERIFICATION OF CONSISTENCY FOR PEAK FLOWS

In this study, Eq (5) is recommended for calculating the volume-based runoff coefficients. Eq's (19), (22), and (23) are recommended for determining the regional time of concentration. A total of 15822 cases were analyzed to verify if these equations are closely parallel to CUHP 2005 for peak-flow predictions. Figure 7.1 presents several samples of the data analyses using the least-square-error method. For each case, the value of runoff coefficient was first derived using Eq. (14) from the CUHP hydrograph and hyetograph. Then, the time of concentration, Eq (20), and the design IDF curve, Eq (11), were applied to the Rational Method for peak flow predictions, Eq (10). Most of the best fitted values show good agreement with Eq (5), except a few cases in Type A soils that need a minor adjustment to conform to Eq (5).



Volume Based Runoff C for Soils C/D
100-yr event, Imp=65%, C=0.79

Volume Based Runoff C for Soils C/D
2-yr event and Imp=85%, C=0.76

Volume Based Runoff C for B Soils
100-yr event, Imp=45%, C=0.64

Volume Based Runoff C for A Soils 100-yr event
Imp=25%,C=0.33 best fitted (C=0.36 used)

Fig. 7.1 Samples of Peak Flow Analyses for Catchments < 90 Acres.

The new runoff coefficients derived in this study were further tested with a set of hypothetical catchments. As summarized in Table 7.1, these catchments have an area varying from 20 to 100 acres and impervious percent ranging from 5% to 99%. Figure 7.2 presents the comparison of regional and computed times of concentration. Apparently, Eq. (19) is the best-fitted line to represent the computed times of concentration, Eq. (16), determined for the test catchments.

Catchment Data				Computation of Time of Concentration						Computed	Regional
Area	Imperv	Runoff Coef	Effective Area	Overland Flow			Channel Flow			Tc	Tc
				Slope	Length	Time	Slope	Length	Time		
acres	%		acres	%	ft	min	%	ft	min	min	min
A		C	CA	So	Lo	To	S2	L2	T2	Tc-comp	Tc-reg
20	99.0	0.89	17.8	2.00	300.0	5.24	2.00	1014.7	7.36	12.60	13.12
20	85.0	0.80	16.0	2.00	300.0	7.48	2.00	1014.7	7.36	14.84	13.12
20	65.0	0.57	11.4	2.00	300.0	13.22	2.00	1014.7	7.36	20.58	13.12
20	45.0	0.32	6.4	2.00	300.0	19.45	2.00	1014.7	7.36	26.82	13.12
20	25.0	0.11	2.2	2.00	300.0	24.69	2.00	1014.7	7.36	32.05	13.12
20	5.0	0.02	0.3	2.00	300.0	27.01	2.00	1014.7	7.36	34.37	13.12
20	65.0	0.57	11.4	2.00	300.0	13.22	2.00	1014.7	7.36	20.58	13.12
40	65.0	0.570	22.8	2.00	300.0	13.22	2.00	1559.2	11.31	24.53	16.48
60	65.0	0.570	34.2	2.00	300.0	13.22	2.00	1977.1	14.34	27.56	19.06
80	65.0	0.570	45.6	2.00	300.0	13.22	2.00	2329.4	16.90	30.12	21.23
100	65.0	0.570	57.0	2.00	300.0	13.22	2.00	2639.7	19.15	32.37	23.15
60	45.0	0.320	19.2	1.00	300.0	24.45	1.00	1977.1	16.48	40.93	19.06
60	45.0	0.320	19.2	2.00	300.0	19.45	2.00	1977.1	14.34	33.80	19.06
60	45.0	0.320	19.2	3.00	300.0	17.02	3.00	1977.1	13.23	30.24	19.06
60	45.0	0.320	19.2	4.00	300.0	15.48	4.00	1977.1	12.49	27.96	19.06
60	45.0	0.320	19.2	5.00	300.0	14.38	5.00	1977.1	11.94	26.32	19.06

