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SPATIAL-TEMPORAL ADJUSTMENTS OF TIME OF CONCENTRATION

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ABSTRACT: Current methods of computing a time of concentration do not correctly account for many spatial and temporal inputs, such as return period and sheet flow length. The magnitude of a storm affects both the roughness and the hydraulic radius, not only the rainfall intensity. This should be reflected in the calculation of the time of concentration. Maximum sheet flow lengths are generally specified for computing design peak discharge rates; however, the proper length to use is subject to considerable debate. This research provides a method of solving for times of concentration while accounting for return period. The method involves a multiplication factor that adjusts a computed concentration time for any return period. Guidelines for sheet flow inclusion in design were developed. The sheet flow guidelines provide the minimum sheet flow length to include in design based on varying inputs.

Keywords: Time of Concentration, Basin Management, Runoff**,** Travel Time.

1. INTRODUCTION

Conventional ways for calculating the time of concentration t_c ignore the effects of return period and recommend including all sections of the principal flow path. While rainfall intensity attempts to account for return period, the effects of return period on the hydraulic radius and roughness of a flow path are not considered. Failure to fully account for return period reduces the accuracy of t_c estimates. Similarly, it is not clear if all parts of a watershed should be used in calculating t_c. Ignoring the effects of these spatial and temporal inputs can cause error in computing of the time of concentration.

Many different methods are currently available to estimate the time of concentration. The three inputs to most methods include Manning's roughness coefficient n and the slope and length of the flow path. If a time of concentration method is dependent on return period, a rainfall characteristic, such as the rainfall intensity, is generally used. However, other inputs are dependent on the return period, and failure to include these factors can decrease the accuracy of a computed time of concentration. Methods for selecting the roughness n are generally dependant only on the type of surface cover even though surface roughness varies significantly with the depth of flow, which is return period dependent. The hydraulic radius also varies along the principal flow path and is dependent on the magnitude of a storm. Methods for estimating t_c generally do not take into account the effect that return period has on runoff characteristics and, therefore, on the time of concentration. The SCS Lag method (McCuen, 2005) and the FAA equation (FAA, 1970) are examples of this. McCuen *et al.* (1984) discuss a variety of empirical t_c equations. From a hydrologic standpoint, the flow velocity and therefore the t_c would be expected to vary with return period as both n and the hydraulic radius vary with the magnitude of the storm. Methods of estimating the time of concentration that do not allow the hydraulic radius or the roughness to vary may not provide accurate estimates of t_c.

Many current policies for calculating peak discharge rates specify a maximum sheet flow length. The basis for selecting a maximum length is generally not stated, although it seems to be based on a length specified in some publication or policy statement rather than watershed characteristics. The concept of using a maximum length seems to be based on the observation that a long sheet flow length results in a relatively low computed peak discharge. The concept of a minimum sheet flow length needs investigation, as it can deflate peak discharge estimates.

The goal of this research was to improve the current knowledge of time of concentration estimation, both temporal and spatial aspects. The first objective was to develop a method of adjusting computed times of concentration for variation of storm return period, as using only rainfall intensity is inadequate. The second objective was to develop guidelines for the inclusion of sheet flow in small watershed designs. The current thinking of using length as the decision variable to define the extent of sheet flow along the principal flowpath does not seem reasonable in all cases.

2. EFFECT OF RETURN PERIOD ON TIME OF CONCENTRATION

Estimates of the time of concentration often use a computed velocity based on Manning's equation. The velocity method defines the travel time for a flow path segment to equal the ratio of the flow length to the flow velocity. It is generally assumed that the hydraulic radius of sheet flow is equal to the flow depth at the end of the flow path segment. The hydraulic radius, however, varies with position along the principal flow path, which is often not given adequate consideration in computing a velocity. This is especially true for sheet flow calculations, where obviously the depth of flow for 10 m of sheet flow would be much less than for 30 m. The kinematic wave equation inherently uses the depth at the end of the flow path, which is not representative of the depth of flow over the sheet flow portion of the principal flow path. For the velocity t_c method, a tabled value of the hydraulic radius is most often used such as the table in TR-55 (1986). This is especially true for sheet flow calculations, where obviously the depth of flow for 10 m of sheet flow would be much less than for 30 m. McCuen and Okunola (2002) derived the following equation that computes the depth at any point along a flow path with uniform characteristics:

$$D = 0.0117 * i_e^{0.6} \left(\frac{nx}{\sqrt{S}} \right)^{0.6} \quad (1)$$

where D = hydraulic flow depth (cm), n = Manning's roughness coefficient, x = the distance from the watershed divide (m), i_e = excess rainfall intensity (mm/hr), and S = slope (m/m). This equation shows that the flow depth varies with the length of flow.

