Technical Memorandum:

ESTIMATION OF TIME OF CONCENTRATION FOR THREE FIRST FLUSH HIGHWAY RUNOFF CHARACTERIZATION SITES

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SUMMARY

Values of time of concentration (T_c) for three highway sites were estimated using different formulas and the best design T_c was determined. Several T_c formulas available for impervious watersheds were classified into two groups based on whether rainfall intensity is a variable in the formula or not (Groups 1 and 2). Formulas in Group 1 are modified ASCE, Kirpich, FAA, and SCS lag equation, returning a unique T_c value for each site. Group 1 formulas were evaluated based on the calculated peak flow rates, and the best T_c estimation formula was determined for each monitoring site. Five years' rainfall data were used to prepare the partial duration series for the frequency analysis and 2-year, 24-hour rainfall depths (P_2) were obtained as a design rainfall depth. A site survey was also conducted to obtain the longest flow length (L) and bed slope (S), which are essential for the T_c calculation. The SCS lag formula was the best for the monitoring sites, avoiding overestimation of design peak flow. Formulas in Group 2 are ASCE and Izzard formulas, which include rainfall intensity as a variable in the formulas, as well as measured lag time (distance between the centroids of hyetograph and hydrograph). Event-specific T_cs were calculated by each formula in Group 2 using measured rainfall intensity, and the correlation analysis for T_c and mass first flush (MFF) ratio were performed. Few relationships were observed between T_c and MFF. However, when comparing the average MFF ratios and site-specific T_c values from the three sites with different watershed areas, smaller watersheds tended to have a smaller T_c and a higher MFF.

1. Introduction

A stormwater best management practice (BMP) is composed of several components: collection, conveyance, treatment, and disposal of runoff. Design of these facilities requires hydrological and hydraulic information. Drainage systems such as drain-inlets, pipes, and channels are designed to carry the maximum flow rate. The capacity of storage systems such as detention basins or constructed wetlands can be determined based on the runoff volume. On the other hand, flow-through devices such as filters need flow rate for design.

An important parameter to estimate hydrological and hydraulic condition is the time of concentration (T_c), which is used to determine peak flow rate, as well as flow patterns under given rainfall characteristics. T_c is a site-specific parameter that depends on the rainfall and watershed characteristics, and accordingly numerous T_c formulas have been developed. Individual formulas have different domains of watersheds with different landuses or geometries that the formulas were developed from. Therefore, it is important to choose an appropriate Tc formula for design application because T_c can be underestimated or overestimated if an inappropriate formula is used (McCuen and Spiess, 1995; Cristina and Sansalone, 2003a).

Several different formulas are available to estimate T_c for highway landuses. T_c for the sheet flow regime in a watershed is typically determined using equations of kinematic wave form such as the ASCE formula and the SCS formula. Formulas from Izzard, Federal Aviation Administration (FAA), and Soil Conservation Service (SCS) are also applicable for watersheds with highly impervious landuses.

In this study, T_c is calculated using different formulas that are considered applicable for the highway runoff monitoring sites (Sites 1, 2, and 3) which are small impervious landuses having relatively steep bed slopes. Using the T_c values, peak flow rates are calculated and compared with real peak flow rates measured in the monitoring periods to evaluate and select the best design value of T_c for each monitoring site. In addition, event-specific values of T_c are calculated using measured rainfall intensity, and then compared with mass first flush ratios for TSS and conductivity for each storm event in order to determine the relationships between water quantity and water quality in the highway runoff.

2. Background

T_c is defined as the time required for a drop of water to travel from the most hydrologically remote point in the catch basin to the point of collection. With uniform rainfall equally contributed over a catch basin, outflow becomes equal to net input water after T_c, reaching equilibrium (Viessman and Lewis, 2003). In a multi-flow segment catch basin, a representative T_c is the summation of the travel time for each flow regime.

Numerous formulas to estimate T_c have been developed for different landuses and geometries as summarized in Table 1. T_c is generally associated with weather and geological parameters such as rainfall intensity, slope, and flow length.

Practically, T_c can be used to calculate a hypothetical peak discharge to determine sizes of flood control systems such as drain pipes or inlets. The rational formula is the simplest method for peak flow calculation. Assuming a uniform rainfall, peak discharge is calculated as follows:

$$q_p = CiA \tag{1}$$

where q_p = peak discharge (L^3/T), C = runoff coefficient, i = design rainfall intensity (L/T), A = catchment area (L^2). T_c is considered a design rainfall duration to obtain i in equation (1), which

Table 1. Formulas for Time of Concentration (T_c)

Method	Formula for tc (min)	Remarks
Kirpich (1940)	$T_c = 0.0078L^{0.77}S^{-0.385}$	Steep slope: 3-10% Reduction factor applied for impervious area (0.4 for overland flow on concrete or asphalt surface)
Izzard (1946)	$T_c = \dfrac{41.025(0.0007i + c)L^{0.33}}{S^{0.333}i^{0.667}}$	Roadway and turf surfaces i×L <500
FAA (1970)	$T_c = 1.8(1.1 - C)L^{0.50} / S^{0.333}$	Overland flow in urban basins
ASCE (1973)	$T_c = \dfrac{0.94L^{0.6}n^{0.6}}{i^{0.4}S^{0.3}}$	From kinematic wave analysis (L<300ft)
SCS lag (1972)	$T_c = \dfrac{1.67L^{0.8}[(1000/CN) - 9]^{0.7}}{1900S^{0.5}}$	Small urban basins <2000acres
SCS avg. vel. charts (1975)	$T_c = \dfrac{1}{60}\sum\dfrac{L}{V}$	

is the rainfall intensity corresponding to a design return period and duration in the intensity-duration-frequency curve (I-D-F curve), which is developed using historical rainfall data. The IDF curve for Southern California is available in Bulletin No. 195 published by Caltrans, DWR, and FHWA in 1976. If iso-hyetal maps are available instead of I-D-F curves, SCS's graphical peak discharge method can be used for the peak flow calculation as follows:

$$q_p = q_u A_m Q F_p \tag{2}$$

where q_p = peak discharge (cfs), q_u = unit peak discharge (cfs/mi^2/in), A_m = drainage area (mi^2), Q = runoff (in), F_p = pond and swamp adjustment factor.

