COMMONWEALTH OF KENTUCKY
DEPARTMENT OF HIGHWAYS
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January 29, 1968

MEMORANDUM

TO: W. B. Drake
Assistant State Highway Engineer
Chairman, Kentucky Highway Research Committee

SUBJECT: Research Report; "Application of Stanford Watershed Model Concepts to Predict Flood Peaks for Small Drainage Areas;" HPR-1(3), Part II, KYHPR-64-23

This report embodies two principal objectives: 1) updating rainfall intensity-duration curves for the hydraulic design of culverts and 2) adaptation of the Stanford Watershed Model concept to small drainage basins in Kentucky. The first objective is familiar -- the curves presently being used for the rational method of design were established from an earlier Department study made by E. M. West and W. H. Sammons, issued in July, 1955 (Report No. 2, "A Study of Runoff from Small Drainage Areas and the Openings in Attendant Drainage Structures"), and were based on rainfall records then available through 1951. The second objective is somewhat more ambitious and more complex; in its most practical sense, it involves an attempt to equate total rainfall to total runoff and losses throughout a span of years; the losses are then accounted for as evaporation, infiltration, etc. Ideally, all of the significant hydrological parameters may be deduced; then through direct measurements of some essential input descriptors and indirect estimates of others, the water-balance concept may be applied to other basins.

This phase of study was assigned to K. D. Clarke because of his interest and training in hydrology while engaged in graduate studies at the University. He plans to submit the work toward the fulfillment of his masters thesis requirement. I should say in that respect that Dr. L. Douglas James, at the University, was Mr. Clarke's graduate study advisor, and some of the computer programs as well as the inspiration to pursue the Stanford Model concept are attributable to him.

The feasibility of undertaking a model-type analysis is attributed almost entirely to the availability of a rapid computer and, of course, to the availability of long term, rainfall-runoff records. We are hopeful that it will be possible in the near future to perform analyses on two additional watersheds: one in the western part of the

State and one in the eastern part. Confirmation and inter-correlations among three independent, widely separated areas are desired before we could confidently recommend its adoption as a design criterion. In that sense, that portion of the report is only a report of progress -- but is perhaps a preview of something that may become a reality.

Comparisons between runoff estimated by using the Stanford Model and using the Rational Formula may provide a basis for evaluating C-factors (Chart 1003, *Manual of Instructions for Drainage Design*, 1967). For example, the 50-year Q at Cave Creek which was determined by Model procedures is 760 cfs whereas by the rational procedure it is 960 cfs; the 100-year Q is 885 cfs as compared to 1057 cfs. Giving full reliance to the Model method indicates that the true C-factor for Cave Creek would be 0.174 (Note: Chart 1003 assigns a value of 0.21 to the entire Central Kentucky Area). Bear Branch (University of Kentucky, Robinson Forest) in Breathitt County was used as another comparative example; there the 50-year Model Q was 499 cfs; and the rational Q, using a C-factor of 0.15, from Chart 1003, was 643 cfs. (Note: Using a C-factor of 0.12, given in Chart 1003 for the most eastern zone of the State, the rational Q would be 514 cfs -- which is in much closer agreement with the Model Q; it is interesting to note also that Bear Branch lies close to the boundary between the 0.15- and 0.12-zone). Of course, this comparison with the Bear Branch basin is only a cursory one, and we are unable at this time to evaluate the normal variation within a general area of the State.

Precise estimates of time-of-concentration remain problematical. The Ramser equation still needs to be proof-tested by direct measurements on a number of small drainage areas in different physiographic regions of the State.

On the basis of our re-analysis of rainfall data, I recommend revision of Chart 1004 (to correct an error) and all 1005-Charts in the Manual.

Respectfully submitted,

Jas. H. Havens

Jas. H. Havens
Director of Research
Secretary, Research
Committee

JHH:em
Attachment
cc: Research Committee
- A. O. Neiser
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Research Report

APPLICATION OF STANFORD WATERSHED MODEL CONCEPTS TO PREDICT FLOOD PEAKS FOR SMALL DRAINAGE AREAS
HPR-1(3): KYHPR-64-23

by

K. D. Clarke, Assistant Research Engineer

Division of Research
DEPARTMENT OF HIGHWAYS
Commonwealth of Kentucky

In Cooperation with the
U.S. Department of Transportation
Federal Highway Administration
Bureau of Public Roads

January, 1968

CHAPTER I

INTRODUCTION

A major problem in the design of drainage structures for small basins is the determination of a design discharge. A large percentage of highway drainage facilities are for small areas wherein flow occurs only during storm periods and for which few, if any, records are available for rainfall or runoff. It has been estimated that approximately 15 percent (3, p. 1) of the expenditures for highway construction (nationwide) go toward drainage facilities for small basins. Current, annual expenditures for highway culverts within the United States are in the order of $500 million and it is estimated that the cost of construction of all drainage facilities, exclusive of bridges, for the interstate system alone will total approximately $4 billion (12, p. 25). The magnitude of these figures in addition to the fact that maintenance and construction costs are continually increasing suggests that due care should be exercised in determining design discharges in order to minimize the temptation to overdesign drainage structures.

Method of Estimating Peak Flows

The hydraulic sizing of a culvert for given physical conditions and a prescribed runoff is a rather well defined process. Determination of the design discharge, on the other hand, is not always a simple or straightforward procedure. Ideally, a culvert is designed to convey the peak runoff that may be expected to occur once within a given number of years (return period or frequency). The return period is the frequency of recurrence of runoff (generally in cubic feet per second) of a given magnitude; thereby, the runoff for a 10-year return period would be the peak flow that might be expected to be equalled or exceeded once every 10 years. Runoff exceeding the return period runoff would be expected to cause ponding within the basin, overtopping of the roadway, etc. For the larger drainage areas having gaging stations, peak runoffs for various return periods may be estimated quite accurately through frequency analyses of flood records. Other methods must be employed for the large percentage of smaller basins, for which such records are unavailable. The problem of determining waterway-area requirements for culverts has been under study well over a century; and, during this time, a number of approximation methods involving use of empirical equations, tables, and charts have evolved.

Some of the earlier methods, such as Myer's formula and Talbot's formula, attempted a direct estimation of waterway-area requirements on the basis of total basin area and essentially excluded hydrologic as well as hydraulic design considerations. Later methods included various forms of hydrologic analysis of the basin or general area and provided for hydraulic design of the structure. The several methods developed have been grouped into five principal classes by Chow (3, pp. 66-90) and are as follows: 1) waterway-area formulas, 2) simple flood formulas, 3) rainfall intensity formulas, 4) frequency formulas, and 5) elaborate discharge formulas. The Rational Formula (Class 3) is presently used by the Kentucky Department of Highways for design of structures draining basins having areas up to 10 square miles. In previous years, both Dicken's and Talbot's formulas were employed; however, these methods were discontinued because they are based upon data obtained from other areas of the country and were not necessarily intended for general use nationwide. Additionally, the formulas basically exclude hydrologic and hydraulic design considerations.

The Rational Formula provides a simple form of hydrologic analysis of the drainage basin in arriving at a design discharge. The formula is

$$Q = CIA \qquad 1$$

where Q is the design runoff in cubic feet per second, A is the basin area in acres, I is the design rainfall intensity in inches per hour, and C is the runoff coefficient which is defined as the ratio of runoff to rainfall. The basin area is readily obtainable from a survey or topographic map. The design rainfall intensity may be obtained from intensity-duration curves which have been developed for Kentucky using Gumbel's method of frequency analyses of rainfall data. Records from nine first-order Weather Bureau stations in and surrounding Kentucky were used in developing the Department's initial series of curves in 1951 (23). These curves were plotted for frequencies ranging from 2 to 100 years and were based upon approximately 50 years of records from each station. Additional years of records are now available, and a portion of this report is devoted to up-dating the intensity-duration curves. These curves indicate the intensity of rainfall expected from a storm of given duration and given return period. Use of the intensity-duration curves in conjunction with the Rational Formula is based upon the assumption that the design storm must be of a duration equivalent to the time-of-concentration of the drainage area. Records of previous storms indicate a definite relationship between duration of storms of a given magnitude and recurrence interval. A storm of 6 inches per hour which lasts for 10 minutes may occur on the average of once every 2 years whereas a storm of the same intensity but lasting for 30 minutes may occur only once every 10 to 15 years.

Limitations to Rational Formula

A significant problem in use of the Rational Formula is the selection of a value for the runoff coefficient. Ideally, the runoff coefficient should be of such value that the computed design discharge would have a return period equivalent to the design intensity return period. Rainfall and runoff return periods, normally, are not equal and may vary appreciably for a given storm. Variations in antecedent moisture conditions within a basin may appreciably alter the rainfall-runoff return period relationships from storm to storm. It is estimated that as many as fifty variables affect the rainfall-runoff relationship -- some of these factors are basin shape and slope, stream system pattern, elements of the channel, depth of hydrologic activity, soil exposure, amount of development, soil permeability and conditions of vegetation and cultivation. Restrictive assumptions (*cf.* 3, p. 16) made in formulation of the Rational Formula are:

1. The rate of runoff resulting from any rainfall intensity is maximum for a rainfall of duration equivalent to or exceeding the time-of-concentration of the basin.
2. The peak runoff from a rain of a duration equal to the time-of-concentration is a fractional part of the intensity.
3. The rainfall and runoff frequencies are equal.
4. The peak discharge and basin area relationship corresponds to the intensity-duration relationship.
5. The runoff coefficient of a given basin is constant for storms of all frequencies.

Various tables are available for use in arriving at values of the runoff coefficient. Some list values of C as a function of the basin area while others list variations of C as a function of soil cover, land use, type of surface, etc. The Department's Manual of Instructions for Drainage Design (9) recommends that values of C for urban areas be computed by use of a table listing C as a function of type of surface wherein percentages of the basin area within various surface-type categories are estimated and a weighted or average value of C is then computed. A similar procedure is suggested for rural areas less than 100 acres. Runoff coefficients for rural areas exceeding 100 acres are obtained from a map which denotes values of C for various regions within the State. These suggested values are for average conditions prevailing within each region. Hydrologic characteristics of various basins within a given region may vary considerably, and the general applicability of the C-value map is somewhat questionable. Present methods for arriving at an estimate of C involve a great deal of guesswork and rely primarily upon the designer's judgement.

Explicit analysis of the interactions between watershed variables and precipitation is a complex process, and the quantity of data and man hours necessary for analysis has previously limited investigations of many hydrologic phenomena. Recent development of a complex computer program, known as the Stanford Watershed Model (4), has provided a means for more complete analysis of phenomenological occurrences within the hydrologic cycle. The model may be used to mathematically simulate a natural watershed from which the relationships between watershed variables and runoff coefficients may be studied. The model is based upon a complete moisture balance; all precipitation falling onto the watershed is accounted for until such time it evaporates or flows out of the basin. Interception, surface detention, infiltration and interflow may cause retention of the precipitation; the amount of retention is dependent upon the amount of water already stored within the watershed at the time of precipitation as well as characteristics of the watershed surface, and these variables may be defined by input data into the computer program -- watershed-parameter variations are represented by change of input data in order to control allocation of moisture to the various storages. Surface runoff is entered into overland-flow storage, from which it may be routed to the channel and then downstream by the time-area histogram in order to account for channel travel time. Channel storage effects are accounted for through use of a theoretical reservoir.

Approach of This Study

The Stanford Watershed Model mathematically portrays the runoff process and potentially permits a more refined and less arbitrary procedure for determining runoff coefficients than has heretofore been possible. Assuming that the input data to the model can be related to such measurable characteristics as depth of hydrologic activity, soil permeability, soil cover, and slope, the runoff coefficients may be correlated to these same characteristics. The design engineer may then evaluate these characteristics for the drainage area under analysis, obtain the runoff coefficient from the correlation, and then compute the design flow. The approach has many advantages:

1. Since moisture accounting within the model considers the time variation in surface runoff characteristics, coefficients may be developed which express the 50-year flood as a fraction of a 50-year storm (recognizing the two may occur at different times).
2. By using the correlation, the coefficients may be related to characteristics of the specific drainage area rather than the average regional drainage area.
3. The correlation incorporates the interdependence among noted watershed characteristics in order to better evaluate their combined effect upon flood peaks.

For this study, the Model was applied to a watershed selected from a survey of the small watersheds gaged by the U. S. Geological Survey within Kentucky. Criteria used in selecting the study watershed were:

1. A minimum of 10 years of continuous runoff record in order to firmly establish the existing rainfall-runoff relationship.
2. A drainage area of less than 5 square miles so as to be representative of small drainage basins for which better runoff coefficients are needed.
3. Location in close proximity to a rain gage for which hourly-precipitation data are available.
4. Availability of soil surveys for the watershed under study.

The Cave Creek watershed (Fig. 1) near Lexington was chosen on the basis of the foregoing criteria. The watershed has an area of 2.53 square miles and is located 1.20 miles from the Lexington recording rain gage. Extensive soil surveys and 13 years of runoff data were available for the area. The stream-gage records were used in a reiterative process as input data to the model to describe the watershed characteristics, and a long-term rainfall record was used to establish the relation between flood peak and frequency. Input data were then varied randomly, but within possible ranges of characteristics expected in the State at large, and computer runs were repeated in order to determine the effect of variation of watershed characteristics upon the flood-frequency relationship. The flood peak for a specific frequency was determined from each run for a set of watershed characteristics. Results of the series of runs were then correlated with the measurable watershed characteristics by the coaxial method.

The correlation, as developed in this study, may be used directly to establish the 50-year flood peak for a drainage area of 2.53 square

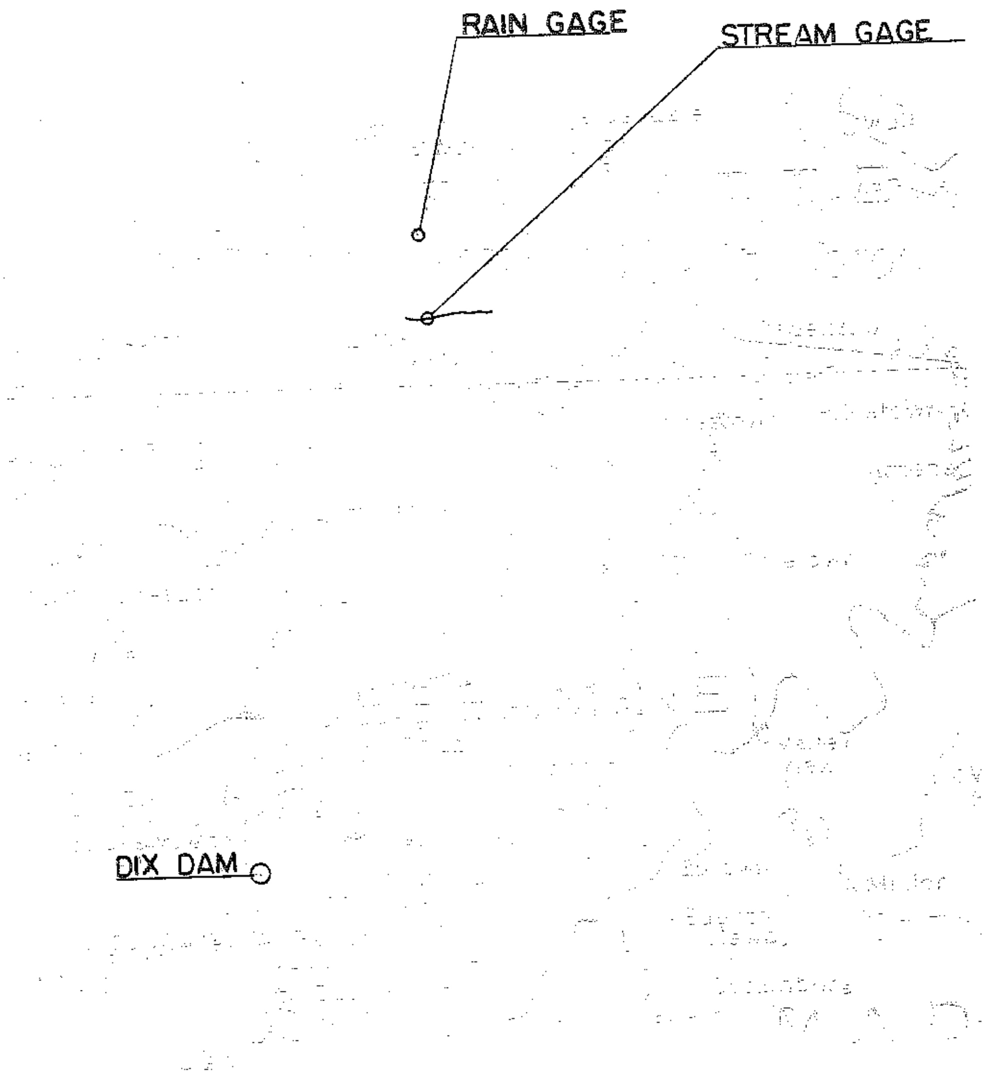


Fig. 1. Cave Creek Watershed Location Map

miles subjected to rainfall patterns similar to those of the Lexington area of influence. Procedures were developed to extend the analysis to flood peaks of different frequencies, various size drainage areas, and intensity-duration patterns different from those of the Lexington area. The key to extended utilization of the method is the selection of values for the measurable watershed characteristics. Guidelines for estimating these values have been established and are presented herein. Revised intensity-duration curves, based upon an extended period of records, were prepared in conjunction with this study and are presented in Chapter II.

