science for a changing world

In cooperation with the Illinois Department of Natural Resources, Office of Water Resources

Equations for Estimating Clark Unit-Hydrograph Parameters for Small Rural Watersheds in Illinois

Water-Resources Investigations Report 00–4184

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

In cooperation with the Illinois Department of Natural Resources, Office of Water Resources

Equations for Estimating Clark Unit-Hydrograph Parameters for Small Rural Watersheds in Illinois

By Timothy D. Straub, Charles S. Melching, and Kyle E. Kocher

Water-Resources Investigations Report 00–4184

Urbana, Illinois
2000

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

For additional information write to:

District Chief
U.S. Geological Survey
221 North Broadway Avenue
Urbana, IL 61801

Copies of this report can be purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286
Denver, CO 80225-0286

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
	Area	
square mile (mi^2)	2.590	square kilometer
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer

Equations for Estimating Clark Unit-Hydrograph Parameters for Small Rural Watersheds in Illinois

By Timothy D. Straub, Charles S. Melching, *and* Kyle E. Kocher

Abstract

Equations for estimating the time of concentration (T_C) and storage coefficient (R) of the Clark unit-hydrograph method were developed for small rural watersheds [0.02–2.3 square miles (mi^2)] in Illinois. The equations will provide State and local engineers and planners with more accurate methods to estimate the T_C and R for use in simulating discharge hydrographs on small rural watersheds when designing stormwater-management facilities and other hydraulic structures, determining flood-plain boundaries, and assessing the safety of structures in rivers.

The rainfall and runoff data from gaged small rural watersheds (0.02–2.3 mi^2) with insignificant amounts of impervious land cover in Illinois were used to develop the equations. Equations were developed on the basis of data for 121 storms that occurred in 39 watersheds. Data for 29 storms in 18 watersheds were used to verify the equations.

T_C and R were determined by calibrating available rainfall and runoff data, using the U.S. Army Corps of Engineers Flood Hydrograph Package HEC-1. The mathematical relations between watershed and storm characteristics, and T_C and R were determined by multiple-linear regression of the logarithms of the values. Main-channel length and slope were identified as important watershed characteristics for estimating T_C and R. The estimation equations had coefficients of determination of 0.73 and 0.64 for the logarithms of T_C and R, respectively. When storm characteristics were added in the regression of hydrograph parameters utilizing length and slope, only minimal increases to the coefficient of determination resulted. Thus, storm characteristics were not considered further in development of the equations.

Simulation of the measured discharge hydrographs for the verification storms utilizing T_C and R obtained from the estimation equations yielded good results. The error in peak discharge for 21 of the 29 verification storms was less than 25 percent, and the error in time-to-peak discharge for 18 of the 29 verification storms also was less than 25 percent. Therefore, applying the estimation equations to determine T_C and R for design-storm simulation may result in reliable design hydrographs, as long as the physical characteristics of the watersheds under consideration are within the range of those characteristics for the watersheds in this study [area: 0.02–2.3 mi^2, main-channel length: 0.17–3.4 miles, main-channel slope: 10.5–229 feet per mile, and insignificant percentage of impervious cover].

[A compact disk containing the rainfall and runoff data, HEC-1 input files and digital format of this report is included with the report.]

INTRODUCTION

Designing stormwater-management facilities and other hydraulic structures (such as culverts and bridge waterways), determining flood-plain boundaries, and assessing the safety of structures in rivers typically involve applying a design hydrograph. These design hydrographs are computed on the basis of design storms of a specified probability of occurrence determined from standard references, such as the

U.S. Weather Bureau Technical Paper Number 40 (Hershfield, 1961) or the Illinois State Water Survey Bulletin 70 (Huff and Angel, 1989). Abstractions from rainfall resulting from interception, depression storage, and infiltration then are determined on the basis of available data from the literature and considering the effects of the soil type, land cover/land use, and antecedent-moisture conditions. Typically, the Soil Conservation Service (SCS, now known as the Natural Resources Conservation Service) (1985) curve-number method is applied to determine the abstractions. By subtracting the abstractions from the design rainfall, the precipitation excess, which approximately equals the direct runoff (effective precipitation) resulting from the design storm, is obtained. By utilizing a synthetic unit hydrograph, the precipitation excess then is transformed into a simulated discharge hydrograph at the outlet of the watershed. Areas larger than 1 mi^2 often are subdivided into a number of subwatersheds, and the runoff hydrographs from each subwatershed is routed to the watershed outlet with hydrologic- or hydraulic-routing methods.

This procedure for determining design hydrographs described above is utilized by the Illinois Department of Natural Resources, Office of Water Resources (IDNR-OWR) for many different water-resources-management issues. When determining design hydrographs, the IDNR-OWR typically divides watersheds into subwatersheds less than 1 mi^2 in area. Synthetic hydrographs then are developed for each subwatershed, utilizing the Clark (1945) unit-hydrograph method as implemented in the U.S. Army Corps of Engineers (1990) Flood Hydrograph Package (HEC-1). In the Clark method, the time of concentration (T_C) and storage coefficient (R) for a watershed must be specified. Therefore, values of T_C and R must be estimated for each subwatershed. Equations have been developed by Graf and others (1982a,b) and by Melching and Marquardt (1996) that relate T_C and R to watershed characteristics for watersheds in Illinois. Most data used to derive these equations were collected for watersheds with drainage areas greater than 10 mi^2. Therefore, the U.S. Geological Survey (USGS), in cooperation with the IDNR-OWR, began a study in 1998 to develop a new set of equations to estimate T_C and R derived from data for small rural watersheds (0.02–2.3 mi^2). These estimated values then could be used to apply the HEC-1 model with the Clark unit-hydrograph method in hydrologic design and analysis in Illinois.

Purpose and Scope

This report describes the results of the study to develop improved equations for estimating T_C and R for small rural watersheds (0.02–2.3 mi^2) in Illinois. The new equations will provide State and local engineers and planners with more accurate methods to estimate the T_C and R typically used to estimate design hydrographs. These more accurate estimates of T_C and R should result in more reliable design hydrographs relative to the current practice for water-resources-management activities, including designing stormwater-management facilities and other hydraulic structures, determining flood-plain boundaries, and assessing the safety of structures in rivers.

Selection and analysis of storms for use in calibrating and verifying the estimation equations for the hydrograph parameters is described. The established data base of rainfall and runoff data from gaged small rural watersheds in Illinois with insignificant amounts of impervious land cover is listed in table 1. For all storms in the data base, the direct-runoff depth is greater than 0.4 in. Watershed areas used in the storm analysis range from 0.02 to 2.3 mi^2. T_C and R for each storm were derived by calibrating rainfall and runoff data using the HEC-1 model. Multiple-linear regression techniques were used to develop mathematical relations that express T_C and R as functions of watershed characteristics for 39 small rural watersheds in Illinois. To verify and test the accuracy of the developed equations, two methods were used. For the verification storms, verifying the equations involved comparing T_C and R values derived by calibration using HEC-1 to T_C and R values estimated with the equations developed in this study. Verification also included comparing hydrographs computed on the basis of the estimated values of T_C and R to measured hydrographs for the verification storms.

Small Rural Watersheds for Which Rainfall and Runoff Data are Available

For the purpose of flood-frequency analysis on small streams in Illinois, a network of streamflow and rainfall gages on watersheds less than 10 mi^2 was established throughout the State (Curtis, 1977). The USGS operated these gages from 1956 to 1975. Typically, continuous records of rainfall and streamflow were collected for a period of 2-4 years, which was long

Table 1. Characteristics of small rural watersheds in Illinois and the number of storms used for developing and verifying equations for the estimation of Clark unit-hydrograph parameters

[mi^2, square miles; mi, miles; ft/mi, feet per mile; ISWS, Illinois State Water Survey; USDA, U.S. Department of Agriculture; na, not applicable]

Station number	Watershed	Number of storms for equation development	Number of storms for verification	Drainage area (mi^2)	Main channel Length (mi)	Main channel Slope (ft/mi)	Forest area (percent)
03336100	Big Four Ditch Tributary near Paxton	1	0	1.05	2.16	21.0	3.72
03338100	Salt Fork Tributary near Catlin	2	1	2.20	3.40	15.8	.00
03338800	North Fork Vermilion River Tributary near Danville	2	0	1.42	2.21	33.2	1.61
03341900	Raccoon Creek Tributary near Annapolis	3	2	.04	.303	52.8	.00
03344250	Embarras River Tributary near Greenup	1	1	.08	.38	10.5	.00
03380300	Dums Creek Tributary near Iuka	6	0	.08	.403	98.7	29.4
03380450	White Feather Creek near Marlow	5	2	.43	1.11	87.7	17.5
03381600	Little Wabash River Tributary near New Haven	2	0	.16	.62	89.8	43.0
03382025	Little Saline Creek Tributary near Goreville	4	1	.52	1.13	75.5	33.0
03385500	Lake Glendale Inlet near Dixon Springs	1	0	1.05	1.86	145	72.0
03612200	Q Ditch Tributary near Choat	2	0	.27	.80	141	40.0
05438850	Middle Branch of South Branch Kishwaukee River near Malta	1	1	1.67	2.60	28.7	.00
05439550	South Branch Kishwaukee River Tributary near Irene	0	2	1.71	2.22	53.8	6.00
05440900	Leaf River Tributary near Forreston	1	0	.15	.814	144	.00
05448050	Sand Creek near Milan	1	0	.22	.758	67.1	.00
05469750	Ellison Creek Tributary near Roseville	4	0	.26	1.67	28.8	.00
05495200	Little Creek near Breckenridge	8	1	1.45	1.82	34.5	5.27
05496900	Homan Creek Tributary near Quincy	1	0	.50	1.29	106	4.00
05502120	Kiser Creek Tributary near Barry	7	3	.78	1.20	78.7	15.0
05551800	Fox River Tributary Number Two near Fox	2	0	.45	1.02	87.1	7.00
05554600	Mud Creek Tributary near Odell	7	0	.16	.79	60.7	.00
05557100	West Bureau Creek Tributary near Wyanet	0	1	.33	1.65	97.2	.00
05558050	Coffee Creek Tributary near Florid	1	1	.03	.303	229	.00
05558075	Coffee Creek Tributary near Hennepin	3	1	.22	.852	139	2.00
05572100	Wildcat Creek Tributary near Monticello	3	0	.10	.330	18.0	.00
05577700	Sangamon River Tributary at Andrew	5	0	1.50	1.36	40.1	1.13
05586200	Illinois River Tributary at Florence	3	0	.49	1.11	132	23.8
05586500	Hurricane Creek near Roodhouse	3	0	2.30	3.30	24.3	5.16
05586850	Bear Creek Tributary near Reeders	3	0	.02	.17	63.4	.00
05587850	Cahokia Creek Tributary near Carpenter	2	0	.45	.918	42.5	12.7
05592700	Hurricane Creek Tributary near Witt	5	3	.14	.44	27.1	.00
05594200	Williams Creek near Cordes	3	0	1.90	2.88	17.2	2.12
05596100	Andy Creek Tributary at Valier	3	1	1.03	1.78	39.0	10.0
05599640	Green Creek Tributary near Jonesboro	3	0	.43	1.19	112	74.6
ISWSFS01	ISWS Field Site 1 near Highland	2	0	.073	.47	26.4	.00
ISWSFS06	ISWS Field Site 6 near Highland	3	1	.096	.48	24.5	.00
USDAIA1M	USDA Watershed IA1 near Monticello	1	2	.048	.33	54.4	.00
USDAIAMO	USDA Watershed IA near Monticello	2	3	.128	.49	33.5	.00
USDAIBMO	USDA Watershed IB near Monticello	6	2	.071	.53	31.9	.00
USDAW1ED	USDA Watershed W-1 near Edwardsville	4	0	.043	.21	72.3	.00
USDAW4ED	USDA Watershed W-4 near Edwardsville	5	0	.453	.81	196	.00
	Total	121	29	na	na	na	na

enough to measure six or more storms that could be used for model calibration. The continuous-record gages then were moved to another location and a crest-stage gage was used to measure annual peak flows at the given site.

Rainfall and streamflow data from two stations near Edwardsville, Ill., which were operated by the U.S. Department of Agriculture (USDA) from 1938 to 1955, were used in this study. The USDA and University of Illinois at Urbana-Champaign operated rainfall and streamflow gages on small watersheds at Allerton Farms and Park near Monticello, Ill., from 1949 to 1983. Data from three USDA Monticello gages are used in this study. Monitoring of the USDA watersheds at Allerton Farms and Park near Monticello, Ill., was supported by USDA Hatch project funds. The Illinois State Water Survey (ISWS) operated rainfall and streamflow gages on small watersheds near Highland Silver Lake, Ill., from 1981 to 1984. Data from two ISWS gages were used in this study.

Data collected from 150 storms with direct-runoff depths greater than 0.4 in. occurring in 41 watersheds were used in the study (fig. 1, table 1). Useful storm rainfall and runoff data are available for only 30 watersheds with areas less than 1 mi^2 in Illinois, which are of interest with respect to current IDNR-OWR practice. To broaden the range of storms, watershed conditions, locations within the State, and data from slightly larger watersheds (up to 2.3 mi^2) were included in the analysis. Inclusion of data from slightly larger watersheds should increase the general applicability of the developed equations for estimating T_C and R on watersheds less than 1 mi^2 without biasing the equations.

