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Predicting the existence of stormwater first flush from the time of concentration

Joo-Hyon Kang[a,*], Masoud Kayhanian[b], Michael K. Stenstrom[a]

[a]Department of Civil and Environmental Engineering, University of California, Los Angeles, CA 90095-1953, USA
[b]Center for Environmental and Water Resources Engineering, Department of Civil and Environmental Engineering, University of California, Davis, CA 95616, USA

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ABSTRACT

Simulations were performed using a one-dimensional kinematic wave model to examine the relationships between the time of concentration (T_c) and the first flush (FF) for impervious landuses. The model used chemical oxygen demand parameters from a highway runoff site in west Los Angeles for eight storm events. FF indices such as the mass first flush ratio (MFF_n) and the partial event mean concentration to event mean concentration ratio ($PEMC_t/EMC$) were calculated from simulations using various rainfall intensities, rainfall durations, bed slopes, and watershed lengths (L), and matched measured values with an RMS error of 25% for six events. Resulting values of MFF_{20} and $PEMC_{60}/EMC$ were correlated to T_c calculated using ASCE's kinematic wave formula, and showed a non-monotone relationship, with very short or long T_c having low MFF_{20} with a maximum for mid-range T_c. Contours of the MFF_{20} and $PEMC_{60}/EMC$ were created to predict and quantify FF from known T_c, L, and rainfall duration (T).

1. Introduction

A characteristic of pollutant emissions from impervious landuses such as roads and highways is the first flush (FF) phenomenon, which implies a greater discharge rate of pollutant mass or concentration in the early part of the runoff volume as compared with later in the storm (Ma et al., 2002; Sansalone and Cristina, 2004). This phenomenon provides an opportunity for best management practices (BMPs) to be designed more effectively by optimizing removal efficiency for the early part of runoff. The challenge in using the FF phenomenon is to reliably predict when it occurs and how large it will be.

The FF phenomenon is strongly related to weather and site conditions. Numerous efforts have been made to relate FF with rainfall intensity, flow rate, watershed area, or bed slope, using statistical analyses of empirical observations (Gupta and Saul, 1996; Deletic and Maksimovic, 1998; Cristina and Sansalone, 2003). However, no clear relationship has been found. Kang et al. (2006) developed an alternate approach using a one-dimensional kinematic wave model considering short- and long-term pollutant sources to reveal the relationship between the mass first flush ratio (MFF_n) and several physical factors such as rainfall intensity, rainfall duration, bed slope, infiltration rate, initial pollutant mass, and pollutant erosion rate. They simulated the degree of FF as a function of watershed length (L) under different site and weather conditions, and found that there exists an optimum watershed length to maximize FF for a specific, constant rainfall intensity.

One of the most familiar design parameters to hydraulic engineers is the time of concentration (T_c), which estimates the peak runoff flow rate and is used to determine the size of hydraulic structures. T_c is a specific value for a specific

*Corresponding author. Tel.: +1 310 626 3328.
E-mail address: joohyon@ucla.edu (J.-H. Kang).
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Nomenclature

c	kinematic wave velocity or celerity (m/s)
D	dispersion coefficient (m^2/s)
E	pollutant erosion rate from the bed surface ($g/m^2/s$)
ε_s	erosion coefficient of pollutant from the short-term source (s/m^2)
ε'_l	redefined erosion coefficient of pollutant from the long-term source ($g\,s/m^4$)
f	infiltration rate (cm/s)
h	flow depth (m)
h_{T_c}	flow depth at T_c (m)
I	rainfall intensity (mm/h)
K_p	hydraulic conductivity of the pavement (cm/s)
L	length of overland flow plane or watershed length (m)
$m_{b,t}$	total pollutant mass on the bed surface (g/m^2)
$m_{b,s}$	pollutant mass from the short-term source on the bed surface (g/m^2)
m_w	pollutant mass in the water (g/m^2)
n	Manning's roughness coefficient
S_0	bed slope (fraction)
t	time (s)
T	storm duration (h)
T_c	time of concentration (min)
T_p	thickness of the pavement layer (m)
u	flow velocity (m/s)
u^*	friction velocity (m/s)
V_{T_c}	average flow velocity at T_c, L/T_c (m/min)
x	distance in the flow direction (m)

catchment and rainfall condition and represents the steady-state hydraulic condition formed in the catchment. If a relationship between T_c and FF exists, it may be possible to include FF considerations into catchment design; that is, the drain inlet spacing or the bed slope can be selected to obtain the desired FF. In this paper, quantitative descriptors of FF such as MFF_n and the partial event mean concentration to event mean concentration ratio ($PEMC_t$/EMC) are investigated on the basis of chemical oxygen demand (COD) measurements using the kinematic wave model suggested by Kang et al. (2006). The goal is to relate water quantity and water quality design considerations, and to provide improved design procedures for BMPs such as locations of drain inlets and pipes, slopes, and catchment geometry.

2. Background

2.1. *Time of concentration (T_c)*

T_c is defined as the time required for a flow wave to travel from the most hydrologically remote point in the catchment to the point of collection, such as a catch basin or BMP. Under the assumption of uniform rainfall equally distributed over a catchment, outflow reaches equilibrium and becomes equal to net rainfall input at T_c (Bedient and Huber, 1992; Viessman and Lewis, 2003).

