A TECHNIQUE FOR ESTIMATING TIME OF CONCENTRATION AND STORAGE COEFFICIENT VALUES FOR ILLINOIS STREAMS

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GLOSSARY OF TECHNICAL TERMS

Discharge. The volume of water that passes a given point and within a given period of time, in cubic feet per second.

Drainage area. The area, measured in a horizontal plane, which is enclosed by a drainage divide, in square miles.

Hydrograph. A graph showing stage, discharge, velocity, or other property of water with respect to time.

Instantaneous unit hydrograph. A hydrograph of direct runoff resulting from 1 inch of uniformly distributed excess rainfall occurring instantaneously over the entire drainage area.

Length. Stream length measured along the channel from the gage to the basin divide, in miles.

Regression equation. A mathematical relationship between a dependent variable and one or more independent variables.

Runoff. That part of rainfall that appears in streams.

Slope. Main channel slope determined from elevations at points 10 and 85 percent of the distance along the channel from the gaging station to the drainage basin divide, in feet per mile.

Standard error. A measure of the scatter of data points about a regression line. The standard deviation of the distribution of residuals about the regression line.

Storage. The volume of water detained in a drainage basin.

Storage coefficient. Proportionality constant between storage and discharge at the outflow point of a basin, a time characteristic of a basin indicative of channel storage capacity.

Time of concentration. The time required for excess rain falling on the remotest part of a drainage area to reach the outlet or point of discharge on the stream.

Unit hydrograph. A hydrograph of direct runoff resulting from 1 inch of uniformly distributed excess rainfall occurring in unit time.

FACTORS FOR CONVERTING INCH-POUND UNITS TO INTERNATIONAL SYSTEM OF METRIC UNITS (SI)

Multiply inch-pound unit	By	To obtain SI unit
Inch (in)	25.4	Millimeter (mm)
	0.0254	Meter (m)
Mile (mi)	1.609	Kilometer (km)
Foot per mile (ft/mi)	0.1894	Meter per kilometer (m/km)

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ABSTRACT

Values of the unit hydrograph parameters time of concentration (TC) and storage coefficient (R) can be estimated for streams in Illinois by a two-step technique developed from data for 98 gaged basins in the State. The sum of TC and R is related to stream length (L) and main channel slope (S) by the relation $(TC + R)_e = 35.2\,L^{0.39}\,S^{-0.78}$. *Regional values of R/(TC + R) are used with values of* $(TC + R)_e$ *to compute estimated values of time of concentration* (TC_e) *and storage coefficient* (R_e). *The variable R/(TC + R) is not significantly correlated with drainage area, slope, or length, but does exhibit a regional trend. That variable accounts for variations in unit hydrograph parameters caused by physiographic variables such as basin topography, flood plain development, and basin storage characteristics.*

INTRODUCTION

The ability to estimate peak discharge, volume of runoff, and time distribution of runoff in response to rainfall is often required in water resources management. Time of concentration, a measure of the time difference between rainfall and runoff, and storage coefficient, a routing constant, are two parameters used in the application of unit hydrograph theory for construction of a discharge hydrograph from a given excess rainfall (Clark, 1945). For a given basin, time of concentration defines the hydrograph which would result from runoff from incremental subareas if storage within the basin were neglected. To account for storage, this hydrograph is routed through a hypothetical linear reservoir. The storage coefficient is used in the Muskingum method to do the routing and compute the modified hydrograph.

Values of time of concentration and storage coefficient are available for many gaged basins in Illinois (Graf and others, 1982). For ungaged basins, values of time of concentration and storage coefficient must be estimated, and these estimated values then used to generate synthetic hydrographs. In 1978, the U.S. Geological Survey (USGS), in cooperation with the Illinois Department of Transportation, Division of Water Resources, began an investigation with the purpose of developing a technique for estimating time of concentration and storage coefficient values for ungaged basins in Illinois.

ESTIMATING TECHNIQUE

Development

A technique for estimating time of concentration and storage coefficient was developed from the relation between basin characteristics and unit hydrograph parameters computed by calibration of the U.S. Army Corps of Engineers' flood hydrograph package (HEC-1) (U.S. Army Corps of Engineers, 1973) for 98 gaged basins in Illinois (Graf and others, 1982).

