Variations of Time of Concentration Estimates Using the NRCS Velocity Method

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Abstract: Time of concentration (T_c) is the time required for runoff to travel from the hydraulically most distant point to the outlet of a watershed. The Natural Resource Conservation Service (NRCS) velocity method commonly is used to estimate T_c for hydrologic analysis and design. The NRCS velocity method applies the physical concept that travel time is a function of runoff flow length and flow velocity. Time of concentration for 96 Texas watersheds is independently estimated by three research teams using the NRCS velocity method. Drainage areas of the 96 watersheds considered in the study are approximately 0.8 to 440.3 square kilometers (0.3 to 170 square miles). 30-meter digital elevation models were used to derive watershed physical characteristics using ArcGIS or HEC-GeoHMS. Average channel width was estimated from 1-meter or 1-foot digital orthoroimagery quarter quadrangle or aerial photography. Each team made independent decisions to estimate parameters needed for the NRCS velocity method. Estimates of time of concentration made by three research teams are compared, and both graphic comparison and statistical summary demonstrate that time of concentration estimated using the NRCS velocity method is subject to large variation, dependent on the analyst-derived parameters used to estimate flow velocity. Because of the propensity for different analysts to arrive at different results, caution is required in application of the NRCS velocity method to estimate T_c.

Introduction

The time of concentration (T_c) is a widely used time parameter to estimate time of peak discharge used for hydrologic design. For example, design of urban drainage systems implements the rational formula (Kuichling, 1889) and requires an estimate of T_c to determine the average rainfall intensity from IDF (intensity-duration-frequency) curves (Viessman and Lewis, 2002). Furthermore, implementation of the Natural Resources Conservation Service (NRCS) dimensionless unit hydrograph procedure requires an estimate of T_c to calculate the time of peak discharge, duration of the unit hydrograph, and unit hydrograph peak discharge. Errors in T_c estimation contribute to errors in estimation of design parameters. Bondelid and others (1982) showed that as much as 75 percent of the total error in an estimate of peak discharge can result from errors in the T_c estimation. Recognizing the importance of T_c in hydrologic designs, hydrologists have developed many methods for estimating T_c. Examples are the NRCS velocity method (NRCS, 1972; 1986) and various empirical equations (Kirpich, 1940; McCuen et al., 1984, Haktanir and Sezen, 1990).

The T_c of a watershed is the time required for a water parcel (runoff) to travel from the hydraulically most distant point of the watershed to the outlet. This concept has been used in many hydrologic studies and applications (Kirpich, 1940; US Army Corps of Engineers, 1966; Bell and Kar, 1969; NRCS, 1972; Schultz and Lopez, 1974; McCuen et al., 1984; Subramanya, 1984; Ben-Zvi, 1987; Huber, 1987; MacBroom, 1987; Garg, 2001; McCuen, 2005). The NRCS velocity method commonly is used to estimate T_c for hydrological analysis. The NRCS velocity method applies the physical concept that travel time is a function of runoff flow length and runoff flow velocity. McCuen and others (1984) assumed that T_c computed using the velocity method was the “true” value and used that value as the basis for comparing other empirical formulas. Essentially, the true value of T_c for a watershed is not known because T_c is influenced by variations of rainfall characteristics, topographic setting, and channel characteristics. Therefore, the T_c used for hydrologic analysis is only an estimate.

The NRCS velocity method uses the longest flow path to estimate T_c of a watershed (Kent, 1972). A flow path may be composed of various segments with different lengths, slopes, and flow velocities. T_c is the sum of travel time for the number of reaches or segments (*i = 1, 2, …M*) along a flow path:

$$T_c = \sum_{i=1}^{M} T_{ti} = \sum_{i=1}^{M} \frac{L_i}{60V_i} = T_{ol} + T_{sc} + T_{ch} \qquad (1)$$

where T_c is in minutes, T_{ti} is the travel time in minutes, L_i is the flow length in meter or feet, and V_i is the runoff velocity in meter or feet per second for the ith reach along the flow path. Travel time is typically estimated for three components of watershed response: overland flow (T_{ol}), shallow-concentrated flow (T_{sc}), and channel flow (T_{ch}). Kent (1972) stated that runoff is usually concentrated into small gullies or terrace channels within less than a thousand feet of its origin. "A velocity of 0.46 m/s (1.5 ft/s) can be assumed for the average terrace channel (Kent, 1972)." The velocity in the equation (1) is a function of the type of flow (overland or channel flow, laminar or turbulent flow), the roughness of the flow path, the channel shape and geometry, and the slope of the flow path. Flow velocity for shallow-concentrated and channel flow is typically computed using Manning's equation:

$$V = \frac{1}{n} R_h^{2/3} S^{1/2} \qquad (2)$$

where V is the mean flow velocity in meter per second, *n* is the Manning's roughness coefficient, R_h is the hydraulic radius in meter (flow area A divided by the wetted perimeter P*)*, and S is the channel bottom slope in meter per meter.

In this study, time of concentration for selected watersheds in Texas is estimated using the NRCS velocity method by three research teams (Lamar University – LU; the United States Geological Survey, Austin, Texas – USGS; and Texas Tech University – TTU). Information about method used and results developed by the USGS is presented in this paper with permission from USGS researchers and was also summarized in a project report (Roussel *et al.*, 2006) developed by the research group of LU, TTU, USGS, and the University of Houston. Drainage areas of watersheds considered in the study are approximately 0.8 to 440.3 square kilometers (0.3 to 170 square miles). 30-meter digital elevation models (DEM) were used to derive watershed parameters using ArcGIS (ESRI, 2004) or HEC-GeoHMS (US Army Corps of Engineers, 2003). Average channel width was estimated from 1-meter or 1-foot digital orthoroimagery quarter quadrangle (DOQQ) or aerial photography. Each research team independently estimated input parameters for T_c computation using the NRCS velocity method. T_c estimated by three research teams is compared and analyzed.