T_c can also be used to predict flow changes for the design of drain inlets and pipes, and for the capacity of treatment systems. The detail methods for these calculations are described in TR-55 and other publications (USDA, 1985; USDA, 1986).

Although flood control has been the main concern for hydraulic structure design, water quality control has recently become an important issue in the stormwater runoff from highways, which are known to generate significant amount of pollutants such as heavy metals, oil and grease, and poly aromatic hydrocarbons (PAHs) (Roger et al., 1998; Furumai et al., 2002).

A representative characteristic of pollutant emission from impervious landuses is the first flush (FF) phenomenon, suggesting the emission of a greater fraction of pollutant mass or concentration in the early part of the runoff volume (Ma et al., 2002; Sansalone and Cristina, 2004). This phenomenon enables compact best management practice (BMP) design with high removal efficiency by treating only the earlier part of runoff. The first flush phenomenon is believed to be strongly related to hydrodynamic conditions as well as to the geometry of the catchment. Numerous efforts have been made to relate pollutant washoff behaviors with rainfall intensity, flow rate, watershed area, or bottom slope, using statistical analyses of empirical observations (Gupta and Saul., 1996; Deletic and Maksimovic, 1998; Cristina and Sansalone, 2003b). However, no clear relationship has been found. In addition, the performance of a BMP depends on hydrologic and hydraulic conditions (Jacopin et al., 2001; Persson and Wittgren, 2003), which make it important to consider both water quantity and quality aspects in a BMP design.

3. Methodology

As described in the previous section, a formula is basically used to calculate a unique value of T_c (for design application), which is site-specific and determines the maximum capacity of hydraulic structures. To calculate T_c for design application, design rainfall intensity or design rainfall depths is required. However, event-specific T_c values can also be obtained using event rainfall intensity instead of design rainfall intensity. The event-specific T_c values depend on the hydrodynamic conditions of each storm event and therefore can be used for the correlation analysis with other event-specific parameters such as MFF ratios.

In this study, T_c formulas were classified into two groups as shown in Table 2: one for design T_c (Group 1) and the other for event-specific T_c (Group 2). Formulas in Group 1 are modified ASCE, Kirpich, FAA, and SCS lag formulas and calculate T_cs for design applications. These formulas do not require individual storm characteristics such as measured rainfall and runoff. Single value of T_c for each site is calculated from each formula and used to calculate design peak flow rate of the runoff. Group 2 includes ASCE and Izzard formulas and measured lag time. ASCE and Izzard formulas commonly include rainfall intensity as a variable: as a result, the iterative process is required to obtain T_c for design application. In this study, these formulas were only used to calculate event-specific values of T_c using monitored average rainfall intensity for individual storm events. The calculated T_c values and measured lag time were compared with mass first flush (MFF) ratios for TSS and conductivity (e.g. MFF_{10}, MFF_{20}) for the monitored storm events to investigate relationships between water quality and hydrological condition. TSS and conductivity were selected as representative pollutants in particulate and dissolved forms.

Table 2. T_c Formulas in Two Groups

Formulas		Purposes
Group 1	Modified ASCE, Kirpich, FAA, SCS lag	• Site-specific T_c based on frequency analyses of rainfall patterns • Determining sizes of hydraulic structures • Hydrological estimation
Group 2	ASCE, Izzard, ***measured lag time***	• Event-specific T_c based on individual storm data • Investigating relationships between water quality and quantity

3.1 ASCE's T_c Formula

Based on the ASCE's kinematic wave analysis, the U.S. Federal Highway Administration suggests the following formula to calculate T_c for the sheet flow:

$$T_c = \frac{0.933 L^{0.6} n^{0.6}}{i^{0.4} S^{0.3}} \tag{1}$$

where L = overland flow length (ft); n = Manning's roughness coefficient (sec/ft$^{1/3}$); i = the rainfall intensity (in/hr); and S = the bed slope (ft/ft). In order to calculate T_c in equation (1), the trial and error method is used by adjusting rainfall intensity until the calculated T_c matches the storm duration corresponding to the applied rainfall intensity for the selected recurrence interval in the I-D-F curve. To avoid the iterative calculation process, the Soil Conservation Service (SCS) uses the modified ASCE equation as follows:

$$T_c = \frac{0.007 L^{0.8} n^{0.8}}{P_2^{0.5} S^{0.4}} \tag{2}$$

where P_2 = 2-year, 24-hour rainfall depth (in). To apply equation (2) in this study, design rainfall depths for three sites were obtained by frequency analysis using five years' monitoring rainfall data.

3.2 Site Description and Monitored Storm Events

To acquire site conditions and dimensions, the most recent construction drawings were collected for the three first flush highway runoff characterization study sites. A site survey was also conducted to verify the site slope, dimensions, and area for each site. Pertinent site dimensions and related information is summarized in Table 3.

Table 3. Summary of Site Dimensions

Parameter	Site 1	Site 2	Site 3
Area, A (m^2)	12,800	16,900	3,900
Longest flow length, L (m)	304.8	370.9	178.9
Average slope, S (%)	0.17	2.70	2.50

A stormwater monitoring program has been performed for six years from 1999 to 2005 and Table 4 summarizes the storm events used for the T_c calculation and correlation study. For the frequency analysis, the hydrologic data gathered during the 1999-05 rainy seasons were used.

