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TIMING PARAMETER ESTIMATION USING A PARTICLE TRACKING METHOD

Report 0-4696-3

Texas Department of Transportation
Research Project Number 0-4696

TIMING PARAMETER ESTIMATION USING A PARTICLE TRACKING METHOD

by

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Sponsored by the
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August 31, 2005

Department of Civil and Environmental Engineering
University of Houston
Houston, Texas 77204-4003

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16. Abstract

Characterization of hydrologic processes of a watershed requires estimation of the specific time-response characteristics of the watershed. 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. An exploratory assessment of a particle-tracking approach for estimating time of concentration for applicable Texas watersheds is presented.

The method is successfully applied to 84 of the 92 watersheds considered for the study. The 92 watersheds analyzed had drainage areas ranging from approximately 0.25 to 150 square miles, main channel lengths ranging from approximately 1 to 50 miles, and dimensionless main channel slopes are between approximately 0.002 to 0.02. The resulting timing parameters are used in a performance test against historical storms on the same watersheds and qualitatively evaluated. The resulting timing parameters are tabulated and compared to timing parameters determined by other methods in this research. The parameters estimated by the particle tracking approach are within two-standard deviations of the mean value for time-of-concentration estimated by five other methods in the research project.

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ABSTRACT

Characterization of hydrologic processes of a watershed requires estimation of the specific time-response characteristics of the watershed. 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. An exploratory assessment of a particle-tracking approach for estimating time of concentration for applicable Texas watersheds is presented.

The method is successfully applied to 84 of the 92 watersheds considered for the study. The 92 watersheds analyzed had drainage areas ranging from approximately 0.25 to 150 square miles, main channel lengths ranging from approximately 1 to 50 miles, and dimensionless main channel slopes are between approximately 0.002 to 0.02. The resulting timing parameters are used in a performance test against historical storms on the same watersheds and qualitatively evaluated. The resulting timing parameters are tabulated and compared to timing parameters determined by other methods in this research. The parameters estimated by the particle tracking approach are within two-standard deviations of the mean value for time-of-concentration estimated by five other methods in the research project.

INTRODUCTION

Estimation of the time-response characteristics of a watershed is fundamental in hydrologic analysis and rainfall-runoff response modeling. Responses to real or design rainfall such as peak discharge, hydrograph recession, and the time evolution of cumulative runoff are greatly influenced by time characteristics. Rainfall-runoff models that incorporate timing parameter variables are used by engineers and others for hydrologic design purposes including the design of bridges, culverts, and detention facilities. Therefore, during 2004-2005, a consortium of researchers at Lamar University (LU), Texas Tech University (TTU), the University of Houston (UH), and the U.S. Geological Survey (USGS), in cooperation with the Texas Department of Transportation (TxDOT) Research Management committee 3, investigated timing parameter estimation approaches for applicable Texas watersheds (TxDOT Research Project 0-4696).

The time-response characteristics of the watershed frequently are represented by two conceptual time parameters, time of concentration (T_c) and time to peak (T_p). The T_c is typically defined as the time it takes for runoff to travel from the most distant point along a hydraulic pathline in the watershed to the outlet. The T_p is typically defined as the time from the beginning of direct runoff to the peak discharge value of a unit runoff hydrograph. Conversion between the two is required as most hydrologic models use T_p but hydrologic engineers often first consider T_c because this timing characteristic is thought to be easier to conceptualize.

For this study, 92 watersheds with USGS streamflow-gaging stations were selected for estimation. The necessary rainfall and runoff data (Asquith and others, 2004) for investigation are available for these watersheds. Locations of the 92 stations are shown on Figure 1. Ancillary station information is listed in Table 1 (at the end of the report). For the 92 watersheds considered for the study, drainage areas are between approximately 0.25 to 150 square miles, main channel lengths are between approximately 1 to 50 miles, and dimensionless main channel slopes are range approximately from 0.002 to 0.02.

This report is a companion report presenting an independent estimation of T_c and T_p for comparison to the several other methods examined in this research project and reported in Roussel and others (2005). This report was prepared separately because the estimation technique, while conceptually related to the techniques in Roussel and others (2005), directly estimates the timing parameters from digital elevation maps without explicit consideration of watershed physical characteristics such as channel length, slope. The physical characteristics are implicitly considered in a kinematic computation used to simulate the motion of water particles (parcels) over the watershed. The method in this report also assumes a particular hydrograph distribution model and two values for flow resistance and flow depth that are specified ad-hoc. As such, the work in this report was not considered to be sufficiently refined enough for generalization. Despite these limitiations the work constitutes an independent consideration of timing parameters consistent with the general research objectives of the project and consistent in a fashion with the timing parameters reported in Rousseau and others (2005).

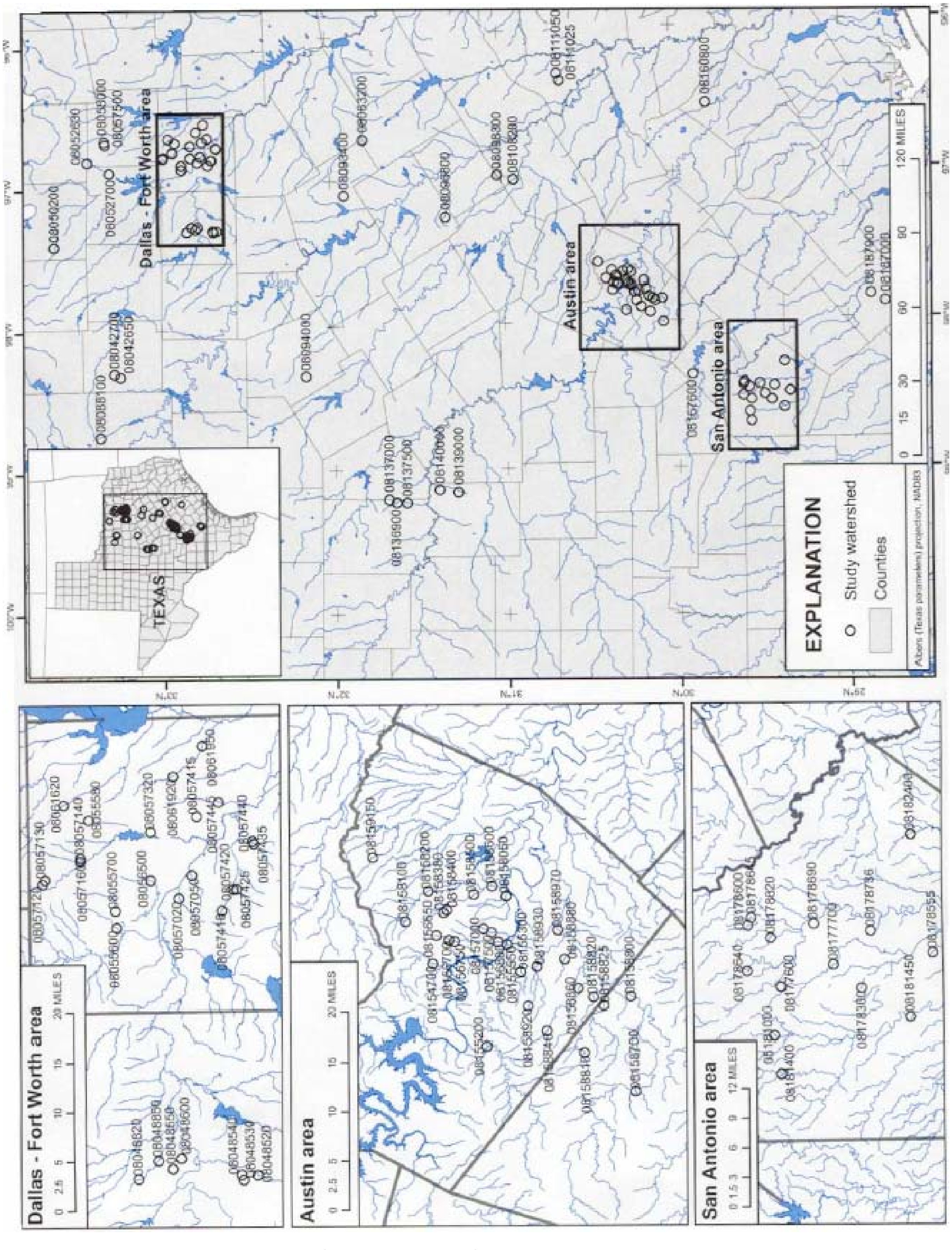

Figure 1. Locations of USGS streamflow-gaging stations used in the study.

(Map courtesy of F. T. Heitmuller, Geographer, U.S. Geological Survey, Texas Water Science Center, 8027 Exchange Dr. Austin, TX., used with permission)

Objectives

The objectives of this report are (1) to present direct estimates of T_p and T_c by a particle tracking method, (2) test the performance of the estimated time parameters by estimating direct runoff hydrographs for historical storm data, and (3) compare the timing parameters estimated by the particle tracking method and other methods reported in Roussel and others (2005).

The methods examined in 0-4696-2 for estimation timing parameters generally require one or more watershed physical characteristics such as main channel length, slope, etc. The method examined in this report requires the same topographic information used to determine these physical characteristics, but instead tracks conceptual rainfall particles over the watershed topography according to simplified kinematics equations and records the arrival times of these particles. The normalized arrival time distribution is a unit hydrograph.

Previous Studies

Results of an extensive literature review on T_c are presented in Fang and others (2004). References pertinent to the work here are presented in this section.

Clark (1945) presented a method for developing unit hydrographs for a watershed based on routing a time-area relationship through a linear reservoir. Conceptually water covering a watershed to some unit depth is released instantly and allowed to run off the watershed, and the time-area relationship represents the translation hydrograph as water makes its way to the outlet. The linear reservoir is added to reflect storage effects of the watershed. The principal challenge in the past was the computation of the time-area relationship.

Using digital elevation maps the determination of travel distance from a point on the watershed to the outlet is straightforward and the present challenge is to specify the travel speed along these paths, and consequently the travel time, and finally the use the ensemble of travel times to infer a unit hydrograph. Many time-area models have been encoded and examined using geographic information systems (GIS) because the GIS greatly simplifies the requisite grid arithmetic for the path length and time determination.

Of the available time-area models most use digital elevation models (DEM) where runoff routing is performed on a grid cell basis. Maidment (1993) is one example of this approach using the classical time-area method and GIS scripts. This work was considered limited by the use of overland routing based on a constant velocity or subjectively (i.e. NRCS land-use) predetermined velocity map. Muzik (1996) approached the time-area modeling in a similar fashion.

Saghafian and Julien (1995) derived a time-to-equilibrium approach for any location on a watershed based on a Manning's type overland flow model. Saghafian and others (2002) used this concept to develop a time-variable isochrone GIS technique to generate runoff hydrographs for non-uniform hyetographs (non-uniform in space and time). The technique in Saghafian and Julian is this report is closely related to the analysis presented here.

Kull and Feldman (1998) assumed that travel time for each cell in the watershed was simply proportional to the time of concentration scaled by the ratio of travel length of the cell over the maximum travel length. Thus the velocity from any point to the outlet is uniform and constant. Each cell's excess rainfall is lagged to the outlet based on the travel distance from the cell. Travel time in overland and channel flow are determined beforehand. This approach is essentially a version of Clark's (1945) methodology and is implemented in HEC-GEOHMS (HEC 2000).