Numerous formulas to estimate T_c have been developed for different landuses and geometries. Table 1 summarizes several T_c formulas applicable for impervious watersheds and commonly used in the United States. Similar approaches are used in Europe and South America (Moisello, 1985; Témez, 1991). As shown, T_c is typically associated with rainfall and hydrological parameters such as rainfall intensity, slope, and flow length. Each formula was developed for a particular watershed type with different landuses or geometries. Therefore, it is important to choose an appropriate T_c formula for design application because T_c can be underestimated or overestimated when an unsuitable formula is applied (McCuen and Spiess, 1995).

2.2. *Kinematic wave analyses for sheet flow*

The kinematic wave equation is a simplification of the Saint Venant equation and has been popularly used to model sheet flow over a plane surface due to simplicity and accuracy of the calculation (Tomanovic and Maksimovic, 1996; Singh, 2002a, b). In the kinematic wave equation, the flood wave is approximated by kinematic wave celerity ($c = mu$), which is a function of bed slope, Manning's roughness coefficient, and flow depth. The one-dimensional form of the kinematic wave equation is

$$\frac{\partial h}{\partial t} + c\frac{\partial h}{\partial x} = 2.78 \times 10^{-8} I - 10^{-2} f, \tag{1}$$

$$c = mu = m(\sqrt{S_0}/n)h^{m-1}, \tag{2}$$

where h is flow depth (m), t is time (s), c is kinematic wave velocity, m is a constant ($=5/3$), u is flow velocity (m/s), x is distance in the flow direction (m), I is rainfall intensity (mm/h), f is infiltration rate (cm/s), S_0 is bed slope, and n is Manning's roughness coefficient (the 2.78×10^{-8} conversion factor is needed when customary units are used for rainfall (mm/h) and infiltration (cm/s)).

The kinematic wave equation (Eq. (1)) implies that an object moving at a speed of c ($= dx/dt$) will observe a flow depth increment at the product of rainfall intensity and travel time (infiltration rate is assumed negligible, $I \gg f$). Therefore, the flow depth observed at T_c can be calculated as follows (Morgali and Linsley, 1965):

$$h_{T_c} = 1.667 \times 10^{-5} I T_c, \tag{3}$$

where T_c is the time of concentration (min), h_{T_c} is flow depth at T_c (m), and 1.667×10^{-5} is the unit conversion factor. Substituting Eqs. (2) and (3) into the relationship, $c = dx/dt$, and integrating the resulting equation from $x = 0$ to L for the corresponding time $t = 0$ to T_c, respectively, ASCE's kinematic wave T_c formula (the ASCE formula) can be derived as follows (Morgali and Linsley, 1965):

$$T_c = \frac{6.94 L^{0.6} n^{0.6}}{I^{0.4} S_0^{0.3}}. \tag{4}$$

Table 1 – Formulas for time of concentration (T_c)

Methods	Formulas for T_c (min)	Remarks
Kirpich (1940)	$T_c = 0.0078l^{0.77}S_0^{-0.385}$	Steep slope: 3–10% Reduction factor applied for impervious area (0.4 for overland flow on concrete or asphalt surface)
Izzard (1946)	$T_c = \frac{41.025(0.0007i + c)l^{0.33}}{S_0^{0.333}i^{0.667}}$	Roadway and turf surfaces $i \times l < 500$
FAA (1970)	$T_c = 1.8(1.1 - C)l^{0.50}/(100 \times S_0)^{0.333}$	Overland flow in urban basins
ASCE (Morgali and Linsley, 1965)	$T_c = \frac{0.933l^{0.6}n^{0.6}}{i^{0.4}S_0^{0.3}}$	From kinematic wave analysis ($l < 300$ ft)
Modified ASCE (SCS, 1986)	$T_c = \frac{0.007l^{0.8}n^{0.8}}{P_2^{0.5}S_0^{0.4}}$	Modified from ASCE to avoid iterative calculation procedure
SCS lag equation (1972)	$T_c = \frac{1.67l^{0.8}[(1000/CN) - 9]^{0.7}}{1900(100 \times S_0)^{0.5}}$	Small urban basins <2000 acres

l = flow length (ft), S_0 = surface slope (ft/ft), i = rainfall intensity (in/h), c = retardance coefficient, C = rational method runoff coefficient, n = Manning's roughness coefficient, P_2 = 2-year, 24-h rainfall depth (in), and CN = SCS runoff curve number.

3. Methodology

3.1. Model description

To calculate water quantity, Eqs. (1) and (3) were used with the uniform rainfall intensity and infiltration equation as follows (Kang et al., 2006):

$$f = -\frac{K_p}{T_p}h - K_p, \tag{5}$$

where f is infiltration rate (cm/s), K_p is hydraulic conductivity of the pavement ($=10^{-5}$ cm/s), and T_p is thickness of the pavement layer ($=0.1$ m for the study site).

