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RESEARCH ARTICLE

Calculation of Proper Time of Concentration for Drainage Design in Construction Projects for Urban Development

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ABSTRACT - The design and construction of a proper drainage system are important for any urban development project, small or big. Hydrological and hydraulic calculations are used to design the drainage systems. The calculation of peak flow is one of the common hydrological methods applied to determine the drain sizes for all construction projects. Peak flows and hydrographs can be calculated using several techniques. In order to calculate the peak flow, the design rainfall duration has to be appropriate, which will reflect the critical storm duration. The critical storm duration, on the other hand, depends on the time of concentration (t_c) of the catchment. However, most of the equations for t_c available in the literature are empirical. At least 23 equations could be traced in various references, which consist of different geophysical and other hydrological parameters. This paper is intended to explain the importance of the proper use of t_c to calculate peak runoff flow for construction projects, as accurately as possible. A review of the existing methods used to calculate the time of concentration revealed inconsistencies among a few methods found in the literature. The correct value of the time of concentration (t_c) is important for the application of the Rational Method, as the value of t_c helps the designer assume the storm duration critical to get the maximum peak flow value. If the critical storm duration is not used in the Rational Method, the drain will be undersized, and the overflow of the storm runoff may happen. Therefore, ample attention should be given to the calculation of the time of concentration to ensure the safety, economy, and sustainability of the drainage system in any development project.

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1.0 INTRODUCTION

Calculating storm runoff peaks is not only essential for hydrologists but also required by civil engineers; mainly for drainage design in any development project and many other usages [1, 2]. The cost of the design and construction largely depends on the accuracy of the estimation of the flow peak (Q, in m^3/s). On the other hand, it is not easy to calculate the storm runoff peak flow with good reliability, as the accuracy depends on many types of data [3 - 8]. For example, rainfall intensity, imperviousness, runoff coefficient, distance, the slope of the catchment, and area [9]. Although various computer models are available for reliable calculation of storm runoff hydrographs, they are not feasible for small companies to afford for small jobs, such as construction projects in small areas. Simple methods are preferred over complex [10 - 12] calculations, which can be done with greater accuracy by using modern tools such as geographical information systems (GIS).

The rational method is a simple method to estimate the peak flow rate for a small watershed (usually less than 80 ha). It was developed by Kuichling in 1889 for small drainage basins in urban areas [13]. This method involves certain parameters such as runoff coefficient, design rainfall intensity, and watershed drainage area. It is widely used as it is simple and minimum data is required to obtain the required peak flow. However, it usually gives an overestimated value of the peak flows which causes high construction costs because this method has limitations and does not include other crucial parameters that may also influence the peak flow rate like slope, distance, and shape of the catchment.

Although the rational method has been widely used by millions of practitioners, there has been no improvement to the formula. Due to its very simplistic nature, usually it produces high peak flow values, causing high construction costs. However, some countries have come up with their method of calculating runoff peak flow.

On the other hand, the existence of numerous equations and methods available [14, 15] for t_c also makes the users confused about which methods would produce reliable values of t_c, as a wrong value of t_c would lead to a wrong estimation of runoff peak flow. Sometimes, the users also get confused with similar hydrological parameters such as time to peak of the hydrograph (t_p) and lag time (t_L), as shown in Figure 1. Therefore, the main objective of this paper is to attempt to

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clarify the terms and methods to avoid confusion in using the terms and equations related to the time of concentration and peak flow of the runoff hydrograph.