Table 4. Storm Event Summary (1999-2005 wet seasons)

Event Date (m/d/y)	First flush highway runoff characterization monitoring sites											
	Site 1 (7-201)				Site 2 (7-202)				Site 3 (7-203)			
	Event Rainfall (cm)	Storm Duration (hr)	Total Flow (m^3)	Avg. Rainfall Intensity (mm/hr)	Event Rainfall (cm)	Storm Duration (hr)	Total Flow (m^3)	Avg. Rainfall Intensity (mm/hr)	Event Rainfall (cm)	Storm Duration (hr)	Total Flow (m^3)	Avg. Rainfall Intensity (mm/hr)
11/08/1999									0.13	2.5	5.0	0.51
11/20/1999					0.18	0.5	5.0	3.56				
12/31/1999									0.05	3.0	2.0	0.17
01/17/2000	0.13	9.6	6.4	0.13	0.18	10.2	9.7	0.17	0.15	10.2	5.9	0.15
01/25/2000	1.70	19.4		0.88	2.51	19.4	422.7	1.30	1.83	17.9	71.3	1.02
01/30/2000	0.25	11.8	8.2	0.22	1.27	2.1	205.8	6.05	1.35	14.1	52.5	0.95
02/10/2000	0.74	12.9	91.1	0.57	1.17	19	181.6	0.61	1.50	7.3	58.4	2.05
02/11/2000	1.85	2.8		6.62	2.51	4.6	313.6	5.47	2.11	4.7	82.2	4.49
02/20/2000	9.07	39.6	1092.0	2.29	9.25	38.2	1258.3	2.42	5.89	52.2	229.8	1.13
02/27/2000	0.33	5.4	20.3	0.61	0.74	5.1	71.6	1.44	1.02	4.5	39.6	2.26
03/05/2000	4.57	36.3	283.2	1.26	5.08	36.3	340.7	1.40	0.58	2.5	22.8	2.34
03/08/2000	1.78	10.8	186.6	1.65	2.34	10.6	254.9	2.20	1.88	8.8	73.3	2.14
04/17/2000	1.32	2.0		6.60	4.45	8.6	302.8	5.17	5.64	16.1	219.9	3.50
10/26/2000	2.39	11.0	260.7	2.17	2.39	11	200.8	2.17	2.59	11.8	101.0	2.20
01/08/2001	0.38	3.6	43.7	1.06	0.51	4.3	52.2	1.18	0.53	4.4	20.8	1.21
01/10/2001	12.70	16.3	1327.4	7.79	15.60	17.1	1416.2	9.12	12.85	14.6	501.2	8.80
02/10/2001	1.32	7.2	155.2	1.83					1.55	5.5	60.4	2.82
02/19/2001	0.71	4.1	80.9	1.73	2.39	8.9	261.6	2.68	3.02	6.9	117.9	4.38
02/24/2001	1.45	19.1	165.6	0.76	1.91	19.2	241.6	0.99	1.14	14.2	44.6	0.80
03/04/2001	1.19	10.2	139.1	1.17	0.89	4.6	140.2	1.93	0.51	3.7	19.8	1.37
04/06/2001									2.54	10.8	99.1	2.35
04/20/2001	0.81	5.2	79.0	1.56	3.02	9.3	501.9	3.25				
10/30/2001					0.33	1.6	47.5	2.06	0.28	1.6	10.9	1.75
11/12/2001	0.79	3.9	83.9	2.02	1.19	1.7	172.3	7.02	0.74	1.4	28.7	5.26
11/24/2001	4.72	4.4	539.4	10.74	5.03	4.5	737.8	11.18	2.97	4.6	115.9	6.46
12/14/2001					0.36	4.0	52.0	0.89				
12/20/2001	1.07	10.1	118.0	1.06					1.22	4.3	47.5	2.84
01/27/2002	1.19	10.1	127.4	1.18	3.18	8.6	445.6	3.69	2.46	8.6	96.1	2.86
02/17/2002	0.20	2.0	16.9	1.02	0.74	4.1	88.0	1.80	0.74	2.9	28.7	2.54
03/06/2002					0.25	4.1	25.7	0.62	0.46	10.0	17.8	0.46
03/17/2002					0.23	0.9	23.5	2.54	1.04	1.4	40.6	7.44
11/07/2002	2.90	47.5	210.3	0.61	5.87	46.5	791.8	1.26	7.14	47.1	278.4	1.52
11/29/2002	0.97	2.1	72.6	4.60	0.18	7.7	17.8	0.23	0.15	6.9	5.9	0.22
12/15/2002					0.25	3.3	30.3	0.77				
12/16/2002	2.97	6.0	348.3	4.95	5.99	6.0	825.7	9.99	4.06	4.6	158.5	8.83
12/19/2002	3.61	7.2	436.4	5.01					3.25	10.4	126.8	3.13
02/11/2003	2.34	10.5	235.3	2.23	2.44	11.9	339.2	2.05	2.01	15.6	78.3	1.29
03/15/2003	6.65	18.4	481.1	3.62					12.32	21.7	480.4	5.68
04/12/2003									1.98	15.6	77.3	1.27
04/14/2003					2.13	16.0	311.3	1.33				
05/02/2003	5.03	15.0	324.0	3.35								
10/31/2003	0.76	12.8	17.0	0.60	1.37	7.3	179.8	1.88	2.06	7.1	80.2	2.90
11/12/2003									0.61	3.8	23.8	1.60
11/15/2003					0.20	3.4	29.5	0.60				
10/16/2004	1.19	9.51	19.9	1.26	2.18	14.3	254.3	1.53				
10/26/2004	6.15	21.1	704.2	2.91	4.83	21.05	711.0	2.29	4.42	10.0	172.4	4.42
12/05/2004	1.42	16.9	53.2	0.84	1.70	16.8	250.6	1.01	1.47	15.8	57.5	0.93
01/07/2005	15.60	80.6	1847.6	1.93	28.70	80.3	4392.6	3.57	20.22	13.0	788.5	15.55
02/10/2005	6.88	31.7	449.6	2.17	7.82	31.6	1011.2	2.48	5.21	29.6	203.1	1.76
03/18/2005					0.51	18.0	51.6	0.28	0.28	1.4	10.9	2.00
04/28/2005					3.28	3.5	522.0	9.36	2.97	3.5	115.9	8.49

3.3 Frequency Analysis of the Rainfall

Frequency analysis was conducted using partial duration series to obtain 2-year, 24-hour rainfall depth (P_2), which is required to calculate T_c in the modified ASCE equation (equation (2)). Three different partial duration series were prepared by sorting out the three, four, and five largest storms from each rainy season. P_2 values obtained from the three different partial duration series were compared each other.

