TIME OF CONCENTRATION

IN

SMALL RURAL WATERSHEDS

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by

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August 1986

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1.0 INTRODUCTION

The determination of peak discharges for a given return period is necessary for the appropriate design of drainage structures. Peak discharges of a given frequency are related to rainfall intensity which in turn depends on rainfall duration. Since the maximum runoff for a given frequency occurs when the rainfall duration becomes equal to the time of concentration of the watershed, the time of concentration is the most significant variable in the computation of peak runoff.

Many empirical and a few theoretically founded equations used to compute the time of concentration were evaluated in this study. Some of these equations consider the time of concentration to be only a function of physical watershed parameters, such as length, slope, roughness and degree of imperviousness. Other equations also consider the characteristics of rainfall excess, such as rainfall intensity and duration. Times of concentration computed by these equations for a given watershed and for the same rainfall event were found to vary by more than 500%.

Data were gathered and analyzed from: (a) measurements from tests on three experimental watersheds conducted by the Corps of Engineers. Colorado State University, and the University of Illinois and from (b) measurements from 84 small rural watersheds from 22 states obtained by the USDA Agricultural Research Service for selected runoff events. From this data, two global regression equations were developed for the estimation of the time of concentration in small rural watersheds. One of these equations is based on four independent parameters and the second is based on only one independent parameter. These equations have general applicability and could be used in design with a good degree of confidence.

2.0 REVIEW OF EXISTING METHODS

The first phase of this study involved an exhaustive literature search which revealed a plethora of methods developed to compute the time of concentration. These formulas share the general format:

$$T_c = k\, L^a\, n^b\, S^{-y}\, i^{-z} \tag{1}$$

where T_c = Time of concentration, in minutes
L = Length of flow path, in feet
n = Roughness coefficient (See Section 4.2)
S = Average slope of flow path, in ft/ft
i = Intensity of excess rainfall, in in/hr (See Section 4.3)
k = Constant
a, b, y, z = Exponents

In some cases $b = 0$ and/or $z = 0$ which indicates that the time of concentration was considered to be independent of watershed surface roughness and/or excess rainfall intensity. Eleven of the most commonly encountered formulas used in computing the time of concentration are summarized below:

a. Kirpich (1940) [8,9]

$$T_c = 0.0078\, L^{0.77}\, S^{-0.385} \tag{2}$$

b. Izzard (1946) [8]

$$T_c = 41\, L^{0.33}\, (0.0007\, i + C_i)\, S^{-0.333}\, i^{-0.667} \tag{3}$$

Type of Surface	Retardance Coef. C_i
Very smooth pavement	0.007
Concrete pavement	0.012
Dense grass	0.060

c. Kerby/Hathaway (1959) [6,7,8]

$$T_c = 0.827\, L^{0.467}\, n_k^{0.467} S^{-0.233} \quad (4)$$

Type of Surface	Average Surface Retardance n_k
Smooth impervious surfaces	0.02
Smooth bare packed soil	0.10
Poor grass, cultivated row crops or moderately rough bare surface	0.20
Pasture or average grass	0.40
Deciduous timberland	0.60
Conifer timberland, deciduous timberland with deep forest litter or dense grass	0.80

d. Carter (1961) [10,15]

$$T_c = L^{0.6}\, C_c\, S^{-0.3} \quad (5)$$

where C_c = retardance coefficient equal to 0.045 for pristine conditions

e. Eagleson (1962) [15]

$$T_c = (L\, L_{ca})^{0.38}\, C_e\, S^{-0.19} \quad (6)$$

Type of Surface	Retardance Coefficient C_e
Mountain drainage	0.178
Foothill drainage	0.107
Valley drainage	0.052
Urban drainage	0.027

f. Kinematic Wave Equation reported by Henderson and Wooding (1964), Ragan and Duru (1972), and Aron (1973), [8]

$$T_c = 0.94\, L^{0.6}\, n^{0.6}\, S^{-0.3}\, i^{-0.4} \tag{7}$$

Type of Surface	Manning Roughness Coefficient n for flood plains [3]
Smooth impervious surface	0.01-0.02
Smooth bare packed soil, (no crop)	0.02-0.04
Poor grass, moderately bare surface	0.025-0.035
Gravels, Cobbles	0.03-0.05
Pasture or average grass cover	0.03-0.05
Mature field crops	0.03-0.05
Light brush and trees	0.04-0.08
Dense brush	0.07-0.16
Dense willows, dense grass, forest	0.11-0.20

g. Morgali and Linsley (1965) [11]

$$T_c = 0.99\, L^{0.593}\, n^{0.605}\, S^{-0.38}\, i^{-0.388} \tag{8}$$

where n = Manning's roughness coefficient

h. Federal Aviation Agency, FAA (1970) [8,10]

$$T_c = 0.39\, L^{0.5}\, (1.1 - C)\, S^{-0.333} \tag{9}$$

where C = rational method runoff coefficient

Type of Surface	Value of C
Concrete, asphalt	0.80 - 0.95
Drives and walks	0.75 - 0.85
Business districts and local areas	0.50 - 0.70
Residential single family areas	0.35 - 0.45
Res. with 1/2 acre lots or larger	0.25 - 0.40
Parks, cemeteries	0.10 - 0.25
Unimproved areas	0.10 - 0.30

i. SCS Curve Number (1975) [8,20]

$$T_c = \frac{1}{190} L^{0.8} \left(\frac{1000}{CN} - 9\right)^{0.7} S^{-0.5} \tag{10}$$

Type of Surface	SCS Runoff Curve Number CN
Paved areas	95 - 98
Cultivated land (soil group B&C)	80 - 90
Pasture or range land	70 - 80
Meadow (good condition), (A30)	60 - 70
Wood or forest: thin stand, poor cover	65 - 75
good cover, (A 25)	55 - 70
Lawns, parks, cemeteries	
grass cover 75 % or more	60 - 75
grass cover 50% to 75%	70 - 80
Surface mined basins: raw spoils	88
graded spoils	84
top-dressed spoils	82
vegetated spoils	75

j. SCS Velocity Charts [20] $T_c = \frac{1}{60} \frac{L}{V}$

where V = average velocity in fps obtained from charts in TR55 [20]. From the same reference $V = \sqrt{S}/C_v$ where C_v = retardance factor. Therefore:

$$T_c = \frac{1}{60} L C_v S^{-0.5} \tag{11}$$

Type of Surface	Retardance Factor C_v
Paved area and shallow gutter flow	0.05
Grassed waterway	0.06
Nearly bare ground	0.10
Short grass pasture and lawns	0.14
Fallow or minimum tillage cultivation	0.21
Forest, with heavy ground litter and meadow	0.40

k. Singh's Kinematic Wave and Chezy Formula (1976) [19]

$$T_c = 0.58 L^{0.667} C_s^{-0.667} S^{-0.333} i^{-0.333} \quad (12)$$

Type of Surface	Chezy's Roughness Coefficient C_s
Smooth impervious surface	50 - 100
Smooth bare packed soil	25 - 50
Poor grass, moderately bare surface	30 - 40
Gravels, cobbles	20 - 30
Pasture or average grass cover	20 - 30
Mature field crops	20 - 30
Light brush and trees	12 - 25
Dense brush	6 - 14
Dense willows, dense grass, forest	5 - 9

3.0 APPLICATION OF EXISTING FORMULAS

Three rural watersheds were chosen to compare the time of concentration as computed by eleven different formulas. The three watersheds have areas of 3.6 acres, 59 acres and 187 acres respectively. During the rainfall events that were selected, both precipitation and runoff were measured by the US Department of Agriculture, Agricultural Research Service.

3.1 Case Study I

A small rural watershed was selected in Hastings, Nebraska. The watershed has an area of 3.62 acres, a length of flow path of 480 feet, and an average path slope of 0.075. The plan view of the watershed is shown in Figure 1. The surface of the watershed was native grass meadow 14 inches high and heading and in excellent condition. The rainfall event of June 16, 1957 was selected and the measured rainfall hyetograph and resulting runoff hydrograph are presented in Figure 2. The average excess rainfall intensity was found to be equal to 1.7 in/hr and the lag time was measured equal to 6.5 minutes (Figure 2). Therefore, the actual time of concentration was found to be equal to 10.8 minutes.

Eleven formulas were employed to compute the time of concentration of this basin and the results are summarized in Table 1. It is important to note that the minimum time of concentration of 2.5 minutes was computed using the Kirpich equation. The maximum time of concentration of 16.5 minutes was computed by the Kerby equation. This amounts to a discrepancy of over 600% between minimum and maximum computed times of concentration.

3.2 Case Study II

A 59.2 acre natural watershed was selected near Americus, Georgia. The basin has a flow path length of 3,380 feet with an average slope of 0.0035. The plan view of the watershed is shown in Figure 3. The basin surface consisted of 84% oats in the dough stage, 6% peanuts in good stand, 6% sand clay road, and 4% idle weeds and grass. The rainfall event of August 19, 1942 was selected and the measured rainfall hyetograph and resulting runoff hydrograph are presented in Figure 4. The average excess rainfall intensity was found equal to 1.01 in/hr and the lag time was measured equal to 40 minutes (Figure 4). Therefore, the actual time of concentration was found to be 67 minutes.

Eleven formulas were employed to compute the time of concentration of the basin and the results are summarized in Table 1. The minimum times of concentration of 32 and 36 minutes were computed using the Carter and Kirpich formulas respectively. The maximum time of concentration of 175 minutes was computed by the SCS Curve Number method. There is a difference of over 500% between minimum and maximum computed times of concentration.

3.3 Case Study III

A natural watershed with an area of 187 acres was selected near Hamilton, Ohio. The basin has a flow path length of 5,000 feet with an average slope of 0.013. The plan view of the watershed is shown in Figure 5. The surface of the basin comprised 25% row crops, 53% grassland or mature small grain, and 22% woods and miscellaneous uses. The rainfall event of May 17, 1943 was selected and the measured rainfall hyetograph and resulting runoff hydrograph are presented in Figure 6. The average excess rainfall intensity was found equal to 4.95 in/hr and the lag time was measured equal to 16 minutes (Figure 6). Therefore, the actual time of concentration was found to be 27 minutes.

Eleven formulas were employed to compute the time of concentration of the basin and the results are summarized in Table 1. The minimum times of concentration of 27 and 29 minutes were computed again by the Carter and Kirpich formulas respectively. The maximum time of concentration of 94 minutes was computed by the FAA equation. There is a difference of over 300% between computed minimum and maximum times of concentration.

It is important to note that in the above three case studies the Kirpich equation and the Carter equation consistently produced the lowest values of the time of concentration.

4.0 TIME OF CONCENTRATION OF NATURAL WATERSHEDS

4.1 Data Base

A comprehensive data base was compiled for 84 natural rural watersheds from 22 states. Table 2 lists the number of sites selected in each state. Information was obtained from the US Department of Agriculture, Agricultural Research Service [1]. Watersheds were selected only if:

a) they had an area of less than 500 acres,
b) detailed basin topography and surface cover information was available, and
c) a rainfall event had been isolated with good rainfall-runoff measurements.

The length of the flow path L in feet, and the average slope of the flow path S were measured for each watershed and are listed in Table 3. Values of the other two independent parameters, the average surface roughness coefficient n of the basin, and the excess rainfall intensity i in inches/hour, were estimated from the available data according to the procedures outlined below and they are presented in Table 3. Values of the time of concentration T_c were also found from the available data according to the procedure outlined in Section 4.4 and are listed for each watershed in Table 3.

4.2 Roughness Coefficient Estimation

Different depths of flow usually result in different values of roughness coefficient for the same surface roughness. Table 4 provides a comparison between roughness coefficients proposed by V.T. Chow [3] for floodplains (wide channel), roughness coefficients proposed by MITCAT [21] and those proposed by Pennsylvania State University for surface flows [8]. Because of relative roughness effects, the roughness coefficient associated with surface sheet flow is larger than that associated with channel flow over the same surface.

The flow path in a rural watershed is a combination of overland flow and channel flow. The larger the watershed, the larger is the portion of channel flow; therefore, for the same surface roughness, the average roughness coefficient should decrease with increasing area. This relationship for a variety of surface covers is depicted graphically in Figure 7. Values of the roughness coefficient recommended by MITCAT [21] and Pennsylvania State University [8] for predominantly overland flow in small watersheds were adapted in Figure 7. For predominantly channel flow in large watersheds, values of the roughness coefficient suggested by Chow [3] were utilized. Figure 7 was used to estimate the roughness coefficients listed in Table 3 for the 84 rural watersheds.

4.3 Excess Rainfall Intensity Estimation

The area enveloped by a hydrograph curve and the horizontal time-axis represents volume of runoff. This runoff is the result of the excess rainfall that generated the hydrograph. The portion of the rainfall hyetograph that corresponds to the excess rainfall can be determined by finding the volume of total runoff and equating volumes, as shown in Figure 8. The remaining portion of the hyetograph is considered to be rainwater lost to infiltration, retention and evaporation.

The time of excess rainfall, T_r, can be estimated from the rainfall excess portion of the hyetograph. The average excess rainfall intensity is found by dividing the volume of excess rainfall (or the total runoff volume in inches) by the time of excess rainfall. This procedure is approximate, but is simple to use and sufficiently accurate for the ensuing analysis.

Table 3 lists excess rainfall intensities computed according to the procedure outlined above for selected precipitation events recorded by the USDA Agricultural Research Service in 84 rural watersheds across the United States.

4.4 Time of Concentration Estimation

The time of concentration, T_c, is defined as the time from the beginning of excess rainfall needed for the watershed point most hydraulically remote from the basin outlet, to contribute to the runoff at the outlet.