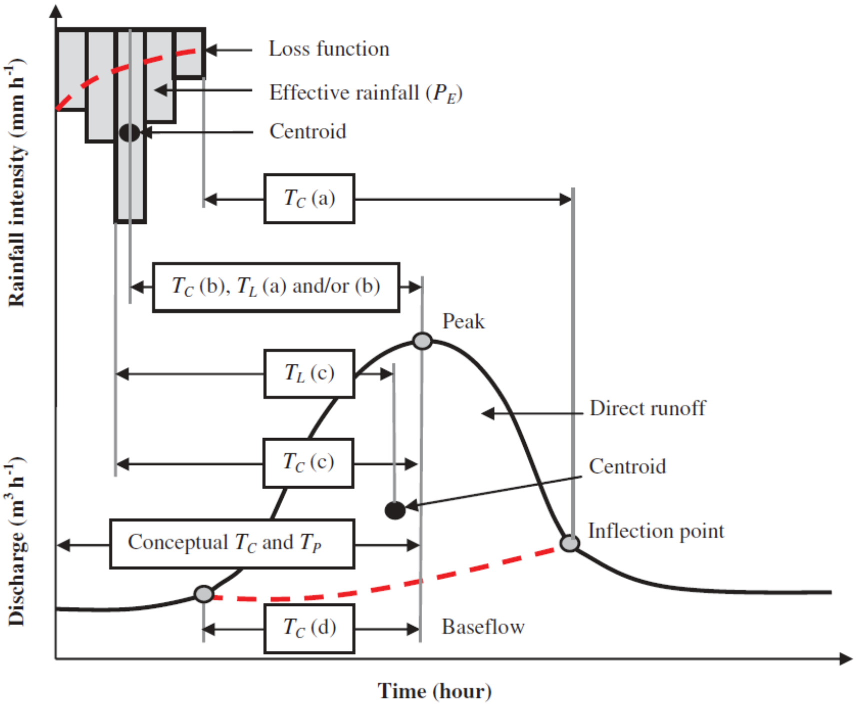


Figure 1. Various components of a storm runoff hydrograph [16]

2.0 TIME OF CONCENTRATION

Theoretically, time of concentration (t_c) is defined as the longest time required for water to flow from the hydraulically furthermost point on the catchment boundary to the basin outlet. The actual value of t_c which can be compared with the time to attain the peak runoff flow value (t_p), cannot be outlined exactly, as it varies from season to season, storm to storm and also depends on various conditions of the catchment. The procedure used to estimate t_c depends on several factors including basin characteristics.

Surface water flow through the watershed occurs as three different flow types: sheet flow, shallow concentrated flow, and open channel flow. The velocity method assumes that the time of concentration (t_c) is the sum of travel times for each of these flow segments along the hydraulically most distant flow path [17].

$$t_c = t_o + t_s + t_d \quad (1)$$

where:

t_c = time of concentration, hours

t_o = travel time for overland sheet flow, hours

t_s = travel time of shallow concentrated flow, hours

t_d = travel time through drain or channel, hours

2.1 Various Definitions of t_c

Time of concentration (t_c) is the time required for runoff to travel from the hydraulically most distant point in the watershed to the outlet. In other words, 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. A few other commonly used definitions of t_c are given in Table 1.

Table 1. Various definitions of time of concentration

No.	Definition	Reference
1.	Time of concentration (t_c) is defined as the time needed for water to flow from the most remote point in a watershed to the watershed outlet.	[14]
2.	Time of concentration (t_c) is defined as the time required for a particle of water to flow hydraulically from the most distant point in the watershed to the outlet or design point.	[18]
3.	The time of concentration t_c of a watershed is the time required for runoff to travel from the hydraulically most distant point to the outlet of a watershed.	[19]

2.2 Calculation of t_c in USMM

In the design of stormwater drainage systems, as stated in the Urban Storm Water Management Manual (USMM) [20], t_c is the sum of the overland flow time (t_o) and roadside swales, drains, channels and small streams (t_d). The equations necessary to calculate the t_c are given in Table 2 [21]. The calculation of t_c is subject to the catchment properties, particularly the length, slope and roughness of the drainage path [22]. The overland flow time can be estimated with a proper judgment of the land surface condition since the length of sheet flow is short for steep slopes and long for mild slopes. This equation shall be applied only to the distances (L) recommended in Table 2. Catchment roughness, length, and slope affect the flow velocity and subsequently the overland flow time (t_o).

The drain flow time equation should be used to estimate t_d for the remaining length of the flow paths downstream. Care should be given to obtaining the values of hydraulic radius and friction slope for use in the drain flow time equation. Note that the recommended minimum time of concentration for a catchment is 5 minutes which applies to roof drainage.