Figure 1 shows the frequency histogram of maximum 24-hr rainfall depth from the partial duration series using five storms for each monitoring year for the monitoring sites. Event distributions in Figure 1 were assumed to have lognormal distribution. Figures 2, 3, and 4 show the graphical fits of lognormal distribution from different partial duration series (three, four, and five largest storms selected for each monitoring year) for Site 1, 2, and 3, respectively. To obtain the rainfall depth for the 2-year return period (P_2), the following equation defining the return period of partial duration series is used (Stedinger et al., 1992).

$$\frac{1}{T} = m[1 - F] \tag{3}$$

where T = return period, m = number of storms per year, and F = empirical estimate of frequency. Using equation (3), F values for 2-year return period for 3-storm (m = 3), 4-storm (m = 4), and 5-storm (m = 5) partial duration series are calculated as 0.83, 0.88, and 0.90, respectively. P_2 values corresponding to these frequency values on the regression line in Figures 2, 3, and 4 are summarized in Table 5. As shown in Table 5, P_2 values calculated from different series did not significantly deviate from each other. Therefore, P_2 from the 5-storm series was used in the T_c calculation.

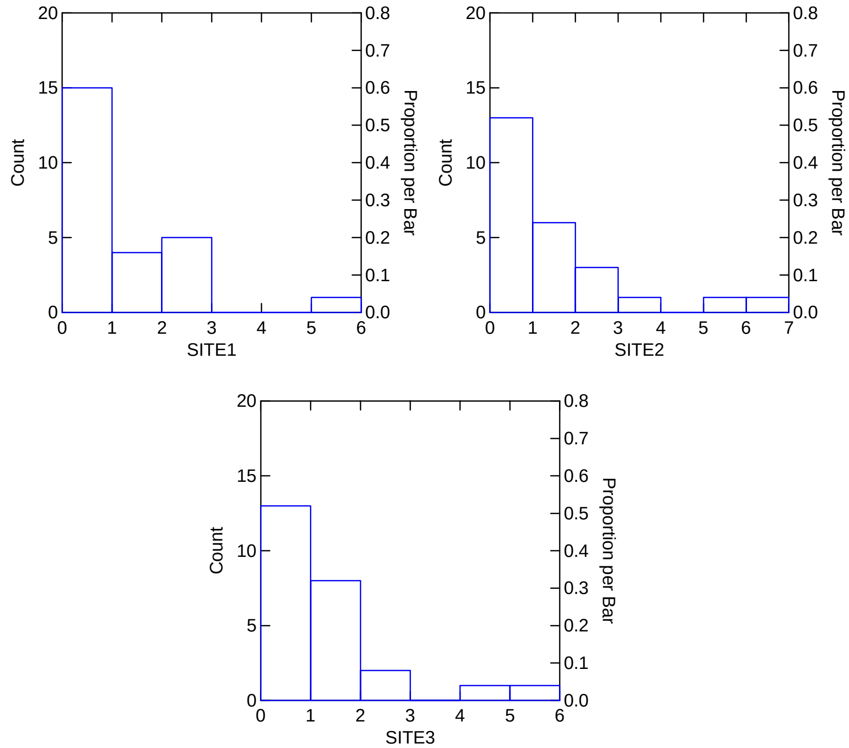

Figure 1. Frequency Histograms of Maximum 24hr Rainfall Depth (in) for the Monitoring Sites.

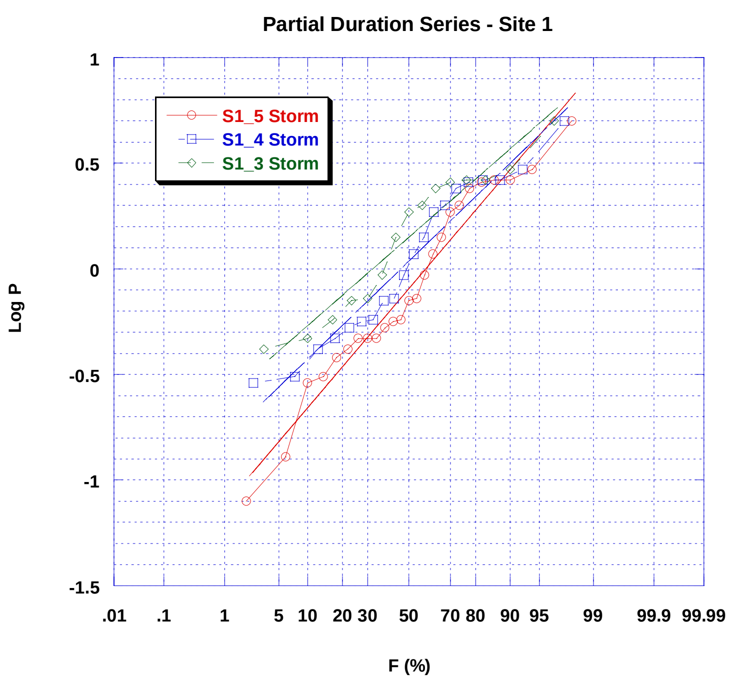

Figure 2. Probability Plots for 24hr Rainfall Depth in Site 1 with Different Partial Duration Series.

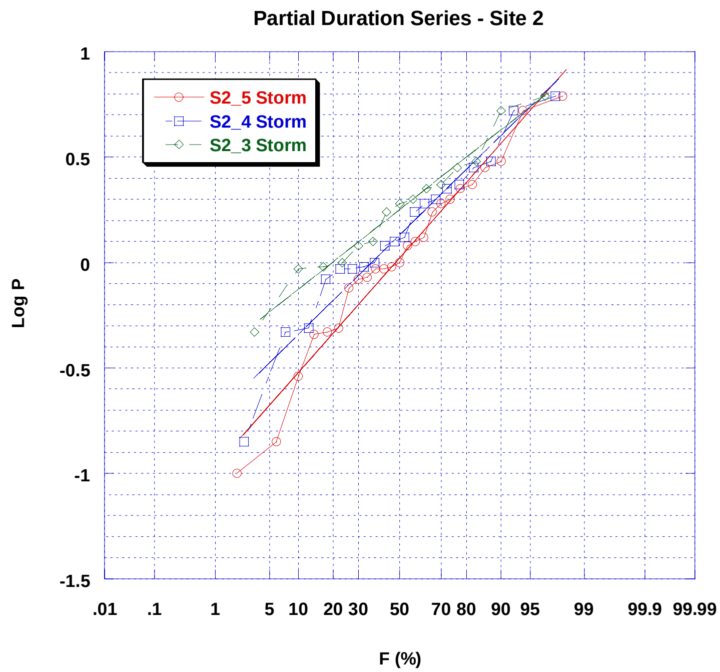

Figure 3. Probability Plots for 24hr Rainfall Depth in Site 2 with Different Partial Duration Series.