The symbols TC and R used in HEC-1 to represent time of concentration and storage coefficient, respectively, are equivalent to Clark's (1945) unit hydrograph parameters. Two composite variables, (TC + R) and R/(TC + R), are introduced in the HEC-1 program to reduce interdependency of TC and R. In the program, optimum values of the composite variables are found and individual values of TC and R computed from those optimum values.

Unit hydrograph parameters are related to variables which are measures or functions of basin size (drainage area, channel length, slope) which have little or no regional trend. Other basin characteristics which may have regional variations (topography, rainfall distribution, land use, geology) also influence the hydrograph parameters. The presence or absence of regional trends was investigated with a linear regression technique called polynomial trend analysis.

In this technique, multiple regression models are formed from polynomials of successively higher degree. Independent variables are the map coordinates and the dependent variable is the parameter for which the regional trend is being investigated. Each regression model defines a surface, a first degree model defining a planar surface, a second degree model defining a parabolic surface, and successively higher degree models describing surfaces of increasing complexity. A third degree model is represented by an equation of the form:

$$z = b_0 + b_1x + b_2y + b_3x^2 + b_4xy + b_5y^2 + b_6x^3 + b_7x^2y + b_8xy^2 + b_9y^3 \qquad (1)$$

where x and y are map coordinates, z is the estimated value of the dependent variable, and b_0 through b_9 are regression coefficients computed by the least squares method. Successively higher degree models can be tested for significance and the model which best represents the data selected. As in any other regression model, the goal is to identify systematic trends and to separate those trends from random variation. (See Krumbein and Graybill, 1965.)

Application of this technique to the hydrograph parameters reveals no significant regional trend to TC and a first degree regional trend to R, when tested at the 5 percent significance level. The variable R/(TC + R) was found to have a significant third degree trend (table 1), whereas the variable (TC + R) was found to have no trend significant at the 5 percent level.

Table 1.--Analysis of variance of R/(TC + R) trend analysis data

[First through third order terms are significant at the 5 percent level. Number of values is 98.]

Source	Sum of squares	Degrees of freedom	Mean square	Value of the F statistic
Linear surface Deviations from linear	0.727 1.855	2 95	0.363 0.020	18.62
Second order terms Deviations from second order	0.189 1.666	3 92	0.063 0.018	3.50
Third order terms Deviations from third order	0.195 1.471	4 88	0.049 0.017	2.89

The relation of hydrograph parameters and the composite variables to drainage area, length, and slope was also investigated. Correlation analysis reveals that although TC and R are correlated, the variables (TC + R) and R/(TC + R) are not significantly correlated with each other (table 2). Also, TC, R, and (TC + R) are significantly related to drainage area, length, and slope, whereas the variable R/(TC + R) is not (table 2).

The relations presented above suggest that the use of the variables (TC + R) and R/(TC + R) in a predictive technique could reduce the interdependence of TC and R and separate the dependence of each parameter on drainage area, length, and slope from the dependence on regionally varying characteristics. Therefore, a two-step approach to finding estimates of time of concentration (TC_e) and storage coefficient (R_e) was developed.

First, a relation between the sum of the two hydrograph parameters, TC and R, and basin characteristics was obtained by stepbackward regression of (TC + R) on drainage area, length, and slope. The coefficient of the drainage area term was not significant at the 5 percent level, and length (L) and slope (S) were found to best represent the relationship:

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

Table 2.--Correlation coefficient matrix for HEC-1 model hydrograph parameters and basin characteristics

[Coefficients of +0.20 and greater or - 0.20 and smaller are significant at the 5 percent level.]

	TC	R	(TC + R)	$\frac{R}{(TC + R)}$
TC	1.00			
R	0.68	1.00		
(TC + R)	0.94	0.89	1.00	
R/(TC + R)	- 0.36	0.27	- 0.09	1.00
Drainage area	0.68	0.56	0.69	- 0.14
Slope	- 0.43	- 0.46	- 0.48	- 0.03
Length	0.66	0.52	0.65	- 0.14

The standard error of the regression is 0.233 log units (equivalent to a standard error for the untransformed variable of 57.8 percent). Therefore, two-thirds of the calculated (TC + R) values lie within +71.0 and - 41.5 percent of the regression surface.