CHAPTER II

DEVELOPMENT OF INTENSITY CURVES

A basic assumption in the Rational Formula is: the rate of runoff resulting from any rainfall intensity is maximum for a rainfall of duration equal to or exceeding the time-of-concentration of the basin (cf. 3, p. 16). Questions then arise as to what intensities of rains may be expected from storms of durations equal to or exceeding these times and what will be the frequency of recurrence of these storms. This chapter presents the method used to develop intensity-duration curves for Kentucky.

Selection of Rain Gages for Frequency

Only first-order Weather Bureau stations have the long-term rainfall record for the short durations required for a dependable frequency analysis of rainfall data. Nine such stations are either located in Kentucky or sufficiently near to the border to be the closest first-order station to some portion of the state. These stations are Louisville and Lexington, Kentucky; Evansville, Indiana; Cairo, Illinois; Cincinnati, Ohio; Parkersburg, West Virginia; Wytheville, Virginia; and Nashville and Knoxville, Tennessee. These stations are located on Fig. 2 and the dates of available records for each station are listed on the caption for each set of curves shown in Figs. 3 through 11. Based on the assumption that the intensity-duration relationship for any point in

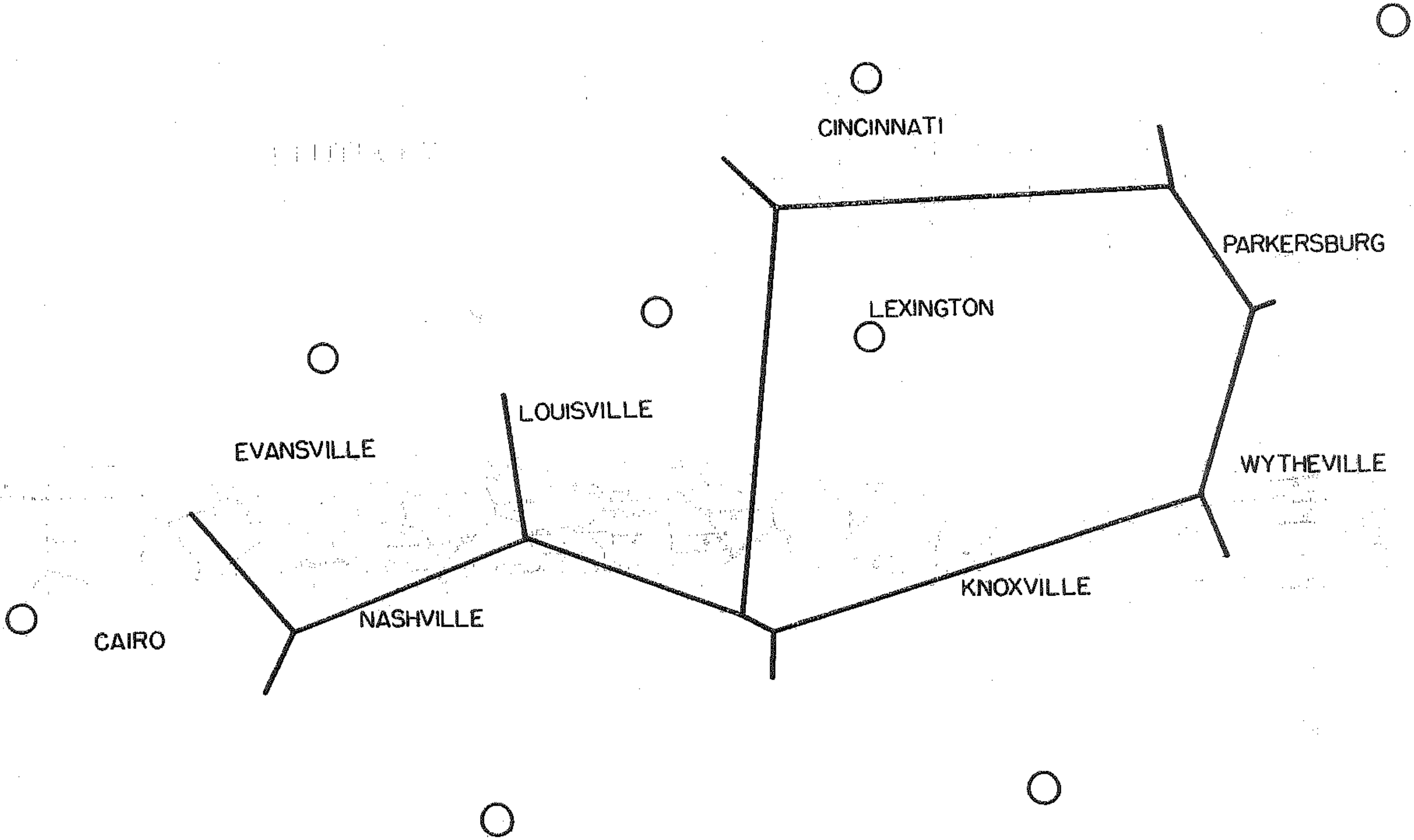


Fig. 2. Area of Influence for Intensity-Duration Curves

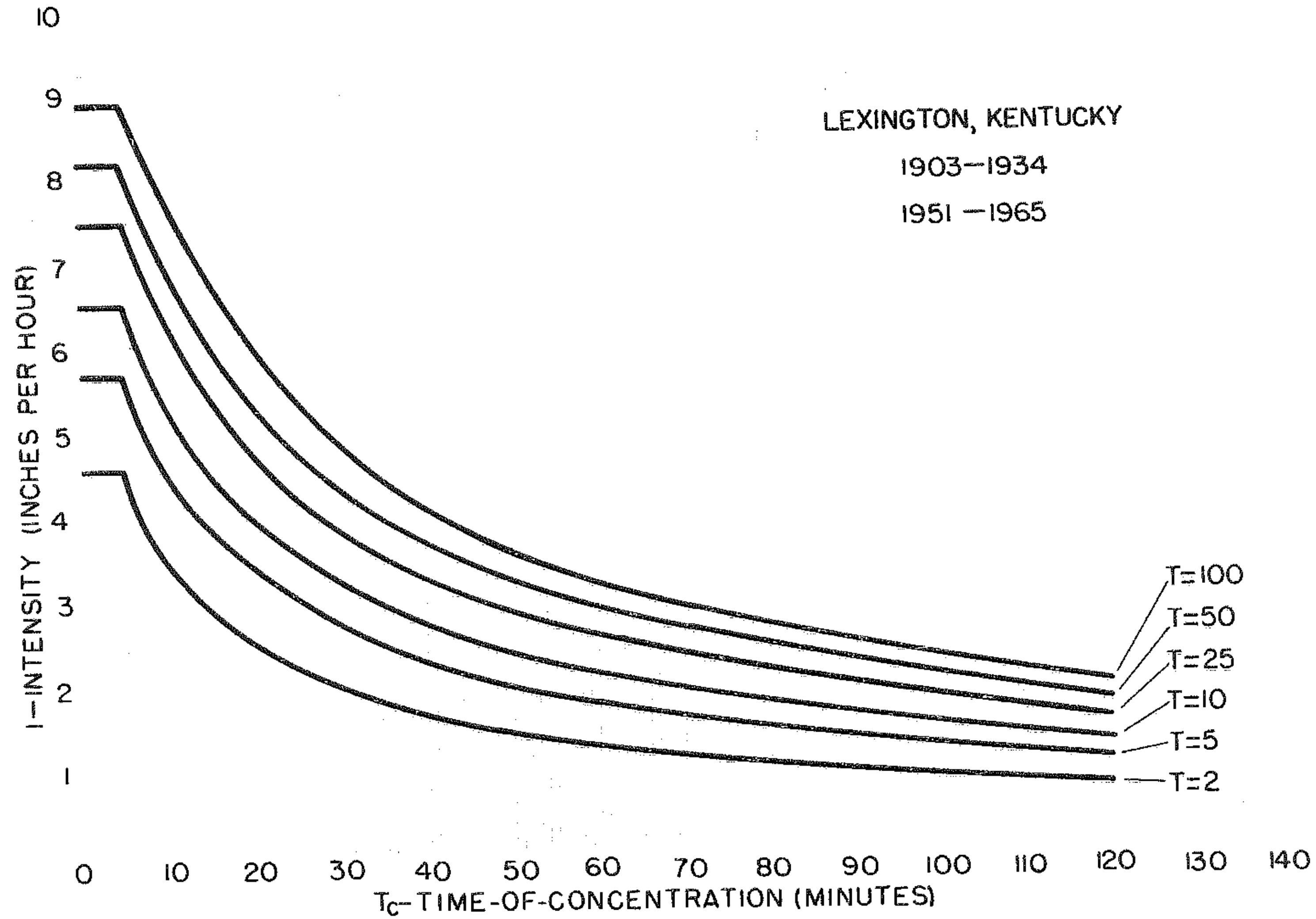


Fig. 3. Intensity-Duration Curves for Lexington, Kentucky

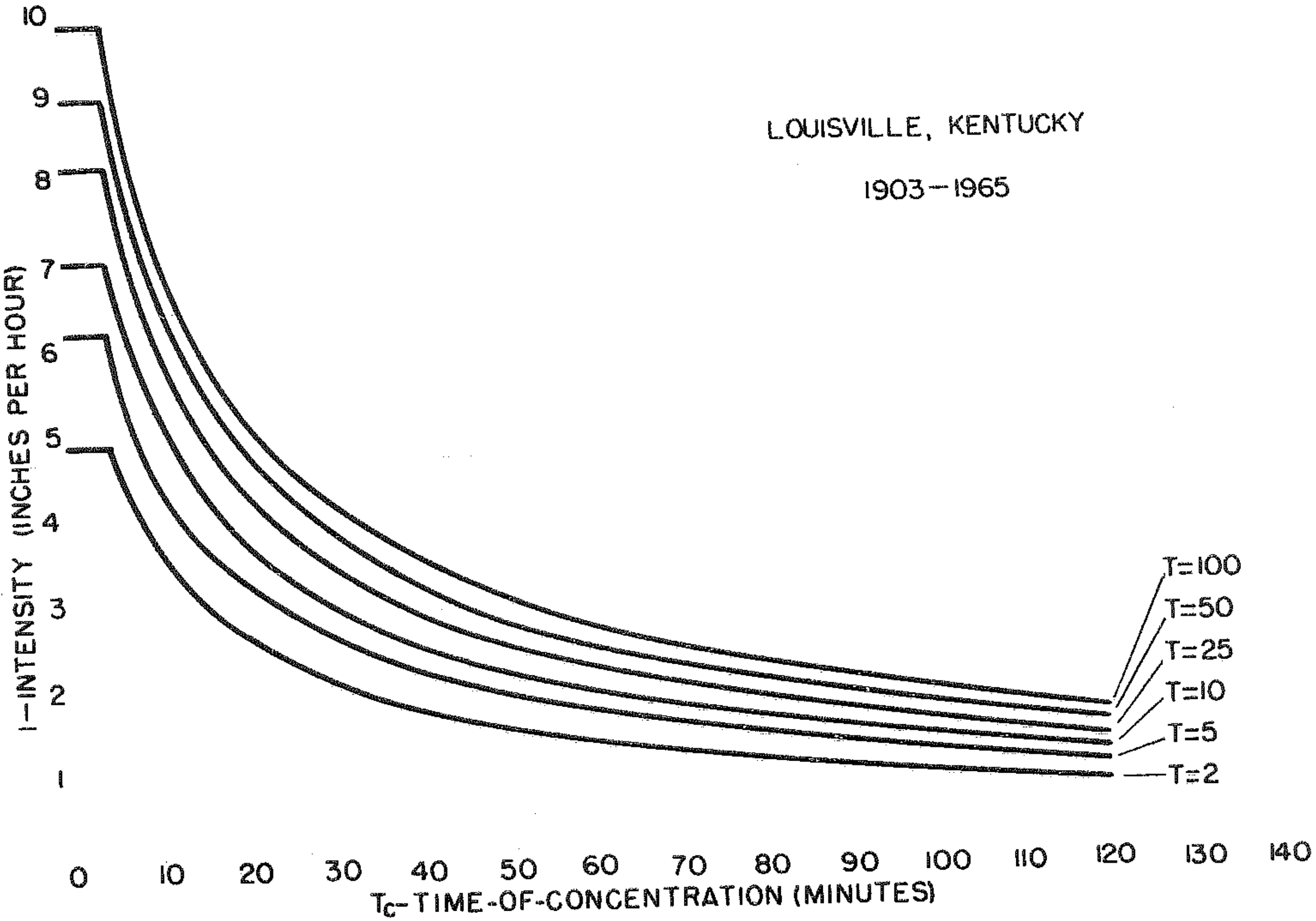


Fig. 4. Intensity-Duration Curves for Louisville, Kentucky

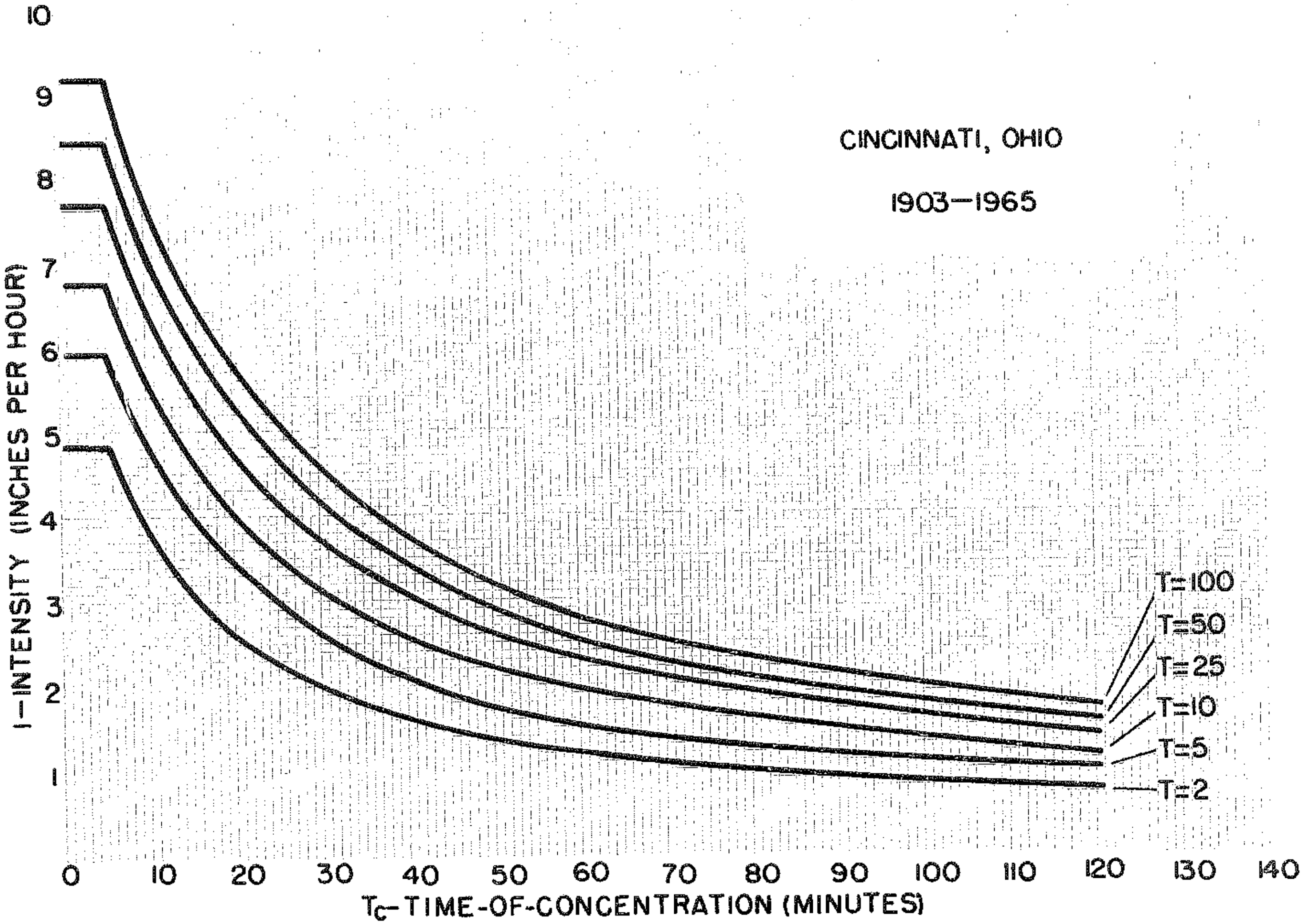


Fig. 5. Intensity-Duration Curves for Cincinnati, Ohio

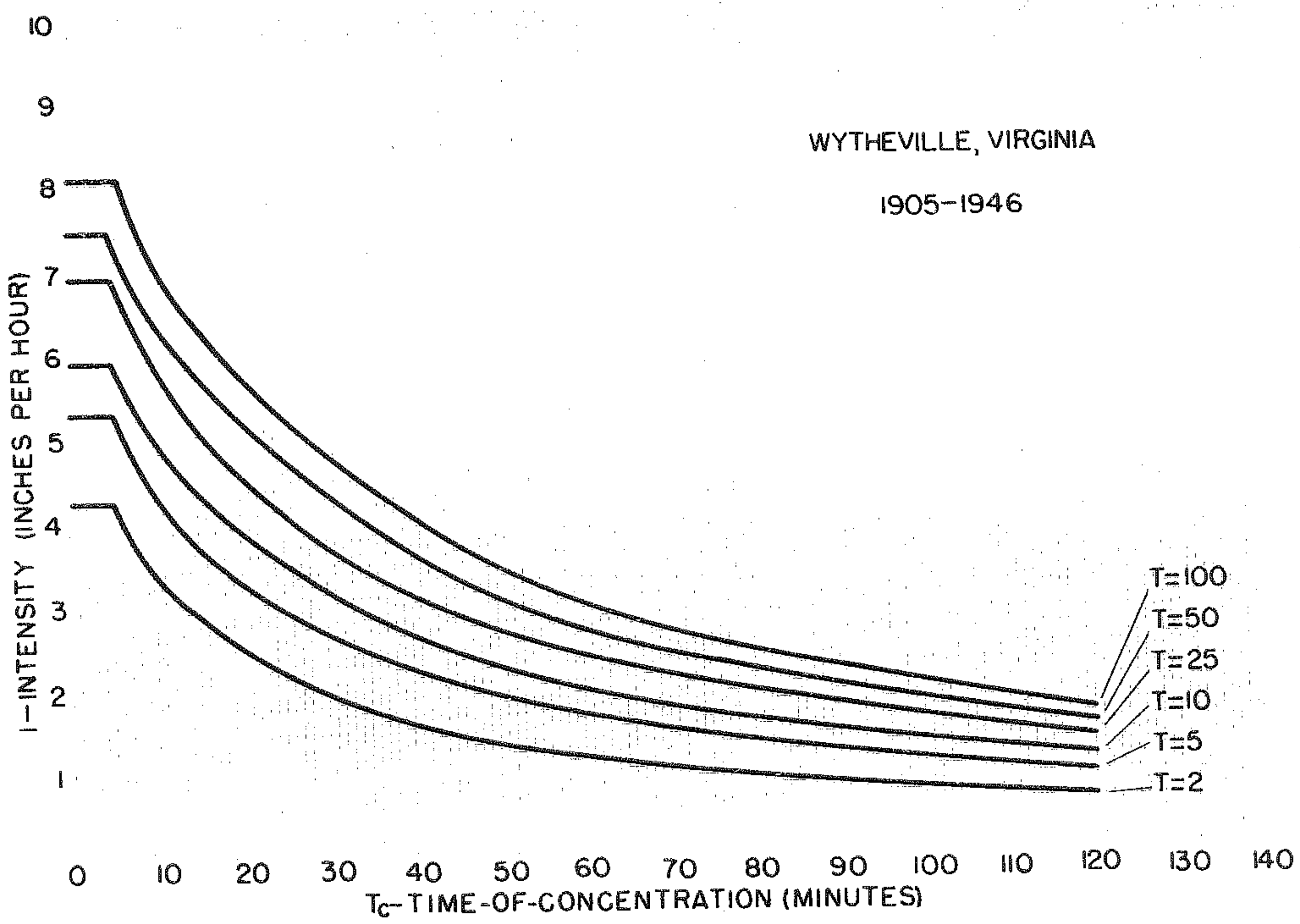


Fig. 6. Intensity-Duration Curves for Wytheville, Virginia

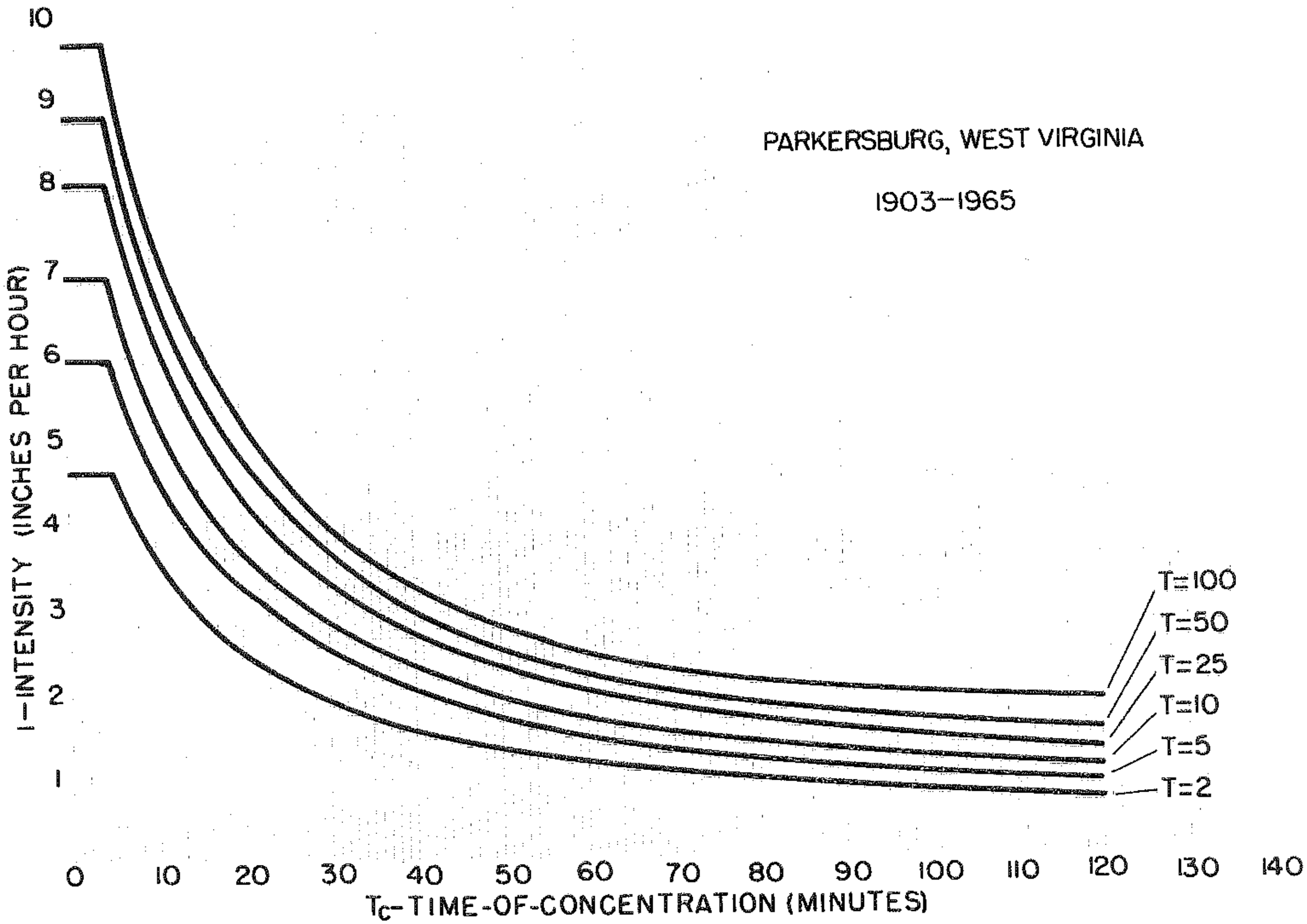


Fig. 7. Intensity-Duration Curves for Parkersburg, West Virginia

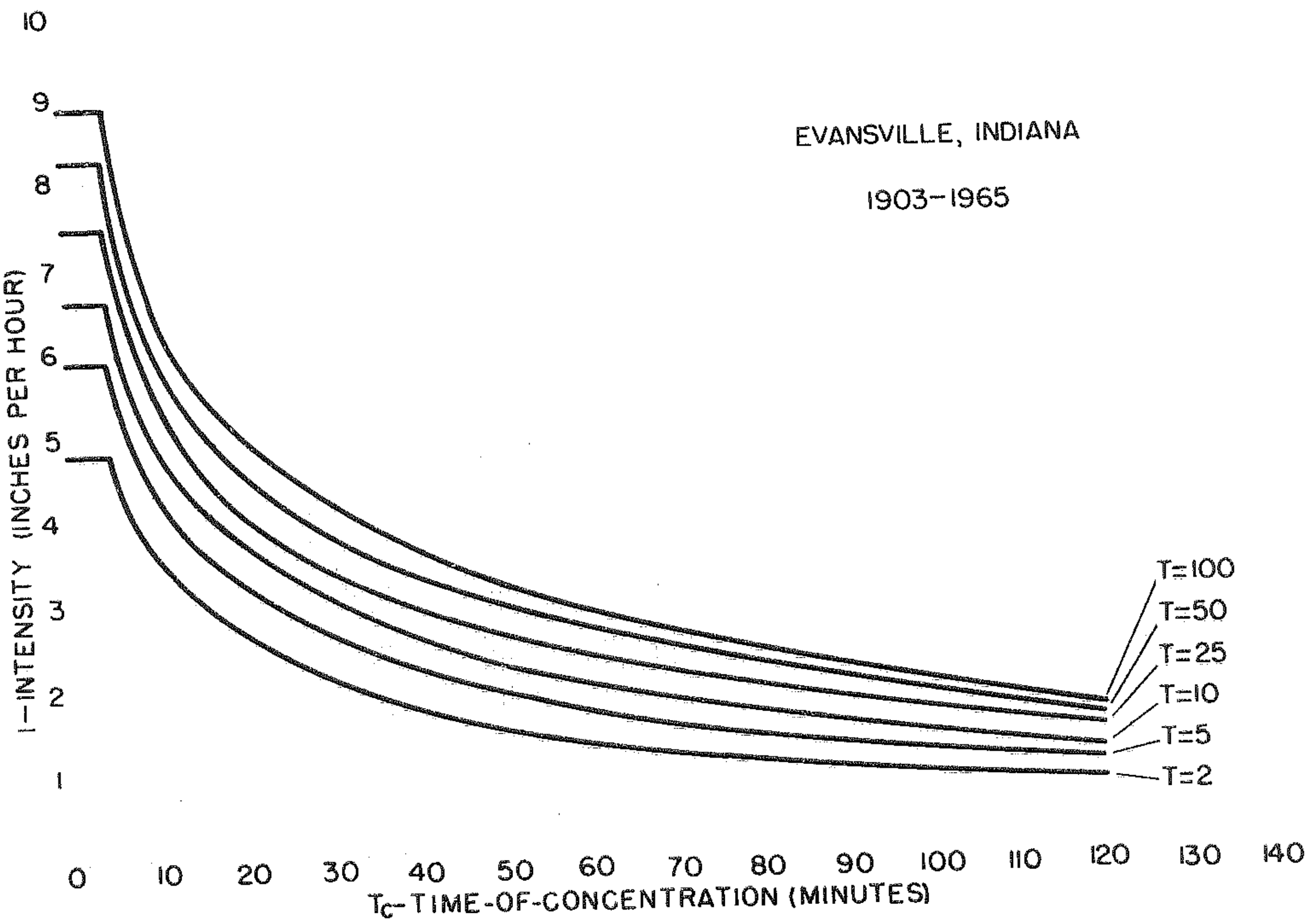


Fig. 8. Intensity-Duration Curves for Evansville, Indiana

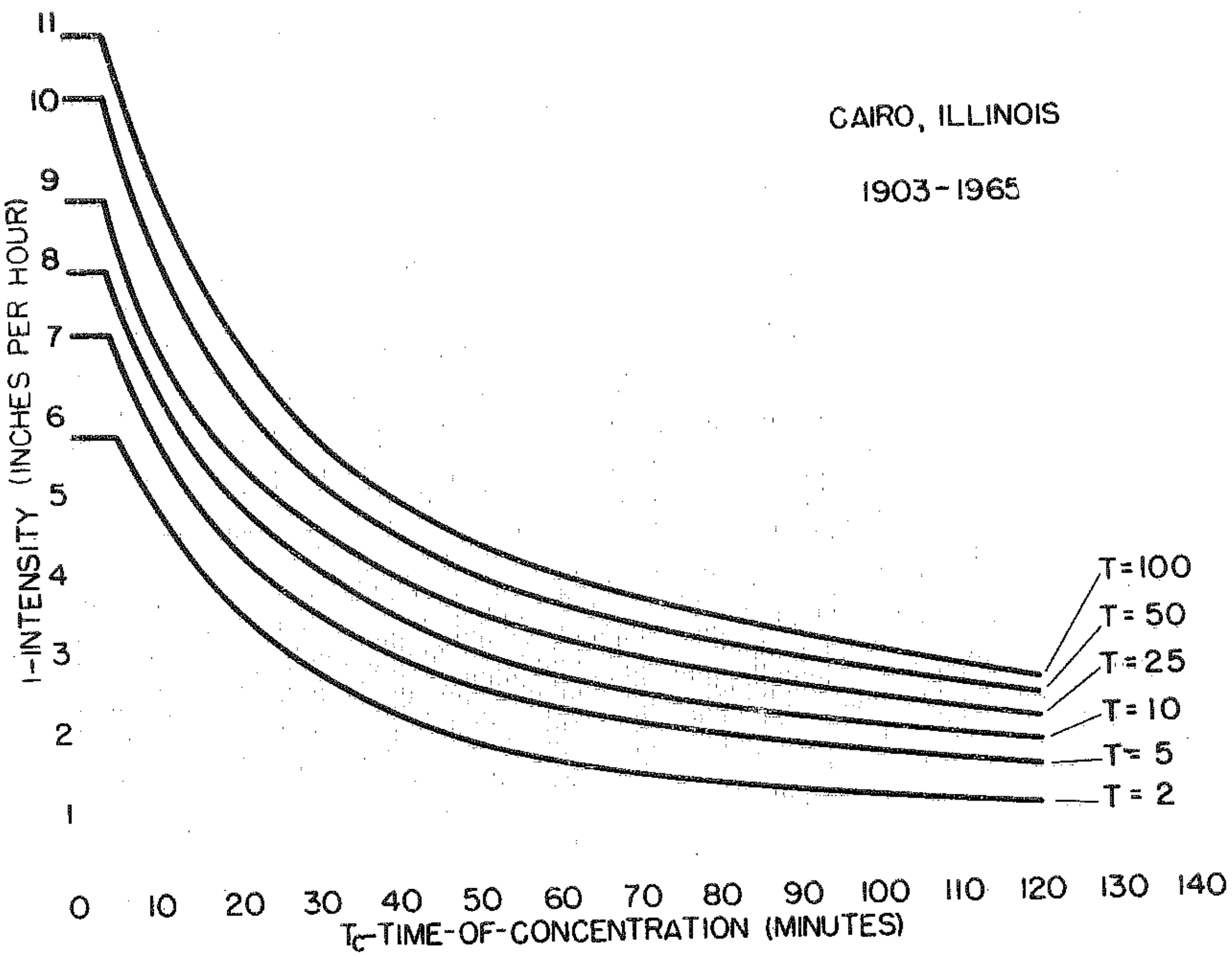


Fig. 9. Intensity-Duration Curves for Cairo, Illinois

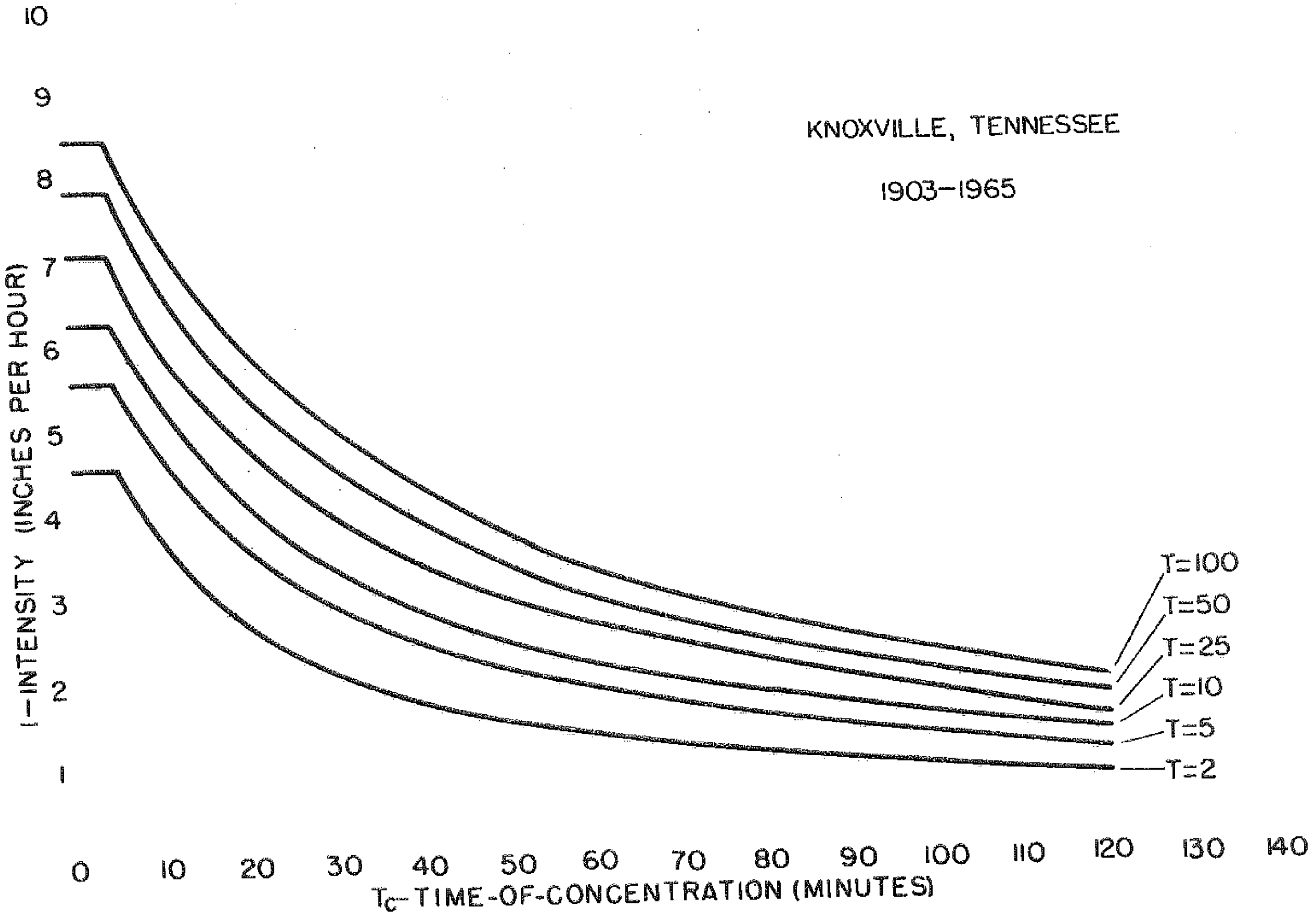


Fig. 10. Intensity-Duration Curves for Knoxville, Tennessee

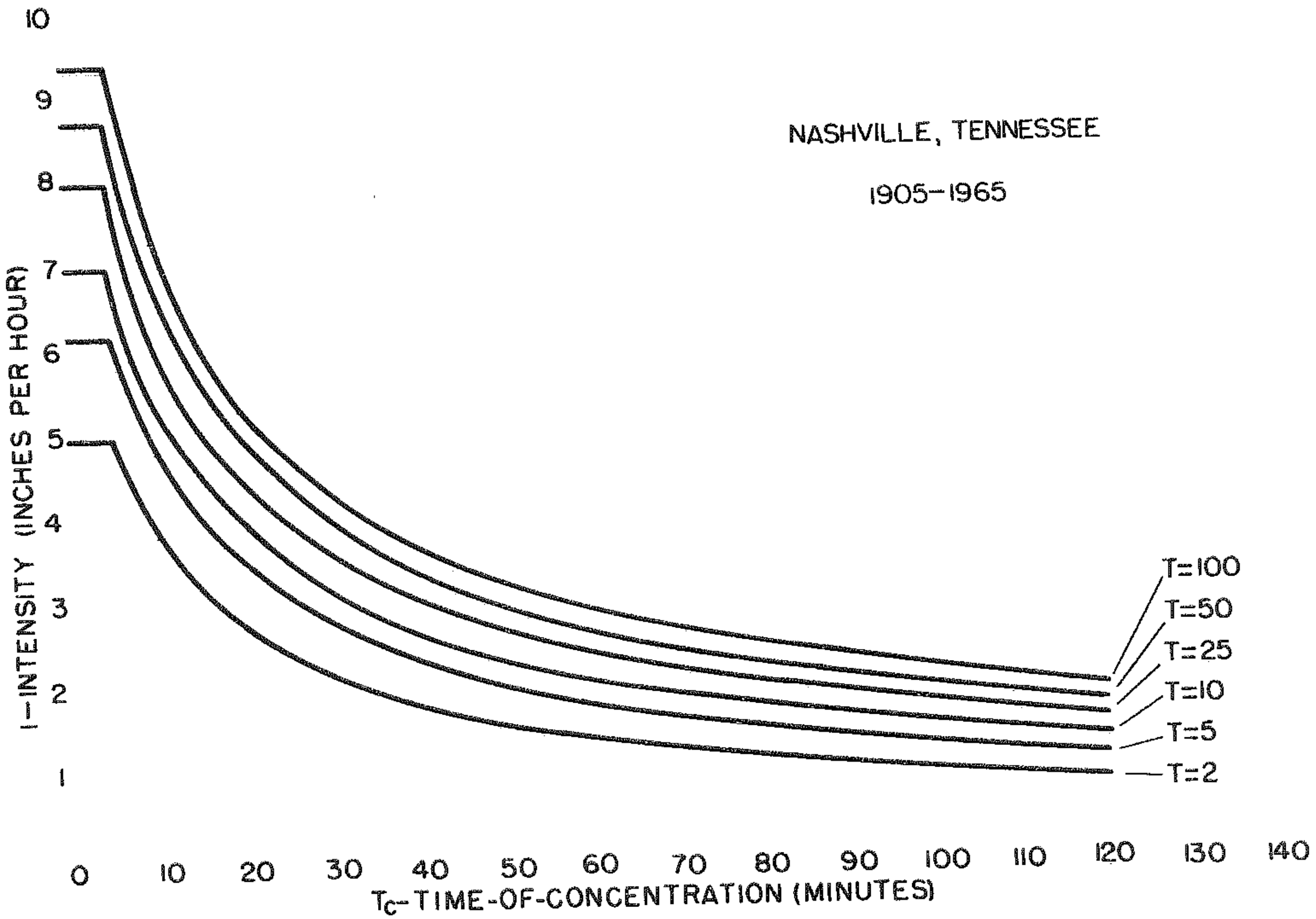


Fig. 11. Intensity-Duration Curves for Nashville, Tennessee

Kentucky is best represented by the closest rain gage, the Thiessen method was used to determine which rain gage should be used in each part of the State.