Other time parameters that are shown in Figure 9 are defined as follows:

i) Time to Peak, T_p, is the time from the beginning of the excess rainfall to the peak runoff.

ii) Lag time, T_l, is the time from the center of mass of the excess rainfall to the peak runoff. The lag time is equal to $T_l = T_p - 0.5\,T_r$.

iii) Time of Equilibrium, T_e, is the time from the beginning of excess rainfall needed for the runoff rate (in in/hr) to reach the excess rainfall intensity. This occurs for large times of excess rainfall, T_r, when $T_r \geq T_c$.

The sketches in Figure 9 depict two types of hydrographs, those that reach equilibrium and the non-equilibrium hydrographs that exhibit a peak discharge. The time of concentration is estimated differently for each of those two cases:

a) Hydrographs reaching equilibrium state. These hydrographs exhibit a maximum discharge platform. If the beginning of the platform is well defined, then the time of concentration $T_c = T_e$ is the time from the start of the excess rainfall to the beginning of the maximum discharge platform. If the beginning of this platform is not well defined, the point corresponding to 97% of the maximum observed discharge was assumed to represent the beginning of the platform.

b) Hydrographs with peak discharge, not reaching equilibrium. In this case the time of concentration is considered to be equal to the lag time divided by 0.6 as proposed by the Soil Conservation Service:

$$T_c = T_l / 0.6 = (T_p - 0.5\,T_r)/0.6 \qquad (13)$$

The times of concentration, T_c, of 84 rural watersheds were computed for selected excess rainfall intensities, using the procedure outlined above and values obtained are listed in Table 3, together with the corresponding times to peak, and lag times or times of equilibrium.

5.0 TIME OF CONCENTRATION OF EXPERIMENTAL WATERSHEDS

5.1 Corps of Engineers Experimental Results

The Corps of Engineers conducted from 1948 to 1952 simulated rainfall tests at the Santa Monica Municipal Airport. The tests were performed on airfield strips having flow-path lengths of 84 to 500 feet and slopes of 0.5, 1 and 2 percent. Simulated rainfall intensities of 0.25 to 10 inches per hour on concrete and simulated turf were utilized. The roughness coefficient for concrete surfaces was considered equal to n = 0.04 and for the turf covered flow surfaces equal to n = 0.20. The results of 162 of these tests as compiled by the Los Angeles District of the Corps of Engineers [2] were used in this study. The length of the flow path, the slope, the applied rainfall intensity, and the measured average time of equilibrium (equal to the time of concentration) are listed in Table 5 for each of 89 cases involving concrete surface and in Table 6 for each of 73 cases involving simulated turf surface.

5.2 Colorado State University Experimental Results

The experimental watershed constructed at the Engineering Research Center of Colorado State University consists of a conic sector which has an interior angle of 104 degrees and a radius of 116 feet with a slope of 0.05. Two 88-foot by 70-foot long intersecting plane surfaces joint the edges of the conic sector with a maximum surface slope of 0.05 and a collecting channel slope of 0.03 [15]. The simulated rainfall tests were conducted in 1970-1971 and utilized different surface cover materials,such as gravel and butyl.

Ninety three of these tests are summarized in Table 7 including the identification of the experimental run, watershed configuration, length of flow-path, slope and rainfall intensity. The Manning's roughness coefficients and the actual times of concentration were estimated according to the criteria established in Section 4.0 and are listed in Table 7.

5.3 University of Illinois Experimental Results.

An experimental basin and a precipitator were used in an indoors laboratory in the University of Illinois at Urbana-Champaign. The size of the basin is 40 feet by 40 feet, its lateral slope is 0.01 and its longitudinal slope can be set at 0.005, 0.01, or 0.03. The length of the flow path is 60 feet and the roughness coefficient of the aluminum plate surface of the basin was estimated equal to n = 0.08. The results of the tests performed in 1974 at the University of Illinois were reported using relative nondimensional variables [17]. The necessary transformations were performed to obtain the values of the rainfall intensity and the times of concentration for 36 tests which are listed in Table 8.

6.0 REGRESSION ANALYSIS

6.1 Four - Parameter Time of Concentration Equation

A four-parameter equation of the general format of equation (1) was chosen to fit the 375 data points developed in Sections 4.0 and 5.0 for natural and experimental watersheds. This is a volume of data far in excess of those used in the development of any of the equations (2) to (12). In equation (1) the time of concentration is the dependent variable and L, n, S and i are the independent variables. This equation exhibits a linear correlation of the logarithms of the variables involved.

A regression analysis was performed for each group of available data. A power model was used to regress the time of concentration on four predictor variables: length of flow path L, roughness coefficient n, slope of flow path S, and intensity of excess rainfall i. Only two predictor variables were used for the Colorado State University data because L and S were constant throughout the measurements, and similarly for the University of Illinois data where L and n were constant. Table 9 summarizes the results of the regression analysis for each data group and for the total data sample. The table includes estimates of the parameters k, a, b, y and z. The standard deviation of a sample of observations, σ, for log T_c, is also listed in Table 9 together with the coefficient of variation which is the ratio of the standard deviation to the mean, $\sigma/\overline{\log T_c}$. The coefficient of determination is equal to the square of the correlation coefficient R and indicates the percentage of the variation in the variable that is explained by the regression equation. The value of R^2 is always in the range from zero to 1.0 with a value of zero indicating that the variable is not related to any of the predictor variables. The coefficient of determination is also included in Table 9.

Based on the total data sample available, the best-fit four-parameter time of concentration equation was found to be:

$$T_c = 0.66\, L^{0.50}\, n^{0.52}\, S^{-0.31}\, i^{-0.38} \qquad (14)$$

Values of T_c computed by Equation 14 versus those measured are plotted in Figure 10 using logarithmic scales. Tolerance limits containing 75, 90 and 95% of the sample points are also enveloped in Figure 10.

Statistical tolerance limits for a given population are limits within which a stated proportion of the population are expected to lie with respect to some measurable characteristic. Whereas a confidence interval provides a measure of the accuracy of a statistic (e.g. a mean or regression coefficient), tolerance limits provide bounds on the extend of the population. That is, confidence intervals deal with population statistics, and tolerance limits deal with proportions of a population.

The width of the two-sided tolerance limits is

$$\Delta \log Tc = \pm D\sigma \quad (15)$$

where σ is the standard deviation computed from a sample of m observations. The factor D is such that the probability is γ that a proportion P(%) of the m observations will be included between the tolerance limits. The factor D is a function of γ, P and m and can be obtained from statistical tables.

The probability γ is called the level of confidence and is equal to (1- α) where α is the level of significance. There is a α% risk of error, for even if the null hypothesis does hold, there is a α% probability that it will be rejected. The value of α is often based on convention and the availability of statistical tables. A value of $\alpha = 0.05$ is being selected frequently. The tolerance interval encloses P percent of the population with a given confidence γ.

For a level of confidence equal to $\gamma = 0.95$ and a sample size of $m = 375$, values of D for three selected values of P are listed in Table 11 together with the corresponding tolerance limits of the dependent variable T_c. These limits can be transformed to a tolerance interval of the constant k of Equation 1 as shown in Table 11. It is of interest to note that as P increases from 75% to 95%, given the same level of confidence and sample size, the width of the two-sided tolerance limits also increases.

6.2 One Parameter Time of Concentration Equation

The exponents of L and n are almost identical in Equation 14. Furthermore the exponents of i and S are also nearly equal. Therefore, Equation 14 was simplified by combining the four independent parameters in one by adopting the form:

$$T_c = k\,[\mathrm{Ln}\,(Si)^{-2/3}]^x \quad (16)$$

A linear regression analysis was performed for each group of available data and for the total data sample. Table 10 summarizes the results of the regression including the parameters k and x, the standard deviation of the sample, the coefficient of variation and the coefficient of determination.

Based on the total data sample available, the best-fit one-parameter time of concentration equation was found to be:

$$T_c = 0.52\,[\mathrm{Ln}\,(Si)^{-2/3}]^{0.52} \qquad (17)$$

Observed values of T_c versus those computed by Equation 17 are plotted in Figure 11 using logarithmic scales. Tolerance limits containing 75, 90 and 95% of the sample are enveloped in Figure 11.

For a level of confidence equal to $\gamma = 0.95$ and a sample size of $m = 375$, values of D for three selected values of P are listed in Table 11 together with the corresponding tolerance limits of the dependent variable T_c. These limits can be transformed to a tolerance interval of the constant k of Equation 16 as shown in Table 11.

7.0 UNCERTAINTY ANALYSIS

The uncertainty in the calculated times of concentration T_c can be estimated on the basis of the uncertainties in the measurements of L, n, S and i. Let u_T be the uncertainty in the result and u_L, u_n, u_S, and u_i be the uncertainties in the independent variables. If the uncertainties in the independent variables are all given with the same odds, then the uncertainty in the time of concentration having these odds, is:

$$u_T = \sqrt{\left(\frac{\partial T_c}{\partial L} u_L\right)^2 + \left(\frac{\partial T_c}{\partial n} u_n\right)^2 + \left(\frac{\partial T_c}{\partial S} u_S\right)^2 + \left(\frac{\partial T_c}{\partial i} u_i\right)^2} \quad \text{, or}$$

$$\frac{u_T}{T_c} = \sqrt{\left(0.5 \frac{u_L}{L}\right)^2 + \left(0.52 \frac{u_n}{n}\right)^2 + \left(0.31 \frac{u_S}{S}\right)^2 + \left(0.38 \frac{u_i}{i}\right)^2} \qquad (18)$$

The degree of accuracy with which the independent variables can be measured depends on the observer. However, the following uncertainties can be reasonably expected even from experienced observers:

$u_L/L = \pm 5\%$, $\quad u_S/S = \pm 7\%$

$u_n/n = \pm 25\%$, $\quad u_i/i = \pm 20\%$

Then, Equation 18 yields $u_T/T_c = \pm 15\%$. The uncertainty propagation in the time of concentration predicted by Equation 18 depends on the squares of the uncertainties of the independent variables. This means that if the uncertainty in one variable is significantly larger than the uncertainties in the other variables, then it is the largest uncertainty that predominates and the others may probably be neglected. To illustrate, suppose that $u_n/n = \pm 25\%$ and the other three uncertainties are zero. Equation 18 would then yield $u_T/T_c = \pm 13\%$, fairly close to $\pm 15\%$, the value computed taking into account all four uncertainties.

8.0 DIMENSIONS AND UNITS

The roughness coefficient, n, was considered to be dimensionless in Equation 1. Then the constant k has the following dimensions:

$$[k] = [T]\,[L]^{-a}\,[i]^{z}$$

English customary units for Equation 1 are the minute as unit of time, the foot as unit of length, and the inch per hour as unit of rainfall intensity. Table 12 summarizes the conversion factors by which k should be multiplied to convert the English customary units to the International System (SI) and to the Metric customary units where meter is the unit of length and the centimeter per hour is the unit of rainfall intensity.

9.0 CONCLUSIONS AND RECOMMENDATIONS

A comparison was performed between the four-parameter time of concentration equation 14 and the equations presented in Section 2.0. The comparison was based on the exponents of the independent variables L, S and i which are listed in Table 13. These exponents were chosen for comparison rather than the numerical values of the time of concentration to avoid the selection of retardance coefficients, the definition of which varies from equation to equation.

From Table 12 the following conclusions can be made:

a) The exponents of L in the equations of Carter, Kinematic Wave, Morgali, FAA and Kerby agree within $\pm 20\%$ with the exponent a of Equation 14.
b) The exponents of S in the equations of Izzard, FAA, Kerby, Carter, Kinematic Wave, Morgali and Singh agree within $\pm 25\%$ with the exponent y of Equation 14.
c) The exponents of i in the equations of Kinematic Wave, Morgali and Singh agree within $\pm 15\%$ with the exponent z of Equation 14.

The three case studies of Section 3.0 were also used to compare the time of concentration computed from Equation 14 with the values obtained from the other eleven equations and those measured (see Table 1). The spread in these values is depicted in Figure 12. Results from Equation 14 closely agree with the measured times of concentration. The 75% tolerance limits are also marked on Figure 12 to show that almost the only other equation that showed good agreement with the measurements is the Kinematic Wave equation. The derived four-parameter Equation 14 has more general applicability compared to the Kinematic Wave equation which is more appropriate for computing the time of concentration of very small rural watersheds where surface flow is predominant.

10. ACKNOWLEDGEMENTS

The authors would like to thank Professor Vujica Yevjevich of George Washington University, Professor Tom Sanders of Colorado State University, Professor Ben Yen of the University of Illinois, Chief Hydrologist Andrew Sienkiewich of the Corps of Engineers Los Angeles District, and Research Hydrologist Ted Engman of the Beltsville USDA-ARS Hydrology Lab for making available the data that made this study possible. Appreciation is extended to the Civil Engineering Department of Aleppo University in Syria for having offered one year of leave to Professor M. N. Kazan to perform this investigation in collaboration with Dr. Papadakis at the Civil Engineering Departments of Colorado State University and of the University of Cincinnati.

