TIME-PARAMETER ESTIMATION FOR APPLICABLE TEXAS WATERSHEDS

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16. Abstract

Characterization of hydrologic processes of a watershed in the context of drainage design requires estimation of specific time-response characteristics. The time-response characteristics of a watershed frequently are represented by two conceptual time parameters, the time of concentration and the time to peak discharge. The study described in this report assesses various approaches for estimating watershed characteristics necessary to estimate time of concentration for applicable Texas watersheds, assesses various established approaches of estimating time of concentration, describes a preferable approach for time of concentration estimation, and evaluates the conversion of values of time of concentration from the preferable method to values of time to peak. A comparison of various approaches (manual and automated) for estimating watershed characteristics indicates that time of concentration is relatively insensitive to the specific approach. For the 92 watersheds considered in the study (applicable watersheds), drainage areas are approximately 0.25 to 150 square miles, main-channel lengths are approximately 1 to 50 miles, and dimensionless main-channel slopes are approximately 0.002 to 0.02. Based on the analysis, the preferable approaches for estimation of time of concentration are the Kirpich-inclusive approaches and more specifically, the Kerby-Kirpich approach for applicable watersheds. The preference is based on simplicity of approach and ease of input-data acquisition. The Kerby-Kirpich approach is straightforward to use and produces time of concentration values, which, through the conventional Natural Resources Conservation Service conversion, mimic time to peak from auxiliary analysis of observed rainfall and runoff data for the 92 watersheds. Comparison of time of concentration and time to peak values substantiates the preferable method. Visually fitting a linear relation between time of concentration and time to peak indicates that alternative conversions to the Natural Resources Conservation Service conversion are more appropriate when the Kerby-Kirpich approach is used.

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DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation. The researcher in charge of this project is Dr. Xing Fang, Lamar University.

No invention or discovery was conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design, or composition of matter, or any new useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

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ABSTRACT

Characterization of hydrologic processes of a watershed in the context of drainage design requires estimation of specific time-response characteristics. The time-response characteristics of a watershed frequently are represented by two conceptual time parameters, the time of concentration and the time to peak discharge. The study described in this report assesses various approaches for estimating watershed characteristics necessary to estimate time of concentration for applicable Texas watersheds, assesses various established approaches of estimating time of concentration, describes a preferable approach for time of concentration estimation, and evaluates the conversion of values of time of concentration from the preferable method to values of time to peak. A comparison of various approaches (manual and automated) for estimating watershed characteristics indicates that time of concentration is relatively insensitive to the specific approach. For the 92 watersheds considered in the study (applicable watersheds), drainage areas are approximately 0.25 to 150 square miles, main-channel lengths are approximately 1 to 50 miles, and dimensionless main-channel slopes are approximately 0.002 to 0.02. Based on the analysis, the preferable approaches for estimation of time of concentration are the Kirpich-inclusive approaches and more specifically, the Kerby-Kirpich approach for applicable watersheds. The preference is based on simplicity of approach and ease of input-data acquisition. The Kerby-Kirpich approach is straightforward to use and produces time of concentration values, which, through the conventional Natural Resources Conservation Service conversion, mimic time to peak from auxiliary analysis of observed rainfall and runoff data for the 92 watersheds. Comparison of time of concentration and time to peak values substantiates the preferable method. Visually fitting a linear relation between time of concentration and time to peak indicates that alternative conversions to the Natural Resources Conservation Service conversion are more appropriate when the Kerby-Kirpich approach is used.

INTRODUCTION

Characterization of hydrologic processes of a watershed in the context of drainage design requires estimation of time-response characteristics. Time-response characteristics are used in hydrologic models and influence model response to rainfall from real or design storms. Rainfall and runoff models that incorporate time parameters are used by engineers and others for hydrologic design including the design of bridges and culverts. During 2004 and 2005, a consortium of researchers at the U.S. Geological Survey (USGS), Texas Tech University (TTU), Lamar University (LU), and University of Houston (UH), in cooperation with the Texas Department of Transportation (TxDOT) Research Management Committee 3, investigated approaches for estimating time parameters for applicable Texas watersheds (TxDOT Research Project 0–4696).

The time-response characteristics of a watershed frequently are represented by two conceptual time parameters, time of concentration (T_c) and time to peak (T_p). The T_c generally is defined as the time it takes for runoff to travel from the most hydraulically distant point in a watershed to the outlet. The T_p generally is defined as the time from the beginning of storm runoff to the peak streamflow value of a unit-runoff hydrograph. Hydrologic models typically require an adjustment or conversion of T_c to T_p because models commonly use T_p; yet in practice T_c often is considered easier to conceptualize.

For this study, 92 watersheds in Texas with USGS streamflow-gaging stations were selected for T_c estimation. The necessary rainfall and runoff data (Asquith and others, 2004) for T_p investigation are available for these watersheds. Data for more than 1,600 storms are available. Locations of the 92 stations are shown in figure 1. Ancillary station information is listed in table 1. Each watershed is categorized on the basis of a qualitative land-use classification as either developed (D) or undeveloped (U). The distinction is provided by the original data sources identified in Asquith and others (2004). Drainage areas for the 92 watersheds considered for the study are about 0.25 to 150 square miles, main-channel lengths (length from the outlet to the watershed divide) are about 1 to 50 miles, and dimensionless main-channel slopes (the difference in elevation between the outlet and the watershed divide divided by the main-channel length) are about 0.002 to 0.02.

Values for T_p are available from auxiliary analysis of observed rainfall and runoff data for the 92 watersheds by four methods as part of TxDOT Research Project 0–4193 (W.H. Asquith, U.S. Geological Survey, written commun., 2005), which is a research project contemporaneous to this TxDOT Research Project. The four methods of computing T_p are (1) the traditional unit hydrograph approach, (2) the Gamma Unit Hydrograph Analysis System (GUHAS) unit-hydrograph approach using a gamma distribution hydrograph model, (3) the linear-programming unit-hydrograph approach, and (4) the instantaneous unit-hydrograph approach using a Rayleigh distribution hydrograph model.

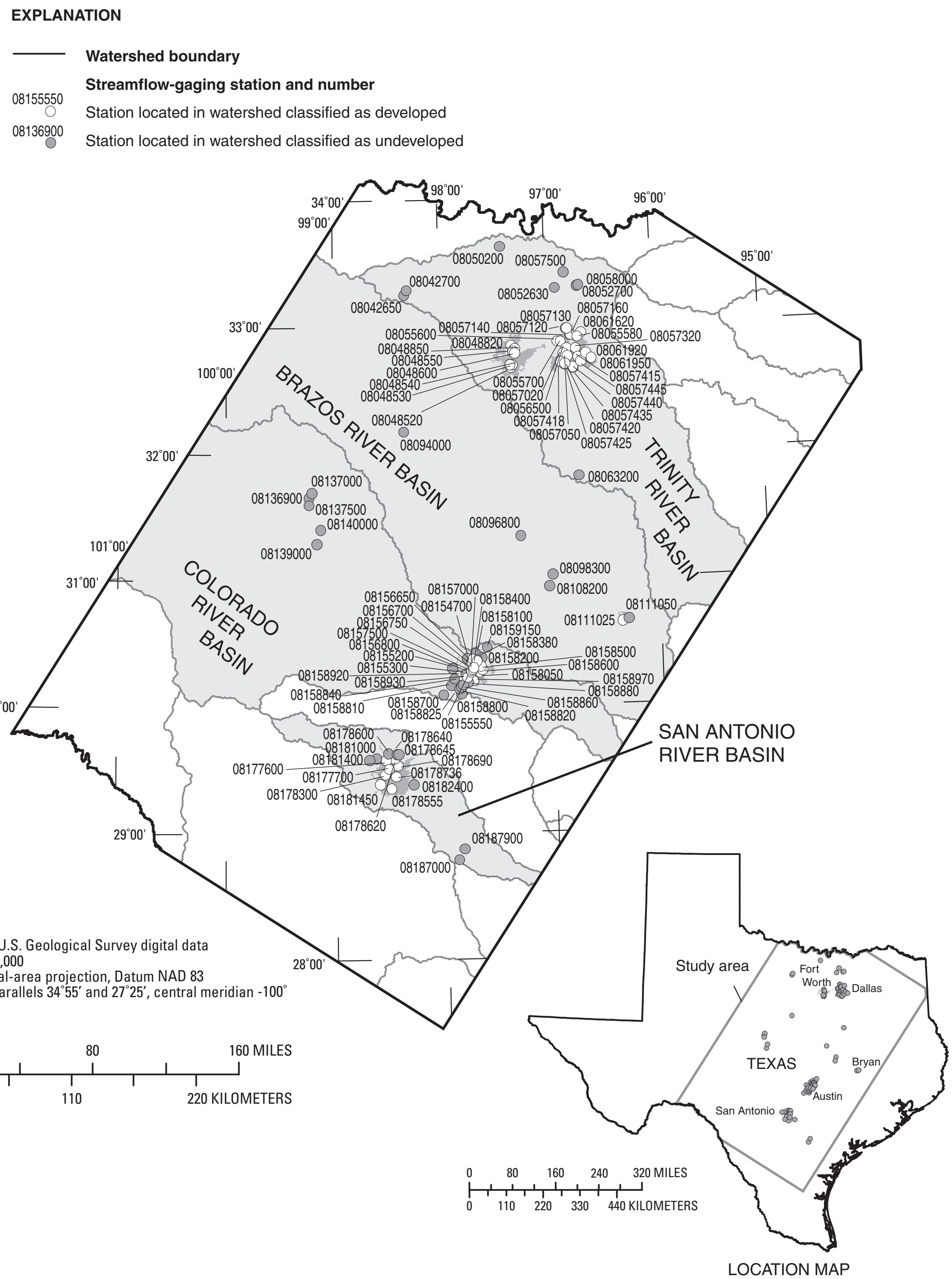


Figure 1. Locations of U.S. Geological Survey streamflow-gaging stations used in study.

Purpose and Scope

The purpose of this report is to (1) qualitatively assess various approaches for estimating watershed characteristics necessary for T_c estimation for applicable Texas watersheds, (2) assess various established approaches for estimating T_c, (3) describe a preferable T_c estimation approach, and (4) evaluate the conversion of T_c values from the preferable approach to T_p values.

Multiple independent approaches to estimate watershed characteristics and T_c were applied to 92 selected watersheds to assess a representative range of established approaches for estimating T_c. All methods for estimating T_c conceptualize the flow path of a parcel of runoff from the most hydraulically distant point in a watershed to the watershed outlet. T_c values obtained by the multiple approaches are compared to each other and to T_p values for the same watersheds from TxDOT Research Project 0–4193.

