CONSISTENCY BETWEEN CUHP AND RATIONAL METHODS

James C.Y. Guo, PhD, P.E., and Ben Urbonas, P.E., D.WRD
08/04/2008

When estimating runoff for a storm event it is assumed that the storm runoff occurs from the entire tributary area. The surface retention volume in the tributary area plays an important role when making such estimates. For a small urban watershed, the surface retention volume is considered negligible and the peak runoff rate is considered to vary linearly with the size of the tributary area. This fact is well portrayed in the Rational method. On the other hand, the rainfall-runoff process in larger watersheds is more complicated and the significance of depression and surface storage volumes is fully considered. As a result, more descriptive computational techniques are used to estimate stormwater runoff from larger watersheds, such as the unit-graph method recommended by the Urban Drainage and Flood Control District. In addition, when conducting a master drainage study, the watershed is divided into small and large sub-watersheds. As a result, it is very important that both the Rational and the unit-graph methods be calibrated for the region to have a consistent basis for flood flow predictions for the ranges in watershed areas where the used of these two methods overlap.

The 2005 Colorado Unit Hydrograph Procedure (CUHP2005) is an urban stormwater runoff prediction method derived and calibrated using data from the metropolitan Denver region and Colorado high plains. This report presents a study that modifies the calculation procedures for both CUHP2005 and Rational methods to improve consistency among the peak runoff flow predictions from small tributary areas (smaller than approximately 100 acres). A set of hypothetic square watersheds were tested for several empirical functions derived to calculate the time parameters used in CUHP2005 and Rational methods. The test tributary areas ranged from 10 to 1000 acres. The major effort was to focus on the flow-area relationship smaller than 160 acres.

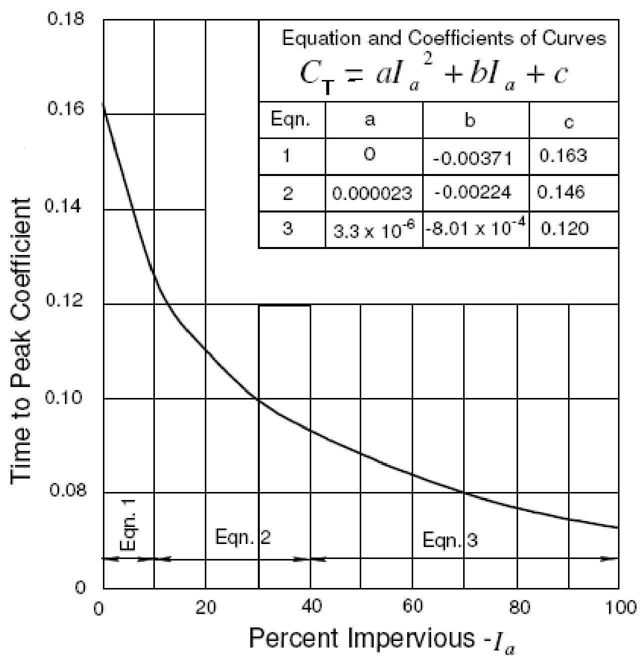
It is proposed that the peaking coefficient (C_p) and time to peak coefficient (C_t) used in CUHP2005 be modified to provide a smooth transition for tributary areas from 10 to 160 acres. Secondly, the calculation protocol for the time of concentration (T_c) used in the Rational method be also modified to recognize the slow overland sheet flows that occur in watersheds with little or no urbanization and the much more rapid sheet flows that occur in highly paved areas. With the proposed revisions, all test watersheds were found to produce a smooth relationship between peak flows and for the test range of tributary areas. Of course, it is recommended that this procedure be further verified using observed rainfall-runoff data and randomly shaped watersheds as well.

