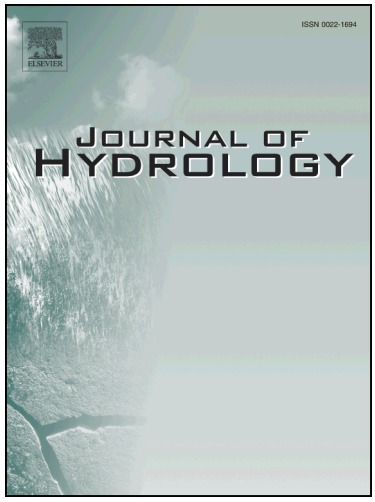

Research papers

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Density-based Global Sensitivity Analysis of Sheet-Flow Travel Time: Kinematic Wave-Based Formulations

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Abstract

Despite advancements in developing physics-based formulations to estimate the sheet-flow travel time (t_{SHF}), the quantification of the relative impacts of influential parameters on t_{SHF} has not previously been considered. In this study, a brief review of the physics-based formulations to estimate t_{SHF} including kinematic wave (K-W) theory in combination with Manning's roughness (K-M) and with Darcy-Weisbach friction formula (K-D) over single and multiple planes is provided. Then, the relative significance of input parameters to the developed approaches is quantified by a density-based global sensitivity analysis (GSA). The performance of K-M considering zero-upstream and uniform flow depth (so-called K-M1 and K-M2), and K-D formulae to estimate the t_{SHF} over single plane surface were assessed using several sets of experimental data collected from the previous studies. The compatibility of the developed models to estimate t_{SHF} over multiple planes considering temporal rainfall distributions of Natural Resources Conservation Service, NRCS (I, Ia, II, and III) are scrutinized by several real-world examples. The results obtained demonstrated that the main controlling parameters of t_{SHF} through K-D and K-M formulae are the length of surface plane (mean sensitivity index $\hat{T}_i$=0.72) and flow resistance (mean $\hat{T}_i$=0.52), respectively. Conversely, the flow temperature and initial abstraction ratio of rainfall have the lowest influence on t_{SHF}

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(mean $\hat{T}_i$ is 0.11 and 0.12, respectively). The significant role of the flow regime on the estimation of t_{SHF} over a single and a cascade of planes are also demonstrated. Results reveal that the K-D formulation provides more precise t_{SHF} over the single plane surface with an average percentage of error, APE equal to 9.23% (the APE for K-M1 and K-M2 formulae were 13.8%, and 36.33%, respectively). The superiority of Manning-jointed formulae in estimation of t_{SHF} is due to the incorporation of effects from different flow regimes as flow moves downgradient that is affected by one or more factors including high excess rainfall intensities, low flow resistance, high degrees of imperviousness, long surfaces, steep slope, and domination of rainfall distribution as NRCS Type I, II, or III.

***Key-Words*:** Unit hydrograph, Sheet-flow, Travel time, Kinematic wave, Sensitivity Analysis, Flow regime.

1. Introduction

Sheet-flow travel time (t_{SHF}) is defined as the time that excess-rainfall originated from rainfall, snowmelt, and saturation excess on the soil surface moves from the furthest segment of the drainage path which is located immediately downstream from the drainage divide line to the nearest stream or becomes shallow-concentrated flow (NRCS, 1986; Yamoto and Islam 1992). This compartment contributes an important part of the time of concentration of watershed to develop the unit hydrograph (Froelich, 2011) and selecting the design storm intensity for estimation of watershed peak-outflow (Bondelid et al., 1982). Almost all hydrologic analyses and modelling require the value of time response characteristics as input (McCuen et al., 1984; Paniconi and Putti, 2015).

Compared with the other compartments of time of concentration of watershed (i.e. shallow-concentrated and stream-flow), t_{SHF} is likely to be the dominant component for small watersheds, parking lots, rooftops, highways, airport runways, artificially

constructed wetlands, agricultural plots, and lawns (Singh, 2002) and at the same time, is the most theoretically questionable of the three compartments (Dewberry, 2003). These challenges arise mainly from non-homogeneity in land cover and land use as major characteristics of micro and partly urbanized watersheds that certainly affect the sheet-flow properties (i.e. travel time and flow depth). Developed formulations to estimate t_{SHF} are an important step to partially compensate for this challenge.

Since Lighthill and Whitham (1955) and thereafter Miller and Gunge (1975) showed that inertial and pressure forces are not important for overland flow during storm events due to the domination of the bed slope term in the motion equation, an increasing number of applications of the kinematic wave (K-W) theory are reported for developing physics-based formulations for accurate and efficient estimation of t_{SHF} over single (Overton and Meadows, 1976; SCS, 1986; Wong and Chen, 1997) or multiple continuous planes (e.g. Kibler and Woolhiser, 1972; Wong 1996).

Whereas successive progressions were obtained by combining the K-W theory with the Manning's resistance formulation (K-M) to estimate t_{SHF} over a single plane (NRCS, 1986; ASCE, 1992; Overton and Meadows, 1976; Froehlich, 2011); two planes in V-shape geometry (Overton and Eagleson, 1970; Singh, 1996); multiple plane surfaces (Brakensiek, 1967; McCuen and Okunola, 2002); converged hillslope (Veal, 1966), diverged hillslope (Campbell and Parlange, 1984) and complex-shaped hillslope (Sabzevari et al. 2013); and watershed geometry and leaf-shape water geometry (Agiralioglu, 1985). However, this formulation was limited to turbulent or near turbulent sheet-flow regime over the whole surface plane. Further simplifications accompanied by the K-W approach are ignoring the effects of momentum due to sheet-flow and rain (Langford and Turner, 1973), and considering one-dimensional sheet-flow and uniform distribution of rainfall over the plane surface.

As sheet-flow is characterized by a small hydraulic radius (i.e. flow depth) and slow velocity at the upgradient region, the flow regime should not be considered fully turbulent over the surface plane (Bulter, 1977). Combining K-W theory with the Darcy-Weisbach friction formulation (K-D) incorporates the effect of different flow regime (laminar, transitional, and turbulent) to estimate t_{SHF} (Singh 1988; Wong and Chen, 1997). Field and laboratory studies on t_{SHF} seem to use the K-D equation whilst the K-M equation is frequently used for channel flow (Abraham et al., 1990). However, selecting the type of equation for estimation of t_{SHF} appears to be much more influenced by personal preference rather than the real properties of sheet-flow. Probably one of the reasons that hydrologists tend to use K-M rather than K-D is the lack of data sources for Manning's roughness coefficient (n) compared with the Darcy-Weisbach coefficient (f), and also the uncertainties in f values for different flow regimes and surfaces (Grismer, 2016).

The input parameters for these formulations can be categorized as 1) physical properties of the plane surface including soil type, land use, land cover, surface slope, flow resistance (roughness), and length of surface in direction of flow; and 2) storm and weather conditions including the temporal and spatial distribution of rainfall intensity, average daily rainfall, temperature, and initial abstractions related to climate conditions. However, previous works report that the parameters which have the dominant influence upon t_{SHF} in the catchment are length, slope, roughness and flow regime (e.g. Wooding, 1965). No attempt has been made to systematically and quantitatively indicate the relative impact of these influential parameters on the t_{SHF}. In addition, applications of developed models have been mainly limited to hypothetical examples that did not fully match with real-world conditions. To fill these gaps, the main objective of this study is to obtain the

relative influence of input parameters of kinematic wave-based formulations to estimate t_{SHF} by a density-based global sensitivity analysis (GSA) for the first time.

An integrated assessment of the developed formulations to estimate the t_{SHF} and the degree of conformity of their results with experimental data and also practical conditions are scrutinized for the first time by considering a single plane. The overall flowchart of the research methodology is shown in Fig. 1. The performance of the developed formulae to estimate the t_{SHF} are also assessed through multiple continuous planes by using numerous real-world systems of hillslope-riparian-stream hydrologic connectivity where the temporal variation of rainfall intensity is also considered. A brief review of the K-W based formulations on the estimation of t_{SHF} is given in the next section.

2. Research Background for t_{SHF} over Single and Multiple Planar Surfaces

The kinematic wave (K-W) model, in addition to the diffusion, full- and steady dynamic, and gravity wave models, is a distinctive approximation of the Saint-Venant equation (Ponce and Simons, 1977). According to Table 1, the K-W model is based on the continuity equation and only approximates the dynamic equation so that the friction slope is parallel to the bed slope (Miller, 1983). The K-W gives a valid approximation for hydraulics of one dimensional, shallow, unsteady and uniform flow travelling down across planar (or wide) surfaces in the absence of backwater effects and incompressibility of flow, as shown in Fig. 2 (Lighthill and Witham, 1955; Wooding 1965; Singh, 1996):

$$\frac{\partial y}{\partial t} + \frac{\partial q}{\partial x} = i - I \quad (1)$$

where y is depth of flow perpendicular to plane surface $[L]$, q is unit discharge $[L^2\ T^{-1}]$, i is average rate of distributed inflow per unit area due to rainfall $[L\ T^{-1}]$, I is losses due to interception, infiltration, and surface storage $[L\ T^{-1}]$, t is the time since excess rainfall

appears $[T]$, and x is distance along the plane in flow direction $[L]$. The right hand side of Eq. 1 can be replaced by the average excess rainfall intensity i_e (e.g. Singh 2001, García-Serrana et al., 2017). The K-W model uses the continuity and simplified form of the motion equation such that the friction slope is equal to the bed slope and, therefore, does not change with flow conditions. The K-W approximation, which also denotes the quasi-steady condition (Wooding, 1965), is also valid when the Froude number of sheet-flow is less than or equal to two, $Fr \leq 2$ (Miller, 1983). The equation of motion states that the lateral inflow (q) is related to flow depth (y) only by using two coefficients α and β in Eq. 2 under the assumption that the hydraulic radius of sheet-flow, R_h $[L]$ equal to y (Eagleson, 1970; Singh, 2001):