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TABLE 1
TIMES OF CONCENTRATION FOR THREE CASE STUDIES

Formula	Hastings, Nebraska 3.62 acres-Case Study I Retardance Coefficient	T_c(min)	Americus, Georgia 59.2 acres-Case Study II Retardance Coefficient	T_c(min)	Hamilton, Ohio 187 acres-Case Study III Retardance Coefficient	T_c(min)
a) Kirpich	---	2.5	---	36	---	29
b) Izzard	C_i = 0.03	16.3	C_i = 0.03	120	C_i = 0.03	33
c) Kerby	n_k = 0.35	16.5	n_k = 0.30	79	n_k = 0.2	57
d) Carter	C_c = 0.045	3.8	C_c = 0.045	32	C_c = 0.045	27
e) Eagleson	C_e = 0.107	14.7	C_e = 0.052	56	C_e = 0.052	59
f) Kinematic Wave	n = 0.05	11.1	n = 0.04	97	n = 0.035	40
g) Morgali	n = 0.05	13.7	n = 0.04	149	n = 0.035	57
h) FAA	C = 0.30	16.2	C = 0.3	119	C = 0.30	94
i) SCS Curve Number	CN = 70	8.6	CN = 85	175	CN = 90	71
j) SCS Velocity	C_v = 0.30	8.8	C_v = 0.14	133	C_v = 0.12	87
K) Singh/Chezy	C_s = 20	9.6	C_s = 25	117	C = 29	45
l) Measured	---	10.8	---	67	---	27

TABLE 2

84 NATURAL RURAL WATERSHEDS IN 22 STATES
USDA AGRICULTURAL RESEARCH SERVICE [1]

State	Number of Watersheds
Arkansas	2
California	2
Colorado	2
Georgia	1
Idaho	3
Illinois	2
Indiana	3
Iowa	5
Maryland	5
Mississippi	2
Missouri	2
Nebraska	9
New Jersey	2
New Mexico	3
Ohio	7
Oklahoma	9
Oregon	3
Texas	9
Virginia	5
Washington	1
West Virginia	3
Wisconsin	4

TABLE 3

PHYSICAL AND HYDROLOGICAL CHARACTERISTICS OF THE SELECTED NATURAL WATERSHEDS USDA - AGRICULTURAL RESEARCH SERVICE [1]

		Physical Characterisitics of Watershed				Excess Rainfall							
No.	Watershed Site,State(#)	Area A Acres	Length L Feet	Roughness (estimated) n	Slope S Feet/Foot	Date Month/ Day/Year	Vol. V Inches	Duration T_r min.	Intensity i inch/hr.	Time of Equi-Librium T_e min.	Time to Peak T_p min.	Lag Time T_e min.	Time of Concen tration T_c min.
1	Bentonville, AR(W5)	19.4	1290	0.16	0.017	5/25/39	0.424	24	1.06	22.0			22.0
2.	Bentonville,AR(W5)	19.4	1290	0.16	0.017	8/31/40	0.227	5	2.72		22.0	19.5	32.5
3.	Watsonville, CA(W3)	27.4	1660	0.16	0.108	2/16/41	0.035	8	0.26		29.0	25.0	41.7
4.	Watsonville,CA(W3)	27.4	1660	0.16	0.108	4/1/41	0.121	25	0.29		41.0	28.5	47.5
5.	Col. Springs, CO(W4)	35.6	2460	0.10	0.039	8/13/45	0.383	6	3.82		15.0	12.0	20.0
6.	Col.Springs, CO(W4)	35.6	2460	0.10	0.039	7/15/46	0.194	10	1.16		18.0	13.0	21.7
7.	Americus,GA(W4)	59.2	3380	0.14	0.0035	8/19/42	0.168	10.	1.01		45.0	40.0	66.7
8.	EMMETT,ID(W2)	69.4	2680	0.10	0.160	6/18/41	0.022	4	0.33		16.0	14.0	23.3
9.	Emmett,ID(W2)	69.4	2680	0.10	0.160	6/19/41	0.020	5	0:24		18.5	16.0	26.7
10.	Moscow,ID(W1)	146.8	4040	0.10	0.047	4/9/41	0.006	5	0.067		70.0	67.5	112.5
11.	Monticello,IL(W1A)	82.0	2540	0.10	0.008	10/21/49	0.212	6	2.12		40.0	37.0	61.7
12.	Monticello,IL(W1A)	61.2	2650	0.13	0.0053	10/21/49	0.255	5	3.06		30.0	27.5	45.8
13.	Lafayette,IN(W5)	2.87	470	0.15	0.017	7/5/43	0.320	9	2.13		10.0	5.5	9.2

No.		A	L	n	S	Date	V	T_r	i	T_e	T_p	T_e	T_c
14	Lafayette, IN(W5)	2.9	470	0.15	0.017	6/19/46	0.360	12	1.80		15.0	9.0	15.0
15	Lafayette, IN(W6)	2.8	580	0.14	0.017	6/24/50	0.920	9	6.13		10.0	5.5	9.2
16	Treynor, IA(W1)	74.5	3100	0.06	0.029	6/22/64	0.571	16	2.14		19.0	11.0	18.3
17	Treynor, IA(W2)	82.4	3000	0.05	0.025	9/22/64	0.295	9	1.97		12.0	7.5	12.5
18	Treynor, IA(W3)	107.0	2930	0.08	0.038	5/26/64	0.108	13	0.50		23.0	16.5	27.5
19	Treynor, IA(W4)	150.0	4000	0.08	0.025	6/22/64	0.223	13	1.06		19.5	13.0	21.7
20	Treynor,IA(W5)	389.0	7800	0.07	0.022	6/22/64	0.147	12	0.79		30.0	24.0	40.0
21	Coll. Park,MD(W1)	8.2	1320	0.18	0.025	8/3/48	1.017	18	4.40	15.0			15.0
22	Coll. Park, MD(W6)	3.5	720	0.24	0.040	8/27/43	0.241	6	2.41		12.0	9.0	15.0
23	Coll. Park, MD(W7)	4.1	810	0.23	0.040	8/27/43	0.549	4	1.44		13.0	11.0	18.3
24	Coll. Park,MD(W9)	12.1	1290	0.26	0.053	11/25/50	0.298	34	0.53		62.0	45.0	75.0
25	Hagerstown, MD(W2)	80.8	3120	0.10	0.045	7/20/42	0.180	15	0.72		25.0	17.5	29.2
26	Oxford, MS(WC1)	3.9	480	0.25	0.062	6/11/59	1.360	22	3.65		21.0	10.0	16.7
27	Oxford, MS(WP4)	3.0	470	0.25	0.068	6/11/59	1.510	22	4.12		18.5	7.5	12.5
28	Bethany, MO(WD3)	4.5	680	0.16	0.062	5/1/35	0.790	23	2.06	13.0			13.0
29	Bethany, MO(WD3)	4.5	680	0.16	0.062	6/17/35	0.560	20	1.68	12.0			12.0
30	Hastings, NE(W3)	481.0	12250	0.05	0.0057	6/7/53	0.879	44	1.20		56.0	34.0	56.7

No.		A	L	n	S	Date	V	T_r	i	T_e	T_p	T_e	T_c
31	Hastings,NE(W5)	411.0	7500	0.09	0.011	7/3/59	1.358	44	1.85		65.0	43.0	71.7
32	Hastings,NE(W1H)	3.6	480	0.15	0.075	6/16/57	0.340	12	1.70		12.5	6.5	10.8
33	Hastings,NE(W2H)	3.4	610	0.17	0.047	6/12/58	0.180	7	1.54		15.0	11.5	19.2
34	Hastings,NE(W5H)	3.9	670	0.13	0.052	5/4/59	0.130	10	0.78	9.0			9.0
35	Hastings,NE(W7H)	4.3	670	0.13	0.034	5/4/59	0.140	6	1.40		8.0	5.0	8.3
36	Hastings,NE(W18H)	3.5	510	0.17	0.055	5/18/59	0.190	10	1.14		18.0	13.0	21.7
37	Hastings,NE(W22H)	3.8	500	0.14	0.026	8/23/62	1.100	19	3.47		18.5	9.0	15.0
38	Hastings,NE(W23H)	4.2	610	0.14	0.036	8/23/62	1.120	19	3.54		20.0	10.5	17.5
39	Freehold,NJ(W1)	15.7	1890	0.09	0.018	6/12/38	0.242	5	2.90		14.0	11.5	19.2
40	Freehold,NJ(W2)	32.9	1740	0.09	0.026	8/6/38	0.436	20	1.31	17.0			17.0
41	Santa Fe,NM(W1)	141.0	2910	0.05	0.019	8/25/47	0.381	9	2.54		17.0	12.5	20.8
42	Santa Fe,NM(W1)	141.0	2910	0.05	0.019	8/4/48	0.171	16	0.64		27.0	19.0	31.7
43	Santa Fe,NM(W3)	183.0	5170	0.05	0.033	8/19/56	0.191	11	1.04		16.0	10.5	17.5
44	Hamilton,OH(W1)	187.0	5000	0.09	0.013	5/17/43	0.495	6	4.95		19.0	16.0	26.7
45	Cochocton,OH(W183)	74.2	3140	0.11	0.071	8/16/47	0.195	12	0.98		21.0	15.0	25.0
46	Cochocton,OH(W196)	303.0	4570	0.10	0.055	8/16/47	0.249	9	1.66		27.0	22.5	37.5
47	Cochocton,OH (W166)	79.2	2910	0.11	0.069	7/7/69	0.362	17	1.28		34.0	25.5	42.5
48	Cochocton,OH(W185)	7.4	560	0.19	0.110	6/12/57	0.700	16	2.63		17.0	9.0	15.0

No.		A	L	n	S	Date	V	T_r	i	T_e	T_p	T_e	T_c
49	Cochocton,OH(W192)	7.6	710	0.18	0.140	6/12/59	0.700	16	2.63		18.0	10.0	16.7
50	Cochocton,OH(W172)	43.6	2430	0.17	0.082	6/12/59	1.372	27	3.05		36.0	22.5	37.5
51	Guthrie,OK(W6)	94.8	3300	0.11	0.024	6/26/45	0.315	10	1.89		25.0	20.0	33.3
52	Stillwater,OK(W3)	92.0	3330	0.13	0.021	6/27/57	0.757	10	4.54		33.0	28.0	46.7
53	Cherokee,OK(W9)	8.5	840	0.16	0.012	6/9/42	0.490	10	2.94		17.0	12.0	20.0
54	Cherokee,OK(W10)	1.7	350	0.20	0.021	6/2/61	1.020	25	2.45		20.0	7.5	12.5
55	Cherokee, OK(W11)	2.1	420	0.19	0.013	6/2/61	0.950	25	2.28		29.0	16.5	27.5
56	Cherokee, OK(W12)	1.7	400	0.21	0.015	6/2/61	1.290	30	2.58	24.0			24.0
57	Cherokee, OK(W14)	2.2	350	0.20	0.021	6/2/61	1.080	35	1.85	25.0			25.0
58	Cherokee, OK(W15)	2.2	430	0.20	0.010	6/2/61	1.120	35	1.92	30.0			30.0
59	Chickasha, OK(WC8)	27.3	2440	0.18	0.018	9/19/65	0.274	32	0.51		60.0	44.0	73.3
60	Newberg, OR(W1)	13.2	1170	0.16	0.142	10/1/41	0.138	10	0.83		14.5	9.5	15.8
61	Newberg, OR(W3)	12.8	800	0.16	0.087	3/31/40	0.076	9	0.51		20.0	15.5	25.8
62	Newberg, OR(W4)	6.2	820	0.19	0.079	1/26/40	0.011	10	0.066		37.5	32.5	54.2
63	Vega, TX(W2)	95.9	4440	0.08	0.018	5/30/38	0.700	13	3.23		21.5	15.0	25.0
64	Riesel(Waco), TX(W1)	176.0	5500	0.10	0.0091	6/10/41	2.024	34	3.57		44.0	27.0	45.0
65	Riesel(Waco), TX(SW12)	3.0	420	0.20	0.029	6/4/57	0.270	13	1.25		23.0	16.5	27.5

No.		A	L	n	S	Date	V	T_r	i	T_e	T_p	T_e	T_c
66	Riesel(Waco), TX(Y13)	11.3	1380	0.19	0.012	5/23/69	0.341	30	0.68		59.0	44.0	73.3
67	Riesel(Waco), TX(SW20)	3.2	500	0.20	0.040	10/23/70	0.080	10	0.45		16.0	11.0	18.3
68	Sonora, TX(W1)	10.2	890	0.20	0.037	4/30/66	1.299	30	2.60	20.0			20.0
69	Sonora, TX(W3)	6.7	820	0.20	0.022	4/30/66	1.259	26	2.91	25.0			25.0
70	Sonora, TX(w4)	4.5	570	0.20	0.019	4/30/66	0.247	15	0.99		27.0	19.5	32.5
71	Sonora, TX(W6)	6.9	710	0.20	0.021	4/30/66	0.911	20	2.73	16.0			16.0
72	Chatham, VA(W3)	17.1	1380	0.16	0.021	8/31/40	0.898	19	2.84		23.0	13.5	22.5
73	Staunton, VA(W1)	390.0	8250	0.08	0.025	4/13/49	0.474	20	1.42		46.0	36.0	60.0
74	Blacksburg, VA(PCW1)	182.0	4830	0.12	0.021	7/22/64	0.230	24	0.58		52.0	40.0	66.7
75	Blacksburg,VA(PMBW1)	192.0	4640	0.15	0.097	6/17/68	0.069	35	0.12		80.0	62.5	104.2
76	Blacksburg, VA(W3)	19.3	1490	0.16	0.047	8/15/39	0.368	16	1.38		22.0	14.0	23.3
77	Pullman, WA(GS2)	68.2	2720	0.11	0.064	3/3/41	0.015	15	0.06		35.0	27.5	45.8
78	Moorefield, WV(W1	8.2	1210	0.17	0.100	8/3/58	0.300	24	0.75		27.0	15.0	25.0
79	Moorefield, WV(W2)	10.1	1010	0.17	0.110	8/3/58	0.522	30	1.04	25.0			25.0
80	Moorefield, WV(W5)	9.5	1180	0.17	0.070	8/3/58	0.540	13	2.26		19.0	12.5	20.8
81	Colby, WI (W1)	345.0	7100	0.07	0.010	5/13/56	0.439	11	2.36		29.0	23.5	39.2
82	Fennimore, WI (W1)	330.0	5300	0.09	0.024	6/28/45	0.483	8	3.63		24.0	20.0	33.3
83	Fennimore, WI (W2)	22.8	1210	0.15	0.063	6/28/45	0.615	6	6.15		8.5	5.5	9.2
84	Fennimore, WI (W4)	171.0	3330	0.10	0.026	6/28/45	0.468	8	3.51		15.0	11.0	18.3

TABLE 4
COMPARISON BETWEEN (n) VALUES PROPOSED BY
V.T. CHOW, MITCAT, AND PENN. STATE U.

