

Time of Concentration Estimated Using Watershed Parameters Determined by Automated and Manual Methods

Xing Fang, Ph.D.¹; David B. Thompson, Ph.D.²; Theodore G. Cleveland, Ph.D.³; Pratistha Pradhan, D.E.⁴; and Ranjit Malla⁵

Abstract: The time of concentration (T_c) for a watershed is a widely used time parameter to estimate peak discharges in hydrologic designs. In this study, T_c is estimated for 96 Texas watersheds using five empirical equations: Williams, Kirpich, Johnstone–Cross, Haktanir–Sezen, and Simas–Hawkins methods. The drainage areas of watersheds studied are approximately 0.88–440.3 km². Watershed parameters used to estimate T_c were developed by researchers at three institutions using three different methods: the automated method using digital elevation models and geographic information system software, the manual method with watershed delineation, and the manual method without watershed delineation. T_c estimated from five empirical equations using three sets of watershed parameters is compared and analyzed. T_c estimated using watershed parameters developed by the three methods is qualitatively similar and has average relative differences ranging from 6.4 to –16.9%. Differences between manual and automatic-based watershed characteristics are considered minor sources of error in relation to other uncertainties inherent in time parameter estimation. Average relative differences of T_c estimated using different empirical equations with the same set of watershed parameters range from –38 to 207% (absolute average differences range from –3.0 to 2.8 h) and are much larger than differences estimated using three sets of watershed parameters. Kirpich and Haktanir–Sezen methods provide reliable estimates of mean values of T_c variations.

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Introduction

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 (Kirpich 1940; Bell and Kar 1969; NRCS 1972; McCuen et al. 1984; Garg 2001). T_c is a time parameter widely used to estimate peak discharges in hydrologic designs. For example, the rational formula is used for design of urban drainage systems (Kuichling 1889) and requires an estimate of T_c to select the average rainfall intensity from intensity-duration-frequency (IDF) curves (Viessman and Lewis 2002). Implementation of the Natural Resources Conservation Service

(NRCS) dimensionless unit hydrograph procedure requires an estimate of T_c in order to calculate duration of the unit hydrograph, time to peak discharge, and peak discharge. Bondelid et al. (1982) indicated that as much as 75% of the total error in estimates of peak discharge could result from errors in the T_c estimation. Recognizing the importance of T_c in hydrologic designs, hydrologists developed many methods of estimating T_c , for example, the NRCS velocity method (NRCS 1972, 1986) and various empirical equations. McCuen et al. (1984) reviewed and evaluated nine empirical equations used for estimating time of concentration. Because some of the equations were not originally developed for computing T_c , they adjusted those equations to compute T_c in minutes. For methods designed to predict the lag time, computed lag time was multiplied by a constant that varies depending on the definition of the lag time and was determined on the basis of the relation between the lag time and T_c for a NRCS triangular hydrograph (McCuen et al. 1984; McCuen 1998). A constant of 1.417 was used for the lag time (L_H) defined as the time difference between centers of mass of rainfall excess and direct runoff, and 1.67 was used for the lag time (T_L) defined as the time difference between the center of mass rainfall excess and the peak discharge (McCuen et al. 1984; McCuen 1998)

$$T_c = T_L/0.6 = 1.67T_L \quad \text{or} \quad T_c = 1.417L_H \quad (1)$$

Most empirical equations of estimating T_c are based on four types of input parameters: slope, watershed size, flow resistance, and water input (McCuen 1998). Manning's roughness coefficient (n) is often used in some of the equations because Manning's equation is used to estimate runoff velocity. A rainfall parameter, such as the 2-year, 24-h rainfall depth or rainfall intensity (NRCS 1972, 1986; Welle and Woodard 1986), is sometimes used as water input to indicate the effect of the surface runoff availability

¹Professor, Dept. of Civil Engineering, Lamar Univ., Beaumont, TX 77710-0024; presently, Auburn Univ., Auburn, AL 36849 (corresponding author). E-mail: xing.fang@auburn.edu

²Associate Professor, Dept. of Civil & Environmental Engineering, Texas Tech Univ., Lubbock, TX 79409. E-mail: daivd.thompson@ttu.edu

³Associate Professor, Dept. of Civil & Environmental Engineering, Univ. of Houston, Houston, TX 77204. E-mail: cleveland@uh.edu

⁴Research Assistant, Dept. of Civil Engineering, Lamar Univ., Beaumont, TX 77710-0024. E-mail: pratishpradhan@hotmail.com

⁵E.I.T., Stanley Consultants, 1661 E. Camelback Rd., Suite 400, Phoenix, AZ 85016; formerly, Research Assistant, Dept. of Civil Engineering, Lamar Univ., Beaumont, TX 77710-0024. E-mail: mallaranjit@stanleygroup.com

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on estimating travel time of overland flow (McCuen 1998). Some empirical equations were developed for watersheds where overland flow dominates, such as the formula by Izzard (1946) and Kerby–Hathaway (1959), the kinematic wave formula by Henderson and Wooding (1964), Woolhiser and Liggett (1967), and Aron and Erborge (1973), the dynamic wave formula by Morgali and Linsley (1965), and Su and Fang (2004). Wong and Chen (1997) developed a kinematic Darcy–Weisbach time of concentration formula, and Wong (2005) assessed the accuracies of nine formulas for overland flow. Other empirical equations were developed for watersheds in which channel flow dominates, such as the formulae by Williams (1922), Kirpich (1940), Johnstone–Cross (1949), and Haktanir and Sezen (1990). These empirical equations were typically developed using regression analysis with input parameters as watershed and channel parameters, which include watershed drainage area, channel length, watershed or channel slope, and watershed shape parameters (Kirpich 1940; Wu 1963; McCuen 1998; Haktanir and Sezen 1990). These parameters could be derived or estimated from different watershed topographic data and by different methods. This study determines how parameters estimated by different methods impact estimation of T_c for a watershed. As mentioned above there are many empirical equations for estimating time of concentration, and equations primarily developed for overland flow are not tested in this study since study watersheds include many relatively large watersheds where channel flow dominates.

In the study, T_c is estimated for 96 Texas watersheds using five empirical equations: Williams (1922), Kirpich (1940), Johnstone–Cross (1949), Haktanir–Sezen (1990), and Simas–Hawkins (2002) methods. These equations were selected to study since they use only a few readily available watershed parameters for engineering practice. Drainage area of study watersheds is approximately 0.8–440.3 km² (0.3–170 mi²). Watershed parameters used to estimate T_c were developed by three research teams using three different methods: automated method using digital elevation models and geographic information system (GIS) software, manual method with watershed delineation, and manual method without watershed delineation. The three research teams are from Lamar University (LU), Beaumont, Tex.; University of Houston (UH), Houston, Tex.; and the U.S. Geological Survey (USGS), Austin, Tex. T_c estimates from five empirical equations using three sets of watershed parameters are compared and analyzed. This study is part of a larger study to compare methods for estimating time parameters associated with unit hydrographs for Texas watersheds and is sponsored by the Texas Department of Transportation (TxDOT).