Estimation of Watershed Characteristics

Methods for estimating time parameters generally require one or more watershed characteristics. For example, a method might require channel length or channel slope. Each research entity within the consortium independently estimated watershed characteristics for the 92 watersheds in order to mimic actual hydrologic practice. Three manual approaches and one automated approach were used and comparisons between the approaches were made. Manual approaches are based on well-established methods such as hand delineation of drainage area on paper maps, use of planimeters to compute drainage area, and use of a map wheel to determine channel length. An algorithmic foundation for automated computation of basin characteristics is described by Brown and others (2000). A graphical comparison of methods for estimation of watershed characteristics is shown in figure 2. The graphs depict manual-based watershed characteristics, which were computed by researchers at the University of Houston, on the horizontal axis and automatic-based watershed characteristics on the vertical axis. The equal value line indicates differences between manual- and automatic-based watershed characteristics and emphasizes the uncertainty inherent in watershed-characteristic estimation.

The drainage-area graph in figure 2 shows that drainage area is estimated consistently across a wide range of scales, as indicated by the few deviations from the equal value line. The main-channel length graph shows that as channel length decreases, the automatic-based channel length becomes larger than the manual-based channel length. The main-channel slope graph shows that as channel slope increases, the automatic-based channel slope becomes smaller than the manual-based channel slope.

Despite differences in watershed-characteristic values, the authors conclude that the differences are few and that it is appropriate to estimate watershed characteristics using a variety of methods. Differences between manual- and automatic-based watershed characteristics are considered a comparatively minor source of uncertainty in relation to other sources inherent in time-parameter estimation, in particular, and to hydrologic models incorporating time parameters, in general.

Previous Studies

The literature addressing T_c is rich and varied. A contemporaneous and extensive literature review is presented by Fang and others (2005). Consequently, only references pertinent to the research reported here are presented in this section. Methods for estimating T_c are classified into two broad categories—empirical or regression-based and hydraulic-based. The regression-based method uses watershed characteristics and observations of time parameters derived from analysis of rainfall and runoff data. The hydraulic-based method uses estimates of channel flow velocity using Manning's equation.

One of the earliest works on T_c for watersheds is Kirpich (1940). Example publications that discuss Kirpich (1940) include Pilgrim and Cordery (1993) and Dingman (2002). Kirpich studied the hydrographs of seven small watersheds in Tennessee. Drainage areas ranged from 1.25 to 112 acres and dimensionless slopes from 0.03 to 0.10. Kirpich (1940) concludes that the method is applicable to watersheds with drainage areas less than about 200 acres. The T_c computed using the Kirpich method is multiplied by 0.4 for overland flow on concrete and 0.2 for concrete channel flow. Kerby (1959) used data gathered by Hathaway (1945) from very small watersheds to develop an equation for estimating T_c for overland flow. Watersheds studied by Kerby (1959) have drainage areas less than 10 acres, have dimensionless slopes less than 0.01, and have lengths of overland flow less than 1,200 feet. A method based on the kinematic wave approximation (Kinematic Wave Formula, KWF) to the dynamic wave equations is presented by Morgali and Linsley (1965) and Aron and Erborge (1973). The Natural Resources Conservation Service (NRCS)(2004) travel-time method (hereinafter, NRCS travel-time method) uses hydraulic-based estimates of flow velocity in the watershed to estimate T_c. Haktanir and Sezen (1990) apply two-parameter gamma and three-parameter beta distributions to approximate time parameters using unit hydrographs for 10 watersheds in Anatolia, Turkey. Simas and Hawkins (2002) studied rainfall and runoff relations including time parameters for 168 small watersheds throughout the United States with 3,100 observed storms. Watershed drainage area ranged from 0.3 to 3,490 acres.

TIME-PARAMETER ESTIMATION FOR APPLICABLE TEXAS WATERSHEDS

Multiple independent approaches to estimate T_c were applied to the 92 study watersheds to assess a representative range of previously established approaches for estimating T_c. All methods for estimating T_c conceptualize the flow path of a parcel of runoff from the most hydraulically distant point in a watershed to the watershed outlet. One method uses three distinct flow paths, or components—overland flow, shallow concentrated flow, and channel flow; other methods use only two components—overland flow and channel flow. In general, the more complex the conceptualization of runoff flow path (the more components), the more complex the ensuing method for estimating T_c.

For this study, the selected subset of available T_c estimation approaches consists of three overland flow methods, one shallow concentrated flow method, and four channel flow methods. Individual time of travel (flow duration) of the *i*th component is represented by T_t^i. The T_t^i components are summed to yield T_c for each watershed.

Travel Time for Overland Flow

Three methods were used to calculate the overland flow component of T_c, the NRCS travel-time method, the Kerby method, and the KWF method.

The NRCS travel-time method was implemented using equation 1 (McCuen, 2005) and Manning's equation,

$$T_t^i = \frac{L}{60 V_i} \text{ and} \tag{1}$$

$$V_i = \frac{1.486}{n} R_h^{0.67} S^{0.5}, \tag{2}$$

where T_t^i is in minutes; length of overland flow (L) is in feet; average velocity (V_i) is in feet per second; hydraulic radius (R_h), or the area divided by wetted perimeter of the channel, is in feet; S is the dimensionless main-channel slope; and n is Manning's roughness coefficient.

Kerby (1959) provides a method to estimate T_t^i using the following equation:

$$T_t^i = \left[\frac{0.67(L \times N)}{S^{0.5}}\right]^{0.467}, \tag{3}$$

where T_t^i is in minutes; length of overland flow (L) is in feet; S is the dimensionless main-channel slope; and the retardance coefficient (N) is based on condition of the overland flow surface and ranges from 0.1 for bare and packed soil to 0.8 for dense grass or forest.

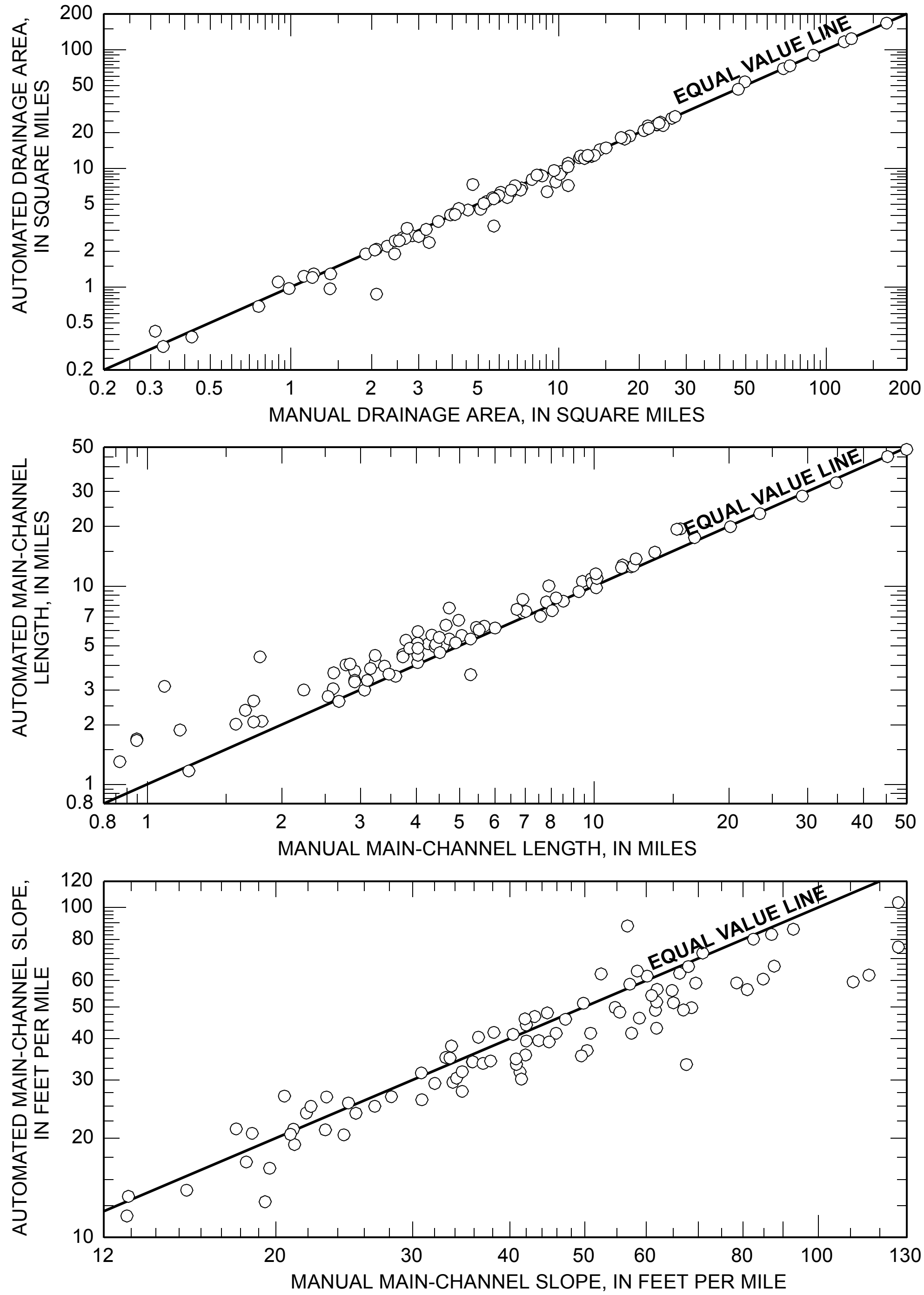


Figure 2. Relation between manual-based watershed characteristics and automatic-based watershed characteristics derived from a 30-meter digital elevation model.

The KWF method (Morgali and Linsley, 1965; Aron and Erborge, 1973) was implemented using

$$T_t^i = \frac{0.94(L \times n)^{0.6}}{i^{0.4} S^{0.3}}, \tag{4}$$

where T_t^i is in minutes; length of overland flow (L) is in feet; S is the dimensionless main-channel slope; rainfall intensity (i) is in inches per hour; and n is Manning's roughness coefficient. Rainfall intensity for each watershed is estimated using the 2-year recurrence interval, and rainfall duration is computed by an iterative process and is watershed specific. Rainfall intensity for Texas was obtained from Asquith and Roussel (2004).

Travel Time for Shallow Concentrated Flow and Channel Flow

Only the NRCS travel-time method was used to calculate the shallow concentrated flow component of T_c, as that is the only method in which it is explicitly computed. The four methods used to calculate the channel flow component of T_c are the NRCS travel-time method, the Kirpich method, the Haktanir and Sezen method, and the Simas and Hawkins method.