Watersheds Studied

The dataset used in this study was taken from a larger data set (Asquith *et al.*, 2004) assembled by researchers at USGS, TTU, LU, and University of Houston for use in a series of research projects funded by the Texas Department of Transportation (TxDOT). The dataset comprise 99 USGS streamflow-gaging stations located in Texas, as shown on Figure 1. Of the

99 gaging stations, 32 are located in the rural regions and 67 are located in the urban areas of Austin, San Antonio, and Dallas-Ft. Worth. In this study, 92 watersheds were studied by researchers at the USGS and LU, and 40 watersheds were studied by researchers at TTU. Watershed drainage areas are approximately 0.8 to 440.3 square kilometers (0.3 to 170 square miles), as shown on Table 1. LU and USGS researchers (Roussel *et al.*, 2006) used watershed parameters developed from 30-meter digital elevation models using ArcGIS (ESRI, 2004). A summary of watershed characteristics developed using ArcGIS is listed in Table 1. The bankfull top width of the main channel was determined using high resolution 1-foot and 1-meter digital orthoroimagery quarter quadrangle (DOQQ) data. Of the 28 watersheds within the boundaries of the available high resolution 1-foot DOQQ data, 50 percent of the bank-full stream top widths were digitized with minimal visual interpretation; the other 50 percent were visually estimated. The principal visual interference was large vegetation located along the stream banks with canopies covering the bank and occasionally the entire width of the stream. One-meter resolution DOQQ data was used to determine the bankfull top width of the main channel for 64 watersheds located outside high resolution DOQQ boundaries and similar visual estimations were applied. To facilitate the computation of the hydraulic radius for the assumed trapezoidal channel shape, the bank-full stream top width was assumed to be the bottom width of the channel.

TTU researchers analyzed a subset of study watersheds. Other ongoing research at TTU dictated that watersheds with a minimum period of record of 10 years be selected (Harle, 2002). Of the watersheds in the study dataset, 40 met the selection criteria. Drainage areas of selected watersheds are approximately 0.8 to 321.2 km^2 (0.3 to 124 square miles). Of the 40 selected watersheds, 24 were developed and 16 were undeveloped. TTU researchers determined flow lengths and slopes for time of concentration computations using Hydrologic Engineering Center – Geospatial Hydrologic Modeling System (HEC-GeoHMS, US Army Corps of Engineers, 2003), a GIS extension used to delineate watersheds and define stream networks using 30-meter DEMs. It was assumed that the overland flow length did not exceed 152.4 meters (500 feet). A summary of watershed characteristics developed by TTU researchers is given in Table 2.

Implementation of the NRCS Velocity Method

The research teams applied the NRCS velocity method to the study watersheds to estimate time of concentration. Analysts from each team made estimates of physical watershed parameters necessary to apply the NRCS velocity method. As would occur in practice, the analysts on the different teams constructed slightly different approaches to computation of travel time and used different parameter values. Such is the nature of hydrologic computation.

Implementation of the Velocity Method by LU

Three flow regimes were considered along a flow path for T_c estimation by researchers at LU; two of the flow regimes (overland and shallow concentrated flow) were combined into a single entity and that result was then combined with the channel-flow travel time. A sensitivity analysis of travel time for overland flow and shallow-concentrated flow was performed by varying channel geometry and watershed parameters (such as watershed/channel length and slope) (Malla, 2004). Kerby’s (1959) formula and Manning’s equation were used to estimate travel time for overland and shallow-concentrated flow, respectively.

The travel time for channel flow was computed using the NRCS velocity method. Average flow velocity was estimated using Manning's equation. The following steps were used:

(a). The 2-year discharge (Q_2) for each watershed was assumed to be bankfull discharge (Kent, 1972; McCuen, 2005) and was calculated using the regional regression equations for estimating peak streamflow discharge with different frequencies (Asquith and Slade, 1997). T-year discharge is given by the equation (Asquith and Slade, 1997)

$$Q_T = a\,DA^b\ SH^c\ SL^d \tag{3}$$

where DA is the contributing drainage area in square miles (CDA in Table 1), SH is the basin-shape factor defined as the ratio of main channel length (MCL) squared to contributing drainage area (CDA) (square miles/square miles), SL is the mean channel slope defined as the ratio of headwater elevation of longest channel minus main channel elevation at site to main channel length (ft/mile, MCS2 in Table 1), and a, b, c, d are multiple linear regression coefficients dependent on region number and frequency.

(b). Water depth under bankfull conditions is unknown and was estimated by applying Manning's equation (Equation 2) and computing the depth. Discharge in the channel was assumed to be the 2-year discharge (Q_2) computed using Equation (3). Channel flow was assumed to occur in a rectangular or trapezoidal channel with a side slope of 2:1 (horizontal: vertical or H:V). The bankfull stream bottom width (W in Table 1) estimated using DOQQ and the channel slope estimated using DEM (MCS2 in Table 1) were used.

(c). Travel time is main channel length divided by average velocity computed using Manning's equation, Equation (2). Sensitivity analysis of travel time to channel parameters was performed (Malla, 2004; Fang *et al.*, 2006). Results indicate that channel length and Manning's *n* are two of the most important parameters in T_c estimation using the NRCS velocity method (Fang *et al.*, 2006).

Implementation of the Velocity Method by the USGS

Computation of time of concentration was implemented using ArcGIS Spatial Analyst (ESRI, 2004) by researchers at USGS. Travel time for overland flow was estimated using a simplified version of Manning's equation (McCuen, 2005):

$$T_{ti} = \frac{L}{60V_i} \tag{4}$$

$$V_i = k(S)^{0.5} \tag{5}$$

where T_{ti} is the travel time for overland flow in minutes, L is the length of overland flow in meter or feet (set as 91.4 meters or 300 feet), V_i is the average velocity in meter per second or feet per second, and S is the dimensionless basin slope (BS in Table 1). The roughness coefficient (k) which is function of the land cover with the effect measured by the value of *n* and R_h (McCuen, 2005) was calculated using weighted values from Table 3, based on the land cover classifications within the overland flow area. Land cover classifications were applied to the 92 watersheds using the 1992 National Land Cover Dataset (NLCD), a digital raster-dataset classifying the nation into land cover categories. The watersheds encompass 18 land cover classifications ranging from open water to shrub-land to high intensity residential. The NLCD classifications were coupled with coefficient estimation resources for the NRCS velocity method (McCuen, 2005, Table 3.14) and reduced to eight classifications for the purposes of this study. Because the NRCS velocity method accounts for shallow-concentrated flow, weighted values of

NLCD for the overland flow areas (encompassing a flow distance of 91.44 meter or 300 feet) were applied.