The governing equations for water quality are composed of two components, representing erosion and transport (Kang et al., 2006; Elder, 1959):

$$\text{Transport}: \quad \frac{\partial m_w}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial m_w}{\partial x}\right) - \frac{\partial}{\partial x}(um_w) - E, \tag{6}$$

$$D = 6.0hu^* \quad \text{(Elder, 1959)}, \tag{7}$$

$$\text{Erosion}: \quad E = \frac{dm_{b,t}}{dt} = \frac{dm_{b,s}}{dt} = -\varepsilon_s u^2 m_{b,s} - \varepsilon_l' u^2, \tag{8}$$

where m_w is pollutant mass in water of unit area (g/m^2), D is dispersion coefficient (m^2/s), E is pollutant erosion rate from the bed surface (g/m^2/s), u^* ($=\sqrt{ghS_0}$) is friction velocity (m/s), $m_{b,t}$ is total pollutant mass per area (g/m^2), $m_{b,s}$ is pollutant mass per area from the short-term source (g/m^2), and ε_s (s/m^2) and ε_l' (g s/m^4) are erosion coefficients of pollutant mass from the short- and long-term sources, respectively.

Eqs. (6), (7) and (8) were coupled with Eqs. (1), (2) and (5), and solved numerically. The method of characteristics (Wood, 1993) was used for the water quantity Eqs. (1), (2), and (5) and the Crank–Nicolson method was used to solve the water quality Eqs. (6)–(8). The four model parameters ($K_p = 10^{-5}$ cm/s, $\varepsilon_s = 1.09$ s/m^2, $\varepsilon_l' = 0.0024\,g$ s/m^4, initial value of $m_{b,s} = 1.0$ g/m^2) were previously determined for a highway site in Los Angeles from our previous work (Kang et al., 2006) and were used in the model calculations for different watershed lengths and rainfall intensities. The simulated rainfall intensities were assumed constant and homogeneous with respect to time and space. Details including model derivation, parameter estimation, and calculation methods can be found in Kang et al. (2006).

3.2. T_c calculation and evaluation

The value of T_c is typically used for design applications to determine the maximum required hydraulic capacity of a structure and calculated using a design rainfall intensity corresponding to a specified return period consistent with local codes and regulations (FHWA, 2001), but T_c can also be calculated for specific events using the event's rainfall intensity instead of the design rainfall intensity. The event-specific values of T_c vary depending on the hydrodynamic conditions of each storm event, and can be used to correlate with water quality parameters such as MFF$_n$. In this study, event-specific values of T_c were calculated using the ASCE formula under various combinations of different rainfall intensity (I), bed slope (S_0), and watershed length (L), and then compared with the corresponding values of T_c obtained from the numerical solutions of the kinematic wave equation in order to evaluate the validity of the ASCE formula for the site and weather conditions simulated. The ASCE formula was selected over simpler formulas without rainfall intensity, since rainfall intensity is needed to solve the kinematic wave model. The values of T_c from the ASCE formula were also related to MFF$_n$ and PEMC$_t$/EMC, which were calculated from the kinematic wave model under the same site and rainfall conditions. The site and rainfall conditions used in this study were based on the typical ranges observed in the west Los

Table 2 – Range of model parameters simulated

Parameters	Ranges	Remarks
Rainfall intensity, I (mm/h)	1.2–12.0	
Bed slope, S_0 (–)	0.005–0.06	
Watershed length, L (m)	1–2000	
Rainfall duration, T (h)	1–12	
Manning's roughness coefficient, n	0.011	Smooth concrete or asphalt
Initial pollutant mass from the short-term sources, $m^o_{b,s}$ (g/m^2)	1.0	Corresponding to 17 days[a] of ADD

[a] Average ADD in west Los Angeles.

Angeles area and summarized in Table 2. Finally, values of MFF_{20} predicted by the model were compared with experimentally measured values of MFF_{20}.

3.3. First flush quantification

The degree of FF can be quantified by FF descriptors such as MFF_n (Ma et al., 2002) and $PEMC_t/EMC$ (Han et al., 2006), which represent mass first flush (MFF) and concentration first flush (CFF), respectively. The mathematical definitions of MFF_n and $PEMC_t/EMC$ are as follows:

$$MFF_n = \frac{\int_0^t C(t)Q(t)dt/M}{\int_0^t Q(t)dt/V}, \tag{9}$$

$$PEMC_t/EMC = \frac{\int_0^t C(t)Q(t)dt}{\int_0^t Q(t)dt} \Bigg/ \frac{\int_0^T C(t)Q(t)dt}{\int_0^T Q(t)dt}, \tag{10}$$

where MFF_n is mass first flush ratio at a cumulative flow volume corresponding to n% of total flow volume, t is lapsed flow time corresponding to n% of total flow volume, $C(t)$ is concentration of pollutant at time t, and $Q(t)$ is runoff flow rate at time t. M is total mass washed off, V is total runoff volume, and $PEMC_t/EMC$ is the ratio of PEMC to EMC for storm elapsed time t. MFF_n and $PEMC_t/EMC$ ratios larger than 1.0 show the existence of MFF or CFF, respectively. In this study, the values of MFF_{20} and 60 min PEMC to EMC ratio ($PEMC_{60}/EMC$) for COD were compared with the value of T_c calculated with the ASCE formula under various combinations of different values of I, T, S_0, and L.