Table 7.1 Hypothetical Catchments Used for Independent Tests

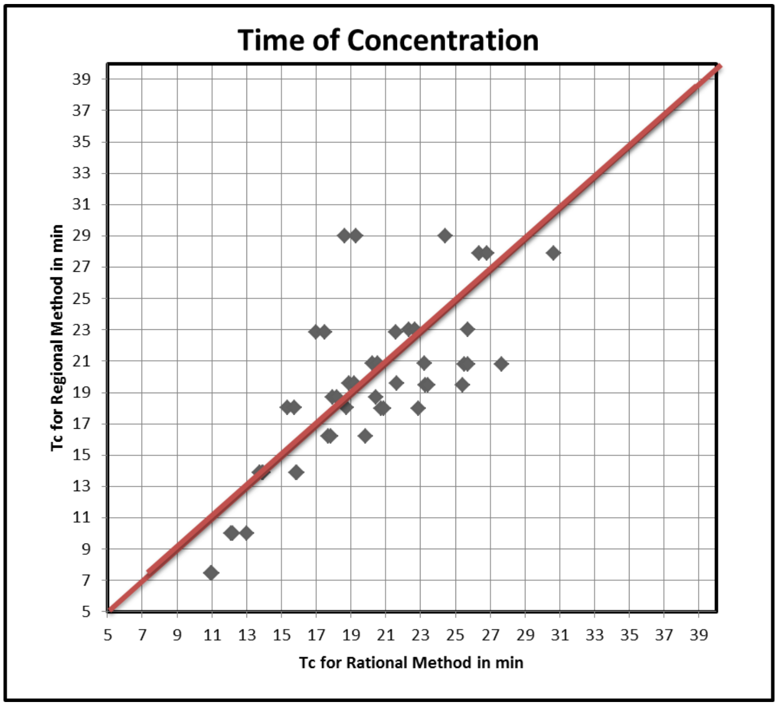


Figure 7.2 Comparison of Regional and Computed Times of Concentration

Figures 7.3 to 7.5 present the improvements on modeling consistency with the effort in this study. For all types of soils, the Rational Method can closely reproduce CUHP's peak flows using the new runoff coefficients and modified time of concentration for catchments smaller than 90 acres.

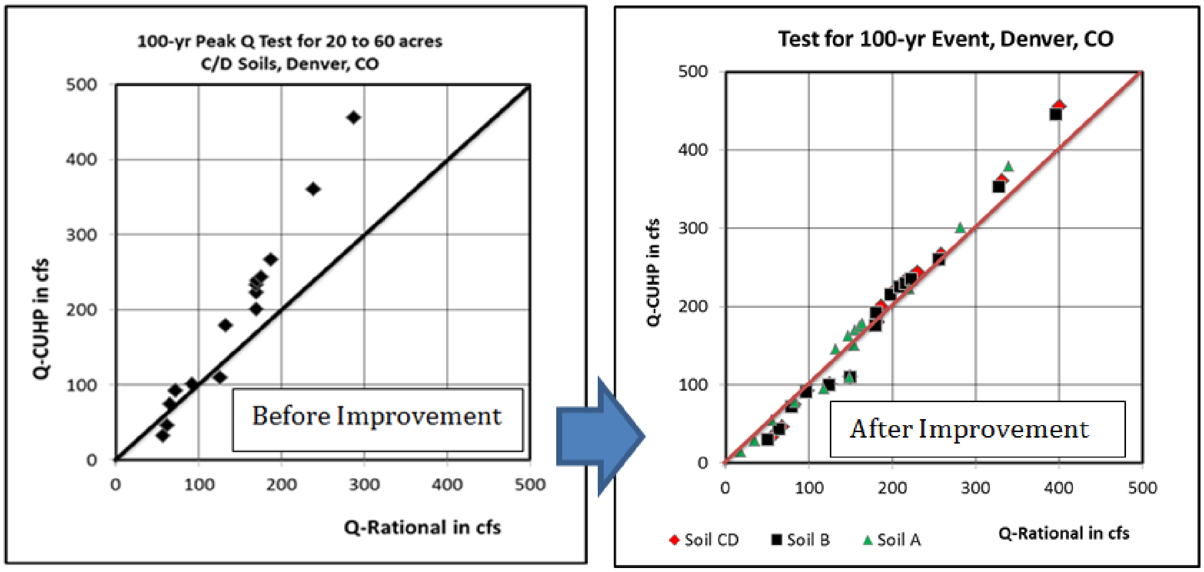
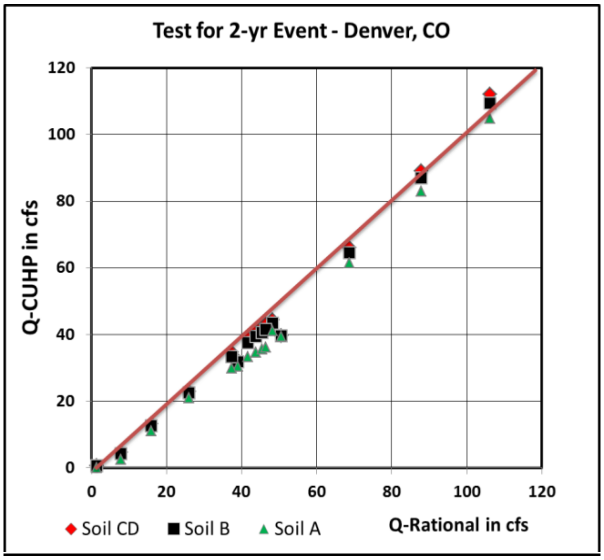