In the hydrologic data base, watershed areas range from 0.02 to 2.3 mi^2 and have insignificant impervious areas (only one or two country roads and an occasional rooftop from a house or shed). Most of the watersheds also have insignificant forest cover (table 1). The main-channel length of streams within the watersheds ranged from 0.17 to 3.4 mi (table 1). The main-channel length is measured along the main channel from the watershed outlet to the watershed divide. Main-channel slope ranged from 10.5 to 229 ft/mi. For all USGS, ISWS, and USDA Monticello sites, the main-channel slope was determined from elevations at points 10 and 85 percent of the distance along the main channel from the watershed outlet to the watershed divide. The slope and length were determined from USGS topographic maps (if an adequate number of contours were within the watershed) or from a field survey (for the smaller watersheds with an inadequate number of contours). Slopes for the two USDA watersheds near Edwardsville were determined from a report describing the length, area, and percent slope (U.S. Department of Agriculture, 1957). The slope values were given in the form “63% of the watershed is in 0–1.5% class; 21% in 1.5–4%; 9% in 4–7%; 7% in 7–12%.” For these two watersheds, 10 percent of the gentlest sloping area and 15 percent of the steepest sloping area were removed and a weighted average was computed from the remaining values to determine the slope.

Data from 150 storms that occurred in 41 watersheds were used in the calibration and verification of the equations (table 1). Equations were developed using data for 121 storms that occurred in 39 watersheds (table 1). In the verification, data for 29 storms that occurred in 18 watersheds were used (table 1). The storms used in the verification generally were double peaked and too complicated to use in equation development. Two of the watersheds, from which verification data were available, were not used in the equation development. Additional testing was done using 74 storms that occurred in 9 watersheds from a study done in Lake County, Illinois (Melching and Marquardt, 1996). To test the limitations of the equations, these watersheds were chosen because the physical characteristics of these watersheds were not within the limitations of the types of watersheds used in the equation development and verification. The watersheds that were used violated one or more limitation: larger than 2.3 mi^2, a significant amount of impervious cover, or a main-channel slope smaller than 10.5 ft/mi.

Acknowledgments

Timothy B. Kosiek, USGS employee from 1997 to 1999 in Urbana, Ill., greatly contributed to retrieving, processing, and tabulating the data. Data from Allerton Farms and Park watersheds were provided by J.K. Mitchell, Department of Agricultural Engineering, University of Illinois, Urbana-Champaign. Vernon Knapp provided data collected at watersheds monitored by the ISWS. USDA and ISWS data were useful in compiling a large data base of storms with a wide spatial distribution of watersheds.

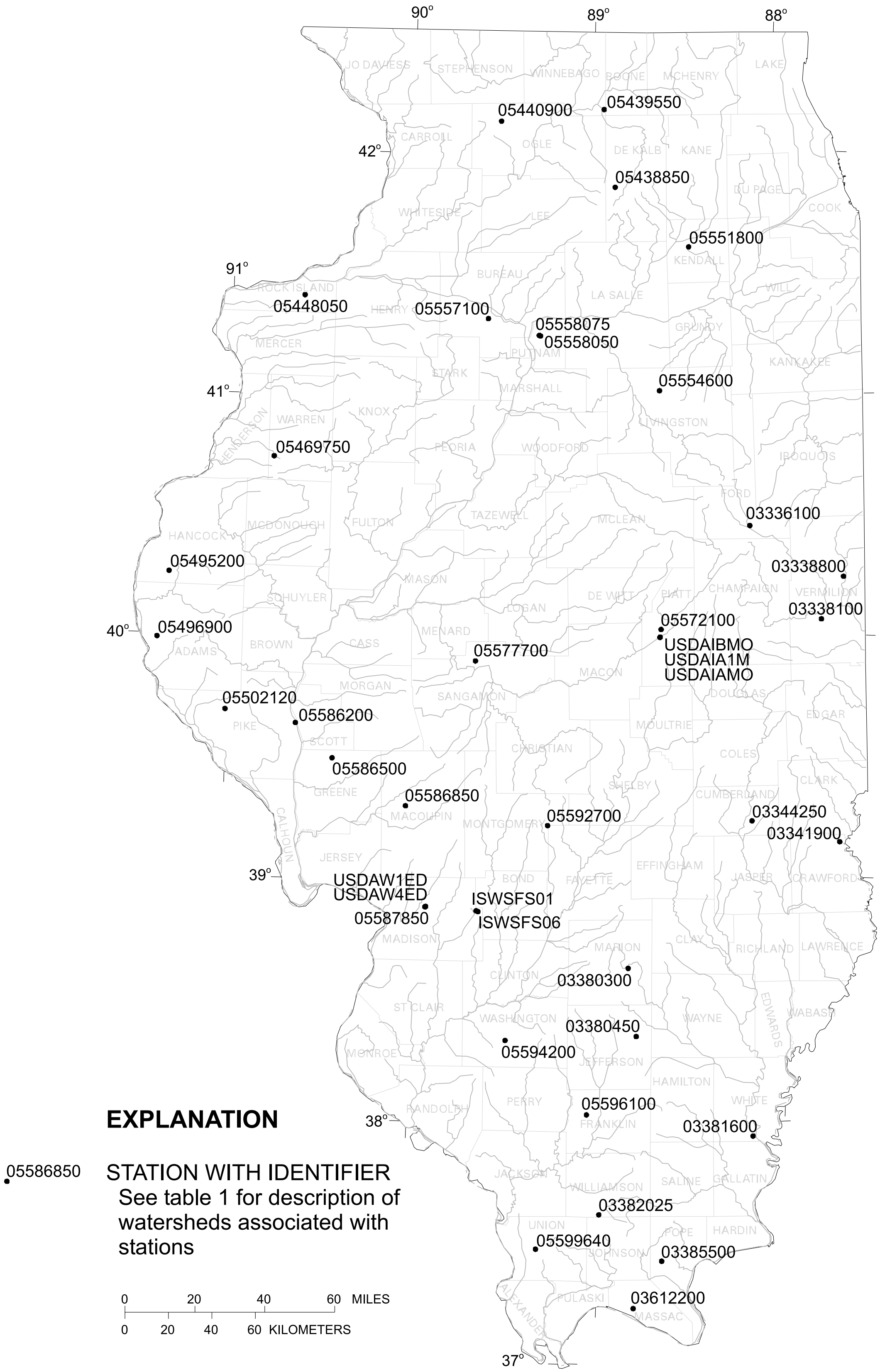

Figure 1. Location of stations where rainfall and discharge data were collected and used in the development and verification of equations for estimating time of concentration and storage coefficient for the Clark unit hydrograph for small watersheds in Illinois.

SYNTHETIC UNIT-HYDROGRAPH METHOD

Synthetic unit-hydrograph methods are utilized to describe the entire unit hydrograph for a gaged watershed with only a few hydrograph parameters. Needed hydrograph parameters vary among the different synthetic unit-hydrograph methods. These hydrograph parameters can be related to the characteristics of the watersheds and storms from which the parameters were determined. This method can be applied to ungaged watersheds with geomorphology, soils, land cover/land use, and climate similar to the gaged watersheds. Many synthetic unit-hydrograph methods have been proposed in the hydrologic literature. In this report, only the Clark (1945) unit-hydrograph method is considered because this method commonly is applied for hydrologic design and analysis in Illinois.

Clark Unit-Hydrograph Method

The processes of translation and attenuation dominate the movement of flow through a watershed. Translation is the movement of flow downgradient through the watershed in response to gravity. Attenuation results from the frictional forces and channel-storage effects that resist the flow. Clark (1945) noted that the translation of flow throughout the watershed could be described by a time-area curve, which expresses the curve of the fraction of watershed area contributing runoff to the watershed outlet as a function of time since the start of effective precipitation. Effective precipitation is that precipitation that is neither retained on the land surface nor infiltrated into the soil (Chow and others 1988, p. 135). The time-area curve is bounded in time by the watershed T_C. Thus, T_C is a hydrograph parameter of the Clark unit-hydrograph method. Attenuation of flow can be represented with a simple, linear reservoir for which storage is related to outflow as

$$S = RO, \tag{1}$$

where

S is the watershed storage,
R is the watershed-storage coefficient, and
O is the outflow from the watershed.

Therefore, Clark (1945) proposed that a synthetic unit hydrograph could be obtained by routing 1 in. of direct runoff to the channel in proportion to the time-area curve and routing the runoff entering the channel through a linear reservoir.

Numerous researchers have found that determining the time-area curve for the watershed was not needed to obtain a reasonable unit hydrograph. For example, Turner and Burdoin (1941) and O'Kelly (1955) found that reasonable unit hydrographs were obtained when simple geometric shapes were substituted for the actual time-area curve. Experience with the Clark unit-hydrograph method at the U.S. Army Corps of Engineers, Hydrologic Engineering Center, indicates that a detailed time-area curve usually is not necessary for accurate synthetic unit-hydrograph estimation (Ford and others, 1980). In most instances, the dimensionless time-area curve included in HEC-1 (U.S. Army Corps of Engineers, 1990) is satisfactory for obtaining a reliable synthetic unit hydrograph.

In Illinois, HEC-1 (U.S. Army Corps of Engineers, 1990) typically is utilized to compute the Clark unit hydrograph. T_C and R are the hydrograph parameters required for HEC-1 computation of the Clark unit hydrograph. The T_C for the Clark unit hydrograph is slightly different than the typical definition applied in stormwater management, such as that in the Rational method (Kuichling, 1889). In the typical definition, the time of concentration (t_c) is the traveltime for the first drop of effective precipitation at the hydraulically most distant point in the watershed to reach the watershed outlet. In the Clark unit-hydrograph method, T_C is the time from the end of effective precipitation to the inflection point of the recession limb of the runoff hydrograph. The inflection point on the runoff hydrograph corresponds to the time when overland flow to the channel network ceases and beyond that time the measured runoff results from drainage of channel storage. Therefore, Clark's T_C is the traveltime required for the last drop of effective precipitation at the hydraulically most distant point in the watershed to reach the channel network. From a linear-system theory and the conceptual model of pure translatory flow, the two definitions of time of concentration are equivalent. The subtle differences, however, between the definition of time of concentration in the Rational method and in the Clark unit-hydrograph method imply the time of concentration estimation equations commonly applied in the Rational method may not be appropriate for application to the Clark unit-hydrograph method. In most applications of HEC-1, T_C is determined from values calibrated with measured rainfall and runoff data either directly, by scaling from hydrologically similar watersheds, or from equations, such as those developed in this study.

Previous Clark Unit-Hydrograph Parameter Relations for Watersheds in Illinois

Methods and equations have been developed previously that relate T_C and R to watershed characteristics for watersheds in Illinois (Graf and others, 1982a,b; Melching and Marquardt, 1996). Most data used to derive these equations were collected for watersheds with areas larger than 10 mi^2.

T_C and R values for the study by Graf and others (1982a,b) were determined for 98 watersheds in Illinois ranging in size from 0.45 to 362 mi^2 by calibration of HEC-1 for rainfall and runoff data for six to eight storms per watershed. Multiple-regression analysis was applied to determine relations among (T_C+R), R/(T_C+R), and watershed characteristics. These combined parameters were utilized to reduce the effects of correlation between T_C and R. The relation among (T_C+R), main-channel length, and main-channel slope was determined as

$$(T_C+R) = 35.2\, L^{0.39} S^{-0.78}, \qquad (2)$$

where

L is the stream length measured along the main channel from the watershed outlet to the watershed divide, in mi, and

S is the main-channel slope determined from elevations at points that represent 10 and 85 percent of the distance along the channel from the watershed outlet to the watershed divide, in ft/mi.

Regional values of R/(T_C+R) were determined for various areas of the State (fig. 2). The hypothesis was that these regional values account, in part, for aspects of watershed geomorphology and land cover/land use not considered in the analysis, such as impervious and wetland areas. Scattergrams of the estimated and measured T_C and R values showed no clear separation of the results for the 19 urban watersheds studied relative to the results for all other watersheds.

T_C and R values for the Melching and Marquardt (1996) study were determined from 66 storms with effective-precipitation depths greater than 0.4 in. on 9 watersheds (areas between 0.06 and 37 mi^2, main-channel length: 0.33–16.6 mi, main-channel slope: 3.13–55.3 ft/mi, and percentage of impervious cover: 7.32–40.6). Data from 11 storms on 8 of these watersheds were utilized to verify (test) the Melching and Marquardt (1996) estimation equations. The peak discharge for 8 of the 11 storms was estimated within 25 percent and the time-to-peak discharge for 10 of the 11 storms was estimated within 20 percent. Separate sets of equations were developed with watershed area and main-channel length as the starting parameters. Percentage of impervious cover, main-channel slope, and depth of effective precipitation also were identified as important watershed and storm characteristics for estimation of T_C and (or) R. The equations for estimating T_C and R, in hours, as a function of watershed and storm characteristics with watershed area as the primary watershed characteristic are

$$T_C = 39.1 A^{0.577} (I+1)^{-1.146} D^{0.781} \text{ and} \qquad (3)$$

$$R = 123\, A^{0.390} (I+1)^{-0.722} S^{-0.303}, \qquad (4)$$

where

I is the percentage of impervious cover;

A is the watershed area, in mi^2; and

D is the effective precipitation depth, in inches.