The Thiessen network is developed graphically by drawing straight lines connecting adjacent gages and constructing perpendicular bisectors for each line. These bisectors define a set of polygons, one for each gage, and each polygon contains only points that are closer to the gage at its center than to any other. The sides of the resultant polygons are the boundaries of the assumed area of influence for each station. The network developed during this study is presented in Fig. 2 and differs slightly from that network in present use by the Department. Herein, it is suggested that the revised network be incorporated into any future revision of the Department's drainage manual. The remainder of this chapter is devoted to development of the intensity-duration curves for the nine gage stations.

Data Homogeneity Test

In order to be assured that the precipitation data were statistically homogeneous with time, they were tested for consistencies. Inconsistencies in precipitation data may arise because of intervening changes in gage location, exposure, instrumentation, or observational procedures. To test for data consistency, a double-mass analysis (15, pp. 33-34) was conducted for each station except Wytheville, Virginia, from which annual rainfall totals could not be obtained. For the remaining eight stations, accumulated annual precipitation was computed along with concurrent accumulated values of mean precipitation for the remaining seven stations. The two accumulated values were then plotted against each other.

Double-mass analysis plots for the Weather Bureau stations, shown in Figs. 12 through 19, indicated the precipitation data to be homogeneous for five of the eight stations -- evinced by the straightness of the line. However, the breaks in slope of the lines plotted in Figs. 17, 18, and 19 indicate that definite changes had occurred at Cairo, Illinois, and Knoxville and Nashville, Tennessee. The ratios of the slopes of the segments of the double-mass curve were used to adjust the earlier data, thus making the entire record comparable to that at the more recent gage locations.

Intensity-Duration Curves

For purposes of this study, annual, maximum values for durations of 5, 10, 15, 30, 60, and 120 minutes were used in the analysis. The annual, maximum rainfall intensity of a given duration is the largest of all observed values, for rainfalls of the stated duration, in a year. The number of annual maxima per stated duration used in the analysis was equal to the number of years of record per station; there is only one annual, maximum per year, and none of the values was excluded from the overall analysis. When all of the observed data in N years of observations are arranged in a descending order of magnitude, the top N-values values are designated as the annual exceedances. In cases where only the annual maxima are used, the number of exceedances in a period of