Figure 7.3 Improvements on Modeling Consistency for 100-yr Peak Flows



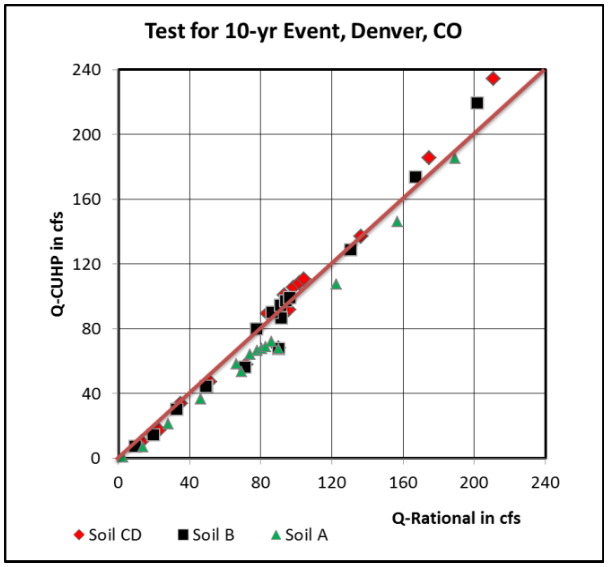


Figure 7.4 Comparison of 2-yr Peak Flows

Figure 7.5 Comparison of 10-yr Peak Flows

8. VERIFICATION OF CONSISTENCY FOR DETENTION VOLUMES

Originally, the Rational Method was developed for peak flow predictions. For convenience, the Rational Method was expanded into a detention volume method for airport drainage study (FAA 1970). The method was further modified into a volumetric method to satisfy the mass balance between rainfall and runoff volumes (Guo 1999). In this study, the new runoff coefficients were tested with the hypothetical catchments listed in Table 7.1. The detention volume for each case was maximized using the recommended procedure, and then compared with the Denver's regional detention volume equations as (USDCM 2001):

$$V_{100} = \frac{A}{900}(1.78I_a - 0.002I_a^{\ 2} - 3.56) \quad \text{for 100-yr event} \tag{24}$$

$$V_{10} = \frac{A}{1000}(0.95I_a - 1.90) \quad \text{for 10-yr event} \tag{25}$$

in which V_{100} = 100-yr detention volume in acre-ft, V_{10}=10-yr detention volume in acre-ft, A = watershed area in acres, and I_a = watershed area imperviousness in percentage.

Figure 8.1 presents the improvements to the modeling consistency with the new runoff coefficients. Referring to Figures 8.2 and 8.3, Eq (24) agrees well with the Modified FAA Procedure when using the new set of runoff coefficients. Eq (25) underestimates the 10-yr detention volume. The additional work is needed to modify Eq (25).