Development of Watershed Characteristics

Watershed characteristics related to watershed slope and size are often used in empirical equations to estimate T_c . In order to apply empirical equations to estimate T_c , several watershed characteristics were developed for 96 watersheds in central Texas by three different methods. These study watersheds are associated with 96 USGS streamflow gauging stations located in central Texas. Of the 96 gauging stations, 31 are located in the rural regions and 65 in the urban areas of Austin, San Antonio, and Dallas–Ft. Worth. Location of the stations is shown in Fig. 1. The watershed data set was taken from a larger data set accumulated by researchers from the USGS, LU, UH, and TTU (Texas Tech University), and used in a series of research projects funded by TxDOT (Asquith et al. 2004). The original database developed from pre-

vious projects includes 90 USGS streamflow gauging stations that contain information on contributing watershed area and longitude and latitude of the station. Three research teams worked independently to develop watershed parameters using three different methods, and during the project, the USGS team added six additional gauging stations for its study, but LU and UH did not include those six stations.

The first method to develop watershed parameters is an automated or programmed method (Brown et al. 2000) using GIS software—ArcGIS Spatial Analyst (ESRI 2004) and implemented by researchers at the USGS Texas Water Science Center, Austin. Watersheds were delineated first using a 30-m USGS digital elevation model (DEM) before watershed parameters were abstracted (Roussel et al. 2005). The location of the USGS gauging station was treated as the outlet or pour point of the watershed. Forty two characteristics for each individual watershed were determined; however, only total drainage area (TDA), main channel length (MCL), channel slope (MCS2), and basin width (BW) were used for application of the empirical equations. Basin width is the ratio of contributing drainage area to the basin length (BLENG), which is the sum length of a limited number of sequential line segments following the geometric centerline of the watershed from the watershed outlet to the basin divide. Main channel slope (MCS2) is the ratio of the basin divide elevation (BDELEV) minus the outlet elevation (OUELEV) to the main channel length (MCL) (Asquith and Slade 1997). For the 96 watersheds (Fig. 1) studied using the automated method, there are 59 watersheds with areas less than 25 km² (~10 mi²), and 77 with areas less than 50 km² (~20 mi²). The drainage areas are approximately 0.8–440.3 km² (0.3–339.6 mi²). Main channel lengths estimated are approximately 2–80 km (1.2–49.7 mi), dimensionless main channel slopes estimated are approximately 0.002–0.02, and basin widths are approximately 0.4–10 km (0.3–6.2 mi).

Researchers at the University of Houston implemented the second method—a manual method used to estimate watershed parameters with watershed delineation. USGS 7.5-min topographic quadrangle maps (hardcopy paper maps) were used as the data source. The location of each streamflow gauging station was determined and marked on the map using its longitude and latitude. Geo-referenced images of the USGS maps displayed at Topozone (2003) were visually compared with the paper copies to assist in locating the gauging station on the paper map. After locating the outlet, the watershed was delineated manually (He 2004) and the watershed area was determined using a mechanical planimeter. Watershed characteristics used in this study and determined from manually delineated watersheds include the drainage area, the length of the main stream, the maximum distance, the highest elevation within the watershed, and the lowest elevation within the watershed. The maximum distance is the straight-line distance from the streamflow-gauge station location to the farthest point of the drainage area and is used to estimate basin width as drainage area divided by the maximum distance for the application of the Simas–Hawkins equation (2002). The channel slope is estimated from the difference of the highest elevation and the lowest elevation within the watershed divided by the stream length. For the 90 gauging stations UH studied, three stations identified using longitude and latitude were not sufficiently close to any nearby streams (blue lines on USGS topographic map), therefore, watershed parameters for only 87 watersheds were developed by the UH team using manual watershed delineation. Estimated main channel lengths are approximately 1.4–80 km (0.9–49.7 mi), dimensionless main channel slopes