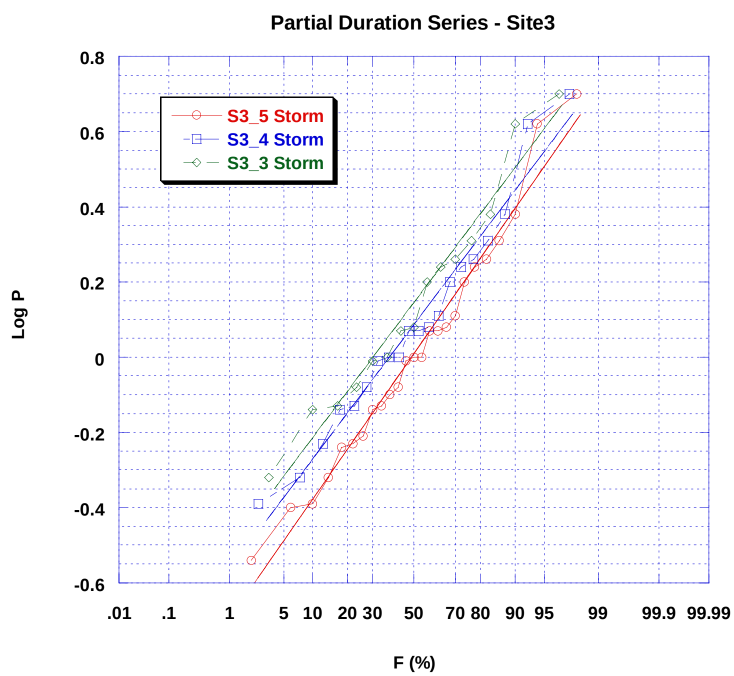

Figure 4. Probability Plots for 24hr Rainfall Depth in Site 3 with Different Partial Duration Series.

Table 5. P_2 (2-year, 24-hour rainfall depth) for the Monitoring Sites from the Frequency Analysis

Monitoring Sites	Partial Duration Series			NOAA*
	5-Storm	4-Storm	3-Storm	
Site 7-201	2.4 in	2.4 in	2.4 in	3.0
Site 7-202	3.0 in	3.0 in	3.0 in	3.0
Site 7-203	2.5 in	2.8 in	2.2 in	2.9

* Source: Atlas 2 Maps for western U.S published in 1973, National Oceanic & Atmospheric Administration (NOAA).

4. Results and Discussion

4.1 T_c for design application

Table 6 shows values of T_c calculated by the modified ASCE, Kirpich, FAA, and SCS lag formulas in Group 1. Each formula returns a single value of T_c for each site. The Kirpich formula returns among the smallest T_c for all sites. This might be caused by the fact that the Kirpich formula was developed for a steep slope area (3-10%); as a result, it underestimates T_c in mildly sloped watersheds. In contrast, the SCS lag formula returns among the largest values of T_c. This may be because this formula was originally developed for agricultural watersheds. Formulas with the kinematic wave forms (i.e., ASCE, modified ASCE formulas) hold for the sheet flow with steep bed slopes. Use of this formula is typically limited by a maximum flow length of 300 ft to insure that the kinematic assumption is valid, although there is no documented evidence that supports this criterion. McCuen and Spiess (1995) proposed the upper limit as $nL/\sqrt{S}$ less than 100 (English units) from an empirical analysis using data from 59 watersheds. Values of $nL/\sqrt{S}$ for Sites 1, 2, and 3 are calculated as 267, 81, and 41, respectively, using site dimensions in Table 3 and 0.011 of n for smooth asphalt or concrete beds. This suggests that the kinematic wave T_c formula (Equations (1) and (2)) might estimate well for Sites 2 and 3, and might not for Site 1. The FAA formula returned slightly larger values of T_c than those by the modified ASCE formula, with little difference when 0.95 of the runoff coefficient (C) is applied for asphalt and concrete bed surfaces.

Table 6. Time of Concentration for Design of Hydraulic Structures Calculated by Different Methods.

Methods	Time of Concentration (Tc, min)			Remarks
	Site 7-201	Site 7-202	Site 7-203	
Modified ASCE	13	6	4	*n* = 0.011 applied for smooth concrete or asphalt
Kirpich	7	3	2	Reduction factor (0.4) applied for concrete or asphalt surface
FAA	15	7	5	C = 0.95 for asphalt and concrete
SCS Lag	37	11	6	CN = 98 for paved area

4.2 Peak Flow Calculation and Evaluation of Calculated T_c

Peak flow rates were calculated using different values of T_c as shown in Table 6, and evaluated in terms of their capacity to accommodate actual peak flows generated during the storms events in 1999-2005. SCS's graphical peak discharge method was used. Design rainfall depth was 3.0 in for all three sites, which was obtained from NOAA's Atlas 2 maps (1973), showing an iso-hyetal map of 2-year, 24-hour rainfall depth in west Los Angeles. A unit peak flow discharge graph for type I rainfall area (Figure 5) was used to obtain the q_u for the west Los Angeles area. An example of the peak flow calculation is:

- CN = 98 for all sites (pavement with larger than 95% imperviousness)
- S (potential maximum retention after runoff begins, in) = 1000/CN-10 = 0.2 in
- Q (runoff) = $\frac{(P-0.2S)^2}{(P+0.8S)}$ = 2.77 in where, P = design rainfall (= 3.0 in)
- I_a (initial abstraction) = 0.0041 in (from table 4-1 in TR-55)
- I_a/P = 0.0041/3 = 1.37x10^{-3}
- q_u is obtained from figure 8 using calculated I_a/P and T_c
    - Limiting value should be used for outside of the range.
    - q_u for site 1, site 2 and site 3 are 400, 500, 500 csm/in, respectively.
- q_p for site 1= $q_p = q_u A_m Q F_p$ = 400×0.004942108×2.77×1= 5.48 cfs (155 L/s)

  q_p for site 2 = 500×0.006525126×2.77×1 = 9.03 cfs (256 L/s)

  q_p for site 3 = 500×0.001505798×2.77×1 = 2.09 cfs (59 L/s)