The equations for estimating T_C and R, in hours, as a function of watershed and storm characteristics with main-channel length (L, in mi) as the primary watershed characteristic are

$$T_C = 87.5\, L^{0.868} (I+1)^{-1.563} D^{0.780} \text{ and} \qquad (5)$$

$$R = 81.1\, L^{0.759} (I+1)^{-0.994}. \qquad (6)$$

The differences in T_C and R estimated with the area-based equations and length-based equations may be substantial; however, the differences in the final computed hydrographs may be small. Melching and Marquardt (1996, p. 26) recommended that the design hydrographs obtained using the area-based and length-based equations should be compared and the most reasonable hydrograph applied.

When applying the results of Graf and others (1982b) and Melching and Marquardt (1996) to estimate T_C and R for small rural watersheds (less than 1 mi^2) in Illinois, three general problems occur. These problems are discussed in detail below.

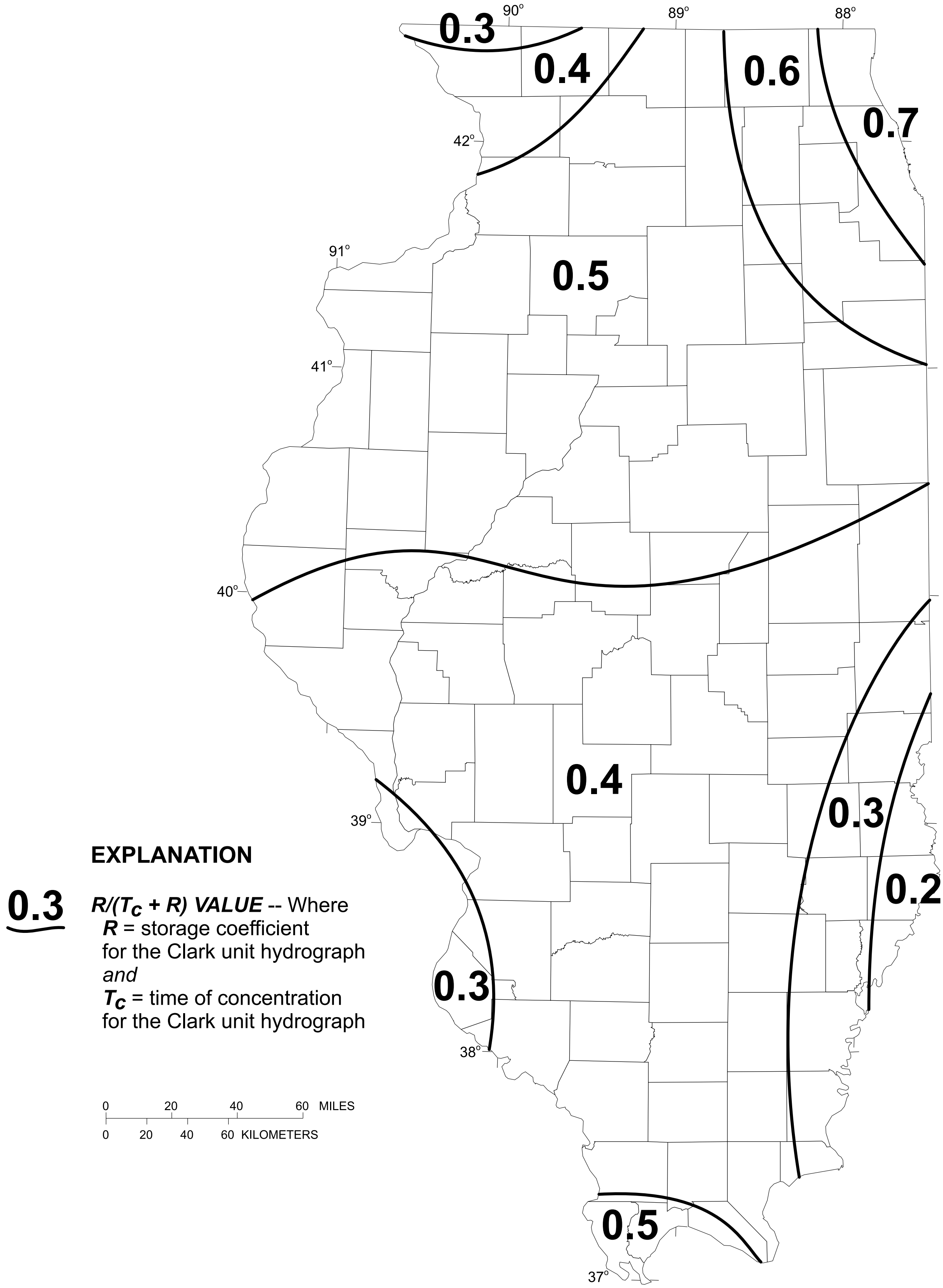

Figure 2. Regional values of $R/(T_C + R)$ determined by Graf and others (1982b) for Illinois.

The first problem is that most data were obtained from watersheds larger than 1 mi^2. In the study by Graf and others (1982a,b), only 8 of the 98 watersheds used were within selected parameters for this study. Also, seven of the nine watersheds analyzed by Melching and Marquardt (1996) were larger than 1 mi^2. The substantial amount of data from larger watersheds may appreciably affect the reliability of estimating T_C and R for small watersheds.

The second problem is that the locations of the rain gages, which were used in the study by Graf and others (1982a,b) to determine the watershed-average storm rainfall and the temporal rainfall distribution, commonly were 5 to 25 mi outside of the watershed, where runoff data were available. Therefore, uncertainties in the temporal distribution of the effective precipitation could substantially affect the reliability of the T_C and R values determined from calibration in the HEC-1 modeling.

The third problem is that both Graf and others (1982a,b) and Melching and Marquardt (1996) used watersheds with appreciable amounts of impervious area. Also, the substantial amount of wetland areas coupled with extremely small watershed slopes (six of the nine watersheds with slopes less than 10 ft/mi) could affect the T_C and R values in the Melching and Marquardt (1996) study that focused on data from Lake County, Illinois. The 41 watersheds used in this study were primarily small agricultural areas with insignificant amounts of impervious and wetland land cover.

To assess the utility of the method of Graf and others (1982b), T_C and R are estimated for each watershed studied using that method and the equations developed in this study. The estimated values then are compared with each other and to the values obtained from calibrating the HEC-1 model. Because impervious area is an important factor in the Melching and Marquardt (1996) equations for determining T_C and R, the methods of their study were not assessed on runoff data for each watershed in this study. The data used by Melching and Marquardt (1996), however, were used to test and determine limitations of the new statewide equations developed herein.

DETERMINING AND EVALUATING CLARK UNIT-HYDROGRAPH PARAMETERS

Selected storms were calibrated with HEC-1 to obtain optimal T_C and R values for the Clark unit hydrograph. T_C and R values determined in this study were evaluated by comparing the fit of the calibrated hydrographs to the observed hydrographs and by comparing T_C and R values derived during this study to values from previous studies.

Storm Selection

Storms for determining parameters for synthetic unit hydrographs should be selected to conform as closely as possible to the definition of a unit hydrograph. A unit hydrograph is the discharge-time graph (hydrograph) of a unit volume of direct runoff resulting from a spatially uniformly distributed effective precipitation (approximately equal to precipitation excess if interflow is small) with a uniform intensity over a given duration. Viessman and others (1989, p.186) recommend that, ideally, the storms utilized to determine unit hydrographs should include the following characteristics:

- a simple-storm structure, resulting in well defined hydrographs with distinct peaks;
- uniform rainfall distribution throughout the period of effective precipitation; and
- uniform spatial distribution (of rainfall) over the entire watershed.

Calibrating HEC-1 (U.S. Army Corps of Engineers, 1990) reduces the importance of the second characteristic because the multiple periods of effective precipitation are adequately deconvoluted in the calibration process if the direct-runoff hydrograph is well defined with a distinct peak (characteristic 1). Further, Viessman and others (1989, p. 186) recommend the direct runoff for the selected storm should range from 0.5 to 1.75 in. The design storms to be simulated with the synthetic unit hydrographs typically will result in direct-runoff values in this range. Further, Laurenson and Mein (1985, p. 87) stated that small storms, resulting in less than about 0.4 in. of runoff, often are more difficult to fit than large storms because of extreme areal variability of runoff, partial-area runoff, and large differences in the time distribution of effective precipitation resulting from small errors in the applied model. Therefore, storms that resulted in at least 0.4 in. of direct runoff were selected for analysis in this study. Hydrographs affected by snowmelt were not considered.

Base flow was not a part of the total-runoff hydrographs for the majority of the storms selected. Some storms, however, did include base flow, and the base flow had to be separated (subtracted) from the total-runoff hydrograph to obtain the direct-runoff hydrograph. For the majority of the storms for which the total-runoff hydrographs included base flow, the base flow was estimated by extending the trend in flow throughout the entire hydrograph prior to the start of the storm. This method was used because the trend in flow before and after the storm was approximately equal for most of the storms. For those storms that had an unusually large amount of time elapse before the flow returned to its prestorm trend, base flow was estimated by extending the trend in flow prior to the start of the storm to the time-of-peak discharge. After the time-of-peak discharge, the base flow was assumed to increase linearly to the time when the total-runoff hydrograph consisted of only base flow. This time was defined as the point on a semilogarithmic plot of the total-runoff hydrograph (with discharge on the logarithmic scale) at which the recession limb is approximately linear (as described in Chow, 1964, p. 10-14).

Storms may be distributed in time such that well-defined rises in the hydrograph with distinct peaks result, but a second rise begins in the latter part of the recession curve of the first rise. In this case, rises in the hydrograph must be separated so that the direct-runoff hydrographs from each storm may be evaluated. Storms were separated on the basis of a standard recession curve. The standard recession curve was developed on the basis of an average recession for the storms that were not affected by additional rainfall during the recession period on the given watershed. Typically, the agreement among these recession curves was close. In storm separation, the standard recession curve was matched to the recession curve of the first rise and utilized to extend the normal recession under the second rise. In some cases, the second rise began at discharges above those utilized in the standard recession curve, and the direct-runoff hydrographs resulting from the two storms could not be reliably separated. For storms that the hydrograph could not be separated, the data were used for equation verification.

Hydrograph-Parameter Determination

The T_C and R needed for the Clark (1945) unit-hydrograph method were determined by calibrating the HEC-1 model (U.S. Army Corps of Engineers, 1990) for hyetographs from rain gages at or very near (within the watershed) the streamflow-gaging station and direct-runoff hydrographs. A total of 121 storms that occurred in 39 watersheds were utilized to develop the T_C and R equations. To verify the T_C and R estimation equations, 29 storms that occurred in 18 watersheds were utilized. Optimal values of the initial-loss and continuing-loss rate also were determined in the HEC-1 calibration, primarily to match the effective-precipitation depths (that is, the direct runoff), and were not used further in the development of the estimation equations. The calibration quality was assessed on the basis of the coefficient of model-fit efficiency (Nash and Sutcliffe, 1970) as

$$EFF = \frac{\sum_{i=1}^{n}(Qm_i - Qm)^2 - \sum_{i=1}^{n}(Qm_i - Qs_i)^2}{\sum_{i=1}^{n}(Qm_i - Qm)^2}, \quad (7)$$

where

EFF is the coefficient of model-fit efficiency,
Qm_i is the measured direct runoff at time i,
Qm is the average measured direct runoff for the storm,
Qs_i is the simulated direct runoff at time i, and
n is the number of simulated hydrograph ordinates.

Multiple starting points (for initial-loss and continuing-loss rates, T_C, and R) were utilized, as necessary, in the nonlinear optimization applied in HEC-1 to ensure a close match between the measured and simulated direct-runoff hydrographs. The percentage error between the measured and simulated direct-runoff peak discharges was computed as a measure of the reliability when applying the Clark unit-hydrograph method. The T_C and R values, the model-fit efficiency, and the percentage error in the simulated direct-runoff peak discharge for the storms utilized to develop and verify the hydrograph-parameter estimation equations are listed in table 12 (at the back of this report). The average coefficient of model-fit efficiency and percentage error in simulation of direct-runoff peak discharge for each watershed are listed in table 2. Model-fit efficiency coefficients greater than 0.9, generally, indicate a close match between measured and simulated direct-runoff hydrographs. The model-fit efficiency for 6 of the 121 storms utilized to develop the hydrograph-parameter estimation equations and for 5 of the 29 storms utilized to verify equations was less than 0.9 (table 12 at the back of the report).