REVISIONS TO CUHP2005

CUHP2005 is a synthetic unit-graph method that is sensitive to unit-graph peaking coefficient, peaking parameter, time to peak coefficient, and catchment area. As recommended in 2001 USDCM, the time to peak for the unit-graph is calculated as:

$$t_p = C_T \left(\frac{LL_{cs}}{\sqrt{S}} \right)^{0.48} \tag{1}$$

in which, t_{op} = time to peak of the unit hydrograph from midpoint of unit rainfall in hours, L = length along the drainage way path from study point to the most upstream limits of the catchment in miles, L_{ace} = length along the flow path from study point to a point along it adjacent to the centroid of the catchment in miles, S = length weighted average slope of catchment along the flow path to upstream limits of the catchment in feet per foot, and C_T = coefficient reflecting time to peak as depicted in Figure 1.



<u>Figure 1 Variation of C_T as Function of Imperviousness</u>

As shown in Figure 1, the more development in the catchment, the faster the runoff. In addition to the watershed imperviousness, the time to peak is also inversely varied with respect to the tributary area. In fact, the empirical formula in Figure 1 was calibrated for watersheds greater than 90 acres (USDCM, 2001) and shall be considered as the limiting value that is suitable for large watersheds. For smaller watersheds, it is suggested that the time to peak coefficient be revised as follows:

$C_t = C_T(0.65A^{-0.31})$ applicable to areas up to cutoff size (2)

$C_t = C_T$ applicable to area>cutoff in size (3)

in which, A = tributary area in square mile, C_T = limiting time to peak coefficient in Figure 1 as published in 2001 USDCM. As illustrated in Figure 2, the variable, C_t, decreases with respect to tributary area and then converges to its limiting value of C_T at the cutoff size.

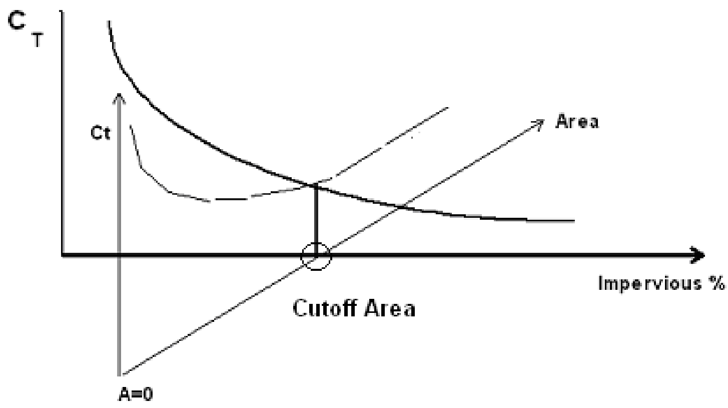


Figure 2 Variation of Time to Peak Coefficient for Specified Imperviousness

Table 1 summarizes the results from the investigation of the cutoff sizes for watershed imperviousness ratios of 5, 40, and 80%. For these three cases, the cutoff size is found to be 160 acres. It implies that the empirical equation for C_T in Figure 1 was applicable to watersheds greater than 160 acres. For tributary areas less than 160 acres, the time of peak coefficient must be decayed as a function of watershed area.

Table 1. Convergence of C_t and C_T functions

Area	Imp =	5%	Imp =	40%	Imp =	80%
acre	C_t	C_t-C_T	C_t	C_t-C_T	C_t	C_t-C_T
10.000	0.342	0.197	0.221	0.127	0.182	0.105
20.000	0.276	0.131	0.178	0.085	0.147	0.070
30.000	0.243	0.099	0.157	0.064	0.130	0.053
40.000	0.222	0.078	0.143	0.050	0.119	0.042
50.000	0.207	0.063	0.134	0.041	0.111	0.034
60.000	0.196	0.052	0.127	0.033	0.105	0.028
70.000	0.187	0.042	0.121	0.027	0.100	0.023
80.000	0.179	0.035	0.116	0.023	0.096	0.019
90.000	0.173	0.028	0.112	0.018	0.092	0.015
100.000	0.167	0.023	0.108	0.015	0.089	0.012
110.000	0.162	0.018	0.105	0.012	0.087	0.010
120.000	0.158	0.014	0.102	0.009	0.084	0.007
130.000	0.154	0.010	0.100	0.006	0.082	0.005
140.000	0.151	0.006	0.097	0.004	0.080	0.003
150.000	0.148	0.003	0.095	0.002	0.079	0.002
160.000	0.145	**0.000**	0.093	**0.000**	0.077	**0.000**