Second, regional values of the variable R/(TC + R) were developed from the third degree regression model discussed previously. The analysis of variance of that trend analysis is given in table 1. The third degree surface has a standard deviation of 0.12 and explains 43 percent of the variation in the data. That surface was contoured, and regional values were computed as the average of the values at the contours bounding each region.

Estimated values of time of concentration and storage coefficient (TC_e and R_e) were computed for the 98 basins calibrated with the HEC-1 program, with the combination of equation 2 and figure 1. Estimated values were plotted against the values computed during model calibration for each basin (figs. 2 and 3). A standard error of the estimation for TC_e and R_e was found from a

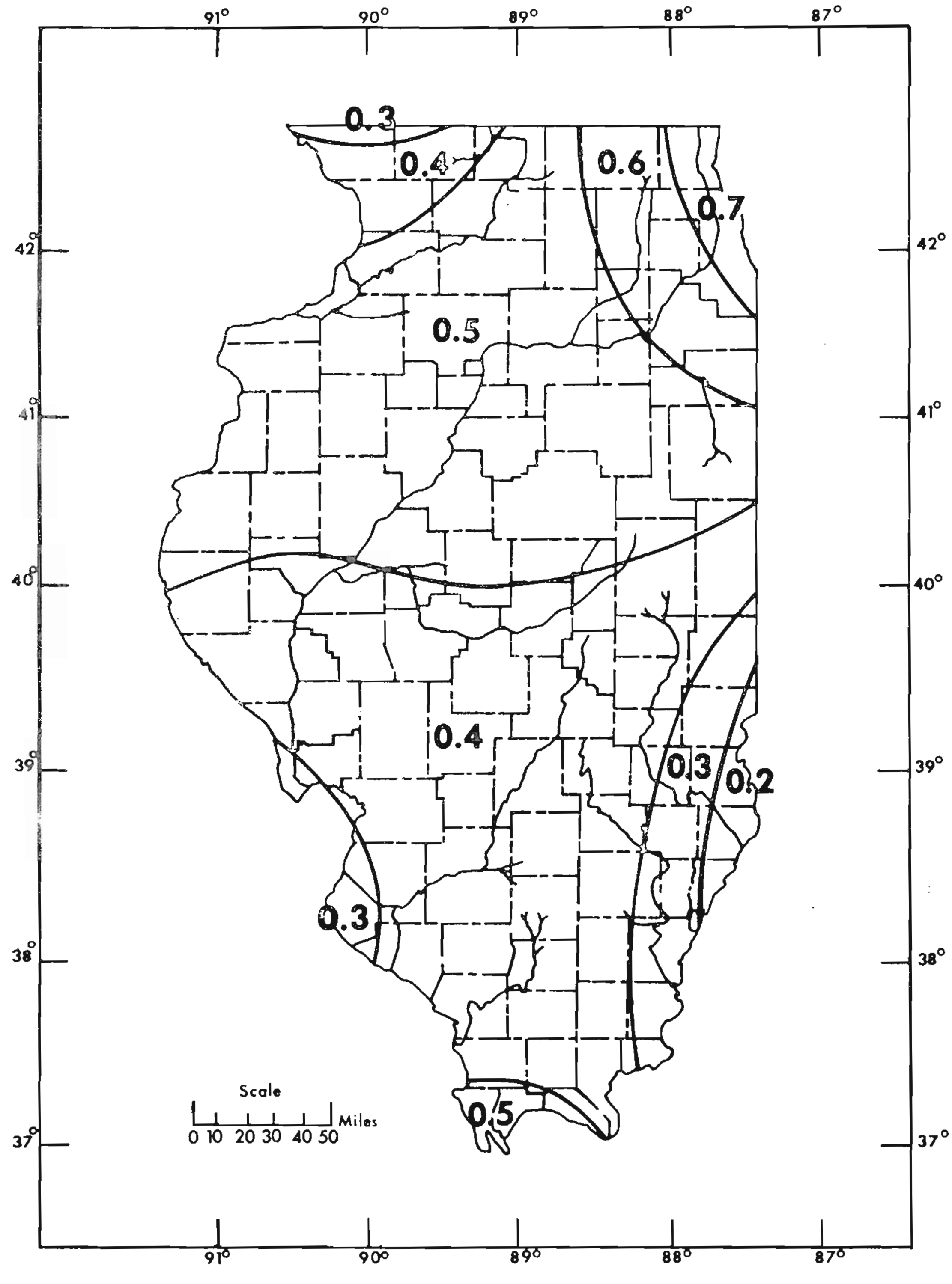

Figure 1.--Regional values of R/(TC + R).