The NRCS travel-time method was implemented for shallow concentrated and channel flow using equation 1 by substituting the length of shallow concentrated flow or the main-channel length for L as appropriate. The average velocity (V_i) was computed for shallow concentrated flow and channel flow by using Manning's equation (eq. 2) in the equation of continuity for steady flow (eqs. 5, 6):

$$Q = \frac{1.486}{n} A R_h^{0.67} S^{0.5} \text{, and} \tag{5}$$

$$V_i = \frac{Q}{A}, \tag{6}$$

where discharge (Q) is in cubic feet per second; area (A) is the cross-sectional area in square feet for either shallow concentrated flow or channel flow; other variables as defined for equation 2.

The Kirpich (1940) method was implemented using the equation

$$T_t^i = 0.0078 L^{0.77} S^{-0.385}, \tag{7}$$

where T_t^i is in minutes; length of the longest channel from basin divide to outlet (L) is in feet; and S is dimensionless watershed slope.

The Haktanir and Sezen (1990) method was implemented using equation 8 to estimate T_L (Haktanir and Sezen define T_L as the difference in time between when the center of excess rainfall occurs in a basin and when peak streamflow occurs) and equation 9 to convert T_L to T_c:

$$T_L = 0.401 L_m^{0.841} \text{ and} \tag{8}$$

$$T_c = \frac{T_L}{0.6}, \qquad (9)$$

where T_L is in hours; main-channel length (L_m) is in miles; and T_c is in hours, computed from the NRCS relation in equation 9.

The Simas and Hawkins (2002) method was implemented using equation 10 to estimate T_L (Simas and Hawkins defined T_L as the difference between the center of excess rainfall and the centroid of direct runoff) and equation 11 to convert T_L to T_c

$$T_L = 0.0051 W^{0.594} S^{-0.150} S_{nat}^{0.313}, \text{ and} \qquad (10)$$

$$T_c = 1.417 T_L, \qquad (11)$$

where T_L is in hours; watershed width (W), which is obtained by dividing the watershed area by the watershed length is in feet; S is dimensionless watershed slope; and the maximum potential retention (S_{nat}) is in inches. The maximum potential retention is computed using the NRCS curve number (CN) in the equation

$$S_{nat} = \frac{1,000}{CN} - 10, \qquad (12)$$

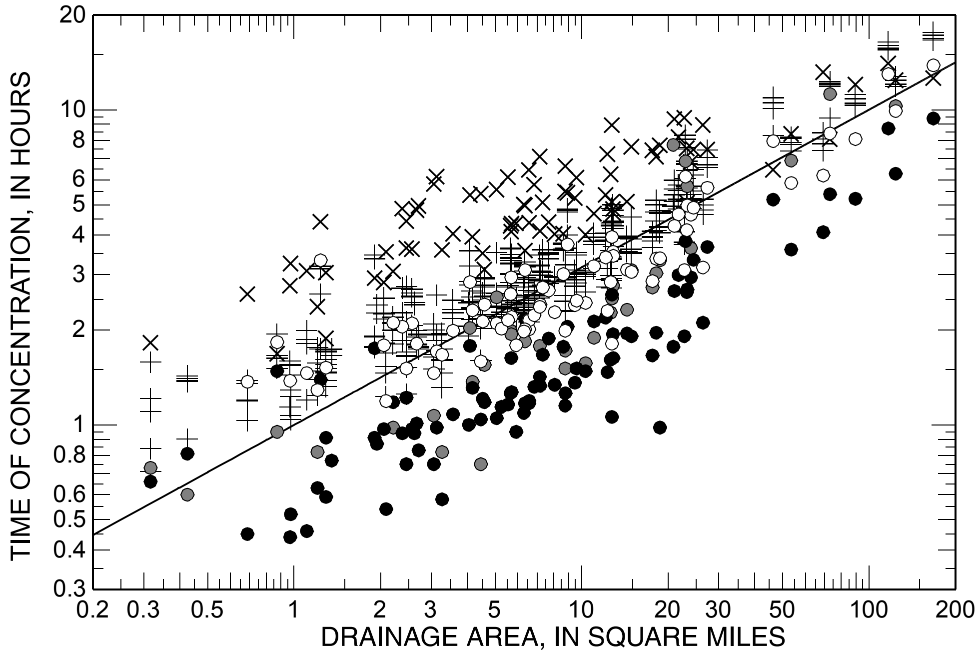
where CN is a site-specific value from a study of climatic adjustments to CN by Thompson and others (2003).

Finally, an analysis of the overland and shallow concentrated flow components of T_c was conducted by researchers at LU to determine whether a consistent travel time could be associated with those two flow components to simplify T_c calculations. The analysis included sensitivity of T_c to variations in input parameters such as roughness and slope. The analysis is not presented in this report; however, the results are summarized. For the 92 watersheds, a reasonable estimate of the duration of the combined overland and shallow concentrated flow components is on the order of 30 minutes. The authors conclude that, for rapid T_c estimation, both the overland and shallow concentrated flow components can be accounted for by adding 30 minutes to channel-flow duration for applicable Texas watersheds.

Discussion

Estimates of T_t^i and T_c for 92 Texas watersheds are listed in tables 2–4 (at end of report). Estimates of T_c are not available for all methods for all 92 watersheds. The relation between drainage area and T_c for each method is depicted in figure 3. Estimates of T_c vary considerably for a given drainage area. The variation is expected because a variety of methods are represented and because input parameter estimates for each method are subject to differences in analyst interpretations; that is, interpretations in estimation of input parameter values.

T_c estimates from the Simas and Hawkins method generally are greater than those from other estimates. Although, as drainage area increases, the differences become smaller. The Simas and



EXPLANATION

- LINE DEPICTING SQUARE ROOT OF DRAINAGE AREA
- × SIMAS AND HAWKINS METHOD PLUS 30 MINUTES FOR OVERLAND FLOW
- ○ NRCS TRAVEL-TIME METHOD IMPLEMENTED BY LAMAR UNIVERSITY RESEARCHERS
- ● (gray) NRCS TRAVEL-TIME METHOD IMPLEMENTED BY TEXAS TECH UNIVERSITY RESEARCHERS
- ● NRCS TRAVEL-TIME METHOD IMPLEMENTED BY USGS RESEARCHERS
- + ESTIMATES FROM ALL OTHER APPROACHES CONSIDERED

Figure 3. Relation between drainage area and time of concentration from evaluated approaches.

Hawkins method uses an estimate of S_{nat}, which is derived from the NRCS CN. Standard (or tabulated) values of CN generally are greater than those computed from watershed rainfall and runoff for a substantial part of Texas (Thompson and others, 2003), resulting in T_c values that most likely are too large. As a result, the authors conclude that the Simas and Hawkins method is inappropriate for the watersheds of this study. Additionally, as CN approaches 100, a value appropriate for impervious cover, T_L approaches zero regardless of watershed size. Logic dictates that T_L is greater than zero for any watershed. For this report, the Simas and Hawkins method is not considered further.

Estimates of T_c from the NRCS travel-time method vary over about one-half order of magnitude and generally are less than T_c estimates from other methods. The effect of a smaller T_c is an increase in peak streamflow of the unit hydrograph. An increase in the unit-hydrograph peak translates into an increase in the peak streamflow of the direct runoff hydrograph. Many hydrologic design decisions are sensitive to peak streamflow. Overestimation of peak streamflow could lead to the overdesign of drainage structures.

Estimates of T_c by the NRCS travel-time method require a substantial number of input parameters, more than any other method presented in this report. Results from the NRCS T_c travel-time method are sensitive to analyst-selected inputs for overland flow slope and land-use condition; shallow concentrated flow channel geometry, roughness, and slope; and main channel geometry, roughness, and slope.

The differences in the three independent computations of T_c (those of LU, TTU, and USGS) using the NRCS travel-time method are attributed to differing length estimates for each flow component, differing estimates of the remaining watershed characteristics, and differing implementations of Manning's equation for open-channel flow. Different assumptions were made regarding channel geometry and Manning's roughness coefficient. Precise estimation of some of the input parameters for the NRCS travel-time method is difficult. In particular, repeatable application of Manning's equation using generalized measures of geometry and roughness that are representative of the hydraulic and hydrologic processes influencing T_c of the watershed is difficult. The potential exists for analysts to have substantially different T_c estimates as demonstrated by the results in figure 3.

Kirpich-inclusive (Kerby-Kirpich, KWF-Kirpich, and Kirpich method plus 30 minutes approaches) T_c estimates are shown in figure 4. Whereas T_c estimates using Kirpich-inclusive approaches still exhibit much variation, less variability appears to be in these estimates compared to estimates obtained using the NRCS travel-time method. The smaller variability in the Kirpich-inclusive approaches is partially expected because some of the methods used for channel flow incorporate overlapping methodology.

Kirpich-inclusive approaches are preferable from a usability perspective. Kirpich-inclusive approaches require fewer input parameter estimates than the NRCS travel-time method. The actual number of parameters for Kirpich-inclusive approaches is dependent on the particular method for estimating the overland flow component. Input parameters for Kirpich-inclusive approaches are available from published resources, such as topographic maps, NRCS county soil surveys, and geographic information software; this is not the case for NRCS travel-time input parameters. Examples of unpublished input parameters for the NRCS travel-time method are the appropriate Manning's roughness coefficient for the channel and appropriate measures of channel

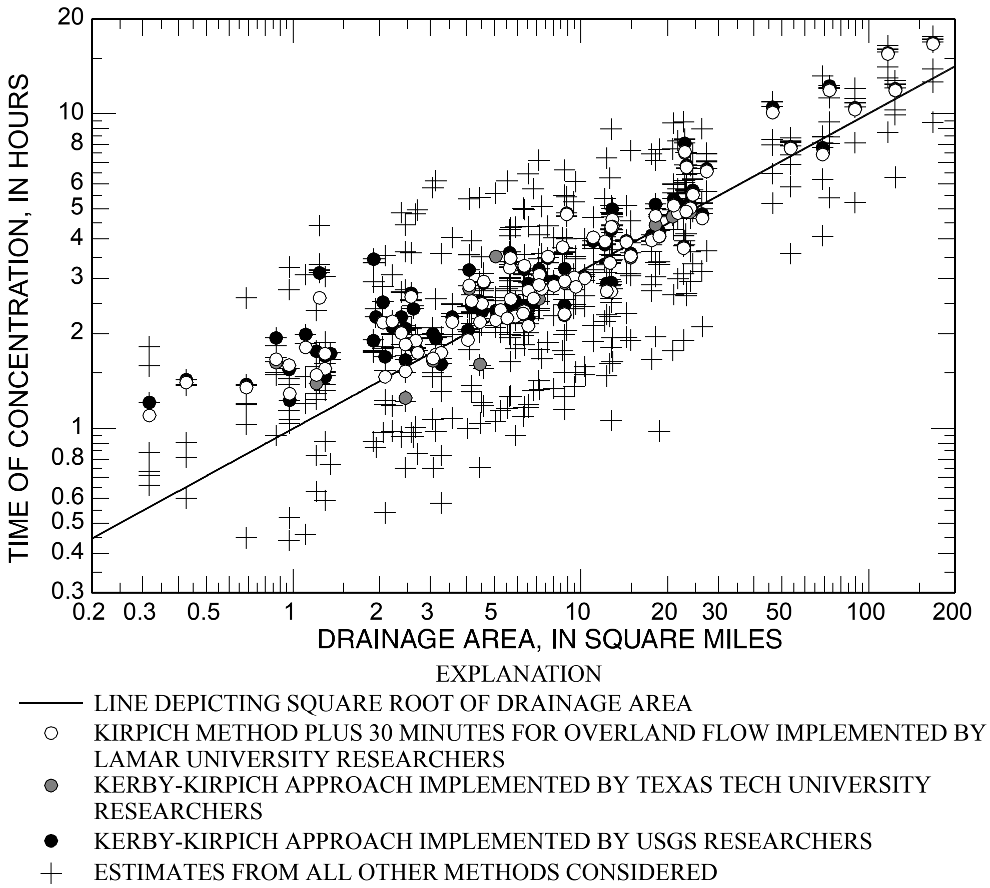


Figure 4. Relation between drainage area and time of concentration from evaluated approaches with distinction of Kirpich-inclusive approaches.

geometry. Additionally, identification of the most appropriate method to acquire some of the NRCS input parameters is difficult.