In this study, an investigation on the unit-graph peaking coefficient, C_p, was also conducted. Among various empirical formulas recommended in 2001 USDCM, the following equation was selected for testing:

$$C_p = PC_T A^{0.15}$$ applicable to tributary area of any size. (4)

in which, C_p = unit hydrograph peaking coefficient and P = peaking parameter. The equation for variable, P, is published in 2001 USDCM as:

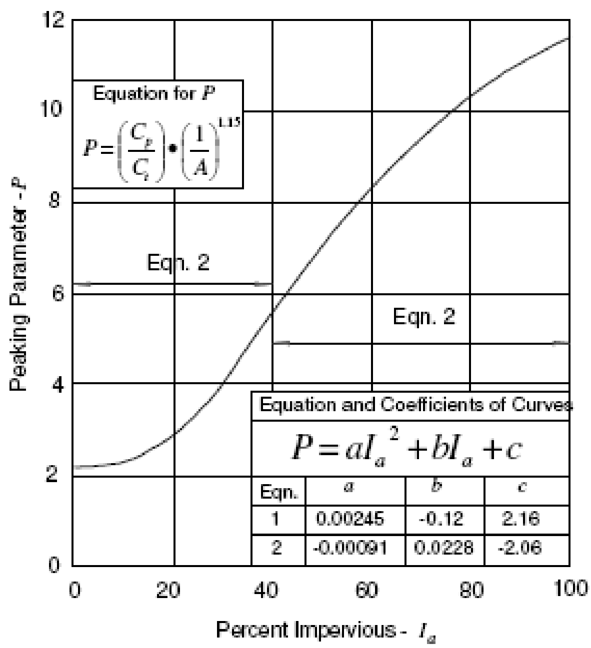


Figure 3 Unit-graph Peak Coefficient Varied with Imperviousness

Revisions to Rational Method

The Rational method is simple for use, but difficult to fully understand. For small watersheds the most sensitive parameter in the Rational method is the time of concentration, T_c, of the watershed. The time of concentration is composed of overland flow and channel flow times as:

$$T_c = T_o + T_f$$ (5)

In which T_o = overland flow time, and T_f = channel flow time. The empirical formulas recommended for T_f *and* T_o are:

$$T_o = \frac{0.395(1.1 - C)L_o^{0.5}}{S_o^{0.33}} \quad (6)$$

$$T_f = \frac{L_f}{60K\sqrt{S_f}} \quad (7)$$

In which, T_o = overland flow time in minutes, L_o = overland flow length in feet, S_o = overland flow slope in ft/ft, L_f = channel flow length in feet, K = conveyance coefficient, S_f = channel slope in ft/ft, and C = design event's runoff coefficient (i.e., not the runoff coefficient for the 5-yr event, C_5), in 2001 USDCM.

For smaller watersheds, the time of concentration is typically dominated by the overland flow time. The length of sheet flow depends on the watershed development, namely it's imperviousness. The common practice of a constant 300 feet as the maximal overland flow length was fount to be not appropriate when addressing the overland flow characteristics of urbanized watersheds. In this study, the maximal allowable overland flow length was set to vary with the watershed imperviousness and watersheds with imperviousness less than and equal to 20% were considered to be rural in drainage nature. Therefore, Denver's regional formula for maximum T_c was found to be only applicable to watersheds with imperviousness less than 20% as expressed by the following relationships:

$$T_c = Min(T_o + T_f, T_R) \quad (8)$$

$$T_R = \frac{L_o + L_f}{180} + 10 \qquad \text{Applicable to Imp>20\%} \quad (9)$$

In which T_R = regional time of concentration in minutes.