Olivera and Maidment (1999) developed a raster-based, spatially distributed routing technique based on a first-passage-time response function (a gamma-type unit hydrograph at the cell scale) which is conceptually similar to the work reported here, except that we route the particles first according to specific kinematics, then construct the response function.

Common to all these methods is the use of spatially distributed topology, but they all require some independent evaluation of overland versus channel flow to route from cell to cell. For example, HEC-HMS modelers will need to determine a time-of-concentration value; Olivera and Maidment (1999) work appears to need response function parameters in advance of analysis, Saghafian and others (2002) require regression equations to relate channel geometry to flow for the channel routing component of their analysis. Also common to these methods is the concept of accumulating flows cell-by-cell and determining the travel time from the outlet back to the contributing area.

In all these previous studies it is clear that the time-area relationship is incorporated either directly as a hydraulic relationship (constant velocity, CN-based velocity, kinematic-wave) or indirectly as a ratio of gird travel time to time of concentration. Thus it is concluded that specification of some meaningful grid kinematics based on hydraulic considerations can provide a technique to directly determine T_c and T_p.

THEORY

In this work a variation on these basic concepts was applied to produce a response function at the outlet with *S*-curve hydrograph properties. This empirical *S*-curve hydrograph is a residence time distribution of rainfall on the watershed and thus this distribution must contain information equivalent to the time-area histogram. A particle-tracking code originally developed by Cleveland (1991) and subsequently used in numerical dye-tracing of the confluence of two streams in Houston, Texas (Wang and others, 1991 and 1996) was modified to perform the grid arithmetic. This research code tracks the position of particles and records the exit time from the watershed of each particle and the cumulative exit times for all particles (the *S*-curve). This program is referred to as the Digital Terrain Runoff Model (DTRM) in the remainder of this report. Specification of how the particles move in response to their position on the watershed elevation grid determines the specific shape of the S-curve and ultimately the estimates for T_p and T_c.

Motion Equations

Figure 2 depicts the watershed that drains past USGS gaging station 08057320. This watershed is referred to as the Ash Creek watershed in this report. In the figure the solid curve represents the path that a raindrop would follow from the northeast part of the watershed to the outlet located in the southwest corner of the watershed. This curve is called the pathline in this report.

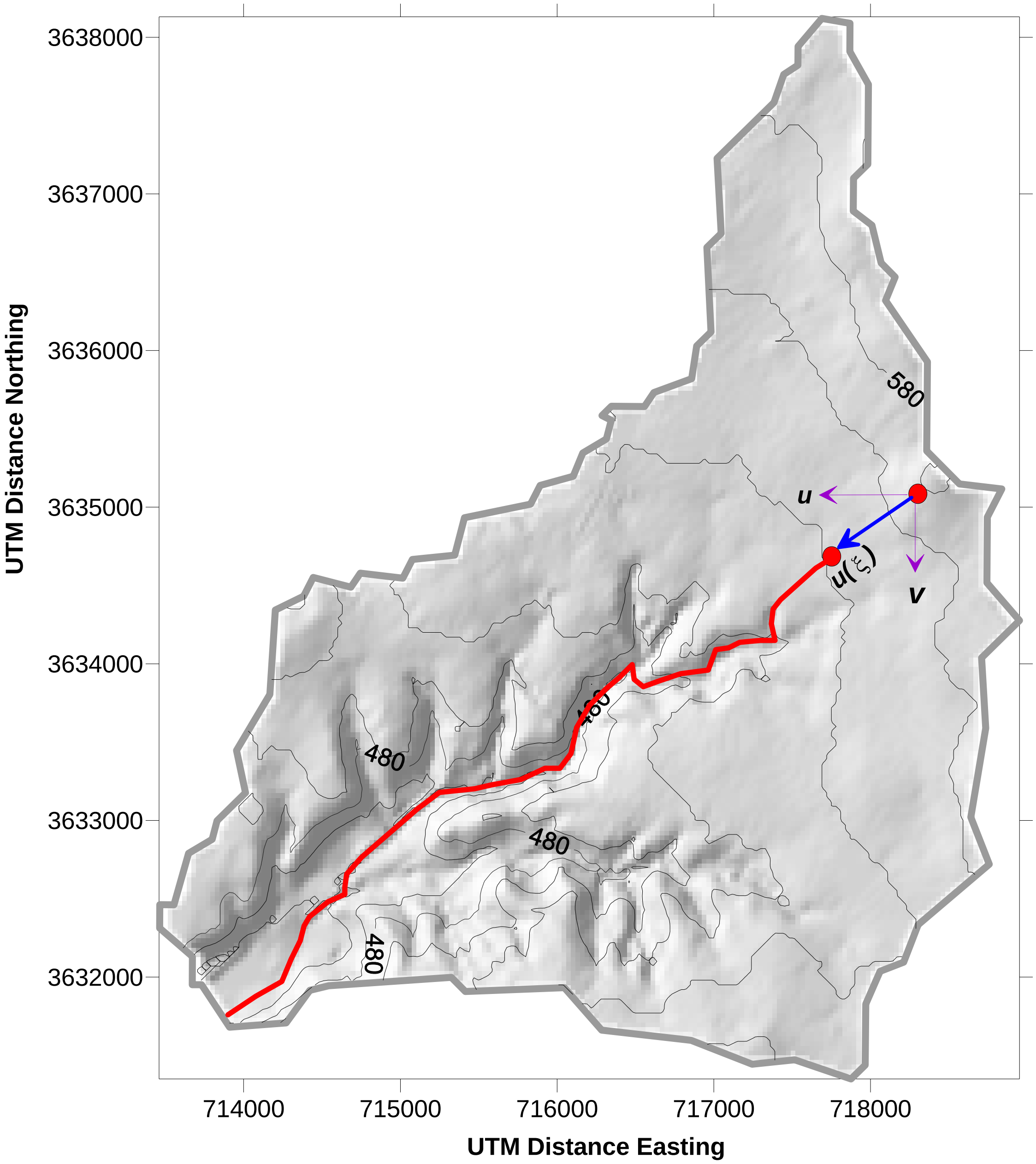

Figure 2. Shaded relief map of watershed associated with USGS gaging station 08057320. A particle pathline, pathline and Cartesian velocities are depicted for a single runoff particle.

Any point in the watershed can be represented by its Cartesian coordinates, x and y. A particle at any point in the watershed will lie on its pathline (determined by the particle's initial position relative to the outlet). The particle at any position will have an x-component and y-component of velocity, and these two components can be resolved into a pathline component of velocity. The relationship between the pathline system and the Cartesian system is depicted in Figure 2 as the two velocity vector systems on the Eastern side of the figure, near the peak of a hill.

In the analysis reported in this report, both coordinate systems were used. The pathline system was used to determine pathline velocities then these were converted into Cartesian velocities for the displacement steps. The reason for this seemingly duplicate effort was in anticipation of incorporating more complex kinematics in the future.

Over a short time interval, the particle will move according to ordinary mechanics a distance determined by the product of the appropriate component velocities and the time interval. In the Cartesian coordinates, the set of trajectory equations for a particle is

$$\begin{aligned} x_p(t+\Delta t) &= x_p(t) + u_p(x_p(t), y_p(t), t)\Delta t \\ y_p(t+\Delta t) &= y_p(t) + v_p(x_p(t), y_p(t), t)\Delta t \end{aligned} \tag{1}$$

In equation 1, *x* and y are spatial locations, *u* and *v* are *x*-, and *y*- components of velocity at a location, *t* is time, and the subscript *p* is a particle index (i.e. the *p*-th particle). The equation, as written, represents a first-order Euler model to integrate the displacement rates of the particles. The equations require specification of the velocity of a particle at any location. In addition to these requirements, the specification of direction is critical. Either a Cartesian system (as above) or a path-line system can be used.

The principle advantage of a path-line system (if the pathlines are straightforward to compute), is that the kinematic equations reduce into a single spatial dimension (distance along the path). In the case of the constant, linear, and quadratic flux law models a pathline system is feasible and convenient.

There are three conventional simplified-physics approaches to velocity specification. The first is to assume velocity is a constant, and assign velocity independent of topographic relief (slope). Travel time is proportional to the path-line distance from the particle's initial placement to the outlet. This approach appears to be the method used by Kull and Feldman (1998), although they do acknowledge more complicated methods involving estimating overland and channel flow times. In the constant velocity approach a very flat watershed and a very steep watershed would have identical particle travel speeds.

The second approach is to assume velocity is proportional to watershed slope, and compute the velocity field based on the particle positions. Operationally one would compute velocities for each grid cell, and assign these velocities to particles residing in the cell until they exit that cell and enter another. This assumption is a potential flow approach where the watershed elevation is the flow potential. Equation 2 represents the formula in a path line coordinate system used to determine the velocity at any location in the watershed. In practice we only have elevations at discrete grid points so a difference equation is used to determine the local watershed slopes.

$$u(\xi) = k * \left.\frac{dz}{d\xi}\right|_{(\xi)} \tag{2}$$

The value of k represents the velocity of the particle on a unit slope. These unit velocities could be estimated from classical overland flow equations or tabulations in use in current hydrology methods (e.g. NRCS, Fig 15.2). This motion equation is similar to time-area methods of Laurenson (1964), and Muzik (1996).

The third approach is to assume the square of velocity is proportional to watershed slope, and compute the velocity field dependent on the particle positions. This assumption is essentially a potential flow approach where the watershed elevation is the square-root of flow potential. Equation 3 represents the formula in a path line coordinate system used to determine the velocity at any location in the watershed.

$$u(\xi) \cdot |u(\xi)| = k^2 * \left.\frac{dz}{d\xi}\right|_{(\xi)} \tag{3}$$

The value of k^2 represents the square of velocity of the particle on a unit slope. The absolute value formulation is used so that the numerical method preserves correct directional information (flow is always downslope). This approach is similar to existing NRCS methods, but makes no distinction between channel and overland flow. All the results in this chapter are based on this kinematic model, and the procedure here could be interpreted as a modified NRCS-velocity method.

In the present work we have adopted the following structure for k

$$k^2 = \left(\frac{1.5}{n} d^{\frac{2}{3}}\right)^2 \tag{4}$$

where n is a frictional term (an adjustable parameter) that is conceptually analogous but not numerically equal to Manning's n, d is a mean flow depth (an adjustable parameter).

Thus the combination of equations 3 and 4 is

$$u(\xi) = \frac{1.5}{n} d^{\frac{2}{3}} \left(\left.\frac{dz}{d\xi}\right|_{(\xi)}\right)^{\frac{1}{2}} \tag{5}$$

Equation 5 is intended to look like a Manning's equation (the last term is the local slope of the watershed at the particle location). These kinematics are identical to Wooding (1965) kinematic wave analysis for overland flow and similar to the isochrone derivation technique of Sagafian and Julien (1995) who adapted the kinematic wave theory for distributed rainfall-runoff modeling, and presented an example (Saghafian and others, 2002) for a single watershed in West Africa.