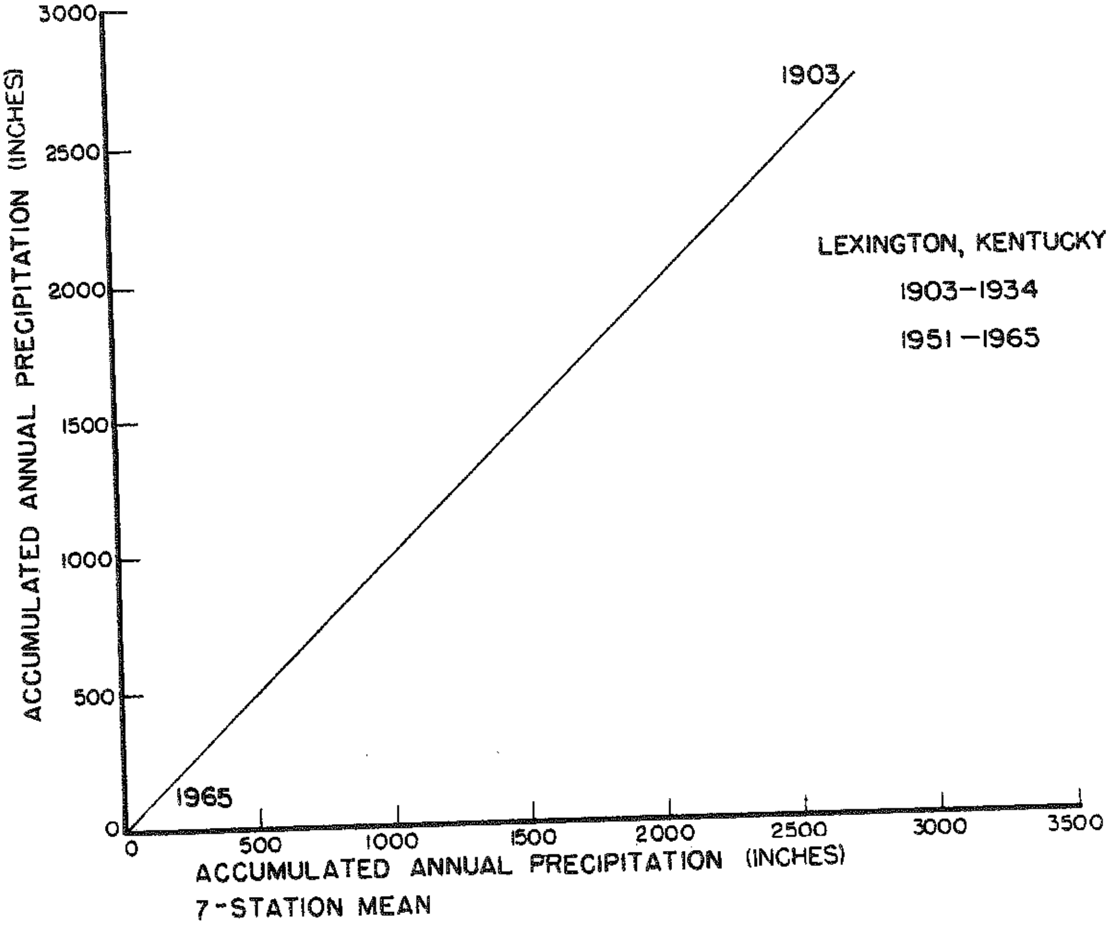


Fig. 12. Double-Mass Curve for Lexington, Kentucky

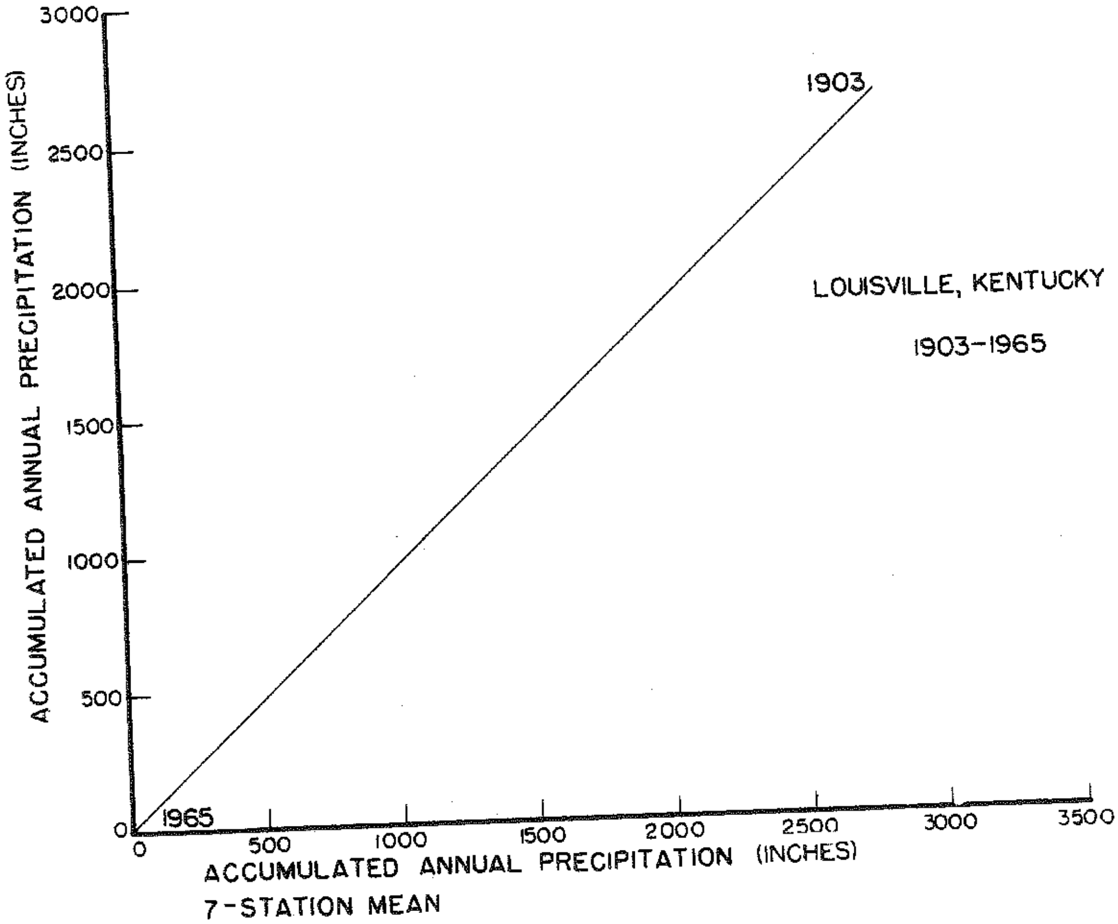


Fig. 13. Double-Mass Curve for Louisville, Kentucky

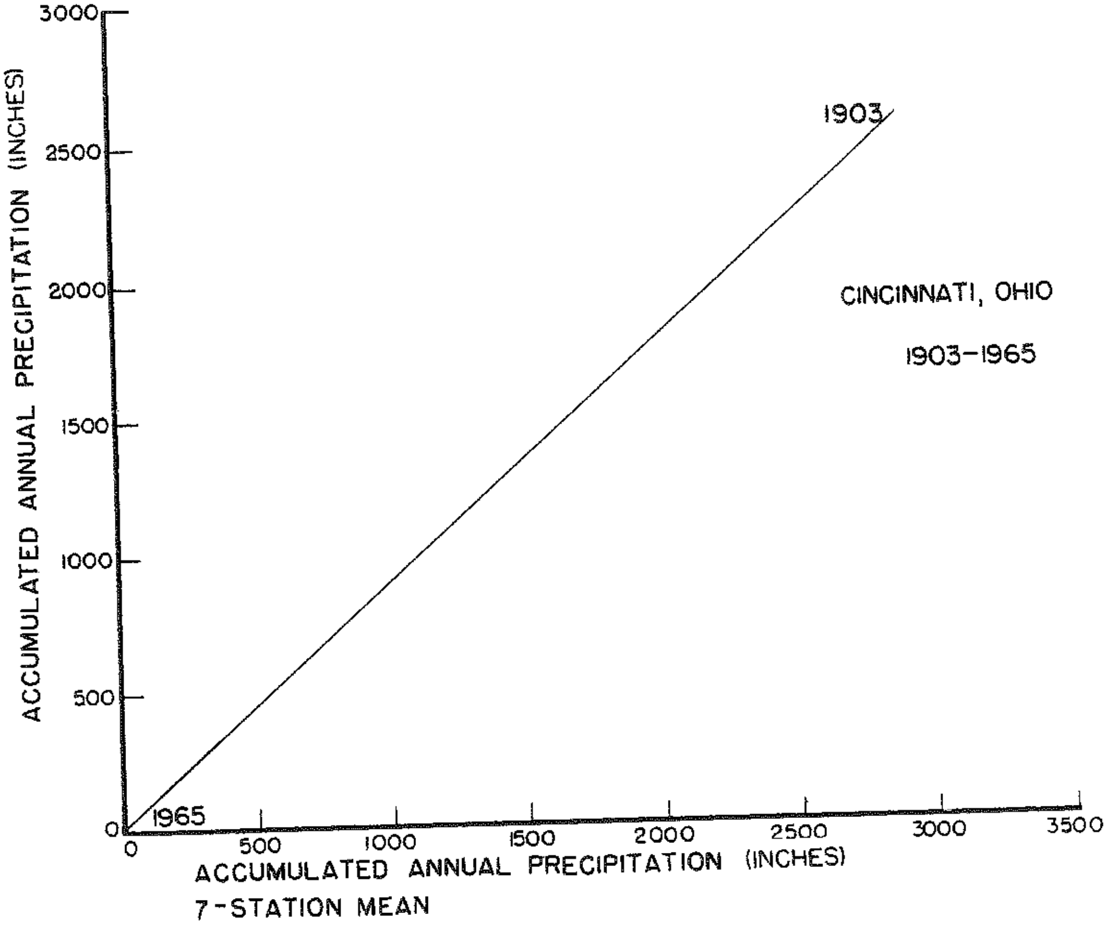


Fig. 14. Double-Mass Curve for Cincinnati, Ohio

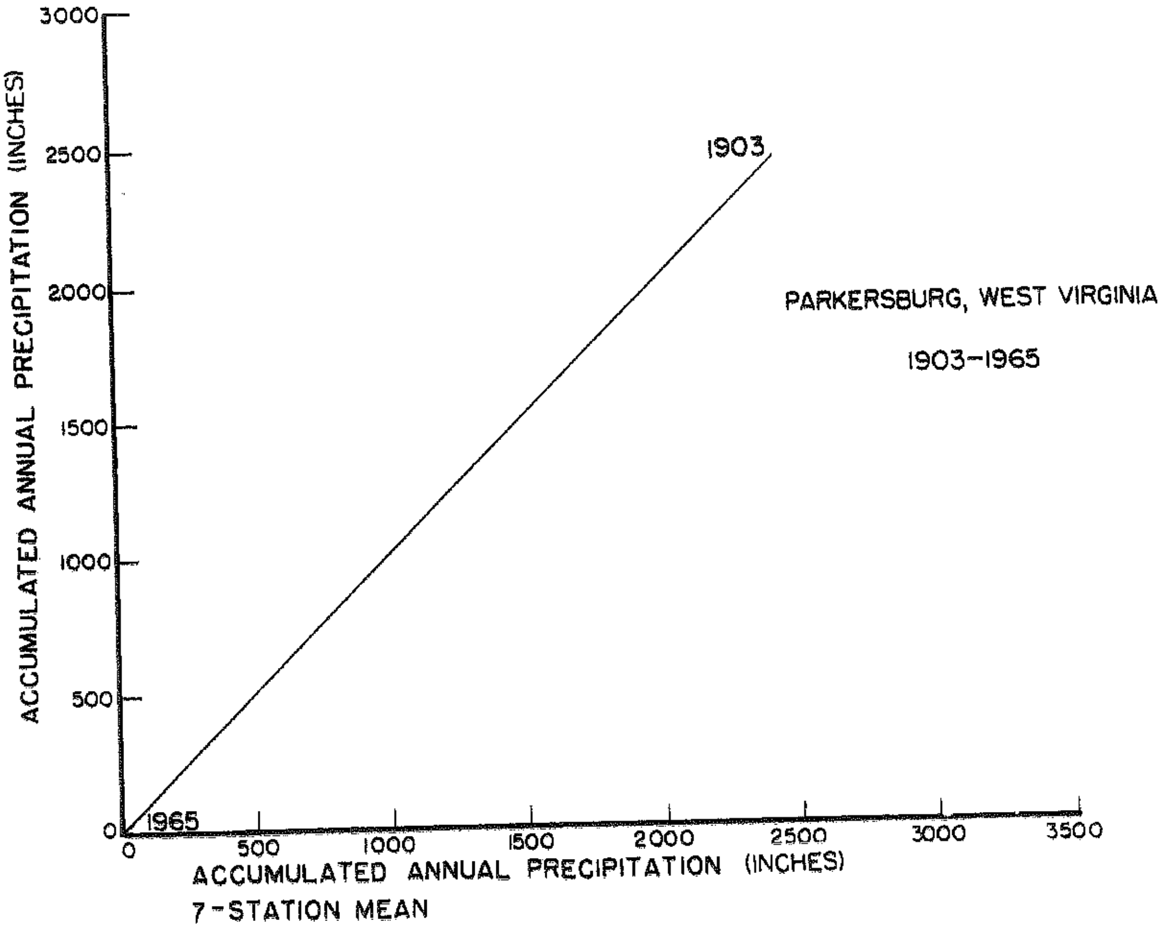


Fig. 15. Double-Mass Curve for Parkersburg, West Virginia

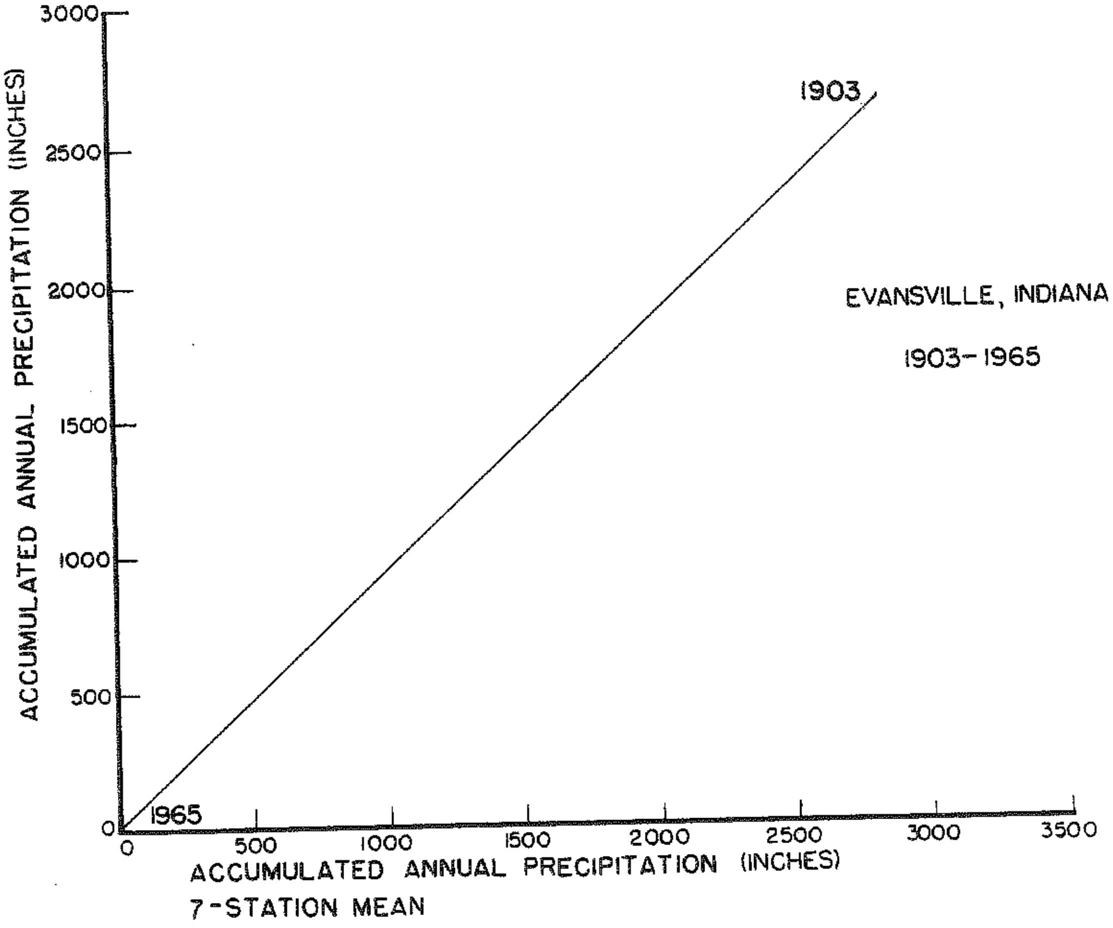


Fig. 16. Double-Mass Curves for Evansville, Indiana

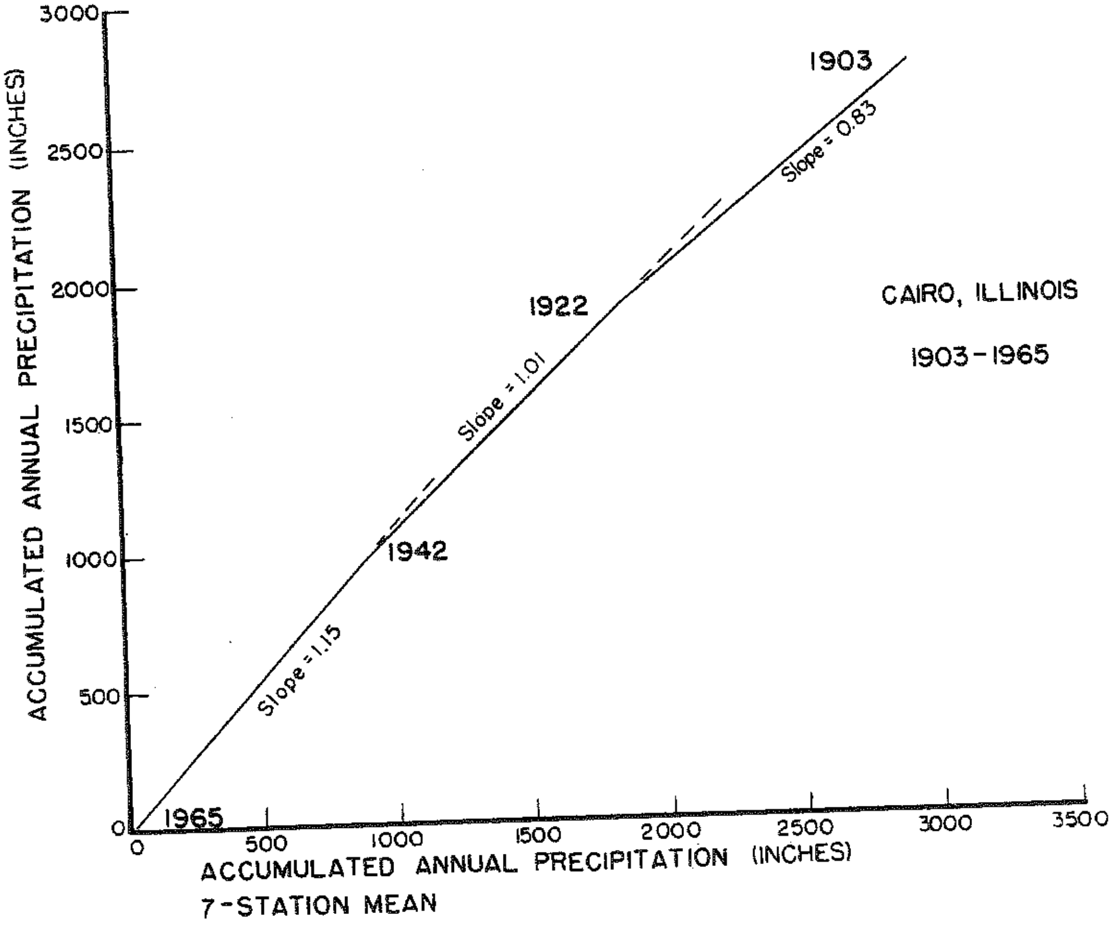


Fig. 17. Double-Mass Curves for Cairo, Illinois

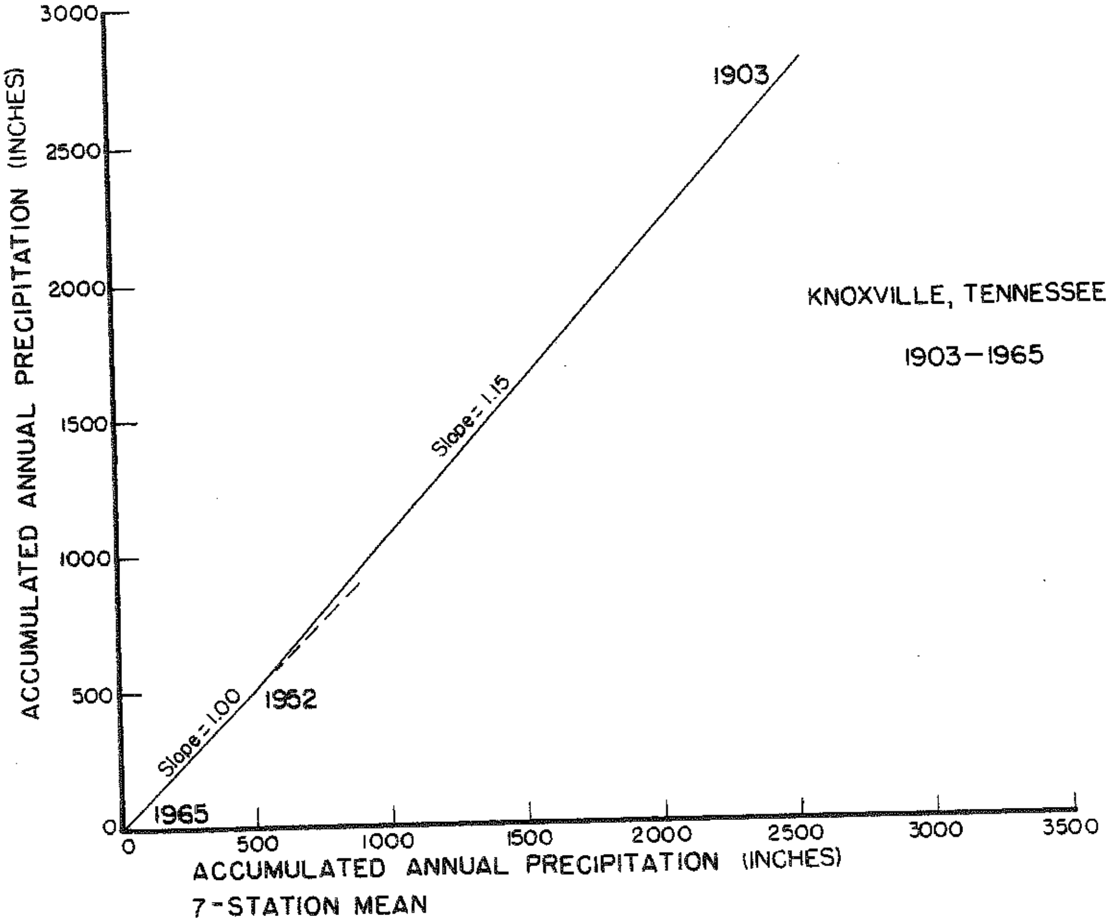