Manning's equation, Equation (2), was used to compute average velocity for shallow-concentrated and channel flow by substituting 365.8 meters or 1,200 feet as length of shallow-concentrated flow and the MCL from Table 1 as the length of channel flow. Basin slope (BS in Table 1) was used as channel slope for shallow-concentrated flow and the main channel slope (MCS2 in Table 1) was used as channel slope for channel flow. The hydraulic radius under bankfull conditions is unknown; therefore several additional computation steps were used to estimate it. The bankfull stream top width of each watershed was measured using DOQQ to compute the area and wetted perimeter of the channel; a triangular channel was assumed for shallow-concentrated flow, with a side slope of 1:1 (H:V), and a trapezoidal channel was assumed for channel flow, with a side slope of 2:1 (H:V). To facilitate the computation of the hydraulic radius for the assumed trapezoidal channel shape for the study watersheds, the bankfull top width was used for the channel bottom width.

Manning's *n* was assumed as 0.06 for shallow-concentrated flow, 0.04 for a natural channel, and 0.015 for a concrete channel. Concrete channels were identified using 1-foot DOQQ data only where available (28 watersheds). Concrete-line channel lengths were digitized and subtracted from the total channel length to compute a roughness coefficient weighted on relative channel composition (concrete-lined and natural). The weighted values of roughness coefficient were applied to the watersheds containing concrete-line channels (along the main channel) and a more representative Manning's *n* was calculated. Discharge ($Q = VA$) was assumed to be the peak discharge associated with the 2-year recurrence interval, calculated using the regional regression equation (3) (Asquith and Slade, 1997).

Implementation of the Velocity Method by TTU

Researchers at TTU estimated travel time using the NRCS velocity method for 40 watersheds in the database. Overland flow velocity was estimated using the chart published in the online hydraulic design guidelines (TxDOT, 2002), which is a function of the type of land cover and watercourse slope. The length of overland flow was taken to be a maximum 152.4 meters (500 feet).

Shallow concentrated flow length was taken to be the length from the watershed boundary to the main channel less 152.4 meters (500 feet). If the length from watershed divide to the main channel was less than 152.4 meters (500 feet), then it was assumed that no shallow concentrated flow occurred. The velocity of shallow concentrated flow was computed using Manning's equation, Equation (2). For developed watersheds, shallow-concentrated flow was assumed to occur in gutters with a flow depth of 0.15 meter (0.5 feet), slope estimated from local topography, and Manning's n of 0.016. For undeveloped watersheds, shallow concentrated flow was assumed to occur in a triangular channel with a flow depth of 0.15 meter (0.5 feet), side slopes of 1:1 (H:V), slope from local topography, and Manning's $n = 0.075$.

The channel length from the outlet to the watershed divide was used for the main channel flow computation. Channel flow was assumed to occur in a trapezoidal channel with side slopes assumed to be 1:3 (H:V) and longitudinal slope and roughness were taken as appropriate based on examination of aerial photographs. Manning's n values used for main channel flow are 0.035, 0.05, and 0.075. The top width was also estimated from aerial photographs and ranges from 1.13 to 5.43 meters (3.7 to 17.8 ft) (Table 2). Flow depth was assumed to be 0.914 meter (3 feet). Estimated channel velocity ranged from 0.64 to 2.01 m/s (2.1 to 6.6 ft/s) with an average value of 1.40 m/s (4.6 ft/s).

Results of Estimated T_c

Results of the sensitivity analysis implemented by LU researchers demonstrate that travel time for overland flow ranged from 0.16 to 0.38 hours, and travel time for shallow-concentrated flow ranged from 0.05 to 0.29 hours (Malla, 2004, Fang *et al.*, 2006)). When these values are combined, the estimate for overland flow and shallow-concentrated flow travel time combined ranges from 0.21 to 0.67 hours. Therefore, a combined travel time for overland and shallow-concentrated flow of 0.5 hours is a reasonable estimate. Estimates of T_c are computed from the travel time for channel flow plus 0.5 hour for combined travel time for overland flow and shallow-concentrated flow. Figure 2 shows estimated T_c versus drainage area for 92 Texas watersheds using the NRCS velocity method implemented by LU and assuming both rectangular channels and trapezoidal channel geometry. Assuming for rectangular channels and Manning's *n* equals 0.06, average channel velocity estimates were from 0.52 to 2.07 m/s (1.7 to 6.8 ft/s) with an average value of 1.52 m/s (5.0 ft/s), and average Froude number is 0.38 (subcritical flow). The same Manning's coefficient was used for all channels of 92 watersheds for T_c estimation. For trapezoidal channels, two Manning's *n* coefficients of 0.04 and 0.06 were used. Decrease of Manning's coefficient results in increase of flow velocity, and therefore decrease of travel time for channel flow and T_c as shown in Figure 2. The average difference between T_c estimated for trapezoidal channel assuming Manning's n = 0.04 and Manning's n = 0.06 is -0.66 hour (-20 percent of relative difference) ranging from -0.2 to -3.3 hour. The average difference between T_c estimated for rectangular channels and for trapezoidal channels is -0.41 hour (-12 percent of relative difference) ranging from 0.3 to -2.3 hour when Manning's n = 0.04 was used. There are two small watersheds (area less than 5.18 km^2 or 2 $mile^2$) having estimated T_c higher than others because estimated bankfull stream bottom width from DOQQ are much greater than others with similar drainage area.

Another method for T_c estimation for small watersheds is an ad hoc method that uses the square root of watershed drainage area in square miles, which reportedly produces in hours (David Stolpa, personal communication, 2004). If drainage area in square kilometers (km^2) is used, it can written as $\boldsymbol{T_c = 0.62\,A^{0.5}}$. The origin of the method is uncertain. The method lacks apparent physical basis and is dependent on the unit system indicated. Remarkably, the square root of drainage area (mile^2) passes through the generalized center of the data values of T_c derived from observed rainfall-runoff data analysis (Roussel et al., 2006). Although producing of the right order T_c, the authors suggest that the method be considered as an engineering rule-of-thumb, which can be a check of other methods. Square root of area (mile^2) is superimposed in Figures 2, 3, and 5 as the solid line for reference and comparison.