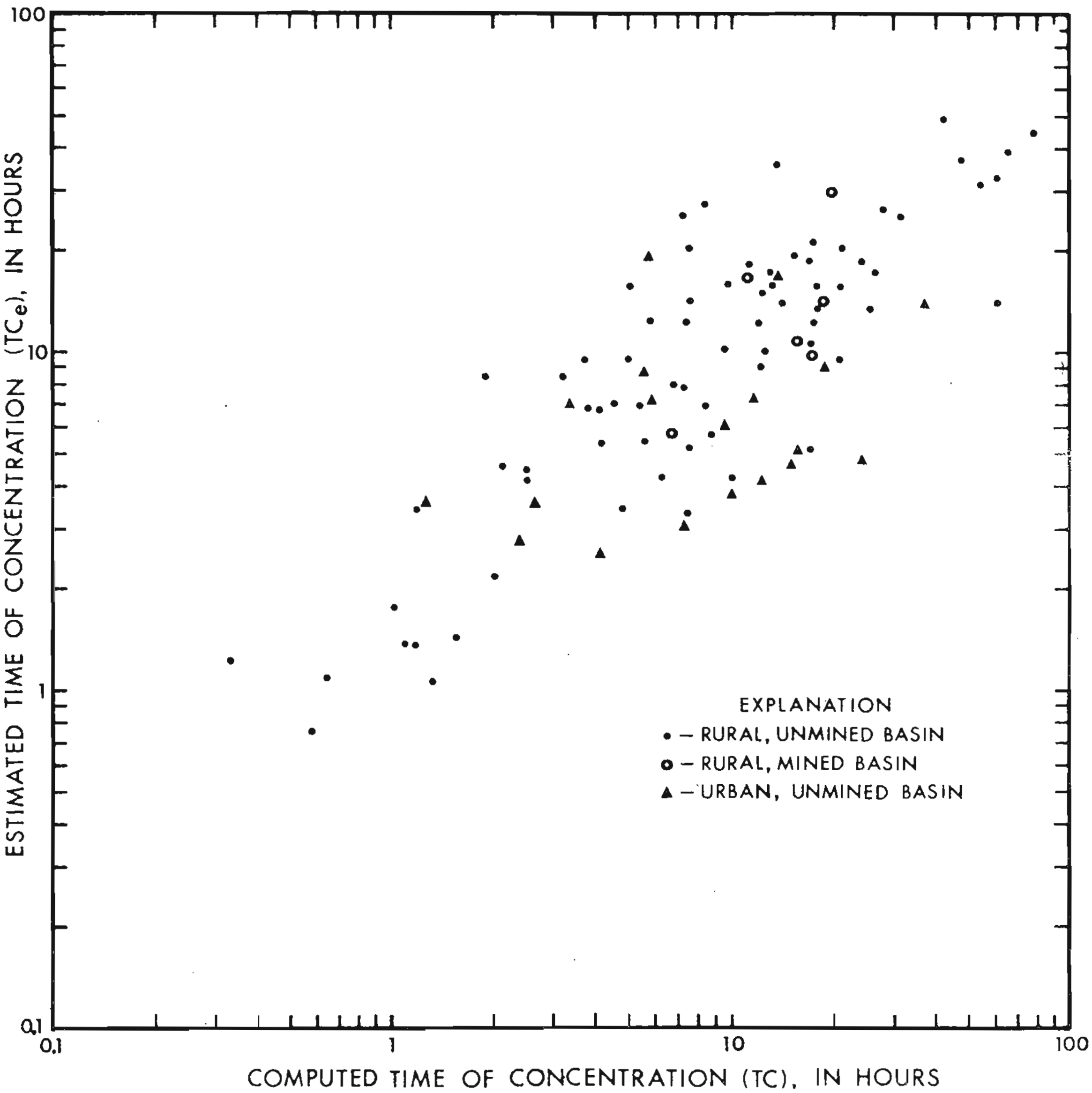

Figure 2.--Computed versus estimated time of concentration.