Fig. 18. Double-Mass Curve for Knoxville, Tennessee

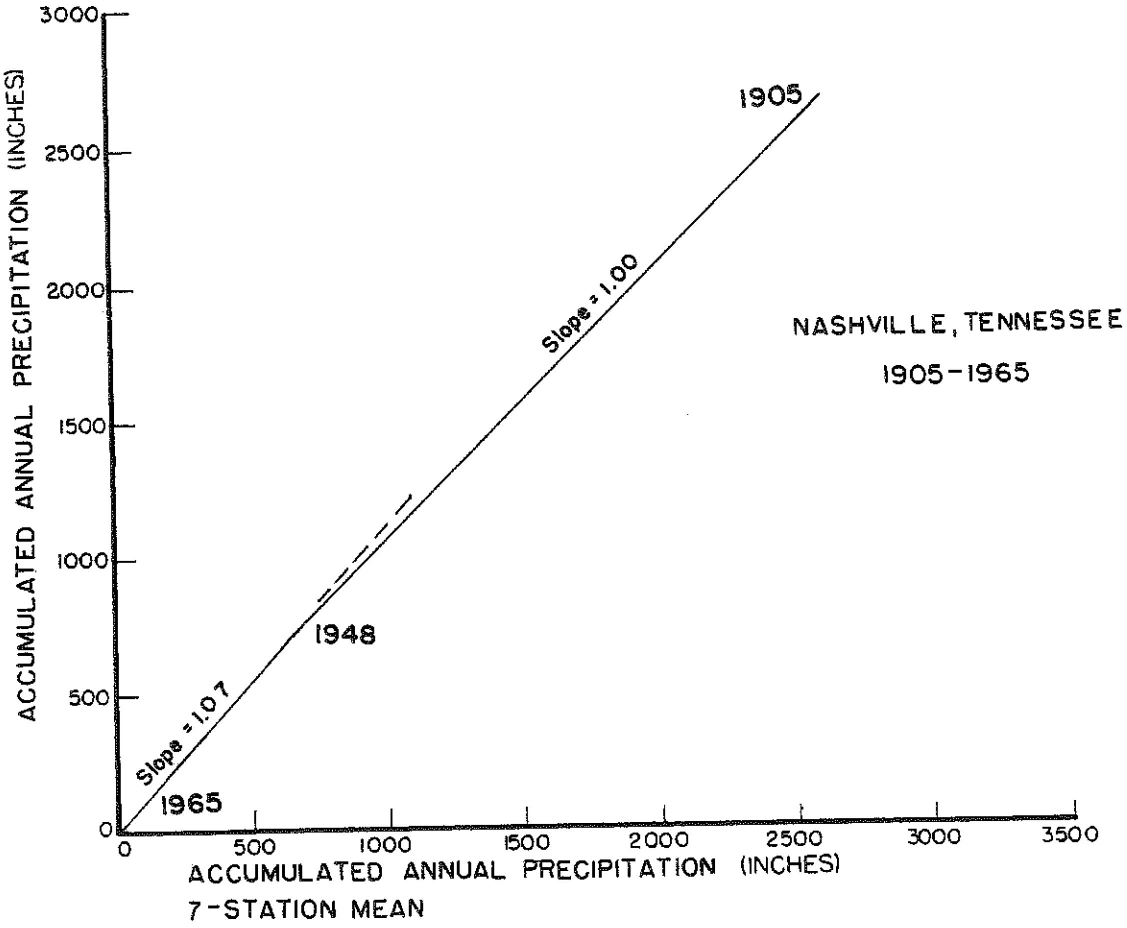


Fig. 19. Double-Mass Curve for Nashville, Tennessee

observations equals the number of years of observations; and the annual exceedances form an extreme portion of all data. The annual exceedances do not form a complete continuum; however, as the number of data items in the initial distribution becomes large, the annual exceedances converge to an asymptotic pattern of distribution which may be subjected to further statistical analysis -- similar to that employed in survivor statistics and life-expectancy analyses.