$$q = \alpha\, y^{\beta} \tag{2}$$

Where α $[-]$ is a resistance parameter and reflects the interaction between the fluid particles themselves and between the fluid and the surface boundary and whose value varies in space and time. The parameter β $[-]$ is an exponent indicating the regime of flow and degree of nonlinearity which varies from 1 (highly turbulent) to 3 (laminar) (Singh, 2002). Two coefficients α and β can be defined by the Darcy-Weisbach friction formula using Eq. 3 (for laminar, transitional, and turbulent flow regimes) or by the Manning's resistance formula using Eq. 4 (for turbulent or near turbulent flow regime) regardless of their spatial and temporal heterogeneities (Julien and Simons, 1985):

$$\begin{cases} \alpha = \dfrac{8\, g\, S}{\tau_1\, \nu} \;\; ; \quad \beta = 3 & \text{for laminar flow} \qquad (3-a) \\ \alpha = \left(\dfrac{8\, g\, S}{\tau_2\, \nu^k}\right)^{\frac{1}{2-k}} \;\; ; \;\; \beta = \dfrac{3}{2-k} \;\; ; \quad 0 < k < 1 & \text{for transitional flow} \qquad (3-b) \\ \alpha = \left(\dfrac{8\, g\, S}{\tau_3}\right)^{1/2} \;\; ; \quad \beta = \dfrac{3}{2} & \text{for turbulent flow} \qquad (3-c) \end{cases}$$

$$\alpha = \frac{\sqrt{S}}{n} \quad ; \qquad \beta = \frac{5}{3} \tag{4}$$

where g is gravity acceleration $[L\,T^{-2}]$, S is slope of surface plane in flow direction $[L\,L^{-1}]$,ν is kinematic viscosity of sheet-flow $[L^2\,T^{-1}]$, τ is a constant value that related Reynolds number (R_e) to the Darcy-Weisbach resistance coefficient (f) through the $f = \tau_1/R_e$ (for laminar flow), $f = \tau_2/{R_e}^k$, $0 < k < 1$ (for transitional flow), and $f = \tau_3$ (for turbulent flow) (Wenzel, 1970). Solving the first-order hyperbolic differential equation of Eq. 1 by the method of characteristics yields a nearly analytic solution for celerity of the wave, ω $[L\,T^{-1}]$ that, therefore, involves very little numerical dispersion (Crandall, 1956):

$$\omega = \frac{dx}{dt} = \frac{dq}{dy} \quad ; \quad \frac{dy}{dt} = i_e \tag{5}$$

Integrating Eq. 5 with respect to $x = 0 \rightarrow L$, $t = 0 \rightarrow t_t$, and considering the upstream boundary condition (i.e., $q_{x=0} = q_u$, where u denotes upstream), the travel time for a planar surface, t_{SHF} can be obtained (Wong, 1996; Beldring *et al*., 2000):

$$t_{SHF} = \frac{{q_d}^{1/\beta} - {q_u}^{1/\beta}}{\alpha^{1/\beta}\, i_e} \quad ; \quad q_d = q_u + i_e\, L \tag{6}$$

where L is the total length of plane in flow direction $[L]$. According to K-W theory, Eq. 1 defines the travel time as the time needed for establishing the equilibrium state for discharge (i.e. inflow =outflow) at any point of interest over the surface plane (ASCE, 1992; Akan, 1986).

For zero up-stream boundary condition (i.e. q_u=0), and considering turbulent flow over the entire surface (replacing α and β by Manning formula, Eq. 4), Eq. 6 reduces to that obtained by the previous studies (i.e. Wong, 1994; Henderson and Wooding, 1964):

$$t_t = \left(\frac{L}{\alpha}\right)^{1/\beta} i_e^{\frac{1}{\beta}-1} \rightarrow t_t = \frac{\gamma}{i_e^{0.4}}\left(\frac{Ln}{S^{0.5}}\right)^{0.6} \quad (7)$$

where γ is conversion factor of units. γ =9.80 for SI units (min for t_t, m for L, $\mathrm{m.m^{-1}}$ for S, and $\mathrm{mm.hr^{-1}}$ for i_e), and γ=1.315 for the British Imperial (BG) units (min for t_t, ft for L, $\mathrm{ft.ft^{-1}}$ for S, and $\mathrm{in.hr^{-1}}$ for i_e), and n $[L^{-1/3}\,T]$ is Manning's roughness coefficient. Some studies (i.e. Ragan and Duru, 1972; Overton and Meadow, 1976) obtained t_t equation by considering uniform flow depth over the planar surface ($y_{x=0\rightarrow L} = y$) with keeping turbulent flow assumption. A schematic watershed and the above mentioned variables are shown in Fig. 2. Assuming uniform flow depth over the surface reduces the conversion factor γ to 6.988, and 1.40 for SI and BG units, respectively. However, employing a zero-upstream boundary condition to obtain the t_t (Eq. 7) gives a greater travelling time by a factor of 1.4, but it is more realistic and coincides with real cases as flow depth (or flow velocity, V $[L\,T^{-1}]$) increases as flow travels to the downstream of the surface, such that the maximum depth (or V) occur at downstream edge of surface ($y_{x=L} = y_{max}, V_{x=L} = V_{max}$). Applying uniform flow depth over the surface assumed identical flow velocity over the planar surface which is equal to V_{max}. It should be noted that Eqs. (6 and 7) are valid if the parameters of S, n, i_e (i.e. infiltration), and flow regime (i.e. turbulent) are constants over the plane surface (Wong, 1996). Considering the zero-upstream flow condition, and therefore flow-depth growth, implies a changing flow regime from laminar, at the upstream edge through transitional, at the middle distance to turbulent flow, at the downstream edge. If the Reynolds number is defined as $R_e = V.R_h/\nu = q_d/\nu$ (Savat, 1977), the critical values of R_e for changing the flow regimes yields the portion of plane length with laminar (L_1), transitional (L_2), and turbulent (L_3) flow regime as follows (Wong and Chen, 1997):

$$L_1 = \frac{\delta \nu Re_1}{i_e} \;\; ; \;\; L_2 = \frac{\delta \nu (Re_2 - Re_1)}{i_e} \;\; ; \;\; L_3 = L - (L_1 + L_2) \;\; ; \;\; \delta = 3.6 \times 10^6 \quad (8)$$

where Re_1, and Re_2 are critical Reynolds numbers for the laminar, and the transitional flow regime over the plane, respectively. According to Wenzel (1970), Re_1 and Re_2 are assumed equal to 200 and 2000, respectively. As the plane surface is continuous, the unit discharge (q) changes between $[q_u = 0,\ q_d = i_e\, L_1/\delta]$, $[q_u = i_e\, L_1/\delta,\ q_d = i_e\,(L_1 + L_2)/\delta]$, and $[q_u = i_e\,(L_1 + L_2)/\delta,\ q_d = i_e\, L/\delta]$ for the portion of plane with laminar, transitional, and turbulent regime, respectively. Considering these boundary conditions, and also the length of flow with different regimes (Eq. 8), the final form of t_{SHF} based on the kinematic wave solution for single planar surface in conditions of constant S, n, i_e, water temperature, and absence of back water is as $t_{SHF} = t_1 + t_2 + t_3$, where t_1, t_2, and t_3 are sheet-flow travel time for laminar, transitional, and turbulent flow portion, defined respectively as (Wong and Chen, 1993)

$$t_1 = 0.595 \left(\frac{\delta \nu f\, Re_1 L_1}{S\, {i_e}^2}\right)^{1/3} \qquad for \quad 0 \le x \le L_1 \; or \; Re < Re_1 \tag{9}$$

$$t_2 = 0.595 \left(\frac{f\,(Re_2\, \delta \nu)^k}{S\, {i_e}^{k+1}}\right)^{\frac{1}{3}} \times \left[(L_1 + L_2)^{\frac{2-k}{3}} - {L_1}^{\frac{2-k}{3}}\right]$$

$$for\ L_1 \le x \le L_2 \; or \; Re_1 < Re < Re_2 \tag{10}$$

$$t_3 = 0.595 \times \left(\frac{f}{S\, i_e}\right)^{1/3} \times \left[L^{2/3} - (L_1 + L_2)^{\,2/3}\right] \quad for\ L_2 \le x \le L \; or \; Re > Re_2 \tag{11}$$

For laminar and transitional sheet-flow regimes on a given surface (i.e. R_e< 2000), the flow resistance (f) increases by the growth of the flow depth (or excess rainfall intensity), whereas for the higher Reynolds number, the effect of intensity becomes insignificant (Zoltani, 1992). The relations of f and Re for laminar, transitional, and turbulent flows are $f = \tau_1/Re$, $f = \tau_2/\sqrt{Re}$, and $f = \tau_3$, respectively. Constants of τ_1, τ_2, and τ_3 are a function of surface slope and rainfall intensity (or flow depth) which can

be obtained from the previous analysis on different surfaces (i.e. Phelps, 1970; Wenzel, 1970; Radojkovic and Maksimovic, 1986).

Estimation of t_{SHF} using the Manning formula is valid for turbulent or near turbulent flow regimes in two conditions of zero-upstream ($y_u = 0$) and uniform flow depth over the planar surface ($y_u = y_d$) (McCuen and Okunola, 2002):

$$t_{SHF} = \begin{cases} 6.988 \times \left(\dfrac{n\,L}{\sqrt{S}\,{i_e}^{2/3}} \right)^{3/5} & for\ \ y_u = 0 \qquad (12-a) \\ 4.984 \times \left(\dfrac{n\,L}{\sqrt{S}\,{i_e}^{2/3}} \right)^{3/5} & for\ \ y_u = y_d \qquad (12-b) \end{cases}$$

The current version of Natural Resources Conservation Service (NRCS) software, TR-55 (SCS, 1986), regardless of flow regime, considers a maximum length of 300 feet (~100 m) for sheet-flow or the distance between the drainage divide and the upper end of a defined stream (each one is smaller). After this distance, even if the plane surface continues, the sheet-flow becomes shallow-concentrated flow.