Table 2. Average values of measures of calibration quality for the calibrated Clark unit-hydrograph method for all storms on selected small rural watersheds in Illinois utilized to develop and verify the equations for estimation of time of concentration and storage coefficient

[Negative percent indicates the simulated peak discharge was less than the measured peak discharge; ISWS, Illinois State Water Survey; USDA, U.S. Department of Agriculture]

Watershed	Number of storms	Model-fit efficiency	Error in simulated peak discharge (percent)
Big Four Ditch Tributary	1	0.985	3.70
Salt Fork Tributary	3	.981	-.95
North Fork Vermilion River Tributary	2	.963	-2.00
Raccoon Creek Tributary	5	.968	.75
Embarras River Tributary	2	.958	-1.31
Dums Creek Tributary	6	.975	8.00
White Feather Creek	7	.956	1.16
Little Wabash River Tributary	2	.991	2.26
Little Saline Creek Tributary	5	.911	-12.35
Lake Glendale Inlet	1	.915	-7.40
Q Ditch Tributary	2	.981	-7.20
Middle Branch of South Branch Kishwaukee River	2	.941	-5.77
South Branch Kishwaukee River Tributary	2	.982	2.70
Leaf River Tributary	1	.968	-2.60
Sand Creek	1	.973	6.40
Ellison Creek Tributary	4	.976	.83
Little Creek	9	.957	-2.74
Homan Creek Tributary	1	.982	-.40
Kiser Creek Tributary	10	.944	-.21
Fox River Tributary Number Two	2	.967	6.51
Mud Creek Tributary	7	.962	-5.95
West Bureau Creek Tributary	1	.958	-10.80
Coffee Creek Tributary near Florid	2	.947	-3.26
Coffee Creek Tributary near Hennepin	4	.867	.05
Wildcat Creek Tributary	3	.923	1.07
Sangamon River Tributary	5	.954	-4.44
Illinois River Tributary	3	.974	-2.67
Hurricane Creek	3	.994	-.75
Bear Creek Tributary	3	.929	-.07
Cahokia Creek Tributary	2	.976	1.83
Hurricane Creek Tributary	8	.961	2.68
Williams Creek	3	.989	-.22
Andy Creek Tributary	4	.973	2.68
Green Creek Tributary	3	.960	-.93
ISWS Field Site 1	2	.942	2.33
ISWS Field Site 6	4	.968	-.25
USDA Watershed IA1	3	.933	2.50
USDA Watershed IA	5	.882	-1.21
USDA Watershed IB	8	.943	-1.44
USDA Watershed W-1	4	.963	2.07
USDA Watershed W-4	5	.952	-4.47

Equation Development

For small rural watersheds in Illinois, three methods were used to develop new equations for estimating T_C and R. Similar to the Graf and others (1982b) study, a multiple-linear regression analysis was used to determine mathematical relations among watershed characteristics and (T_C+R), and an attempt was made to determine regional values of $R/(T_C+R)$. The second method involved using multiple-linear regression analysis to determine mathematical relations among watershed characteristics and average values of T_C and R for each watershed. No storm characteristics or seasonal effects were analyzed in the second method. The third method involved using multiple-linear regression analysis to determine mathematical relations among watershed, storm, and seasonal characteristics and values of T_C and R for each storm. Overall, the second method yielded the best equations, as described in the following sections.

Results Based on Methods Similar to the Graf and others (1982b) Study

In the first method, equations for estimating (T_C+R) were developed utilizing multiple-linear regression to relate the logarithm of the average (T_C+R) for each watershed to logarithms of watershed area and main-channel length and slope. The multiple-linear regression of logarithms resulted in an estimation equation

$$h_{pi} = aW_1^{b1}\ W_2^{b2}\ , \qquad (8)$$

where

h_{pi} is hydrograph parameter i [in this case (T_C+ R)],

W_j are watershed characteristics j,

bj are exponents corresponding to watershed characteristics j, and

a is a coefficient.

Watershed characteristics were added one at a time to the regression model (eq. 8), and characteristics were retained in the regression model only if the corresponding exponents were statistically significant (the corresponding 95-percent confidence interval for the parameter did not include zero) and the sign of the exponent was correct from a physical viewpoint. For example, hydrograph-timing parameters should increase with increasing area and main-channel length and decrease with increasing main-channel slope. From the regression, an equation involving the length and slope was determined to yield the highest coefficient of determination (R^2=0.74).

Next, the average [$R/(T_C+R)$] values for each watershed were plotted on a map of the State of Illinois. Contours were drawn to try to determine regional trends in the values, but all such attempts were unsuccessful. Before abandoning the method similar to that used by Graf and others (1982b) because of the inability to find regional trends in average [$R/(T_C+R)$], the logarithm of these values were regressed against watershed characteristics similar to the previous regression, using values of average (T_C+R). All combinations of the regression yielded very poor coefficient of determination (R^2) values (highest equaling 0.38). With no reliable method of determining [$R/(T_C+R)$], this method was abandoned.

Interestingly, the coefficient and exponents for the Graf and others (1982b) equation for (T_C+R) were not within the 95-percent confidence intervals when compared to the equation developed for (T_C+R) for this study, except for a slight overlap in the length exponent. The upper and lower confidence bounds for the length exponent were 0.650 and 0.339, respectively, for the (T_C+R) equation developed in this study.

Results Based on Average Values of T_C and R for Each Watershed

The second method, determined to be the overall best method in this study, utilized multiple-linear regression analysis to relate the logarithms of the average T_C and average R for each watershed to logarithms of watershed area and main-channel length and slope. Equations for the T_C and R estimations (in hours) that yield the highest R^2 values included main-channel length and slope and are

$$T_C = 1.54\ L^{\ 0.875}\ S^{\ -0.181} \text{ and} \qquad (9)$$

$$R = 16.4\ L^{\ 0.342}\ S^{\ -0.790}, \qquad (10)$$

where

L is the stream length measured along the main channel from the watershed outlet to the watershed divide, in mi, and

S is the main-channel slope determined from elevations at points that represent 10 and 85 percent of the distance along the channel from the watershed outlet to the watershed divide, in ft/mi.

The coefficient of determination and standard error for the logarithmic data resulting from the stepwise multiple-linear regression for estimating T_C and R are listed in tables 3 and 4, respectively.

Equation 9 explains 73 percent of the variance in the logarithms of T_C. Equation 10 explains 64 percent of the variance in the logarithms of R. The T_C and R values estimated using equations 9 and 10, respectively, and the values determined through calibration are shown in scattergrams in figures 3 and 4, respectively. The T_C and R values estimated using equations developed in this study, the Graf and others (1982b) method, and the values determined through calibration in this study are listed in tables 5 and 6, respectively.

Results Using T_C and R for All Storms Independently

The third method utilized multiple-linear regression analysis to relate the logarithm of the T_C and R for each storm to logarithms of watershed area, main-channel length and slope, storm duration and intensity, and Julian day (as a measure of time in the growing season). The multiple-linear regression in logarithms resulted in estimation equations of the form

Table 3. Coefficient of determination and standard error for logarithmic data in the equations for estimating time of concentration for the Clark unit hydrograph

[R^2, coefficient of determination]

Parameter	R^2	Standard error
Slope	0.10	0.8096
Area	.67	.4920
Length	.70	.4673
Length and slope	.73	.4523

Table 4. Coefficient of determination and standard error for logarithmic data in the equation for estimating the watershed storage coefficient for the Clark unit hydrograph

[R^2, coefficient of determination]

Parameter	R^2	Standard error
Area	0.17	0.8188
Length	.18	.8143
Slope	.55	.6036
Slope and length	.64	.5501

$$h_{pi} = aW_1^{b1} \; W_2^{b2} \; \ldots S_1^{c1} \, S_2^{c2} \ldots J^{d} \ldots , \qquad (11)$$

where

- h_{pi} is hydrograph parameter I,
- W_j are watershed characteristics j,
- bj are exponents corresponding to watershed characteristics j,
- S_k are storm characteristics k,
- ck are exponents corresponding to storm characteristics k,
- J denotes the Julian day,
- d is an exponent corresponding to the Julian day, and
- a is a coefficient.

Nonlinear equations, such as equation 11, among hydrograph parameters, and watershed and storm characteristics have been determined theoretically from the kinematic wave approximation (Ragan and Duru, 1972), experimentally in the laboratory (Shen, 1974), and empirically from field data (Snyder, 1938; Rao and others, 1972; and others).

Regressions involving length and slope resulted in the highest R^2 values when considering all possible watershed parameters regressed against T_C and R. Only minimal increases in R^2 resulted from adding storm characteristics to the regression of length and slope, and no increase in R^2 resulted when adding Julian day to the regression. The extra effort needed to obtain storm characteristics did not warrant the slight increase in the accuracy of estimating T_C and R. The distribution of Julian day was limited primarily to the summer months. This limitation possibly has caused the Julian day to have an insignificant effect on the regression.

Comparison of Calibrated Hydrograph-Parameter Values with Results Obtained Using the Graf and others (1982b) Method

When applying the method of Graf and others (1982b) to estimate T_C, the mean square error (in real space) is 0.432 when comparing computed T_C and measured T_C for all 150 storms on the 41 watersheds. When estimating T_C using equation 9, the mean square error (in real space) is 0.292 when comparing computed and measured T_C for all 150 storms on the 41 watersheds.

When applying the method of Graf and others (1982b) to estimate R, the mean square error (in real space) is 0.341 when comparing computed R and

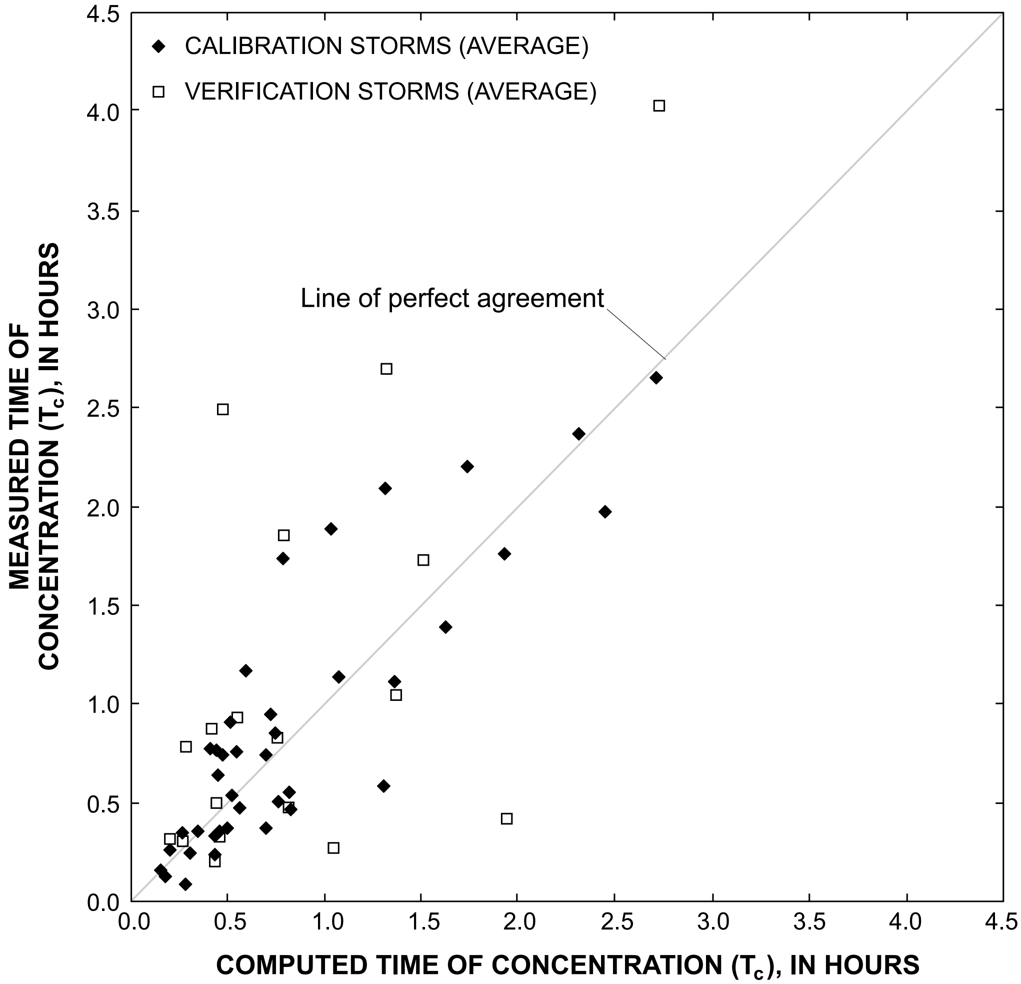

Figure 3. Time of concentration for storms on 41 watersheds in Illinois for the Clark unit-hydrograph method measured (average) and computed as a function of watershed main-channel length and slope.

measured *R* for all 150 storms on the 41 watersheds. When estimating *R* using equation 10, the mean square error (in real space) is 0.333 when comparing computed *R* and measured *R* for all 150 storms on the 41 watersheds.

When applying the method of Graf and others (1982b) to estimate T_C+R, the mean square error (in real space) is 0.777 when comparing computed T_C+R and measured T_C+R for all 150 storms on the 41 watersheds. When estimating T_C+R using equations 9 and 10, the mean square error (in real space) is 0.636 when comparing computed and measured T_C+R for all 150 storms on the 41 watersheds.