In order to determine the recurrence interval of the selected events, Gumbel's theory of distribution of extreme events (cf. 15, pp. 250-258) was selected. Gumbel's theory states: if X_1, X_2 ..., X_n are the extreme values observed in n samples of equal size, N, and if X is an unlimited, exponentially distributed variable, as n and N approach infinity, the cumulative probability P that any of the n extremes will be less than X approaches the expression

$$P = e^{-e^{-y}} \qquad 2$$

where e is the base of the Napierian logarithms and y, termed the reduced variate, is given by the equation

$$y = a\left[X-X_f\right] . \qquad 3$$

In case of an infinitely large sample, it may be shown by theory of extreme values that the mode of the distribution, X_f, and the dispersion parameter, a, are functions of the arithmetic mean, $\overline{X}$, and the standard deviation, σ_x; thus

$$X_f = \overline{X}-0.4500\sigma_x \qquad 4$$

and

$$a = \frac{1.28255}{\sigma_x} . \qquad 5$$

Equation 2 is an expression for the probability of nonoccurrence from which the return period may be computed as

$$T = \frac{1}{1-P} . \qquad 6$$

Equations 4 and 5 are not strictly applicable for limited samples; however, Gumbel's method enables determination of values of a and X_f from annual series. The approach is based on a least-squares analysis of Equation 3 (cf. 15, p. 25). The equation may be represented by a straight line (X vs y) on Cartesian coordinates, and Gumbel's solution minimizes the squares of the deviations measured perpendicular to the derived line of expected extremes; the resulting equations are

$$X_f = \overline{X} - \sigma \left[\frac{\overline{y}_n}{\sigma_n} \right] \qquad 7$$

and

$$a = \frac{\sigma_n}{\sigma_x} \qquad 8$$

wherein the theoretical quantities $\overline{y}_n$ and σ_n are functions of the sample size. Combining Equations 3, 7, and 8 leads to:

$$X = \overline{X} + \frac{\sigma_x}{\sigma_n} \left[y - \overline{y}_n \right] . \qquad 9$$

Values of the variables $\overline{X}$ and σ_x may be computed by solution of the following equations:

$$\overline{X} = \frac{\Sigma X}{N} \qquad 10$$

and

$$\sigma_x = \left[\frac{\Sigma X^2 - \overline{X}\Sigma X}{N-1}\right]^{1/2} \qquad 11$$

where N is the number of years of record. Solution of Equation 10 and 11 for values of $\overline{X}$ and σ_x allows solution of Equation 9 in the event values of $\overline{y}_n$, σ_n, and y are known; thereby, intensity may be determined as a function of duration and return period.

Intensity-duration curves developed during this study on the basis of existing records for the nine first-order Weather Bureau stations in and surrounding Kentucky are presented in Figs. 3 through 11. Very minor changes were noted between the curves developed by Sammons and West (23) in 1955 and the up-dated curves for the 2- and 5-year return periods. More pronounced changes were noted for some stations while small or no changes were noted for other stations. In large, the up-dated curves follow the same trends noted in the initial curves.

CHAPTER III

APPLICATION OF STANFORD WATERSHED MODEL TO CAVE CREEK WATERSHED

This chapter describes the application of the Stanford Watershed Model to the Cave Creek watershed and outlines the procedure used to evaluate parameters describing the watershed. The results provide a basis for subsequent variation of parameters to describe watersheds having characteristics differing from those of Cave Creek. The Kentucky, Fortran IV version of the model dated May 24, 1967, was used in the analysis. Other versions vary in detail, but all follow the same basic moisture accounting procedure. All precipitation was taken as rainfall, i.e. to simplify the computational process; snow-melt does not produce extreme flood events on small Kentucky watersheds.

Development and Interpretation of Input Data

The Stanford Watershed Model acts on input climatological data to produce a continuous runoff hydrograph which may be checked against input streamflow data. Specifically, the input data may be divided into six groups (7, p. 11):

1. Input data to specify the program options.
2. Input data to initialize the watershed soil-moisture storage conditions prevailing on October 1 of the first water-year being synthesized.

3. Input data to describe climatological events.

4. The time-area histogram.

5. Input data to assign values to the 24 watershed parameters.

6. Input data to provide recorded flow values as a basis for comparison with the synthesized streamflows.

Each of the types of input data enumerated is discussed more completely:

1. Control Data - Fourteen control options are available and allow application to a variety of situations without reprogramming. Thirteen of the options permit use of additional input data (streamflow diversions for example), request additional output, or specify special procedures (one being snow-melt) (7, p. 12). The fourteenth option, MINH, is the maximum, hourly, synthesized streamflow which must be reached within a day before the 24-hour flows for that day are printed.

2. Starting Moisture Data - In order to initiate moisture accounting, initial values of the groundwater storage, soil-water storage and surface-water storage must be specified. Watershed variables influencing initial storage volumes include water-holding capacity of the soil, density and type of vegetative cover, and antecedent rainfall. The starting soil-moisture storage values affect flood flows for about the first month of the generated record. After the first run, average end-of-the-year values as indicated on model output may be used for subsequent runs. All storage values are expressed in average inches of moisture throughout the drainage area.

3. Climatological Data - The climatological data collected for the study include: 1) hourly rainfall amounts, 2) average daily pan-evaporation values by 10-day intervals, and 3) monthly pan coefficients.

   a. Rainfall - Hourly precipitation data from the Lexington weather station were collected for the period 1916-1965. Daily precipitation data for the years 1885-1916 were obtained from the Lexington Water Plant. The daily rainfall totals were not used for streamflow synthesis, and none were noted. The homogeneity test described in Chapter II indicated the record from 1916 to 1965 to be homogeneous, even though the Lexington station had been moved on several occasions.

   b. Evaporation - The model uses lake-evaporation data as a basis for computing evapotranspiration losses as a function of soil-moisture storage. Pan-evaporation values were obtained for the summer months in the water years 1960-1965 from Dix Dam (about 25 miles south of the Cave Creek watershed). Winter evaporation was estimated from other climatological data based on charts developed by Penman (cf. 15, pp. 99-108). Evaporation data were read into the program as average, daily values by 10 day intervals. Flood peaks are not sensitive to evaporation rates, and average values by time of year (rather than specific values for the year in question) were used for years prior to 1960.

c. Pan coefficients - Monthly, Class A, pan coefficients were computed through application of other meteorological data to curves prepared by the U. S. Weather Bureau (cf. 15, pp. 99-108). Information necessary for use of the curves includes average wind speed, mean elevation above sea level, and temperatures of the air and lake surfaces. Data obtained from the Lexington station were used to determine these coefficients.

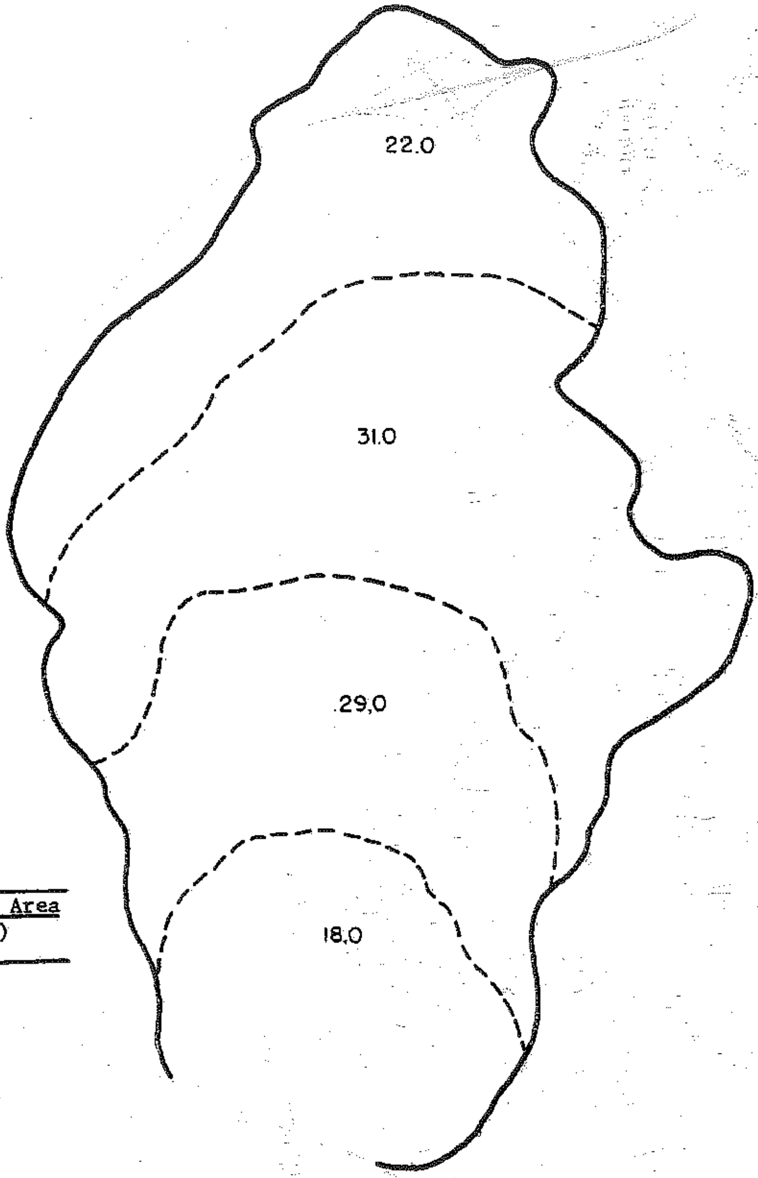
4. Time-Area Histogram - Several approaches have been advocated for use in routing runoff through natural channels to a watershed outlet. C. O. Clark (cf. 4, p. 23) devised a simple, empirical method which has been modified and adapted to the watershed model. The time required for runoff to travel downstream is accounted for by lagging flows according to the time-area histogram as described herein. Effects of channel storage on the hydrograph shape are handled by routing flows through a theoretical storage reservoir. Inflow entering the stream channels does not arrive at the gaging point immediately, and adjustments were made in order to lag the channel inflow. Lagging was accomplished by separating the basin into zones by isochrones of travel time to the outlet. The number of isochronic zones within a watershed is dependent upon the time increment used in routing and the time-of-concentration.

Fifteen-minutes time increments were used to define each zone for the Cave Creek flood routing.

The time-of-concentration was computed by the empirical equation (used by the Kentucky Department of Highways) developed by Z. P. Kirpich based on data by C. E. Ramser (cf. 9) as

$$T_c = 0.0078\left[\frac{L}{\sqrt{S}}\right]^{0.77} \qquad 12$$

in which T_c is the time-of-concentration in minutes, L is the horizontal length in feet from the most distant point in the basin to the outlet, and S is the slope between these points. Measured values of L and S for the Cave Creek watershed were 13,200 feet and 0.0107 feet per foot, respectively, from which a time-of-concentration of 67 minutes was computed. A value for T_c of 60 was used in this study since all rainfall values used in the program were hourly values and 60 divided by the 15-minute routing interval provided a whole number of isochrones. The average, stream-flow velocity was computed by dividing 60 into the horizontal length, L. Length of travel during the 15-minute time increment was obtained by multiplying the average, streamflow velocity by the time increment. This distance was then used as the stream distance for separating isochrones on a map of the area (Fig. 20). The area bounded by each pair of isochrones was planimetered, and the fraction of the total watershed area contained within each pair was computed. The time-area histogram is a tabulation of these fractions -- proceeding upstream. The number of histogram elements is



TIME-AREA HISTOGRAM

Time (minutes)	Contributing Area (percent)
0-15	18.0
15-30	29.0
30-45	31.0
45-60	22.0

Fig. 20. Derivation of the Time-Area Histogram for the Cave Creek Watershed

primarily governed by basin size, and the relative size of individual elements is largely determined by basin shape.

5. Watershed Parameters - The twenty-four watershed parameters serve to quantify the characteristics of the watershed surface which govern its interaction with precipitation. Many of the Stanford Watershed Model parameters may be evaluated from hydrologic and meteorologic records, topographic maps, or aerial photographs. Some of the parameters are not discernible directly and must be determined by reiteration procedures wherein synthesized and recorded streamflows are matched. The Stanford Watershed Model parameters may be divided into three categories:
   a. Parameters determined from observed watershed characteristics.
   b. Parameters determined through analysis of recorded hydrographs.
   c. Parameters determined by trial and adjustment.

The three types of parameters are discussed further:

a. Observed Watershed Characteristics
   (1.) K1 - K1 is the ratio of average rainfall on the basin to the average rainfall at the recording gage and is used only in the event that no storage gage data are available. Due to its small size and close proximity of the study watershed to the recording gage, K1 was assumed to be 1.0.

(2.) AREA - AREA is the watershed area in square miles and is determined from topographic maps or aerial photographs.

(3.) A - A is the fraction of the watershed which is impervious area draining directly into a stream. The impervious area includes paved areas, rooftops, and rock outcroppings and may be measured directly from aerial photographs. This parameter is usually zero for rural areas unless there are large areas of exposed rock. Runoff from a portion of the impervious area may flow onto a pervious area as overland flow; such areas are not to be included as a portion of A. A may be approximated from the total impervious area for urbanized watersheds by use of Fig. 21 (4, p. 66).

(4.) ETL - ETL is the fraction of total watershed covered by water surfaces and may be estimated from topographic maps or aerial photographs. ETL is zero for watersheds containing neither lakes or swamps.

(5.) EPXM - EPXM is the maximum interception rate for a dry watershed. EPXM is dependent upon the type and density of vegetative cover and may be estimated directly or interpolated from Table 1 (4, p. 66).

(6.) K3 - K3 is a measure of the rate of loss through evapotranspiration. K3 values may be estimated or interpolated from Table 2 (4, p. 67).

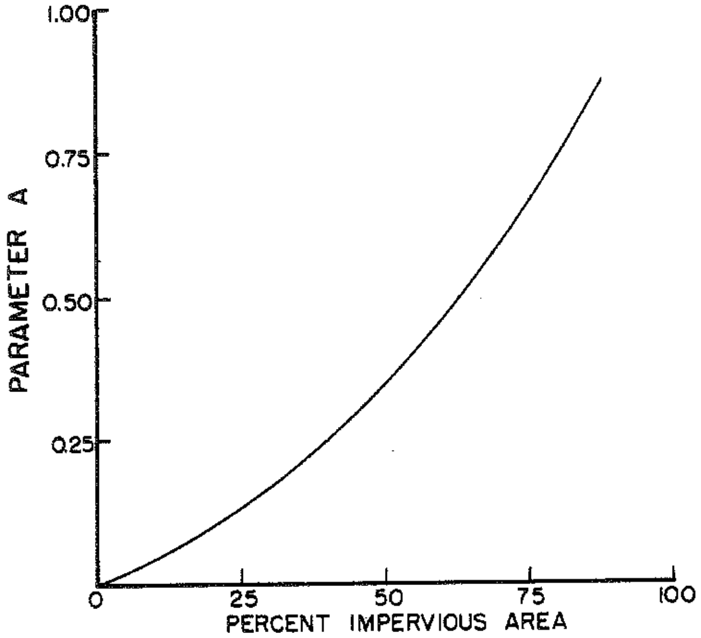


Fig. 21. Model Impervious Area vs Total Watershed Impervious Area

TABLE 1

INTERCEPTION VALUES FOR VARIOUS TYPES OF COVER

Watershed Cover	EPXM
Grassland	0.10
Moderate Forest Cover	0.15
Heavy Forest Cover	0.20

TABLE 2

EVAPOTRANSPIRATION INDICES FOR VARIOUS TYPES OF COVER

Watershed Cover	K3
Barren Ground	0.20
Grassland	0.23
Light Forest	0.28
Heavy Forest	0.30

(7.) K24EL - K24EL is the fraction of moisture lost from groundwater storage through evapotranspiration and is zero unless a significant quantity of vegetation draws water from below the watertable.

(8.) K24L - K24L is the fraction of moisture lost from groundwater storage through subsurface flow across the drainage basin boundary (generally equals zero).

(9.) SS - SS is the average slope in feet per foot of the overland flow surfaces perpendicular to the channel and may be obtained from measurements on topographic maps.

(10.) L - L is the mean overland flow length in feet and may be estimated from topographic maps or aerial photographs.

(11.) NN - NN is Manning's roughness coefficient for overland flow on soil surfaces and may be estimated from Table 3 (4, p. 68).

(12.) NNU - NNU is Manning's roughness coefficient for overland flow over impervious surfaces and may be estimated from Table 3 (4, p. 68).