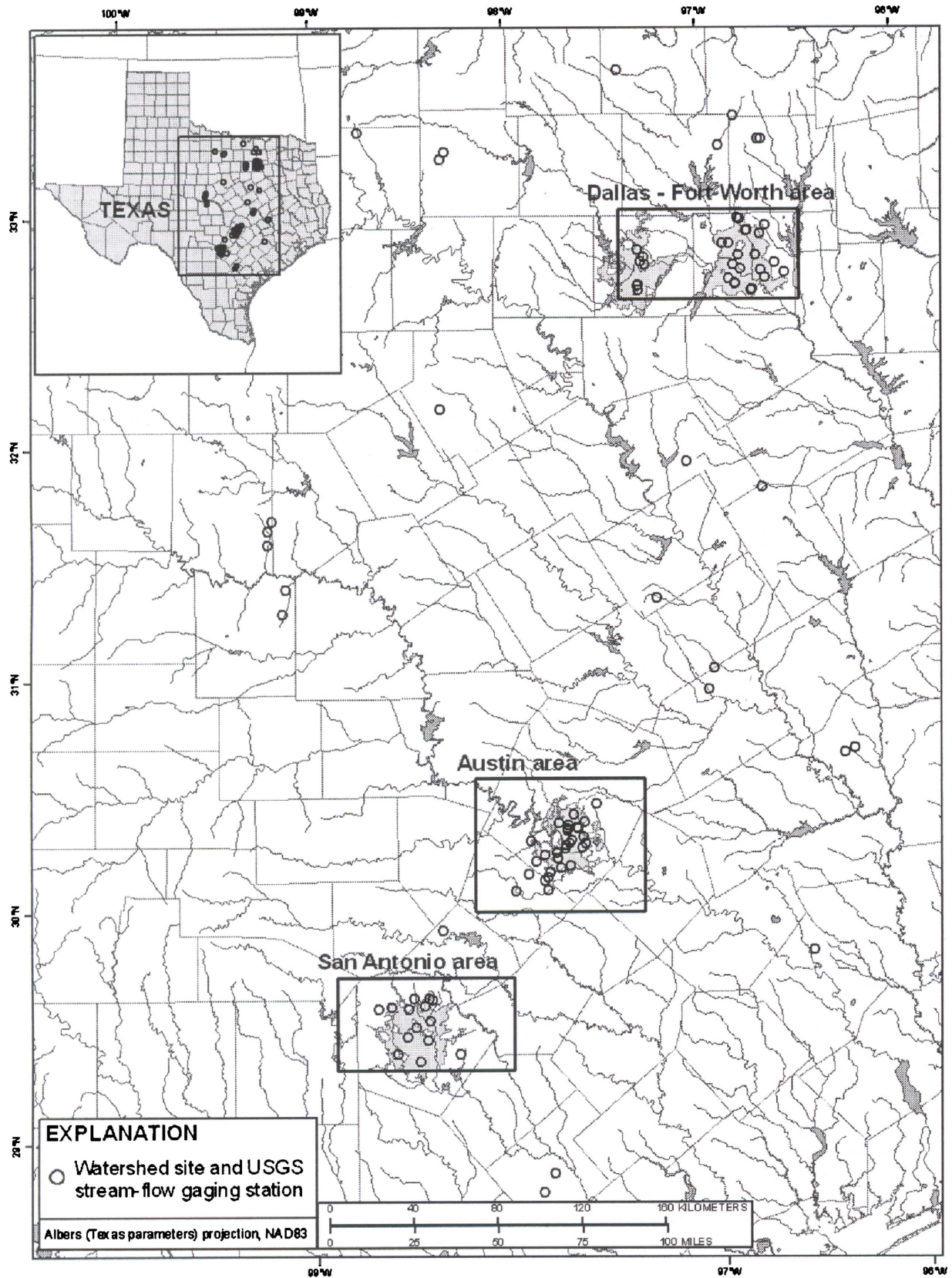


Fig. 1. Location of 96 watersheds studied in central Texas (Courtesy of Franklin Heitmuller, USGS, Austin, Tex.)

are approximately 0.002–0.024, and basin widths approximately 0.5–11.5 km (0.3–7.1 mi).

Researchers at Lamar University used DeLorme's 3D TopoQuads (DeLorme 1999) to implement the third method to develop watershed parameters. Each USGS gauging station was located on DeLorme's digitized USGS 7.5-min topographic map using the latitude/longitude index method in 3D TopoQuads. Watershed delineation was not performed using the gauging station as an outlet; therefore, the watershed area used for Williams equation is from the USGS gauging station information file (presumably manual watershed delineation was used to estimate the drainage area by USGS when these gauging stations were established in the 1960s–1970s). The longest stream route upstream from the station (blue line on a USGS topographic quadrangle map) was determined and linear tracing along the stream was developed. From the profile along the longest stream, the elevation at the upstream end, the elevation at the downstream end (the outlet or gauging station), and the linear distance of the stream were obtained (Malla 2004). The channel slope was calculated as the ratio of the elevation difference between the upstream end and the outlet to the linear distance of the stream. These two watershed parameters (channel length and slope) were determined for 83 Texas watersheds based on the manual method without watershed delineation. For the 83 watersheds LU studied, estimated main channel lengths are approximately 1.2–76 km (0.7–47.2 mi), and dimensionless main channel slopes ranged from 0.002 to 0.018. For the 90 gauging stations LU studied, seven stations identified using longitude and latitude were not sufficiently close to any nearby streams in 3D TopoQuads and were unable to develop any watershed parameters. These seven stations are associated with relatively small watersheds. Additional information such as specific stream or creek name and intersection with a specific road or highway crossing could be useful to locate a gauging station accurately.

Comparison on Watershed Parameters

A graphic comparison for two watershed parameters, channel length and channel slope, is shown in Fig. 2; and the horizontal axis shows automated results by USGS and the vertical axis shows manually determined results by LU and UH. Absolute difference and relative difference in percent (numbers in parentheses) for channel lengths and slopes determined between using manual (UH and LU) and automated (USGS) methods are listed in Table 1. Automatic-based channel lengths using 30-m DEM is typically larger than manually determined channel lengths by LU and UH (average 15% larger) since automatic-based channel length (MCL) is measured along the longest flow path from the watershed outlet to the basin divide. The average difference between automated (USGS) and manual methods (LU and UH) is 1.2 km (0.75 mi) with standard deviation of 1.4 km (0.87 mi) (Table 1). The average difference of channel lengths between manual and automated methods for smaller watersheds or shorter channel lengths is about the same (<0.1 km difference) for larger ones but the difference looks bigger in Fig. 2 for shorter channel lengths because a log scale is used in Fig. 2. Channel slopes estimated by UH are on average 15% greater than the ones estimated by USGS, which are an average of 11% greater than the ones estimated by LU (Table 1). This is because channel slopes determined by UH use the highest and the lowest elevations in the watershed and USGS extends the channel to the basin divide where its elevation is greater than the elevation at the most up-

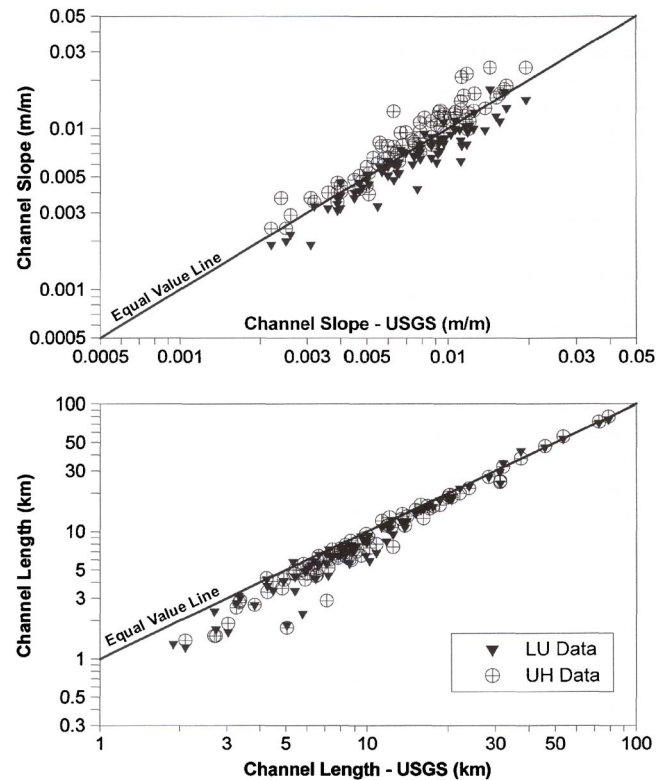


Fig. 2. Channel length and slope developed using different methods

stream point of a stream that LU used. Discrepancy in channel slope is much larger (maximum 102% difference, Table 1) because the average watershed slope is also sensitive to grid size and the source of the digital elevation model (Hill and Neary 2005). The average difference of basin width (BW) between manual (UH) and automated (USGS) methods is -0.34 km (0.21 mi) with standard deviation of 0.59 km (0.37 mi) with a relative difference of -13.7% (Table 1). A detailed comparison of automated and manually determined watershed parameters by USGS and UH is given elsewhere (Cleveland et al. 2005). Drainage areas determined by automated and manual methods have a median relative difference of 0.2% only (Cleveland et al. 2005). Manual and automated measures of selected watershed characteristics are qualitatively similar in the watersheds studied but