Another method for T_c estimation for small watersheds is an ad hoc method that uses the square root of drainage area in square miles, which reportedly produces T_c in hours (David Stolpa, Texas Department of Transportation, oral commun., 2004). The origin of the method is uncertain. The method lacks apparent physical basis and is dependent on the unit system indicated. Square root of drainage area is superimposed on the graphs of the relations between T_c and drainage area (figs. 3, 4). The square root of drainage area equation isolates length by removing units of length squared. Remarkably, the square root of drainage area passes through the generalized center of the data in the T_c/drainage area graphs. Although the method produces the correct order of T_c, the authors stress that the method remains an ad hoc method, perhaps best used as a check of other methods.

The relation between T_p for each watershed derived from regression analysis from TxDOT Research Project 0–4193 and T_c from the Kerby-Kirpich approach is shown in figure 5. The conventional conversion (Natural Resources Conservation Service, 2004) of T_c to T_p is $T_p = d/2 + T_L$ and $T_L = 0.6T_c$ (form of eq. 9), where d is equal to rainfall duration. The ratio $d/2$ is assumed negligible for this report because 1- and 5-minute rainfall durations were considered for TxDOT Research Project 0–4193. Therefore, $T_p \approx 0.6T_c$; this relation is shown in figure 5. An important distinction for the regression analysis is the watershed development classification. In the graph of the relation between T_p and T_c, the generalized regions for the two development classifications are indicated by two ellipses. The generalized regions shown are applicable to three of the unit hydrograph approaches—the traditional unit hydrograph approach indicates less influence of watershed development.

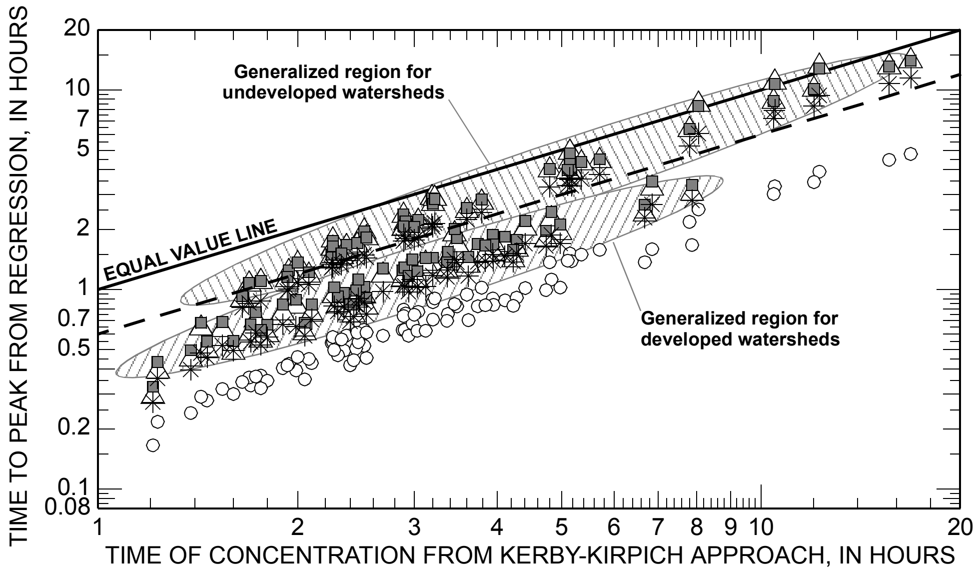
An interpretation of the $T_p - T_c$ graph (fig. 5) is that the NRCS conventional $T_p \approx 0.6T_c$ conversion overestimates T_p for developed watersheds and slightly underestimates T_p for undeveloped watersheds. The authors conclude that the NRCS $T_p \approx 0.6T_c$ conversion is of the correct order and straddles the distinction between watershed classification. Inspection of figure 5 suggests that a moderate curvilinear relation between T_p and T_c exists—this is particularly evident for undeveloped watersheds with T_c values less than about 2 hours. Graphical fitting of alternative T_c-to-T_p conversions onto the data in figure 5 indicates that the following conversions are more appropriate when the Kerby-Kirpich approach is used,

$T_p \approx 0.4T_c$ for developed watersheds, and

$T_p \approx 0.7T_c$ for undeveloped watersheds.

The alternative T_c-to-T_p conversions are shown in figure 6. T_p from the regression analysis from the traditional unit hydrograph approach is not included in figure 6. Inspection of the figure suggests some nonlinearity exists, particularly for small values of T_c.

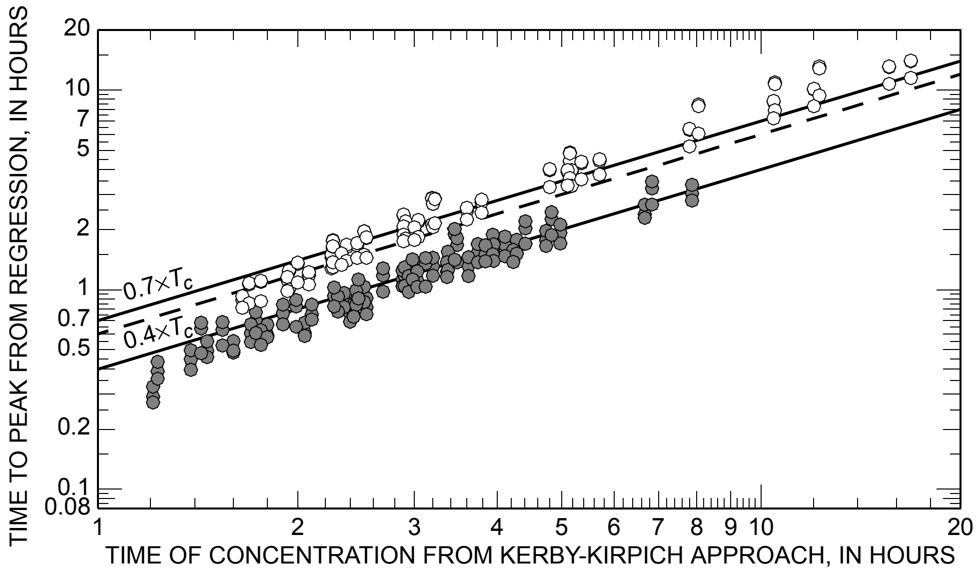
Based on relations depicted in figure 5, the authors conclude that the Kerby-Kirpich approach produces estimates of T_p consistent with observed rainfall and runoff. Whereas considerable variability exists in predictions of T_p, the Kerby-Kirpich approach for estimating T_c (and hence T_p) is reasonable. The Kerby-Kirpich approach thus is useful for T_c estimation for applicable Texas watersheds.



EXPLANATION

- – – 0.6×(TIME OF CONCENTRATION)
- ○ TIME TO PEAK FROM REGRESSION ANALYSIS FROM TRADITIONAL UNIT HYDROGRAPH APPROACH
- △ TIME TO PEAK FROM REGRESSION ANALYSIS FROM GUHAS UNIT HYDROGRAPH APPROACH
- ■ TIME TO PEAK FROM REGRESSION ANALYSIS FROM LINEAR PROGRAMMING UNIT HYDROGRAPH APPROACH
- ✳ TIME TO PEAK FROM REGRESSION ANALYSIS FROM INSTANTANEOUS UNIT HYDROGRAPH APPROACH

Figure 5. Relation between time of concentration and time to peak.



EXPLANATION

0.6×(TIME OF CONCENTRATION)

MODELED TIME TO PEAK FOR DEVELOPED WATERSHED

MODELED TIME TO PEAK FOR UNDEVELOPED WATERSHED

Figure 6. Relation between time of concentration and time to peak showing alternative time-of-concentration to time-to-peak conversions.

CONCLUSIONS

Conclusions concerning time-parameter estimation in the context of hydrologic design are made. The conclusions are applicable for Texas watersheds with drainage areas about 0.25 to 150 square miles, main-channel lengths about 1 to 50 miles, and dimensionless main-channel slopes about 0.002 to 0.02. Whereas other observations are included in the body of the report, the enumerated conclusions in this section are deemed most informative for hydrologic design practitioners.

1. It is appropriate to estimate watershed characteristics using a variety of methods. Differences between manual- and automatic-based watershed characteristics are a comparatively minor source of uncertainty relative to other sources inherent in time-parameter estimation in particular, and to hydrologic models incorporating time parameters in general.

2. In general, Kirpich-inclusive approaches, and specifically the Kerby-Kirpich approach, are appropriate for T_c estimation. Kirpich-inclusive approaches require a small number of input parameters, and the parameters needed are straightforward to estimate. Furthermore, Kirpich-inclusive approaches have greater repeatability than some alternative approaches such as the NRCS travel-time method because fewer analyst-specific interpretations are needed. A comparison of Kerby-Kirpich estimates with T_p from TxDOT Research Project 0–4193 suggests that Kerby-Kirpich estimates are more consistent with the characteristics of actual storm hydrographs. Therefore, the Kerby-Kirpich approach is preferable for applicable Texas watersheds.

3. The number and sensitivity of time-response characteristics to input parameters for the NRCS travel-time method make the method sensitive to decisions made by the analyst.Whereas the NRCS travel-time method is intuitively appealing because of its reliance on hydraulics-based estimates of flow velocity, determination of the many input parameters necessary requires considerable judgement. Estimates of input parameters are heavily dependent on analyst assumptions of hydraulic properties, such as channel geometry, that are difficult to measure and lack repeatability.