4. Results and discussion

4.1. Evaluation of the ASCE formula

Formulas with kinematic wave forms (e.g., the ASCE formula, the modified ASCE formula) are applicable for sheet flow with steep bed slopes. Use of these formulas is typically limited by a maximum flow length of 90 m (SCS, 1986), although there is no documented evidence that supports this limit. To evaluate the validity of the ASCE formula for the watersheds simulated in this study, the values of T_c calculated using the ASCE formula were compared with the values of T_c calculated from the numerical solution of the kinematic wave equation. Fig. 1 compares the two solutions, and the ASCE formula systematically underestimates T_c, especially for small watersheds. The absolute difference increases as the watershed becomes larger but the relative difference decreases from approximately 80% to less than 10% for watersheds longer than 500 m (not observable from the figure but calculated from the data). This suggests that the ASCE formula's appropriateness should be evaluated for watersheds longer than 90 m (the maximum flow length suggested by SCS (1986)) when the bed slope is steep enough ($S_0 \geq 0.005$) to satisfy the kinematic wave assumption. The general tendency of the ASCE formula to underestimate T_c can be viewed as a conservatism or safety factor, since the use of a smaller T_c in design produces higher peak runoff rates. The horizontal trends in the relationship, especially for short T, occur because the ASCE formula is independent of T, and produces the same T_c for short and long durations.

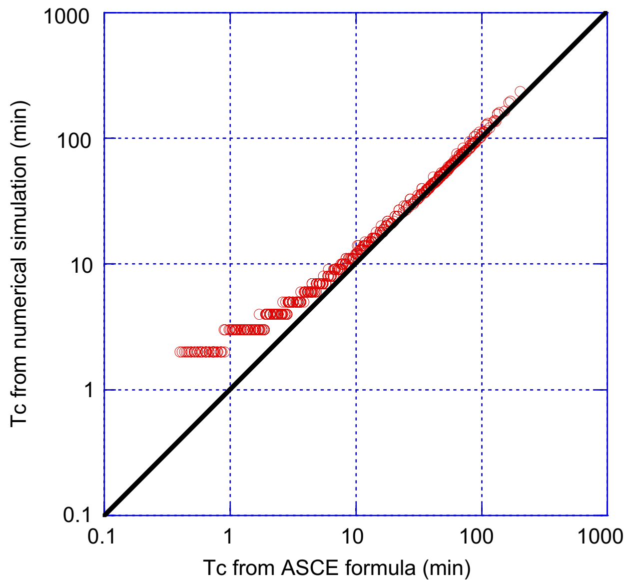

Fig. 1 – Values of T_c calculated by the ASCE formula and simulated by the kinematic wave equation.

4.2. Relationship between T_c and the first flush

T_c is a function of I, S_0, L, and n, which are also important factors affecting pollutant washoff behavior (MFF ratios and PEMCs). If a relationship can be established between T_c and FF from the model simulations, then well-known hydraulic design procedures may be able to predict FF as well as peak runoff rate. Fig. 2(a) shows the relationship between T_c and MFF_{20} for COD obtained from the model simulation for different values of L from 1 to 10^3 m at $T = 3$ h for the ranges of I and S_0 shown in Table 2. The relationship between MFF_{20} and T_c is not monotone. For a particular watershed length, short or long T_c results in low MFF_{20}. Fig. 2(a) suggests that MFF_{20} usually has a quasi-concave functional relationship with T_c and is less sensitive to T_c as the watershed becomes larger. In a very small watershed ($L < 10$ m), a larger T_c usually

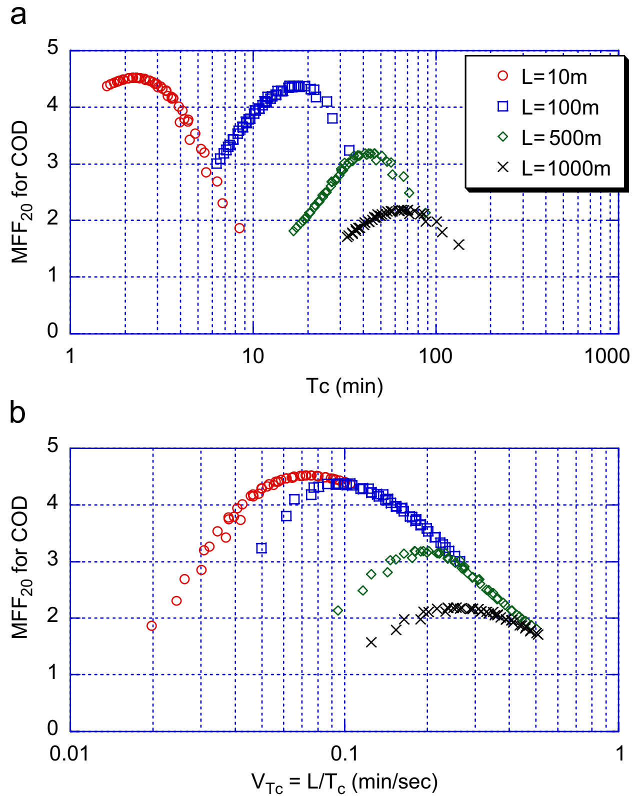

Fig. 2 – MFF_{20} for COD at $T = 3$ h as a function of (a) T_c and (b) V_{T_c}.

has a smaller MFF_{20}. For larger watersheds, an optimum value of T_c exists that maximizes MFF_{20}, and MFF_{20} generally decreases with increasing watershed size, as expected (Kang et al., 2006).