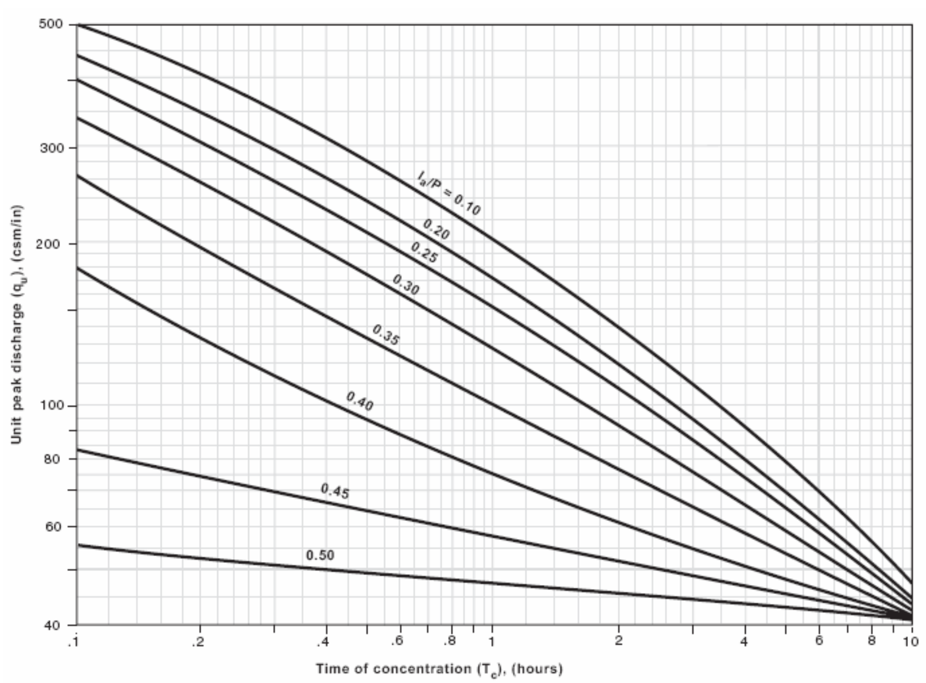

Figure 5. Unit peak flow discharge with respect to T_c for different I_a/P values (type I rainfall distribution).

Table 7 summarizes peak flow rates and corresponding frequency (F) values for three sites calculated using T_c values from different formulas through the procedure described above. A value of F for a q_p represent the probability of peak flow of a storm to be less than q_p and were obtained from the probability plots of six years' monitoring events from 1999 to 2006 (figure 6). Because all T_c formulas resulted in design q_p values large enough to accommodate most of the peak flows occurred for six years (F > 96%), A T_c formula resulting in less overestimated q_p should be used for cost-effective design. For example, q_p obtained from SCS lag formula for site 2 (215 L/s) is among the smallest when compared to results from the other formulas, but still much higher than the maximum q_p occurred during the monitoring period. Therefore, for the monitoring sites (site 1, site 2 and site 3), SCS lag equation, returning less overestimated peak flow, was better than other formulas for the design purpose.

Table 7. Design peak flow rates (q_p) calculated with T_c values from different formulas.

Methods	Site 7-201		Site 7-202		Site 7-203	
	q_p (L/s)	F (%)	q_p (L/s)	F (%)	q_p (L/s)	F (%)
Modified ASCE	155	100	256	100	59	97
Kirpich	182	100	256	100	59	97
FAA	143	99	240	100	59	97
SCS Lag	101	96	215	100	59	97

F = Frequency of the q_p, corresponding to the probability plot obtained from measured peak flows (Figure 6).

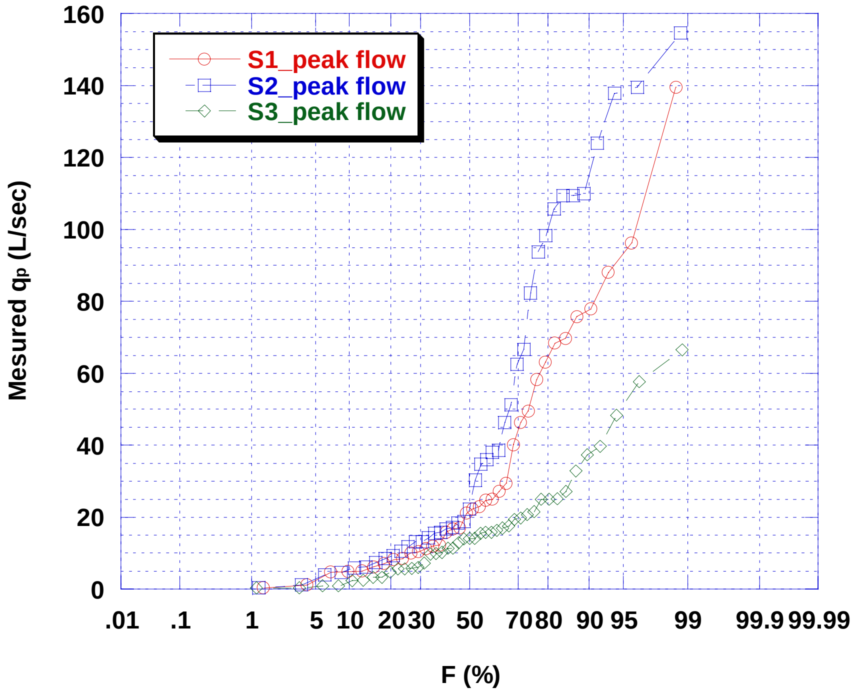

Figure 6. Probability Plots for peak flow measured in 1999-2005

4.3 Correlations between T_c and mass first flush (MFF) ratios

T_c is a function of watershed size and slope, which are also factors influencing mass emission rate. Small watersheds with highly impervious landuse (e.g. highway, parking lot) are supposed to have small T_c and usually have strong MFF in the pollutant emission (Ma et al., 2003; Sansalone, 2004). Therefore, it is worth investigating relationships between T_c and MFF ratios.