Direction and Slope in DTRM

Unit runoff in the model moves downhill according to the Manning's-like formula (Equation 5). Downhill direction in the model coordinates is determined by the relationship of the index (current cell) and the 8-cells surrounding it (O' Calligan and Mark, 1984). Figure 3 is a diagram of an index cell and its surrounding cells.

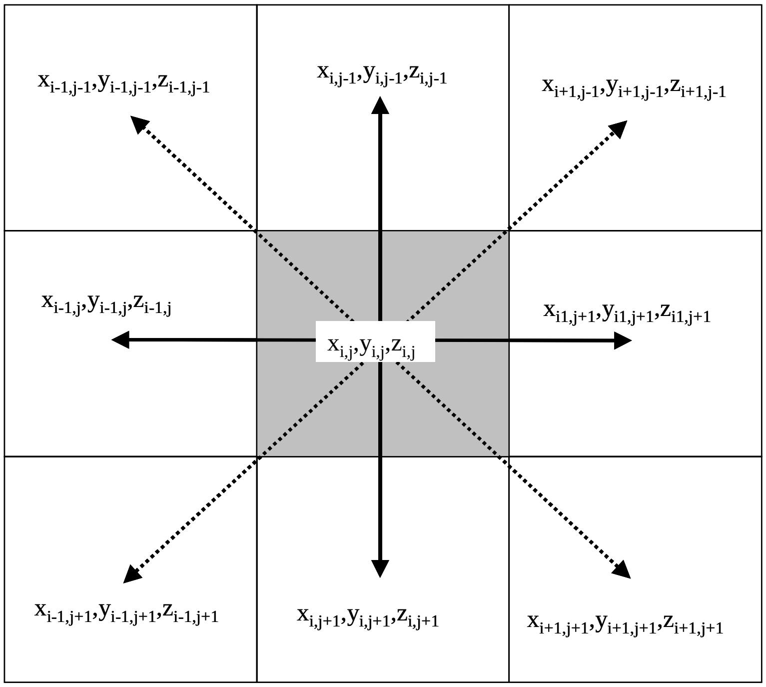

Figure 3. 8-cell pour-point model used to determine downhill direction and slopes for particle kinematics.

Downhill is determined in the following fashion: The elevation differences between the index cell and the 8 surrounding cells are computed (z-values in figure 3). This computation produces 8 different elevation differences. Of the 8 differences the largest positive value is chosen as the downhill direction (negative differences are uphill relative to the index cell). This direction is stored in a direction map array. It represents the direction a water parcel will move if it resides anywhere in the index cell. Furthermore this direction map also defines the pathline system for the index cell. If there is no downhill direction the cell is labeled as a sink and treated separately below. The slope is computed using the selected difference value (from the direction finding step), and dividing by the travel distance from cell-to-cell. Once the speed is known, the time to travel from cell-to-cell can be determined from the ratio of cell-to-cell distance along the travel path and the speed just calculated, or the particle can simply be allowed to move downhill for a specified time interval.

For example in Figure 2, the marker where the velocity vectors originate is located approximately at elevation 577 feet in the digital map array. The eight cells surrounding the marker starting directly North and moving clockwise are at elevations 580, 581, 581, 579, 578, 576, 577, and 579 feet. Only 576 feet is lower in elevation than the reference cell of 577 feet so the direction that the particle could move is to the South-West. The difference in elevation between the two cells is 1 foot of elevation. The distance from the two cell centers is $\sqrt{2} \times 30$ meters = 138 feet. Thus the dimensionless slope in the cell is computed to be 1/138 = 0.007. The travel speed of the particle in this cell is $u(\xi) = (1.5/n)d^{0.67}(0.007)^{0.5}$. The numerical values of *n* and *d* were determined by trial-and-error for a single storm. Details of this specification are discussed later in the report.

Pits and Channel Flow

Sinks (pits) in the elevation grid are treated separately. In the data for station 08057320, Ash Creek at Highland Road, Dallas, Texas it was observed that the sinks occurred at or near locations where there was an obvious channel in the relief map, so it was subsequently assumed that sinks (in this model) represent locations where channel flow begins. Rather than smooth the watershed elevation map as was done by many other researchers, it was decided to force the particle to move from the sink towards the outlet using the following kinematics. The flow direction is directly from a sink to the single watershed outlet. For example, Figure 4 is a rendering of the Ash Creek watershed looking from the West. The location of a sink is depicted on the figure, there are other sinks, but the one in the figure is most apparent. The flow path is the Euclidian path from the sink to the outlet. This path is indicated by the dashed line on Figure 4. Slope is determined from the elevation difference between the sink and the outlet and this straight-line flow distance. Speed and time of travel are then computed as above.

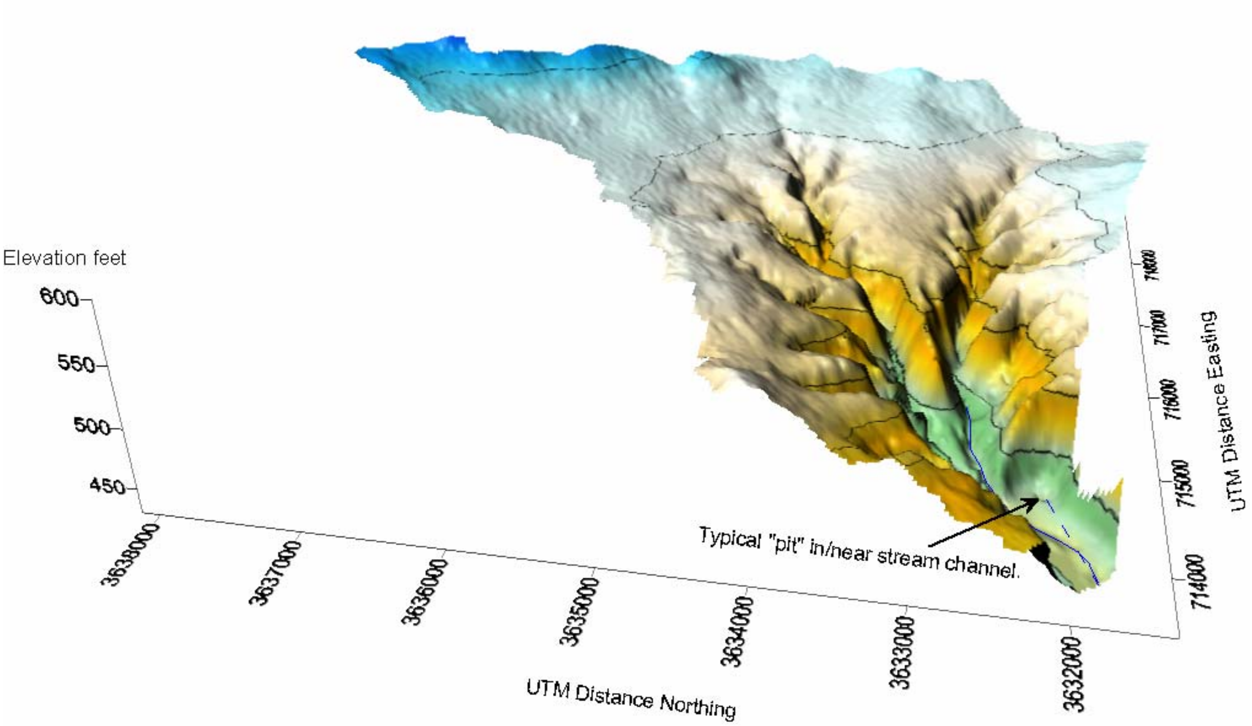

Figure 4. Surface rendering of watershed associated with USGS gaging station 08057320 showing a sink and the assumed flow path from sink to the outlet.

This ad-hoc treatment of pits is a significant departure from previous studies, but replaces the need to carefully identify channel paths, and eliminates a smoothing step thus preserving the elevation array intact.

Watershed representation.

All time-area methods require some kind of information about the spatial distribution of watershed elevation. This information can be obtained manually from USGS topographical maps, by engineering survey, or from USGS digital elevation models (DEM). Regardless of the original source, the representation will eventually be a grid whose horizontal and vertical elements will represent locations on the surface of the Earth, and whose entries will represent elevation above some datum. The results reported here are based on USGS 30-meter DEM maps downloaded from the Internet. Details of the procedure are available in Fang and others (2005).

Once the DEM is constructed, the file is converted into a format for the particle-tracking model. Essentially this step adds the location of the outlet to the file, some simulation control instructions, and the values of *n* and *d*. One file for each watershed was prepared in this manner. In addition the Ash Creek watershed was constructed entirely manually (using elevations read from paper maps) at a lower resolution to demonstrate the generality of the procedure.

Particle position maps

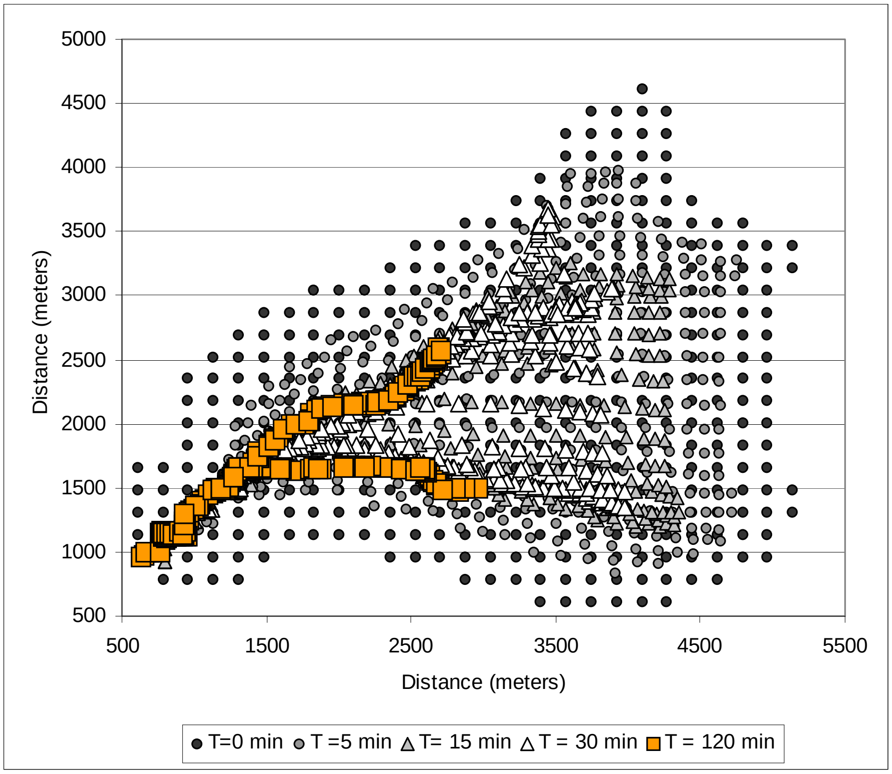

Figure 5 Particle positions at various times; Ash Creek watershed.