When comparing the results utilizing equation 9 to estimate T_C with the results utilizing the Graf and others (1982b) method to estimate T_C for the same data set, the Graf and others results are not as favorable because the mean square error is larger when using the Graf and others method than the mean square error when using equation 9. Further, equation 9 provides a better T_C estimate for 93 of the 150 storms compared to the estimates obtained with the Graf and others (1982b) method.

When the results of utilizing equation 10 to estimate *R* are compared to the results of the Graf and others (1982b) method to estimate *R* for the same data set, the Graf and others results are similar to the results utilizing equation 10 because the mean square error is nearly identical for the two cases. These results also are reflected in the computations for estimating *R*. The Graf and others (1982b) method provided a better *R* estimate for 77 storms, and equation 10 provided a better *R* estimate for 73 storms. The Graf and others (1982b) method is more cumbersome than using equations to

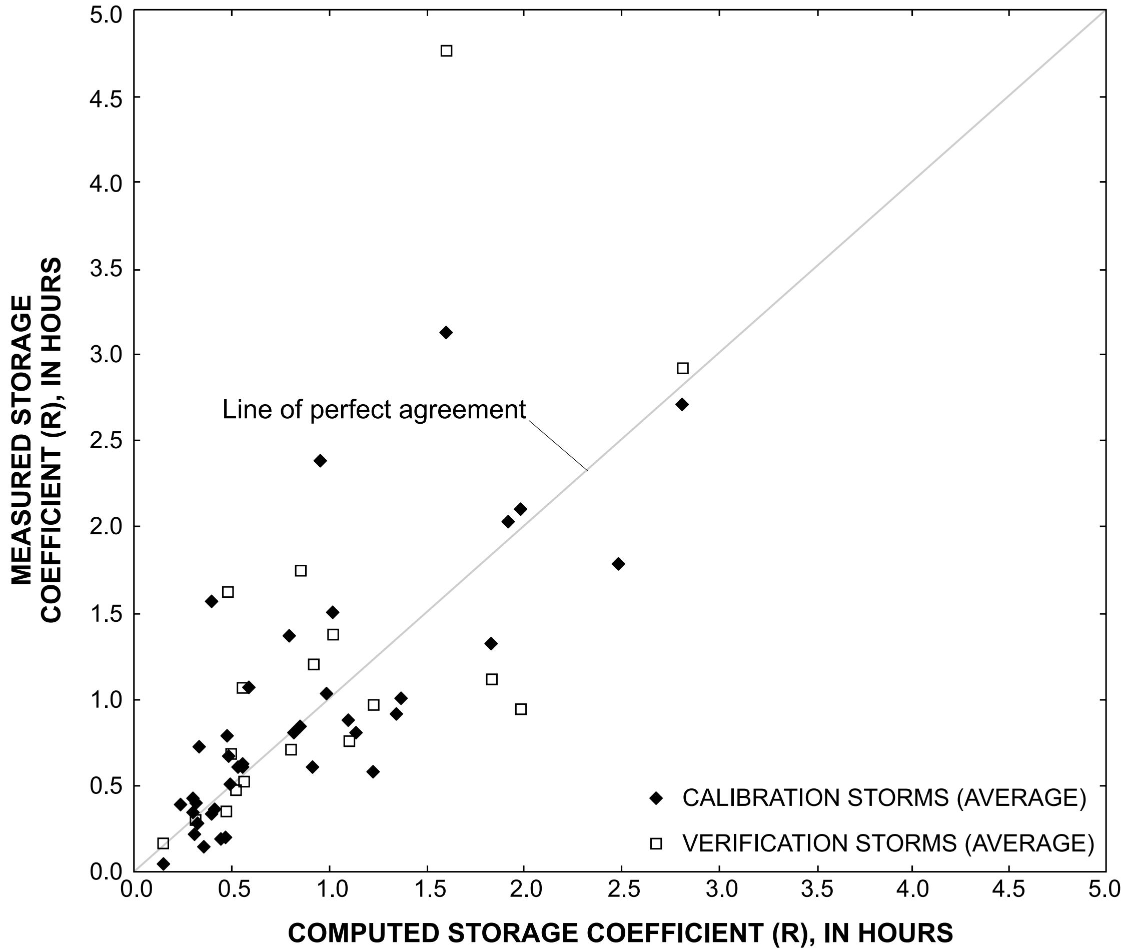

Figure 4. Storage coefficient for storms on 41 watersheds in Illinois for the Clark unit-hydrograph method measured (average) and computed as a function of watershed main channel-length and slope.

solve directly for T_C and R. Therefore, although the results based on the Graf and others (1982b) method are similar for the computation of R, equation 10 is much easier to use.

When the results of utilizing equations 9 and 10 to estimate T_C+R were compared to the results of the Graf and others (1982b) method to estimate T_C+R for the same data set, the Graf results are not as favorable because the mean square error is larger than the mean square error when using equations 9 and 10. Further, equation 9 provides a better estimate of T_C+R for 85 of the 150 storms compared to the estimates derived by the Graf and others (1982b) method.

The better performance of equations 9 and 10 in estimating T_C and T_C+R (compared to the Graf and others (1982b) method) was expected because 80 percent of the storms considered were used developing equations 9 and 10. The primary purpose of this comparison, however, was to assess the accuracy of the Graf and others (1982b) method for small watersheds (less than 2.3 mi^2). The good performance of the Graf and others (1982b) method in estimating R indicates this method may yield reasonable results for some small rural watersheds. The poor performance of the Graf and others (1982b) method in estimating T_C and T_C+R, however, indicates generally this method will not yield reliable results.

Equation Verification

Data for 29 storms in 18 watersheds were used to verify equations 9 and 10 (table 1). Two of the watersheds for which verification data were available were not used in the equation development. The storms used in the verification generally were double peaked and too complicated to use in equation development. The verification results using the complicated storms should

Table 5. Time of concentration for the Clark unit-hydrograph method estimated with equations developed in this study and with the method of Graf and others (1982b) compared to the average values determined from calibration for all storms used in equation development on selected small rural watersheds in Illinois

[T_C, time of concentration; ISWS, Illinois State Water Survey; USDA, U.S. Department of Agriculture]

Watershed	Number of storms	T_C estimated from equations developed in this study (hours)	T_C estimated from equations developed in Graf and others study (hours)	Mean T_C determined from storm calibration in this study (hours)
Big Four Ditch Tributary	1	1.741	2.210	2.205
Salt Fork Tributary	2	2.727	3.952	2.651
North Fork Vermilion River Tributary	2	1.635	1.872	1.390
Raccoon Creek Tributary	3	.264	.801	.350
Embarras River Tributary	1	.432	2.312	.330
Dums Creek Tributary	6	.303	.412	.244
White Feather Creek	5	.751	.671	.855
Little Wabash River Tributary	2	.449	.613	.637
Little Saline Creek Tributary	4	.784	.760	1.735
Lake Glendale Inlet	1	1.077	.554	1.138
Q Ditch Tributary	2	.517	.340	.905
Middle Branch of South Branch Kishwaukee River	1	1.935	1.862	1.760
Leaf River Tributary	1	.523	.336	.537
Sand Creek	1	.564	.594	.475
Ellison Creek Tributary	4	1.313	1.564	.586
Little Creek	8	1.370	1.405	1.115
Homan Creek Tributary	1	.827	.616	.469
Kiser Creek Tributary	7	.820	.753	.556
Fox River Tributary Number Two	2	.698	.544	.741
Mud Creek Tributary	7	.596	.653	1.172
Coffee Creek Tributary near Florid	1	.203	.160	.258
Coffee Creek Tributary near Hennepin	3	.548	.352	.757
Wildcat Creek Tributary	3	.346	1.436	.356
Sangamon River Tributary	5	1.033	1.337	1.887
Illinois River Tributary	3	.697	.489	.373
Hurricane Creek	3	2.457	2.794	1.975
Bear Creek Tributary	3	.154	.416	.157
Cahokia Creek Tributary	2	.725	1.097	.948
Hurricane Creek Tributary	5	.413	1.170	.771
Williams Creek	3	2.322	3.475	2.368
Andy Creek Tributary	3	1.314	1.518	2.091
Green Creek Tributary	3	.763	.570	.508
ISWS Field Site 1	2	.440	1.225	.763
ISWS Field Site 6	3	.454	1.307	.355
USDA Watershed IA1	1	.283	.607	.088
USDA Watershed IA	2	.437	1.034	.239
USDA Watershed IB	6	.472	1.107	.740
USDA Watershed W-1	4	.181	.507	.124
USDA Watershed W-4	5	.493	.398	.373

Table 6. Storage coefficient estimated with equations developed in this study and with the method of Graf and others (1982b) compared to the average values determined from calibration for all storms used in equation development on selected small rural watersheds in Illinois

[*R*, storage coefficient; ISWS, Illinois State Water Survey; USDA, U.S. Department of Agriculture]

Watershed	Number of storms	*R* estimated from equations developed in this study (hours)	*R* estimated from equations developed in Graf and others study (hours)	Mean *R* determined from storm calibration in this study (hours)
Big Four Ditch Tributary	1	1.926	2.210	2.035
Salt Fork Tributary	2	2.816	2.635	2.715
North Fork Vermilion River Tributary	2	1.352	1.248	.920
Raccoon Creek Tributary	3	.475	.200	.197
Embarras River Tributary	1	1.838	1.541	1.320
Dums Creek Tributary	6	.319	.275	.398
White Feather Creek	5	.496	.448	.511
Little Wabash River Tributary	2	.399	.263	.334
Little Saline Creek Tributary	4	.562	.506	.606
Lake Glendale Inlet	1	.398	.369	1.572
Q Ditch Tributary	2	.305	.340	.426
Middle Branch of South Branch Kishwaukee River	1	1.603	1.862	3.130
Leaf River Tributary	1	.301	.336	.343
Sand Creek	1	.538	.594	.605
Ellison Creek Tributary	4	1.374	1.564	1.009
Little Creek	8	1.227	1.405	.579
Homan Creek Tributary	1	.449	.410	.191
Kiser Creek Tributary	7	.555	.502	.629
Fox River Tributary Number Two	2	.484	.544	.674
Mud Creek Tributary	7	.590	.653	1.071
Coffee Creek Tributary near Florid	1	.149	.160	.042
Coffee Creek Tributary near Hennepin	3	.315	.352	.219
Wildcat Creek Tributary	3	1.144	.957	.804
Sangamon River Tributary	5	.986	.891	1.033
Illinois River Tributary	3	.359	.326	.147
Hurricane Creek	3	1.984	1.863	2.105
Bear Creek Tributary	3	.337	.277	.729
Cahokia Creek Tributary	2	.824	.731	.803
Hurricane Creek Tributary	5	.914	.780	.605
Williams Creek	3	2.488	2.317	1.786
Andy Creek Tributary	3	1.105	1.012	.879
Green Creek Tributary	3	.419	.380	.362
ISWS Field Site 1	2	.954	.816	2.382
ISWS Field Site 6	3	1.019	.872	1.505
USDA Watershed IA1	1	.478	.405	.792
USDA Watershed IA	2	.802	.689	1.366
USDA Watershed IB	6	.856	.738	.843
USDA Watershed W-1	4	.327	.338	.282
USDA Watershed W-4	5	.236	.265	.393

be of similar quality to the results for a simple (single peaked) storm because, once derived, a unit hydrograph should be applicable to any type of storm through the principle of linear superposition. Therefore, storms not suitable for deriving a unit hydrograph may be applicable for testing the unit hydrograph.

The verification storms were analyzed through HEC-1 calibration to determine hydrograph characteristics, T_C, and R in the same manner as the 121 storms utilized to develop the estimation equations. The T_C, R, model-fit efficiency, and percentage error in the peak discharge from the HEC-1 calibration of the Clark unit-hydrograph method for the verification storms are listed in table 12 (in the back of this report). Equations 9 and 10 were used to estimate T_C and R values for the verification storms. The computed and average measured T_C and R values for the verification storms are presented in figures 3 and 4, respectively, and tables 7 and 8, respectively.

The percentage errors in the estimated peak discharge and time-to-peak discharge for the verification storms simulated with the Clark unit-hydrograph method utilizing T_C and R estimated with equations 9 and 10, respectively, are listed in table 9. For 21 of the 29 verification storms, the error in the peak discharge is less than 25 percent. For 18 of the 29 verification storms, the error in the time-to-peak discharge is less than 25 percent.

Selected computed and measured hydrographs are shown in figures 5-7. The selected graphs show a representative sample of the 29 verification storms. Approximately one-third of the verification storms resulted in good agreement (less than 15 percent error in peak discharge and time-to-peak discharge) with measured values (fig. 5). Approximately another one-third of the verification storms resulted in fair agreement (between 15 and 35 percent error in peak discharge and time-to-peak discharge) with measured values (fig. 6). The final one-third of the verification storms resulted in poor agreement (greater than 35 percent error in peak discharge or time-to-peak discharge) with the measured values (fig. 7).