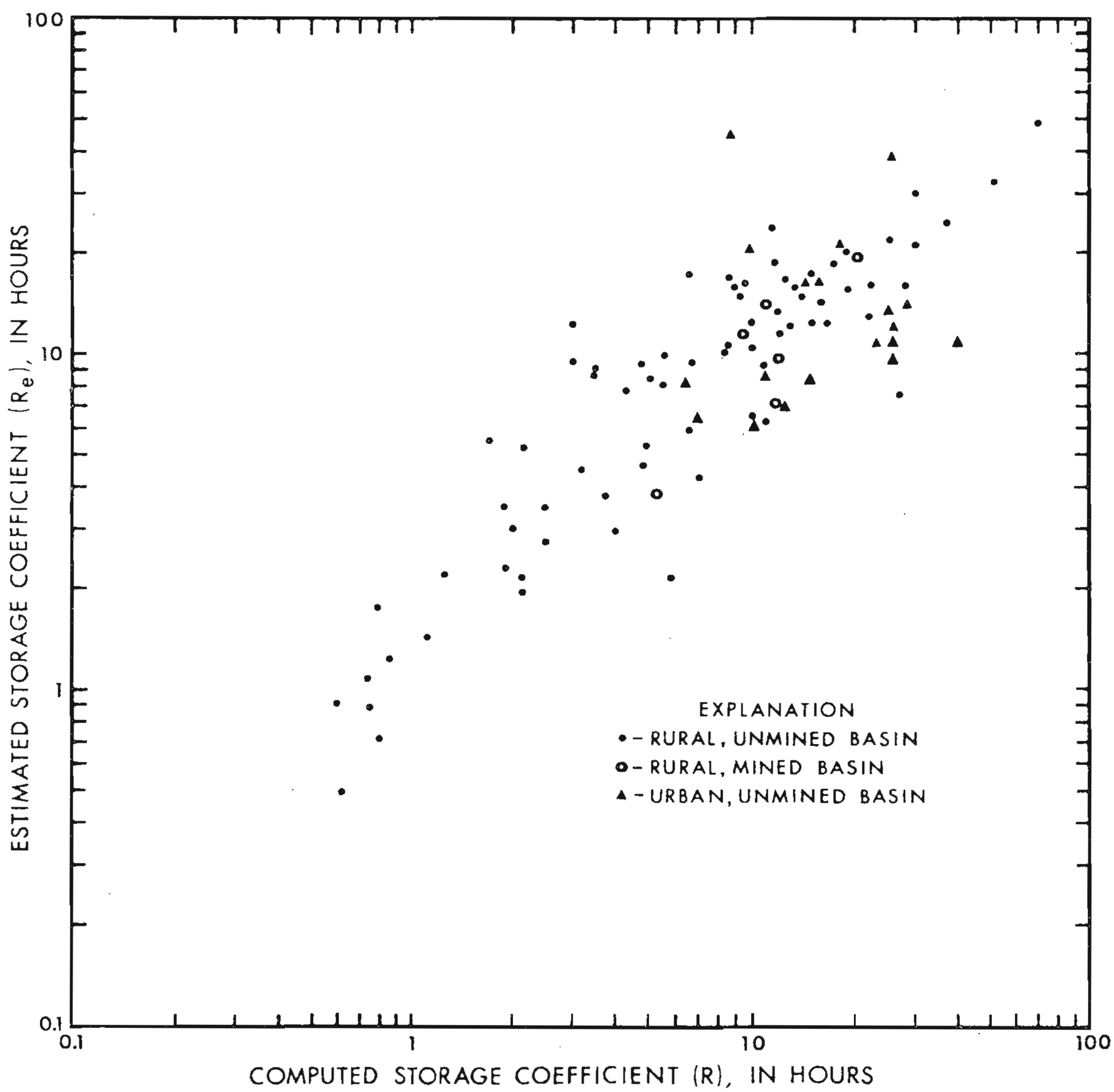

Figure 3.--Computed versus estimated storage coefficient.