Estimated T_c developed by USGS is shown in Figure 3 (inverse open triangles) versus drainage area and includes a reference line of the square root of area. Estimated T_c is typically lower in comparison to the reference line representing mean value of T_c variations. A summary of travel time for each flow component (overland, shallow-concentrated, and channel flow) is given in Table 3. Travel time estimated for overland flow ranges from 0.02 to 0.16 hours, travel time estimated for shallow-concentrated flow ranges from 0.02 to 0.12 hours, and travel time for channel flow ranges from 0.33 to 9.28 hours. T_c estimated by TTU is also shown in Figure 3 versus drainage area and summary of T_c variations is given Table 3.

Synthesis of Estimates by NRCS Velocity Method

A comparison of T_c estimated is shown in Figure 4. The abscissa of Fig. 4 is T_c estimated by LU and the ordinate is T_c estimated by the USGS and TTU for corresponding watersheds. Based on the results presented on Figures 2, 3, and 4, T_c estimated using the NRCS velocity method has large variations dependent on analyst estimates of input parameters. Statistical results of absolute difference in hours and relative difference in percent (numbers in parentheses) of T_c estimated among three groups are summarized in Table 4. Estimates of T_c using the NRCS velocity method vary over about one-half order of magnitude (Figures 2, 3 and 4) and generally are less than T_c estimated using other methods, e.g., application of Kerby-Kirpich equations, and T_c derived from measured rainfall and runoff data (Roussel *et al.*, 2006). The impact of reduced T_c is an increase in unit hydrograph peak streamflow. An increase in the unit hydrograph peak transfers into an increase in the peak streamflow of the direct runoff hydrograph. Hydrologic designs are sensitive to peak streamflow. Implementation of the NRCS velocity method to estimate T_c is more complex than implementation of empirical equations (Roussel *et al*., 2006). Many parameters are estimated by the analyst and not directly measured either in the field or from mapping. Even when parameter estimates are reasonable on the basis of engineering judgment, different analysts arrive at different results. The differences in T_c are attributed to factors including differing length estimates for each flow component, differing estimates of the remaining watershed characteristics, and differing implementations of Manning's equation. Different assumptions were made regarding channel geometry and Manning's roughness coefficient. Precise estimation of input parameters for the NRCS velocity method is difficult. In particular, repeatable application of Manning's equation using generalized measures of geometry and roughness that are representative of the hydraulic processes of the watershed is difficult. The potential exists for analysts to have substantially different T_c estimates as demonstrated by the results in Figures 2, 3 and 4.

Statistical results of absolute differences in hours and relative differences in percent (numbers in parentheses) of T_c estimated among the three teams are summarized in Table 4. Average difference of T_c estimates between the USGS and LU (trapezoidal with n=0.06) is -1.29 hours with a standard deviation of 0.77 hour and maximum difference of -4.46 hours when T_c estimated for 92 watersheds are compared (Table 4). Average relative difference of T_c between the USGS and LU is 43.6 percent with maximum difference of 71 percent. Table 4 also includes statistical summary of T_c estimates by dividing data into two watershed groups: drainage area less than 51.8 square kilometer (20 square miles) and greater than 51.8 square kilometer (20 square miles). Average difference of T_c between estimates for watersheds with area (A) greater than 51.8 km^2 (20 mile^2) is typically greater than one for watersheds with area less than 51.8 km^2 (20 mile^2), but average relative difference is on the same order. Maximum value for both absolute and relative differences occurs in larger watersheds (Table 4). Absolute average difference of T_c between TTU and LU is -0.29 hour with a standard deviation of 1.06 hours and maximum difference of 3.76 hours when T_c estimated for 36 common watersheds are compared. The maximum relative difference between TTU and LU estimation of T_c by the velocity method is 94.4 percent. Statistical results (absolute average differences and standard deviations) in Table 4 further support that T_c estimated using the NRCS velocity method has relative larger variations.

The number and sensitivity of input parameters for the NRCS velocity method make the method sensitive to decisions made by the analyst. Whereas the NRCS velocity method is appealing because of its reliance on hydraulics-based estimates of flow velocity, determining the many input parameters necessary requires considerable effort. Estimates of required input parameters are heavily dependent on analyst assumptions of hydraulic properties such as channel geometry that are difficult to measure and lack repeatability because of dependence on analyst experience and interpretation. Figure 5 shows T_c estimated for selected watersheds using three different methods: NRCS velocity method and Kerby-Kirpich method implemented by USGS (Roussel *et al*., 2006), and average T_c derived from Gamma unit hydrographs (Fang *et al.*, 2006). Gamma unit hydrographs were developed from observed rainfall and runoff data of more than 1600 events (Khanal, 2004). Figure 5 shows that T_c estimated by application empirical equations (Kerby-Kirpich) presents reasonably well of average T_c estimated from observed rainfall and runoff data, but T_c estimated from NRCS method for some of selected watersheds are significantly lower than ones estimated by other methods.

Summary and Conclusions

Time of concentration for selected Texas watersheds was estimated by independent analysts working in three research groups using the NRCS velocity method. Watersheds drainage areas are approximately 0.78 to 440.3 square kilometer (0.3 to 170 square miles). 30-meter digital elevation models were used to derive watershed parameters using ArcGIS or HEC-GeoHMS. Input parameters required for the NRCS velocity method were estimated independently by each research team. The resulting T_c for each watershed was compared and analyzed. T_c estimated using velocity method is subject to large variation, dependent on the approach and parameters selected by the analyst responsible for estimating the flow velocity. This is because implementation of the NRCS velocity method requires of the analyst to estimate a substantial number parameters, including channel geometric properties, roughness parameter, and others. The differences in approach of different analysts naturally lead to different results. In fact, it is the authors’ opinion that there is no single value that represents the time of concentration for a watershed. Because of the propensity for different analysts to arrive at different results, caution is required in application of the NRCS velocity method to estimate time of concentration, especially, estimate or specify parameters for channel geometry and watershed characteristics. Alternatives to the NRCS velocity method for estimating time of concentration are manifest, and require estimating many less watershed and hydraulic parameters. A selection of these alternatives is presented elsewhere (Roussel *et al.*, 2006).