4. The NRCS conventional T_c-to-T_p conversion can be slightly improved to account for watershed development and additional empirical calibration available as part of TxDOT Research Projects 0–4696 and 0–4193. The NRCS $T_p \approx 0.6T_c$ conversion is of the correct order and yields T_p values between those associated with undeveloped watersheds and those associated with developed watersheds obtained from other methods. Inspection of a graph showing the relation between time of concentration and time to peak suggests that a moderate curvilinear relation between T_p and T_c exists—this is particularly evident for the undeveloped watersheds with T_c values less than about 2 hours. Visual fitting of alternative T_c to T_p conversion to the graph suggests that the following conversions are more appropriate when the Kerby-Kirpich approach is used

$T_p \approx 0.4T_c$ for developed watersheds, and

$T_p \approx 0.7T_c$ for undeveloped watersheds.

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Table 1. U.S. Geological Survey streamflow-gaging stations used in the study.

[sub., subwatershed; U, undeveloped watershed; IH, Interstate Highway; D, developed watershed; US, United States; SH, State Highway; FM, Farm to Market. Developed and undeveloped classification was done on a qualitative basis.]

Station no. (fig. 1)	Station name	Latitude	Longitude	Development classification
08042650	North Creek sub. 28A near Jermyn, Texas	33°14'52"	98°19'19"	U
08042700	North Creek near Jacksboro, Texas	33°16'57"	98°17'53"	U
08048520	Sycamore Creek at IH 35W, Fort Worth, Texas	32°39'55"	97°19'16"	D
08048530	Sycamore Creek tributary above Seminary South Shopping Center, Fort Worth, Texas	32°41'08"	97°19'44"	D
08048540	Sycamore Creek tributary at IH 35W, Fort Worth, Texas	32°41'18"	97°19'11"	D
08048550	Dry Branch at Blandin Street, Fort Worth, Texas	32°47'19"	97°18'22"	D
08048600	Dry Branch at Fain Street, Fort Worth, Texas	32°46'34"	97°17'18"	D
08048820	Little Fossil Creek at IH 820, Fort Worth, Texas	32°50'22"	97°19'20"	D
08048850	Little Fossil Creek at Mesquite Street, Fort Worth, Texas	32°48'33"	97°17'28"	D
08050200	Elm Fork Trinity River sub. 6 near Muenster, Texas	33°37'13"	97°24'15"	U
08052630	Little Elm Creek sub. 10 near Gunter, Texas	33°24'33"	96°48'41"	U
08052700	Little Elm Creek near Aubrey, Texas	33°17'00"	96°53'33"	U
08055580	Joes Creek at Royal Lane, Dallas, Texas	32°53'43"	96°41'36"	D
08055600	Joes Creek at Dallas, Texas	32°51'33"	96°53'00"	D
08055700	Bachman Branch at Dallas, Texas	32°51'37"	96°51'13"	D
08056500	Turtle Creek at Dallas, Texas	32°48'26"	96°48'08"	D
08057020	Coombs Creek at Sylvan Ave, Dallas, Texas	32°46'01"	96°50'07"	D
08057050	Cedar Creek at Bonnieview Road, Dallas, Texas	32°44'50"	96°47'44"	D
08057120	McKamey Creek at Preston Road, Dallas, Texas	32°57'58"	96°48'11"	U
08057130	Rush Branch at Arapaho Road, Dallas, Texas	32°57'45"	96°47'44"	D
08057140	Cottonwood Creek at Forest Lane, Dallas, Texas	32°54'33"	96°45'54"	D
08057160	Floyd Branch at Forest Lane, Dallas, Texas	32°54'33"	96°45'34"	D
08057320	Ash Creek at Highland Road, Dallas, Texas	32°48'18"	96°43'04"	D
08057415	Elam Creek at Seco Boulevard, Dallas, Texas	32°44'14"	96°41'36"	D
08057418	Fivemile Creek at Kiest Boulevard, Dallas, Texas	32°42'19"	96°51'32"	D
08057420	Fivemile Creek at US Highway 77W, Dallas, Texas	32°41'15"	96°49'22"	D
08057425	Woody Branch at IH 625, Dallas, Texas	32°40'58"	96°49'22"	D
08057435	Newton Creek at IH 635, Dallas, Texas	32°39'19"	96°44'41"	D
08057440	Whites Branch at IH 625, Dallas, Texas	32°39'26"	96°44'25"	D
08057445	Prarie Creek at US Highway 175, Dallas, Texas	32°42'17"	96°40'11"	D
08057500	Honey Creek sub. 11 near McKinney, Texas	33°18'12"	96°41'22"	U
08058000	Honey Creek sub.12 near McKinney, Texas	33°18'20"	96°40'12"	U
08061620	Duck Creek at Buckingham Road, Garland, Texas	32°55'53"	96°39'55"	D
08061920	South Mesquite Creek at SH 352, Mesquite, Texas	32°46'09"	96°37'18"	D
08061950	South Mesquite Creek at Mercury Road, Mesquite, Texas	32°43'32"	96°34'12"	D
08063200	Pin Oak Creek near Hubbard, Texas	31°48'01"	96°43'02"	U
08094000	Green Creek sub. 1 near Dublin, Texas	32°09'57"	98°20'28"	U
08096800	Cow Bayou sub. 4 near Bruceville, Texas	31°19'59"	97°16'02"	U
08098300	Little Pond Creek near Burlington, Texas	31°01'35"	96°59'17"	U
08108200	North Elm Creek near Cameron, Texas	30°55'52"	97°01'13"	U
08111025	Burton Creek at Villa Maria Road, Bryan, Texas	30°38'48"	96°20'57"	D
08111050	Hudson Creek near Bryan, Texas	30°39'38"	96°17'59"	U
08136900	Mukewater Creek sub. 10A near Trickham, Texas	31°39'01"	99°13'30"	U
08137000	Mukewater Creek sub. 9 near Trickham, Texas	31°41'40"	99°12'18"	U
08137500	Mukewater Creek at Trickham, Texas	31°35'24"	99°13'36"	U

Table 1. U.S. Geological Survey streamflow-gaging stations used in the study—Continued.

Station no. (fig. 1)	Station name	Latitude	Longitude	Development classification
08139000	Deep Creek sub. 3 near Placid,Texas	31°17'25"	99°09'22"	U
08140000	Deep Creek sub. 8 near Mercury, Texas	31°24'08"	99°07'17"	U
08154700	Bull Creek at Loop 360, Austin, Texas	30°22'19"	97°47'04"	U
08155200	Barton Creek at SH 71, Oak Hill, Texas	30°17'46"	97°55'31"	U
08155300	Barton Creek at Loop 360, Austin, Texas	30°14'40"	97°48'07"	U
08155550	West Bouldin Creek at Riverside Drive, Austin, Texas	30°15'49"	97°45'17"	D
08156650	Shoal Creek at Steck Avenue, Austin, Texas	30°21'55"	97°44'11"	D
08156700	Shoal Creek at Northwest Park, Austin, Texas	30°20'50"	97°44'41"	D
08156750	Shoal Creek at White Rock Drive, Austin, Texas	30°20'21"	97°44'50"	D
08156800	Shoal Creek at 12th Street, Austin, Texas	30°16'35"	97°45'00"	D
08157000	Waller Creek at 38th Street, Austin, Texas	30°17'49"	97°43'36"	D
08157500	Waller Creek at 23rd Street, Austin, Texas	30°17'08"	97°44'01"	D
08158050	Boggy Creek at US 183, Austin, Texas	30°15'47"	97°40'20"	D
08158100	Walnut Creek at FM 1325, Austin, Texas	30°24'35"	97°42'41"	U
08158200	Walnut Creek at Dessau Road, Austin, Texas	30°22'30"	97°39'37"	U
08158380	Little Walnut Creek at Georgian Drive Austin, Texas	30°21'15"	97°41'52"	D
08158400	Little Walnut Creek at IH 35, Austin, Texas	30°20'57"	97°41'34"	D
08158500	Little Walnut Creek at Manor Road, Austin, Texas	30°18'34"	97°40'04"	D
08158600	Walnut Creek at Webberville Road, Austin, Texas	30°16'59"	97°39'17"	D
08158700	Onion Creek near Driftwood, Texas	30°04'59"	98°00'29"	U
08158800	Onion Creek at Buda, Texas	30°05'09"	97°50'52"	U
08158810	Bear Creek below FM 1826, Driftwood, Texas	30°09'19"	97°56'23"	U
08158820	Bear Creek at FM 1626, Manchaca, Texas	30°08'25"	97°50'50"	U
08158825	Little Bear Creek at FM 1626, Manchaca, Texas	30°07'31"	97°51'43"	U
08158840	Slaughter Creek at FM 1826, Austin, Texas	30°12'32"	97°54'11"	U
08158860	Slaughter Creek at FM 2304, Austin, Texas	30°09'43"	97°49'55"	U
08158880	Boggy Creek (south) at Circle S Road, Austin, Texas	30°10'50"	97°46'55"	U
08158920	Williamson Creek at Oak Hill, Texas	30°14'06"	97°51'36"	D
08158930	Williamson Creek at Manchaca Road, Austin, Texas	30°13'16"	97°47'36"	D
08158970	Williamson Creek at Jimmy Clay Road, Austin, Texas	30°11'21"	97°43'56"	D
08159150	Wilbarger Creek near Pflugerville, Texas	30°27'16"	97°36'02"	U
08177600	Olmos Creek tributary at FM 1535, Shavano Park, Texas	29°34'35"	98°32'45"	D
08177700	Olmos Creek at Dresden Drive, San Antonio, Texas	29°29'56"	98°30'36"	D
08178300	Alazan Creek at St. Cloud Street, San Antonio, Texas	29°27'29"	98°32'59"	D
08178555	Harlendale Creek at West Harding Street, San Antonio, Texas	29°21'05"	98°29'32"	D
08178600	Panther Springs Creek at FM 2696 near San Antonio, Texas	29°37'31"	98°31'06"	U
08178620	Lorence Creek at Thousand Oaks Boulevard, San Antonio, Texas	29°35'24"	98°27'47"	D
08178640	West Elm Creek at San Antonio, Texas	29°37'23"	98°26'29"	U
08178645	East Elm Creek at San Antonio, Texas	29°37'04"	98°25'41"	U
08178690	Salado Creek tributary at Bitters Road, San Antonio, Texas	29°31'36"	98°26'25"	D
08178736	Salado Creek tributary at Bee Street, San Antonio, Texas	29°26'38"	98°27'13"	D
08181000	Leon Creek tributary at FM 1604, San Antonio, Texas	29°35'14"	98°37'40"	U
08181400	Helotes Creek at Helotes, Texas	29°34'42"	98°41'29"	U
08181450	Leon Creek tributary at Kelly Air Force Base, Texas	29°23'12"	98°36'00"	D
08182400	Calaveras Creek sub. 6 near Elmendorf, Texas	29°22'49"	98°17'33"	U
08187000	Escondido Creek sub. 1 near Kenedy, Texas	28°46'41"	97°53'41"	U
08187900	Escondido Creek sub. 11 near Kenedy, Texas	28°51'39"	97°50'39"	U

Table 2. Summary of travel-time and time-of-concentration computations for 92 watersheds in Texas by U.S. Geological Survey researchers.