regression of TC_e against TC and R_e against R. For TC_e, the standard error with this method is 0.237 log units or +72.6 and - 42.1 percent, and that for R_e is 0.208 log units or +61.4 and - 38.1 percent.

Application

As an example of application of this technique, values of TC_e and R_e for station 05577500 Spring Creek at Springfield, Ill., are computed as follows. Spring Creek has a length of 30.2 miles and a slope of 5.39 feet per mile. Substituting these values into equation 2 gives a value for $(TC + R)_e$ of 35.7 hours. The value of R/(TC + R) from figure 1 for Spring Creek is 0.40.

Then
$$R_e = R/(TC + R) \times (TC + R)_e$$
$$= 0.40 \times 35.7 \text{ hours}$$
$$= 14.3 \text{ hours},$$

and
$$TC_e = (TC + R)_e - R_e$$
$$= 35.7 \text{ hours} - 14.3 \text{ hours}$$
$$= 21.4 \text{ hours}.$$

DISCUSSION

Regionally varying basin characteristics are indirectly considered in the technique presented above through the use of the variable R/(TC + R). Illinois has been divided into hydrologic regions (Mitchell, 1954) based on the physiographic divisions of the State (Leighton and others, 1948). In developing the hydrologic regions, Mitchell modified physiographic region boundaries to improve relations with hydrologic variables. Characteristics of the divisions which could affect hydrographs include basin shape, topographic relief, development of flood plains, and basin storage characteristics. According to Mitchell (1954), the Wheaton Morainal Region in northeastern Illinois is characterized by long, narrow drainage basins and many small lakes and swamps. These factors, as well as urbanization, combine to cause times of concentration to be low relative to storage coefficient. This is reflected in R/(TC + R) values (fig. 1), which are the highest in the State. In northwestern Illinois, in the Wisconsin Driftless and Rock River Hill Regions, greater relief and more exposed bedrock surfaces result in a smaller storage coefficient relative to time of concentration and, therefore, low values of R/(TC + R). Other areas of low R/(TC + R) values (fig. 1) are found along the southwest edge of the State (Lincoln Hills and Salem Plateau Regions) and in the southeast. These are also areas of greater relief, steeper slopes, and less storage capacity than other areas of the State. The trend toward larger values of R/(TC + R) to the south may be caused by the low slopes and broad, flat flood plains described by Mitchell (1954).

Although most of the drainage basins used in this study are rural and have not been strip mined, 19 urban stations (greater than about 7 percent impervious area) (Allen and Bejcek, 1979) were included, as were 6 stations with significant areas of strip-mined land. Because the number of stations in each group was too small for separate analysis, they were included in this analysis and marked on figures 2 and 3. No clear separation of either of these groups from the remaining data can be seen on either of the figures. The estimating technique presented here appears to compensate for any effects that those land use characteristics might have on unit hydrograph parameters.

SUMMARY

A two-step technique is presented for estimating the unit hydrograph parameters for ungaged basins. Equation 2 is used with channel slope and length to compute estimated values of $(TC + R)_e$. Regional values of the variable R/(TC + R) given in figure 1 are used with $(TC + R)_e$ to compute the estimates, TC_e and R_e.

Use of the variables (TC + R) and R/(TC + R) reduces the effects of interrelation between TC and R. The technique incorporates the dependence of TC and R on basin characteristics which have regional trends in addition to those which do not.

The pattern of regional variation in R/(TC + R) ressembles that of the hydrologic regions of Illinois developed by Mitchell (1954). That trend reflects trends in basin storage characteristics, topography, and surficial materials.

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