Reed and Stong (1993) derived a relationship between *n* and the Reynold's number, which depends on flow depth and, therefore, return period. Experimental measurements of 789 flow depths were made on three surface roughnesses, each with three different slopes. Three rainfall intensities were used over a channel length of 24 feet. Based on the experimental results, the following regression equation resulted:

$$D = 0.74922 * q^{0.279} * S^{-0.290} \tag{2}$$

where D = sheet flow depth (cm), q = flow rate (m^3/sec/m) and S = slope (m/m). Using the flow depth to compute the Reynold's number N_R, they developed a formula for estimating *n*:

$$n = 0.413 N_R^{-0.535} \tag{3}$$

Equation 3 shows that the roughness coefficient varies with the Reynold's number, which is dependant on flow depth.

Wu *et al.* (1999) developed a relationship between the depth of flow and the roughness coefficient of a surface. For their experimental purposes, a surface constructed of rubberized horsehair mattress material acted as vegetative roughness. Varying the height of the material, the slope of the surface, and the discharge rate, they conducted 14 tests. All measurements of the discharge and stage were taken at steady and uniform flow conditions. Using Manning's equation and the experimental results, they calculated *n* for multiple hydraulic radii. By graphing *n* against the flow depth, four subregions were apparent.

Wu *et al.* (1999) provided the following equation to express the roughness coefficient as a function of depth:

$$n_b = \left[\frac{(3.44 * 10^6) v}{2g} \right] D^{-1/3} = K * D^{-1/3} \tag{4}$$

where n = Manning's roughness coefficient of the bottom of the test area, v = kinematic viscosity of water (N-s/m^2), and g = gravity (m/s^2). For shallow sheet flow, the hydraulic radius is approximately equal to the depth of flow. Then eq. 4 shows that the roughness coefficient varies with the hydraulic radius at the rate of K with the roughness inversely proportional to depth. The values of K for four materials (short grass, dense grass, asphalt, and cement) were computed from tables of *n* and hydraulic radii. Using standard values of the roughness coefficient from tables, the depth of flow that correlated with these *n* values was determined by setting *n* of dense grass equal to eq. 4. Based on Wu *et al.*'s experiment, the K value of unsubmerged vegetation resulted in a depth of 0.1 meters. Using the same flow depth, *n* values were calculated and the K values of dense grass, short grass, asphalt, and cement were determined as 0.05171, 0.03232, 0.00259, and 0.00237, respectively.

The flow depth and roughness coefficient vary with both the distance from the top of the watershed and the return period. Therefore, they would be needed at different distances to calculate the time of concentration of a particular flow path. The number of values and the spacing would vary with the conditions, but five values will usually be sufficient. Substituting eq. 3 into eq. 1 and solving for D yields:

$$D = 0.02456 \frac{(i_e * K * x)^{0.5}}{S^{0.25}} \tag{5}$$

Equation 5 allows the hydraulic flow depth to be computed from K, distance, slope, and excess intensity. For this study, the intensity i_e was based on the local IDF curve, return period, and the Rational formula coefficient C, which was used to convert the IDF intensity to a rainfall excess intensity. Using the K values computed for the four materials, the flow depth could be determined for any return period and any point along a flow path. The roughness coefficient n was then computed with eq. 4, using the calculated flow depths for each condition and the respective K value.

With the value of n and the hydraulic flow depth calculated, the velocity for each return period was calculated with Manning's equation using the flow depth as the hydraulic radius. The time of concentration was computed using the velocity method. As the flow velocity depends on the return period, the time of concentration also depends on the storm return period.