Table 2. Equations to calculate the time of concentration [21]

Travel Path	Travel Time			Remark
Overland Flow	$t_o = \frac{107.n^*.L^{1/3}}{S^{1/5}}$	t_o	=	Overland sheet flow travel time (minutes)
		L	=	Overland sheet flow path length (m) *for Steep Slope (>10%), L ≤ 50 m* *for Moderate Slope (<5%), L ≤ 100 m* *for Mild Slope (<1%), L ≤ 200 m*
		n^*	=	Horton's roughness value for the surface
		S	=	Slope of overland surface (%)
Drain Flow	$t_d = \frac{n.L}{60R^{2/3}S^{1/2}}$	n	=	Manning's roughness coefficient
		R	=	Hydraulic radius (m)
		S	=	Friction slope (m/m)
		L	=	Length of reach (m)
		t_d	=	Travel time in the drain (minutes)

To compute the time of concentration, several methods are in use. The most prominent is the one that uses the computation of time for sheet flow, shallow concentrated flow, and open channel flow separately and adds them to get the overall time of travel or time of concentration.

Salimi et al. [14] studied 22 formulas from various references for calculating the time of concentration for the Shaforoud basin located in northern Iran. The review included methods from Ventura, Passini, Branbsy-Williams, Carter, Izzard and other Hydrological Procedures (HPs). Table 3 shows a summary of the most commonly used time of concentration methods reported in the literature. In this table, the calculated values of t_c for a hypothetical catchment (L = 1 km, A = 50 ha, S = 1%, n = 0.035, C = 0.40 and I = 50 mm/hr) are also added to show that the equations published in the literature may vary significantly. It is noticed that for the same catchment, the lowest and highest values of the t_c are produced by NRCS and HP 5 methods, respectively.

To compute the time of concentration; we are looking for a point from where it will take the longest time to travel to the drainage outlet or any other point of interest. Runoff from a closer area may take longer time due to flatter slopes or more roughness. This point does not necessarily have to have the longest distance to the drainage outlet, which is wrongly taken by less experienced professionals.

Table 3. Commonly used empirical equations and their calculated values of t_c for a hypothetical catchment

No.	Name/Source			Equation	Value of t_c (min)
1.	Kirpich	t_c	=	$0.01947\,L^{0.77}\,S^{-0.385}$	*23.4*
		t_c	=	*time of concentration, min*	
		L	=	*channel flow length, in m*	
		S	=	*dimensionless main-channel slope, m/m*	
2.	Williams	t_c	=	$0.272LA^{0.4}\,D^{-1}\,S^{-0.2}$	*38.9*
		t_c	=	*time of concentration, hr*	
		A	=	*catchment area, km^2*	
		L	=	*length of the flow path, km*	
		S	=	*surface slope, m/m*	
		D	=	*equivalent diameter of the catchment, km*	

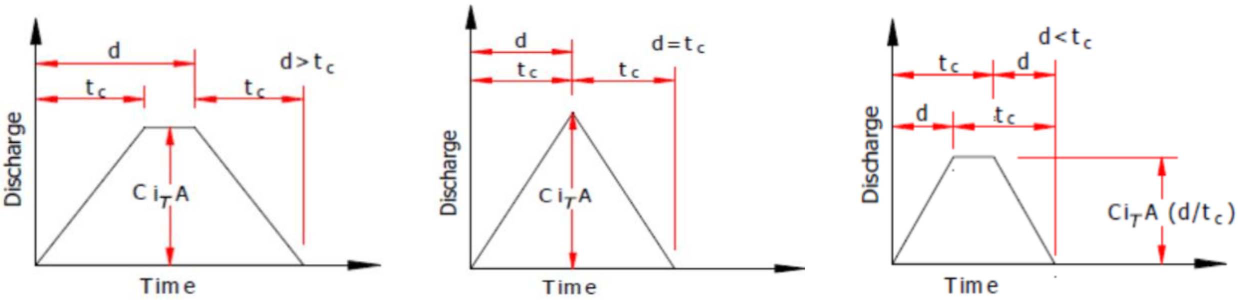
Table 3. (cont.)