In the physical context, T_c and L are associated with the transport time and erosion rate of a pollutant at hydraulic equilibrium. Pollutant transport time is directly related to T_c whereas pollutant erosion rate is related to prior pollutant accumulation and flow velocity. Flow velocity at T_c (V_{T_c}) was calculated ($V_{T_c} = L/T_c$) as an event-representative flow velocity for the same conditions of T and L used in Fig. 2(a), and plotted with MFF_{20} for COD in Fig. 2(b). As shown in Fig. 2(b), MFF_{20} has typically quasi-concave functional relationships, which are independent for different values of L. Very small V_{T_c} results in low MFF_{20}. As V_{T_c} increases, MFF_{20} increases as the pollutant erosion rate (E) increases. At a certain point of V_{T_c}, MFF_{20} again decreases. This occurs because the short-term pollutant source ($m_{b,s}$) is depleted and the long-term pollutant sources (pollutant sources that are not depleted in a watershed) become the dominant pollutant source. Fig. 2(b) shows that MFF_{20} decreases as the watershed becomes longer. Similar to the case of T_c (shown in Fig. 2(a)), larger watersheds have less sensitivity of MFF_{20} to V_{T_c}. Fig. 2(a) and (b) conceptually show how FF can be influenced by the transport time and erosion rate of a pollutant.

An FF prediction tool for a given weather condition such as I, T, and antecedent dry days (ADD) can be created as shown in Fig. 3. Fig. 3 is a graphical relationship between MFF_{20} and T_c for given ranges of L and S_0 at $I = 3.6$ mm/h, $T = 8$ h, and

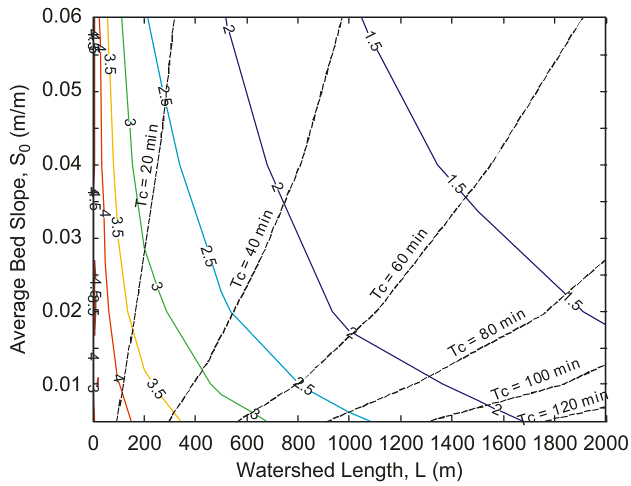

Fig. 3 – MFF_{20} as a function of L and S_0 at $I = 3.6$ mm/h, $T = 8$ h, and $m^o_{b,s} = 1.0\,g/m^2$.

$m^o_{b,s} = 1.0\,g/m^2$ (typical means of values observed in west Los Angeles). For the given conditions of I, T, and $m^o_{b,s}$, MFF_{20} tends to increase as the values of L, S_0, or T_c decrease. A large watershed with a steep slope (T_c between 40 and 80 min) tends to create a weak FF effect.

In order to obtain a more general relationship among FF, T_c, and L, contours can be created from a series of model simulations. Fig. 4 shows contours of MFF_{20} for COD as functions of L and $T_c/L^{0.6}$ for four different rainfall durations, using the ASCE formula for T_c (Table 1). By rearranging this formula, the value of $T_c/L^{0.6}$ can be calculated for given values of I, S_0, and n, and then used to predict FF for specific watershed lengths, L. The term $6.94n^{0.6}/I^{0.4}S_0^{0.3}$ has minimum and maximum values, depending upon the ranges of I, n, and S_0, which are useful to define the ranges of $T_c/L^{0.6}$ for analysis. Fig. 4 was created using values of n, I, and S_0, which are shown in Table 2. Using Fig. 4, watershed length and slope can be adjusted to obtain maximum MFF_{20}, or knowing rainfall and site conditions, MFF_{20} can be predicted. Fig. 4 can be applied to any location using appropriate parameters for that location.

Fig. 5 is similar to Fig. 4, except that the contours are $PEMC_{60}$/EMC for COD, and the storm duration, T, is calculated for 3, 5, 7, and 11 h. All the values of $PEMC_{60}$/EMC that appear in Fig. 5 are larger than 1.0, which means that the mean COD concentration during the first hour of runoff is always higher than EMC (CFF). Using Figs. 4 and 5, one can obtain the FF indices (i.e., MFF_{20}, $PEMC_{60}$/EMC) corresponding to intermediate storm duration by interpolation.

4.3. *Other factors for the first flush*

4.3.1. *Effect of rainfall duration*

Rainfall duration increases total runoff volume, which influences FF (Sansalone and Cristina, 2004, Kang et al., 2006). Fig. 6 shows MFF_{20} for COD as a function of T. As shown in Fig. 6, very short rainfall duration results in relatively low MFF_{20}. As rainfall duration increases, MFF_{20} increases to a maximum and then decreases. This occurs for the following reasons. For very short storm duration, short-term pollutant