2.1. *Goodness of K-W Theory to Estimate t_{SHF}*

Despite numerous studies successfully applying the K-W theory for modelling overland flow, Woolhiser and Liggett (1967) derived a criterion referred to as the kinematic wave number (η) for judging the goodness of the K-W approximation in modelling of sheet-flow over a sloping plane

$$\eta = \frac{S\,L}{y\,Fr^2} \qquad (13)$$

All variables in Eq. 13 are defined previously. Substituting $Fr = V/\sqrt{g\,y}$, Eq. 13 reduces to

$$\eta = \frac{S\,gL}{V^2} \qquad (14)$$

Woolhiser and Liggett (1967) indicated that for η> 50, the K-W approximation would be very good. Replacing g=9.81 $m\,s^{-2}$ in Eq. 14, $S\,L/V^2$ should be greater than 2.04 to have good approximation with K-W theory (units of V and L are $m\,s^{-1}$ and m, respectively) which is valid for sheet-flow over numerous natural surfaces. Therefore, the criterion of η needs to check only for smooth surfaces in which applying the K-W theory may produce a crude approximation (for example, in urban surfaces η may be below 20). Another goodness of fit criteria was suggested by McCuen and Spiess (1995) which implies that the K-W assumption should be limited to the kinematic wave number $N_{K-W} = nl/\sqrt{S}$< 100.

2.2. *Estimation of excess rainfall intensity, i_e*

In Eqs. (9) to (12), i_e is the average excess rainfall intensity for the storm with duration equal to t_t ($D = t_t$), therefore repeated solution of these equations are required to find an appropriate value of D that is equal to t_t. To eliminate this repetition problem, Chen and Evan (1977) proposed the use of an intensity-duration relation ($i - D$) in the form of $i = a \times D^{-b}$ (where a and b are regional constants) in the Manning formula (Eq. 12). Average rainfall intensity (i) is related to i_e by a runoff coefficient (C) through the rational formula of $i_e = C \times i$ (ASCE, 1992). Welle and Woodward (1986) used $i - D$ relations for two NRCS standard design storms Type II and III in the form of $i = a' \times P_{24} \times D^{-b'}$, where P_{24} is 24-hr rainfall depth in mm, and constants a' and b' are 5.7 and -0.62 (for storm Type II), and 4.76 and -0.63 (for storm Type III), respectively. The NRCS design storms I, Ia, II, and III are characterized by an intense rainfall period somewhere near the middle and lesser rainfall intensities at the beginning and end of the storm and have been applied to very large geographic regions (Cronshey and Woodward, 1989). For instance, the Type II distribution has been applied to a large part of the central

continental United States, and Type Ia has been used in the Pacific Northwest (SCS, 1973).

TR-55 model uses a modified form of the Manning formula (Eq. 12) in which i_e is replaced by 2-years P_{24}:

$$t_{SHF} = \frac{5.5}{\sqrt{P_{24}}} \times \left(\frac{n\,L}{\sqrt{S}}\right)^{4/5} \tag{15}$$

However, using $i - D$ relations in the estimation of t_{SHF} solves the repetition problem, but leads to different results as reported by McCuen and Spiess (1995). Froehlich (2009) showed that estimation of t_{SHF} with the Manning formula and $i - D$ relations proposed by Welle and Woodward (1986) produces significant error especially for a small duration, i.e. D <15 min. Precise estimation of i for four types of rainfall distributions of NRCS and wide range of D were proposed by Froehlich (2009) as

$$i_e = C \times \begin{cases} 16.138 \times \dfrac{P_{24}}{D} \times (1 - e^{-0.049 \times D}) + 0.0305 \times P_{24} & \text{for storm Type I} \\ 13.963 \times \dfrac{P_{24}}{D} \times (1 - e^{-0.017 \times D}) + 0.0322 \times P_{24} & \text{for storm Type Ia} \\ 26.911 \times \dfrac{P_{24}}{D} \times (1 - e^{-0.0601 \times D}) + 0.0231 \times P_{24} & \text{for storm Type II} \\ 26.998 \times \dfrac{P_{24}}{D} \times (1 - e^{-0.033 \times D}) + 0.0230 \times P_{24} & \text{for storm Type III} \end{cases} \tag{16}$$

Alternate formulation of Eq. (16), which is also used in this study, is the estimation of runoff coefficient (C) through Soil Conservation Service Curve Number (SCS-CN) method (Hawkins, 1983):

$$C = \frac{R}{P} = \frac{1}{P} \times \left[\frac{\left(P - \lambda \times \left(\frac{25400}{\mathrm{CN}} - 254\right)\right)^2}{P + (1 - \lambda) \times \left(\frac{25400}{\mathrm{CN}} - 254\right)}\right] \tag{17}$$

where R is direct runoff depth in mm, P is rainfall depth in mm, λ is initial abstraction ratio, and CN is the curve number. Combining Eq. (16) and (17) one can estimate the average excess rainfall intensity (i_e) for different temporal rainfall distributions of NRCS.

265

266 2.3. *Multiple Planar Surfaces*

267 In the previous section, the approaches for estimation of t_{SHF} over a plane surface are
268 presented, in which the input parameters (e.g. slope and roughness) are homogeneous
269 over the surface. This condition is more consistent with sheet-flow that occurs in the
270 furthest upstream segment of the drainage path or across the street in an urban area.
271 Commonly, sheet-flow from a wooded area may flow onto a dense grass-covered surface,
272 which may then discharge onto a paved surface, such as a driveway, and continue over
273 the rangeland or turf (as shown in Fig. 3). Each of these surfaces has a different resistance
274 to flow or roughness and hydraulic radius and may differ in slope and infiltration. Thus,
275 equations that assume a single section that is homogeneous in land cover, hydraulic
276 radius, and roughness (i.e. one used in TR-55), cannot be applied (McCuen and Okunola,
277 2002).

278 The assumptions of zero-upstream boundary conditions ($q_u = 0$) and uniform flow
279 distribution ($q_u = q_d$) behind Eq. (12) that lead to these formulae cannot be applied
280 precisely for the cascade of surface planes. For a multi-planar flow path with N planes in
281 which flow from an upgradient plane discharges onto the next down-gradient plane, Eqs.
282 (9-12 and 15-17) should be extended. Wong (1996) derived the kinematic wave and
283 Manning formula for estimation of t_{SHF} for a series of planes. The general form of t_{SHF}
284 formulation for cascade of N planes is as follows:

$$t_{SHF} = \sum_{j=1}^{N} \frac{L_j}{\alpha_j^{1/\beta_j}} \left\{ \frac{\left[\sum_{m=1}^{j} (i_{e_m} L_m)\right]^{1/\beta_j} - \left[\sum_{m=1}^{j-1} (i_{e_m} L_m)\right]^{1/\beta_j}}{\left[\sum_{m=1}^{j} (i_{e_m} L_m)\right] - \left[\sum_{m=1}^{j-1} (i_{e_m} L_m)\right]} \right\} \quad (18)$$

285 where j is index for planes in direction of sheet-flow. Eq. (18) is based on the
286 assumption that downstream outflow of one plane becomes the inflow to the adjacent
287 plane downstream, without backwater condition, and all surfaces contribute in runoff

generation. Replacing the values of α and β from Eqs. 3(a-c) corresponding to the flow regime in each section, reduces Eq. (18) to a kinematic wave approximation. The Manning expression for estimation of the t_{SHF} over continuous multi-planar surface for turbulent or near turbulent flow regimes (so called K-M3) can be obtained with parameters α and β from Eq. (4) employed in Eq. 18 as follows:

$$t_{SHF} = \sum_{j=1}^{N} 6.988\, L_j \left(\frac{n_j}{\sqrt{S_j}}\right)^{0.6} \left\{\frac{\left[\sum_{m=1}^{j}\left(i_{e_m} L_m\right)\right]^{0.6} - \left[\sum_{m=1}^{j-1}\left(i_{e_m} L_m\right)\right]^{0.6}}{\left[\sum_{m=1}^{j}\left(i_{e_m} L_m\right)\right] - \left[\sum_{m=1}^{j-1}\left(i_{e_m} L_m\right)\right]}\right\} \quad (19)$$

3. Global Sensitivity Analysis

Global Sensitivity Analysis (GSA) is a useful tool in understanding the relative influences of the different sources of uncertainty (e.g. model parameters, errors in forcing data, or non-numerical uncertainties) in the variability of the model output (Saltelli *et al.*; 2008, Baroni and Tarantola, 2014; Rajabi *et al.*, 2015). Density-based sensitivity indices (DSI) have become progressively widespread in GSA applications across different hydrological modelling fields (e.g. Pappenberger *et al.*, 2008; Peeters *et al.*, 2014). In the DSI approach proposed by Pianosi and Wagener (2015) which is named PAWN (derived from the authors names), the model output distribution for t_{SHF} is characterized by a data sample Cumulative Density Function (CDF) rather than its Probability Density Function (PDF). Practically, in the PAWN indices, the sensitivity to input x_i is measured by the distance between the empirical unconditional CDF of output t_{SHF}, $\hat{F}_{t_{SHF}}(t_{SHF})$ that is obtained when all inputs vary simultaneously, and the empirical conditional CDF, $\hat{F}_{t_{SHF}|x_i}(t_{SHF})$ that are obtained when varying all inputs but x_i is fixed at a nominal value, through the Kolmogorov-Smirnov statistic, $\widehat{KS}$ (Kolmogorov, 1933):

$$\widehat{KS}(x_i) = \max_{t_{SHF}} \left|\hat{F}_{t_{SHF}}(t_{SHF}) - \hat{F}_{t_{SHF}|x_i}(t_{SHF})\right| \quad (20)$$