Type of Surface	V.T. Chow	MITCAT	Penn. State
Smooth impervious,concrete, asphalt	0.01-0.02	0.05-0.15	0.035
Smooth bare packed soil (no crop)	0.02-0.04		0.05
Poor grass, moderately bare surface	0.025-0.035		0.10
Lawns		0.20-0.30	
Gravel, cobbles	0.03-0.05		
Pasture or average grass cover	0.03-0.05	0.30-0.40	0.20
Mature field crops	0.03-0.05		
Light brush and trees	0.04-0.08		
Dense brush	0.07-0.16		
Dense grass or forest (dense willows)	0.11-0.20	0.40-0.50	0.40

TABLE 5

SIMULATED RAINFALL TESTS - CORPS OF ENGINEERS [2]
CONCRETE SURFACE WITH n = 0.04

Length L (ft)	S = 0.005 Rain Rate i (in/hr)	S = 0.005 Average T_e (min)	S = 0.010 Rain Rate i (in/hr)	S = 0.010 Average T_e (min)	S = 0.020 Rain Rate i (in/hr)	S = 0.020 Average T_e (min)
84	--	--	0.44	8.26	0.62	5.30
84	0.86	8.92	1.04	5.41	1.03	3.60
84	1.75	5.82	2.02	3.60	2.12	3.11
84	3.82	4.64	3.81	2.83	4.11	2.16
84	6.55	3.25	7.35	2.15	7.34	1.75
168	0.90	11.09	0.58	9.49	0.57	7.04
168	1.68	8.22	1.00	6.55	1.07	4.98
168	3.85	5.65	1.93	5.15	2.04	3.96
168	6.95	4.21	4.19	3.79	4.11	3.28
168	8.26	3.77	7.52	3.01	7.46	2.39
252	0.91	12.50	0.45	12.54	0.62	8.12
252	1.79	8.94	1.02	7.95	1.04	6.42
252	3.84	6.50	1.74	6.33	2.01	4.88
252	6.79	5.02	4.14	4.44	4.08	3.66
252	8.40	4.07	7.47	3.54	7.31	2.86
336	0.89	13.53	0.52	12.66	0.63	9.15
336	1.76	10.38	0.90	9.80	1.01	7.55
336	3.75	6.95	2.02	6.88	2.03	5.68
336	6.50	5.65	4.17	5.22	4.06	4.34
336	8.31	4.97	7.61	4.14	7.43	3.34
420	0.89	14.94	0.63	12.08	0.56	11.12
420	1.77	11.05	1.04	10.60	1.01	8.39
420	3.85	8.02	2.03	7.67	2.02	6.42
420	6.57	6.22	4.19	5.80	3.99	4.82
420	8.24	5.49	7.63	4.54	7.43	3.72
500	0.85	16.33	0.61	13.98	0.58	11.83
500	1.79	11.89	0.92	11.73	0.98	9.16
500	3.71	8.72	2.00	8.64	2.05	7.04
500	6.61	6.59	4.02	6.31	3.99	5.21
500	7.94	5.86	7.49	4.95	7.44	4.22

Slope of the Trough (S) applies to the column groups above.

TABLE 6

SIMULATED RAINFALL TESTS - CORPS OF ENGINEERS [2]
SIMULATED TURF WITH n = 0.20

Slope of the Trough

Length L (ft)	S = 0.005		S = 0.010		S = 0.020	
	Rain Rate i (in/hr)	Average T_e (min)	Rain Rate i (in/hr)	Average T_e (min)	Rain Rate i (in/hr)	Average T_e (min)
84	0.61	24.00	0.61	16.66	0.63	12.09
84	1.04	16.84	0.99	13.24	1.03	10.07
84	2.00	11.20	1.98	9.03	2.02	7.91
84	3.94	7.78	3.82	5.89	4.06	5.36
84	7.45	5.28	8.13	4.05	7.40	4.00
168	1.02	21.25	1.01	16.94	1.02	15.27
168	2.03	14.31	1.88	11.50	1.97	10.76
168	3.89	9.84	4.08	7.82	4.04	7.04
252	1.04	24.50	0.99	19.92	1.05	17.52
252	2.00	16.61	1.95	13.57	1.92	12.40
252	3.98	11.57	3.98	9.95	4.08	8.45
336	0.60	36.67	0.57	30.54	0.60	26.87
336	1.05	27.14	0.99	21.74	1.03	19.66
336	2.01	18.59	2.00	15.37	1.97	13.99
336	3.95	12.92	4.05	10.93	3.92	9.59
336	7.53	9.35	7.50	7.56	7.61	6.56
420	0.62	38.37	--	--	--	--
420	1.03	29.18	0.96	23.88	1.04	21.40
420	2.02	20.14	2.04	17.62	1.92	15.20
420	3.99	14.16	3.83	12.29	3.93	10.37
500	0.61	41.51	0.60	33.06	0.65	29.19
500	1.00	31.82	1.00	25.91	1.01	23.82
500	2.00	22.02	2.03	18.93	1.94	16.85
500	3.93	15.29	3.92	13.17	3.96	10.80
500	7.45	10.94	7.50	8.78	7.46	7.78

TABLE 7

TIMES OF CONCENTRATION FOR THE COLORADO STATE UNIVERSITY EXPERIMENTS

No.	Run #	Date	Rainfall Intensity i inch/hr	Rainfall Duration T_r min	Time of Equilibrium T_e min	Time to Peak T_p min	Lag Time T_l min	Time of Concentr. T_c min
	Configuration No. 9 (1970): L = 110 ft., S = 0.05, n = 0.13							
1	71B	8/7	0.440	1.25		5.22	4.60	7.66
2	72	8/7	0.859	10.63	6.83			6.83
3	73	8/7	1.922	9.87	5.33			5.33
4	74A	8/10	4.228	9.87	3.73			3.73
5	74B	8/10	4.250	9.85	3.67			3.67
6	75A	8/10	2.019	10.37	4.45			4.45
7	75B	8/10	2.017	10.22	5.10			5.10
8	77B	8/10	0.440	1.36		4.67	3.99	6.65
9	78B	8/11	0.440	2.01		4.80	3.80	6.33
10	79B	8/11	0.440	2.83		4.97	3.56	5.93
11	80B	8/11	0.440	3.40		5.45	3.75	6.25
12	84	8/11	0.859	1.01		4.00	3.50	5.83
13	85	8/11	0.859	1.88		4.05	3.11	5.18
14	86	8/11	0.859	3.03		4.67	3.16	5.26
15	88B	8/11	2.019	1.09		3.52	2.98	4.96
16	89	8/11	2.019	1.74		3.50	2.63	4.38
17	90	8/11	2.019	2.21		3.55	2.45	4.08
18	91	8/11	2.019	2.38		3.43	2.24	3.73
19	94	8/12	4.228	1.14		2.42	2.35	3.92
20	96	8/12	4.228	1.29		2.93	2.29	3.81
	Configuration No. 14 (1970): L = 110 ft., S = 0.05, n = 0.16							
21	144	8/24	0.427	7.32	6.13			6.13
22	145	8/24	0.935	8.50	6.12			6.12
23	146A	8/24	1.839	8.00	5.13			5.13
24	147	8/24	2.838	9.05	4.75			4.75
25	148	8/24	3.559	8.10	4.45			4.45
26	149	8/27	0.784	4.54		5.67	3.40	5.67
27	150	8/27	0.784	1.03		4.63	4.12	6.86
28	151	8/27	1.802	3.79		4.83	2.94	4.89
29	153	8/27	2.838	3.25		3.88	2.26	3.76
30	155	8/27	3.675	3.41		3.77	2.07	3.44
31	159	8/28	0.784	8.35	6.53			6.53
32	160	8/28	1.805	7.70	4.85			4.85
33	161	8/28	2.610	16.85	4.62			4.62
34	162A	8/28	3.675	6.77	4.37			4.37

Table 7 (Cont.)

No.	Run	Date	Rainfall Intensity i inch/hr	Rainfall Duration T_r min	Time of Equilibrium T_e min	Time to Peak T_p min	Lag Time T_l min	Time of Concentr. T_c min
	Configuration No. 20 (1970): L = 110 ft., S = 0.05, n = 0.20							
35	162B	9/1	0.390	11.05	8.05			8.05
36	163	9/1	0.837	9.15	6.48			6.48
37	164	9/1	1.799	9.52	5.68			5.68
38	165	9/1	2.619	8.90	5.23			5.23
39	166	9/1	3.769	8.32	4.98			4.98
40	169	9/2	0.837	4.30		6.40	4.25	7.08
41	170	9/2	1.799	1.13		5.58	5.02	8.36
42	171	9/2	1.799	4.24		6.03	3.91	6.52
43	173A	9/2	3.769	3.50		4.17	2.42	4.03
44	175A	9/2	2.619	4.18		4.87	2.78	4.63
	Configuration No. 21 (1970):L = 110 ft., S = 0.05, n = 0.25							
45	177A	9/4	0.391	13.25	10.97			10.97
46	178A	9/4	0.842	10.38	10.27			10.27
47	179A	9/4	1.760	10.75	6.97			6.97
48	180A	9/4	2.617	8.63	6.00			6.00
49	181A	9/4	3.552	8.70	5.03			5.03
	Configurations No. 22, 23, 24 (1970): L = 110 ft., S = 0.05, n = 0.035							
50	182B	9/16	1.791	2.08		7.67	6.63	11.05
51	183	9/16	1.791	3.42		7.75	6.04	11.07
52	184	9/16	1.791	5.58		6.67	3.88	6.47
53	186	9/17	3.709	1.42		6.00	5.29	8.82
54	187	9/17	3.709	1.79		5.83	4.94	8.23
55	188	9/17	3.709	2.62		4.82	3.51	5.85
56	190	9/22	0.895	9.85	8.83			8.83
57	191	9/22	0.890	1.10		7.50	6.95	11.58
58	192	9/22	0.890	3.79		6.20	4.31	7.18
59	193	9/22	0.890	5.74		6.67	3.80	6.33
60	194	9/22	4.025	12.65	5.72			5.72
61	196	9/22	4.025	2.07		3.33	2.30	3.83
62	197	9/22	4.025	3.50		4.00	2.25	3.75
63	198	9/24	0.877	10.73	8.47			8.47
64	199	9/24	0.877	1.35		5.77	5.10	8.49
65	200	9/24	0.877	3.72		4.88	3.02	5.03
66	203	9/25	3.368	9.30	5.80			5.80
67	204	9/25	3.734	6.80	5.47			5.47
68	207	9/25	3.734	2.25		3.12	2.00	3.33

Table 7 (Cont.)

No.	Run	Date	Rainfall Intensity i inch/hr	Rainfall Duration T_r min	Time of Equilibrium T_e min	Time to Peak T_p min	Lag Time T_l min	Time of Concentr. T_c min
	Configuration No. 17 (1970): L = 100 ft., S = 0.05, n = 0.035							
69	113B	8/14	0.871	11.63	4.23			4.23
70	114	8/14	1.821	9.83	2.77			2.77
71	115	8/14	3.610	9.85	2.25			2.25
72	118	8/18	0.871	1.70		2.50	1.65	2.75
73	120	8/18	1.821	1.47		1.87	1.14	1.89
74	121	8/18	1.821	1.99		2.33	1.34	2.23
75	123	8/18	3.756	2.30	1.75			1.75
76	125	8/19	0.740	9.55	4.80			4.80
77	126	8/19	0.816	6.88	4.05			4.05
78	127	8/19	1.850	4.93	2.77			2.77
79	128	8/19	3.756	3.97	1.90			1.90
80	129	8/20	0.437	8.95	6.80			6.80
	Configuration No. 27 (1971): L = 186 ft, S = 0.0425, n = 0.035							
81	306	7/28	0.997	5.93	4.45			4.45
82	307	7/28	0.413	7.10	5.77			5.77
83	308	7/28	2.097	4.95	3.05			3.05
84	309	7/28	4.086	3.03	2.22			2.22
85	312	7/28	4.234	1.06		1.75	1.22	2.03
86	313	7/28	4.234	1.48		1.92	1.18	1.97
87	314	7/28	4.270	4.02	2.04			2.04
88	316	7/28	2.097	1.94		2.50	1.53	2.55
89	317	7/28	2.097	2.90		3.13	1.68	2.80
90	319	7/29	0.977	1.89		3.27	2.33	3.88
91	320	7/29	0.977	3.10		3.83	2.28	3.80
92	322	7/30	0.413	1.67		4.37	3.54	5.89
93	323	7/30	0.413	2.38		4.55	3.36	5.60