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Notation

The following symbols are used in this paper:

T_c = time of concentration
T_{ti} = travel time in minutes for the i^{th} reach along flow path
L_i = flow length in meter or feet for the i^{th} reach along flow path
V_i = runoff velocity in meter or feet per second for the i^{th} reach along flow path
T_{ol} = travel time for overland flow
T_{sc} = travel time for shallow-concentrated flow
T_{ch} = travel time for channel flow
V = mean flow velocity
k = roughness coefficient
n = Manning’s roughness coefficient
R_h = hydraulic radius
P = wetted perimeter
S = channel bottom slope
S or BS = dimensionless basin slope
Q = discharge
Q_2 = 2-year discharge
SL or MCS2 = mean channel slope
MCL = main channel length
W = bankfull stream bottom width
L = length of overland flow in meter or feet
DA or CDA = contributing drainage area in square miles
A = area
H:V = horizontal: vertical
a, b, c, d = multiple regression coefficients
ft/s = feet/second
m/s = meter per second
km^2 = square kilometers
$miles^2$ = square miles
hr = hour

NLCD = National Land Cover Dataset
NRCS = Natural Resource Conservation Services
LU = Lamar University
USGS = United States Geological Survey
TTU = Texas Tech University
DEM = Digital Elevation Models
GIS = Geographical Information System
HEC = Hydrologic Engineering Center
HEC-GeoHMS= Geospatial Hydrologic Modeling Extension
DOQQ = Digital Orthoroimagery Quarter Quadrangle
TxDOT = Texas Department of Transportation

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Watershed Characteristics	Mean	Standard deviation	Range		Coefficient of variation
			Minimum	Maximum	
Drainage Area, CDA in km^2 (miles^2)	51.8 (20)	69.15 (26.7)	0.78 (0.3)	433.30 (167.3)	1.72
Main Channel Length, MCL in km (mile)	12.87 (8.0)	12.87 (8.0)	1.93 (1.2)	78.70 (48.9)	1.01
Main Channel Slope, MCS2 in m/m (ft/mile)	0.0079 (41.8)	0.0036 (19.2)	0.0022 (11.6)	0.0196 (103.5)	0.46
Basin Slope, BS in m/m (ft/mile)	0.0354 (186.9)	0.0228 (120.6)	0.0046 (24.3)	0.1313 (693.5)	0.65
Channel Top-width, W in meter (ft)	8.56 (28.1)	4.75 (15.6)	2.35 (7.7)	24.81 (81.4)	0.56

Table 2. Summary of Watershed Characteristics Developed using 30-meter DEM and HEC-GeoHMS for 40 Study Watersheds.

Watershed Characteristics	**Mean**	**Standard deviation**	**Range**		**Coefficient of variation**
			Minimum	**Maximum**	
Total drainage area in km^2	39.89	58.02	0.78	321.16	
($miles^2$)	(15.4)	(22.4)	(0.3)	(124.0)	1.46
Overland flow length in meter	121.16	51.42	30.48	182.88	
(ft)	(397.5)	(168.7)	(100.0)	(600.0)	0.42
Channel flow length in kilometer	2.40	1.56	0.34	10.12	
(mile)	(7.9)	(6.1)	(1.1)	(33.2)	0.78
Basin slope for overland flow in m/m	0.024	0.026	0.004	0.120	1.06
(ft/mile)	(126.7)	(137.3)	(21.1)	(633.6)	
Channel slope in m/m	0.007)	0.004	0.002	0.020	0.54
(ft/mile)	(37.0	(21.1)	(10.6)	(105.6)	
Channel Top-width, W in meters	2.65	1.04	1.13	5.43	0.12
(ft)	(8.7)	(3.4)	(3.7)	(17.8)	(0.39)

Table 3. Summary of Travel Time for Each Flow Component and T_c (hour) Estimated Using Velocity Method and Implemented by Three Research Teams.

Variations of estimation method	Mean (hour)	Standard deviation	Range		Coefficient of variation
			Minimum	Maximum	
LU: Overland and shallow-concentrated flow	0.50	0.0	0.50	0.50	0.00
LU: Channel flow (trapezoidal with n =0.06)	2.63	2.28	0.65	13.35	0.87
LU: Channel flow (trapezoidal with n =0.04)	1.97	1.71	0.49	10.02	0.87
LU: Channel flow (rectangular with n =0.06)	2.21	1.92	0.55	11.15	0.87
USGS: Overland flow	0.05	0.03	0.02	0.16	0.52
USGS: Shallow-concentrated flow	0.04	0.02	0.02	0.12	0.42
USGS: Channel flow	1.75	1.57	0.33	9.28	0.90
USGS: Total travel time (T_c)	1.84	1.57	0.45	9.38	0.85
TTU: Overland flow	0.14	0.13	0.02	0.48	0.88
TTU: Shallow-concentrated flow	0.004	0.007	0.00	0.021	1.60
TTU: Channel flow	2.76	2.44	0.57	10.93	0.89
TTU: Total travel time (T_c)	2.91	2.49	0.60	11.23	0.86

Table 4. Statistical Summary of Absolute Difference in Hour and Relative Difference in Percent (numbers inside parenthesis) of T_c Estimates Using Velocity Method.

Difference of T_c estimated between		Mean	Standard deviation	Range		Coefficient of variation
				Minimum	Maximum	
n = 0.04 and n =0.06 for trapezoidal channel (LU)	All areas	-0.66 (-19.7)	0.58 (2.6)	-0.16 (-13.7)	-3.32 (-24.5)	-0.88
	A < 51.8 km^2 or 20 mile^2	-0.43 (-18.8)	0.18 (2.0)	-0.16 (-13.7)	-0.86 (-22.1)	-0.41
	A < 51.8 km^2 or 20 mile^2	-1.52 (-23.1)	0.66 (4.0)	-0.65 (-20.9)	-3.32 (-24.5)	-0.43
rectangular and trapezoidal channel with n =0.06 (LU)	All areas	-0.41 (-12.2)	0.40 (4.3)	0.26 (11.5)	-2.26 (-17.4)	-0.96
	A < 51.8 km^2 or 20 mile^2	-0.26 (-11.4)	0.15 (4.3)	0.26 (11.5)	-0.60 (-16.1)	-0.55
	A < 51.8 km^2 or 20 mile^2	-0.99 (-15.2)	0.46 (5.5)	-0.42 (-5.1)	-2.26 (-17.4)	-0.46
USGS and LU trapezoidal channel (n=0.06)	All areas	-1.29 (-43.6)	0.77 (9.1)	-0.35 (-19.2)	-4.46 (-71.0)	-0.60
	A < 51.8 km^2 or 20 mile^2	-1.00 (-45.2)	0.37 (9.3)	-0.35 (-19.2)	-2.40 (-37.6)	-0.37
	A < 51.8 km^2 or 20 mile^2	-2.37 (-37.6)	0.88 (11.5)	-1.19 (-31.6)	-4.46 (-71.0)	-0.37
TTU and LU trapezoidal channel (n=0.06)	All areas	-0.29 (-18.5)	1.06 (29.9)	-1.42 (-56.9)	3.76 (94.4)	-3.73
	A < 51.8 km^2 or 20 mile^2	-0.65 (-28.3)	0.42 (18.1)	0.44 (20.7)	-1.42 (-56.9)	-0.65
	A < 51.8 km^2 or 20 mile^2	1.21 (22.1)	1.59 (36.0)	-1.01 (-21.8)	3.76 (94.4)	1.32