The first step was to select the index return period. In flood hydrology, the 2-yr and 10-yr return periods are common. Evidence in flood hydrology suggests that this is not a critical decision because the intent is to develop ratios. Based on the values of the hydraulic radius and roughness from TR-55 (1986), the flow depths computed from eq. 5 suggest that computed t_c values are for return periods of about 10 years. Therefore, a ratio was developed from the above concepts by dividing the time of concentration for each return period by the time of concentration for a 10-year return period (see Table 1). The ratios derived from this analysis can be used to determine the time of concentration for any return period by computing the time of concentration using a standard approach with Manning's equation and multiplying the value by the corresponding ratio from Table 1.

Table 1
Return Period vs. Time of Concentration Adjustment Ratio

Return Period (Years)	2	5	10	25	50	100
Time of Concentration Ratio	1.235	1.053	1.000	0.920	0.873	0.823

3. EFFECT OF INCLUDING SHEET FLOW ON TIME OF CONCENTRATION

The effective sheet flow length varies with the roughness and slope of a watershed, which implies that a standard length is not always applicable (McCuen and Okunola, 2002). Drainage policies often specify a required sheet flow length or a maximum value. The use of an incorrect sheet flow length can affect the accuracy of a peak discharge estimate. For example, if the sheet flow velocity is much slower than the velocity of concentrated flow, then the inclusion of sheet flow in a time of concentration calculation may lead to an underestimated peak discharge rate. Wong (1996) investigated peak discharge formulas for watersheds with different characteristics.

The accuracy of peak discharge estimates may be improved by not including sheet flow in computing a time of concentration. This supported by research on the concept of partial-area or variable–source area hydrology (Betson, 1964; Hewlett and Hibbert, 1967; Dunne and Leopold, 1978). This concept is based on the idea that all parts of a watershed do not uniformly contribute to storm flow and that very often; it is primarily the response of the watershed adjacent to the drainage network that is responsible for flooding.

The idea that the peak discharge for part of a watershed could be greater than when the entire watershed is contributing flow may seem counter to the concept of time of concentration. Consider the case where the upper sections of a watershed are low sloped and forested while the lower parts are developed and moderately sloped. If only the lower part is considered, the weighted *C* would be much higher than if the weighted *C* for the entire watershed is used. Furthermore, for the shorter *tc* when only the lower portion of the watershed is used, the rainfall intensity would be greater than when using a relatively long t_c for the entire watershed. Thus, the higher C and greater intensity for just the lower portion of the watershed offsets the reduction in area due to using only the lower part of the watershed. While this discussion has been approached from a modeling perspective, the idea is rational from a watershed processes perspective. It is quite feasible to imagine that the peak portion of a hydrograph is the result of the near-the-outlet portion of the watershed and that the tail of the hydrograph is the result of the upper forested portion of the watershed.

Since peak discharge is of design interest, the ratio of the peak discharge for only the concentrated flow portion of the watershed to the peak discharge of the total watershed was selected as the criterion. A peak discharge ratio (R_q) greater than 1.0 indicates that the peak discharge of the concentrated flow portion of the watershed is greater than the peak discharge of the total flow that includes the sheet flow. Such a value implies that the inclusion of sheet flow would lead to an underestimate of a computed peak discharge for the entire watershed.

The peak discharge ratio for different watershed characteristics was calculated using a watershed model based on the Rational formula. The return-period-dependent rainfall intensity was taken from an IDF curve. The return-period-dependent rainfall intensity was taken from an IDF curve. The results were similar for the different return periods and Rational coefficients. Analyses indicate that the effect of including sheet flow in computing a time of concentration depends on the relative slope and roughness of the concentrated and sheet flow portions of the principal flow path. Two ratios were formed to indicate the relative roughness (R_n) and relative slope (R_S):

$$R_n \; {}^{n_c}\!/_{n_s} \tag{6}$$

$$R_S \; {}^{S_c}\!/_{S_s} \tag{7}$$

where *n* and *S* refer to roughness and slope, respectively, and the subscripts *c* and *s* refer to the concentrated and sheet flow portions of the flow path. The results indicated that sheet flow should only be included when it significantly contributed to peak discharge magnitudes. A critical sheet flow length, which was computed for a peak discharge ratio of 1.0, is the minimum distance at which sheet flow should be included. The critical lengths of each and combination were obtained from analyses with the model and the following equation was developed:

$$L_c = (105 + 38.2 * R_S)R_n^{-0.706} \quad (8)$$

which is valid for 0.05<= R_S <=10 and 1<= R_n <=5.