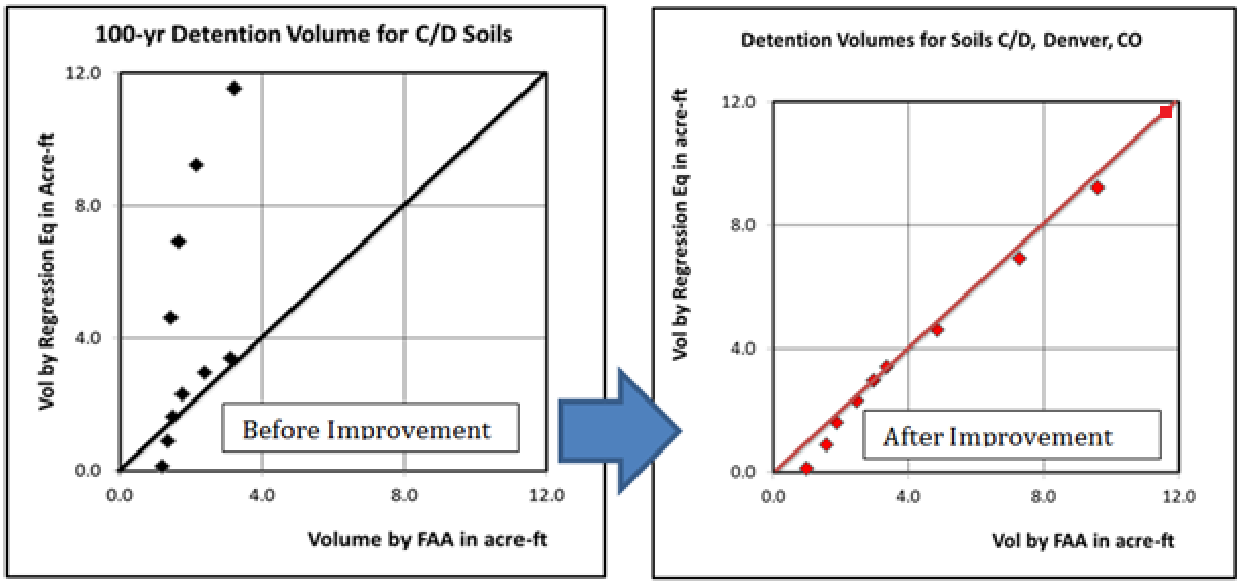
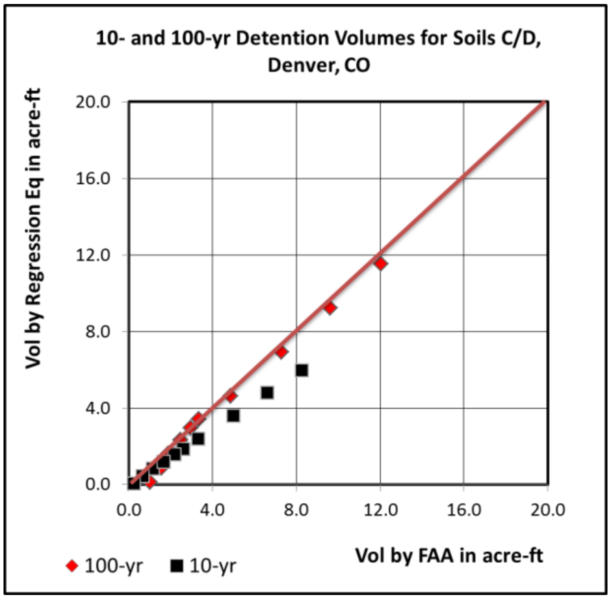


Figure 8.1 Improvements to Modified FAA Procedure



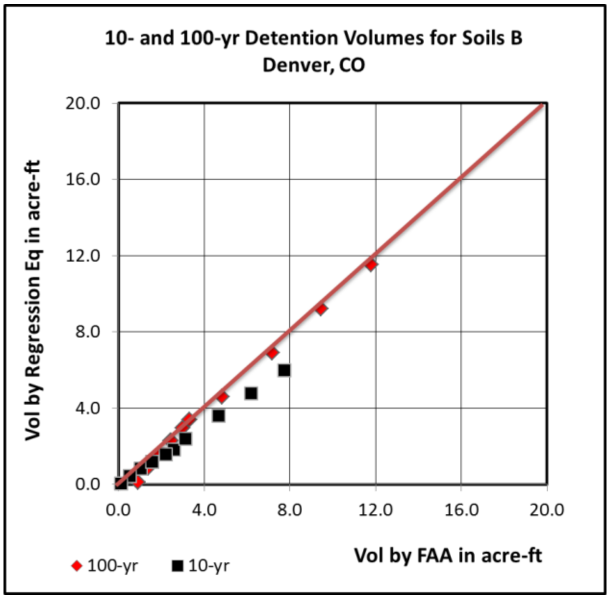


Figure 8.2 Detention Volumes for Soils C/D **Figure 8.3 Detention Volumes for Soil B**

The evaluation and validation processes presented in Sections 7 and 8 confirm that Eq (5) for new runoff coefficients and Eq's (19), (20), (22), and (23) for the modified regional time of concentration can serve as a basis of consistency between small and large watershed studies using the CUHP/Rational Method for the metro Denver area.

9. CONCLUSION

1. In this study, the runoff coefficient in the Rational Method is defined as the volume ratio between runoff hydrograph and rainfall hyetograph. A new set of runoff coefficients was derived and then evaluated with the CUHP 2005 computer model. The required time of concentration was modified to apply Denver's IDF curve to the Rational Method for peak flow and detention volume predictions.