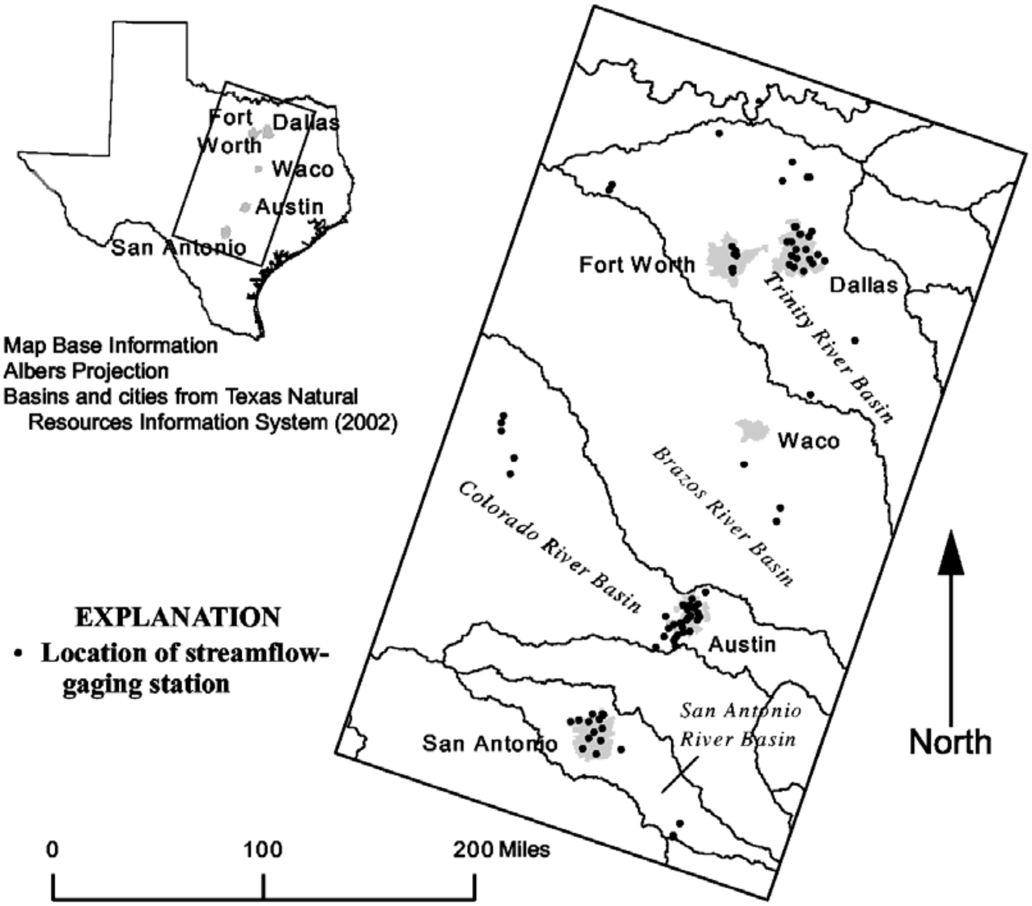

Fig. 1. Location of 96 Watersheds Studied in Texas.