[T_t^i, travel time for a specified flow component, in hours; NRCS, Natural Resources Conservation Service; KWF, Kinematic Wave Formula; T_c, time of concentration, in hours, which equals a sum of flow components from selected methods]

Station no.	T_t^i overland (NRCS travel time method)	T_t^i overland (Kerby method)	T_t^i overland (KWF method)	T_t^i shallow-concentrated (NRCS travel-time method)	T_t^i channel (NRCS travel-time method)	T_t^i channel (Kirpich method)	T_c (NRCS travel-time method)	T_c (Kerby-Kirpich approach)	T_c (KWF-Kirpich approach)
08042650	0.068	0.634	0.865	0.03	1.06	1.62	1.16	2.25	2.48
08042700	.072	.646	.865	.03	2.84	4.51	2.94	5.16	5.38
08048520	.036	.652	.470	.04	1.59	3.46	1.67	4.11	3.93
08048530	.027	.431	.272	.05	.44	.79	.52	1.22	1.06
08048540	.027	.415	.268	.05	.83	1.05	.91	1.46	1.32
08048550	.048	.673	.546	.07	.34	1.31	.46	1.98	1.86
08048600	.043	.576	.430	.06	.86	2.12	.96	2.70	2.55
08048820	.055	.885	.655	.05	1.16	2.74	1.26	3.62	3.40
08048850	.053	.875	.676	.04	1.84	4.11	1.93	4.98	4.79
08050200	.041	.778	.468	.05	1.40	1.16	1.49	1.94	1.63
08052630	.045	.856	.585	.04	.88	1.67	.96	2.53	2.26
08052700	.051	.889	.692	.03	5.32	11.4	5.40	12.3	12.1
08055580	.030	.416	.276	.05	.83	1.49	.91	1.91	1.77
08055600	.031	.396	.273	.04	1.56	2.98	1.63	3.38	3.25
08055700	.029	.388	.270	.04	2.07	3.55	2.14	3.94	3.82
08056500	.029	.411	.275	.04	2.10	2.79	2.17	3.20	3.06
08057020	.021	.356	.236	.03	1.16	1.99	1.21	2.35	2.23
08057050	.023	.354	.230	.03	1.30	2.52	1.35	2.87	2.75
08057120	.035	.644	.483	.04	1.11	2.24	1.18	2.88	2.72
08057130	.035	.475	.379	.06	.50	1.23	.60	1.70	1.61
08057140	.029	.467	.301	.04	1.70	3.27	1.77	3.74	3.57
08057160	.030	.473	.335	.04	1.11	2.43	1.18	2.90	2.76
08057320	.028	.394	.285	.04	1.26	2.58	1.33	2.97	2.86
08057415	.043	.451	.348	.07	.33	1.09	.44	1.54	1.44
08057418	.032	.600	.593	.03	1.27	2.34	1.33	2.94	2.93
08057420	.028	.544	.519	.03	1.90	3.41	1.96	3.95	3.93
08057425	.026	.529	.447	.03	1.42	2.50	1.48	3.03	2.95
08057435	.040	.767	.668	.04	.87	1.77	.95	2.54	2.44
08057440	.048	.813	.857	.04	.85	1.59	.94	2.40	2.45
08057445	.034	.536	.436	.04	1.98	4.29	2.05	4.83	4.73

Table 2. Summary of travel-time and time-of-concentration computations for 92 watersheds in Texas by U.S. Geological Survey researchers—Continued.

Station no.	T_t^i overland (NRCS travel time method)	T_t^i overland (Kerby method)	T_t^i overland (KWF method)	T_t^i shallow-concentrated (NRCS travel-time method)	T_t^i channel (NRCS travel-time method)	T_t^i channel (Kirpich method)	T_c (NRCS travel-time method)	T_c (Kerby-Kirpich approach)	T_c (KWF-Kirpich approach)
08057500	0.039	0.725	0.566	0.04	0.46	0.96	0.54	1.68	1.53
08058000	.049	.779	.587	.05	.54	.98	.64	1.76	1.57
08061620	.038	.461	.336	.05	1.79	3.02	1.88	3.48	3.36
08061920	.032	.538	.397	.03	1.56	3.88	1.62	4.42	4.28
08061950	.032	.589	.451	.03	2.62	6.26	2.68	6.85	6.71
08063200	.054	.909	.739	.03	1.87	4.24	1.95	5.15	4.98
08094000	.081	.758	1.21	.04	.82	1.51	.94	2.27	2.72
08096800	.064	.659	.891	.03	.96	1.71	1.05	2.37	2.60
08098300	.074	.985	1.22	.04	3.71	7.07	3.82	8.06	8.29
08108200	.078	.905	1.31	.03	5.08	9.59	5.19	10.5	10.9
08111025	.029	.408	.336	.05	.69	1.32	.77	1.73	1.66
08111050	.054	.871	1.01	.05	.77	1.39	.87	2.26	2.40
08136900	.094	.844	1.43	.04	2.85	4.34	2.98	5.18	5.77
08137000	.081	.834	1.21	.06	1.65	2.35	1.79	3.18	3.56
08137500	.100	.878	1.52	.03	3.96	6.92	4.09	7.80	8.44
08139000	.107	.716	1.36	.04	.83	1.22	.98	1.94	2.58
08140000	.089	.769	1.32	.04	1.54	2.28	1.67	3.05	3.60
08154700	.034	.548	.859	.02	1.86	3.24	1.91	3.79	4.10
08155200	.075	.635	1.01	.02	5.13	9.81	5.22	10.4	10.8
08155300	.068	.620	.983	.02	8.65	15.0	8.74	15.6	16.0
08155550	.022	.399	.389	.04	.94	1.40	1.00	1.80	1.79
08156650	.030	.519	.689	.05	.75	1.24	.83	1.76	1.93
08156700	.027	.445	.498	.04	1.10	1.86	1.17	2.30	2.36
08156750	.026	.438	.477	.04	1.26	2.09	1.33	2.53	2.57
08156800	.025	.414	.397	.04	2.53	3.87	2.60	4.28	4.27
08157000	.028	.416	.304	.05	1.10	1.69	1.18	2.11	1.99
08157500	.026	.409	.301	.04	1.24	2.04	1.31	2.45	2.34
08158050	.027	.497	.489	.03	1.55	2.86	1.61	3.36	3.35
08158100	.052	.695	1.19	.04	.98	2.22	1.07	2.92	3.41
08158200	.042	.646	1.03	.03	2.04	4.15	2.11	4.80	5.18
08158380	.027	.389	.315	.04	1.07	1.88	1.14	2.27	2.20
08158400	0.027	0.392	0.329	.04	1.20	2.08	1.27	2.47	2.41

Table 2. Summary of travel-time and time-of-concentration computations for 92 watersheds in Texas by U.S. Geological Survey researchers—Continued.

Station no.	T_t^i overland (NRCS travel time method)	T_t^i overland (Kerby method)	T_t^i overland (KWF method)	T_t^i shallow-concentrated (NRCS travel-time method)	T_t^i channel (NRCS travel-time method)	T_t^i channel (Kirpich method)	T_c (NRCS travel-time method)	T_c (Kerby-Kirpich approach)	T_c (KWF-Kirpich approach)
08158500	0.024	0.413	0.400	0.03	2.14	3.43	2.19	3.84	3.83
08158600	.037	.608	.896	.02	3.54	7.26	3.60	7.87	8.16
08158700	.087	.658	1.03	.02	6.16	11.4	6.27	12.1	12.4
08158800	.089	.672	1.05	.02	9.28	16.2	9.39	16.8	17.2
08158810	.082	.658	1.07	.03	1.36	2.23	1.47	2.89	3.30
08158820	.089	.676	1.16	.02	3.23	5.03	3.34	5.71	6.19
08158825	.119	.742	1.35	.03	2.51	4.61	2.66	5.35	5.96
08158840	.054	.656	1.14	.03	1.07	1.81	1.15	2.47	2.95
08158860	.075	.722	1.31	.03	2.54	4.39	2.64	5.11	5.70
08158880	.032	.575	.801	.04	1.01	1.68	1.08	2.26	2.48
08158920	.045	.607	1.00	.03	1.02	1.82	1.10	2.43	2.82
08158930	.046	.651	1.11	.03	.90	3.58	.98	4.23	4.69
08158970	.038	.611	.972	.03	3.60	6.06	3.67	6.67	7.03
08159150	.092	.863	1.25	.05	.90	1.68	1.04	2.54	2.93
08177600	.038	.609	.981	.07	.55	.60	.66	1.21	1.58
08177700	.031	.567	.761	.03	1.71	4.18	1.77	4.75	4.94
08178300	.020	.365	.222	.04	.52	1.24	.58	1.60	1.46
08178555	.062	.600	.508	.10	1.59	2.85	1.75	3.45	3.36
08178600	.106	.680	1.20	.03	1.38	2.32	1.52	3.00	3.52
08178620	.043	.640	1.02	.04	.91	1.41	.99	2.05	2.43
08178640	.053	.630	1.03	.04	.66	1.02	.75	1.65	2.05
08178645	.160	.737	1.40	.04	1.02	1.35	1.22	2.09	2.75
08178690	.055	.526	.472	.12	.64	.90	.82	1.43	1.37
08178736	.036	.524	.337	.08	.34	.85	.46	1.37	1.19
08181000	.092	.592	.991	.02	1.05	1.74	1.16	2.33	2.73
08181400	.070	.570	.843	.02	1.82	3.03	1.91	3.60	3.87
08181450	.085	1.02	1.08	.10	1.21	2.10	1.40	3.12	3.18
08182400	.067	.841	1.09	.04	1.32	2.36	1.43	3.20	3.45
08187000	.065	.748	.841	.04	.65	1.25	.76	2.00	2.09
08187900	.079	.785	1.20	.04	1.15	2.44	1.27	3.22	3.64

Table 3. Summary of travel-time and time-of-concentration computations for 92 watersheds in Texas by Lamar University researchers.