The computation of the trajectory of each individual particle produces a "cloud" of particles distributed on the watershed at any simulation time. These particle maps have some value in determining how the particles traverse the watershed and when channel-like flow begins (i.e. all particles confined to narrow curvilinear features). Figure 5 is an example of the particle maps for the Ash Creek watershed using manually entered elevations. In the figure the positions of particles still in the watershed are plotted at different times. In Figure 5 one can see the general outline of the watershed is illustrated at time zero. As time evolves the particle "cloud" moves downslope toward the outlet. At about 30 simulated minutes (white triangles) the channel structure is apparent. It is noted that the elevation array in Figure 5 was manually prepared from paper-based maps and is at a much different resolution (~190 meters) than in Figures 2 and 4. It is also noted that Figure 5 is distorted with respect to vertical and horizontal distances.

Particle map images (Figure 5) are illustrative of what is going on in the calculations, but are not particularly useful for unit hydrograph analysis. Instead the cumulative arrival time distribution of particles at the outlet is more important.

Generating the *S*-Curve Hydrograph

Figure 6 is a plot of the normalized arrival time distribution for the simulation in Figure 5 and represents the *S*-curve hydrograph for the watershed. Counting particles as they exit the computational domain and recording their exit time thus generates a cumulative arrival time distribution. The *S*-curve outlet hydrograph is derived from this arrival time distribution.

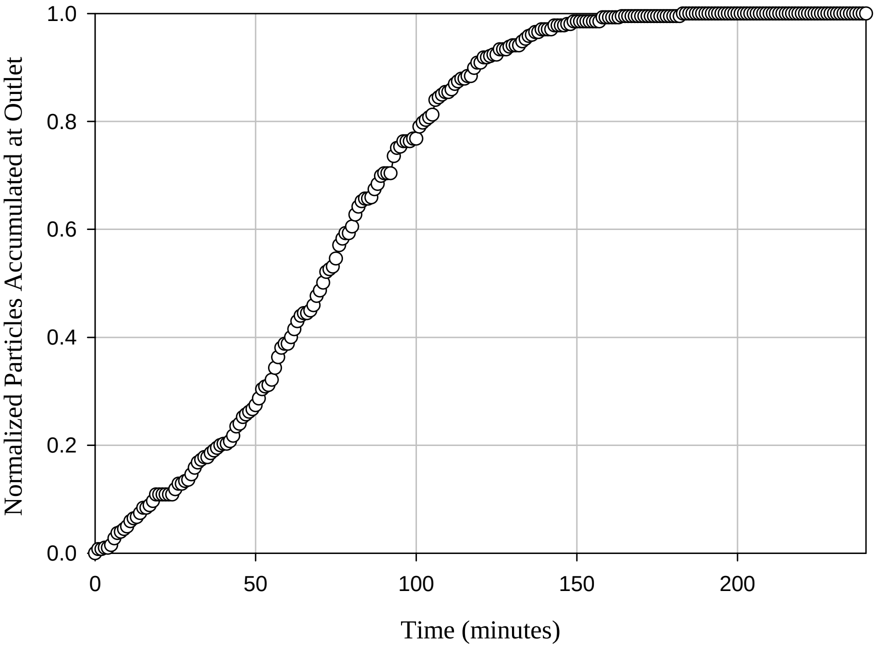

Figure 6. Empirical S-curve hydrograph.

The cumulative arrival time distribution is normalized by dividing the arrival time distribution (number of particles arrived at a given time) by the total number of particles placed on the watershed. This normalized distribution (Figure 6) is used in the next step to fit an equivalent curvilinear unit hydrograph model and from that model extract the timing values.

Generating the Curvilinear Model

The output from the DTRM program is a time series that represents the empirical cumulative hydrograph. This cumulative hydrograph is shown on Figure 7 as the open circles. It is monotonically increasing towards its asymptotic value of unity as expected with a cumulative hydrograph. A curvilinear function is fit to the cumulative hydrograph so that we can use the curvilinear model for simulation of the direct runoff hydrograph. The curvilinear model used is the Rayleigh model developed and tested by Cleveland, and others (2003) and He (2004). The formula that is fit to the empirical data is

$$q(t) = 2z_0\left(\frac{t^{2N-1}}{\bar{t}^{2N-1}}\right)\exp(-\left(\frac{t}{\bar{t}}\right)^2); \quad Q(t) = \int_0^t q(\tau)d\tau \tag{6}$$

In equation(s) 6, discharge is L/T units, thus to convert to conventional units multiplication by the watershed area is required. As all the data were converted into L/T units before analysis the results are left in the L/T units. The value of z_0 in the equation is 1 depth unit (in this case one inch).

The solid *S*-curve is the cumulative distribution function based on the unit hydrograph function (Equation 3.1 above). It is “fit” to the empirical cumulative distribution function generated by the particle-tracking model using a least square error criterion and a reduced gradient method to minimize the error.

Once the distribution parameters are recovered ($\bar{t}$ and N) these are then converted into conventional hydrograph parameters using Equations 7 and 8.

$$T_p^2 = \frac{(2N-1)}{2}\bar{t}^2 \tag{7}$$

$$Q_p = \frac{(2N-1)^N}{2^{N-1}\Gamma(N)}\frac{1}{t_p}\exp(-\frac{(2N-1)}{2}) \tag{8}$$

The time of concentration, T_c, was obtained by computing the time at which the cumulative distribution function reaches a value of 0.98, as in Equation 9.

$$0.98 = \int_0^{T_{98}} 2z_0\left(\frac{\tau^{2N-1}}{\bar{t}^{2N-1}}\right)\exp(-\left(\frac{\tau}{\bar{t}}\right)^2)d\tau \tag{9}$$

The rationale for selecting the time of concentration as the time to accumulate 98 percent of the hydrograph is strictly ad hoc, and no rigorous selection method was applied. Values as low as 85 percent might make sense, higher than 98 percent resulted in unrealistically long times (the hydrograph asymptotically approaches zero, so large times to accumulate close to 100 percent are not surprising). The T_{98} values were reasonable multiples of T_p; although the ratio is quite different than the ratio using an NRCS unit hydrograph.

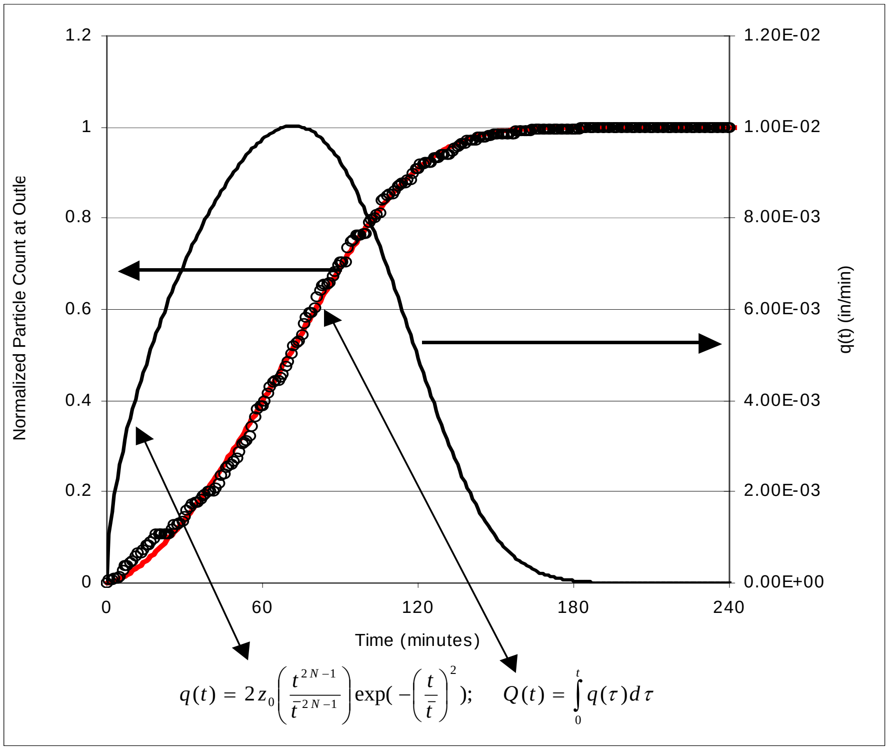

Figure 7. Fitting curvilinear hydrograph model to empirical S-curve.

RESULTS

The DTRM was applied to the entire set of watersheds using 30-meter digital elevation data. The values used in equation 5 for generating the cumulative hydrographs are *n=0.04* and *d=0.2* specified beforehand. These values were determined by trial-and-error using the Ash Creek watershed and the June 3, 1973 storm to "calibrate" the particle-tracking model. Then these values were applied to all watersheds regardless of size and location.

The DTRM procedure failed to produce results on 8 watersheds. No further investigation was made on these 8 watersheds.

Table 2 is a list of the estimated watershed parameter values for each watershed successfully analyzed. The list is a composite of manual and automated results in an effort to extend the number of successful analysis.

Performance Evaluation

The DTRM is a method to synthesize unit hydrographs from topographic data. Passing the historical rainfall hyetographs through the unit hydrograph parameterized by the DTRM values and comparing the model hydrograph with the historical hydrograph tested the performance of the method.

For each watershed DRTM was run once and a single Rayleigh hydrograph, with two parameters, a residence time, and a reservoir number, are generated (i.e. two values for each watershed). These results are already listed in Table 2. These two values are determined entirely from topographic data and the assumed friction coefficient.

The rainfall loss model is an initial abstraction constant proportion model whose coefficients were taken as the average value for each station from the storm-optimum values determined by the authors in TxDOT Research Project 0-4193.

Figure 8 is a representative example of output from this testing. The observed hydrograph is the dashed line with the step-wise changes in value, while the smooth curve is the model result using the same hyetograph (input rainfall).

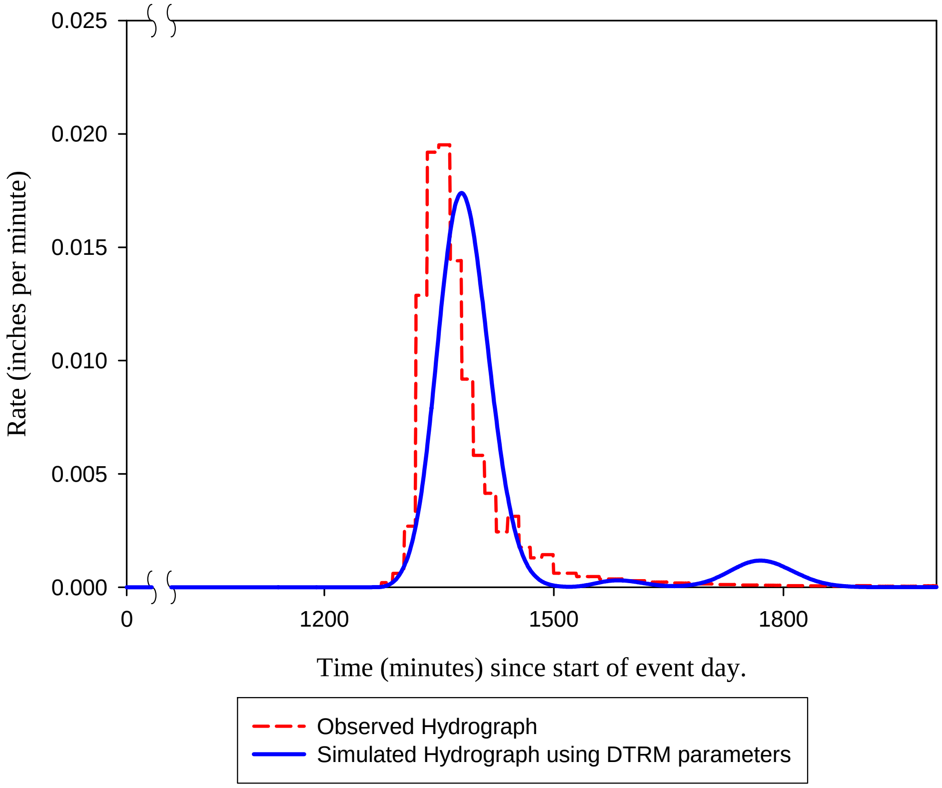

Figure 8. Model (based on DTRM parameters) and observed hydrographs for Ash Creek for May 27, 1975 storm.