TABLE 8
TIMES OF CONCENTRATION FOR THE UNIVERSITY OF ILLINOIS EXPERIMENTAL WATERSHED TESTS

Fig. in Ref. [17]	No.	Average Slope S ft/ft	Rainfall Intensity i inch/hr	Rainfall Duration T_r min	Time of Equilibrium T_e min	Time to Peak T_p min	Lag Time T_l min	Time of Concen. T_c min
A1.a	1	0.067	2.72	1.22		3.27	2.66	4.43
A1.a	2	0.067	2.72	2.44		3.78	2.56	4.27
A1.a	3	0.067	2.72	9.84	5.03			5.03
A1.b	4	0.067	4.29	1.23		3.05	2.44	4.06
A1.b	5	0.067	4.29	2.45		3.68	2.46	4.09
A1.b	6	0.067	4.29	9.84	4.64			4.64
A1.c	7	0.067	4.83	1.22		3.09	2.48	4.13
A1.c	8	0.067	4.83	2.54		3.84	2.57	4.28
A1.c	9	0.067	4.83	9.75	4.91			4.91
A1.d	10	0.067	6.86	1.23		2.80	2.19	3.64
A1.d	11	0.067	6.86	2.44		3.10	1.88	3.13
A1.d	12	0.067	6.86	4.93	3.85			3.85
A2.a	13	0.010	2.73	1.22		2.77	2.16	3.60
A2.a	14	0.010	2.73	2.45		3.26	2.04	3.39
A2.a	15	0.010	2.73	9.95	4.14			4.14
A2.b	16	0.010	4.34	1.23		2.61	2.00	3.33
A2.b	17	0.010	4.34	2.46		3.32	2.09	3.48
A2.b	18	0.010	4.34	9.93	3.71			3.71
A2.c	19	0.010	4.82	1.23		2.50	1.89	3.14
A2.c	20	0.010	4.82	2.46		3.20	1.97	3.28
A2.c	21	0.010	4.82	9.80	3.42			3.42
A2.d	22	0.010	6.88	1.21		2.24	1.64	2.73
A2.d	23	0.010	6.88	2.49		2.89	1.65	2.74
A2.d	24	0.010	6.88	4.92	3.14			3.14
A3.a	25	0.023	2.75	1.23		2.37	1.76	2.93
A3.a	26	0.023	2.75	2.43		2.98	1.77	2.94
A3.a	27	0.023	2.75	9.87	3.49			3.49
A3.b	28	0.023	4.32	1.23		2.06	1.45	2.41
A3.b	29	0.023	4.32	2.46		2.78	1.55	2.58
A3.b	30	0.023	4.32	9.84	3.03			3.03
A3.c	31	0.023	4.82	1.22		2.14	1.53	2.55
A3.c	32	0.023	4.82	2.44		2.85	1.68	2.72
A3.c	33	0.023	4.82	4.92	3.13			3.13
A3.d	34	0.023	6.84	1.21		2.05	1.45	2.41
A3.d	35	0.023	6.84	2.47		2.76	1.53	2.54
A3.d	36	0.023	6.84	4.95	3.01			3.01

TABLE 9
FOUR-PARAMETER T_c EQUATION*
REGRESSION ANALYSIS RESULTS

Data Source & Watershed Type	No.of Data	k	a	b	y	z	Standard Deviation σ	Coeff. of Variation $\sigma/\overline{\log T_c}$ (%)	R^2 (%)
USDA-ARS Natural	84	1.04	0.60	0.96	0.24	0.29	0.126	9.0	76.8
US Corps Experimental	162	0.95	0.41	0.49	0.33	0.47	0.035	3.7	98.6
CSU Eperimental	93			0.43		0.30	0.089	12.4	75.2
Univ. of Illinois Experimental	36				0.30	0.24	0.044	8.4	76.4
All Experimental Corps + CSU + UI	291	0.75	0.42	0.48	0.26	0.42	0.062	7.7	95.5
All data Natural plus Experimental	375	0.66	0.50	0.52	0.31	0.38	0.092	9.8	94.1

* Equation $T_c = k L^a n^b S^{-y} i^{-z}$

TABLE 10

ONE-PARAMETER T_c EQUATION*
REGRESSION ANALYSIS RESULTS

Data Source & Watershed Type	No. of Data	k	x	Standard Deviation σ	Coef. of Variation $\sigma/\overline{\log T_c}$(%)	R^2 (%)
USDA-ARS Natural	84	0.98	0.44	0.140	10.0	70.5
UC Corps Experimental	162	0.49	0.52	0.070	6.8	95.1
CSU Experimental	93	0.62	0.47	0.090	12.6	79.3
Univ. of Illinois Experimental	36	0.75	0.43	0.040	8.4	75.6
All Experimental Corps + CSU + UI	291	0.55	0.50	0.070	8.8	94.1
All data Natural plus Experimental	375	0.52	0.52	0.095	10.0	93.7

* Equation $T_c = k\,[L\,n\,(Si)^{-2/3}]^x$

Table 11
TOLERANCE LIMITS

	P(%)	D	$\Delta \overline{\log T_c}$	Tolerance Interval of T_c	Best Fit k	Tolerance Interval of k
Four Parameter	75	1.23	± 0.113	$0.77 < T_c/\overline{T}_c < 1.30$		$0.51 < k < 0.86$
Equation 14	90	1.75	± 0.161	$0.69 < T_c/\overline{T}_c < 1.45$	0.66	$0.45 < k < 0.96$
	95	2.09	± 0.192	$0.64 < T_c/\overline{T}_c < 1.56$		$0.42 < k < 1.03$
One Parameter	75	1.23	± 0.117	$0.76 < T_c/\overline{T}_c < 1.31$		$0.40 < k < 0.68$
Equation 17	90	1.75	± 0.166	$0.68 < T_c/\overline{T}_c < 1.47$	0.52	$0.35 < k < 0.76$
	95	2.09	± 0.199	$0.63 < T_c/\overline{T}_c < 1.58$		$0.33 < k < 0.82$

TABLE 12
UNITS OF THE TIME OF CONCENTRATION EQUATION

Units	T	L	i	k of Four-Parameter Equation 14	k of One-Parameter Equation 17
English Customary	min	ft	in/hr	k	k
International System (SI)	sec	m	m/sec	1.18k	1.86k
Metric Customary	min	m	cm/hr	2.60k	2.55k

TABLE 13

COMPARISON OF EXPONENTS BETWEEN VARIOUS TIME OF CONCENTRATION EQUATIONS

Equation	Exponent of L	Exponent of S	Exponent of i
a) Kirpich	0.77	−0.385	0
b) Izzard	0.33	−0.333	−0.667
c) Kerby	0.467	−0.233	0
d) Carter	0.60	−0.30	0
e) Eagleson	0.76	−0.19	0
f) Kinematic Wave	0.60	−0.30	−0.40
g) Morgali	0.593	−0.38	−0.388
h) FAA	0.50	−0.333	0
i) SCS Curve	0.80	−0.50	0
j) SCS Velocity Method	1.0	−0.50	0
k) Singh/Chezy	0.667	−0.333	−0.333
l) 4-parameter Equation 14	0.50	−0.31	−0.38
m) 1-parameter Equation 17	0.52	−0.35	−0.35

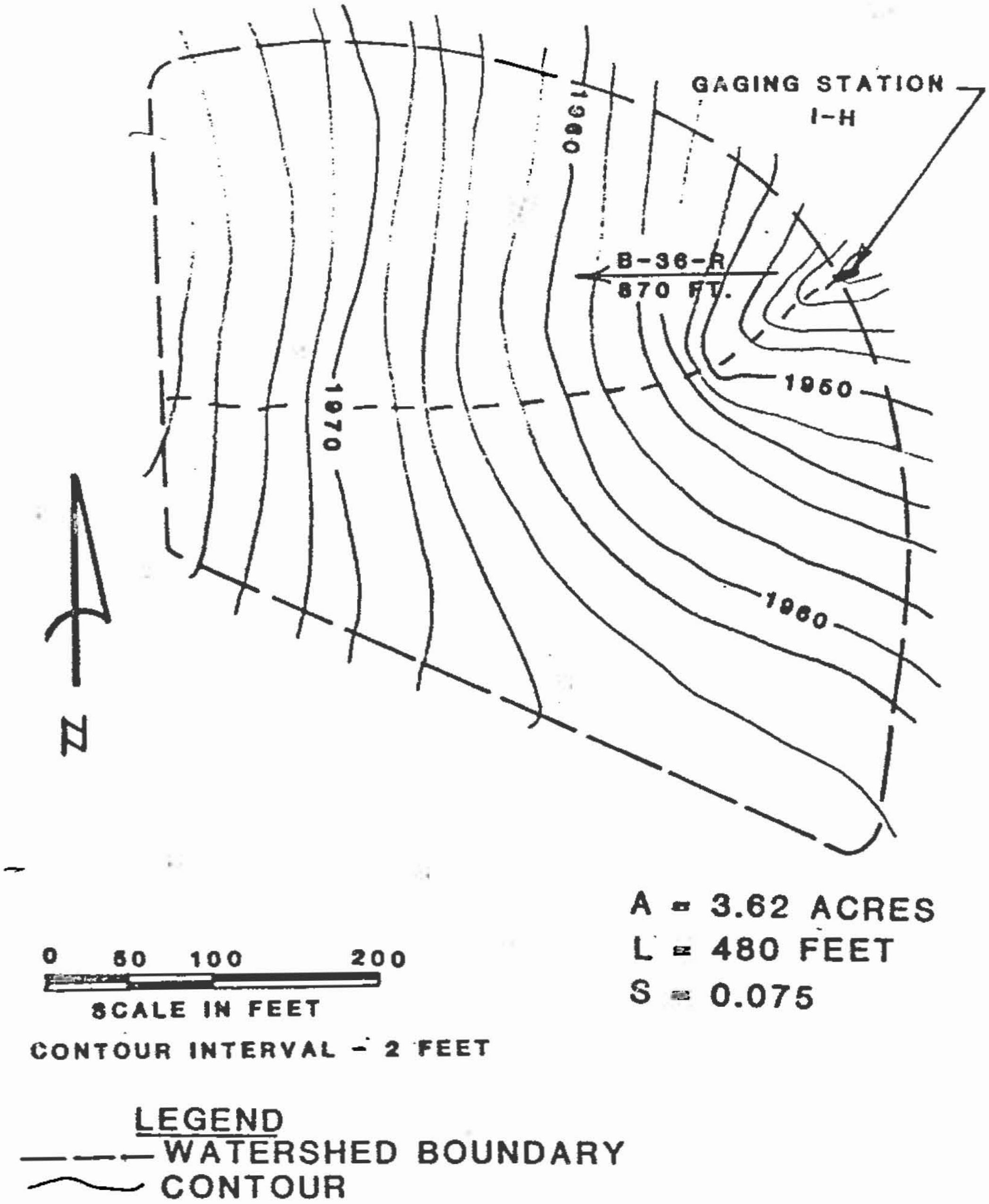


Figure 1. WATERSHED 1-H IN HASTINGS, NEBRASKA. PLAN VIEW.

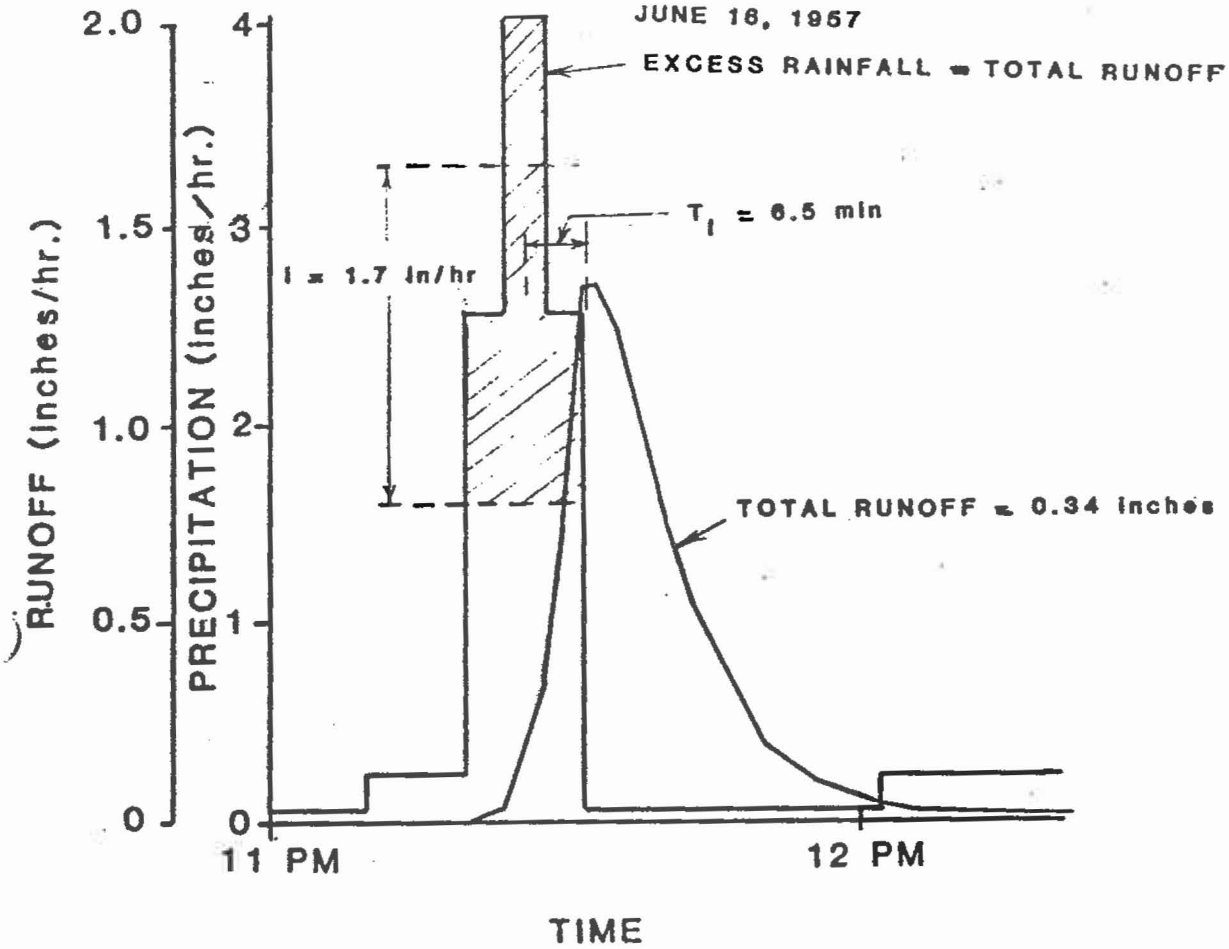


Figure 2. WATERSHED 1-H IN HASTINGS, NEBRASKA.
RAINFALL EVENT OF JUNE 16, 1957.
AVER. EXCESS RAINFALL INTENSITY i = 1.7 in/hr
TIME OF CONCENTRATION T_c = 6.5/0.6 = 10.8 min.