Table 2 Calculation Protocols for Time of Concentration

Imperviousness	Max Overland Flow	Channel Flow	Check with Regional T_R
Percentage	Length in feet	Conveyance K	
5	500	0.7	No
20	350	1.5	No
40	150	2	Yes
60	50	2	Yes
80	25	2	Yes

TEST ON CONSISTENCY BETWEEN CUHP2005 AND RATIONAL METHODS

In this study, the test cases were selected to cover a wide range of engineering practice. All test watersheds are hypothetical, symmetric squares with a diagonal waterway. The tributary area varies from 10 through 1000 acres. Numerous computer runs were made using watershed area imperviousness ratios that varied from 5 to 80% and waterway slopes from 0.5 to 2.0%. For all test cases, Equations 1 and 2 provide a smooth transition from 10 to 160 acres. As shown in Figures 4 through 8, reasonable agreement can be achieved between the revised CUHP2005 and the Rational method up to areas less than 90 acres.

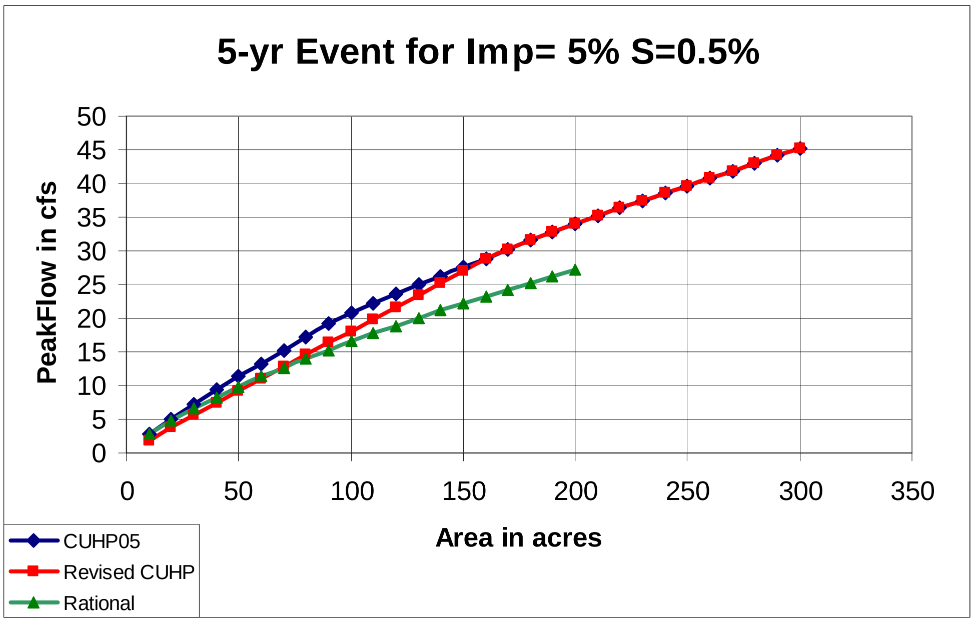


Figure 4 Comparison of Predicted 5-yr Peak Flows for Imp=5% and S=0.5%

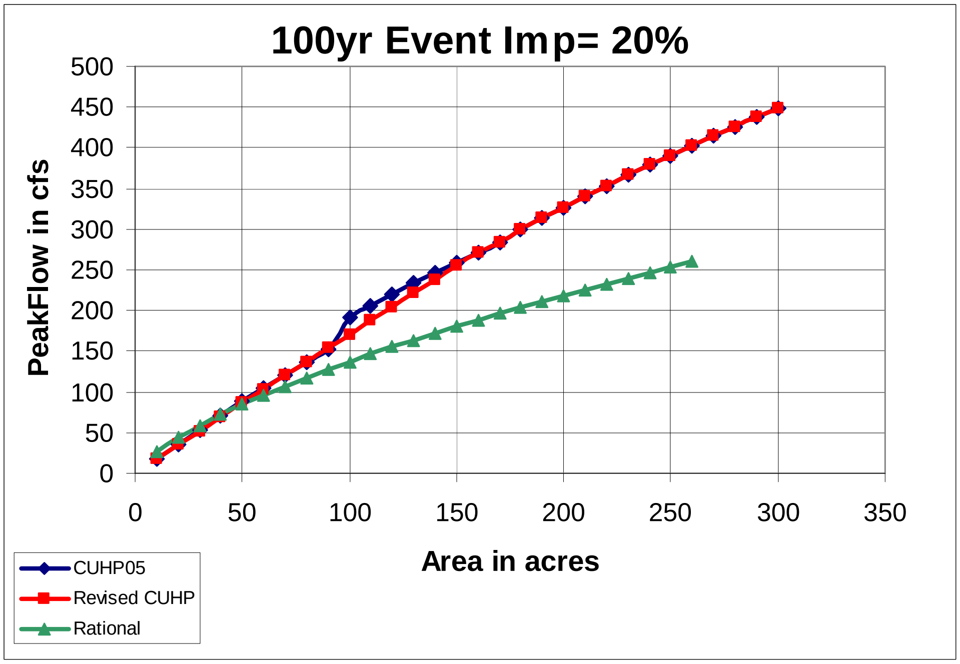


Figure 5 Comparison of Predicted 100-yr Peak Flows for Imp=20% and S=2%

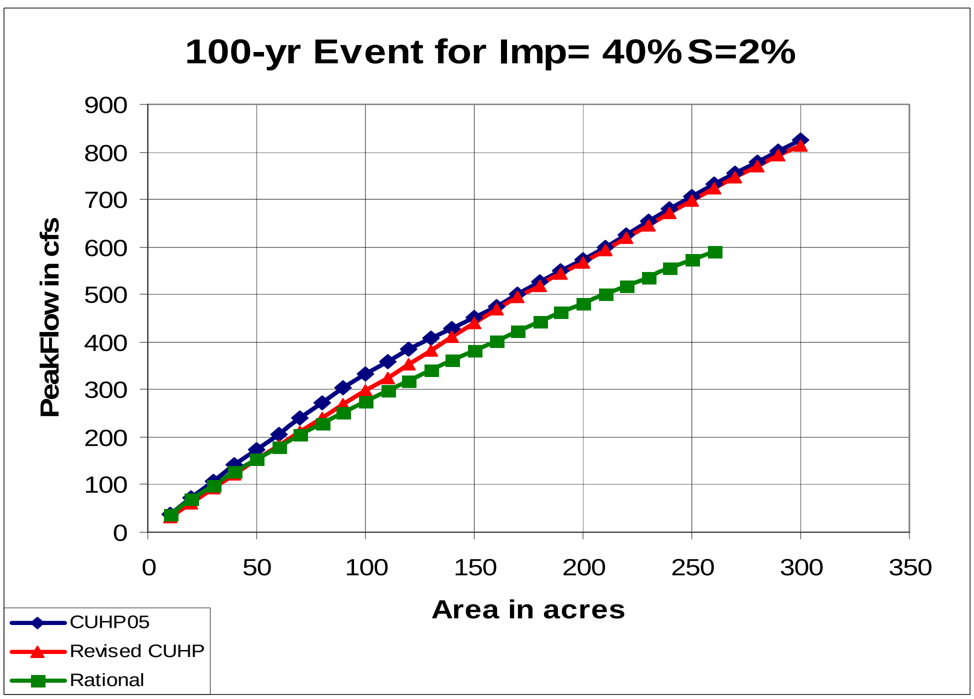


Figure 6 Comparison of Predicted 100-yr Peak Flows for Imp=40% and S=2%