Testing with Lake County Data

T_C and R values were estimated using equations 9 and 10, respectively, for the nine watersheds analyzed

Table 7. Time of concentration for the Clark unit-hydrograph method estimated with equations developed in this study and with the method of Graf and others (1982b) compared to the average values determined from calibration for all storms used for verification of the developed equation on selected small rural watersheds in Illinois

[T_C, time of concentration; ISWS, Illinois State Water Survey; USDA, U.S. Department of Agriculture]

Watershed	Number of storms	T_C estimated from equations developed in this study (hours)	T_C estimated from equations developed in Graf and others study (hours)	Mean T_C determined from storm calibration in this study (hours)
Salt Fork Tributary	1	2.734	3.952	4.019
Raccoon Creek Tributary	2	.265	.801	.300
Embarras River Tributary	1	.432	2.312	.197
White Feather Creek	2	.754	.671	.816
Little Saline Creek Tributary	1	.787	.760	1.849
Middle Branch of South Branch Kishwaukee River	1	1.942	1.862	.413
South Branch Kishwaukee River Tributary	2	1.510	1.073	1.725
Little Creek	1	1.375	1.405	1.040
Kiser Creek Tributary	3	.818	.753	.468
West Bureau Creek Tributary	1	1.047	.603	.263
Coffee Creek Tributary near Florid	1	.202	.160	.310
Coffee Creek Tributary near Hennepin	1	.550	.352	.927
Hurricane Creek Tributary	3	.415	1.170	.864
Andy Creek Tributary	1	1.319	1.518	2.691
ISWS Field Site 6	1	.455	1.307	.321
USDA Watershed IA1	2	.284	.607	.775
USDA Watershed IA	3	.438	1.034	.495
USDA Watershed IB	2	.474	1.107	2.484

Table 8. Storage coefficient estimated with an equation developed in this study and with the method of Graf and others (1982b) compared to the average values determined from calibration for all storms used for verification of the developed equation on selected small rural watersheds in Illinois

[*R*, storage coefficient; ISWS, Illinois State Water Survey; USDA, U.S. Department of Agriculture]

Watershed	Number of storms	*R* estimated from equations developed in this study (hours)	*R* estimated from equations developed in Graf and others study (hours)	Mean *R* determined from storm calibration in this study (hours)
Salt Fork Tributary	1	2.815	2.635	2.911
Raccoon Creek Tributary	2	.475	.200	.341
Embarras River Tributary	1	1.837	1.541	1.114
White Feather Creek	2	.496	.448	.685
Little Saline Creek Tributary	1	.562	.506	.521
Middle Branch of South Branch Kishwaukee River	1	1.603	1.862	4.747
South Branch Kishwaukee River Tributary	2	.925	1.073	1.201
Little Creek	1	1.228	1.405	.960
Kiser Creek Tributary	3	.555	.502	1.062
West Bureau Creek Tributary	1	.524	.602	.467
Coffee Creek Tributary near Florid	1	.149	.160	.160
Coffee Creek Tributary near Hennepin	1	.314	.352	.293
Hurricane Creek Tributary	3	.914	.780	.943
Andy Creek Tributary	1	1.105	1.012	.759
ISWS Field Site 6	1	1.019	.872	1.369
USDA Watershed IA1	2	.478	.405	1.621
USDA Watershed IA	3	.802	.689	.708
USDA Watershed IB	2	.856	.738	1.737

in the Lake County, Ill., study (Melching and Marquardt, 1996). Watershed characteristics of these watersheds are presented in table 10. The average percentage errors in the estimated peak discharge and time-to-peak discharge for the Lake County storms simulated with the Clark unit-hydrograph method utilizing T_C and R estimated with equations 9 and 10, respectively, are listed in table 11. The average error in peak discharge is greater than 100 percent for five of the nine watersheds, and four of these five watersheds have a negative percentage of error for the time-to-peak discharge. The Green Lake Ditch watershed had different results, with a negative average percentage error in peak discharge and a large positive error in the time-to-peak discharge. Further discussion of the results of testing the equations with Lake County data is included in the following section.

Application Limits for the Estimation Equations

Unaccounted for storage depressions (for example, wetlands, undersized culverts causing ponding upstream from the culvert, and (or) extremely flat slopes) could explain the extremely high overestimation of the peak discharge and the underestimation of the time-to-peak discharge in the verification and testing of equations. This result seems to be the case on many of the Lake County watersheds (Green Lake Ditch is the only exception) where wetlands and flat slopes are scattered throughout the watershed. Among the watersheds considered in this study, the flattest slope is 10.5 ft/mi. In the Lake County data set, six of the nine watersheds have a slope of less than 10 ft/mi. The effects of extremely flat slopes and large depression storage in eight Lake County watersheds seem to overshadow any effects of impervious area on the measured hydrograph shape. In general, equation 10 seems to underestimate storage in watersheds in Lake County.

The testing results for Green Lake Ditch (table 11) show the effects of simulating discharge for an urban watershed using T_C and R values computed with equations developed for small rural watersheds. The results show a late and undersimulated peak of the computed hydrograph compared to the peak of the measured hydrograph of the urban (Green Lake Ditch) watershed.

Table 9. Percentage error in estimated peak discharge and time-to-peak discharge for the verification storms on selected small rural watersheds in Illinois, simulated with the Clark unit-hydrograph method utilizing estimated values of time of concentration and watershed-storage coefficient developed in this study

[Negative percent indicates the simulated peak discharge was less than or occurred before the measured peak discharge; ISWS, Illinois State Water Survey; USDA, U.S. Department of Agriculture]

Watershed	Date	Error in peak discharge (percent)	Error in time-to-peak discharge (percent)
Salt Fork Tributary	August 4, 1968	11.0	-14.6
Raccoon Creek Tributary	June 27, 1957	-22.4	8.00
Raccoon Creek Tributary	June 20, 1959	8.80	.00
Embarras River Tributary	June 13, 1958	-31.3	8.50
White Feather Creek	May 18, 1959	24.8	-17.6
White Feather Creek	May 8, 1961	14.0	-2.83
Little Saline Creek Tributary	February 20, 1971	12.3	-60.8
Middle Branch of South Branch Kishwaukee River	June 14, 1972	58.4	30.2
South Branch Kishwaukee River Tributary	September 13, 1972	9.86	-15.8
South Branch Kishwaukee River Tributary	April 21, 1973	12.0	-3.85
Little Creek	December 31, 1964	-13.9	11.6
Kiser Creek Tributary	September 13, 1961	-13.3	50.0
Kiser Creek Tributary	October 11, 1973	31.5	3.78
Kiser Creek Tributary	April 21, 1974	14.1	-18.8
West Bureau Creek Tributary	April 21, 1973	-34.0	42.0
Coffee Creek Tributary near Florid	July 18, 1969	1.47	.00
Coffee Creek Tributary near Hennepin	September 23, 1970	17.8	-26.4
Hurricane Creek Tributary	June 13, 1958	12.7	-40.0
Hurricane Creek Tributary	June 27, 1958	22.1	-20.0
Hurricane Creek Tributary	August 7, 1958	40.9	-27.3
Andy Creek Tributary	August 17, 1959	-2.21	7.76
ISWS Field Site 6	July 10, 1982	19.6	90.2
USDA Watershed IA1	July 2, 1982	123	-15.9
USDA Watershed IA1	May 30, 1982	76.9	-40.6
USDA Watershed IA	July 23, 1973	6.69	17.0
USDA Watershed IA	June 22, 1974	-5.68	27.2
USDA Watershed IA	May 30, 1982	-6.05	.00
USDA Watershed IB	February 4, 1971	23.1	-18.5
USDA Watershed IB	April 19, 1972	202	-58.3

The equations developed during this study for estimating T_C and R for the Clark unit-hydrograph method work well on watersheds that are within the characteristic limitations used in the equation development. Most data used in equation development was obtained for watersheds less than 0.5 mi^2 in area (26 of 39 watersheds). Therefore, these equations probably are most accurate for watersheds less than 0.5 mi^2 in area, and the equation's accuracy probably decreases as the upper limit of the area is approached. The equations do not estimate T_C and R well for watersheds that contain wetlands, undersized culverts that cause ponding upstream from the culvert, or very flat slopes (less than 10 ft/mi). The use of T_C and R values computed with equations 9 and 10 tend to undersimulate peak discharge and oversimulate time-to-peak discharge for highly impervious watersheds that do not have any items mentioned in the previous sentence.

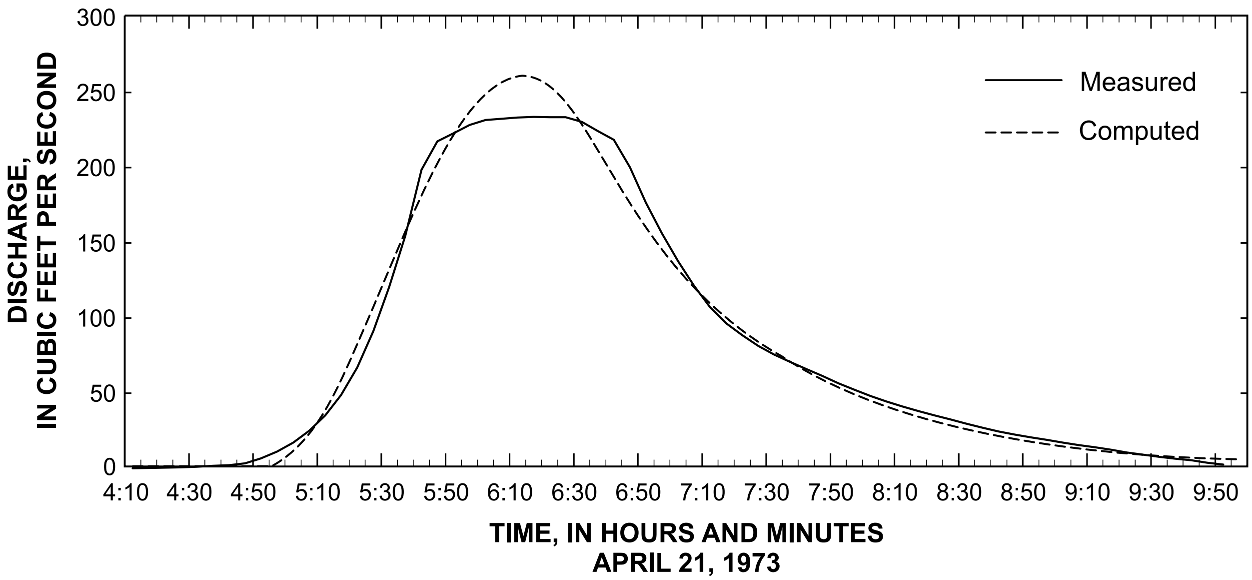

Figure 5. Measured direct-runoff hydrograph and computed direct-runoff hydrograph simulated with the Clark unit-hydrograph method in the U.S. Army Corps of Engineers Flood Hydrograph Package HEC-1 with the time of concentration and storage coefficient determined from the estimation equations for Illinois developed in this study for the storm of April 21, 1973, on South Branch Kishwaukee River.

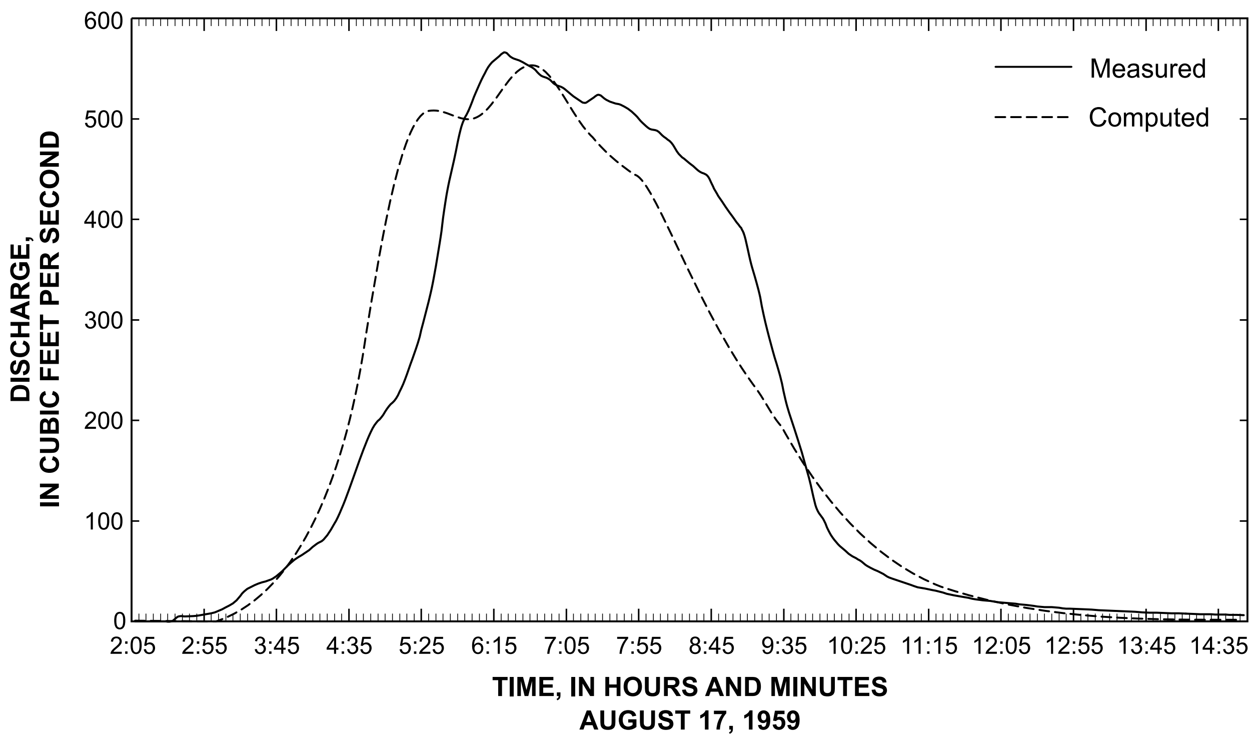

Figure 6. Measured direct-runoff hydrograph and computed direct-runoff hydrograph simulated with the Clark unit-hydrograph method in the U.S. Army Corps of Engineers Flood Hydrograph Package HEC-1 with the time of concentration and storage coefficient determined from the estimation equations for Illinois developed in this study for the storm of August 17, 1959, on Andy Creek Tributary.