The plot in Figure 8 is typical, but not all storms were reproduced equally well, especially on the larger watersheds. Despite this current limitation, the analysis suggests that the topographic information alone is sufficient to produce qualitatively acceptable hydrographs.

Additional qualitative results are obtained by plotting the peak discharges obtained from the model and the observed values. Figure 9 is a plot of the observed hydrograph peak discharge (converted to cubic feet per second) on the horizontal axis, with the corresponding model value on the vertical axis. Qualitatively this plot is encouraging as the cloud of markers is close to the

1:1 line that would indicate ideal performance. While encouraging it is noted that the variability is high (roughly 1000% variability for any particular storm).

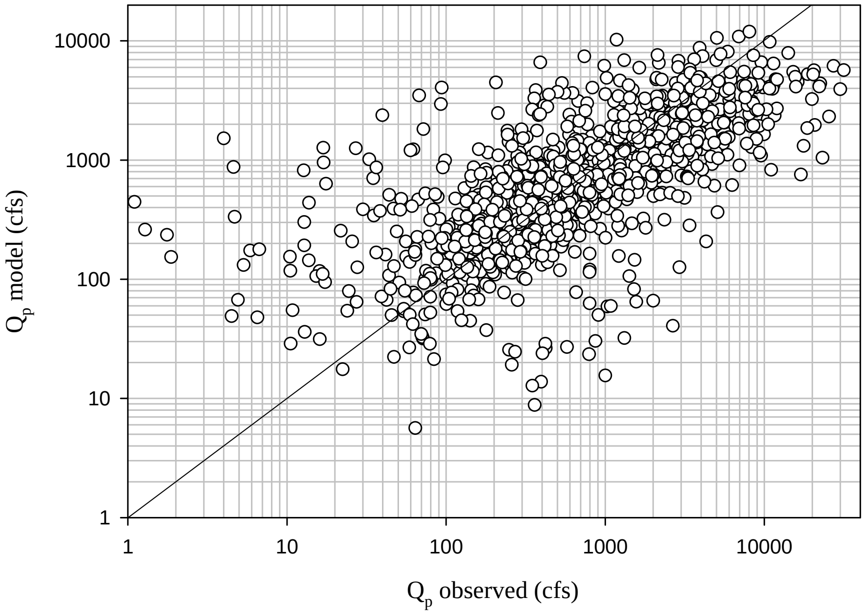

Figure 9. Model peak discharge versus observed peak discharge for 1300 storms.

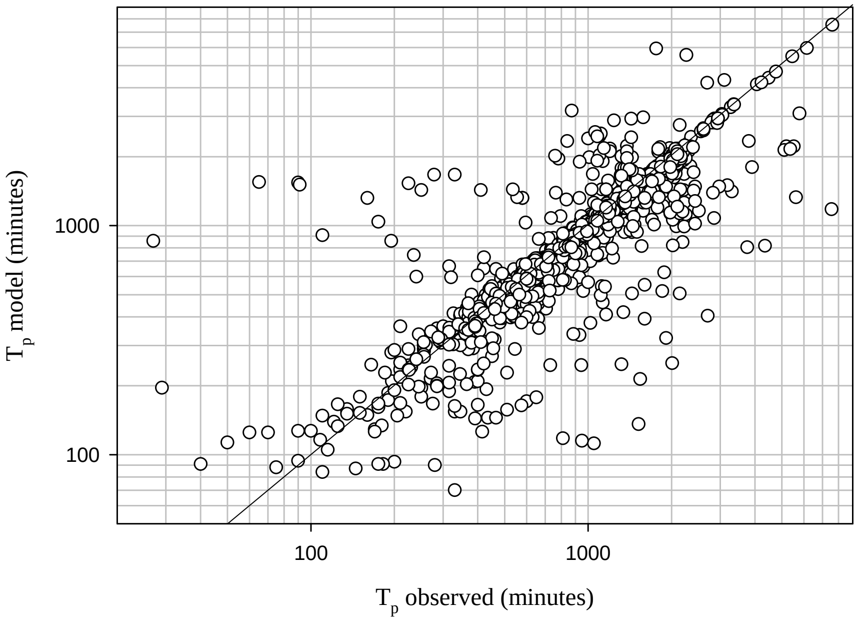

Figure 10. Time of model peak discharge versus observed time of peak discharge for 1300 storms.

Figure 10 is a similar plot of the observed hydrograph time of peak discharge on the horizontal axis, with the corresponding model value on the vertical axis. This plot is also encouraging as the cloud of markers is close to the 1:1 line, with many markers actually on the line.

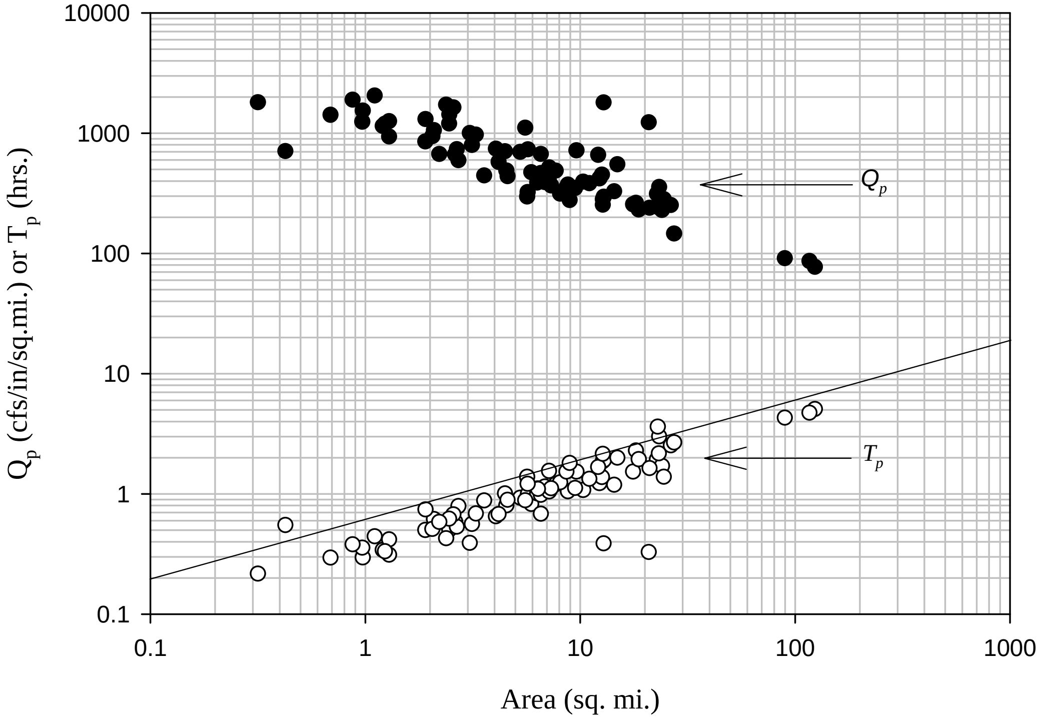

Figure 11. Q_p and T_p versus watershed area. Q_p and T_p in this figure are determined from a single set of Rayleigh parameters fitted to each watershed's DTRM *S*-Curve.

Figure 11 is a plot of the hydrograph parameters expressed in Q_p, T_p form plotted as a function of watershed area. There are 84 watersheds that were analyzed using the DTRM procedure. The marker cloud for Q_p versus watershed area is strongly correlated to area with the exception of 5 watersheds. Similarly the marker cloud for T_p versus watershed area is also correlated to the watershed area. The line shown on Figure 11 is the plot of $Y = 0.6\sqrt{Area(sq.mi.)}$. This line illustrates that the marker cloud for T_p is closely approximated by this empirical rule-of-thumb for these Texas watersheds. Q_p, and T_p are interdependent thus the mirror imaging of the two plots about the horizontal is not coincidental, but expected.

These results qualitatively demonstrate that a terrain-based runoff model can produce acceptable direct runoff hydrographs with minimal calibration using only elevation data to generate a unit hydrograph. Combined with a proportional rainfall loss model the approach can simulate episodic behavior at about the same order of magnitude in terms of peak discharge and temporal bias.

Comparison to Other Methods

The principal purpose of this research component was to compare results to the other methods. The other methods are essentially independent from DTRM, sharing only the same underlying digital elevation data, watershed boundary, and outlet location.

Figure 12 is a plot of T_c computed by selected methods in Roussel and others (2005) versus watershed area. The T_{98} values (the DTRM surrogate for T_c) are plotted as shaded hexagons. These values plot with the same general trend as the other formulas and within a factor of two for the other methods. The data used to generate Figure 12 are tabulated in Table 3. The error bars on Figure 12 represent +/- two standard deviations about a mean value for T_c for all the methods plotted except for the DTRM (i.e. DTRM results are not used to compute a mean or variance for this plot). The DTRM results all plot within the error bars for the other methods indicating that the DTRM results are within +/- two standard deviations of an average value computed by the other methods. The dashed line on Figure 14 is an ordinary least squares log-linear regression through the DTRM results. This line also falls within the error bars for the other methods further reinforcing that the DTRM results are comparable.