TABLE 3

MANNING'S ROUGHNESS VALUE FOR OVERLAND FLOW FOR VARIOUS SURFACE TYPES

Watershed Surface	Manning's n
Smooth Asphalt	0.012
Asphalt or Concrete Paving	0.014
Packed Clay	0.030
Light Turf	0.200
Dense Turf	0.350
Dense Shrubbery and Forest Litter	0.400

(13.) CHCAP - CHCAP is the index capacity in cubic feet per second of the channel and may be determined from hydraulic analysis of the profile and cross-section of the stream channel.

b. Parameters Determined by Hydrograph Analysis

The parameters IRC (for interflow recession) and KV24 and KK24 (for groundwater recession) may be estimated by graphical techniques for hydrograph analysis developed by Barnes (*cf.* 12, pp. 153-154). The hourly recession rate for runoff in a channel is defined as the average ratio of discharge in hour t to discharge in hour t+1. A hydrograph having a constant recession rate plots as a straight line on semilogarithmic paper (discharge is plotted on the logarithmic scale). Plotting an actual hydrograph on semilogarithmic paper results in a curved line and indicates a decreasing recession rate. This may be accounted for by considering that streamflow is derived from three types of storage:

surface storage, mixed surface and groundwater storage or interflow, and groundwater storage -- each having different lag characteristic.

A recession curve as advocated by W. B. Lanbgein was used to establish the base-flow recession constant KK24 (10, pp. 620-627). The base-flow recession curve (Fig. 22) was defined as the envelope on the right side of the plotted points. The plotted data were selected from periods several days after the flood peak in order that no direct runoff would be included. KV24 is used to provide a curvelinear base-flow recession (4, p. 68).

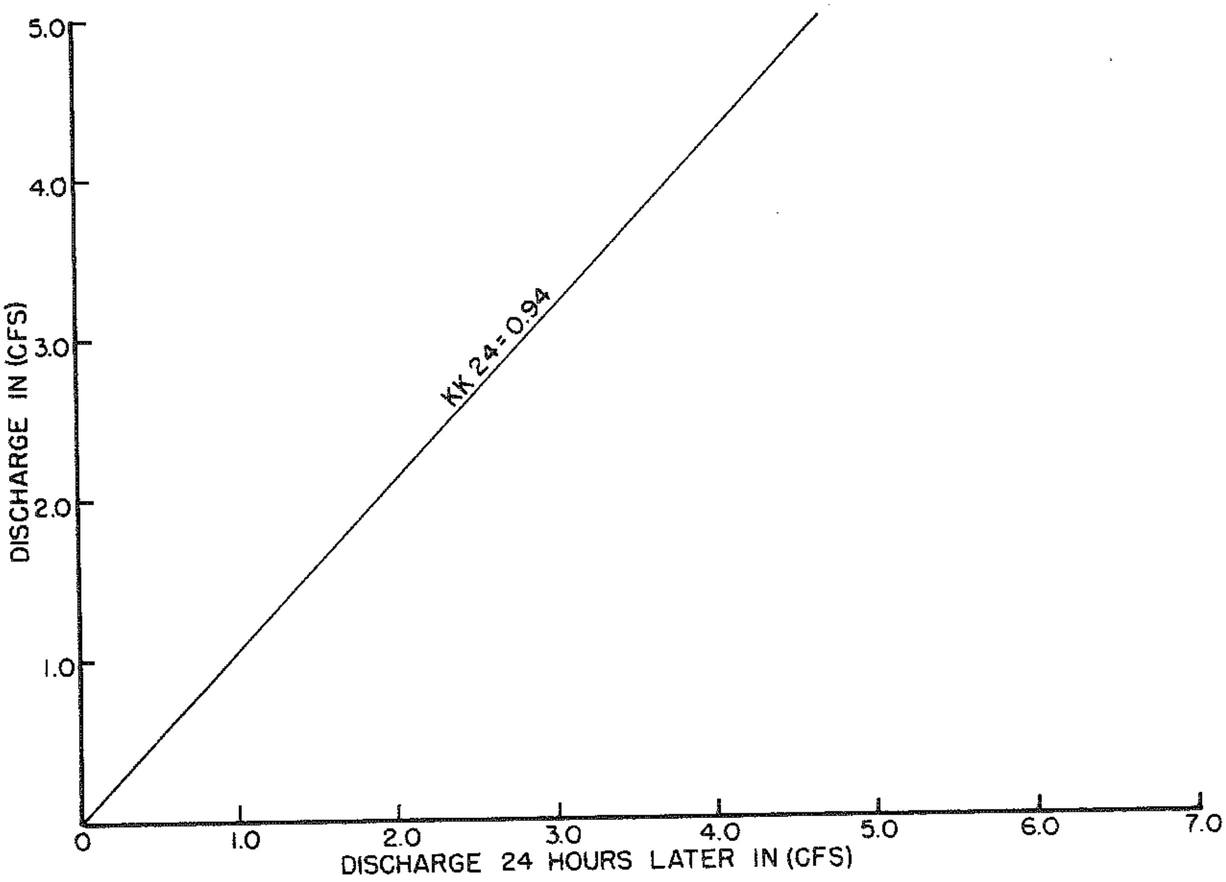


Fig. 22. Groundwater Recession Curve for Cave Creek

Once the base-flow recession constant was established, it was projected back under the hydrograph to the time of peak, and the difference between the projected base flow and the total hydrograph was used to develop the interflow-recession curve. The interflow-recession curve was projected back under the hydrograph to the time of peak, and the slope of this line is defined as the interflow-recession rate IRC. Fig. 23 indicates results obtained using Barnes method to analyze the flood hydrograph.

c. Parameters Determined by Trial and Adjustment

The remaining variables are best established by a process of trial and adjustment. Guidelines for parameter optimization and results of sensitivity studies are presented in Chapter IV.

(1.) CX - CX is an index for estimating the capacity of the soil surface to store water in interception and depression storage. The quantity of water stored at any given time will be less than the storage capacity except for temporary periods during major storms -- at which time, water in excess of normal capacity may accumulate.

(2.) EDF - EDF is also an index for estimating soil-surface moisture storage capacity. Its primary purpose is to vary seasonal storage capacity in order to account for increases caused by summer vegetation.

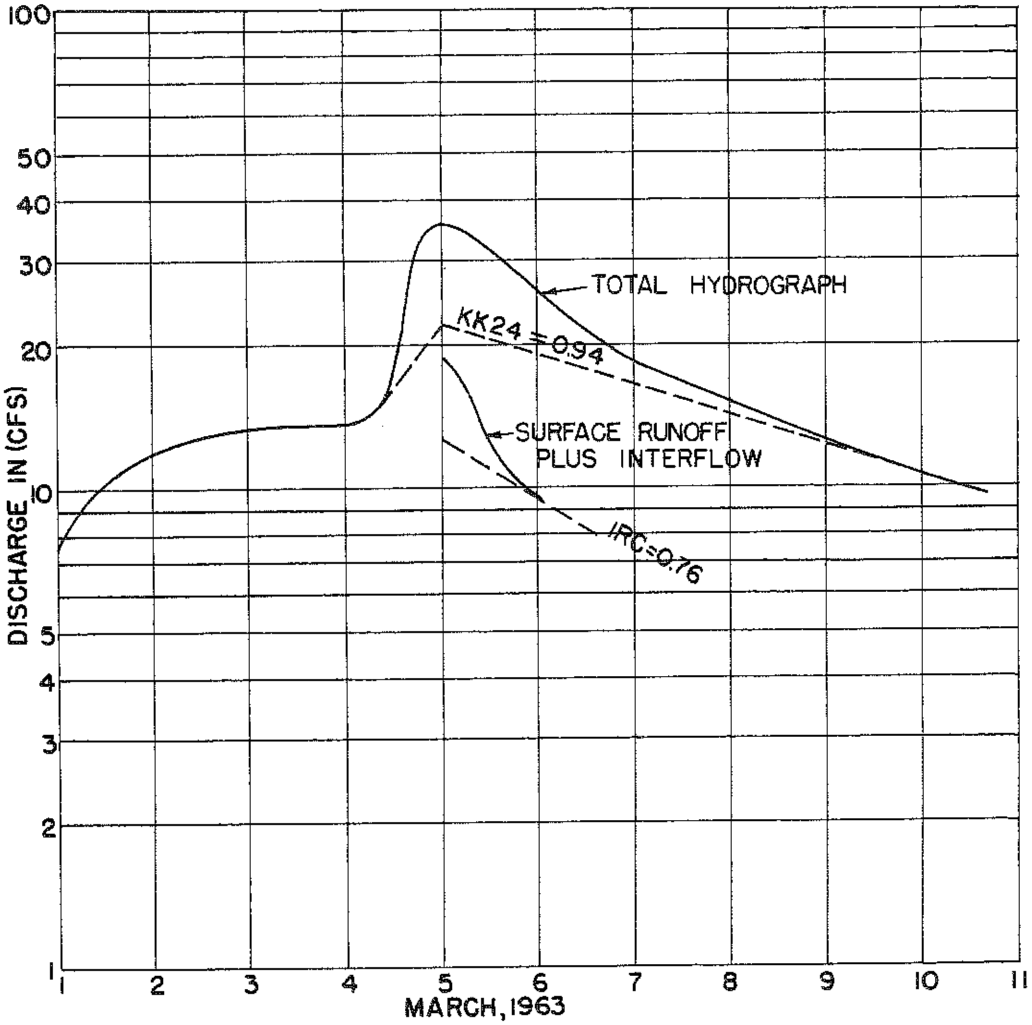


Fig. 23. Recession Analysis (After Barnes)

(3.) LZSN - LZSN is the soil-moisture storage capacity index which approximately equals the volume of water that may be contained in the soil but which will drain freely by gravity. The ratio of current soil moisture and capacity controls the rates of infiltration, evapotranspiration, and percolation of groundwater.

(4.) EF - EF is an evaporation-infiltration factor relating infiltration rates to evaporation rates to account for more rapid infiltration rate recovery during warmer periods.

(5.) CB - CB is the basic infiltration index and controls the rate of infiltration.

(6.) CY - CY is an interflow index controlling the time distribution and quantities of moisture entering interflow.

(7.) KSC - KSC is the streamflow routing parameter used to account for channel storage when channel flows are less than one-half capacity.

(8.) KSF - KSF is the streamflow routing parameter used to account for channel plus flood-plain storage when streamflows are greater than twice the channel capacity. The program interpolates values between KSC and KSF for flows between half and twice the channel capacity.

6. Runoff Data - Daily streamflow values for the water years 1954-1965 were obtained for Cave Creek from the U. S. Geological Survey water supply papers. The ten years of streamflow values were used to establish the watershed parameters. Daily values were not used directly in generating the synthetic, historical hydrograph but provided a means for checking the synthetic hydrograph shape and were used in the statistical computation

of the daily correlation coefficients. In order to accurately simulate the actual runoff hydrographs, it was necessary to compare recorded hourly flows against synthetic hourly flows. Hourly runoff volumes for twenty storms were obtained from the U. S. Geological Survey recorder charts. The hourly values served as a guide for adjustment of the model parameters. A comparison of an actual hydrograph and a generated hydrograph is shown in Fig. 24.

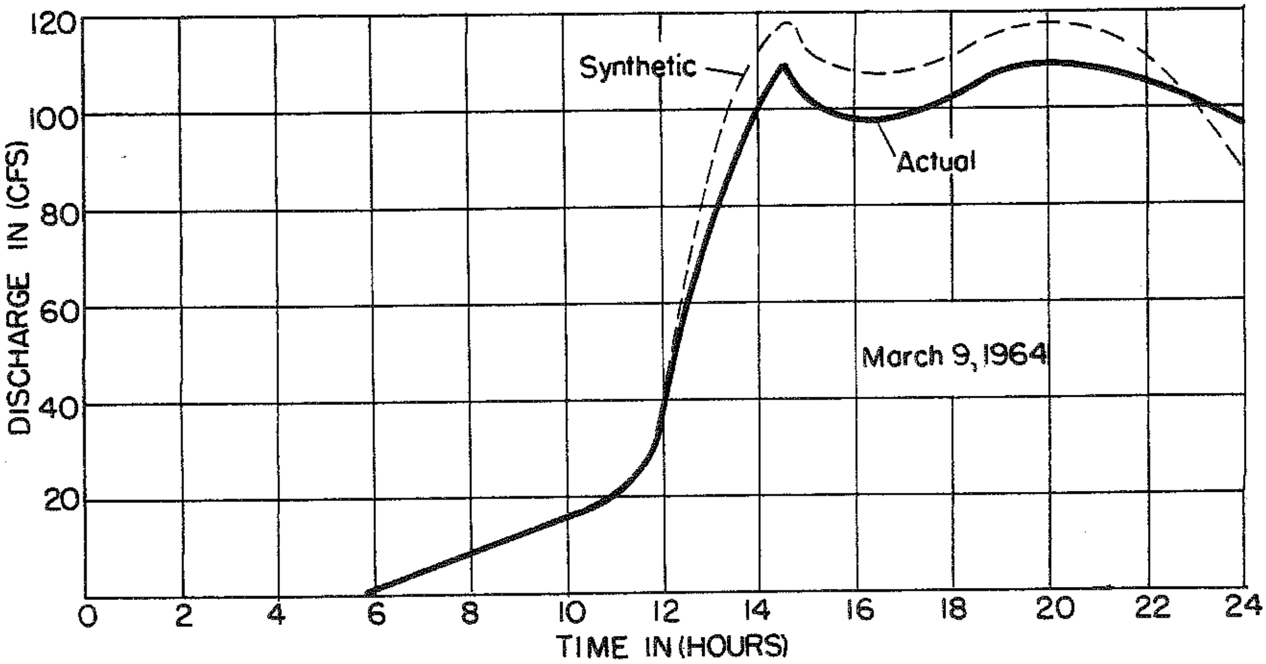
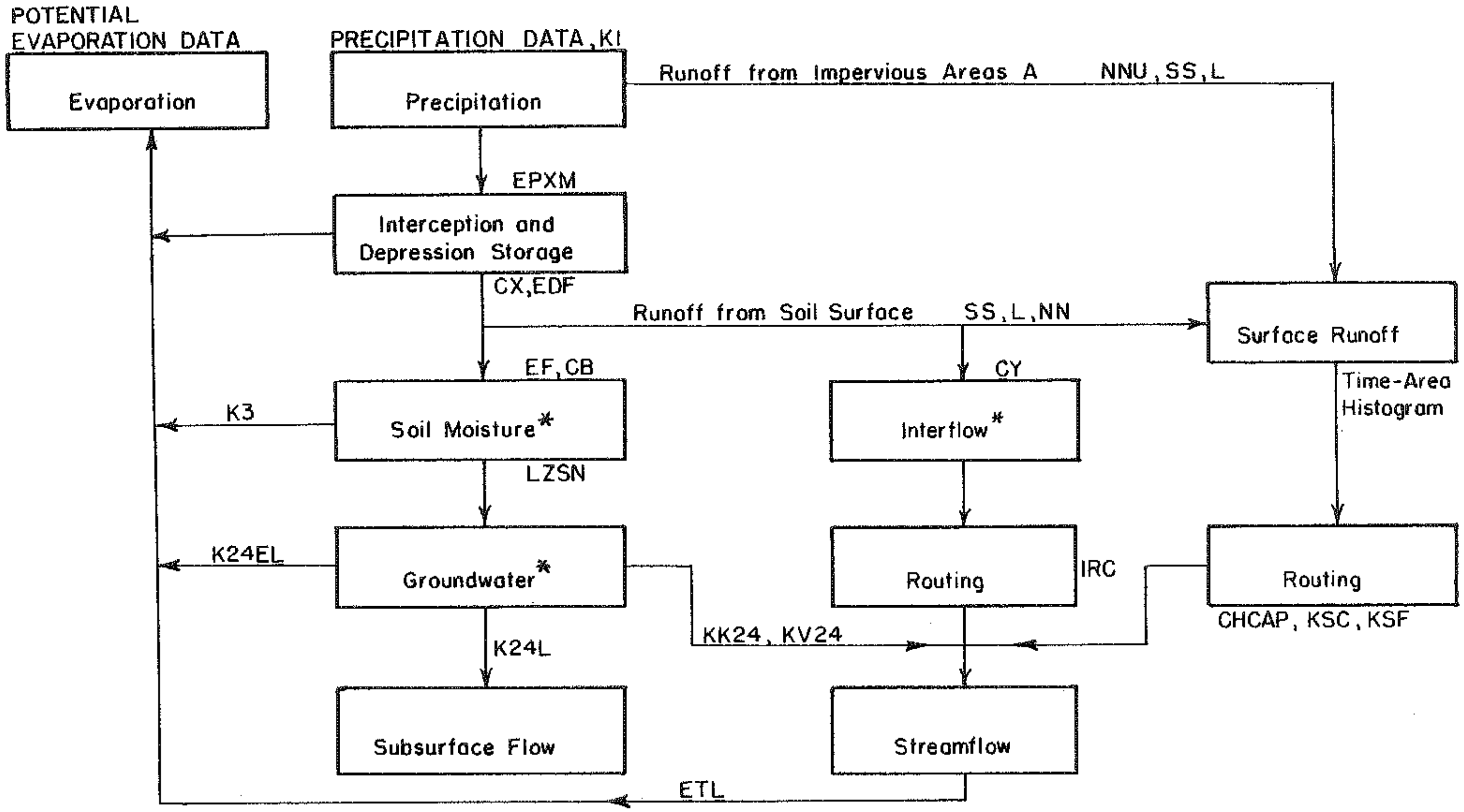


Fig. 24. Comparison of Synthesized with Recorded Hydrographs for Cave Creek

Summary of Input Data

The function of the various input data in describing the phases of the runoff cycle as hypothesised in the Stanford Watershed Model is indicated in Fig. 25. Each flow line is labeled for the specific input data that controls flow of moisture between the indicated storages. The relationships noted in Fig. 25 may be referenced with the preceeding discussion for each item of input data in order to gain a more complete understanding of the model analogy.