Table 1. Summary of Absolute Difference and Relative Difference in Percent (Numbers in Parentheses) for Channel Lengths (km), Slopes (Dimensionless), and Basin Width (km) Determined between Using Manual (UH and LU) and Automated (USGS) Methods

Data set	Between UH and USGS data			Between LU and USGS data	
	Channel length	Channel slope	Basin width	Channel length	Channel slope
Maximum	2.34 (7.4%)	0.01 (102.2%)	2.29 (45.6%)	5.88 (15.7%)	0.32E-2 (22.2%)
Minimum	-6.58 (-65.1%)	-0.02E-1 (-23.5%)	-3.34 (-129.7%)	-7.28 (-63.3%)	-0.49E-3 (-45.5%)
Average	-1.22 (-15.0%)	0.13E-2 (14.6%)	-0.34 (-13.7%)	-1.26 (-15.0%)	-0.99E-3 (-11.3%)
Standard deviation	1.42 (13.9%)	0.22E-2 (22.6%)	0.59 (19.2%)	1.48 (14.2%)	0.14E-2 (13.3%)

Table 2. Empirical Equations Used to Estimate Time of Concentration (Minutes) of Texas Watersheds

Method	Equation in SI units	Equation in English units
Williams (1922)	$T_c = 16.32L_c A^{0.4} / (DS_c^{0.2})$	$T_c = 23.89L_c A^{0.4} / (DS_c^{0.2})$
Kirpich (1940)	$T_c = 3.978L_c^{0.77} S_c^{-0.385}$	$T_c = 5.735L_c^{0.77} S_c^{-0.385}$
Johnstone–Cross (1949)	$T_c = 3.258(L_c/S_c)^{0.5}$	$T_c = 4.129(L_c/S_c)^{0.5}$
Haktanir–Sezen (1990)	$T_L = 26.85L_c^{0.841}$	$T_L = 40.06L_c^{0.841}$
Simas–Hawkins (2002)	$T_L = 53.14 \times W^{0.594} \times S_B^{-0.150} \times S_{nat}^{0.313}$	$T_L = 70.5 \times W^{0.594} \times S_B^{-0.150} \times S_{nat}^{0.313}$

Note: For SI units, channel length L_c , watershed equivalent diameter D , and watershed width W are in km, area A is in km², and S_c (channel slope) and S_B (basin slope) are in m/m. For English units, L_c , D , and W are in mi, A is in mi², and S_c and S_B is in ft/ft. S_{nat} is in in. for both units.

differences in characteristics are statically significant (Cleveland et al. 2005). For a study to estimate time of concentration for one or a few small watersheds, the manual method may be preferable. If the study involves large-size watersheds and multiple watersheds, the speed of the automated method greatly reduces the overall effort required to generate watershed parameters but it requires necessary GIS software, a skilled analyst, and necessary digital elevation maps.

Empirical Equations for Estimating Time of Concentration

Five empirical equations were applied to estimate T_c for 96 Texas watersheds using watershed parameters determined by the three different methods. This study demonstrates how empirical equations for estimating T_c are sensitive to the methods used to estimate watershed parameters. The empirical equations used include Williams equation (1922), Kirpich equations (1940), the Johnstone–Cross equation (1949), the Haktanir–Sezen equation (1990), and the Simas–Hawkins equation (2002). These equations are listed in Table 2 for both System International (SI) and English units.

Williams (1922) conducted a study on flood discharge in India and developed an equation to estimate T_c (Table 2). The equivalent diameter (D) of a circular basin with the same drainage area is used ($A = \pi D^2/4$). The equation was developed for watersheds with drainage areas less than 129.5 km² (50 mi²). Pilgrim and Cordery (1993) stated that Williams equation is used in several countries, and presented the equation for English units as $T_c = 21.3LA^{-0.1}S^{-0.2}$, where A is in mi², L is in mi, and S is in ft/ft. This equation is the same as Williams equation listed in Table 2 after including the relation of drainage area and diameter.

Kirpich (1940) developed an equation to estimate T_c (hours) for small watersheds in Tennessee. Kirpich's equation is often used in the United States (Pilgrim and Cordery 1993) correlating T_c with watershed characteristic L/\sqrt{S} . The channel slope is defined as the difference in elevation between the most remote point (divide) and the outlet divided by channel length. Tennessee watersheds used in the Kirpich study ranged in sizes from 0.004 to 0.45 km², with slopes from 3 to 12%. The Kirpich method is widely accepted for estimating T_c for small drainage areas. McCuen et al. (1984) stated that the Kirpich method developed for Tennessee had the smallest bias for watersheds with significant channel flow.

Johnstone and Cross (1949) developed an empirical equation to estimate T_c for watersheds in the Scioto and Sandusky River (Ohio) basins with areas between 65 and 4,206 km² (25–1620 mi²) (Haestad Methods Inc. 2003). The Johnstone and Cross equation correlates T_c with the ratio of channel length and channel slope (L/S).

Haktanir and Sezen (1990) developed two-parameter gamma and three-parameter beta distributions as synthetic unit hydrographs for ten watersheds in Anatolia, Turkey. Regression analyses for peak discharge and NRCS lag time of ten observed unit hydrographs were performed to develop the regression equations. T_c is computed from lag time based on the NRCS relationship $T_L = 0.6T_c$ (NRCS 1972, 1986). The Haktanir and Sezen method only includes channel length as an input watershed parameter but omits channel slope.

Simas and Hawkins (2002) developed a regression equation to estimate lag time. The equation was derived from over 3,100 rainfall-runoff events in 168 small watersheds in the United States, ranging from 0.0012 to 14 km². Basin width (BW) is used and obtained as the watershed area divided by the watershed length (not channel length). A storage coefficient (S_{nat} in in.) is also used and determined based on the curve number (CN) method as

$$S_{nat} = \frac{1000}{CN} - 10 \quad (2)$$

Lag time equation (L_H = time between the centroid of rainfall excess and the direct runoff hydrograph) developed by Simas–Hawkins was converted to estimate T_c using the NRCS relationship: $T_c = 1.417L_H$ (NRCS 1972, 1986).