[T_t^i, travel time for a specified flow component, in hours; NRCS, Natural Resources Conservation Service; T_c, time of concentration, which equals travel time plus 30 minutes, in hours, from selected methods; --, not available]

Station no.	T_t^i channel (NRCS travel-time method)	T_t^i channel (Kirpich method)	T_t^i channel (Haktanir and Sezen method)	T_t^i channel (Simas and Hawkins method)	T_c (NRCS travel-time method plus 30 minutes)	T_c (Kirpich method plus 30 minutes)	T_c (Haktanir and Sezen method plus 30 minutes)	T_c (Simas and Hawkins method plus 30 minutes)
08042650	1.51	1.62	1.92	5.94	2.01	2.12	2.42	6.44
08042700	4.15	4.51	4.73	6.33	4.65	5.01	5.23	6.83
08048520	1.36	3.46	3.15	6.94	2.86	3.96	3.65	7.44
08048530	--	.79	.54	2.75	--	1.29	1.04	3.25
08048540	--	1.05	.88	2.54	--	1.55	1.38	3.04
08048550	.96	1.31	.70	2.58	1.46	1.81	1.20	3.08
08048600	1.60	2.12	1.57	3.11	2.10	2.62	2.07	3.61
08048820	2.10	2.74	2.52	3.78	2.60	3.24	3.02	4.28
08048850	3.04	4.11	3.89	4.34	3.54	4.61	4.39	4.84
08050200	1.33	1.16	1.01	1.18	1.83	1.66	1.51	1.68
08052630	1.29	1.67	1.32	2.33	1.79	2.17	1.82	2.83
08052700	7.92	11.36	8.91	7.56	8.42	11.86	9.41	8.06
08055580	--	--	--	--	--	--	--	--
08055600	2.44	2.98	2.82	3.60	2.94	3.48	3.32	4.10
08055700	2.69	3.55	3.24	4.18	3.19	4.05	3.74	4.68
08056500	2.60	2.79	2.67	3.07	3.10	3.29	3.17	3.57
08057020	1.63	1.99	2.12	3.00	2.13	2.49	2.62	3.50
08057050	1.90	2.52	2.60	4.75	2.40	3.02	3.10	5.25
08057120	1.65	2.24	2.17	3.88	2.15	2.74	2.67	4.38
08057130	1.02	1.23	1.01	1.38	1.52	1.73	1.51	1.88
08057140	2.51	3.27	3.12	3.54	3.01	3.77	3.62	4.04
08057160	1.91	2.43	2.23	2.61	2.41	2.93	2.73	3.11
08057320	1.91	2.58	2.26	3.62	2.41	3.08	2.76	4.12
08057415	.88	1.09	.64	2.26	1.38	1.59	1.14	2.76
08057418	1.78	2.34	2.36	3.53	2.28	2.84	2.86	4.03
08057420	2.61	3.41	3.47	4.61	3.11	3.91	3.97	5.11
08057425	1.94	2.50	2.58	3.51	2.44	3.00	3.08	4.01
08057435	1.29	1.77	1.70	3.86	1.79	2.27	2.20	4.36
08057440	--	--	--	--	--	--	--	--
08057445	3.24	4.29	3.50	4.95	3.74	4.79	4.0	5.45
08057500	.69	.96	.73	3.04	1.19	1.46	1.23	3.54

Table 3. Summary of travel-time and time-of-concentration computations for 92 watersheds in Texas by Lamar University researchers—Continued.

Station no.	T_t^i channel (NRCS travel-time method)	T_t^i channel (Kirpich method)	T_t^i channel (Haktanir and Sezen method)	T_t^i channel (Simas and Hawkins method)	T_c (NRCS travel-time method plus 30 minutes)	T_c (Kirpich method plus 30 minutes)	T_c (Haktanir and Sezen method plus 30 minutes)	T_c (Simas and Hawkins method plus 30 minutes)
08058000	0.79	0.98	0.74	1.87	1.29	1.48	1.24	2.37
08061620	2.17	3.02	2.31	3.90	2.67	3.52	2.81	4.40
08061920	2.94	3.88	3.19	4.20	3.44	4.38	3.69	4.70
08061950	4.47	6.26	5.14	4.57	4.97	6.76	5.64	5.07
08063200	2.87	4.24	3.63	6.60	3.37	4.74	4.13	7.10
08094000	1.55	1.51	1.35	4.35	2.05	2.01	1.85	4.85
08096800	1.60	1.71	1.86	5.08	2.10	2.21	2.36	5.58
08098300	5.64	7.07	5.54	3.45	6.14	7.57	6.04	3.95
08108200	7.46	9.59	7.78	5.95	7.96	10.1	8.28	6.45
08111025	--	--	--	--	--	--	--	--
08111050	--	--	--	--	--	--	--	--
08136900	4.16	4.34	5.05	7.70	4.66	4.84	5.55	8.20
08137000	2.34	2.35	2.82	4.86	2.84	2.85	2.32	5.36
08137500	5.69	6.92	7.58	12.7	6.19	7.42	8.08	13.16
08139000	1.21	1.22	1.35	5.63	1.71	1.72	1.85	6.13
08140000	2.23	2.28	2.47	4.58	2.73	2.78	2.97	5.08
08154700	2.60	3.24	4.15	8.93	3.10	3.74	4.65	9.43
08155200	7.58	9.81	10.7	11.5	8.08	10.3	11.2	12.0
08155300	12.5	15.0	15.9	13.5	13.0	15.5	16.4	14.0
08155550	1.31	1.40	1.49	4.30	1.81	1.90	1.99	4.80
08156650	--	1.24	--	4.45	--	1.74	--	4.95
08156700	1.51	1.86	1.88	4.46	2.01	2.36	2.38	4.96
08156750	1.73	2.09	2.14	5.28	2.23	2.59	2.64	5.78
08156800	3.45	3.87	4.36	4.60	3.95	4.37	4.86	5.10
08157000	1.61	1.69	1.70	2.57	2.11	2.19	2.20	3.07
08157500	1.81	2.04	2.16	3.45	2.31	2.54	2.66	3.95
08158050	2.34	2.86	3.08	5.74	2.84	3.36	3.58	6.24
08158100	1.31	2.22	2.37	8.44	1.81	2.72	2.87	8.94
08158200	2.66	4.15	4.48	8.45	3.16	4.65	4.98	8.95
08158380	1.52	1.88	1.65	--	2.02	2.38	2.15	--
08158400	1.70	2.08	1.86	3.85	2.20	2.58	2.36	4.35
08158500	2.90	3.43	3.57	4.87	3.40	3.93	4.07	5.37

Table 3. Summary of travel-time and time-of-concentration computations for 92 watersheds in Texas by Lamar University researchers—Continued.

Station no.	T_t^i channel (NRCS travel-time method)	T_t^i channel (Kirpich method)	T_t^i channel (Haktanir and Sezen method)	T_t^i channel (Simas and Hawkins method)	T_c (NRCS travel-time method plus 30 minutes)	T_c (Kirpich method plus 30 minutes)	T_c (Haktanir and Sezen method plus 30 minutes)	T_c (Simas and Hawkins method plus 30 minutes)
08158600	5.36	7.26	7.61	7.88	5.86	7.76	8.11	8.38
08158700	9.42	11.4	12.2	11.9	9.92	11.9	12.7	12.4
08158800	13.4	16.2	17.1	12.1	13.8	16.6	17.6	12.6
08158810	1.80	2.23	2.63	6.73	2.30	2.73	3.13	7.23
08158820	4.39	5.03	5.96	6.97	4.89	5.53	6.46	7.47
08158825	3.78	4.61	5.10	8.84	4.28	5.11	5.60	9.34
08158840	1.49	1.81	2.07	5.00	1.99	2.31	2.57	5.50
08158860	3.65	4.39	5.20	7.04	4.15	4.89	5.70	7.54
08158880	1.49	1.68	1.82	3.54	1.99	2.18	2.32	4.04
08158920	1.48	1.82	2.07	4.50	1.98	2.32	2.57	5.00
08158930	2.88	3.58	4.29	7.21	3.38	4.08	4.79	7.71
08158970	5.16	6.06	6.95	6.98	5.66	6.56	7.45	7.48
08159150	1.09	1.68	1.52	4.92	1.59	2.18	2.02	5.42
08177600	--	.60	.34	1.32	--	1.10	.84	1.82
08177700	--	--	--	--	--	--	--	--
08178300	1.17	1.24	1.45	3.09	1.67	1.74	1.95	3.59
08178555	--	--	--	2.42	--	--	--	2.92
08178600	1.98	2.32	2.95	5.59	2.48	2.82	3.45	6.09
08178620	--	1.41	--	--	--	1.91	--	--
08178640	1.01	1.02	1.20	3.93	1.51	1.52	1.70	4.43
08178645	--	1.35	1.62	3.14	--	1.85	2.12	3.64
08178690	--	.90	--	--	--	1.40	--	--
08178736	.87	.85	.53	2.10	1.37	1.35	1.03	2.60
08181000	1.65	1.74	2.27	5.61	2.15	2.24	2.77	6.11
08181400	2.56	3.03	4.06	7.13	3.06	3.53	4.56	7.63
08181450	2.83	2.10	1.24	3.91	3.33	2.60	1.74	4.41
08182400	1.87	2.36	2.03	6.60	2.37	2.86	2.53	7.10
08187000	.96	1.17	1.00	5.31	1.46	1.67	1.50	5.81
08187900	--	2.44	--	6.12	--	2.94	--	6.62

Table 4. Summary of travel-time and time-of-concentration computations for 92 watersheds in Texas by Texas Tech University researchers.

[T_t^i, travel time for a specified flow component, in hours; NRCS, Natural Resources Conservation Service; KWF, Kinematic Wave Formula; T_c, time of concentration, in hours, which equals a sum of flow components from selected methods; --, not available]

Station no.	T_t^i overland (NRCS travel-time method)	T_t^i overland (Kerby method)	T_t^i overland (KWF method)	T_t^i shallow-concentrated (NRCS travel-time method)	T_t^i channel (NRCS travel-time method)	T_t^i channel (Kirpich method)	T_c (NRCS travel-time method)	T_c (Kerby-Kirpich approach)	T_c (KWF-Kirpich approach)
08042650	--	--	--	--	--	--	--	--	--
08042700	0.13	0.33	--	0	3.51	4.53	3.64	4.86	--
08048520	.48	--	0.43	.01	2.24	3.40	2.73	--	3.83
08048530	--	--	--	--	--	--	--	--	--
08048540	--	--	--	--	--	--	--	--	--
08048550	--	--	--	--	--	--	--	--	--
08048600	--	--	--	--	--	--	--	--	--
08048820	.05	--	.09	0	1.94	2.74	1.99	--	2.83
08048850	.05	--	.10	0	2.72	4.10	2.77	--	4.20
08050200	.28	.51	--	.02	.65	1.11	.95	1.62	--
08052630	--	--	--	--	--	--	--	--	--
08052700	.28	.52	--	.02	10.9	11.4	11.2	11.9	--
08055580	--	--	--	--	--	--	--	--	--
08055600	.05	--	.14	0	1.89	2.86	1.94	--	3.00
08055700	.03	--	.11	0	1.86	3.02	1.89	--	3.13
08056500	.03	--	.09	0	1.81	2.84	1.84	--	2.93
08057020	--	--	--	--	--	--	--	--	--
08057050	--	--	--	--	--	--	--	--	--
08057120	--	--	--	--	--	--	--	--	--
08057130	--	--	--	--	--	--	--	--	--
08057140	--	--	--	--	--	--	--	--	--
08057160	.04	--	.11	0	1.51	2.45	1.55	--	2.56
08057320	--	--	--	--	--	--	--	--	--
08057415	--	--	--	--	--	--	--	--	--
08057418	--	--	--	--	--	--	--	--	--
08057420	.05	--	.15	0	2.27	3.39	2.32	--	3.54
08057425	.04	--	.11	0	1.53	2.53	1.57	--	2.64
08057435	--	--	--	--	--	--	--	--	--
08057440	--	--	--	--	--	--	--	--	--
08057445	--	--	--	--	--	--	--	--	--

Table 4. Summary of travel-time and time-of-concentration computations for 92 watersheds in Texas by Texas Tech University researchers—Continued.