Figure 4 shows the $\widehat{KS}$ obtained from the empirical unconditional and conditional CDFs. The empirical unconditional CDF y, $\hat{F}_{t_{SHF}}(t_{SHF})$ is approximated using N_u output estimations obtained by sampling the entire input feasibility region. The conditional CDF t_{SHF}, $\hat{F}_{t_{SHF}|x_i}(t_{SHF})$ is approximated using N_c output estimations obtained by sampling the non-fixed inputs only, while the value of x_i is kept fix. As statistics KS depends on the value at which x_i fixed, the index $\hat{T}_i$ considers the maximum values of $\widehat{KS}$ over all possible values of x_i (Pianosi and Wagener, 2015):

$$\hat{T}_i = \max_{\mathrm{x_i} = \bar{\mathrm{x}}_\mathrm{i}^{(1)}, \bar{\mathrm{x}}_\mathrm{i}^{(2)}, \dots, \bar{\mathrm{x}}_\mathrm{i}^{(\mathrm{n})}} \left|\widehat{KS}(x_i)\right| \tag{21}$$

where $\bar{\mathrm{x}}_\mathrm{i}^{(1)}, \bar{\mathrm{x}}_\mathrm{i}^{(2)}, \dots, \bar{\mathrm{x}}_\mathrm{i}^{(\mathrm{n})}$ are randomly sampled values for the fixed input x_i. The lower value of $\hat{T}_i$, ($\hat{T}_i \in [0,1]$) indicates the lower influence of the corresponding x_i on t_t. The total number of model evaluations necessary to compute the sensitivity index $\hat{T}_i$ for all the N_{param} inputs is $N_u + n' \times N_c \times N_{param}$ where N_u, n', and N_c are the number of samples to estimate the unconditional CDF, conditional CDF, and condition points, respectively. The proper values for n', N_u and N_c can be selected by trial-and-error to follow regularity properties of CDFs (continuity, monotonicity, relative smoothness). The index $\hat{T}_i$ is a global, model-independent, robust, quantitative, dimensionless, with no need for parameter tuning, no computing costs for computing the CDF, easy to implement, facilitates the application of bootstrapping and convergence analysis, and is unconditional on any assumed input value (Pianosi *et al*. 2015). In this study, the sensitivity index ($\widehat{KS}(x_i)$ and $\hat{T}_i$) of the sheet-flow travel time (t_{SHF}) estimated by K-M and K-D formulations to the input parameters of flow temperature (T), roughness (f or n), surface slope (S), rainfall depth (P), rainfall duration (D), average rainfall depth (P_{24}), runoff-coefficient (C), and length of plane surface (L) are calculated using Eq. 8. Whereas the input parameters related to NRCS storm characteristics are considered according to

Froehlich (2009). The index $\hat{T}_i$ is a helpful tool to investigate the relative influence of model parameters on predictive accuracy as well as to understand the dominant factors which control the precision of t_{SHF}.

4. Results and Discussion

The cumulative density function (CDF) of $\hat{F}_{t_{SHF}}(t_{SHF})$ and $\hat{F}_{t_{SHF}|x_i}(t_{SHF})$ for the model output (t_{SHF}) for the wide range of eight influenced parameters of K-M formulation with zero-upstream boundary condition ($n, S, D, P, \lambda, CN, P_{24}, L$) and also for nine effective parameters of K-D formulation ($T, f, S, D, P, \lambda, CN, P_{24}, L$) are computed (the results are not shown). The CDFs of all parameters grow significantly away from their initial uniform distributions but in different ways which lead to different sensitivity to these parameters. The sensitivity index of $\widehat{KS}(x_i)$ for the influential parameters in the estimation of t_{SHF} by K-D and K-M formulations are shown in Fig. 5 where α=0.05, $n' = 10$, $N_u = 100$, and $N_c = 50$. In both formulations, the effect of the temporal distribution of storm intensity is investigated by incorporating four temporal rainfall distributions of NRCS. The values of $\widehat{KS}(x_i)$ indicate that the storm occurrence time (e.g. winter or spring) are not affected by the t_{SHF} estimated by K-D formula since all values of this index rely on below critical values for a wide range of the flow temperature (between 2 to 45 $^{\circ}$C) as shown in Fig. (5-a). In addition, the t_{SHF} estimated by both formulations of K-D and K-M are not significantly sensitive to the wide range of rainfall depth, P (ranging from 0 to 1000 mm), initial abstraction ratio, λ (ranged 0.001 to 0.8), and also curve number, CN (ranging from 30 to 99) for all types of NRCS storms (except to P<100 mm of NRCS Type II in K-M formula) (Figs. 5 (e-g) and (m-o)). According to Eq. 17, the parameters P, λ, and CN contribute to the calculation of runoff coefficient, C, which is apparently not a significantly influential parameter on t_{SHF}. It should be noted

that the values of $\widehat{KS}$ indicate the relative influence of the corresponding parameter in comparison with other influential parameters. Further investigations indicate that computing the $\widehat{KS}$ for the input parameters of K-D and K-M formulae by directly entering the parameter C into Eq. 16 (in the range of 0.05 to 0.95), show that t_{SHF} is significantly sensitive to lower and upper values of C (<0.15 or >0.80) for all NRCS storms as shown in Fig. 6. However, the sensitivity of t_{SHF} to the lower and upper ranges of parameter C through K-M formula is greater than K-M. According to FWHA (1996), the lower values of C correspond to lawns with sandy soil and un-improved natural area (e.g. forest), whereas the upper values correspondent to asphaltic and concrete area in developed urban watersheds (e.g. rooftops, parking lots, and paved surfaces). Results of the $\widehat{KS}$ corresponding to both K-M and K-D formulations indicate that t_{SHF} is not influenced by C over the areas with intermediate values of runoff coefficient ($0.2<C<0.8$). For the upper values of C, the effect of temporal rainfall distribution (i.e. NRCS storms) is more dominant than for lower values.

The t_{SHF} is influenced by flow resistance (parameter f in K-D and parameter n in K-M formulae) for lower (f<10 and n<0.22) and upper (f>50 and n>0.6) values of surface roughness as shown in Figs. (5-b and 5-j). According to Engman (1986), the lower values of n correspond to asphalt and concrete, bare soil, and natural rangeland areas whereas the upper values link to the surfaces covered with dense grass. Interestingly, the sensitivity of the t_{SHF} estimated by K-D and K-M formulae to lower values of flow resistance is similar for four types of NRCS storms. However, the effect of temporal rainfall distribution is dominant for very rough surfaces. The intermediate rough surfaces (i.e. $0.2<n<0.6$) do not have a significant influence on the t_{SHF}, despite the dominance of temporal rainfall distribution for these surfaces. Surface plane slope (S) less than 10% (or 6°) has a significant influence on the estimation of t_{SHF} by two formulations of K-M and

K-D (Figs. 5-c and 5-k). This surface slope is frequently observed in natural watersheds (except to steep hill slopes which may be unstable) and also for the design of transverse slopes of roads (FHWA 1984).

The meaningfulness of the rainfall duration (D) on the t_{SHF} estimated by K-M and K-D formulae is limited to D<180 min (or 6 hr) for all types of NRCS storms. Storms with a duration greater than 6 hr do not have a significant impact on the t_{SHF} due to the decreasing storm intensity according to $i-D$ relations. The t_{SHF} is influenced significantly by 2-years 24-hr rainfall depth for P_{24} <200 mm or P_{24} >800 mm for both formulations of K-M and K-D and different types of NRCS storms (Figs. 5-h and 5-p). The range of P_{24} <200 mm covers the 2-years daily rainfall depth for all types of NRCS design storms in USA (SCS 1986).

The significant effect of surface plane length (L) on the estimation of t_{SHF} by the K-D and K-M formulations is limited to about L<3500 m (Figs. 5-I and 5-q). Noting the constraint of 100 m (or 300 ft) for sheet-flow length by TR-55, this parameter plays an important role in the t_{SHF} over a wide range of surfaces in natural and urban watersheds.

According to Eq. 18, the sensitivity index $\hat{T}_i$ is calculated as the maximum value of $\widehat{KS}$ over all possible values of input parameters in the K-M and K-D formulations (see Fig. 7). This index can be beneficial for ranking the sensitivity of the parameters that influence t_{SHF} for different storm types. Results of Fig. 7 reveal the dominant influence of parameter L in the estimation of t_{SHF} by K-M and K-D formulae and also for all types of NRCS storms, except in the case of NRCS Type II and K-M formula where the parameter n has the greatest influence. After the parameter L, the order of index $\hat{T}_i$ changes for K-M and K-D formulations and also for NRCS design storms. For all types of NRCS storms, the t_{SHF} estimated by K-M has the minimum sensitivity to the flow temperature. However, the t_{SHF} estimated by both formulations indicate lower sensitivity

to the parameters of the SCS-CN model (i.e. λ, CN, and P according to Eq. 17), but incorporating the runoff coefficient (C) directly in the models results in a significant increase of $\hat{T}_i$ related to this parameter (0.35 for K-D and 0.4 to 0.5 for K-M). On average, the two formulations of K-D and K-M consistently indicate that the plane surface characteristics (i.e. n or f, CN, L, and S) have the greater impacts on the t_{SHF} ($\hat{T}_i$ = 0.43 and 0.41, respectively) in comparison to storm and climate characteristics (i.e. T, D, λ, P, and P_{24}) ($\hat{T}_i$ = 0.20 and 0.27, respectively) for all NRCS storms. The surface related parameters have a near equal influence on t_{SHF}, whereas in the K-M formula, there is higher sensitivity to the parameters related to storm and climate. In addition, the order of average sensitivity of the t_{SHF} on the input parameters of K-D and K-M formulae are associated with the NRCS Type II ($\hat{T}_i$= 0.33 and 0.40), I, III, and then Type Ia, respectively. Table 2 summarizes the values of flow resistance coefficients (τ_1, τ_2, τ_3, and n) for three surfaces of grass, concrete, and turf used for estimation of the t_{SHF} by the four formulae which were obtained from previous experiments.

It should be mentioned that the values of τ_1, τ_2, τ_3, and n in Table 2 are based on selected parameters (e.g. surface slope, rainfall intensity, surface roughness) that were adopted in the application examples. The flow resistance coefficients need revision due to complicated dynamics of flow resistance caused by the influential factors (Saghafian and Julien 1989).

5. Application of Formulae

Twenty sets of experimental data covering a wide range of the influential factors (i.e. L, S, i_e, and n) on the measured t_{SHF} over a single plane surface are collected from previous studies and used to illustrate the performance of the developed formulations. Table 2 indicates the source experimental data, observed values of t_{SHF} and also t_{SHF}

values estimated using the K-M formula in two conditions $q_u = q_d$ (so-called K-M1) and q_u=0 (so-called K-M2), and K-D formula. For these experimental data, the TR-55 formula cannot be used due to lack of available information of P_{24} values. Results of Table 2 indicate that the calculated goodness of fit criteria η (obtained by using Eq. 13 or 14) and N_{K-W} indicates that all values of η and N_{K-W} are significantly greater and smaller than threshold value of 50 and 100, respectively. This guarantees that the K-W theory provides a very good approximation for all cases shown in Table 2. Considering zero-upstream boundary condition (assumed by K-M1 formula) are more realistic as flow runs over the single plane rather than the assumption of uniform flow depth all over the surface plane. For this purpose, the average percentage of error (APE) for three formulae of K-M1, K-M2, and K-D and for different flow regimes downgradient of the surface plane are computed and shown in Fig. 8. This assumption resulted in a reduction of APE in the estimation of t_{SHF} as 22.17%, 26.27%, and 18.90% for laminar, transitional, and turbulent flow regime, respectively. It is noteworthy that incorporating the Darcy-Weisbach friction in K-W theory (i.e. K-D formula) outperforms K-M1 and K-M2, especially for laminar and turbulent sheet-flow regimes. However, in transitional flow regime, the APE values for K-D and K-M2 are close together (6.03% and 6.39%, respectively), but the K-D indicates significant improvement for laminar and turbulent flow regime (6.4% and 5.67%, respectively).