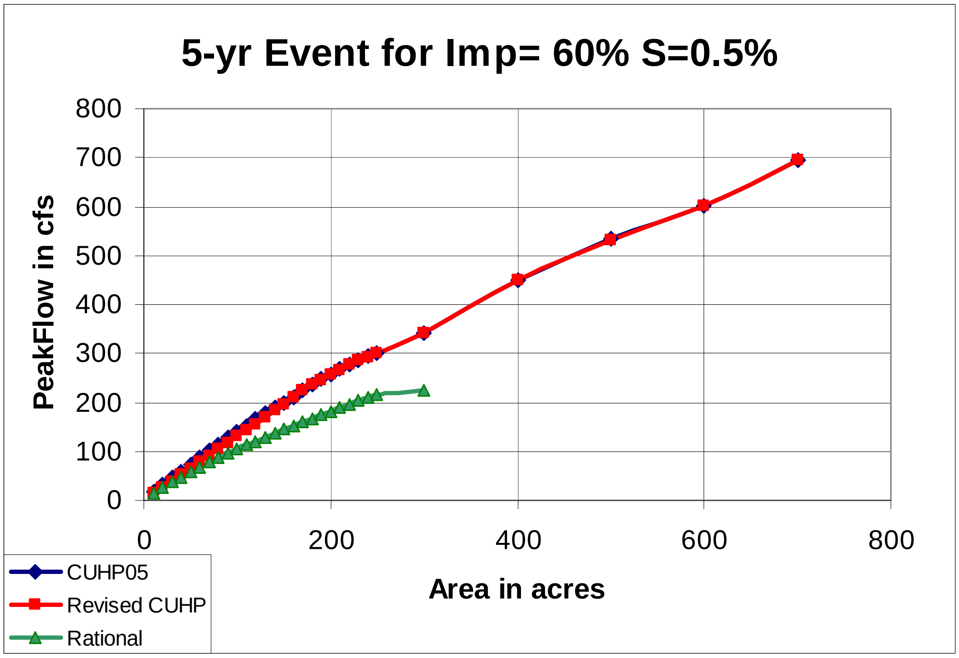


Figure 7 Comparison of Predicted 5-yr Peak Flows for Imp=60% and S=0.5%

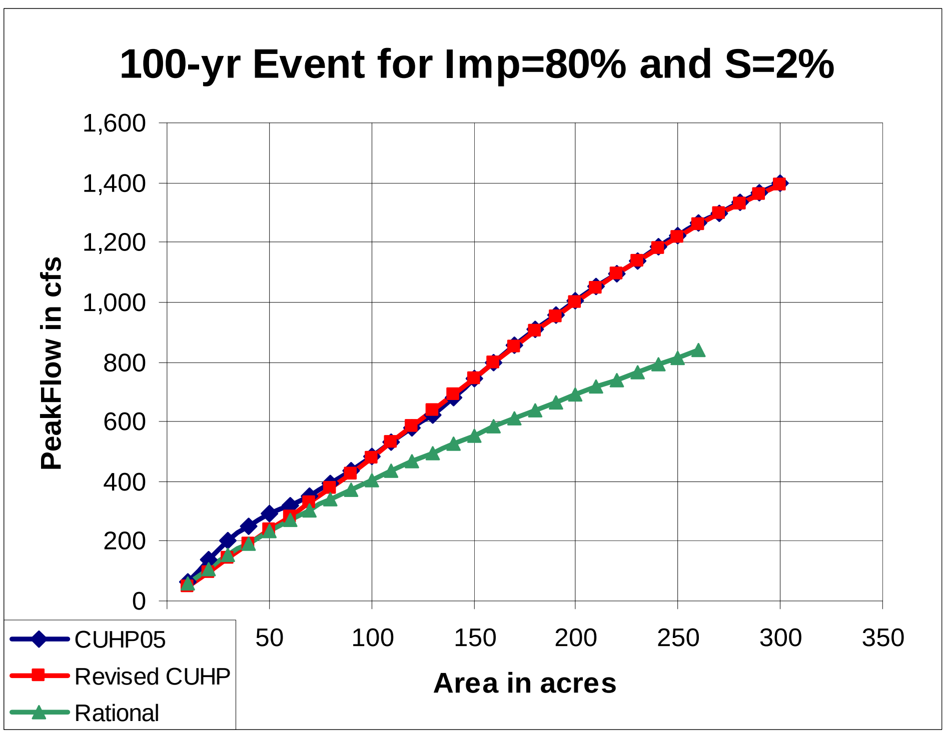


Figure 8 Comparison of Predicted 100-yr Peak Flows for Imp=80% and S=2%

In this study, it was observed that the regional formula, namely Equation 9 for T_R, dominates the time of concentration for a watershed with a slope of 0.5%. On the other hand for a watershed with a slope of 2%, the calculated T_c in Equation 5 is dominated by the recommended overland flow lengths shown in Table 2 (i.e, the tested range).