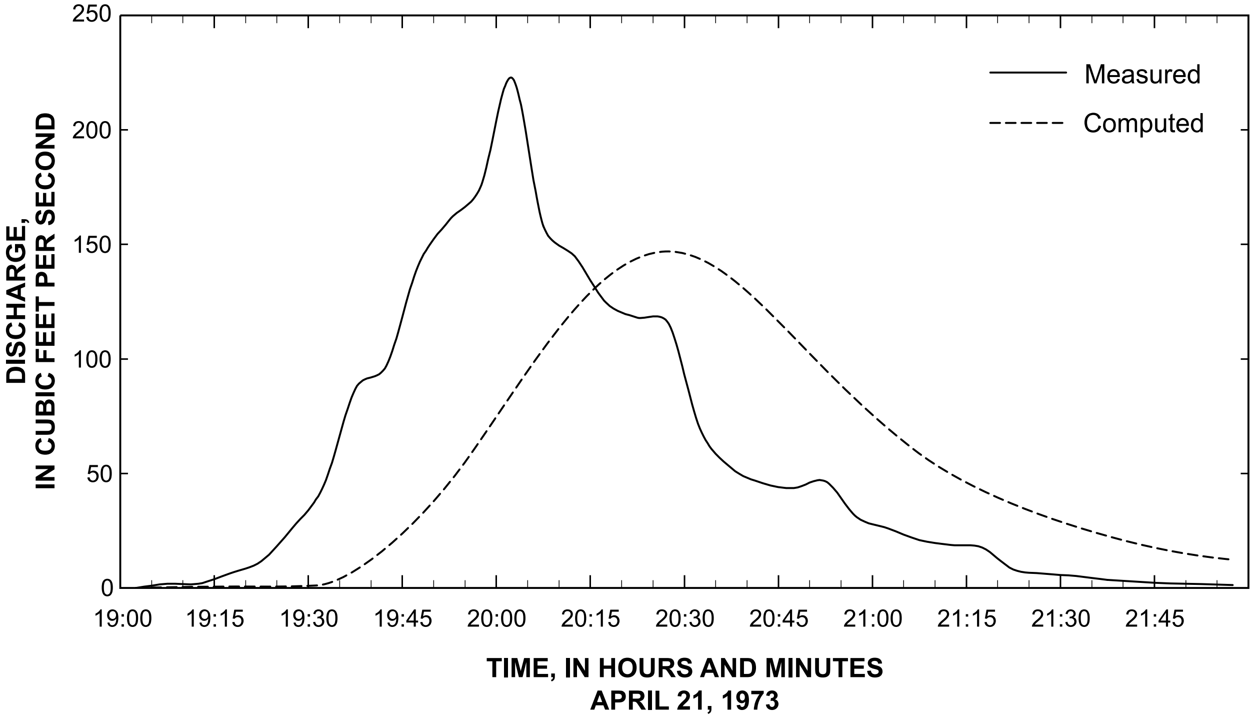

Figure 7. Measured direct-runoff hydrograph and computed direct-runoff hydrograph simulated with the Clark unit-hydrograph method in the U.S. Army Corps of Engineeers Flood Hydrograph Package HEC-1 with the time of concentration and storage coefficient determined from the estimation equations for Illinois developed in this study for the storm of April 21, 1973, on West Bureau Creek Tributary.

Table 10. Characteristics of watersheds in Lake County, Ill., selected for testing the equations developed to estimate time of concentration and storage coefficient for small rural watersheds in Illinois

[mi^2, square miles; mi, miles; ft/mi, feet per mile]

Watershed	Drainage area (mi^2)	Length (mi)	Slope (ft/mi)	Impervious area (percent)	Forest area (percent)	Wetland area (percent)
Bull Creek	6.3	6.4	3.13	13.9	7.48	6.80
Terre Faire Ditch	.077	.33	55.3	27.7	.00	2.00
Indian Creek	35.7	11.6	13.6	15.8	3.48	4.22
Green Lake Ditch	.06	.6	14.0	40.6	.00	.00
North Branch Chicago River	19.7	13.5	3.24	21.3	32.5	.77
Skokie River at Lake Forrest	13.0	10.8	5.58	29.4	24.0	.15
Skokie River near Highland Park	21.1	16.6	5.29	34.4	30.1	.24
Squaw Creek	17.2	7.8	4.79	7.32	3.73	7.32
Flint Creek	37.0	12.9	7.99	8.83	8.97	5.09

Application Example

The Sangamon River Tributary near Andrew, Ill., watershed is 1.36 mi long with a slope of 40.1 ft/mi. The T_C and R values for the watershed can be estimated with equations 9 and 10, respectively, as

$$T_C = 1.54(1.36)^{0.875}(40.1)^{-0.181} = 1.03 \text{ hours}, \text{ and}$$

$$R = 16.4(1.36)^{0.342}(40.1)^{-0.790} = 0.986 \text{ hours}.$$

Table 11. Average percentage error in the estimated peak discharge and time-to-peak discharge for the storms on selected watersheds in Lake County, Ill., simulated with the Clark unit-hydrograph method utilizing estimated values of time of concentration and storage coefficient computed with equations developed in this study for small rural watersheds in Illinois

[T_C, time of concentration; *R*, storage coefficient; negative percent indicates the simulated peak discharge was less than or occurred before the measured peak discharge]

Watershed	Number of storms	Computed T_C (hours)	Computed *R* (hours)	Error peak discharge (percent)	Error time-to-peak discharge (percent)
Bull Creek	11	6.305	12.485	123	16.0
Terre Faire Ditch	4	.285	.471	123	-17.0
Indian Creek	11	8.120	4.789	222	-27.9
Green Lake Ditch	2	.614	1.710	-27.2	64.6
North Branch Chicago River	10	11.995	15.659	34.6	18.9
Skokie River at Lake Forrest	9	8.958	9.447	69.1	28.1
Skokie River near Highland Park	6	13.146	11.405	46.3	21.6
Squaw Creek	10	6.937	9.542	300	-47.5
Flint Creek	11	9.801	7.557	438	-51.0

These T_C and *R* values then could be input to HEC-1 (U.S. Army Corps of Engineers, 1990) along with the design hyetograph.

SUMMARY AND CONCLUSIONS

Equations for estimating the time of concentration (T_C) and storage coefficient (*R*) for use with the Clark unit-hydrograph method were developed for small rural watersheds [0.02–2.3 square miles (mi^2)] in Illinois. The equations provide State and local engineers and planners with more accurate methods to estimate design hydrographs relative to current practice for water-resources-management activities, including designing stormwater-management facilities and other hydraulic structures, determining flood-plain boundaries, and assessing the safety of structures in rivers.

The established hydrologic data base contains rainfall and runoff data from gaged small rural watersheds (0.02–2.3 mi^2) in Illinois with insignificant amounts of impervious land cover. Equations were developed using 121 storms with effective rainfall depths greater than 0.4 inches (in.) on 39 watersheds. In the verification, 29 storms with effective rainfall depths greater than 0.4 in. on 18 watersheds were used. Two of the watersheds used in verification were not used for equation development. The limitations of the developed equations were tested for 74 storms with effective rainfall depths greater than 0.4 in. on 9 larger and (or) urbanized watersheds in Lake County, Illinois.

The Clark unit-hydrograph parameters (T_C and *R*) were determined by calibration, using the U.S. Army Corps of Engineers Flood Hydrograph Package HEC-1. Mathematical relations among watershed and storm characteristics and seasonal effects, and T_C and *R* were determined by multiple-linear regressions of the logarithms of the values. Main-channel length and slope were identified as important characteristics for estimating T_C and *R*. The estimation equations had coefficients of determination (R^2) of 0.73 and 0.64 for logarithms of T_C and *R*, respectively. When adding storm characteristics, only minimal increases to the R^2 resulted. No increase in R^2 resulted when adding Julian day (as a measure of seasonal effects) to the regression with length and slope; therefore, equations utilizing storm characteristics and seasonal effects were not developed. Attempts to estimate T_C and *R* using methods similar to those used in an earlier study were abandoned because a reliable way to determine $R/(T_C+R)$ was not found.

For the verification storms, simulation of the measured hydrographs utilizing T_C and *R* obtained from the estimation equations (utilizing main-channel length and slope) yielded good results. The error in peak discharge for 21 of the 29 storms was less than 25 percent, and the error in time-to-peak discharge for 18 of the 29 storms was less than 25 percent. Application of the estimation equations to determine T_C and *R* for design-storm simulation may result in reliable design-discharge hydrographs, as long as the physical characteristics of the watersheds under consideration are within the range of the physical characteristics for the watersheds used in this study [area: 0.02–2.3 mi^2, main-channel length: 0.17 –3.4 miles, main-channel slope: 10.5–229 feet per mile, and insignificant percentage of impervious cover].

REFERENCES CITED

Clark, C.O., 1945, Storage and the unit hydrograph: Transactions: American Society of Civil Engineers, vol. 110, p. 1419-1488.

Chow, V.-T., 1964, Runoff, section 14 *in* Chow, V-T., ed., Handbook of applied hydrology: New York, McGraw-Hill Book Company, variable pagination.

Chow, V.T., Maidment, D.R., and Mays, L.W., Jr., 1988, Applied hydrology: New York, McGraw-Hill Book Company, 572 p.

Curtis, G.W., 1977, Frequency analysis of Illinois floods using observed and synthetic streamflow records: U.S. Geological Survey Water-Resources Investigations Report 77-104, 32 p.

Ford, D.T., Morris, E.C., and Feldman, A.D., 1980, Corps of Engineers' experience with automatic calibration precipitation-runoff model *in* Haimes, Y., and Kindler, J., eds., Water and related land resource systems: New York, Pergamon Press, p. 467–476.

Graf, J.B., Garklavs, G., and Oberg, K.A., 1982a, Time of concentration and storage coefficient values for Illinois streams: U.S. Geological Survey Water-Resources Investigations Report 82-13, 35 p.

———1982b, A technique for estimating time of concentration and storage coefficient values for Illinois streams: U.S. Geological Survey Water-Resources Investigations Report 82-22, 10 p.

Hershfield, D.M., 1961, Rainfall frequency atlas of the United States for durations from 30 minutes to 24 hours and return periods from 1 to 100 years: Washington, D.C., U.S. Department of Commerce, Weather Bureau Technical Paper 40, 115 p.

Huff, F.A., and Angel, J.R., 1989, Frequency distributions and hydroclimatic characteristics of heavy rainstorms in Illinois: Champaign, Ill., Illinois State Water Survey Bulletin 70, 177 p.

Kuichling, E., 1889, The relation between the rainfall and the discharge of sewers in populous districts: Transactions: American Society of Civil Engineers, vol. 20, p. 1–60.

Laurenson, E.M., and Mein, R.G., 1985, RORB-version 3 runoff routing program user manual: Monash University, Clayton, Victoria, Australia, Department of Civil Engineering, 155 p.

Melching, C.S., and Marquardt, J.S., 1996, Equations for estimating synthetic unit-hydrograph parameter values for small watersheds in Lake County, Illinois: U.S. Geological Survey Open-File Report 96–474, 49 p.

Nash, J.E., and Sutcliffe, J.V., 1970, River flow forecasting through conceptual models, Part 1-A discussion of principles: Journal of Hydrology, v. 10, p. 282–290.

O'Kelly, J.J., 1955, The employment of unit hydrographs to determine the flows of Irish arterial drainage channels: Proceedings, Institution of Civil Engineers (Ireland), vol. 4, no.3, p. 365–412.

Ragan, R.M., and Duru, J.O., 1972, Kinematic wave nomograph for times of concentration: Journal of Hydraulics Division, American Society of Civil Engineers, vol. 98, no. HY10, p. 1765–1771.

Rao, A.R., Delleur, J.W., and Sarma, B.S.P., 1972, Conceptual hydrologic models for urbanizing basins: Journal of the Hydraulics Division, American Society of Civil Engineers, vol. 98, no. HY7, p. 1205–1220.

Shen, Y.-Y., 1974, Experimental investigation of the effects of rainstorm and watershed characteristics on surface runoff: Urbana, Ill., Ph.D. Thesis, Department of Civil Engineering, University of Illinois at Urbana-Champaign, 197 p.