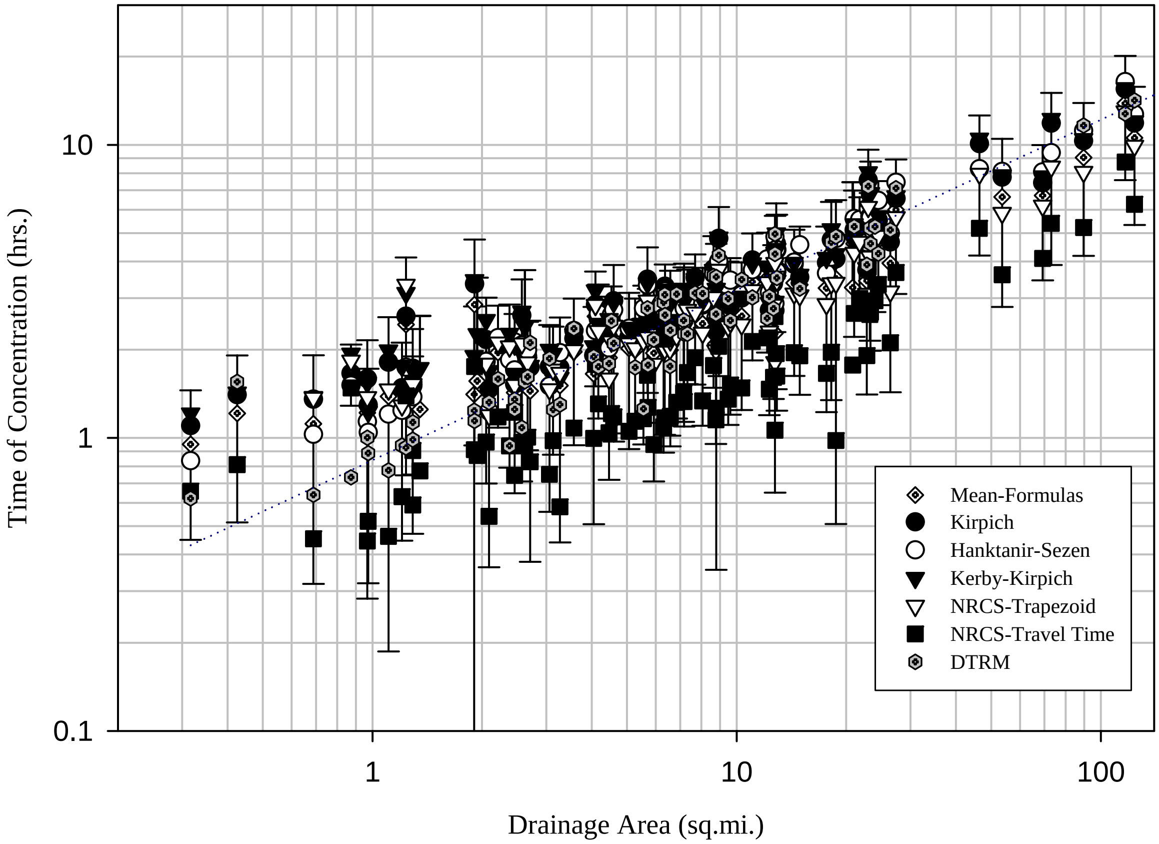

Figure 12. T_c versus watershed area for various methods.

CONCLUSIONS

The terrain-based runoff model in this report can generate qualitatively acceptable direct runoff hydrographs from minimal physical detail of the watershed. In this report, only elevation data and assumptions about travel velocities are required to predict watershed response. The requisite elevation data are freely available on the Internet, or can be hand-prepared from paper-based maps.

No attempt was made to optimize the friction terms in the DTRM model to account for different land-uses, etc., yet combined with an appropriate rainfall loss model the approach has simulated episodic behavior at about the same order of magnitude as observed behavior in terms of peak discharge and temporal bias. Thus, for the small watersheds studied in this research, topography is a significant factor controlling runoff behavior (more so than land-use and other descriptive considerations) and consequently the timing parameters common in all hydrologic models.

The DTRM is related to existing NRCS methods, and could be considered to be a modified NRCS velocity approach where the analysis is completely automated and the kinematics are performed within the model without analyst interaction. The method ignored distinctions between channel flow and overland flow yet produced estimates within +/- two standard deviations of other methods. The similarity of the results to the other methods in this report both increases confidence in the other methods, and indicates that the other methods, while overtly empirical, incorporate similar simplified-physics as does DTRM.

T_{98} is demonstrated to be reasonable surrogate for T_c when compared to T_c computed using the same topographic data using other methodologies.

The terrain-based procedure described here requires considerable effort to construct the input data files from the elevation data and some judgment to guess values at the friction term and flow depths. As such it is currently a research tool and should not be considered for routine analysis, although the calculations are automated.

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

[Latitude in DD()MM’SS” North; Longitude in DD()MM”SS” West; TDA, Total drainage area in square miles; BP, Basin perimeter in miles; MCL, main channel length in miles; BR; basin relief in feet; MCS, main channel slope in feet per mile; MCS2, alternate main channel slope in feet per mile; TDA, BP,MCL,BR,MCS are determined as in Brown and others (2000); MCS2 is determined as in Asquith and Slade (1997)]

Station no.	Latitude	Longitude	TDA	BP	MCL	BR	MCS	MCS2
08155200	30()17'46"	97()55'31"	89.6	67.7	28.5	752.2	19.1	25.6
08155300	30()14'40"	97()48'07"	116.6	91.2	45.1	983.0	15.3	21.3
08158810	30()09'19"	97()56'23"	12.3	19.7	6.3	374.1	49.1	58.5
08158820	30()08'25"	97()50'50"	24.5	37.1	14.8	590.6	28.5	39.4
08158825	30()07'31"	97()51'43"	21.0	29.1	12.5	443.6	27.4	35.1
08158050	30()15'47"	97()40'20"	12.6	20.8	7.4	309.8	39.3	41.8
08158880	30()10'50"	97()46'55"	3.6	12.5	4.4	265.7	43.2	59.5
08154700	30()22'19"	97()47'04"	22.8	31.6	10.0	568.3	36.3	56.5
08158380	30()21'15"	97()41'52"	5.3	13.0	4.0	155.8	32.2	36.9
08158700	30()04'59"	97()00'29"	123.7	78.8	33.3	794.6	16.3	23.8
08158800	30()05'09"	97()50'52"	167.3	106.1	48.9	1013.7	13.9	20.7
08156650	30()21'55"	97()44'11"	2.7	10.2	3.0	183.2	48.0	60.7
08156700	30()20'50"	97()44'41"	6.3	15.2	4.5	242.0	34.0	48.8
08156750	30()20'21"	97()44'50"	6.8	16.6	5.1	257.9	30.2	46.2
08156800	30()16'35"	97()45'00"	12.7	29.3	10.6	438.7	30.5	39.5
08158840	30()12'32"	97()54'11"	8.8	17.9	5.0	313.8	48.7	62.9
08158860	30()09'43"	97()49'55"	23.2	34.2	12.8	534.2	32.0	41.6
08157000	30()17'49"	97()43'36"	2.2	10.1	4.1	212.6	47.2	51.7
08157500	30()17'08"	97()44'01"	4.2	14.8	5.2	256.9	45.6	49.8
08158100	30()24'35"	97()42'41"	12.7	23.9	5.7	292.9	47.1	48.2
08158200	30()22'30"	97()39'37"	26.4	32.9	10.9	401.7	30.1	35.0
08158400	30()20'57"	97()41'34"	5.7	14.2	4.5	167.1	32.2	35.5
08158500	30()18'34"	97()40'04"	12.1	22.2	8.6	315.1	33.8	35.7
08158600	30()16'59"	97()39'17"	53.6	53.7	19.5	528.9	20.5	26.1
08155550	30()15'49"	97()45'17"	2.7	10.2	3.7	243.2	69.9	66.4
08159150	30()27'16"	97()36'02"	4.5	12.1	3.7	169.9	42.4	43.1
08158920	30()14'06"	97()51'36"	6.3	14.8	5.0	315.4	51.3	61.9
08158930	30()13'16"	97()47'36"	18.7	30.3	10.4	492.8	37.5	46.7
08158970	30()11'21"	97()43'56"	27.4	42.0	17.6	607.4	27.1	34.1
08057320	32()48'18"	96()43'04"	7.2	16.6	5.4	174.9	34.4	29.5
08055700	32()51'26"	96()50'12"	11.0	21.5	7.8	213.2	27.4	26.7
08057050	32()44'50"	96()47'44"	9.5	18.4	6.2	258.5	38.3	41.2
08057020	32()46'01"	96()50'07"	4.5	15.1	5.1	261.8	49.4	51.3
08057140	32()54'33"	96()45'54"	8.6	20.1	7.5	231.0	30.0	30.4
08061620	32()55'53"	96()39'55"	7.7	17.0	5.5	122.7	18.3	20.5
08057415	32()44'14"	96()41'36"	1.0	5.7	1.9	71.8	31.4	33.4
08057418	32()42'19"	96()51'32"	8.1	18.5	5.6	235.8	38.0	41.6

Station no.	Latitude	Longitude	TDA	BP	MCL	BR	MCS	MCS2
08057420	32()41'15"	96()49'22"	14.4	24.3	8.3	285.1	30.6	34.1
08057160	32()54'33"	96()45'34"	4.6	15.6	5.3	180.4	32.6	33.7
08055580	32()53'43"	96()41'36"	1.9	7.9	3.0	115.0	38.3	38.0
08055600	32()51'41"	96()52'27"	5.7	17.5	6.7	215.1	31.1	31.7
08057435	32()39'19"	96()44'41"	5.9	13.6	4.1	208.4	46.0	45.8
08057445	32()42'17"	96()40'11"	8.9	21.9	8.4	170.3	18.6	19.1
08057130	32()57'45"	96()47'44"	1.3	7.3	2.6	126.6	41.2	47.9
08061920	32()46'09"	96()37'18"	12.9	24.6	7.6	156.5	18.5	20.5
08061950	32()43'32"	96()34'12"	23.3	37.0	12.6	205.0	13.9	16.2
08057120	32()57'58"	96()48'11"	6.6	15.4	5.2	206.0	34.3	39.1
08056500	32()48'26"	96()48'08"	6.4	17.2	6.4	218.0	32.0	33.5
08057440	32()29'26"	96()44'25"	2.6	9.7	3.5	159.3	45.3	44.1
08057425	32()40'58"	96()49'22"	10.3	19.2	6.2	270.2	37.4	41.6
08048550	32()47'19"	97()18'22"	1.1	6.6	2.0	49.6	23.6	23.8
08048600	32()47'19"	97()18'22"	2.6	11.4	3.8	97.7	23.7	25.0
08048820	32()50'22"	97()19'22"	5.7	16.9	6.0	190.9	30.5	31.5
08048850	32()48'33"	97()17'28"	12.9	26.9	9.4	251.4	25.5	26.7
08048520	32()39'55"	97()19'16"	17.6	24.3	7.5	219.6	25.6	26.8
08048530	32()41'08"	97()19'44"	1.0	5.0	1.7	106.3	65.9	62.4
08048540	32()41'18"	97()19'11"	1.3	6.3	2.4	140.5	49.9	59.1
08178300	29()27'29"	98()32'59"	3.3	10.6	3.6	316.3	81.1	87.9
08181000	29()35'14"	98()37'40"	5.5	14.5	5.4	463.2	52.3	82.8
08181400	29()34'42"	98()41'29"	14.9	31.2	9.8	691.4	48.1	64.1
08181450	29()23'12"	98()36'00"	1.2	8.1	3.1	53.1	16.6	16.9
08177600	29()34'35"	98()32'45"	0.3	3.6	1.3	101.5	69.7	75.9
08177700	29()29'56"	98()30'36"	20.8	30.7	11.0	410.3	25.4	34.8
08178555	29()21'05"	98()29'32"	1.9	10.4	4.1	51.9	13.3	12.8
08178600	29()37'31"	98()31'06"	9.6	21.4	7.1	489.5	43.2	66.2
08178620	29()35'24"	98()27'47"	4.1	11.3	3.6	227.9	51.9	63.2
08178640	29()37'23"	98()26'29"	2.5	9.3	3.0	328.2	80.6	103.5
08178645	29()37'04"	98()25'41"	2.5	10.6	4.0	340.2	58.4	85.9
08178690	29()31'36"	98()26'25"	0.4	4.3	1.2	46.1	18.7	21.3
08178736	29()26'37"	98()27'13"	0.7	5.2	1.7	82.5	46.3	49.7
08096800	31()19'59"	97()16'02"	5.1	14.1	4.5	265.2	52.5	59.0
08094000	32()10'00"	98()20'30"	2.4	9.9	3.4	158.7	45.8	46.0
08098300	31()01'35"	96()59'17"	23.0	40.8	13.7	191.6	10.3	13.9
08108200	30()55'52"	97()01'13"	46.4	60.7	20.0	274.1	11.0	13.3
08139000	31()17'25"	99()08'13"	3.1	11.0	3.4	269.3	83.6	80.1
08140000	31()24'09"	99()08'13"	7.3	18.8	5.9	319.7	31.4	48.9
08136900	31()39'01"	99()13'30"	21.7	37.5	12.4	502.7	22.4	40.4
08137000	31()41'40"	99()12'18"	4.1	13.8	4.4	121.7	18.3	25.0
08137500	31()35'24"	99()13'36"	69.2	61.0	19.4	568.5	15.7	29.3
08182400	29()22'49"	98()17'33"	7.2	17.0	4.9	146.5	33.4	30.2
08187000	28()46'41"	97()53'41"	3.1	9.9	2.8	143.9	48.1	51.4
08187900	28()53'39"	97()53'41"	8.8	16.5	4.9	145.2	21.7	27.7