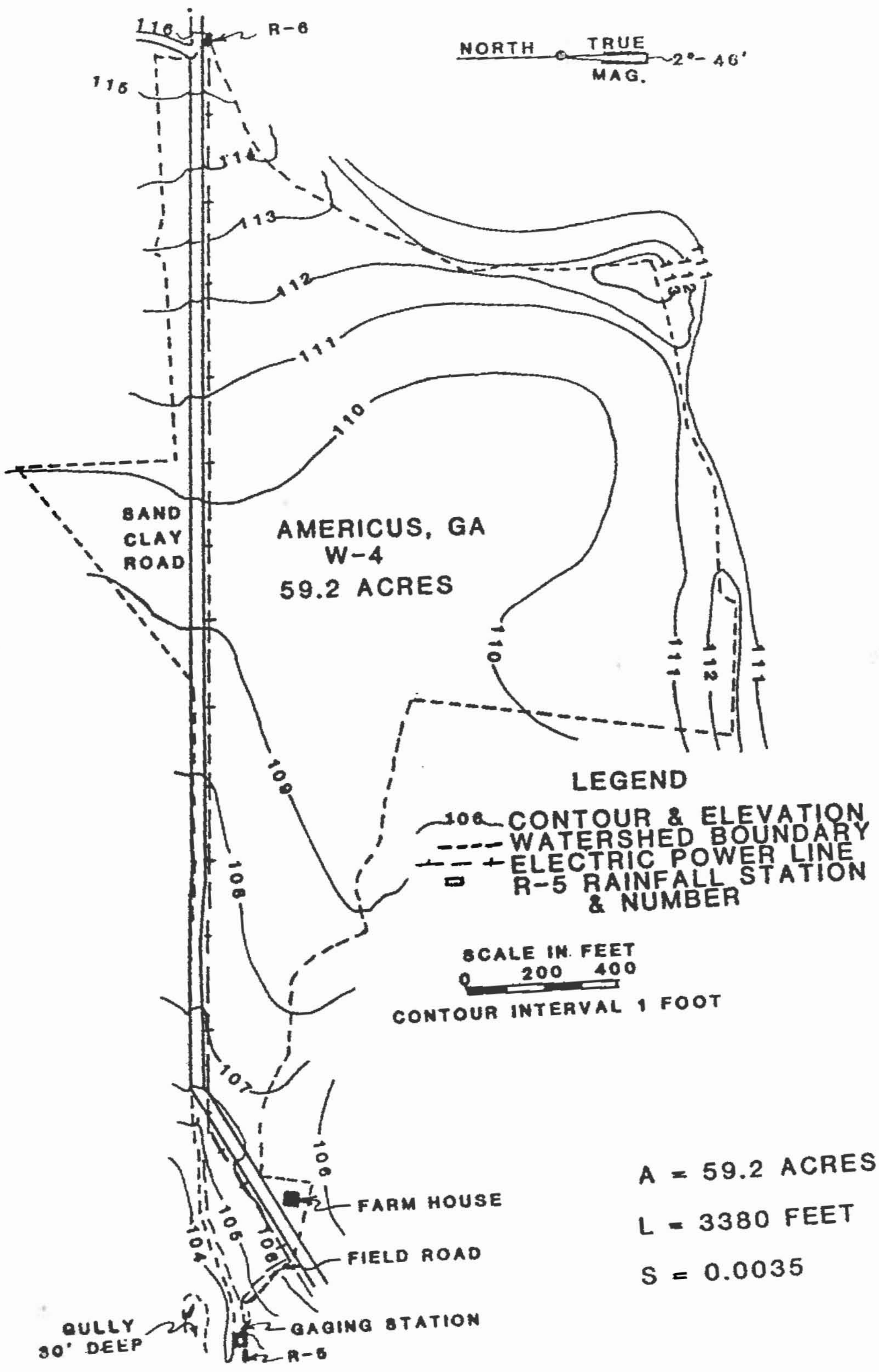


Figure 3. WATERSHED W-IV IN AMERICUS, GEORGIA. PLAN VIEW.

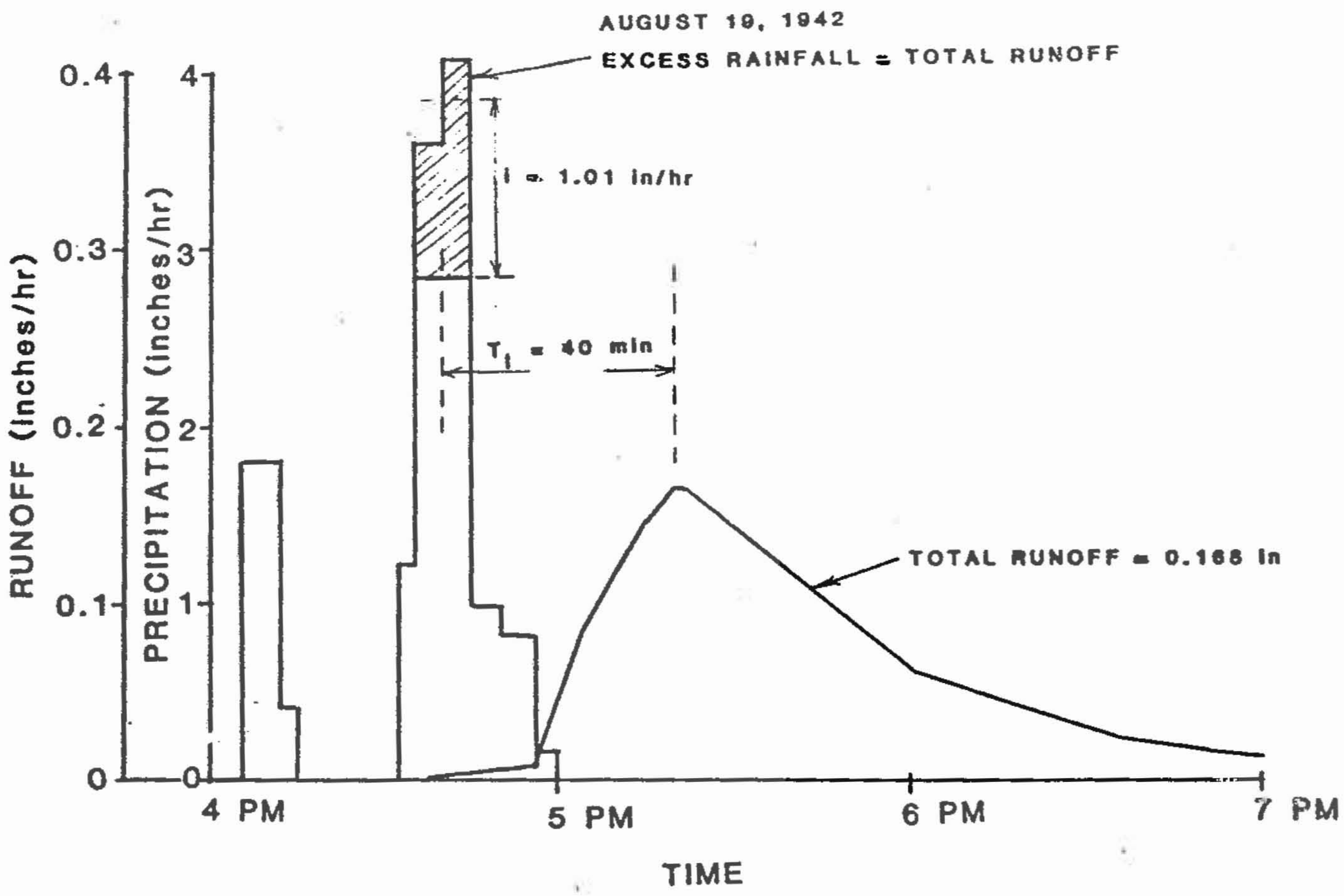


Figure 4. WATERSHED W-IV IN AMERICUS, GEORGIA
RAINFALL EVENT OF AUGUST 19, 1942
AVER. EXCESS RAINFALL INTENSITY i = 1.01 in/hr
TIME OF CONCENTRATION T_c = 40/0.6 = 67 min.