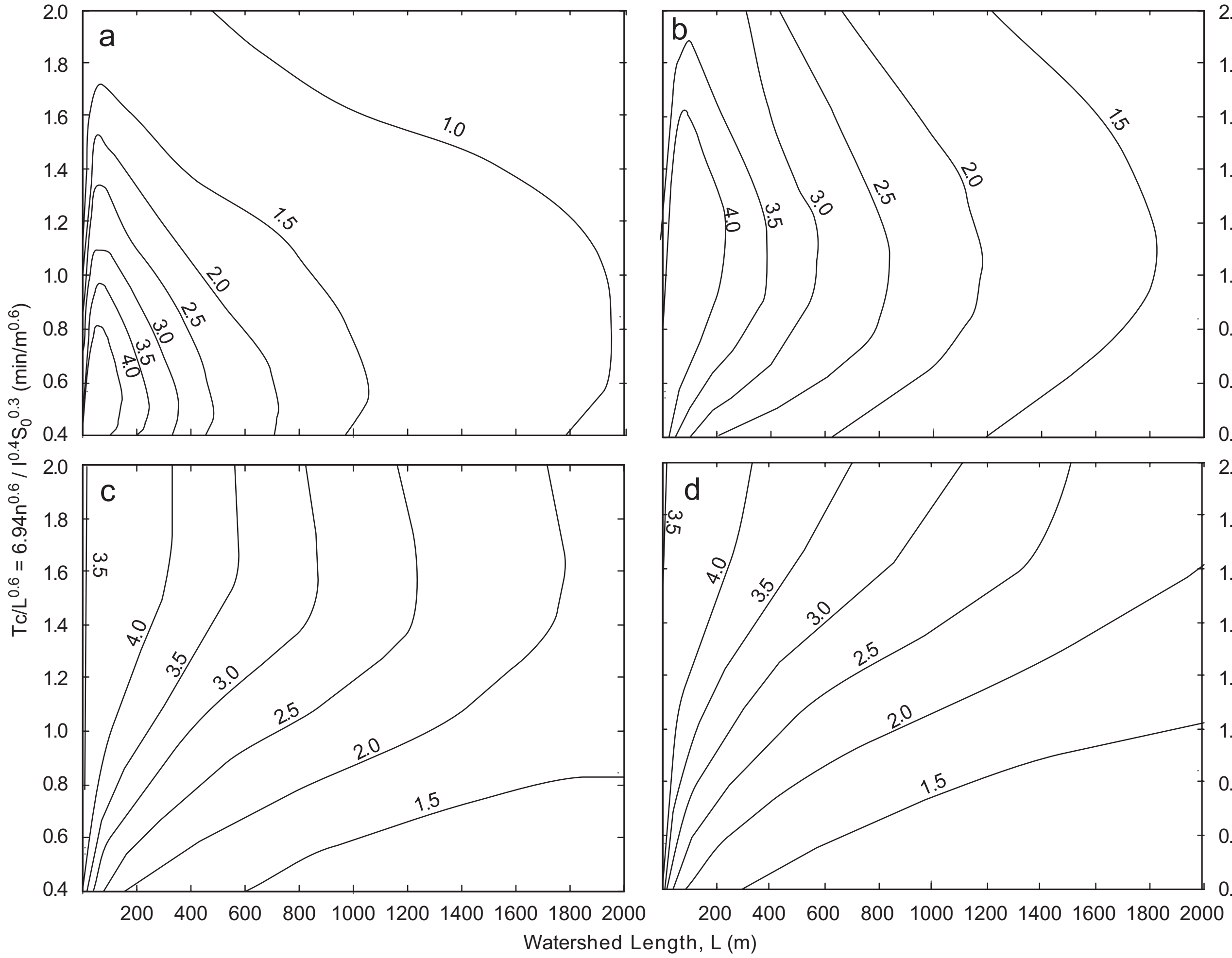

Fig. 4 – Contours of MFF_{20} as a function of $T_c/L^{0.6}$ and L for different rainfall durations: (a) $T = 1$ h; (b) $T = 3$ h; (c) $T = 7$ h; (d) $T = 11$ h.

sources dominate the overall pollutant emission and pollutant concentration in the runoff remains high throughout the storm; as a result, mass emission rate varies little with respect to storm elapsed time, resulting in low MFF_{20}. For moderately long storm duration, short-term sources are depleted before the storm ends, and the later part of the storm has lower pollutant concentration, resulting in high MFF_{20}. If rainfall duration is extremely long, the amount of pollutant emission from long-term source dominates the total amount of pollutant emission, attenuating MFF. Therefore, it is seen that MFF ratios approach 1.0 for an infinitely long storm duration regardless of T_c. The $PEMC_t$/EMC ratio does not approach 1.0 because the initial period, t, for the $PEMC_t$ calculation is not influenced by storm duration.

4.3.2. *FF estimation for different antecedent dry days (ADD)*

Table 3 summarizes the major factors affecting FF and their functional and physical relationships. ADD is an important factor that determines initial pollutant mass from short-term sources ($m^o_{b,s}$) in a watershed. Kang et al. (2006) showed that MFF ratios are sensitive to the initial pollutant mass using simulation results. Short ADD produces less initial pollutant mass, resulting in a low MFF ratio (sometimes, the absence of FF effect). Southern California and other areas having Mediterranean climates can have long dry periods or long ADD, which results in larger short-term sources and even a seasonal FF (Lee et al., 2004). The trends shown in Table 3 can be extended to other areas using simulations.