Station no.	T_t^i overland (NRCS travel-time method)	T_t^i overland (Kerby method)	T_t^i overland (KWF method)	T_t^i shallow-concen-trated (NRCS travel-time method)	T_t^i channel (NRCS travel-time method)	T_t^i channel (Kirpich method)	T_c (NRCS travel-time method)	T_c (Kerby-Kirpich approach)	T_c (KWF-Kirpich approach)
08057500	--	--	--	--	--	--	--	--	--
08058000	0.18	0.42	--	0.01	0.63	0.97	0.82	1.39	--
08061620	--	--	--	--	--	--	--	--	--
08061920	--	--	--	--	--	--	--	--	--
08061950	.04	--	0.15	0	5.68	6.27	5.72	--	6.42
08063200	.13	.33	--	0	2.90	4.10	3.03	4.43	--
08094000	--	--	--	--	--	--	--	--	--
08096800	.39	.55	--	0	2.15	2.97	2.54	3.52	--
08098300	.21	.42	--	0	6.66	7.08	6.87	7.50	--
08108200	--	--	--	--	--	--	--	--	--
08111025	--	--	--	--	--	--	--	--	--
08111050	--	--	--	--	--	--	--	--	--
08136900	--	--	--	--	--	--	--	--	--
08137000	.18	.42	--	.01	1.84	2.36	2.03	2.78	--
08137500	--	--	--	--	--	--	--	--	--
08139000	--	--	--	--	--	--	--	--	--
08140000	--	--	--	--	--	--	--	--	--
08154700	--	--	--	--	--	--	--	--	--
08155200	--	--	--	--	--	--	--	--	--
08155300	--	--	--	--	--	--	--	--	--
08155550	--	--	--	--	--	--	--	--	--
08156650	--	--	--	--	--	--	--	--	--
08156700	--	--	--	--	--	--	--	--	--
08156750	--	--	--	--	--	--	--	--	--
08156800	.04	--	.13	0	2.48	3.82	2.52	--	3.95
08157000	.08	--	.14	0	.90	1.66	.98	--	1.80
08157500	.08	--	.16	0	1.29	2.00	1.37	--	2.16
08158050	.04	--	.11	0	2.23	2.86	2.27	--	2.97
08158100	--	--	--	--	--	--	--	--	--
08158200	--	--	--	--	--	--	--	--	--
08158380	--	--	--	--	--	--	--	--	--
08158400	--	--	--	--	--	--	--	--	--

Table 4. Summary of travel-time and time-of-concentration computations for 92 watersheds in Texas by Texas Tech University researchers—Continued.

Station no.	T_t^i overland (NRCS travel-time method)	T_t^i overland (Kerby method)	T_t^i overland (KWF method)	T_t^i shallow-concen-trated (NRCS travel-time method)	T_t^i channel (NRCS travel-time method)	T_t^i channel (Kirpich method)	T_c (NRCS travel-time method)	T_c (Kerby-Kirpich approach)	T_c (KWF-Kirpich approach)
08158500	--	--	--	--	--	--	--	--	--
08158600	0.04	--	0.16	0	6.86	7.25	6.90	--	7.41
08158700	.41	0.50	--	0	9.87	11.4	10.3	11.8	--
08158800	--	--	--	--	--	--	--	--	--
08158810	--	--	--	--	--	--	--	--	--
08158820	--	--	--	--	--	--	--	--	--
08158825	--	--	--	--	--	--	--	--	--
08158840	.17	.37	--	.01	1.33	1.92	1.51	2.29	--
08158860	--	--	--	--	--	--	--	--	--
08158880	--	--	--	--	--	--	--	--	--
08158920	--	--	--	--	--	--	--	--	--
08158930	.30	.47	--	.02	3.01	3.60	3.33	4.07	--
08158970	--	--	--	--	--	--	--	--	--
08159150	.02	.14	--	0	.73	1.46	.75	1.60	--
08177600	.04	--	.13	0	.69	.58	.73	--	.71
08177700	.25	.40	--	.01	7.48	4.31	7.74	4.71	--
08178300	.03	--	.08	0	.79	1.23	.82	--	1.31
08178555	--	--	--	--	--	--	--	--	--
08178600	--	--	--	--	--	--	--	--	--
08178620	--	--	--	--	--	--	--	--	--
08178640	.08	.24	--	0	1.14	1.01	1.22	1.25	--
08178645	--	--	--	--	--	--	--	--	--
08178690	.03	--	.06	0	.57	.84	.60	--	.90
08178736	--	--	--	--	--	--	--	--	--
08181000	--	--	--	--	--	--	--	--	--
08181400	.16	.35	--	.01	2.93	3.14	3.10	3.49	--
08181450	--	--	--	--	--	--	--	--	--
08182400	.06	.24	--	0	1.72	2.34	1.78	2.58	--
08187000	.24	.44	--	0	.83	1.20	1.07	1.64	--
08187900	.06	.48	--	.01	1.65	2.42	1.72	2.90	--

Supplement: Guidance for Estimation of Time of Concentration in Texas

(At the request of the Texas Department of Transportation, a brief, but encompassing, supplement to this report is included here to provide further guidance for estimation of time of concentration in Texas.)

Introduction

For the watersheds considered in this report, drainage areas are between approximately 0.25 and 150 square miles, main channel lengths are between approximately 1 and 50 miles, and dimensionless main channel slopes are between approximately 0.002 and 0.02. Main channel slope is computed as the change in elevation from the watershed divide to the watershed outlet divided by the curvilinear distance of the main channel (primary flow path) between the watershed divide and the outlet. The authors emphasize that no watersheds with low topographic slopes are available in the underlying database. Therefore, the guidance described in this supplement is not applicable to watersheds with limited topographic slope. Such watersheds are predominant in the High Plains and Coastal Regions of Texas.

This report provides an evaluation of a myriad of alternative approaches. The authors conclude that, in general, Kirpich-inclusive approaches and, in particular, the Kerby-Kirpich approach for estimating watershed time of concentration are preferable. The Kerby-Kirpich approach requires comparatively few input parameters, is straightforward to apply, and produces readily interpretable results. The Kerby-Kirpich approach produces time of concentration estimates consistent with watershed time values independently derived from real-world storms and runoff hydrographs. Application of the Kerby-Kirpich is demonstrated in this supplement.

The Kerby Method

For small watersheds where overland flow is an important component of overall travel time, the Kerby (1959) method can be used. The Kerby equation is

$$T_c = K(L \times N)^{0.467} S^{-0.235},$$

where T_c is the overland flow time of concentration, in minutes; K is a units conversion coefficient, in which $K = 0.828$ for traditional units and $K = 1.44$ for SI units; L is the overland-flow length, in feet or meters as dictated by K; N is a dimensionless retardance coefficient; and S is the dimensionless slope of terrain conveying the overland flow. In the development of the Kerby equation, the length of overland flow was as much as about 1,200 feet (366 meters). Hence, this length is considered an upper limit and shorter values in practice generally are expected. The dimensionless retardance coefficient used is similar in concept to the well-known Manning's roughness coefficient; however, for a given type of surface, the retardance coefficient for overland flow will be considerably larger than for open-channel flow. Typical values for the retardance coefficient are listed in the following table.

Generalized terrain description	Dimensionless retardance coefficient (N)
Pavement	0.02
Smooth, bare, packed soil	.10
Poor grass, cultivated row crops, or moderately rough packed surfaces	.20
Pasture, average grass	.40
Deciduous forest	.60
Dense grass, coniferous forest, or deciduous forest with deep litter	.80

The Kirpich Method

For channel-flow component of runoff, the Kirpich (1940) equation is

$$T_c = KL^{0.770}S^{-0.385},$$

where T_c is the time of concentration, in minutes; K is a units conversion coefficient, in which $K = 0.0078$ for traditional units and $K = 0.0195$ for SI units; L is the channel-flow length, in feet or meters as dictated by K; and S is the dimensionless main-channel slope.

Application

An example (shown below) illustrating application of the Kerby-Kirpich method is informative. For example, suppose a hydraulic design is needed to convey runoff from a small watershed with a drainage area of 0.5 square mile. On the basis of field examination and topographic maps, the length of the main channel from the watershed outlet (the design point) to the watershed divide is 5,280 feet. Elevation of the watershed at the outlet is 700 feet. From a topographic map, elevation along the main channel at the watershed divide is estimated to be 750 feet. The analyst assumes that overland flow will have an appreciable contribution to the time of concentration for the watershed. The analyst estimates that the length of overland flow is about 500 feet and that the slope for the overland-flow component is 2 percent ($S = 0.02$). The area representing overland flow is average grass ($N = 0.40$).

For the overland-flow T_c, the analyst applies the Kerby equation,

$$T_c = 0.828(500 \times 0.40)^{0.467}(0.02)^{-0.235},$$

from which T_c is about 25 minutes.

For the channel T_c, the analyst applies the Kirpich equation, but first dimensionless main-channel slope is required,

$$S = \frac{750 - 700}{5{,}280} = 0.0095,$$

or about 1 percent. The value for slope and the channel length are used in the Kirpich equation,

$$T_c = 0.0078(5{,}280 - 500)^{0.770}(0.0095)^{-0.385},$$

from which T_c is about 32 minutes. Because the overland flow T_c is used for this watershed, the subtraction of the overland flow length from the overall main-channel length (watershed divide to outlet) is necessary and reflected in the calculation.

Adding the overland flow and channel flow components of T_c gives a watershed T_c of about 57 minutes.

Finally, as a quick check, the analyst can evaluate the T_c by using an ad hoc method representing T_c, in hours, as the square root of drainage area, in square miles. For the example, the square root of the drainage area yields a T_c estimate of about 0.71 hour or about 42 minutes, which is reasonably close to 57 minutes. However, the authors emphasize that 57 minutes is preferable.