No.	Name/Source			Equation	Value of t_c (min)
3.	Kerby	t_c	=	$1.442\ (nL)^{0.467}\ S^{0.467}\ S^{-0.233}$	36.3
		t_c	=	*time of concentration, min*	
		L	=	*length of the flow path, m*	
		S	=	*surface slope, m/m*	
		n	=	*overland roughness coefficient*	
4.	NRCS	t_c	=	$0.0167\ nL/\ (R^{0.667} S^{0.5})$	13.1
		t_c	=	*time of concentration, min*	
		n	=	*Manning's roughness parameter*	
		L	=	*length of the flow path, m*	
		S	=	*average overland/channel Slope, m/m*	
		R	=	*hydraulic radius which equals the flow depth, m*	
5.	Izzard	t_c	=	$85.5(i/36286+\ C_r)\ L^{0.33}\ S^{-0.333} i^{-0.667}$	54.9
		t_c	=	*time of concentration, hr*	
		i	=	*rainfall intensity, mm/h*	
		C_r	=	*retardance coefficient (ranges from 0.007 to 0.06)*	
		L	=	*length of the flow path, km*	
		S	=	*surface slope, m/m*	
6.	Bransby-Williams	t_c	=	$58.5LA^{-0.1}S^{-0.2}$	39.6
		t_c	=	*time of concentration, min*	
		L	=	*mainstream length, km*	
		A	=	*catchment area,* km^2	
		S	=	*equal Area Slope, m/km*	
7.	HP 5	t_c	=	$1.286L/\ (A^{0.223}\ S^{0.263})$	90.1
		t_c	=	*time of concentration, hr*	
		L	=	*length of Main River, km*	
		S	=	*slope measured along the main river, %*	
		A	=	*catchment area,* m^2	
8.	HP 27	t_c	=	$2.32A^{-0.1188}L^{0.9573}S^{-0.5074}$	47.0
		t_c	=	*time of concentration, hr*	
		L	=	*main stream length, km*	
		S	=	*weighted slope of the mainstream, m/km*	
		A	=	*catchment area,* km^2	

3.0 IMPORTANCE OF t_c TO CALCULATE PEAK FLOW

The calculation of an appropriate storm duration is necessary to calculate the peak runoff flow as accurately as possible. Usually, the time of concentration of the catchment is taken as the critical storm duration that will generate the peak flow (Q_p), as shown in Figure 2. The storm duration must be properly calculated to get the peak flow right. Because the rainfall intensity reduces with the increase in storm duration [1].

If the chosen storm duration, d > t_c, then the peak flow will be less than that at t_c (discharge < possible maximum value), due to the smaller rainfall intensity. If the chosen storm duration, d < t_c, then the watershed will not fully contribute runoff to the outlet for that storm duration, and the designed drain will be undersized. Therefore, the design storm duration for the drainage design of any development project should be the same as the value of t_c. Variations in peak flow due to the selection of inappropriate storm duration (three possible cases as discussed above) for the catchment area are shown in Figure 2.



(a) Type 1 (b) Type 2 (c) Type 3

Figure 2. Effect of rainfall duration and t_c on runoff peak value [23]

4.0 CONCLUSIONS

In this paper, time of concentration $t_{c,}$ has been explained, and its importance in calculating peak runoff flow and drainage design is highlighted. At least 23 various methods of calculating the value of time of concentration could be traced in the literature. Consideration of appropriate design rainfall duration is important to calculate the peak runoff flow values to make the drainage system safe and sustainable. The maximum peak flow can be obtained properly when the design rainfall duration is the same as the value of the time of concentration (t_c) of the catchment. The engineers and technical people related to urban development and construction industry-related professionals need to have a clear understanding of runoff hydrograph lag time (t_L), and time to reach the peak of the runoff hydrograph (t_p) to avoid confusion with the time of concentration (t_c). Improper calculation of t_c will lead to unsafe drainage systems in the development areas.

5.0 AUTHOR CONTRIBUTIONS

A.A. Mamun: Conceptualization, Investigation and Drafting the manuscript.

S.L. Ibrahim: Hydraulics.

D.I. Masbah: Proofreading and improvements.

J.I. Daud: Mathematical calculations.

N.K.M.E. Yahya Khan: Review and comment.

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7.0 DATA AVAILABILITY STATEMENT

The data used to support the findings of this study are included in the article. No additional data is available.

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9.0 CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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