TEST ON LEVEL OF WATERSHED MODELING DETAILS

A large watershed is often divided into smaller sub-areas for numerical simulations and as a practical matter in master planning and other hydrology studies. It has been observed that the level of watershed discretization can cause an artificial increase in the peak runoff predicted at the outfall point. Often the smaller the subareas, the higher the cumulative peak runoff is at the downstream limits. In this study, the revised procedure to CUHP2005 was further tested for the level of watershed modeling discretization. The test square watershed has a total area of 300 acres on a slope of 2.0% and imperviousness of 40%. Four cases were developed for testing. They are:

Case 1. The watershed is divided into six sub areas of 50 acres (**six small basins**)
Case 2. The watershed is divided into three sub areas of 100 acres (**a small + a large basin**)
Case 3. The watershed is divided into twp subareas: 200- and 100-acre (**mixed sizes**)
Case 4. The watershed is modeled as a 300-acre single tributary area (**a large basin**)

All sub-areas are modeled as a square with a diagonal waterway on a 2.0% slope. Between sub-areas, the channel was defaulted to be a 5-ft trapezoidal channel of 500-ft in length. The predicted peak outflows at the outfall point for this 300-acre watershed are tabulated in Table 3.

Table 3 Tests on Level of Watershed Discretization

Cases	CUHP2005-now Q in cfs	CUHP2005-revised Q in cfs	Comments
Six Areas of 50 acres	947	761	six small basins
Three Areas of 100 acres	885	763	a small + a large basin
Two Areas of 200 and 100 acres	833	793	mixed sizes
Single Area of 300 acres	718	718	a large basin

As shown in Table 3, the revised CUHP2005 procedure can significantly improve the consistency among various levels of watershed modeling discretization. The difference among all cases is within 10% when using the revised CUHP2005.

CONCLUSION

Watersheds are classified into small and large watersheds. Using the basis of watershed's response to rainfall, the demarcation between small and large urban watersheds is specified in the USDCM as 160 acres. However, based on the testing during this investigation a more appropriate demarcation between small and large watersheds was found to be approximately 90 acres.

The existing gap between the CUHP2005 for large watersheds and the Rational method for small watersheds has created serious inconsistency in many master drainage and engineering studies. This study presents sufficient numerical tests on the new equations that are proposed to revise the time parameters used in the CUHP2005 protocol to limit such discrepancies. Similarly, it is also proposed that the procedure for calculating the overland flow time in the Rational method be modified to reflect the watershed development condition. Based on the tests and analyses, it is recommended that

(1) Equations 2, 3, and 4 be adopted to revise the computer model: CUHP2005,
(2) the demarcation between large and smaller watersheds be set at 160 acres when calculating C_t and C_T in the revised CUHP2005,
(3) the peaking parameter be calculated using Equation 5 for all watersheds,
(4) Table 2 be adopted to revise the Rational method outlined in 2001 USDCM
(5) the revised Rational method be used for watersheds smaller than 90 acres

In addition, it was discovered that the USDCM and the CUHP User Manual has typographical errors in the figure represented in this report as Figure 3. The exponent for the peaking factor P shown on that figure needs to be chanced to be 0.15 and not 1.15. In addition, the coefficient b for Equation 1 in that figure should be changed from -0.12 to -0.012 as are reflected in the equations incorporated in the CUHP2005 model.

CUHP2005 had been calibrated before. With the proposed revisions, the new version of CUHP2005 must be further tested using real watersheds of various sizes, especially below 160 acres in size. It is necessary to verify the new CUHP2005 results by comparing with available stream gage data and/or previous master planning studies to test its efficacy and impact on hydrology calculations.