Watersheds with a R_n less than 1.0 should not include sheet flow as part of the t_c calculation. A value of R_n less than 1 would reflect the partial-area effect, as discussed above. Figure 1 shows the graph of eq. 8 and can be used to determine the critical length of a watershed. Based on eq. 8, the critical length depends on different combinations of R_S and R_n values. If the actual sheet flow length is less than the computed critical length, then sheet flow should not be included in the peak discharge calculations, as it would result in a reduced peak discharge rate.

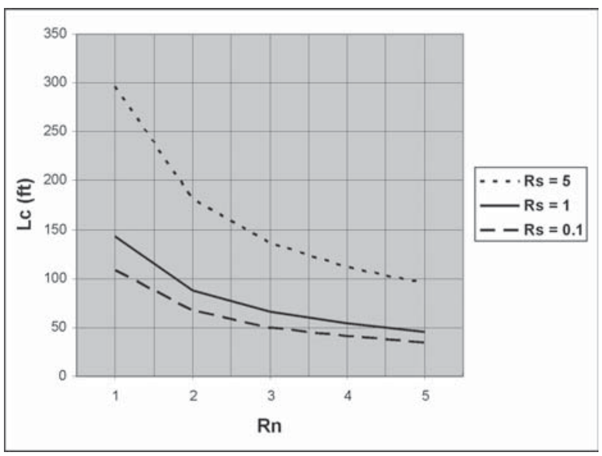

Figure 1: The Critical Sheet Flow Length (L_C) as a Function of the Roughness Ratio (R_n) and Slope Ratio (R_S)

4. CONCLUSIONS

Many methods for calculating the time of concentration do not account for the return period of a storm. Since the storm intensity varies with return period, both the hydraulic flow depth and the coefficient of roughness will vary with return period. Without considering how return period affects the roughness and hydraulic radius, estimates of the time of concentration are less accurate.

The results of Table 1 show that, if inputs based on a 10-year return period are used to design for a 2-year return period, the time of concentration can be underestimated by 23%. Using a t_c based on a 10-year return period to design for a 100-year return period will overestimate t_c by about 18%. These errors in t_c can produce significant errors in computed peak discharge rates. The problem is overcome by altering the computed t_c for the appropriate return period by multiplying by the corresponding ratio value from Table 1. The ratios would apply to any method of computing a time of concentration that does not specify a return period. The ratios are not limited to one equation, such as the Lag model.

Methods that use t_c in the estimation of t_c assume that the variation of the rainfall intensity will adequately reflect the effect of return period on t_c. The magnitude of a storm also influences the roughness and the hydraulic radius. Therefore, modeling the effect of return period solely with t_c will underestimate the effect of return period. The approach developed herein accounts for the effect of storm magnitude through the rainfall excess, the roughness, and the flow depth. Thus, it is expected to provide greater accuracy than the use of rainfall excess alone.

Traditional thinking assigns a standard sheet flow length such as 100 or 200 feet to a watershed. As shown by this investigation, however, the appropriate sheet flow length varies with R_n and R_S, and sometimes sheet flow should not be included. Incorrect use of sheet flow in t_c calculations can result in underestimates of peak discharge rates for a watershed. The method derived from this research can be useful in developing drainage policies. Based on the characteristics of a typical watershed in a region, a critical sheet flow length can be determined. If the observed sheet flow length is less than the critical length and associated with a low velocity, then the time of concentration will be too long, which will underestimate the true peak discharge. Then including the sheet flow length will result in an unsafe design. This will be a negative impact on the public.

Current knowledge of time of concentration overlooks many aspects of both spatial and temporal inputs. These oversights can reduce the accuracy of hydrologic designs. Incorrect inclusion of sheet flow can underestimate the peak discharge of a watershed. Failure to account for return period can cause error in calculating the time of concentration. Both the spatial and temporal aspects of time of concentration calculations are important in design. The model and guidelines developed through this research address these inaccuracies and improve the current knowledge of time of concentration for design.

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