Soil Conservation Service, 1985, National engineering handbook, section 4. hydrology: Washington, D.C., U.S. Department of Agriculture, variable pagination.

Snyder, F.F., 1938, Synthetic unit-graphs: Transactions, American Geophysical Union, vol. 19, p. 447–454.

Turner, H.M., and Burdoin, A.J., 1941, The flood hydrograph: Journal of the Boston Society of Civil Engineers, vol. 28, no. 3, p. 232-281.

U.S. Army Corps of Engineers, 1990, HEC-1 flood hydrograph package, user's manual: Davis, Calif., U.S. Army Corps of Engineers Hydrologic Engineering Center, variable pagination.

U.S. Department of Agriculture, Agricultural Research Service, 1957, Monthly precipitation and runoff for small agricultural watersheds in the United States: Washington, D.C.

Viessman, W., Jr., Lewis, G.L., and Knapp, J.W., 1989, Introduction of hydrology, third edition: New York, Harper and Row Publishers, 780 p.

TABLE 12

Table 12. Parameters for the Clark unit-hydrograph method determined from calibration of the U.S. Army Corps of Engineers (1990) Flood Hydrograph Package HEC-1 and measures of calibration quality for data from small rural watersheds in Illinois, for storms utilized to develop and verify the equations for estimation of Clark unit-hydrograph parameters

[T_C, time of concentration; R, storage coefficient; negative percent indicates that the simulated peak discharge was less than the measured peak discharge; ISWS, Illinois State Water Survey; USDA, U.S. Department of Agriculture]

Watershed	Date	T_C	R	Model-fit efficiency	Error in peak discharge (percent)
Big Four Ditch Tributary	May 26, 1956	2.205	2.035	0.985	3.7
Salt Fork Tributary	August 4, 1968[1]	4.019	2.911	.990	-1.6
	April 19, 1970	2.345	3.375	.974	-6.2
	June 22, 1974	2.956	2.054	.980	4.9
North Fork Vermillion River Tributary	July 4, 1956	1.224	.886	.957	-5.7
	July 16, 1956	1.556	.954	.968	1.7
Raccoon Creek Tributary	June 27, 1957[1]	.299	.191	.956	3.8
	June 28, 1957	.369	.182	.958	1.3
	July 10, 1958	.449	.242	.993	2.7
	July 11, 1958	.232	.168	.973	.8
	June 22, 1959[1]	.300	.490	.958	-4.8
Embarras River Tributary	June 13, 1958[1]	.197	1.114	.927	-3.4
	June 23, 1960	.330	1.320	.988	.8
Dums Creek Tributary	July 3, 1958	.200	.490	.986	9.6
	May 18, 1959	.274	.916	.988	1.6
	June 12, 1960	.202	.228	.994	7.2
	June 28, 1960	.155	.265	.979	6.7
	June 30, 1960	.342	.248	.957	15
	July 1, 1960	.292	.239	.945	7.9
White Feather Creek	December 19, 1957	.542	.748	.941	-2.7
	July 30, 1958	.756	.294	.950	1.4
	May 18, 1959[1]	.951	.689	.928	-.7
	May 6, 1961	.991	.779	.943	-.2
	May 7, 1961	1.058	.372	.976	1.1
	May 8, 1961	.929	.361	.978	4.6
	May 8, 1961[1]	.680	.680	.978	4.6
Little Wabash Tributary	March 31, 1968	.509	.451	.996	2.5
	April 3, 1968	.764	.216	.985	2.0
Little Saline Creek Tributary	April 19, 1970	1.733	.518	.967	-13
	May 1, 1970	1.363	.767	.940	-8.9
	May 10, 1970	2.495	.475	.921	-13
	February 20, 1971[1]	1.849	.521	.831	-12
	December 30, 1971	1.347	.663	.897	-15
Lake Glendale Inlet	March 29, 1960	1.138	1.572	.915	-7.4
Q Ditch Tributary	August 6, 1959	.904	.406	.968	-15
	August 17, 1959	.905	.446	.993	.1
Middle Branch South Branch Kishwaukee River	June 14, 1972[1]	.413	4.747	.950	-5.6
	August 25, 1972	1.760	3.130	.932	-5.9
South Branch Kishwaukee River Tributary	September 13, 1972[1]	1.887	1.483	.977	-5.5
	April 21, 1973[1]	1.562	.918	.987	10.9
Leaf River Tributary	June 7, 1969	.537	.343	.968	-2.6
Sand Creek	June 7, 1967	.475	.605	.973	6.4
Ellison Creek Tributary	April 8, 1965	.714	1.386	.963	2.21
	June 10, 1967	.534	.836	.986	-1.2
	June 21, 1967	.452	1.288	.987	4.5
	July 29, 1967	.644	.527	.966	-2.2
Little Creek	April 19, 1964	1.150	.470	.963	-7.7

Table 12. Parameters for the Clark unit-hydrograph method determined from calibration of the U.S. Army Corps of Engineers (1990) Flood Hydrograph Package HEC-1 and measures of calibration quality for data from small rural watersheds in Illinois, for storms utilized to develop and verify the equations for estimation of Clark unit-hydrograph parameters —Continued

Watershed	Date	T_C	R	Model-fit efficiency	Error in peak discharge (percent)
Little Creek	December 31, 1964[1]	1.040	0.960	0.947	-5.6
	July 13, 1965	.802	.558	.898	-.85
	April 21, 1973	1.218	.522	.958	-4
	April 30, 1973	.891	.569	.985	-.5
	May 27, 1973	1.188	.612	.951	-2.4
	June 18, 1973	1.151	.620	.975	1.3
	July 29, 1973	1.359	.732	.997	2.95
	May 19, 1974	1.163	.547	.935	-7.9
Homan Creek Tributary	July 4, 1962	.469	.191	.982	-.4
Kiser Creek Tributary	August 10, 1961	.657	.323	.982	2.92
	September 13, 1961[1]	.607	.213	.972	-2.7
	May 10, 1962	.322	.548	.873	-4.3
	June 9, 1962	.780	.350	.902	-7
	July 2, 1962	.623	.307	.996	1.95
	August 5, 1962	.620	.790	.959	-6.3
	July 28, 1973	.360	1.440	.973	-.01
	October 11, 1973[1]	.275	2.225	.921	11.5
	April 21, 1974[1]	.521	.749	.928	3.2
	May 29, 1974	.527	.644	.938	-1.4
Fox River Tributary Number Two	August 25, 1972	.897	.573	.979	8.2
	May 15, 1974	.585	.775	.954	4.82
Mud Creek Tributary	May 14, 1970	1.409	.901	.960	-3.6
	June 20, 1970	1.336	1.184	.984	-8.3
	July 17, 1972	1.062	1.298	.947	-3
	July 18, 1972	1.476	.944	.925	-8.1
	August 6, 1972	.448	1.212	.994	1.07
	August 25, 1972	1.505	1.135	.983	-5.8
	June 16, 1973	.967	.823	.942	-13.9
West Bureau Creek Tributary	April 21, 1973[1]	.263	.467	.958	-10.8
Coffee Creek Tributary near Florid	July 18, 1969[1]	.310	.160	.988	-1.5
	July 17, 1972	.258	.042	.906	-5.01
Coffee Creek Tributary near Hennepin	July 30, 1970	.866	.274	.825	-11.8
	September 23-24, 1970[1]	.927	.293	.771	9.6
	August 23, 1972	.774	.126	.969	1.5
	May 16, 1974	.632	.258	.904	.9
Wildcat Creek Tributary	June 10, 1958	.216	.724	.957	6
	July 11, 1958	.558	.802	.923	1.7
	June 23, 1960	.295	.885	.888	-4.5
Sangamon River Tributary	April 19, 1964	1.813	.977	.972	-8.6
	April 20, 1964	1.761	.949	.950	-6.3
	April 27, 1964	2.284	1.026	.950	-1.0
	June 1, 1965	2.218	1.142	.916	-7.0
	August 30, 1965	1.361	1.069	.981	.7
Illinois River Tributary	September 3, 1961	.506	.134	.968	-9.8
	July 2, 1962	.264	.136	.983	1.2
	July 4, 1962	.348	.172	.971	.6
Hurricane Creek	August 9, 1961	1.554	3.016	.998	.04
	June 3, 1962	2.035	1.535	.994	.01
	June 8, 1962	2.337	1.763	.990	-2.3

Table 12. Parameters for the Clark unit-hydrograph method determined from calibration of the U.S. Army Corps of Engineers (1990) Flood Hydrograph Package HEC-1 and measures of calibration quality for data from small rural watersheds in Illinois, for storms utilized to develop and verify the equations for estimation of Clark unit-hydrograph parameters —Continued

Watershed	Date	T_C	R	Model-fit efficiency	Error in peak discharge (percent)
Bear Creek Tributary	July 7, 1962	0.202	0.678	0.941	3.7
	July 13, 1962	.105	.645	.921	2.8
	October 2, 1962	.165	.865	.925	-6.7
Cahokia Creek Tributary	May 8, 1961	1.340	.660	.988	-3.4
	August 10, 1961	.555	.945	.963	7.1
Hurricane Creek Tributary	April 5, 1958	.750	.780	.985	1.8
	June 13, 1958[1]	.735	.935	.880	2.6
	June 27, 1958	1.336	.784	.950	-3.2
	June 27, 1958[1]	.920	.920	.979	7.7
	August 7, 1958[1]	.936	.974	.951	6.1
	May 27, 1959	.572	.398	.961	-.2
	August 6, 1959	.631	.559	.995	1.4
	August 6, 1959	.567	.503	.989	5.2
Williams Creek	March 5, 1961	2.888	1.422	.994	1.6
	May 6, 1961	2.330	2.330	.992	-.1
	May 8, 1961	1.885	1.605	.982	-2.1
Andy Creek Tributary	June 12, 1958	1.878	1.012	.957	4.7
	July 13, 1958	2.081	.770	.971	.6
	July 22, 1958	2.314	.856	.984	5.0
	August 17, 1959[1]	2.691	.759	.980	.4
Green Creek Tributary	March 16, 1963	.318	.422	.965	3.4
	July 15, 1966	.897	.253	.960	-13
	August 19, 1966	.310	.410	.955	6.7
ISWS Field Site 1	April 2, 1982	.304	3.076	.944	.1
	April 3, 1984	1.222	1.688	.954	2.9
ISWS Field Site 6	April 2, 1982	.396	1.404	.987	.5
	May 28, 1982	.318	.953	.959	.0
	July 10, 1982[1]	.321	1.369	.936	4.1
	April 3, 1984	.351	2.159	.988	-5.6
USDA Watershed IA1	May 30, 1982[1]	.937	1.193	.917	-2.6
	July 2, 1982[1]	.612	2.048	.946	6.8
	June 28, 1983	.088	.792	.936	3.3
USDA Watershed IA	July 23, 1973[1]	1.076	.554	.661	-5.8
	June 22, 1974[1]	.087	.883	.893	-2.9
	February 16, 1976	.249	1.531	.979	-6.8
	August 7, 1977	.229	1.201	.968	6.3
	May 30, 1982[1]	.323	.687	.907	3.1
USDA Watershed IB	April 20, 1964	1.165	.745	.974	4.9
	December 21, 1967	.924	.726	.962	-11
	June 15, 1970	.270	.260	.890	-1.0
	February 4, 1971[1]	2.645	.395	.964	-3.6
	April 19, 1972[1]	2.322	3.078	.937	5.0
	June 22, 1974	.137	.623	.909	1.0
	February 16, 1976	1.311	1.669	.932	-4.4
	August 7, 1977	.635	1.035	.974	-2.2
USDA Watershed W-1	May 27, 1938	.085	.145	.959	3.0
	March 31, 1952	.157	.423	.953	-3.6
	March 31, 1952	.162	.288	.965	2.3
	July 2, 1952	.090	.270	.974	6.6

Table 12. Parameters for the Clark unit-hydrograph method determined from calibration of the U.S. Army Corps of Engineers (1990) Flood Hydrograph Package HEC-1 and measures of calibration quality for data from small rural watersheds in Illinois, for storms utilized to develop and verify the equations for estimation of Clark unit-hydrograph parameters —Continued

Watershed	Date	T_C	R	Model-fit efficiency	Error in peak discharge (percent)
USDA Watershed W-4	May 27, 1938	0.345	0.345	0.965	-8.4
	June 21, 1942	.322	.348	.972	-1.5
	March 31, 1952	.441	.719	.914	-8.8
	March 31, 1952	.515	.265	.929	-7.5
	July 2, 1952	.244	.286	.981	3.9

[1]Storm utilized to verify the relations for estimating the Clark unit-hydrograph parameters.

U.S. GEOLOGICAL SURVEY
221 NORTH BROADWAY AVE.
URBANA, ILLINOIS 61801

Straub and others—EQUATIONS FOR ESTIMATING CLARK UNIT-HYDROGRAPH PARAMETERS FOR SMALL RURAL WATERSHEDS IN ILLINOIS—
U.S. Geological Survey Water-Resources Investigations Report 00–4184