Results and Comparison of T_c Estimates

Time of concentrations (T_c) estimated using Williams (1922), Kirpich (1940), Johnstone–Cross (1949), and Haktanir–Sezen (1990) equations and using watershed parameters developed by LU, UH, and the USGS are shown in Fig. 3. Fig. 3 is a log-log plot and shows estimated T_c (h) versus drainage area A (km²), and graphically indicates that T_c estimates are not sensitive to methods used to estimate watershed parameters. Fig. 3 also includes a reference line developed by an ad hoc method that uses the square root of the watershed drainage area in square miles, which reportedly produces T_c in hours (David Stolpa, personal communication, TxDOT, Austin, Tex., 2004). The origin of the method is uncertain (the equation might not be developed from actual data analysis but from engineering experience or observations). The method lacks an apparent physical basis and is dependent on the unit system indicated. Remarkably, the square root of the drainage area passes through the generalized center of the data values of T_c derived from observed rainfall-runoff data analysis (Roussel et al. 2005). Although producing the right order T_c , the writers suggest that the method be considered as an engineering rule of thumb, which can be a check of other methods. If the drainage area in square kilometers (km²) is used, the reference line can be written as $T_c = 0.62A^{0.5}$.

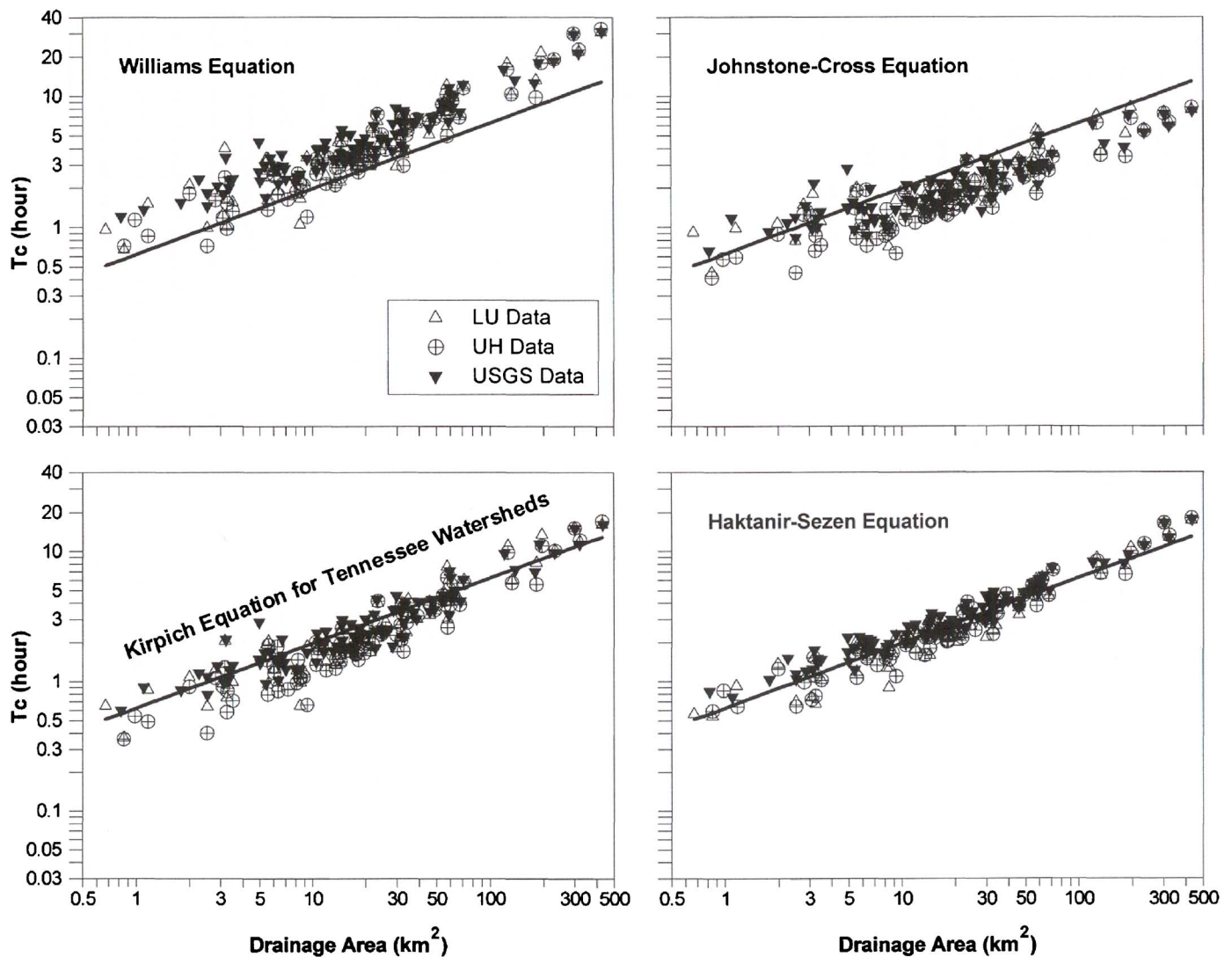


Fig. 3. Estimated time of concentration in Texas watersheds using Williams's, Kirpich, Johnstone–Cross, and Haktanir–Sezen equations with watershed parameters from LU, UH, and USGS

Table 3 gives statistical results of absolute difference in hours and relative difference in percent (numbers in parentheses) for T_c estimates between using LU and USGS or UH and USGS watershed parameters. When Williams equation was used, the average difference of T_c estimated using watershed parameters derived from the three methods is about 0.6 h or 17% of the relative difference (Table 3). The maximum difference is 3.5 h and the maximum relative difference is -85% . Most designers in Texas using TxDOT technology use watershed drainage areas to select different methods for hydrologic designs, and the unit hydrograph method is recommended for watersheds with drainage areas exceeding 0.8 km^2 but less than 50 km^2 (20 mi^2). For watersheds with drainage areas exceeding 50 km^2 (20 mi^2), use of the regional regression equations is recommended. Therefore, for comparison on T_c estimates, Tables 3 and 4 include a statistical summary of T_c estimates by dividing watersheds into two groups: drainage area less than 50 km^2 (about 20 mi^2) and greater than 50 km^2 . Fig. 3 and Table 3 show that T_c estimated using Williams equation has relatively small variations in relation to other uncertainties inherent in T_c estimation. T_c estimated by Williams equation is typically larger than T_c estimated from the square root of area (mi^2)—an ad hoc method.