It is noteworthy that among the used experimental data, the minimum APE value in the estimation of the t_{SHF} by three formulae is obtained in the cases of having the transitional and laminar flow regimes downgradient in the surface plane (Fig. 8). Three formulae have the maximum error in estimation of t_{SHF} for turbulent flow regime downgradient in the plane. Despite the fact that the Manning based formulae (i.e. K-M1 and K-M2) is based on the assumption of occurring turbulent flow regime over the whole surface plane,

457 the K-D formula is also proficient (i.e. less APE value) in this flow-regime condition.
458 Underestimation of t_{SHF} by three formulae, especially when the sheet-flow regime is
459 turbulent (see the calculated values of t_{SHF} in Table 2), may lead to the overestimation of
460 peak discharge in the hydrological design. These findings imply that considering one type
461 of flow regime (i.e. turbulent) throughout the surface plane, as is the case with the
462 Manning based formulae, could not be relied on to coincide with the realistic hydraulic
463 condition of sheet-flow. Previous research works (i.e. Bulter, 1977; Singh, 1988; Chen
464 and Wong, 1993) reported the inevitability of laminar or transitional flow regimes
465 occurring before turbulent flow regime as sheet-flow moves downgradient of the surface
466 plane which leads to increasing the t_{SHF}. Moreover, uncertainties and data scarcity of
467 friction factor f for different flow regimes and surface types are likely reasons why t_{SHF}
468 is underestimated by K-D formula.

469 The performance of the K-M and K-D formulae in the estimation of t_{SHF} are also
470 compared over hillslope-riparian-stream hydrologic connectivity system as multiple
471 continuous planes (MCPs). Unfortunately, no previous experimental data is available to
472 assess the t_{SHF} over MCPs. For the purpose of intercomparison of two K-M and K-D
473 formulae, a continuous cascade of three surfaces are assumed as a grassy surface at up-
474 gradient plane (covered by Kentucky blue grass), a smooth surface at middle plane (e.g.
475 rooftops, parking lot, and paved surfaces such as streets), and a slightly rough surface (i.e.
476 turf) at down-gradient plane. For the real-world application of the results, the surface
477 planes and storm and climate characteristics in these examples were collected from the
478 previous studies. The effect of temporal distributions of rainfall is also investigated by
479 considering four NRCS Type I, Ia, II, and III. The flow resistance parameters (τ_1, τ_2, and
480 τ_3), Manning's roughness coefficient (n), and runoff coefficient (C) of three considered
481 surfaces are given in Table 2. These parameters are kept constant for the corresponding

surfaces in all analysis. The values of t_{SHF} by two formulae (K-M and K-D) are calculated by considering numerous sets of input parameters (some of the results are shown in Table 4).

For each case, the percentage of turbulent flow portion on the three surfaces and the absolute difference of two formulations in the estimation of t_{SHF} are also calculated and given in Table 4. Results shown in Table 4 can be summarized as follows:

1) In all cases, the estimated values of t_{SHF} by the K-D formula are greater than those obtained by the K-M3 approach due to incorporating the effects of three flow regimes (laminar, transitional, and turbulent) in K-D formula instead of turbulent flow only. Longer t_{SHF} leads to delaying the time of peak flow and thus, changes the shape of the unit hydrograph obtained by two formulae.

2) A significant inverse correlation between the difference of K-M3 and K-D results and the portion of turbulent flow regime over the surfaces of planes is observed when the NRCS storm Type I, II, and III is considered. A weak correlation between two formulations of K-D and K-M3 is observed when the NRCS storm Type Ia is applied.

3) Changing the sheet-flow temperature due to weather conditions and rainy season affects the t_{SHF} estimated by K-D formula, whereas the K-M3 formula cannot incorporate the changes in flow temperature. This is one of the disadvantages of Manning based formulations.

4) The estimated values of t_{SHF} over multi-planar surfaces by K-D and K-M3 formulae are also affected by the sequence of the planes. If the sequence of planes in the sheet-flow direction is grassy area-concrete-turf (G→C→T) the t_{SHF} obtained by the K-D and also K-M3 formulae are different from other surface arrangement (e.g. G→T→C or C→T→G). The gradual increase of flow resistance (or decrease of runoff coefficient) in direction of sheet-flow over the cascade of surface planes leads to the two formulations

giving close results and less travel time than other sequences of surfaces (see rows #1, 8, and 9 in Table 3).

5) The calculated values of the t_{SHF} through NRCS storm Type Ia and Type II produces the maximum and minimum values of t_{SHF}, respectively.

6) Since the TR-55 formula uses 2-years P_{24} for the excess rainfall intensity (i_e), the same results are estimated using this formula when P_{24} is constant even if rainfall intensities change significantly (i.e. different NRCS storms).

6. Conclusion

- For small watersheds in which sheet-flow is the major contributor (or possibly the only contributor) to the time of concentration of watershed, the difference in estimation of t_{SHF} made when using various K-W based formulations likely have a considerable influence on peak-flow estimation and hence the appropriate design of drainage structures. The results obtained from GSA demonstrated that the main controlling parameters of t_{SHF} over the single plane and cascade of multiple planes estimated by K-M and K-D formulae are flow resistance, length of the surface plane, surface slope, and excess rainfall intensity. Conversely, the lowest sensitivity of t_{SHF} in K-D formula is to flow viscosity. This implies t_{SHF} is not affected by the weather temperature if the other influential parameters are kept constant.
- Results of this study indicate that the kinematic Darcy-Weisbach formulation (K-D) outperforms the kinematic Manning (K-M) formula in the estimation of t_{SHF} due to the fact that it considers the variations of flow regime on the surface plane. The developed formulae in this study maybe serve in the structure of stormwater hydrological models (e.g. TR-55 and HydroCAD) to have appropriate estimation of t_{SHF} in urban and small watersheds, and therefore increase confidence in design peak

discharge and drainage structure sizes for the required level of risk. Despite the fact that a more precise estimation of t_{SHF} would be obtained using the K-D formula over the single plane surface, of the lack of available data and also uncertainties associated with the friction factor (f) for different flow regimes and surface roughness is a significant challenge with the application of this formula.

- Overestimation of peak discharge may occur in hydrological forecasting and design due to use of shorter estimates of t_{SHF} estimated by both Manning- and Darcy-Weisbach-based formulae.
- The estimated t_{SHF} by two formulations of kinematic Manning (K-M3) and K-D over the cascade of continuous planes is also affected by the sequence of the planes due to change in upstream flow boundary condition.

The kinematic wave approximation of Saint-Venant equations obtained by the method of characteristics is analytic, computationally efficient, considers the effects of flow regime over multiple planes and accurate rainfall intensity in estimation of travel time of sheet-flow in one dimension. More accurate results can be obtained with employing a physically based fully-distributed numerical model that are more realistic, avoiding the simplifications, considering the spatial heterogeneity of data, and also the effect of more flow components (i.e. transverse and depth flow directions).

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Nomenclature

$\widehat{KS}$ $[-]$	Kolmogorov-Smirnov statistic
CN $[-]$	Curve number
C $[-]$	Runoff coefficient
D $[T]$	Rainfall duration
I $[L\,T^{-1}]$	Infirltarion rate
L $[L\,]$	Length of surface plane in direction of sheet-flow
N $[-]$	Number of planes in sheet-flow direction
P $[L]$	Rainfall depth
R $[L]$	Direct runoff depth
S $[L\,L^{-1}]$	Slope of surface plane in flow direction (bed slope)
V $[L\,T^{-1}]$	Average velocity of sheet-flow
V $[L\,T^{-1}]$	Sheet-flow velocity at any point
W $[L]$	Width of sheet-flow
a' $[-]$	Constant of rainfall intensity-duration relation
b' $[-]$	Constant of rainfall intensity-duration relation
f $[-]$	Darcy-Weisbach friction
g $[L\,T^{-2}]$	Acceleration due to gravity
i $[L\,T^{-1}]$	Average of total rainfall intensity
n $[L^{-1/3}\,T]$	Manning's roughness coefficient
n' $[-]$	Number of samples to estimate condition points
q $[L^2\,T^{-1}]$	Unit discharge of sheet-flow
t $[T]$	Time since excess rainfall appears
x $[L]$	Distance along the plane in flow direction
y $[L]$	Depth of sheet-flow perpendicular to plane surface

$\hat{F}_{t_{SHF}}(t_{SHF})$ $[-]$	Empirical unconditional CDF of t_{SHF}
$\hat{F}_{t_{SHF}\|x_i}(t_{SHF})$ $[-]$	Empirical conditional CDF of t_{SHF}
$\hat{T}_i$ $[-]$	Maximum values of $\widehat{KS}$
L_1 $[L]$	Portion of plane length with laminar flow
L_2 $[L]$	Portion of plane length with transitional flow
L_3 $[L]$	Portion of plane length with turbulent flow
N_c $[-]$	Number of samples to estimate conditional CDF
N_u $[-]$	Number of samples to estimate unconditional CDF
P_{24} $[L]$	24-hr rainfall depth
R_h $[L]$	Hydraulic radius of sheet-flow
R_e $[-]$	Reynolds number
Re_1 $[-]$	Critical Reynolds numbers to have laminar flow
Re_2 $[-]$	Critical Reynolds numbers to have transitional flow
S_f $[L\ L^{-1}]$	Friction slope
V_{max} $[L\ T^{-1}]$	Sheet-flow velocity at downstream edge of surface
i_e $[L\ T^{-1}]$	Average of excess rainfall intensity
q_d $[L^2\ T^{-1}]$	Unit discharge of sheet-flow at downstream edge of surface
q_u $[L^2\ T^{-1}]$	Unit discharge of sheet-flow at upstream edge of surface
t_1 $[T]$	Sheet-flow travel time for laminar flow portion
t_2 $[T]$	Sheet-flow travel time for transitional flow portion
t_3 $[T]$	Sheet-flow travel time for turbulent flow portion
t_{SHF} $[T\ ]$	Sheet-flow travel time
y_d $[L]$	Sheet-flow depth at upstream edge of surface
y_{max} $[L]$	Sheet-flow depth at downstream edge of surface
y_u $[L]$	Sheet-flow depth at upstream edge of surface
x_i $[-]$	Input parameters to model
τ_1 $[-]$	Constant value that related R_e to f in laminar flow regime
τ_2 $[-]$	Constant value that related R_e to f in transitional flow regime