To examine the relationship between T_c and MFF, values of T_c were calculated by formulas in group 2 (i.e. ASCE and Izzard formulas) using measured rainfall intensity for each storm event and compared to the MFF ratios for TSS and conductivity, which were considered most representative parameters for particulate and dissolved form of pollutants. Figure 7, 8 and 9 are the correlation charts showing the correlation among MFF_{10} and MFF_{20} for TSS and conductivity, calculated T_cs and measured lag times for the storm events monitored in 2000-2003 for site 1, site2 and site 3, respectively. As can be seen, no clear relationship between T_c (or lag time) and MFF ratios was observed. It is likely because there are other factors, independent of T_c or lag time, but highly impacting on MFF such as antecedent dry days (ADD), antecedent event rain, rainfall duration. Rainfall type can be also an influencing parameter for MFF, which can not be considered in T_c calculation.

In addition, calculated T_cs are poorly related to the measured lag time. The poor correlation between T_cs obtained from formulas and measured lag times may be due to the fact that average rainfall intensity was used to calculate T_c, but temporal change of rainfall and flow is a primary factor that determines lag time. T_cs from Izzard and ASCE formulas have a linear relationship as can be expected.

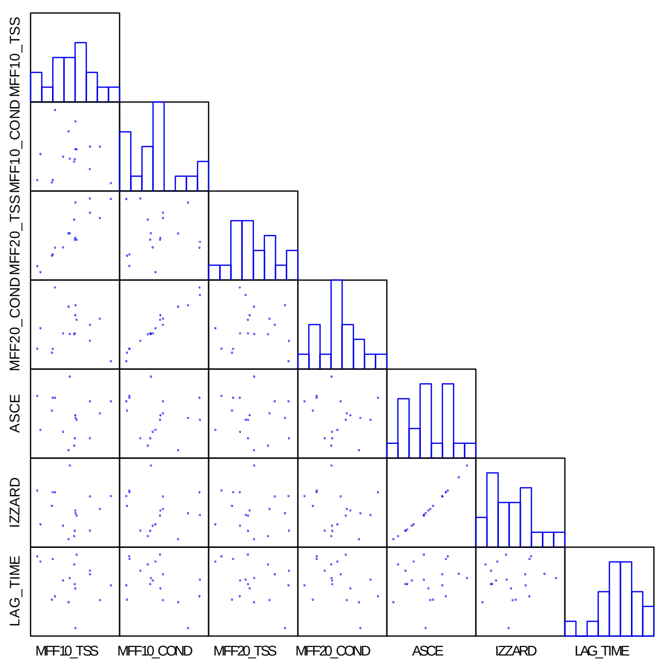

Figure 7. Correlations between time of concentration and mass first flush ratios for TSS and conductivity in site 7-201

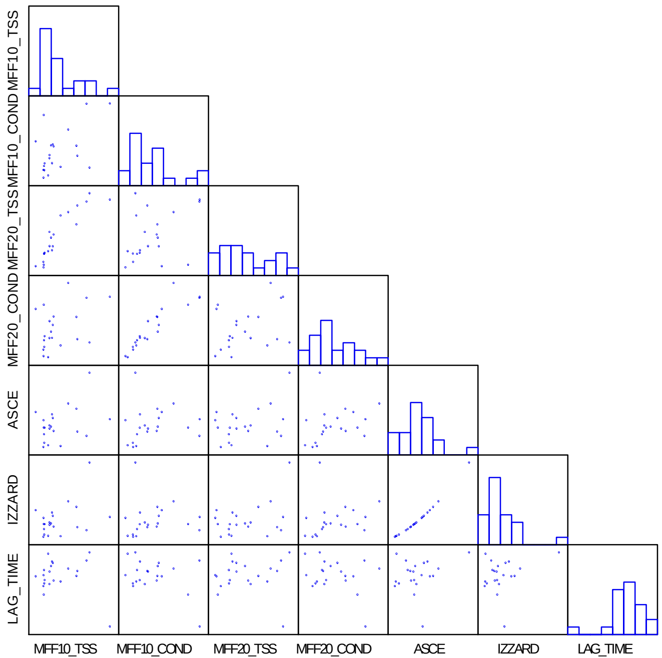

Figure 8. Correlations between time of concentration and mass first flush ratios for TSS and conductivity in site 7-202

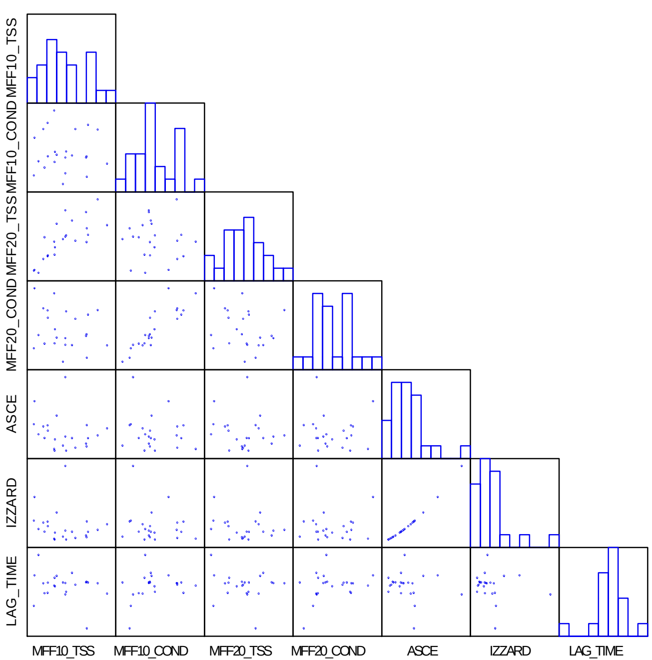

Figure 9. Correlations between time of concentration and mass first flush ratios for TSS and conductivity in site 7-203

Table 8 shows the design T_c and the MFF ratios for TSS and conductivity from monitoring sites. MFF_{10} and MFF_{20} larger than 1 were routinely observed in the storm events with averages of 2.0, 2.0, 2.0 and 1.6 for MFF_{10} and MFF_{20} for TSS and conductivity, respectively. Site 3, with the smallest T_c, has the largest MFF ratios among the three monitoring sites. Site 1 has similar MFF ratio with site 2 with 2.5 times larger T_c. Although it was difficult to obtain general relationship between T_c and MFF ratios, a watershed with small T_c (< 37 min) usually have first flush, having higher MFF with smaller T_c.