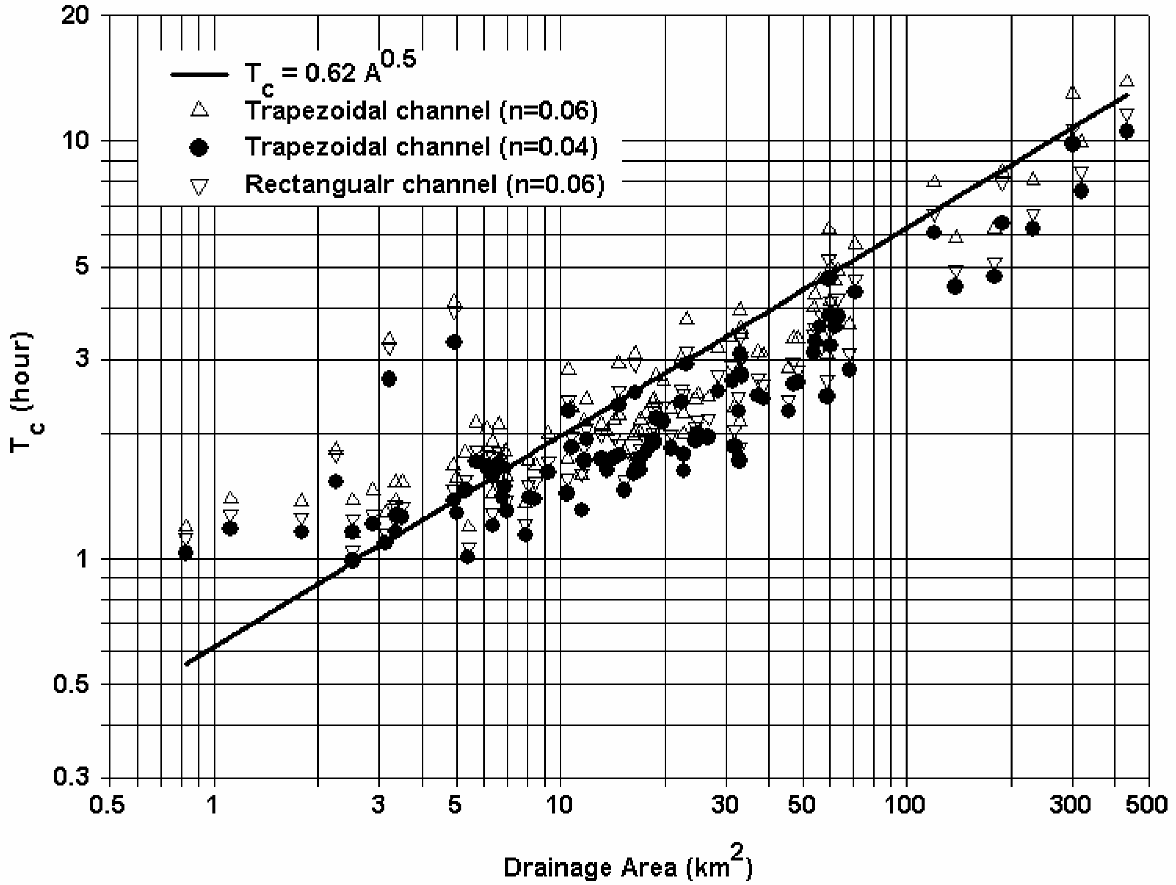

Fig. 2. Time of Concentration Estimated, Using Velocity Method Implemented by LU, Versus Drainage area.

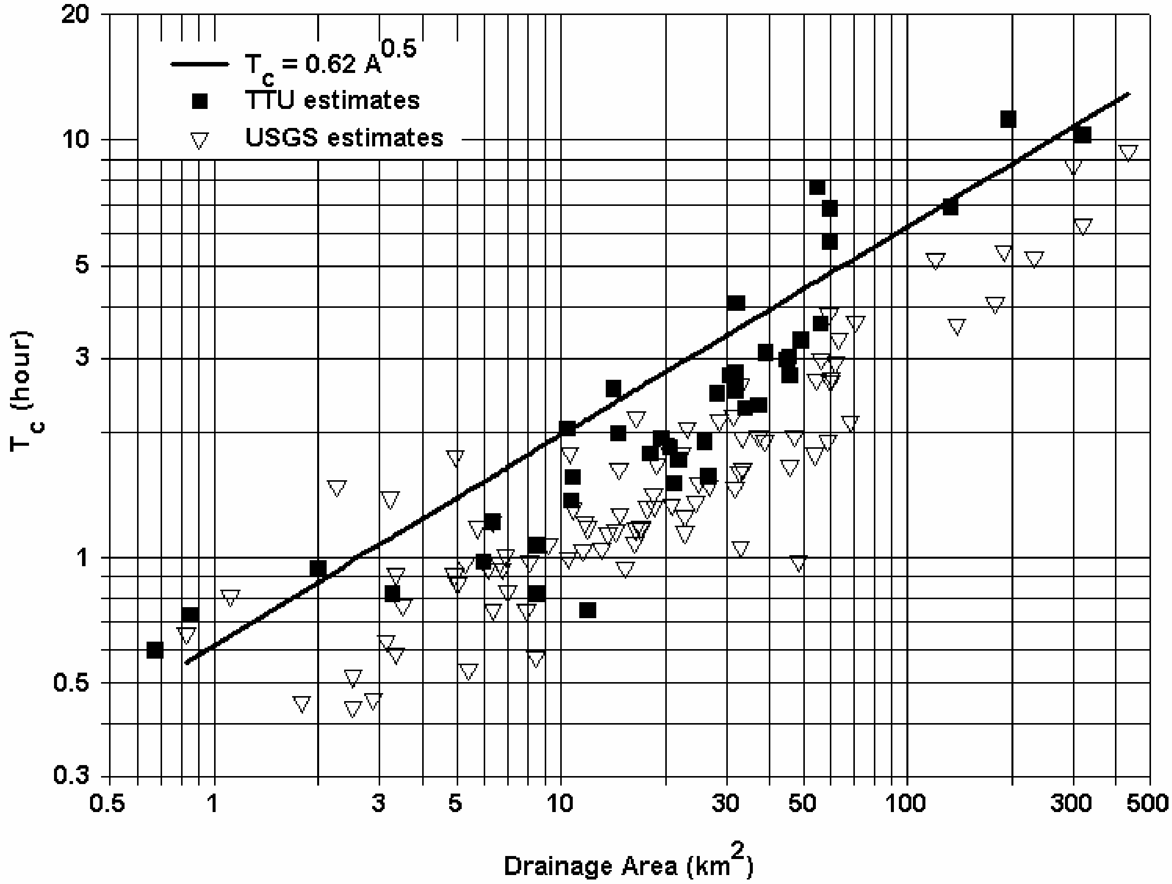

Fig. 3. Time of Concentration Estimated, Using Velocity Method Implemented by USGS and TTU, Versus Drainage Area.