When the Kirpich equation was used, T_c estimated using watershed parameters derived from the three methods is similar as indicated in Fig. 3. The average difference of estimated T_c between using LU and USGS watershed data is -0.14 h (-10.7%), and deviation ranged from 2.09 to -1.41 h or 43–78%. The average difference of estimated T_c between using UH and USGS watershed data is -0.33 h (-15%), and deviation ranged from 0.92 to -1.52 h (Table 3). T_c estimated by the Kirpich equation is similar to T_c as the square root of area (mi^2). T_c estimated by the Kirpich equation was also similar to mean T_c estimated by using observed rainfall-runoff data, which included more than 1,600 runoff-producing events for the 96 watersheds studied (Roussel et al. 2005).

The Johnstone–Cross equation (1949) combined channel length and channel slope into a single parameter (L/S). Using the equation for the Texas watersheds, Fig. 3 and Table 3 show small differences in T_c estimated using watershed parameters derived by the three methods. The average relative differences range from 4 to 15% (Table 3). T_c estimated by the Johnstone–Cross equation is typically lower than T_c estimated from the square root of area (mi^2).

The Haktanir–Sezen equation (1990) requires only the main

Table 3. Statistical Results of Absolute Difference in Hours and Relative Difference in Percent (Numbers in Parentheses) for T_c Estimates Using Different Empirical Equations

Description of comparison between alternatives	Area (km ²)	Average difference [h (%)]	Standard deviation [h (%)]	Maximum deviation [h (%)]	Minimum deviation [h (%)]
Difference of T_c between using LU and USGS watershed data (Williams equation)	All	-0.56 (-16.7)	0.89 (21.3)	3.47 (19.2)	-3.07 (-84.6)
	A < 50	-0.68 (-19.9)	0.67 (21.6)	0.43 (13.9)	-2.64 (-84.6)
	A > 50	0.05 (-1.2)	1.48 (10.2)	3.47 (19.2)	-3.07 (-22.9)
Difference of T_c between using UH and USGS watershed data (Williams equation)	All	-0.65 (-16.6)	0.73 (15.3)	1.32 (12.9)	-3.03 (-65.5)
	A < 50	-0.66 (-19.1)	0.58 (15.6)	0.74 (12.9)	-2.34 (-65.5)
	A > 50	-0.62 (-7.2)	1.17 (9.1)	1.32 (6.2)	-3.03 (-22.7)
Difference of T_c between using LU and USGS watershed data (Kirpich-Tennessee equation)	All	-0.14 (-10.7)	0.54 (20.7)	2.09 (42.6)	-1.42 (-77.7)
	A < 50	-0.24 (-13.5)	0.39 (21.2)	0.76 (42.6)	-1.42 (-77.7)
	A > 50	0.35 (2.9)	0.84 (10.2)	2.09 (18.4)	-1.29 (-17.8)
Difference of T_c between using UH and USGS watershed data (Kirpich-Tennessee equation)	All	-0.33 (-15.3)	0.39 (14.7)	0.92 (-1.5)	-1.53 (-60.7)
	A < 50	-0.34 (-17.7)	0.31 (15.0)	0.58 (16.8)	-1.19 (-60.7)
	A > 50	-0.29 (-6.2)	0.63 (8.6)	0.92 (6.9)	-1.53 (-21.1)
Difference of T_c between using LU and USGS watershed data (Johnstone-Cross equation)	All	-0.02 (-3.9)	0.39 (19.7)	1.11 (76.5)	-1.14 (-64.1)
	A < 50	-0.09 (-6.0)	0.33 (20.6)	0.81 (76.5)	-1.14 (-64.1)
	A > 50	0.34 (6.1)	0.50 (10.4)	1.11 (26.8)	-0.50 (-11.6)
Difference of T_c between using UH and USGS watershed data (Johnstone-Cross equation)	All	-0.22 (-12.7)	0.26 (13.2)	0.50 (18.1)	-0.93 (-53.7)
	A < 50	-0.24 (-14.8)	0.23 (13.7)	0.48 (18.1)	-0.93 (-53.7)
	A > 50	-0.15 (-4.8)	0.33 (7.5)	0.50 (6.6)	-0.77 (-17.8)
Difference of T_c between using LU and USGS watershed data (Haktanir-Sezen equation)	All	-0.40 (-16.5)	0.41 (18.4)	1.22 (13.0)	-1.62 (-78.6)
	A < 50	-0.44 (-20.0)	0.35 (19.1)	0.14 (7.7)	-1.53 (-78.6)
	A > 50	-0.24 (-4.0)	0.55 (7.0)	1.22 (13.0)	-1.62 (-20.0)
Difference of T_c between using UH and USGS watershed data (Haktanir-Sezen equation)	All	-0.33 (-12.7)	0.35 (12.3)	0.46 (6.4)	-1.46 (-58.6)
	A < 50	-0.33 (-14.6)	0.29 (12.7)	0.22 (6.4)	-1.27 (-58.6)
	A > 50	-0.33 (-5.7)	0.52 (7.0)	0.46 (3.6)	-1.46 (-18.3)
Difference of T_c between using UH and USGS watershed data (Simas-Hawkins equation with observed CN)	All	0.26 (6.4)	0.72 (11.5)	2.89 (43.2)	-3.40 (-33.2)
	A < 50	0.31 (8.0)	0.43 (10.2)	-0.62 (-11.7)	1.62 (43.2)
	A > 50	0.09 (0.3)	1.34 (14.2)	2.89 (25.9)	-3.40 (-33.2)
Difference of T_c between using UH and USGS watershed data (Simas-Hawkins equation with predicted CN)	All	0.20 (6.4)	0.61 (11.5)	2.66 (43.5)	-2.92 (-33.3)
	A < 50	0.25 (8.0)	0.35 (10.2)	1.20 (43.5)	-0.48 (-11.6)
	A > 50	0.06 (0.4)	1.18 (14.2)	2.66 (25.9)	-2.92 (-33.3)
Difference of T_c between using observed and predicted CN (Simas-Hawkins equation with UH data)	All	-0.96 (-16.9)	0.79 (14.0)	0.86 (21.4)	-3.72 (-45.2)
	A < 50	-0.89 (-18.1)	0.72 (14.5)	0.86 (21.4)	-2.38 (-45.2)
	A > 50	-1.22 (-12.4)	0.96 (11.1)	0.78 (19.7)	-3.72 (-29.1)
Difference of T_c between using observed and predicted CN (Simas-Hawkins equation with USGS data)	All	-0.89 (-16.9)	0.72 (14.0)	0.93 (21.4)	-3.31 (-45.3)
	A < 50	-0.81 (-18.1)	0.65 (14.5)	0.82 (21.4)	-2.25 (-45.3)
	A > 50	-1.19 (-12.5)	0.92 (11.1)	0.93 (19.7)	-3.31 (-29.1)

channel length as an input watershed parameter estimating T_c . The main channel length (MCL) typically has a good correlation to drainage area. For example, using watershed parameters developed by USGS, regression analysis shows that $MCL = 1.9445 * A^{0.571}$ with R^2 of 0.94, where MCL is in miles and area A is in square miles. Incorporating the above relation

into the Haktanir-Sezen equation (Table 2), T_c can be presented as $T_c = 1.17 * A^{0.48}$, where T_c is in hours and area A is in square miles. Therefore, T_c estimated using the Haktanir-Sezen equation is very similar to T_c estimated from the square root of area (mi²) as graphically shown in Fig. 3. T_c estimated using the Haktanir-Sezen equation is also similar to T_c estimated using the Kirpich-