Table 8. Average MFF ratios for site 1, site 2 and site 3

Parameters		Site 7-201	Site 7-202	Site 7-203	Combined sites
TSS	MFF_{10}	1.9	2.0	2.0	2.0
	MFF_{20}	1.7	1.7	2.5	2.0
Conductivity	MFF_{10}	2.0	1.9	2.0	2.0
	MFF_{20}	1.5	1.5	1.9	1.6
Design T_c (min)*		37	11	6	-

* Obtained from SCS's Lag formula

5. Conclusions

Available time of concentration (T_c) formulas were evaluated to determine design T_c values for the three highway monitoring sites (site 7-201, 7-202 and 7-203) located in west Los Angeles. In the frequency analysis to determine 2-year, 24-hour rainfall depths (P_2) for the sites, partial duration series using 3, 4, and 5 largest storms in the periods, 1999-2003, 2004-2005. Different partial duration series resulted in similar P_2 values.

The T_c formulas were evaluated based on the capacity of resulting design peak flow. The SCS's lag formula provided the best T_c values with less overestimated peak flow. The values of design T_c were 37, 11 and 6 minutes for site 7-201, 7-202 and 7-203, respectively. Design peak flow rates were calculated using SCS's graphical peak discharge method and larger than the measured peak flows for 96% or more of the storm events occurred in six years from 1999 - 2006.

In addition, a correlation study for T_c and MFF was performed. Event-specific T_c values were calculated using two Tc formulas (Izzard, ASCE) and compared with mass first flush ratios (MFF_{10}, MFF_{20}) for TSS and conductivity for the storm events monitored in 1999 to 2005. No clear relationship was found between T_c and MFF. However, when comparing average MFF ratios and design values of T_c, site 3 with among the smallest T_c has higher first flush effect compared to two other sites.

References

Ahlfeld, D.P., and Minihane, M. (2004). "Storm flow from first-flush precipitation in stormwater design." J. of Irrigation and Drainage Engr., ASCE, 130(4), 269-276.

Cristina, C.M., and Sansalone, J.J. (2003). "Kinematic wave model of urban pavement rainfall-runoff subject to traffic loadings." *J. Environ. Engrg.*, ASCE, **129**(7), 629-636.

Vidssman, W, and Lewis, G.L. (2003). Introduction to hydrology. 5^{th} Edition, Prentice Hall, NJ.

Stedinger, J.R., Vogel, R.M., and Foufoula-Georgiou, E. (1992). "Frequency analysis of extreme events." Handbook of hydrology,. D.R. Maidment, ed., McGraw-Hill, New York.

Roger, S., Montréjaud-Vignoles, M., Andral, M.C., Herremans, L. and Fortune, J.P. (1998) Mineral, physical and chemical analysis of the solid matter carried by motorway runoff water. *Wat. Res.*, **32**(4), 1119-1125.

Furumai, H., Balmer, H. and Boller, M. (2002) Dynamic behavior of suspended pollutants and particle size distribution in highway runoff. *Wat. Sci. Tech*., **46**(1), 413-418.

Jacopin, C., Lucas, E., Desbordes, M., and Bourgogne, P. (2001). "Optimisation of operational management practices for the detention basins." *Wat. Sci. Tech*., 44(2), 277-285.

Persson, J., and Wittgren, H.B. (2003). "How hydrological and hydraulic conditions affect performance of ponds." *Ecological Engineering*, 21, 259-269.

Sansalone, J.J. and Cristina, C.M. (2004). First flush concepts for suspended and dissolved solids in small impervious watersheds. *J. Environ. Engrg.*, ASCE, **130**(11), 1301-1314.

Ma, M., Khan, S., Li, S., Kim, L.-H., Ha, S., Kayhanian, M. and Stenstrom, M.K. (2002) First flush phenomena for highways: how it can be meaningfully defined. *Proceedings of 9^{th} International Conference on Urban Drainage*, September, Portlnad, Oregon.

McCuen, R.H. and Spiess, J.M. (1995). “Assessment of kinematic wave time of concentration.” J. of Hydraulic Engineering, ASCE, 121(3), 256-266.

Gupta, K. and Saul, A.J. (1996) Specific relationship for the first flush load in combined sewer lows. *Wat. Res.*, **30**(5), 1244-1252.

Cristina, C.M. and Sansalone, J.J. (2003) "First Flush", Power law and particle separation diagrams for urban storm-water suspended particulates. *J. Environ. Engrg.*, ASCE, **129**(4), 298-307.

Deletic, A.B. and Maksimovic, C.T. (1998) Evaluation of water quality factors in storm runoff from paved areas. *J. Environ. Engrg.*, ASCE, **124**(9), 869-879.

Ma, M., Khan, S., Li, S., Kim, L.-H., Ha, S., Kayhanian, M. and Stenstrom, M.K. (2002) First flush phenomena for highways: how it can be meaningfully defined. *Proceedings of 9th International Conference on Urban Drainage*, September, Portlnad, Oregon.

Sansalone, J.J. and Cristina, C.M. (2004). First flush concepts for suspended and dissolved solids in small impervious watersheds. *J. Environ. Engrg.*, ASCE, **130**(11), 1301-1314

U.S. Department of Agriculture, Soil Conservation Service, Engineering Division, 1985. SCS National Engineering Handbook.

U.S. Department of Agriculture, Soil Conservation Service, Engineering Division, 1986. Urban Hydrology for small Watersheds. Technical Release 55 (TR-55).

http://www.wrcc.dri.edu/pcpnfreq.html (Western U.S. Precipitation Frequency Maps)