4.4. *Comparison of measured and simulated MFF_{20}*

Table 4 compares the experimentally measured values of MFF_{20} and the simulated values of MFF_{20}, which were obtained from the contours in Fig. 4, for the same T_c and L. The measured storm events were from the previously reported highway site (Kang et al., 2006). Eight storm events that are approximately equal to the simulated values of ADD and T were considered for the comparison. Average rainfall intensity, bed slope ($S_0 = 0.02$) and length ($L = 178$ m), and 0.011 of n were used to calculate event-specific T_c with the ASCE formula. As shown in Table 4, simulated values of MFF_{20} for most events were larger than 3.0. Initial pollutant masses ($m^o_{b,s} = 1.0\,\text{g/m}^2$) were sufficiently high, to create high

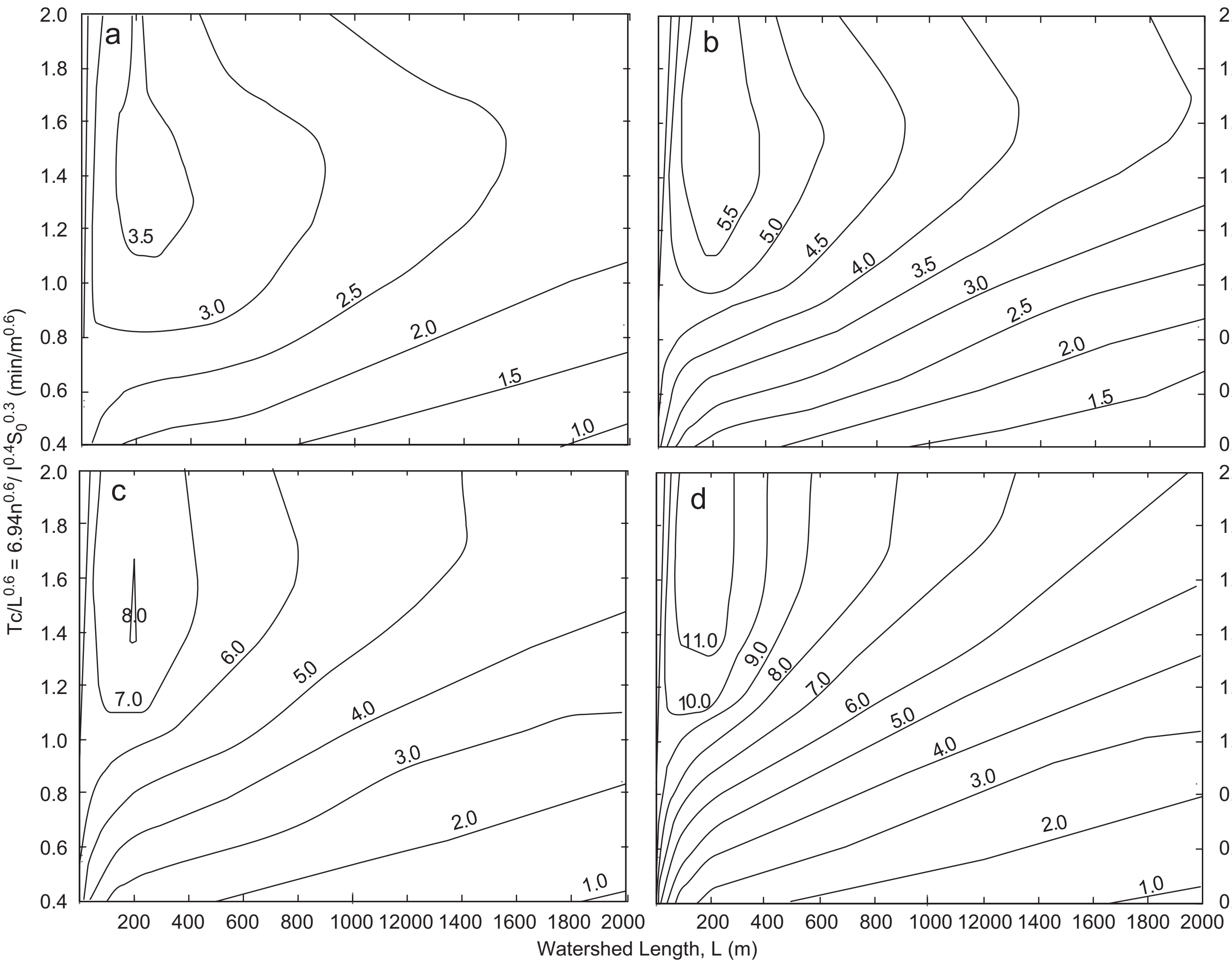

Fig. 5 – Contours of PEMC$_{60}$/EMC as a function of $T_c/L^{0.6}$ and L for different rainfall durations: (a) $T = 3$ h; (b) $T = 5$ h; (c) $T = 7$ h; (d) $T = 11$ h.

MFF$_{20}$. Four events (4/6/2001, 11/24/2001, 1/27/2002, 3/17/2002) matched measured and simulated values of MFF$_{20}$, whereas the simulation slightly overestimated MFF$_{20}$ for two events (2/17/2002, 3/17/2002). Non-uniform rainfall intensity with subsequent flow rate changes in real storms, as compared with ideal storms with constant rainfall, is one reason for the differences between measured and simulated MFF$_{20}$. The large differences in measured and simulated MFF$_{20}$ for the events on 11/12/2001 and 11/29/2002 are caused by non-uniform rainfall, which created two runoff peaks.