Table 4. Statistical Results of Absolute Difference in Hours and Relative Difference in Percent (Numbers in Parentheses) for T_c Estimates Using Different Empirical Equations with Watershed Parameters from UH

Description of comparison between alternatives	Area (km ²)	Average difference [h (%)]	Standard deviation [h (%)]	Maximum deviation [h (%)]	Minimum deviation [h (%)]
Difference of T_c between using Simas–Hawkins equation with observed CN and Kirpich–Tennessee equation	All	2.58 (173.3)	2.04 (149.7)	7.59 (712.5)	−4.46 (−37.2)
	$A < 50$	2.84 (206.8)	1.33 (147.3)	7.23 (712.5)	0.60 (21.9)
	$A > 50$	1.64 (50.6)	3.52 (77.9)	7.59 (262.7)	−4.46 (−37.2)
Difference of T_c between using Simas–Hawkins equation with predicted CN and Kirpich–Tennessee equation	All	1.62 (118.8)	1.84 (108.7)	5.77 (480.0)	−6.06 (−39.6)
	$A < 50$	1.95 (143.6)	1.13 (105.6)	5.77 (480.0)	−0.71 (−17.0)
	$A > 50$	0.42 (28.2)	3.12 (62.8)	5.64 (216.9)	−6.06 (−39.6)
Difference of T_c between using Haktanir–Sezen equation and Kirpich–Tennessee equation	All	0.47 (25.2)	0.53 (20.9)	1.46 (77.4)	−1.52 (−20.9)
	$A < 50$	0.43 (28.6)	0.34 (20.8)	1.46 (77.4)	−0.19 (−20.9)
	$A > 50$	0.63 (13.3)	0.94 (16.6)	1.42 (46.2)	−1.52 (−14.6)
Difference of T_c between using Williams equation and Kirpich–Tennessee equation	All	2.42 (81.7)	2.68 (15.4)	15.61 (113.8)	0.27 (29.7)
	$A < 50$	1.44 (81.1)	0.77 (16.0)	3.48 (113.8)	0.27 (29.7)
	$A > 50$	6.16 (84.0)	3.91 (12.7)	15.61 (101.1)	2.38 (62.6)
Difference of T_c between using Johnstone–Cross equation and Kirpich–Tennessee equation	All	−0.87 (−17.6)	1.56 (16.2)	0.31 (34.1)	−8.88 (−52.0)
	$A < 50$	−0.31 (−12.3)	0.34 (13.4)	0.31 (34.1)	−1.15 (−35.2)
	$A > 50$	−3.03 (−37.9)	2.36 (7.2)	−0.81 (−28.6)	−8.88 (−52.0)

Tennessee equation (Fig. 3), which requires channel length and slope as input parameters. Statistical results in Table 3 show that the average difference of estimated T_c between using LU and USGS watershed data is −0.40 h or −16.5%, and deviation ranged from 1.22 to −1.62 h or 13.0 to −78.6% when all watersheds were compared. When the Haktanir–Sezen equation was used, the average difference of estimated T_c between using UH and USGS watershed data is −0.33 h or −12.7%, and deviation ranged from 0.47 to −1.46 h or 6.2–−58.7%.

The Simas–Hawkins equation is different from the above four equations (Fig. 3) which use conventional watershed parameters such as drainage area, channel length, and channel slope. The Simas–Hawkins equation includes a storage coefficient determined from CN, which relates to potential of rainfall losses. The basin width (BW) as watershed area divided by watershed length (not channel length) is also used. The watershed length used was either the basin length (BLENG) developed by the USGS as the sum length of a limited number of sequential line segments following the geometric centerline of the watershed from the outlet to the basin divide or the max-distance developed by UH as the straight-line distance from the gauging station location to the furthest point of the drainage area. Researchers at LU did not develop watershed length for Texas watersheds; therefore, the Simas–Hawkins equation was not applied to LU data.

Curve numbers (CN) used for Texas watersheds were obtained from a study of climatic adjustments of the NRCS runoff curve numbers by Thompson et al. (2003). Observed CN was determined from methodology developed and used by Hawkins applying available measured rainfall and runoff data for a specific watershed; predicted CN was determined from NRCS procedures. Both predicted and observed CN were used to calculate storage coefficient (S_{nat}), and T_c estimated by the Simas–Hawkins equation is given in Fig. 4. T_c estimated using watershed parameters from UH and USGS is similar for both using observed and

predicted CN (Fig. 4). The average difference of T_c estimated between using UH and USGS watershed data is less than 0.4 h or 11% (Table 3).

T_c estimated using observed CN (top part of Fig. 4) is larger than T_c estimated using predicted CN (bottom part of Fig. 4) since observed CN is typically smaller than predicted CN (Thompson et al. 2003). Table 3 also summarizes statistical results of difference of estimated T_c using different CN values but the same watershed parameters. The average difference of estimated T_c between using observed and predicted CN ranges from 0.8 to 1.2 h or 16–26% (Table 3). These differences are larger than the differences when T_c was estimated using different watershed data sets derived by USGS and UH. Comparison of Figs. 3 and 4 shows T_c estimated using the Simas–Hawkins equation is generally greater than T_c estimated using Kirpich, Johnstone–Cross, and Haktanir–Sezen equations for watersheds with drainage areas less than 50 km² (20 mi²). The Simas–Hawkins equation introduces uncertainty of estimating basin width and specifying CN value.

For five empirical equations tested, overall, T_c estimated using watershed parameters developed by the three different methods is qualitatively similar and has average relative differences ranging from 6.4 to −16.9% (Table 3), and relative differences for watersheds with area less than 50 km² (20 mi²) (from 8.0 to −20.0%) are slightly larger than ones for larger watersheds (2.9 to −12.5%).