τ_3 [−]	Constant value that related R_e to f in turbulent flow regime
α [−]	Coefficient of Darcy-Weisbach friction formula
β [−]	Coefficient of Darcy-Weisbach friction formula
γ [−]	Conversion factor of units
δ [−]	Constant value equal to 3.6×10^6
λ [−]	Initial abstraction ratio
ν $[L^2\ T^{-1}]$	Kinematic viscosity of sheet-flow
ω $[L\ T^{-1}]$	Celerity of the wave

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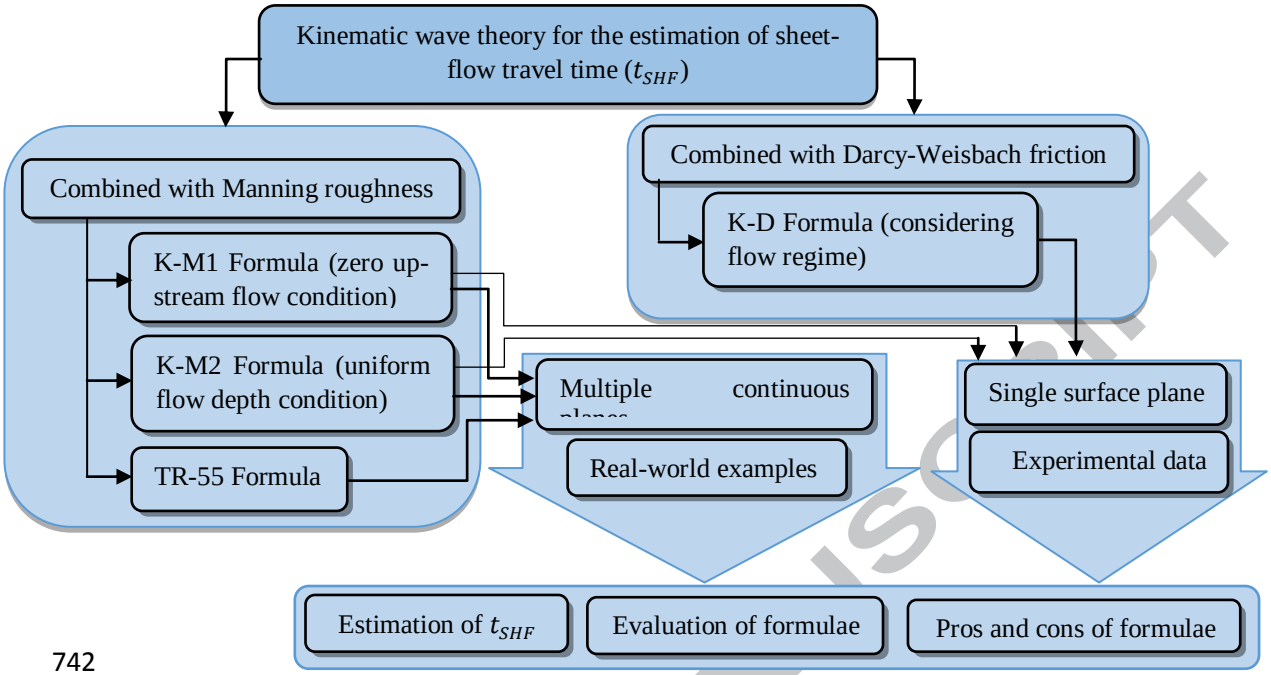

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743 Fig. 1. Flowchart of research methodology and process of sheet-flow travel time formulae employed in this study.

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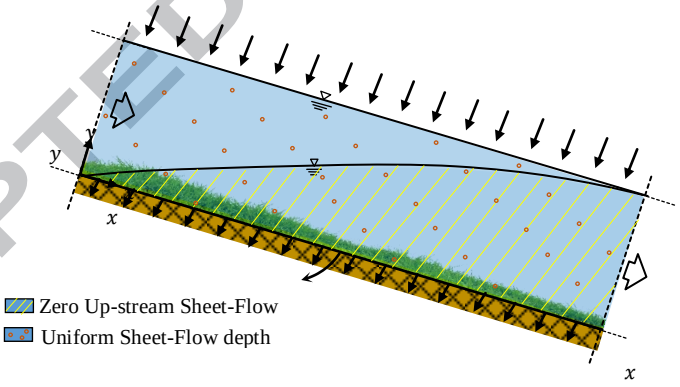

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746 Fig. 2. Unidirectional sheet-flow hydraulics over a planar surface with zero up-stream and uniform flow depth. Rainfall

747 intensity (i), slope (S), Manning's roughness coefficient (n), and infiltration rate (I) are constant over surface.

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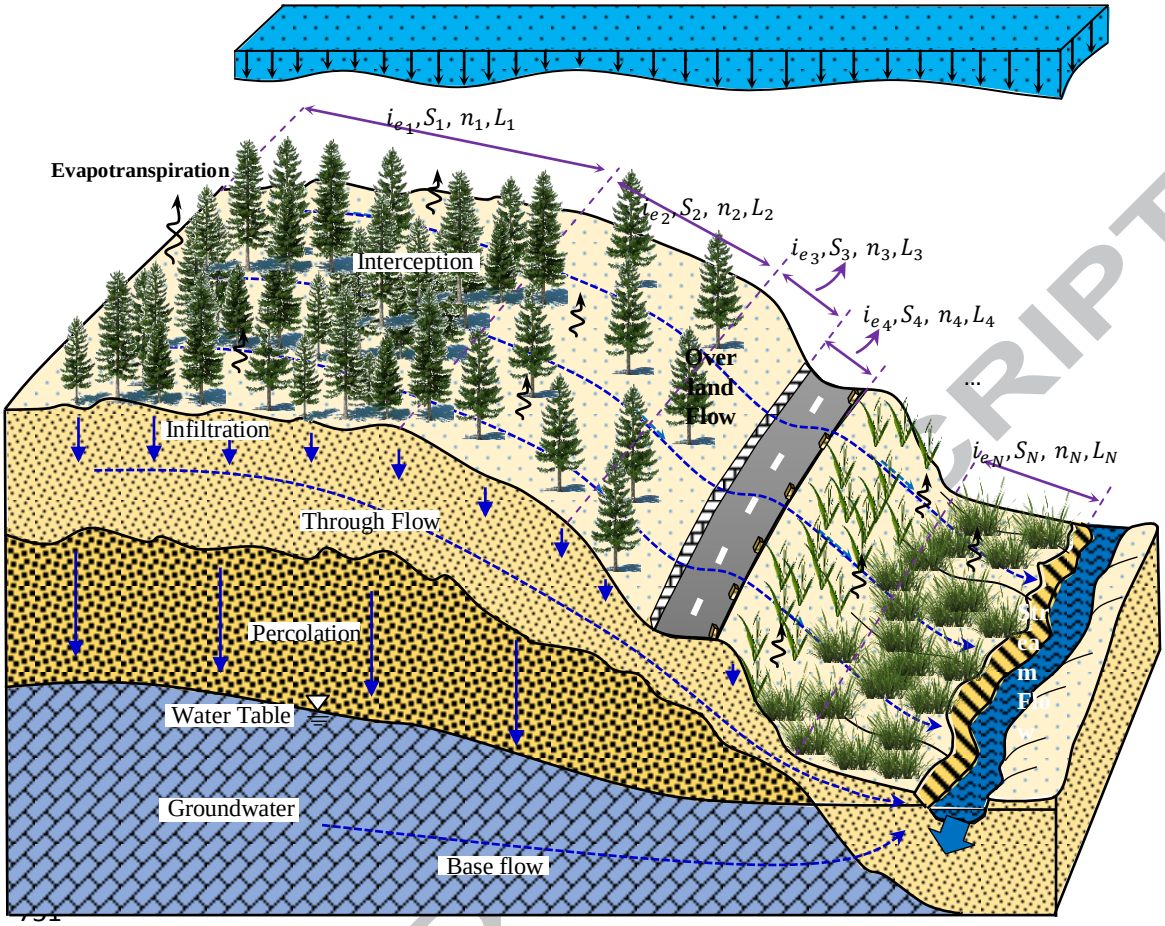

Fig. 3. Schematic of sheet-flow over the cascade of planes with different influential parameters (i is average rainfall intensity, i_e is average excess rainfall intensity, L is length of sheet-flow, n is Manning's roughness coefficient, and S is slope of surface plane).

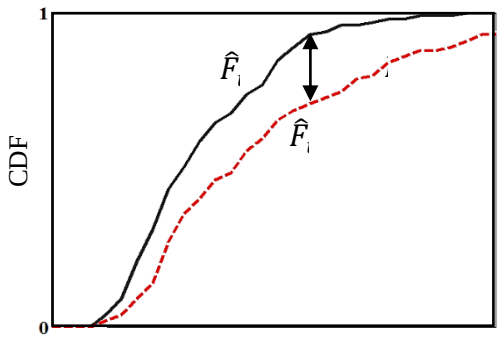

Fig. 4. Computing the Kolmogorov-Smirnov statistic ($\widehat{KS}$) from empirical unconditional and conditional CDFs.