Station no.	Latitude	Longitude	TDA	BP	MCL	BR	MCS	MCS2
08050200	33()37'13"	97()24'15"	0.9	6.9	2.6	149.0	58.9	56.4
08057500	33()18'12"	96()41'22"	2.1	8.3	2.1	120.6	54.7	56.0
08058000	33()18'20"	96()40'12"	1.2	6.1	2.1	113.3	52.7	54.1
08052630	33()24'33"	96()48'41"	2.1	9.3	3.3	114.0	34.7	34.3
08052700	33()17'00"	96()53'33"	73.1	66.9	23.2	297.5	8.7	11.6
08042650	33()14'52"	98()19'19"	6.6	15.0	4.6	338.3	48.2	72.7
08042700	33()16'57"	98()17'53"	24.0	36.3	11.6	416.6	26.5	31.8
08063200	31()48'01"	96()43'02"	18.2	27.3	8.7	192.6	15.8	21.2

Table 2. Summary of Q_p,T_p, and T_c (T_{98}) values generated by DTRM procedure.

[$\overline{T}$, mean residence time(a hydrograph parameter); *N*, reservoir number (a hydrograph parameter); Qp, peak discharge factor (various units); Tp, time to peak; Tc, time of concentration; ^1T_c in this table is the T_{98} value.]

Station no.	Area - (sq.mi.)	$\overline{T}$ - (min)	*N*	Q_p - (in/min)	Q_p - $(\frac{\text{cfs - hr}}{\text{in - sq.mi.}})$	T_p - (hrs)	T_c^1 - (hrs)
08155200	89.70	365.3	1.00	0.00235	90.93	4.30	12.0
08155300	116.00	381.6	1.05	0.00223	86.51	4.74	12.8
08158810	12.2	76.8	1.42	0.01084	419.79	1.23	2.7
08158820	24.00	117.6	1.00	0.00729	282.36	1.39	3.9
08158825	21.00	138.6	1.00	0.00619	239.58	1.63	4.6
08158050	13.10	70.5	1.88	0.01166	451.39	1.38	2.5
08158880	3.58	74.8	1.00	0.01146	443.82	0.88	2.4
08154700	22.30	101.9	1.79	0.00808	312.78	1.93	3.9
08158380	5.22	45.6	2.00	0.01799	696.64	0.93	1.8
08158700	124.00	429.7	1.00	0.00200	77.29	5.07	14.2
08158800	166.00	--	--	--	--	--	--
08156650	2.79	54.7	1.25	0.01536	594.82	0.79	1.9
08156700	7.03	82.0	1.16	0.01031	399.19	1.11	2.8
08156750	7.56	83.6	1.18	0.01009	390.64	1.15	2.9
08156800	12.30	126.5	1.54	0.00656	253.82	2.15	4.7
08158840	8.24	89.0	1.00	0.00964	373.34	1.05	2.8
08158860	23.10	131.3	1.48	0.00633	245.00	2.17	4.7
08157000	2.31	49.5	1.00	0.01734	671.35	0.58	1.6
08157500	4.13	57.6	1.00	0.01489	576.38	0.68	1.9
08158100	12.60	114.6	1.45	0.00726	281.03	1.86	4.2
08158200	26.20	125.8	1.96	0.00652	252.58	2.53	5.0
08158400	5.57	43.1	2.41	0.01891	732.06	0.99	1.8
08158500	12.10	47.3	5.00	0.01702	658.85	1.67	2.6
08158600	51.30	--	--	--	--	--	--
08155550	3.12	45.2	1.00	0.01898	735.01	0.53	1.3
08159150	4.61	44.7	2.33	0.01826	707.18	1.01	1.8
08158920	6.30	85.7	1.00	0.01001	387.44	1.01	2.8
08158930	19.00	141.2	1.18	0.00598	231.36	1.94	4.8
08158970	27.60	227.1	1.00	0.00378	146.23	2.68	7.5
08057320	6.92	61.9	1.53	0.01341	519.13	1.05	2.3
08055700	10.00	84.1	1.40	0.00991	383.56	1.33	3.0
08057050	9.42	95.1	1.00	0.00902	349.24	1.12	3.1
08057020	4.75	67.9	1.00	0.01263	489.06	0.80	2.2
08057140	8.50	91.1	1.52	0.00911	352.56	1.53	3.0
08061620	8.05	65.6	1.71	0.01258	487.15	1.20	2.5
08057415	1.25	26.3	1.16	0.03215	1244.68	0.36	0.9
08057418	7.65	105.7	1.00	0.00811	314.10	1.25	3.5
8057420	5.55	115.5	1.00	0.00743	287.60	1.36	3.8

Station no.	Area - (sq.mi.)	$\overline{T}$ - (min)	N	Q_p - (in/min)	Q_p - $\left(\frac{\text{cfs - hr}}{\text{in - sq.mi.}}\right)$	T_p - (hrs)	$T_c{}^1$ - (hrs)
8057420S	13.20	101.0	1.00	0.00849	328.69	1.19	3.3
08057160	4.17	75.7	1.00	0.01134	438.98	0.89	2.2
08055580	1.94	38.6	1.11	0.02201	852.05	0.50	1.2
08055600	7.51	102.9	1.00	0.00833	322.66	1.21	2.6
08057435	5.91	70.1	1.00	0.01223	473.67	0.83	2.3
08057445	9.03	116.4	1.37	0.00717	277.64	1.81	3.5
08057130	1.22	35.4	1.00	0.02425	938.96	0.42	1.2
08061920	13.40	108.3	1.61	0.00764	295.84	1.90	3.4
08061950	23.00	87.5	4.75	0.00920	356.35	3.01	4.6
08057120	6.77	70.2	1.21	0.01200	464.77	0.98	2.2
08056500	7.98	83.4	1.12	0.01016	393.53	1.10	2.5
08057440	2.53	49.8	1.00	0.01722	666.71	0.59	1.6
08057425	11.50	83.4	1.10	0.01018	394.26	1.08	2.8
08048550	1.08	15.3	3.54	0.05304	2053.49	0.44	0.7
08048600	2.15	19.1	5.00	0.04218	1633.29	0.67	1.0
08048820	5.64	111.4	1.06	0.00765	296.35	1.39	3.7
08048850	12.30	17.6	2.24	0.04641	1796.79	0.39	0.7
08048520	17.70	129.8	1.00	0.00661	255.79	1.53	4.3
08048530	0.97	21.1	1.21	0.03986	1543.35	0.30	0.7
08048540	1.35	26.4	1.00	0.03243	1255.75	0.31	0.9
SSSC	0.38	23.2	1.00	0.03701	1433.00	0.27	0.8
08178300	3.26	32.6	2.10	0.02512	972.41	0.69	1.3
08181000	5.57	28.1	4.07	0.02869	1110.90	0.89	1.4
08181400	15.00	56.6	5.00	0.01424	551.26	2.00	2.9
08181450	1.19	27.7	1.02	0.03089	1196.02	0.33	0.9
08177600	0.33	18.4	1.00	0.04662	1804.86	0.22	0.6
08177700		15.2	1.00	0.03185	1233.02	0.33	7.5
08178555	2.43	3.3	1.02	0.25811	9993.48	0.04	0.1
08178600	9.54	43.4	5.00	0.01857	718.98	1.53	2.2
08178620	4.05	43.7	1.30	0.01915	741.46	0.65	1.6
08178640	2.45	22.1	2.37	0.03693	1429.96	0.50	0.9
08178645	2.33	26.2	2.53	0.03103	1201.57	0.62	1.1
08178690	0.26	46.8	1.00	0.01833	709.82	0.55	1.5
08178736	0.45	23.2	1.08	0.03665	1418.88	0.29	0.8
08096800	5.25	--	--	--	--	--	--
08094000	3.18	18.3	2.46	0.04447	1721.91	0.43	0.8
08098300	22.20	128.8	3.36	0.00629	243.43	3.63	5.8
08108200	48.60	--	--	--	--	--	--
08139000	3.42	41.1	1.17	0.02053	794.79	0.56	1.4
08140000	5.41	90.0	1.05	0.00948	366.98	1.11	3.0
08136900	21.80	--	--	--	--	--	--
08137000	4.02	--	--	--	--	--	--

Station no.	Area - (sq.mi.)	$\overline{T}$ - (min)	N	Q_p - (in/min)	Q_p - $(\frac{\text{cfs - hr}}{\text{in - sq.mi.}})$	T_p - (hrs)	$T_c{}^1$ - (hrs)
08137500	70.40	--	--	--	--	--	--
08182400	7.01	80.0	1.85	0.01028	398.11	1.55	3.1
08187000	3.29	33.2	1.00	0.02584	1000.63	0.39	1.1
08187900	8.43	106.5	1.27	0.00788	305.02	1.56	3.7
08050200	0.77	16.6	2.39	0.04904	1898.66	0.38	0.7
08057500	2.14	29.9	2.03	0.02739	1060.61	0.62	1.2
08058000	1.26	29.0	1.00	0.02959	1145.52	0.34	1.0
08052630	2.10	34.4	1.30	0.02439	944.24	0.51	1.2
08052700	75.50	--	--	--	--	--	--
08042650	6.82	48.7	1.21	0.01730	669.79	0.68	1.7
08042700	21.60	144.6	1.00	0.00593	229.63	1.70	4.8
08063200	17.60	--	--	--	--	--	--

Table 3. Summary of time-of-concentration values for 92 watersheds in Texas.