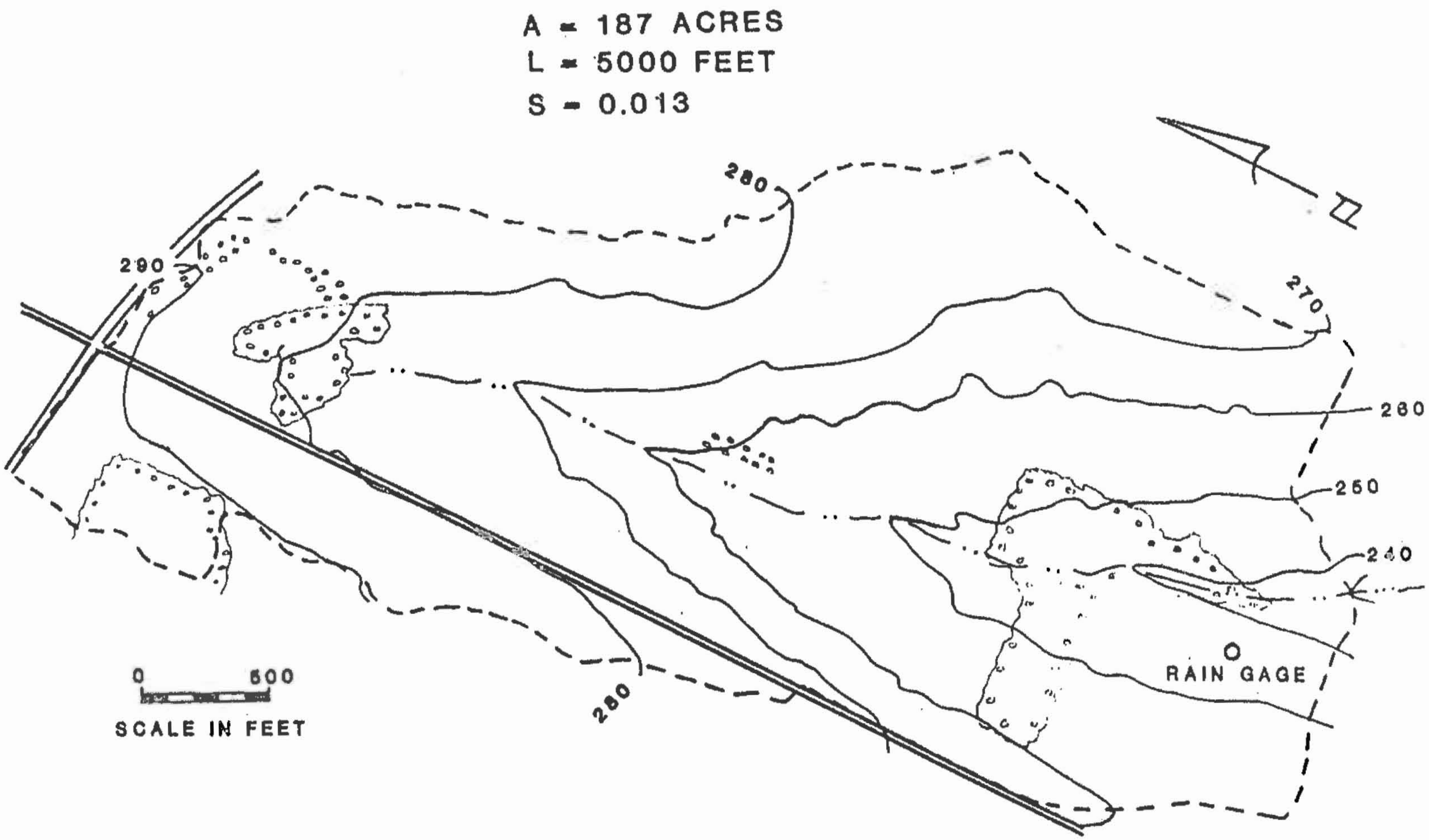


Figure 5. WATERSHED W-I IN HAMILTON, OHIO. PLAN VIEW

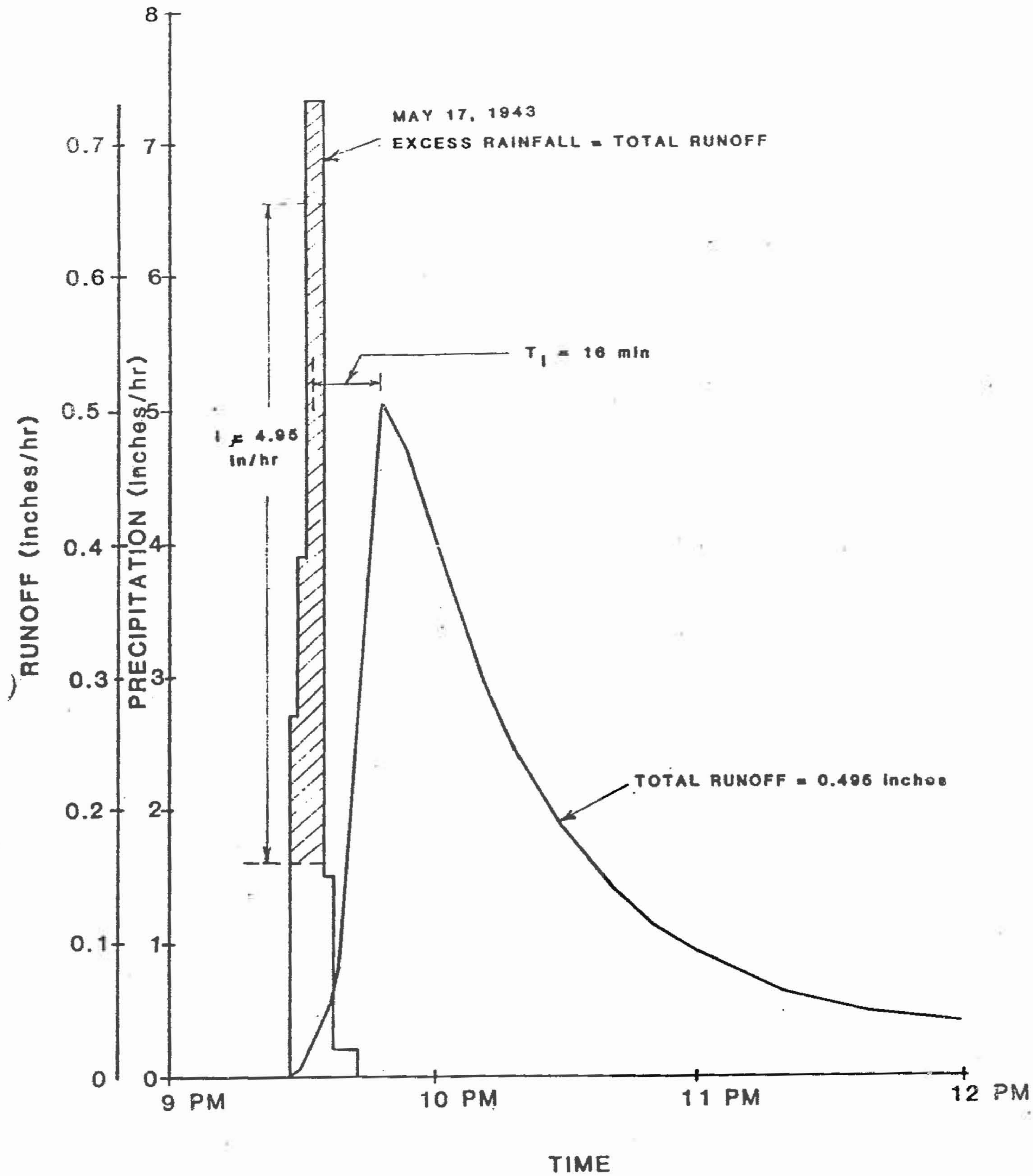


Figure 6. WATERSHED W-I IN HAMILTON, OHIO
RAINFALL EVENT OF MAY 17, 1943
AVER. EXCESS RAINFALL INTENSITY i = 4.95 in/hr
TIME OF CONCENTRATION T_c = 16/0.6 = 27 min.

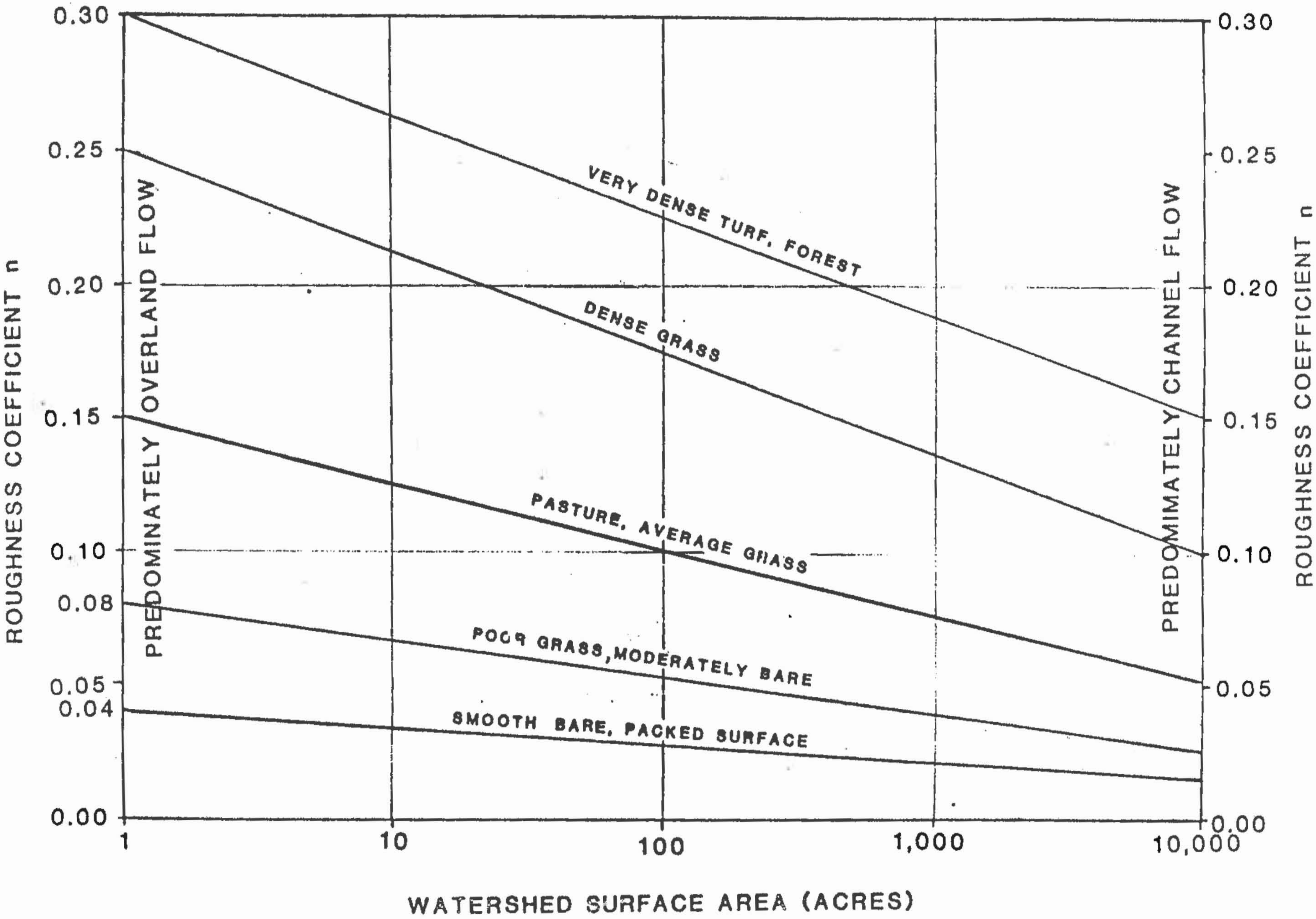


Figure 7. THE EFFECT OF WATERSHED AREA ON THE ROUGHNESS COEFFICIENT.

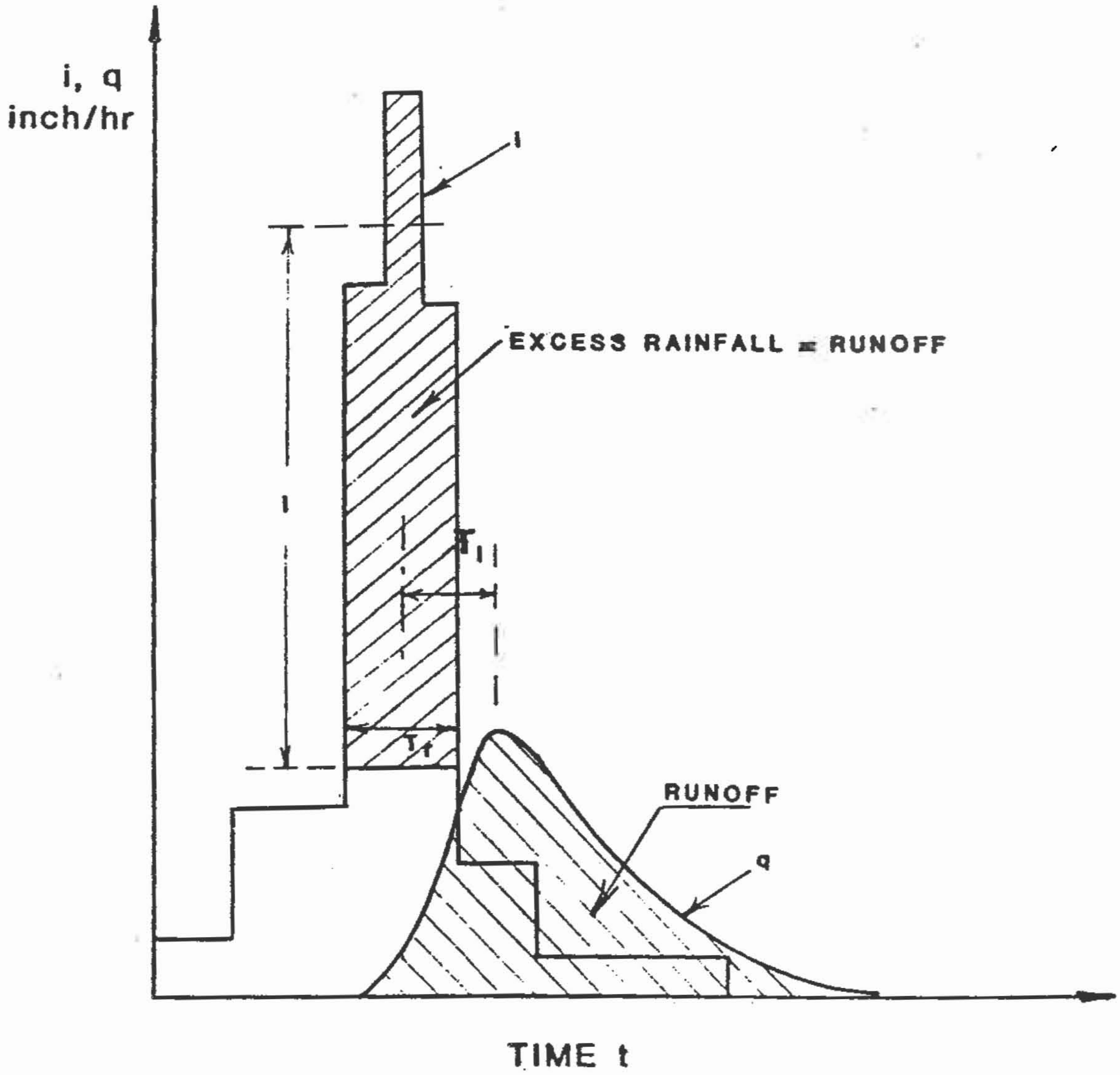
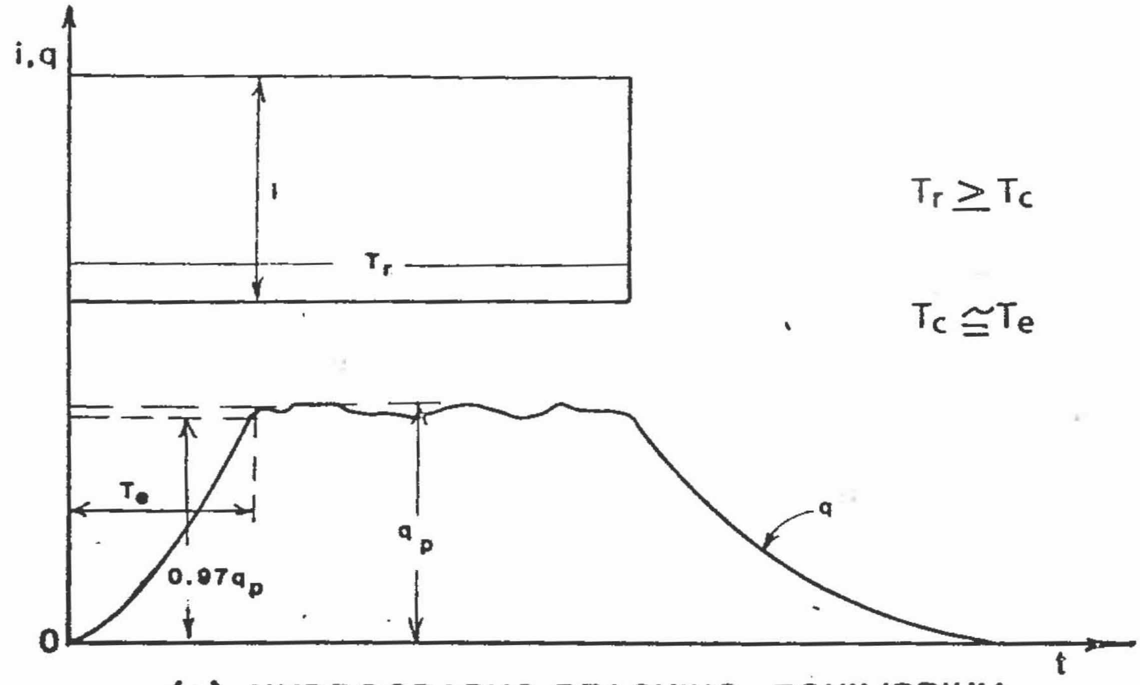
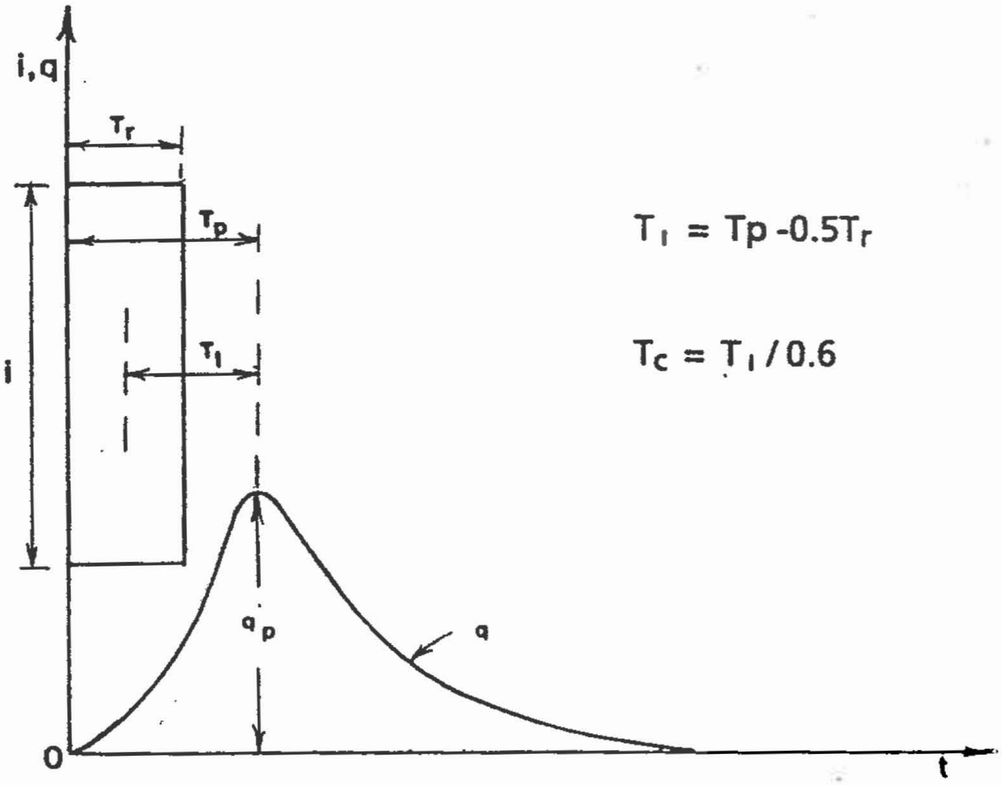


Figure 8. ESTIMATION OF EXCESS RAINFALL INTENSITY i, TIME OF EXCESS RAINFALL T_r, and LAG TIME T_l.