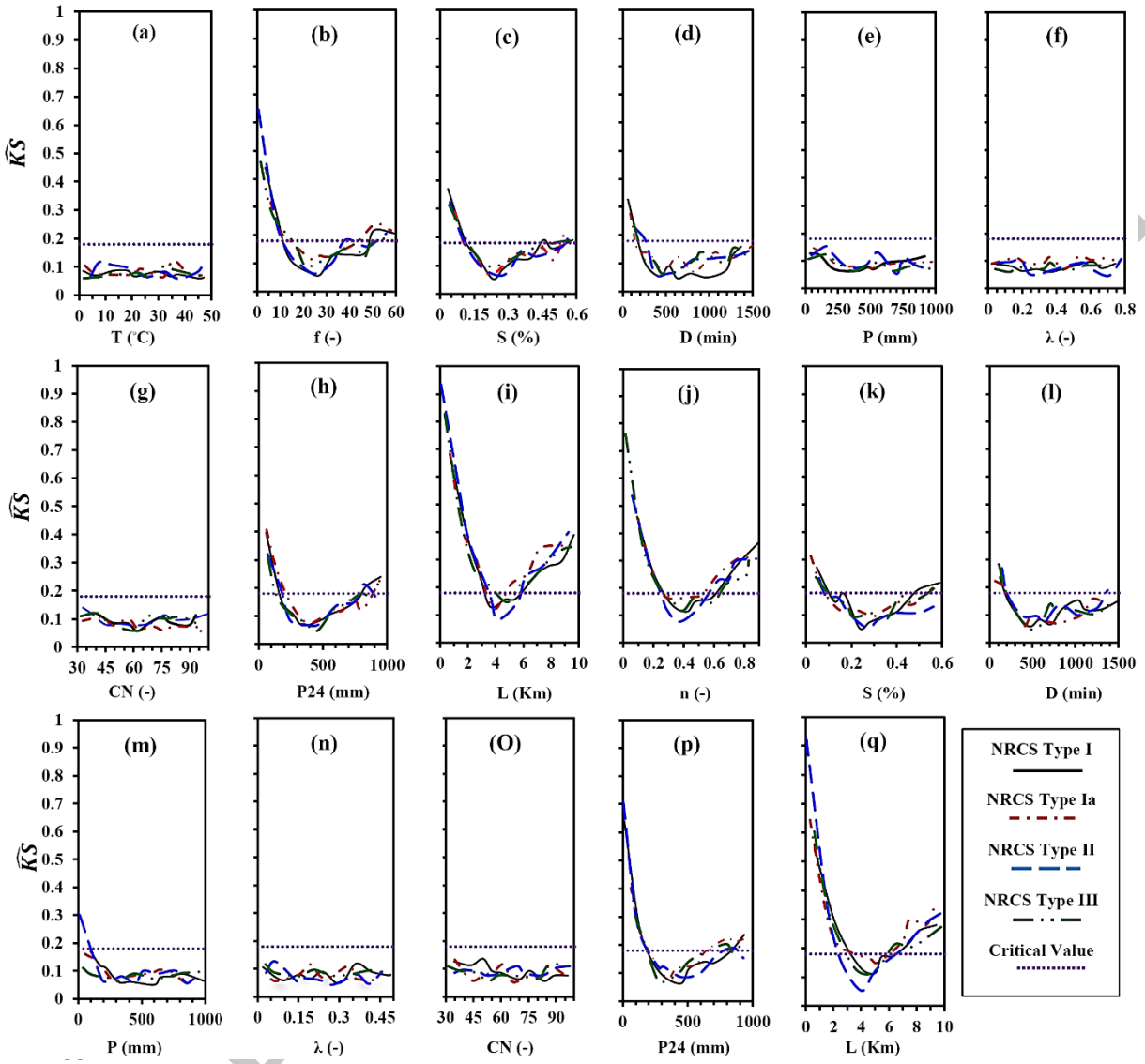

Fig. 760 Kolmogorov–Smirnov statistic ($\widehat{KS}$) at different conditioning values of parameters of the kinematic wave combined with (a-i) Darcy-Weisbach model (K-D), and (j-q) Manning formula with zero-upstream boundary condition (K-M). *For all cases, α=0.05, n' = 10, N_u = 100, and N_c = 50.*

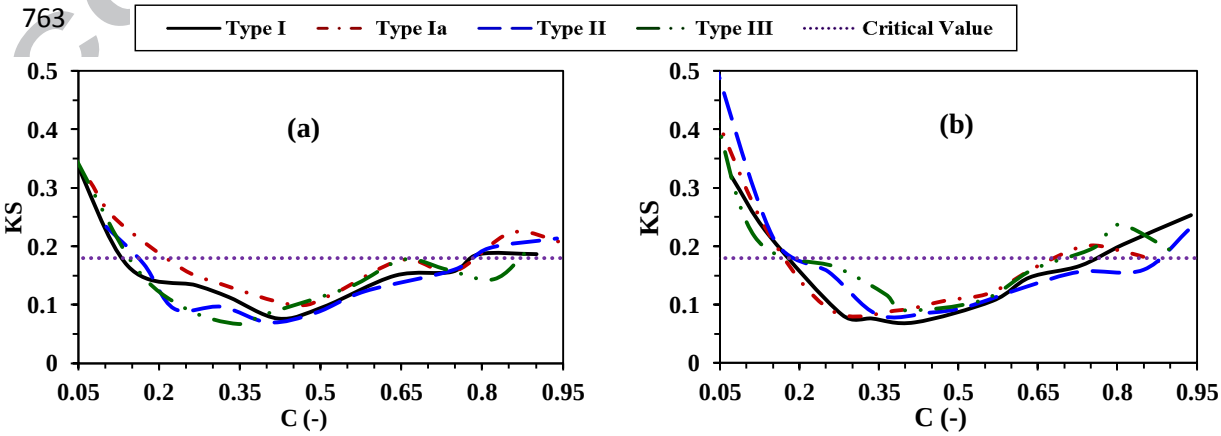

Fig. 764 Sensitivity index ($\widehat{KS}$) of sheet-flow travel time (t_{SHF}) to runoff coefficient (C) estimated by (a) kinematic Darcy-Weisbach formula (K-D) and (b) kinematic Manning formula (K-M) for four types of NRCS design storms.

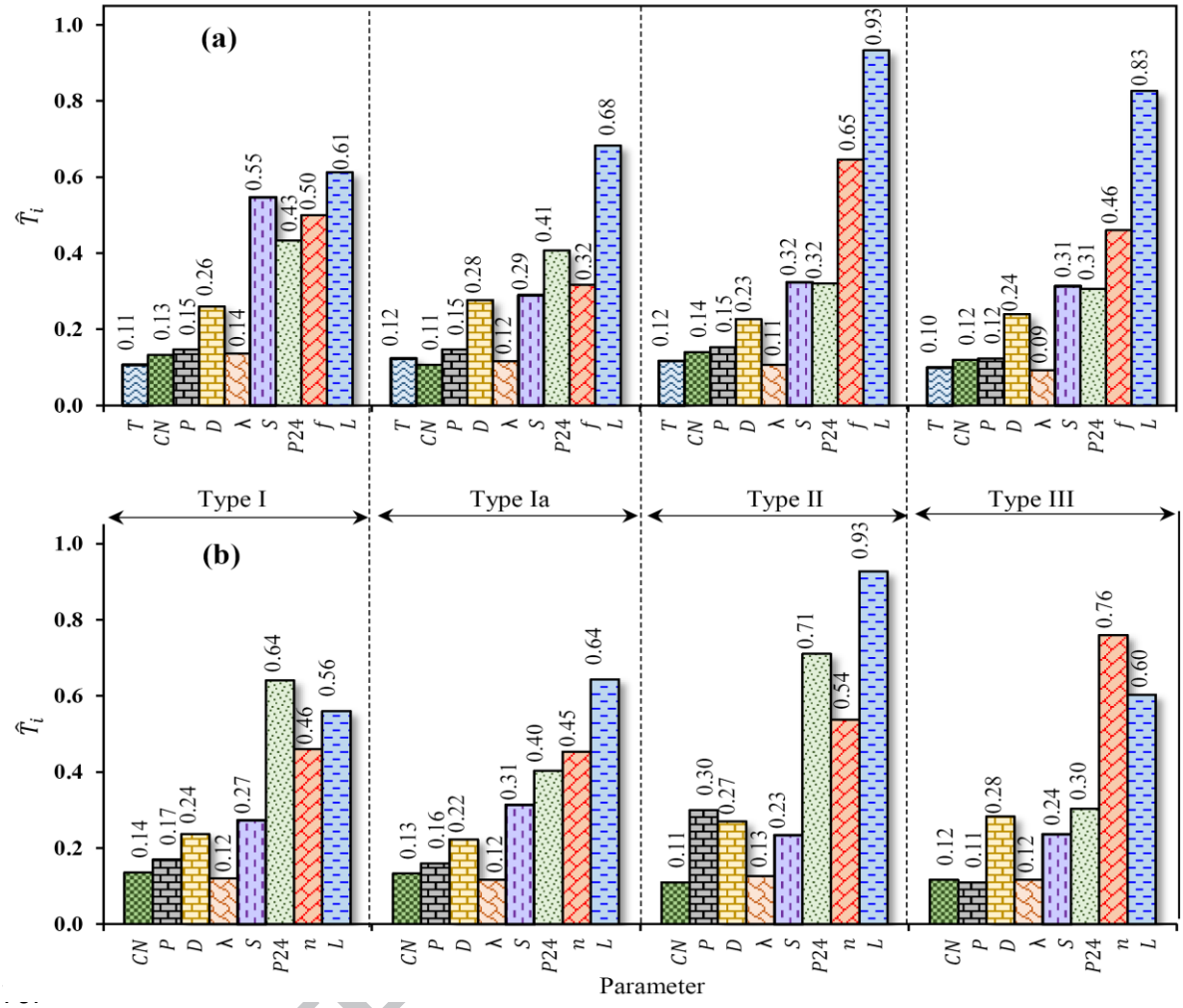

Fig. 7 Sensitivity indices ($\hat{T}_i$) of the sheet-flow travel time to the input parameters estimated by kinematic wave model combined by (a) Manning formula with zero-upstream boundary condition (K-M2), and (b) Darcy-Weisbach formula (K-D).