2. As shown in Fig 5.1, 5.2, and 5.3, the new runoff coefficients were developed for Types A, B, and C/D soils using UDFCD's1-hr rainfall depths for recurrence intervals of 2-, 5-, 10-, 50-, and 100-yr events. The 1-hr soil infiltration depths were identified to be 1.80 inch for Type A soils, 1.0 inch for Type B soils, and 0.88 inch for Type C/D soils. These sets of soil losses and volume-based runoff coefficients were customized using UDFCD's 1-hr rainfall depths and then calibrated with the CUHP. Therefore, they are not

generalized for anywhere else before further verification. However, the same process can be repeated for any selected regions.

3. Regardless of soil type, for all events, the highest runoff coefficient is defined as:

$$C_{100} = \frac{(P_1 - D_{vi})}{P_1} \tag{26}$$

in which C_{100}=runoff coefficient for I_a=100%, P_1=Denver's one-precipitation depth in inches for the select event, and D_{vi}=depression loss on impervious surface recommended as 0.1 inch (USDCM 2001). Runoff coefficient decreases as watershed's impervious percent decreases.

4. All design charts in this report were produced for distributed flow systems, i.e. DCIA=0 in CUHP operations. A preliminary investigation on the Option of DCAI=1 was also conducted in this study for flow interception ratios of 0.0 (no interception), 0.5, and 1.0 (100% interception). As shown in Fig 9.1 using Type C/D soils as an example, the impact of additional infiltration benefits through the cascading flows are limited to the 2-yr event with an imperviousness <45%. No further investigations were conducted because similar studies on infiltration benefits for cascading flows have been well documented using the effective imperviousness approach in Volume 3, USDCM 2001 (Guo, Blackler, Earles, and MacKenzie in 2010).

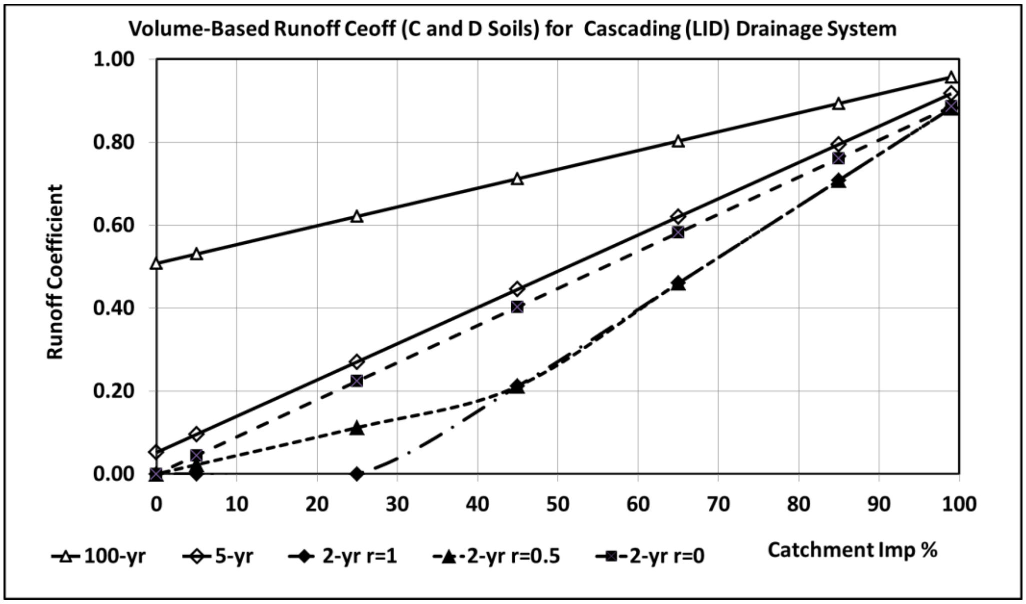


Fig 9.1 Impact of Cascading Flows with Various Flow Interceptions on C/D Soils

5. The Modified FAA Procedure and Hydrograph Methods are two generalized peak flow-based procedures for estimating storm water detention volumes. They were derived with sound and solid hydrologic principles. The current regression equation for the 10-yr event needs minor revisions to improve the modeling consistency.

6. This report presents detailed derivations, calibrations, and verifications when mixing the volume-based parameter into a flow prediction method. As always, care must be taken about the definition of time factor associated with the runoff volume and flow rate. In this study, the modified regional time of concentration is critically important to line up the CUHP and Rational Method when both runoff volume and flow rate were taken into consideration. In closing, for UDFCD's USDCM update, Eq (5) is recommended for calculating the volume-based runoff coefficients. Eq's (19), (20), (22), and (23) are recommended for determining the time of concentration.

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