Fig. 5 shows T_c estimated using all above empirical equations with UH watershed parameters. Fig. 5 shows that T_c estimated by the Johnstone–Cross equation gives a lower bound of T_c estimates, and T_c estimated by the Simas–Hawkins equation gives a higher bound of T_c estimates when the area is less than about 70 km². When the area is greater than about 70 km², T_c estimated by Williams equation gives a higher bound of T_c estimates. Variation of T_c estimates from these empirical equations between lower and higher bounds is about one log scale. Fig. 5

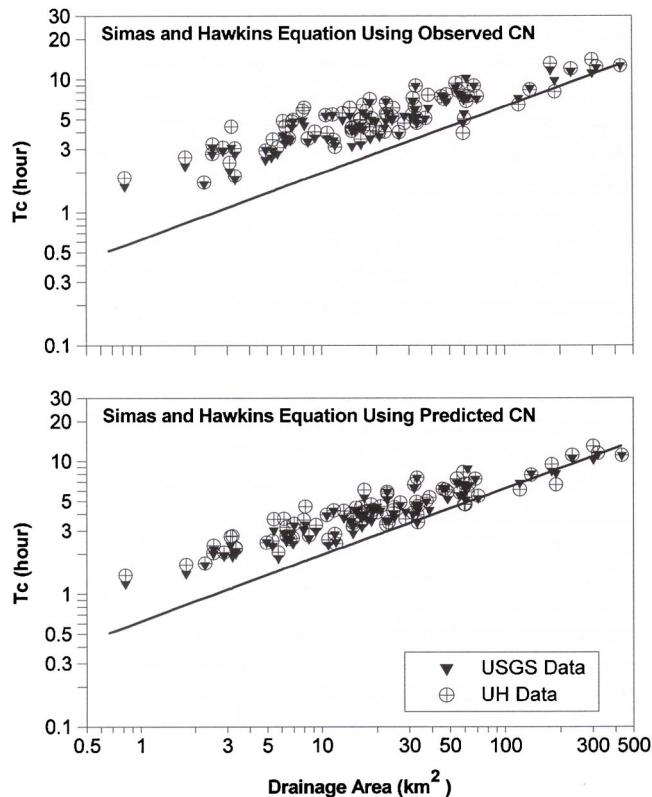


Fig. 4. Estimated time of concentration for Texas watersheds using Simas–Hawkins method, using predicted and observed CN and watershed parameters from USGS (triangles) and UH (circles)

demonstrates that the difference of T_c estimated using different empirical equations is typically much greater than the differences of estimated T_c between using watershed parameters developed using different methods and source data, for example, using a digital elevation model or a hardcopy of USGS quadrangle map, the automated GIS or manual method, and with or without watershed delineation. Statistical results of absolute and relative differences between using different empirical equations are summarized in Table 4. T_c estimated by the Kirpich equation

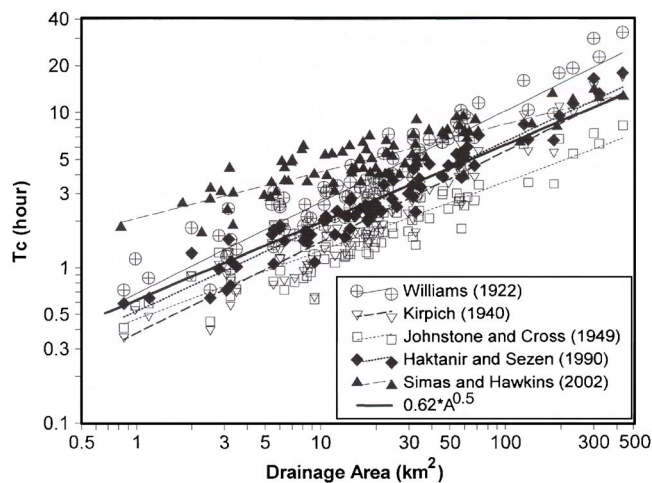


Fig. 5. Estimated time of concentration for Texas watersheds using different empirical equations with watershed parameters derived by UH

was used as a base for the above comparison and development of statistical results in Table 4. Relative average differences range from -38 to 207% and absolute average differences range from -3.0 to 2.8 h. Maximum differences range from -9.0 to 15.6 h (Table 4).

Summary and Discussion

Time of concentration (T_c), a widely used time parameter for hydrological design, is estimated for 96 Texas watersheds using five empirical equations: Williams (1922), Kirpich (1940), Johnstone–Cross (1949), Haktanir–Sezen (1990), and Simas–Hawkins (2002) methods. Drainage areas of watersheds studied are approximately 0.8 – 430 km^2 . Watershed parameters used to estimate T_c were developed by three research groups (USGS, UH, and LU) using three different methods: automated method using digital elevation model and geographic information system software, manual method with watershed delineation, and manual method without watershed delineation. Average relative differences of channel length, slope, and basin width between automated and manual methods are about 15% . Manual and automated measures of selected watershed characteristics are qualitatively similar in the watersheds studied but differences in characteristics are statically significant (Cleveland et al. 2005). T_c estimated using three sets of watershed parameters is compared and analyzed when five empirical equations are applied. T_c estimated using watershed parameters developed by the three different methods is qualitatively similar and has average relative differences ranging from 6.4 to -16.9% . Therefore, it is appropriate to estimate watershed characteristics using a variety of methods. The method chosen to estimate watershed parameters is the choice of the analyst. Differences between manual and automatic-based watershed characteristics are considered minor sources of error in relation to other uncertainties inherent in time parameter estimation and to the hydrologic models incorporating time parameters for purposes of hydrologic engineering design. Average relative differences of T_c estimated using different empirical equations with the same set of watershed parameters range from -38 to 207% (absolute average differences range from -3.0 to 2.8 h) and are much larger than differences estimated using three sets of watershed parameters. Kirpich and Haktanir–Sezen methods provide reliable estimates of mean values of T_c variations.

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Notation

The following symbols are used in this paper:

- A = drainage area;
- BDELEV = basin divide elevation;

BLENG = basin length, sum length of limited number of sequential line segments following geometric centerline of watershed from watershed outlet to basin divide;
 BW = basin width, ratio of contributing drainage area to basin length;
 CN = curve number;
 D = equivalent diameter of circular basin;
 L = channel length;
 L_H = lag time defined as time difference between center of mass rainfall excess and direct runoff;
 MCL = main channel length;
 MCS2 = main channel slope;
 OUELEV = outlet elevation;
 R^2 = R -squared value (coefficient of determination);
 S_B = basin slope;
 S_c = channel slope;
 S_{nat} = storage coefficient (in.) = $1,000/CN - 10$;
 T_c = time of concentration; and
 T_L = lag time defined as time difference between center of mass rainfall excess and peak discharge.

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