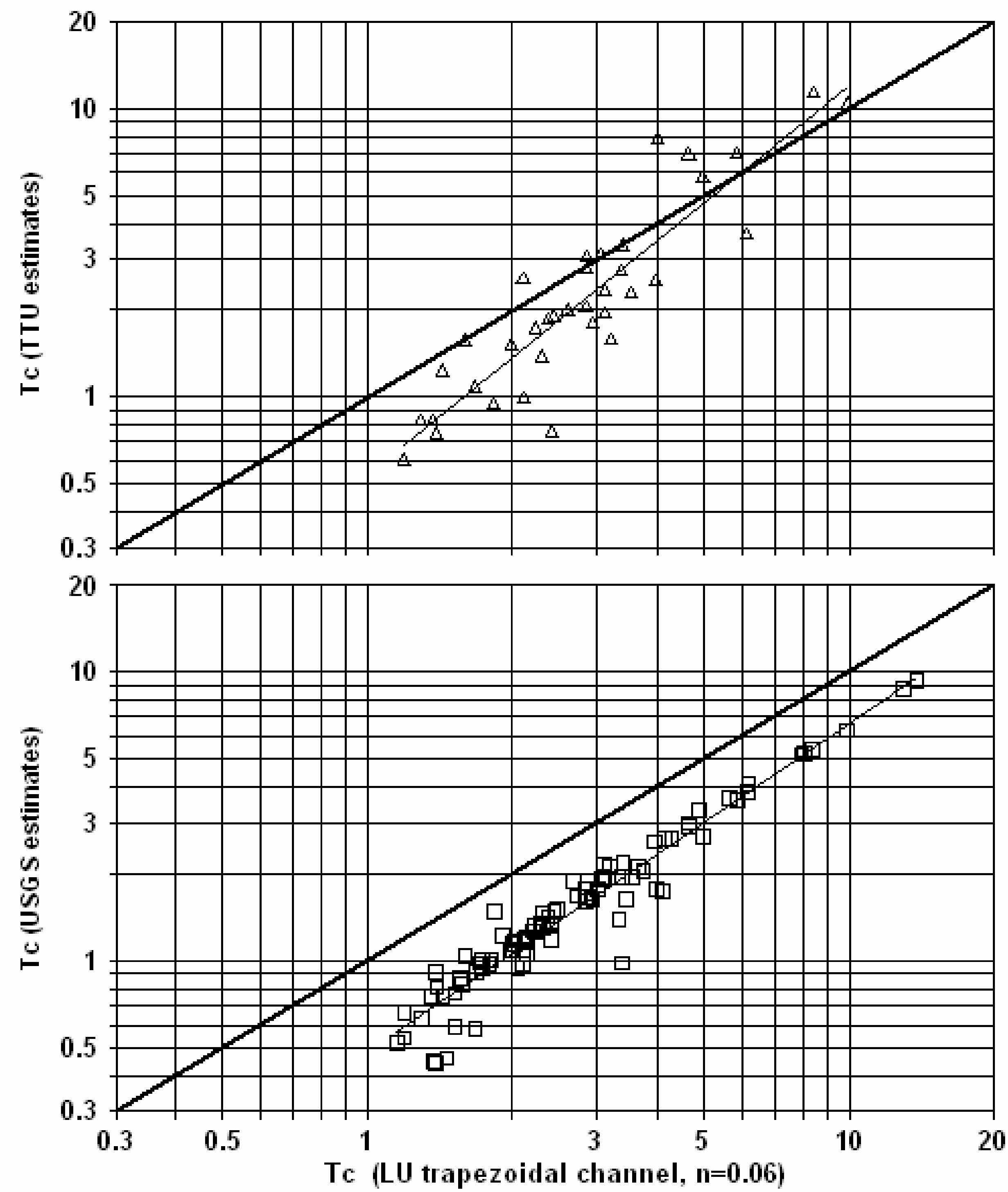

Fig. 4. Comparison of Time of Concentration Estimated Using Velocity Method by Three Teams.

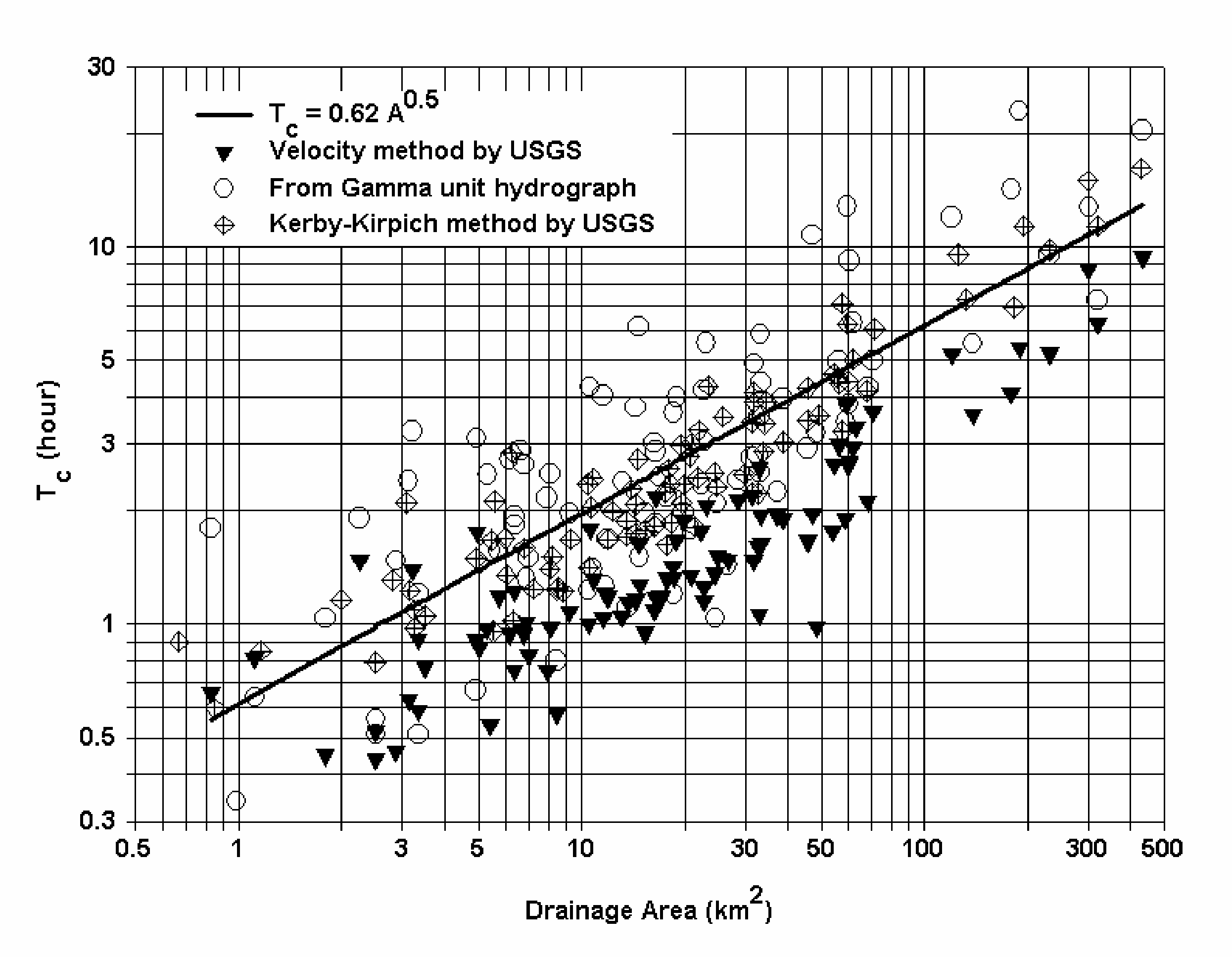

Fig. 5. Comparison of Time of Concentration Estimated Using Three Different Methods.