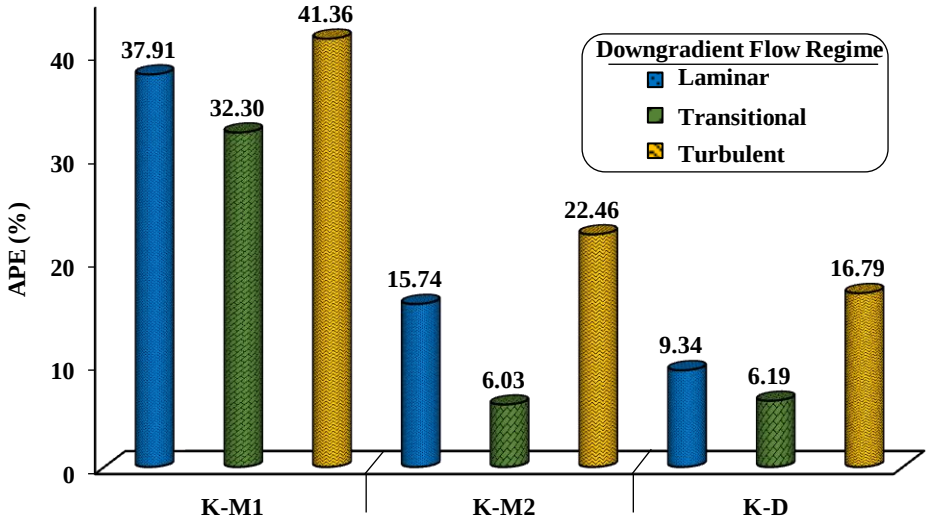

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Fig. 8. The average percentage of errors (APE) of K-M1, K-M2, and K-D formulae for estimation of sheet-flow travel time over a single plane surface computed for different downgradient flow regimes (see also data in Table 3).

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788 **Table 1.** Definition of terms and five approximations of Saint-Venant equations (Henderson, 1966).

No.	Term in Saint-Venant eq. (Motion/Continuity)	Formulation of term*	Solution model	Terms of St-Venant included in the solution model
I	Local Inertia (Motion)	$\frac{1}{g}\frac{\partial V}{\partial t}=0$	Kinematic Wave	IV, V
II	Convective Inertia (Motion)	$\frac{V}{g}\frac{\partial V}{\partial x}=0$	Diffusion Wave	III, IV, V
III	Pressure Differential (Motion)	$\frac{\partial y}{\partial x}=0$	Steady Dynamic Wave	II, III, IV, V
IV	Bed and Friction Slope (Motion)	$S_f - S = 0$	Gravity	I, II, III, V
V	Continuity	$\frac{\partial y}{\partial t}+\frac{\partial q}{\partial x}=i_e$	Dynamic Wave	I, II, III, IV, V

* V $[L\,T^{-1}]$ is flow velocity, x $[L]$ is distance in flow direction, g $[L\,T^{-2}]$ is acceleration due to gravity, t $[T]$ is time, y $[L]$ is depth of flow, S_f $[L\,L^{-1}]$ is friction slope, S $[L\,L^{-1}]$ is surface slope (or bed slope), q $[L^2\,T^{-1}]$ is unit discharge of flow.

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Table 2. Observed and estimated sheet-flow travel time (t_{SHF}) by kinematic wave theory in combination with Manning formulas considering zero-upstream boundary condition, $q_u = q_d$ (K-M1) and uniform flow condition, $q_u = 0$ (K-M2), and kinematic wave in combination with Darcy-Weisbach formula (K-D) in the case of a single plane surface*.

No.		Experimental Data							Calculated T_{SHF} (s)				
	Surface	L (m)	S (%)	n (-)	(-)	i_e (mm/hr)	Other Parameters	Observed T_{SHF} (s)	K-M2	K-M1	K-D	Downgradient Flow Regime	Reference of Experimental Data
1	Crop		28.4	0.136	6.55	390.0***	y_d=4.70 mm V=0.092 m/s	43.48	47.32	26.66	46.35		
2	Crop		27.2	0.103	6.67	440.0	y_d=4.40 mm V=0.011 m/s	36.03	31.90	22.80	41.70		
3	Fallow	4.0	24.7	0.09	5.02	190.0	y_d=2.35 mm V=0.09 m/s	44.44	42.30	30.22	41.68	Transitional	Hessel et al. (2003)
4	Orchard		45.8	0.10	7.29	350.0	y_d=3.0 mm V=0.13 m/s	30.76	29.31	20.94	28.90		
5	Wood		42.6	0.17	23.28	110.0	y_d=2.02 mm V=0.06 m/s	66.67	65.77	47.0	65.73		
6	Acrylic Glass	2.0	5.0	0.016	NR**	0.0417	W=1.0 m	510	456.6	333.0	540.0	Laminar	Sabzevari et al. (2013)
7	Bare Clay		0.43	0.033	NR	47.5	q= 0.08 m^2/s	42.0	44.5	31.8	45.65		
8	Bare Clay	9.15	0.42		NR	37.5	q= 0.20 m^2/s	69.7	61.96	44.3	72.90	Laminar	Cahill and Li (2003)
9	Asphalt		0.35	0.013	NR		q= 0.25 m^2/s	60.0	37.62	26.87	49.84		
10	Pasture		0.48	0.12	NR	33	q= 0.15 m^2/s	240.0	206.74	146.7	214.6		
11	Sand and Bitumen	22.86	1.0	0.059	NR	60.0	q= 0.00038 m^2/s	370.0	388.47	277.65	361.3	Transitional	Langford and Turner (1973)
12			0.5			210	q= 0.00098 m^2/s	140.0	90.82	64.80	116.74		
13	Aluminum	12.2	1.0	0.016	NR	300	q= 0.00072 m^2/s	135.0	63.54	45.32	74.45	Turbulent	Ben-zvi (1984)
14			1.5			225	q= 0.00075 m^2/s	108.0	63.54	45.40	81.78		
15			2.0			225	q= 0.00089 m^2/s	81.0	59.30	41.63	70.50		
16	Turf	142.3	0.5	0.054	NR	55	V=0.28 m/s	1320	1465	1046	1429		
17		142.3	2.0	0.014	NR	190	y_d=11.5 mm	240	262.0	187.1	227.4		
18		152.4	2.0			200	V=0.41 m/s	270	256.6	183.3	232.8	Turbulent	Yu and McNown (1964)
19	Concrete	101.5	0.5	0.014	NR	60	y_d=6.0 mm	610	630.5	450.4	591.2		
20		152.4	0.5			20	V=0.28 m/s	1200	976.9	697.8	964.3		
21						55	V=0.20 m/s	900	706.2	504.4	727.6		

* L is length of surface plane, W is width of surface plane, S is slope of surface plane, n is Manning's roughness coefficient of surface, f is Darcy-Weisbach roughness coefficient, i_e is effective rainfall intensity, y_d is downgradient flow depth, V is downgradient flow velocity, and q is unit discharge at downgradient of surface plane.

** NR= Not reported in the corresponding reference.

*** Underlined values are computed from the other parameters.

Table 3. Parameters used for estimation of sheet-flow travel time over different surface planes in single and cascade arrangement with Manning and kinematic wave formulas.

Type of Surface	τ_1	τ_2	τ_3	n	Reference
Kentucky Blue Grass	10000	380	1.8	0.151	Wenzel (1970), Engman (1986), Chen (1976), Izzard (1944)
Concrete	41.8	2	0.04	0.023	Wenzel (1970), Yoon (1970)
Artificial Turf	2000	19	0.231	0.054	Phelps (1970), Fenzel and Davis (1964)

Table 4. Sheet-flow travel time (t_{SHF}) estimated by kinematic wave approximation in combination with Manning formula (K-M3) and with Darcy-Weisbach formula (K-D) formulae in the case of a cascade of three surfaces: Kentucky blue grass (G), concrete (C), and turf (T) and for different values of input parameters and four types NRCS design storms. The percentage of turbulent flow portion on the three surfaces (L_3/L) and the absolute difference of two methods in estimation of t_t (Diff.) are also calculated.

	Input Parameters					Type I				Type Ia				Type II				Type III			
						t_{SHF} (min)				t_{SHF} (min)				t_{SHF} (min)				t_{SHF} (min)			
Sequence of Planes	S (%)	T (°C)	L (m)	i (mm/hr)	C (-)	K-M3	K-D	L_3/L (%)	Diff. (min)	K-M3	K-D	L_3/L (%)	Diff. (min)	K-M3	K-D	L_3/L (%)	Diff. (min)	K-M3	K-D	L_3/L (%)	Diff. (min)
		20				85.4	126.5	44.1	41.1	113.6	196.7	0.0	83.1	68.5	96.2	56.8	27.7	76.4	110.0	51.4	33.6
		2		100		85.4	147.2	16.5	61.8	113.6	227.7	0.0	114.1	68.5	104.3	40.7	35.8	76.4	127.0	0.0	50.6
	3.0	40			0.2	85.4	117.7	48.9	32.3	113.6	168.8	33.9	55.2	68.5	90.3	53.5	21.8	76.4	102.9	59.2	26.5
G→C→T	0.5			50	0.9	102.0	167.3	22.4	65.3	122.4	218.6	0.0	96.2	84.3	124.5	45.0	40.1	88.2	131.7	41.6	43.5
	1.0		2000	200	0.5	76.3	109.5	46.3	33.2	109.0	185.3	7.2	76.2	59.7	81.4	61.8	21.7	70.2	99.2	55.7	28.9
			200			112.7	194.6	0.0	81.9	149.9	318.0	0.0	168.1	90.4	135.9	39.5	45.5	100.8	166.5	0.0	65.7
		20		1		64.7	89.5	53.2	24.8	86.1	127.5	39.1	41.4	51.9	68.9	65.4	17.0	57.9	78.5	62.7	20.6
C→T→G	0.5 1.0 3.0			00	0.9 0.5 0.2	54.5	71.8	70.0	17.3	72.4	173.5	0.0	101.1	43.7	59.5	82.7	15.8	48.7	65.2	77.3	16.5

G→T →C	3.01.00.5				0.20.50.9	91.4	133.8	29.2	42.3	121.6	196.7	0.0	75.2	73.3	99.5	48.9	26.2	81.7	114.4	39.2	32.6

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Highlights:

- Physically based estimation of sheet-flow travel time are reviewed.
- Global sensitivity analysis of the t_{SHF} formulations are carried out.
- NRCS design storms are used to consider the variation of rainfall intensity.
- Darcy-Weisbach is more proficient than the Manning in estimation of the t_{SHF}.