(a) HYDROGRAPHS REACHING EQUILIBRIUM



(b) NON-EQUILIBRIUM HYDROGRAPHS WITH PEAK DISCHARGE

Figure 9. ESTIMATION OF TIME OF CONCENTRATION, T_c, FROM A MEASURED HYETOGRAPH AND HYDROGRAPH.

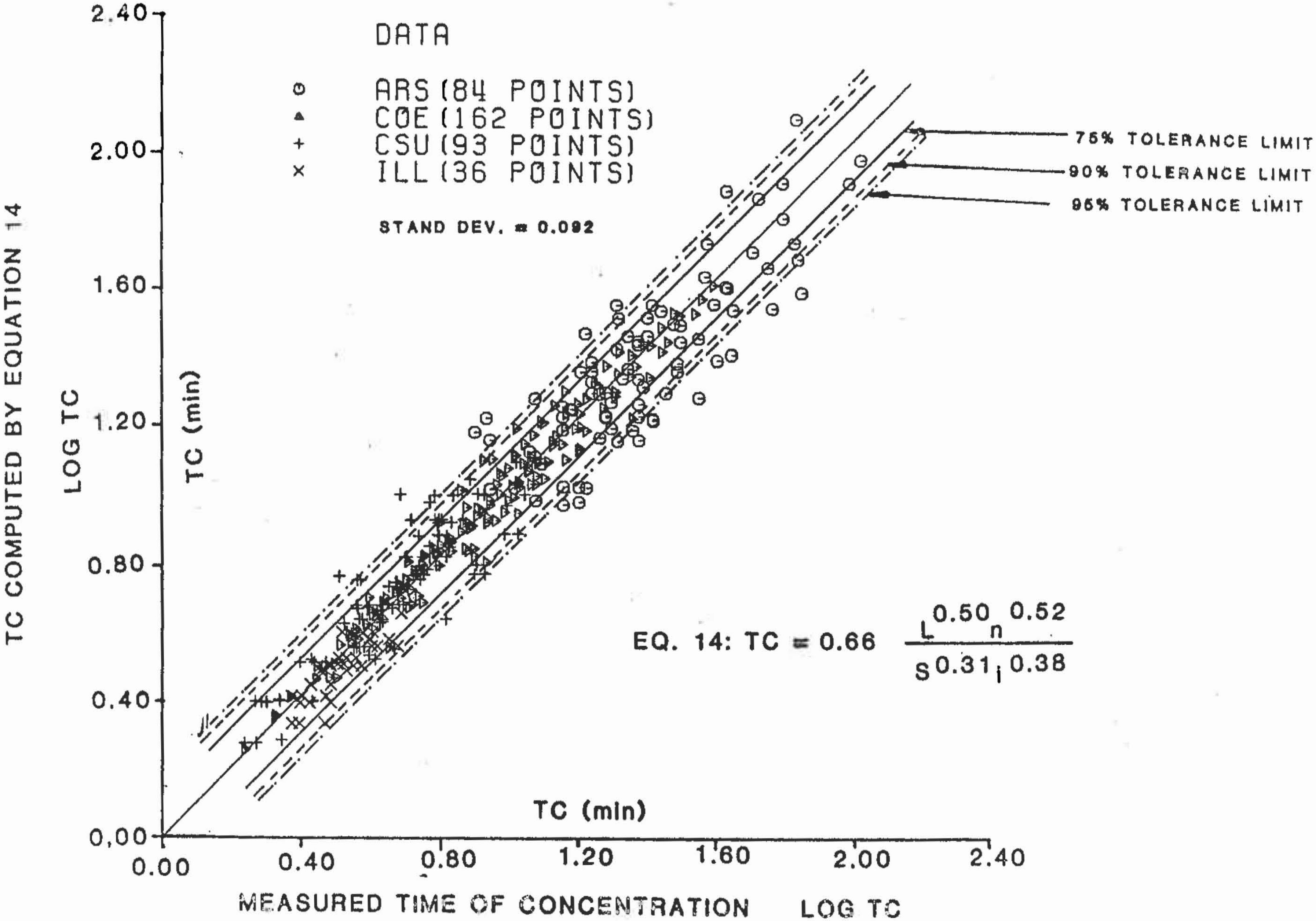


Figure 10. TIMES OF CONCENTRATION COMPUTED BY THE FOUR-PARAMETER EQUATION 14 VERSUS MEASURED VALUES.

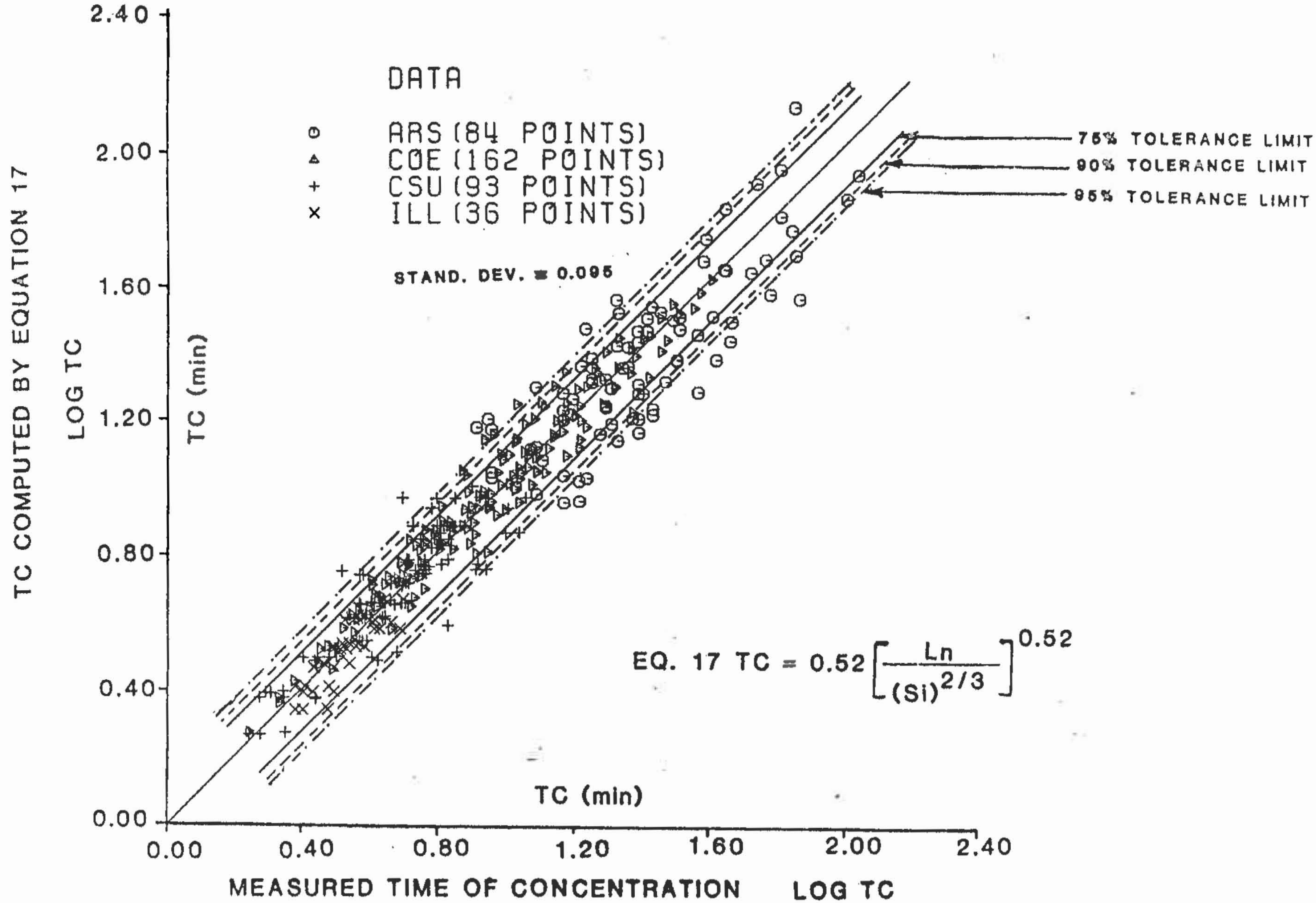


Figure 11. TIME OF CONCENTRATION COMPUTED BY THE ONE-PARAMETER EQUATION 17 VERSUS MEASURED VALUES.

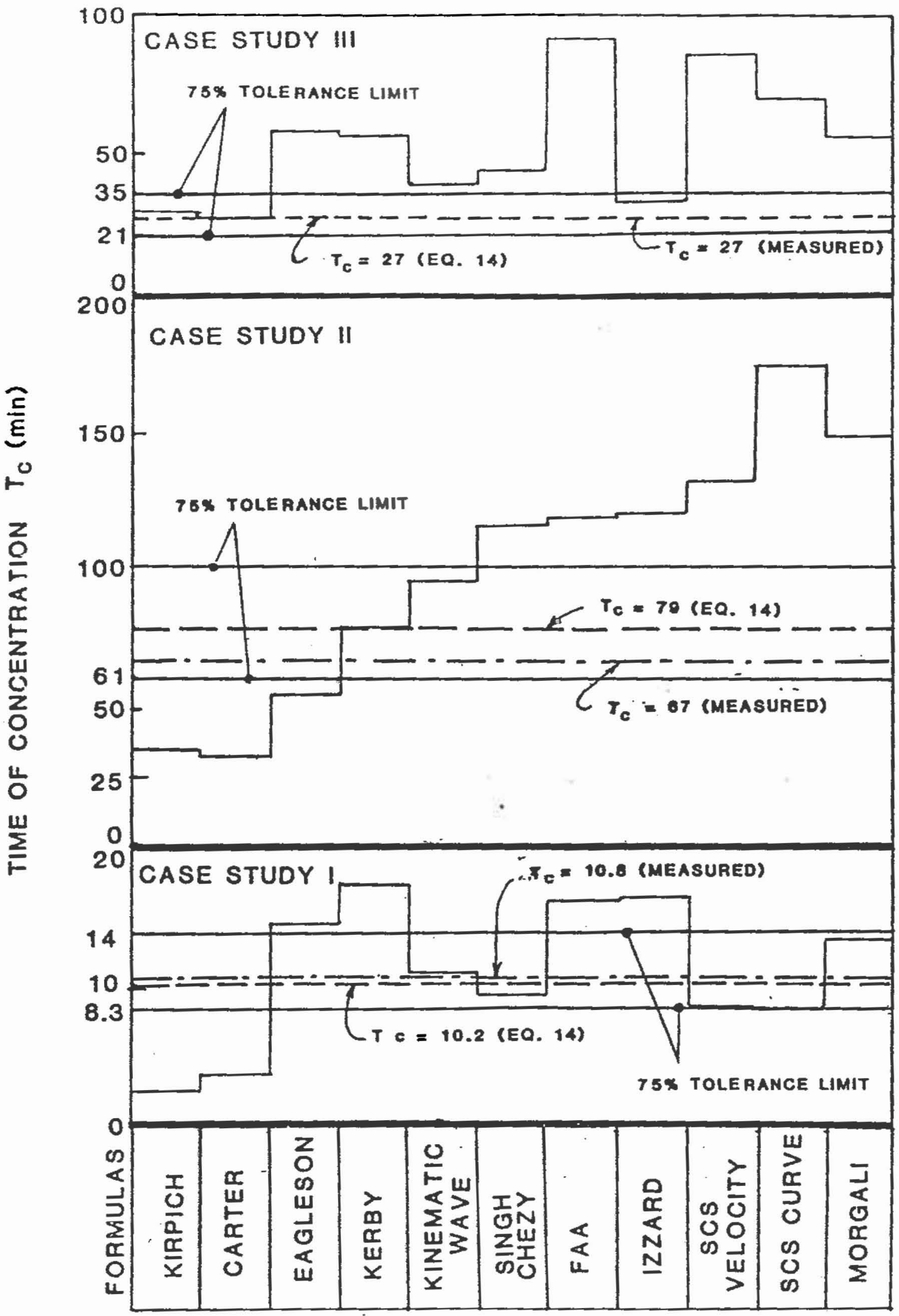


Figure 12. COMPARISON OF TIMES OF CONCENTRATION FOR THREE CASE STUDIES