5. Conclusions

A one-dimensional kinematic wave model (Kang et al., 2006) was used to investigate the theoretical relationship between time of concentration (T_c) and FF effect.

Based on simulations and comparison of simulation results with eight storm events, the following conclusions are made:

- ASCE's kinematic wave formula (the ASCE formula) systematically underestimated T_c when compared with results from the kinematic wave equation model. Although recommended only for watersheds less than 90 m, the ASCE formula provided valid T_c for large water-

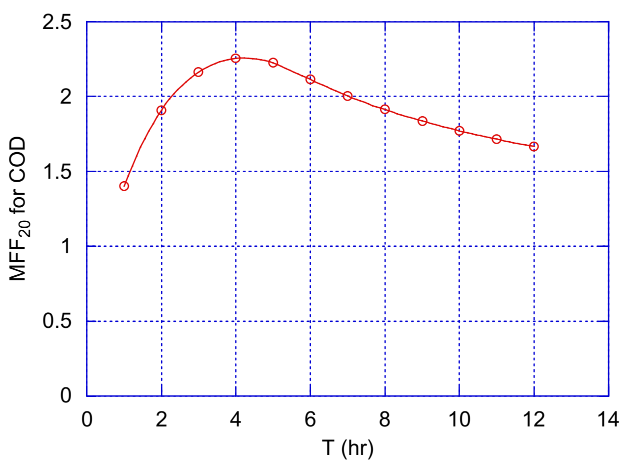

Fig. 6 – Effect of rainfall duration at $I = 3.6$ mm/h, $S_0 = 0.02$, and $L = 1000$ m.

Table 3 – Parameters that determine the degree of first flush

Parameters	Functional relationship with MFF ratios	Physical effects on FF	Descriptions
T_c (or $V_{T_c} = L/T_c$)	Quasi-concave	Pollutant delivery time Pollutant erosion rate	Time of concentration as a function of i, n, S_0, and L
L	Quasi-concave	Pollutant delivery time Pollutant erosion rate	Watershed length (or longest flow length)
T	Quasi-concave	Pollutant mass washed off	Rainfall duration
$m^o_{b,s}$	Monotonically increasing	Pollutant mass washed off	Initial mass of short-term pollutant sources

Table 4 – Comparison of measured and simulated MFF_{20}

Event	I^a (mm/h)	ADD (days)	$m^o_{b,s}$ [b] (g/m^2)	T (h)	T_c (min)	MFF_{20} for COD	
						Measured[c]	Simulated[d]
4/6/2001	2.35	31.5	1.2	10.8	22	2.9	3.1
11/12/2001	5.26	13.0	0.9	1.4	16	0.9	3.5
11/24/2001	6.46	11.6	0.8	4.6	15	3.1	3.2
1/27/2002	2.86	27.1	1.2	8.6	21	3.0	2.8
2/17/2002	3.70	20.3	1.1	2.9	22	2.3	3.5
3/7/2002	0.46	18.0	1.0	10.0	43	3.1	4.0
3/17/2002	7.43	11.0	0.8	1.4	14	3.1	3.3
11/29/2002	0.22	20.2	1.1	6.9	58	1.7	4.0

[a] Average rainfall intensity (= total rainfall/rainfall duration).
[b] Calculated with ADD using the buildup equation suggested by Kang et al. (2006).
[c] Obtained from the water quality data.
[d] Obtained from the contours in Fig. 4 using values of T_c at $L = 178$ m.

sheds ($L > 500$ m), with less than 16% maximum relative difference (less than 10% in most cases) with T_c obtained from the kinematic wave equation model.

- T_c can be used to combine the impact of several site-specific parameters affecting FF such as rainfall intensity, slope, and Manning's roughness coefficient, which was shown using the correlation between T_c and FF calculated from the kinematic wave equation model.
- Under a given condition for the rainfall duration and initial pollutant mass available in the watershed, the magnitude of the FF effect can be estimated using only three parameters, which are T_c, watershed length (L), and rainfall duration (T). These parameters represent average characteristics for the erosion rate and the transport time of pollutants in a watershed.
- T_c was not monotonically related to the MFF ratios, and very short or long watersheds can show low MFF ratios, irrespective of T_c.
- Contours of MFF_{20} and $PEMC_{60}/EMC$ as functions of $T_c/L^{0.6}$ and L are useful tools to predict and quantify the FF effect of runoff in highway landuses.
- Storms with short or long rainfall duration reduce the MFF effect because of the interaction of short- and long-term pollutant sources. For short duration, the short-term sources are not exhausted and pollutant emission rate is high throughout the storm. For long duration, the long-term source dominates and is large compared with emission from the short-term sources. For medium duration, emission from the short-term sources is large compared with emission from the long-term sources, and an MFF is observed.
- Experimentally measured MFF_{20} was compared with simulated MFF_{20} for the eight storm events measured in the highway site. Among six events, having relatively uniform rainfall intensity, simulated MFF_{20} matched the measured MFF_{20} with an RMS error of 25%.

The specific T_c–MFF_{20} and T_c–$PEMC_{60}/EMC$ contours are only valid for sites having similar rainfall, landuse, and traffic conditions to the study area. The same procedure can be used to create the contours for different sites and weather conditions. The generalized relationship between T_c and FF might be possible by means of other types of tools such as nomographs developed using simulations of the kinematic wave model. This is beyond the scope of this paper and is left as future work.

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