[Tc, time of concentration; NRCS, Natural Resource Conservation Service; --, not available; Sources: [1] Table 3, Column 7; [2] Table 3, Column 8; [3] Table 2, Column 9; [4] Table 3, Column 6; [5] Table 2, Column 8; Roussel and others (2005)]

Station no.	T_c- Kirpich method plus 30 minutes[1]	T_c- Hanktanir and Sezen method plus 30 minutes[2]	T_c- Kerby and Kirpich methods[3]	T_c- NRCS method plus 30 minutes[4]	T_c- NRCS Travel-time method[5]	T_c- DTRM method
08177600	1.10	0.84	1.21	--	0.66	0.62
08178690	1.40	--	1.43	--	0.81	1.55
08178736	1.35	1.03	1.38	1.37	0.45	0.64
08050200	1.66	1.51	1.94	1.83	1.48	0.73
08057415	1.59	1.14	1.54	1.38	0.44	1.00
08048530	1.29	1.04	1.23	--	0.52	0.89
08048550	1.81	1.20	1.99	1.46	0.46	0.78
08058000	1.48	1.24	1.76	1.29	0.63	0.94
08181450	2.60	1.74	3.12	3.33	1.39	0.93
08057130	1.73	1.51	1.70	1.52	0.59	1.13
08048540	1.55	1.38	1.46	--	0.91	0.99
08111025	--	--	1.73	--	0.77	--
08055580	--	--	1.90	--	0.91	1.24
08178555	3.35	--	3.45	--	1.75	1.14
08111050	--	--	2.26	--	0.87	--
08052630	2.17	1.82	2.52	1.79	0.97	--
08057500	1.46	1.23	1.69	1.19	0.54	1.32
08157000	2.19	2.20	2.10	2.11	1.18	1.59
08094000	2.01	1.85	2.26	2.05	0.94	0.94
08178645	1.85	2.12	2.08	--	1.22	1.35
08178640	1.52	1.70	1.65	1.51	0.75	1.25
08048600	2.62	2.07	2.69	2.10	0.97	1.08
08057440	--	--	2.40	--	0.94	1.56
08155550	1.90	1.99	1.80	1.81	1.01	1.61
08156650	1.74	--	1.76	--	0.83	2.11
08187000	1.75	1.50	2.00	1.46	0.75	1.87
08139000	1.72	1.85	1.93	1.71	0.98	1.25
08178300	1.74	1.95	1.60	1.67	0.58	1.30
08158880	2.18	2.32	2.26	1.99	1.08	2.36

Station no.	T_c-Kirpich method plus 30 minutes[1]	T_c-Hanktanir and Sezen method plus 30 minutes[2]	T_c-Kerby and Kirpich methods[3]	T_c-NRCS method plus 30 minutes[4]	T_c-NRCS Travel-time method[5]	T_c-DTRM method
08178620	1.91	--	2.05	--	1.00	1.89
08137000	2.85	2.32	3.19	2.84	1.78	--
08157500	2.54	2.66	2.45	2.31	1.31	1.75
08159150	2.18	2.02	2.54	1.59	1.04	1.79
08057020	2.49	2.62	2.35	2.13	1.21	2.51
08057160	2.93	2.73	2.90	2.41	1.18	2.10
08096800	2.21	2.36	2.37	2.10	1.05	--
08158380	2.38	2.15	2.27	2.02	1.14	1.74
08181000	2.24	2.77	2.33	2.15	1.16	1.26
08055600	3.48	3.32	3.37	2.94	1.63	2.77
08158400	2.58	2.36	2.47	2.20	1.27	1.77
08057435	2.27	2.20	2.54	1.79	0.95	2.16
08158920	2.32	2.57	2.43	1.98	1.09	2.90
08156700	2.36	2.38	2.30	2.01	1.17	3.08
08056500	3.29	3.17	3.20	3.10	2.17	2.63
08042650	2.12	2.42	2.25	2.01	1.17	1.76
08057120	2.74	2.67	2.89	2.15	1.19	2.33
08156750	2.59	2.64	2.52	2.23	1.32	3.10
08182400	2.86	2.53	3.20	2.37	1.42	2.52
08057320	3.08	2.76	2.98	2.41	1.33	2.27
08140000	2.78	2.97	3.04	2.73	1.67	2.26
08061620	3.52	2.81	3.48	2.67	1.88	3.12
08057418	2.84	2.86	2.94	2.28	1.34	3.11
08057140	3.77	3.62	3.74	3.01	1.77	3.57
08158840	2.31	2.57	2.46	1.99	1.15	2.64
08187900	2.94	--	3.22	--	1.26	3.54
08057445	4.79	4.00	4.83	3.74	2.05	4.20
08057050	3.02	3.10	2.88	2.40	1.36	2.98
08178600	2.82	3.45	3.00	2.48	1.51	2.52
08057425	3.00	3.08	3.03	2.44	1.48	3.47
08055700	4.05	3.74	3.94	3.19	2.13	3.02
08158500	3.93	4.07	3.84	3.40	2.19	2.56
08158810	2.73	3.13	2.89	2.30	1.47	3.04
08158050	3.36	3.58	3.36	2.84	1.61	2.76
08158100	2.72	2.87	2.91	1.81	1.06	4.25
08156800	4.37	4.86	4.28	3.95	2.59	4.97
08048850	4.61	4.39	4.98	3.54	1.94	--
08061920	4.38	3.69	4.41	3.44	1.63	3.51
08057420	3.91	3.97	3.95	3.11	1.95	--

Station no.	T_c-Kirpich method plus 30 minutes[1]	T_c-Hanktanir and Sezen method plus 30 minutes[2]	T_c-Kerby and Kirpich methods[3]	T_c-NRCS method plus 30 minutes[4]	T_c-NRCS Travel-time method[5]	T_c-DTRM method
08181400	3.53	4.56	3.60	3.06	1.91	3.23
08048520	3.96	3.65	4.11	2.86	1.66	--
08063200	4.74	4.13	5.15	3.37	1.96	4.65
08158930	4.08	4.79	4.23	3.38	0.98	4.87
08177700	--	--	4.74	--	1.77	--
08158825	5.11	5.60	5.36	4.28	2.66	5.26
08136900	4.84	5.55	5.18	4.66	2.99	--
08154700	3.74	4.65	3.79	3.10	1.91	3.90
08098300	7.57	6.04	8.05	6.14	3.83	7.22
08158860	4.89	5.70	5.11	4.15	2.64	5.20
08061950	6.76	5.64	6.85	4.97	2.69	4.60
08042700	5.01	5.23	5.15	4.65	2.94	5.26
08158820	5.53	6.46	5.71	4.89	3.34	4.26
08158200	4.65	4.98	4.80	3.16	2.11	5.12
08158970	6.56	7.45	6.68	5.66	3.67	7.10
08108200	10.09	8.28	10.49	7.96	5.19	--
08158600	7.76	8.11	7.87	5.86	3.60	--
08137500	7.42	8.08	7.80	6.19	4.09	--
08052700	11.86	9.41	12.25	8.42	5.40	--
08155200	10.31	11.17	10.45	8.08	5.22	11.64
08155300	15.49	16.43	15.61	12.99	8.73	12.76
08158700	11.86	12.73	12.02	9.92	6.27	14.18
08158800	16.65	17.60	16.82	13.85	9.39	--

REFERENCES

Asquith, W.H., Thomson, D.B., Cleveland, T.G., and X. Fang. 2004. “Synthesis of Rainfall and Runoff Data Used for Texas Department of Transportation Research Projects 0-4193 and 0-4194.” U.S. Geological Survey Open-File Report 2004-103, 50p.

Asquith, W.H., and R. M. Slade, 1997. “Regional regression equations for estimation of peak streamflow frequency for natural basins in Texas.” U.S. Geological Survey Water Resources Investigations Report 1996-4307, 68p.

Brown, J.R., Ulery, R.L., and Parcher, J.W. 2000. “Creating a standardized watersheds database for the Lower Rio Grande/Rio Bravo, Texas.” U.S. Geological Survey Open-File Report 2000-065, 13p.

Clark, C.O. 1945. “Storage and the unit hydrograph.” Trans. Am. Soc. Civil Engng 110. 1419-1446.

Cleveland, T.G., 1991. "A Comparison of Sampling Design Criterion using a Lagrangian Particle Tracking Model for Transport in Porous Media", Final Report to Houston Advanced Research Center, Woodlands, Texas. 54p.

Fang, X. Cleveland, T. G., Garcia, C. A., Thompson, D. B., and R. Malla. 2005. “Literature review on time parameters for hydrographs.” Texas Department of Transportation Research Report 0-4696-1. Lamar University, 82 p.

Hydrologic Engineering Center (HEC), 2000. Hydrologic modeling system, HEC-HMS. Technical Reference Manual. HEC 149p.

Kull, D.W., and Feldman, A.D., 1998. Evolution of Clark’s unit graph method to spatially distributed runoff.” J. Hydrologic Engineering, ASCE 3(1), 9-19.

Laurenson, E.M. 1964). “A catchment storage model for runoff routing.” J. Hydrology. 2, 141-163.

Maidment, D.R. 1993. “Developing a spatially distributed unit hydrograph by using GIS.” Proceedings of HydroHIS’93. IAHS Pub. No. 211.

Muzik, I. 1996. “Lumped modeling and GIS in flood predictions.” In Singh, V.P. (Ed.) Geographical Information Systems in Hydrology. Kulwer Academic Publishers, The Netherlands.

O’ Calligan, J.F., and Mark, D.M. 1984. “Extraction of drainage networks from digital elevation data.” Computer Vision, Graphics, and Image Processing, No. 28, pp. 323-344.

Olivera, F. and D. Maidment. 1999. “Geographic information systems (GIS)-based spatially distributed model for runoff routing.” Water Resour. Res. 35(4), pp.1135-1164.

Roussel, M. C., Thompson, D. B., Fang, X., Cleveland, T. G., and A. C. Garcia. 2005. “Timing parameter estimation for applicable Texas watersheds.” Texas Department of Transportation Research Report 0-4696-2. *(in review)*.

Saghafian, B. and P.Y. Julien. 1995. “Time to equilibrium for spatially variable watersheds.” J. of Hydrology. 172, pp. 231-245.

Saghafian, B., Julien, P. Y., and H. Rajaie. 2002. “Runoff hydrograph simulation based on time variable isochrone technique” J. of Hydrology. 261, pp. 193-203.

Wang, K.H., T.G. Cleveland, J.R. Rogers, and X. Ren, 1991. “A Three Dimensional Hydrodynamic Model of the Confluence of White Oak and Buffalo Bayou in Houston, Texas - Theory, Numerical Implementation, and Results.” Final report to Harris County Flood Control District, UH-CEE-91-7, Vol 1., 105p.; Vol 2., 287 p.

Wang, KH, Cleveland, T.G., Fitzgerald, S. , and X. Ren, 1996. “Hydrodynamic Flow Model at the Confluence of Two Streams.” American Society of Civil Engineers, Journal of Engineering Mechanics, Vol. 122, No. 10, pp 994-1002.

Wooding, R.A. 1965. “A hydraulic model for the catchment-stream problem.” J. of Hydrology. 3, pp 254-267.