Sixteen input parameters for the Cave Creek watershed were determined directly and the remaining eight parameters were determined by trail and adjustment. The water-years 1961-1965 were selected for initial trial runs. Initial parameter values used were those developed for Elkhorn Creek, a larger basin including the Cave Creek watershed, in a previous study (7, p. 17) but modified and adapted to a small watershed. Results from the initial run indicated too much moisture entering interflow, and flood peaks were considerably lower than those recorded. An adjusted set of parameters was obtained for the second run by utilizing guidelines presented in Chapter IV. Repetitive runs were made, and adjustments were effected after each run until an array of reliable parameters was established. Further runs were made for an extended period of record for water-years 1954-1965 in order to test the reliability of the tentatively established parameters. Results of these runs indicated further adjustments were necessary because the peaks for large summer floods were far too low. The parameters finally selected are presented in Table 4.



* Initial storages read

Fig. 25. Moisture Accounting in Stanford Watershed Model

TABLE 4

STANFORD WATERSHED MODEL PARAMETERS FOR CAVE CREEK

Model Parameter	Parameter Value	Model Parameter	Parameter Value
MINH	10.0	CB	0.65
K1	1.0	CY	3.50
AREA	2.53	SS	0.075
A	0.0	L	300.0
ETL	0.0	NN	0.10
EPXM	0.10	NNU	0.015
CX	0.90	IRC	0.75
EDF	1.25	KSC	0.90
LZSN	4.85	KSF	0.90
K3	0.25	CHCAP	40.0
K24L	0.0	KV24	0.99
K24EL	0.0	KK24	0.94
EF	0.15		

Output Results

Typical output for the water-year 1963-64 is presented in Tables 5, 6, 7, and 8. Hourly flows are printed throughout each day in which an hourly flow exceeded MINH; these are shown in Tables 5 and 6. Daily, synthesized streamflow and monthly flows in second-foot-days, total synthesized monthly flow in inches, synthesized monthly interflow, and base flow in inches, recorded streamflow values in second-foot-days, potential monthly and synthesized monthly evapotranspiration, and the total monthly precipitation are tabulated in Table 7. End-of-month moisture conditions within the watershed are described by UZS, the amount of moisture stored on the soil surface in inches; LZS, the moisture stored within the soil in inches; and, SGW, the amount of moisture stored in groundwater in inches. Month-to-month variations of moisture storages

TABLE 5

TYPICAL STORM HYDROGRAPH OUTPUT FROM STANFORD WATERSHED MODEL

```
           CAVE CREEK, PRM $ RUN 1, K. CLARKE ,OCT. 18,1966
     CAVE CREEK NEAR LEXINGTON , KENTUCKY                       WATER YEAR 1963-64      KY. VERSION STANFORD WATERSHED MODEL
 OCTOBER
   1      RECORDED FLOW=     0.0
 NOVEMBER
   1      RECORDED FLOW=     0.0
 DECEMBER
   1      RECORDED FLOW=     0.1
 JANUARY
   1      RECORDED FLOW=     0.0
  20  AM      0.2      0.3      1.8      5.5      6.6      6.7       6.7      6.7      6.7      6.7      6.7      6.7
      PM      6.7      6.7      6.7      6.7      6.6      6.6       6.6      6.5      6.5      6.4      6.4      6.3      5.8
          MAXIMUM=     6.7  C.F.S.      TIME    10.00  A.M.
  21  AM      6.3      6.2      6.1      6.1      6.0      6.0       5.9      5.8      5.8      5.7      5.7      5.6
      PM      5.5      5.5      5.4      5.3      5.3      5.2       5.1      5.1      5.0      5.0      4.9      4.8      5.6
          MAXIMUM=     6.3  C.F.S.      TIME     0.15  A.M.
 FEBRUARY
   1      RECORDED FLOW=     0.8
  15  AM      4.3      4.2      4.2      4.2      4.1      4.1       4.0      4.0      4.0      3.9      3.9      3.8
      PM      3.8      3.7      3.7      4.0      4.1      4.3       4.5      4.6      4.8      4.9      5.0      5.1      4.2
          MAXIMUM=     5.1  C.F.S.      TIME    12.00  P.M.
  16  AM      5.2      5.2      5.3      5.4      5.4      5.4       5.5      5.5      5.5      5.5      5.5      5.5
      PM      5.5      5.5      5.5      5.4      5.4      5.4       5.4      5.3      5.3      5.3      5.2      5.2      5.4
          MAXIMUM=     5.5  C.F.S.      TIME    10.30  A.M.
  17  AM      5.1      5.1      5.0      5.0      5.0      4.9       4.9      4.8      4.8      4.7      4.7      4.6
      PM      4.6      4.5      4.5      4.4      4.4      4.3       4.3      4.2      4.2      4.1      4.1      4.0      4.6
          MAXIMUM=     5.2  C.F.S.      TIME     0.15  A.M.
 MARCH
   1      RECORDED FLOW=     2.0
   4  AM      3.1      3.1      3.0      3.0      3.0      3.4       6.8     10.2     13.2     16.4     23.1     42.3
      PM     87.2    112.9    112.8    107.4    107.5    112.2     117.0    118.4    115.5    112.0    108.5    104.1     60.3
          MAXIMUM=   118.7  C.F.S.      TIME     7.30  P.M.
   5  AM     99.8     95.6     91.7     88.1     84.6     81.4      78.3     75.4     72.6     70.0     67.6     65.2
      PM     63.0     60.9     59.0     57.1     55.3     53.6      52.0     50.5     49.0     47.6     46.3     45.0     67.1
          MAXIMUM=   101.4  C.F.S.      TIME     0.15  A.M.
   6  AM     43.8     42.7     41.6     40.5     39.5     38.5      37.6     36.7     35.9     35.1     34.3     33.5
      PM     32.8     32.1     31.4     30.8     30.1     29.5      29.0     28.4     27.8     27.3     26.8     26.3     33.8
          MAXIMUM=    44.3  C.F.S.      TIME     0.15  A.M.
   7  AM     25.8     25.3     24.9     24.4     24.0     23.6      23.2     22.8     22.4     22.0     21.6     21.3
      PM     20.9     20.6     20.2     19.9     19.6     19.3      19.0     18.7     18.4     18.1     17.8     17.5     21.3
          MAXIMUM=    26.0  C.F.S.      TIME     0.15  A.M.
   8  AM     17.2     17.0     16.7     16.5     16.2     16.0      16.0     16.7     24.6     41.3     47.0     46.0
      PM     44.5     43.2     42.1     41.1     41.5     45.7      47.3     46.4     45.5     44.5     43.6     42.8     34.2
          MAXIMUM=    47.4  C.F.S.      TIME     6.30  P.M.
   9  AM     41.9     41.1     40.3     39.6     39.1     40.9      41.4     40.9     40.3     39.8     39.2     38.7
      PM     38.1     37.7     37.2     36.9     36.5     36.3      36.9     45.4     66.5     97.2    118.6    130.9     50.1
          MAXIMUM=   134.9  C.F.S.      TIME    12.00  P.M.
```

TABLE 6

TYPICAL STORM HYDROGRAPH OUTPUT FROM STANFORD WATERSHED MODEL

```
10  AM    139.1   136.5   130.6   124.9   119.6   114.6     110.0   105.6   101.5    97.6    93.9    90.5
    PM     87.2    84.1    81.1    78.4    75.7    73.2      70.9    68.6    66.5    64.5    62.6    60.7    93.3
       MAXIMUM=   140.0   C.F.S.    TIME    0.45   A.M.

11  AM     59.0    57.3    55.8    54.2    52.8    51.4      50.1    48.9    47.7    46.5    45.4    44.4
    PM     43.3    42.4    41.4    40.5    39.7    38.8      38.0    37.2    36.5    35.8    35.1    34.4    44.9
       MAXIMUM=    59.6   C.F.S.    TIME    0.15   A.M.

12  AM     33.7    33.1    32.5    31.9    31.3    30.7      30.2    29.6    29.1    28.6    28.1    27.7
    PM     27.2    26.7    26.3    25.9    25.4    25.0      24.6    24.2    23.9    23.5    23.1    22.8    27.7
       MAXIMUM=    34.0   C.F.S.    TIME    0.15   A.M.

13  AM     22.4    22.1    21.7    21.4    21.1    20.7      20.4    20.1    19.8    19.5    19.2    19.0
    PM     18.7    18.4    18.1    17.9    17.6    17.4      17.1    16.9    16.6    16.4    16.1    15.9    18.9
       MAXIMUM=    22.5   C.F.S.    TIME    0.15   A.M.

14  AM     15.7    15.5    15.3    15.0    14.8    14.6      14.4    14.2    14.1    13.9    13.8    13.6
    PM     13.5    13.4    13.2    13.1    12.9    12.8      13.1    13.4    13.6    13.8    14.1    14.5    14.0
       MAXIMUM=    15.8   C.F.S.    TIME    0.15   A.M.

15  AM     14.8    15.2    15.5    15.7    16.0    16.2      16.3    16.5    16.6    16.7    16.8    16.8
    PM     16.8    16.8    16.8    16.8    16.8    16.7      16.7    16.6    16.5    16.4    16.3    16.2    16.4
       MAXIMUM=    16.8   C.F.S.    TIME    1.45   P.M.

16  AM     16.1    16.0    15.9    15.8    15.6    15.5      15.4    15.2    15.1    14.9    14.8    14.7
    PM     14.5    14.4    14.2    14.0    13.9    13.7      13.6    13.4    13.3    13.1    13.0    12.8    14.5
       MAXIMUM=    16.2   C.F.S.    TIME    0.15   A.M.

17  AM     12.7    12.5    12.4    12.2    12.1    11.9      11.8    11.6    11.5    11.4    11.2    11.1
    PM     10.9    10.8    10.7    10.5    10.4    10.3      10.1    10.0     9.9     9.8     9.6     9.5    11.0
       MAXIMUM=    12.7   C.F.S.    TIME    0.15   A.M.

18  AM      9.4     9.3     9.2     9.0     8.9     8.8       8.7     8.6     8.5     8.4     8.3     8.2
    PM      8.1     8.0     7.9     7.8     7.7     7.6       7.5     7.4     7.3     7.2     7.1     7.0     8.1
       MAXIMUM=     9.4   C.F.S.    TIME    0.15   A.M.

19  AM      6.9     6.8     6.7     6.7     6.6     6.5       6.4     6.3     6.3     6.2     6.1     6.0
    PM      5.9     5.9     5.8     5.7     5.7     5.6       5.5     5.5     5.4     5.3     5.3     5.2     6.0
       MAXIMUM=     6.9   C.F.S.    TIME    0.15   A.M.

20  AM      5.1     5.1     5.0     5.0     5.0     5.1       5.1     5.1     5.1     5.1     5.1     5.1
    PM      5.1     5.1     5.1     5.1     5.0     5.0       5.0     5.0     5.3     8.6    10.2    10.3     5.7
       MAXIMUM=    10.2   C.F.S.    TIME   11.15   P.M.

21  AM     10.3    10.4    10.5    10.6    10.6    10.7      10.7    10.7    10.7    10.7    10.7    10.7
    PM     10.7    10.7    10.6    10.6    10.5    10.5      10.4    10.3    10.3    10.2    10.1    10.0    10.5
       MAXIMUM=    10.8   C.F.S.    TIME    9.00   A.M.

22  AM      9.9     9.9     9.8     9.7     9.6     9.5       9.4     9.3     9.2     9.1     9.0     8.9
    PM      8.8     8.8     8.7     8.6     8.5     8.4       8.3     8.2     8.1     8.0     7.9     7.8     8.9
       MAXIMUM=    10.0   C.F.S.    TIME    0.15   A.M.

23  AM      7.7     7.6     7.5     7.5     7.4     7.3       7.2     7.1     7.0     6.9     6.9     6.8
    PM      6.7     6.6     6.5     6.4     6.4     6.3       6.2     6.1     6.1     6.0     5.9     5.9     6.8
       MAXIMUM=     7.8   C.F.S.    TIME    0.15   A.M.

24  AM      5.8     5.7     5.6     5.6     5.5     5.4       5.4     5.3     5.2     5.2     5.1     5.1
    PM      5.0     4.9     4.9     4.8     4.8     4.7       4.6     4.6     4.5     4.5     4.4     4.4     5.0
       MAXIMUM=     5.8   C.F.S.    TIME    0.15   A.M.
APRIL

   1      RECORDED FLOW=      1.9
MAY

   1      RECORDED FLOW=      1.0
JUNE
```

TABLE 7

TYPICAL DAILY AND MONTHLY MOISTURE SUMMARY OUTPUT FROM STANFORD WATERSHED MODEL

```
               CAVE CREEK, PRM G RUN 1, K. CLARKE ,OCT. 18,1966
                                                        WATER YEAR  1963-64          KENTUCKY WATERSHED MODEL
    CAVE CREEK NEAR LEXINGTON , KENTUCKY
        DAY       OCT    NOV    DEC    JAN    FEB    MAR    APR    MAY    JUN    JUL    AUG    SEPT           ANNUAL

         1        0.0    0.0    0.0    0.0    0.3    0.6    0.9    1.7    0.1    0.1    0.0    0.0
         2        0.0    0.0    0.0    0.0    0.2    0.6    0.8    1.3    0.1    0.1    0.0    0.0
         3        0.0    0.0    0.0    0.0    0.2    2.6    0.7    1.0    0.1    0.1    0.0    0.0
         4        0.0    0.0    0.0    0.0    0.1   60.3    0.7    0.8    0.1    0.1    0.0    0.0
         5        0.0    0.0    0.0    0.0    0.1   67.1    0.6    0.7    0.1    0.1    0.0    0.0

         6        0.0    0.0    0.0    0.7    1.9   33.8    1.4    0.6    0.1    0.1    0.0    0.0
         7        0.0    0.0    0.0    1.9    3.3   21.3    1.7    0.5    0.1    0.1    0.0    0.0
         8        0.0    0.0    0.0    1.7    2.8   34.2    1.5    0.4    0.1    0.1    0.0    0.0
         9        0.0    0.0    0.0    1.5    2.1   30.1    1.2    0.4    0.1    0.1    0.0    0.0
        10        0.0    0.0    0.0    1.4    1.8   93.3    0.9    0.3    0.1    0.1    0.0    0.0

        11        0.0    0.0    0.0    1.0    2.8   44.9    0.8    0.3    0.1    0.1    0.0    0.0
        12        0.0    0.0    0.0    0.8    2.5   27.7    0.6    0.3    0.1    0.1    0.0    0.0
        13        0.0    0.0    0.0    1.1    3.2   18.9    0.6    0.2    0.1    0.1    0.0    0.0
        14        0.0    0.0    0.0    0.9    4.6   14.0    0.5    0.2    0.2    0.1    0.0    0.0
        15        0.0    0.0    0.0    0.7    4.2   16.4    0.4    0.2    0.4    0.1    0.0    0.0

        16        0.0    0.0    0.0    0.5    5.4   14.5    0.4    0.2    0.4    0.1    0.0    0.0
        17        0.0    0.0    0.0    0.4    4.6   11.0    0.4    0.2    0.3    0.1    0.0    0.0
        18        0.0    0.0    0.0    0.3    3.6    8.1    0.3    0.2    0.4    0.1    0.0    0.0
        19        0.0    0.0    0.0    0.3    3.1    6.0    0.3    0.2    1.1    0.1    0.0    0.0
        20        0.0    0.0    0.0    5.8    2.5    5.7    0.5    0.2    1.0    0.1    0.0    0.0

        21        0.0    0.0    0.0    5.6    1.9   10.5    0.5    0.1    0.8    0.1    0.0    0.0
        22        0.0    0.0    0.0    4.1    1.5    8.9    0.7    0.1    0.6    0.1    0.0    0.0
        23        0.0    0.0    0.0    2.9    1.1    6.8    0.8    0.1    0.5    0.1    0.0    0.0
        24        0.0    0.0    0.0    2.1    0.9    5.0    0.7    0.1    0.4    0.0    0.0    0.0
        25        0.0    0.0    0.0    1.7    0.7    3.8    0.6    0.1    0.3    0.0    0.0    0.0

        26        0.0    0.0    0.0    1.3    0.7    3.1    0.7    0.1    0.2    0.0    0.0    0.0
        27        0.0    0.0    0.0    1.0    0.9    2.5    1.5    0.1    0.2    0.0    0.0    0.0
        28        0.0    0.0    0.0    0.7    0.8    2.0    2.0    0.1    0.1    0.0    0.0    0.5
        29        0.0    0.0    0.0    0.5    0.8    1.6    2.4    0.2    0.1    0.0    0.0    1.4
        30        0.0    0.0    0.0    0.4           1.3    2.1    0.2    0.1    0.0    0.0    1.4
        31        0.0           0.0    0.3           1.1           0.1           0.0    0.0

   SYNTHETIC      0.     0.     0.    40.    59.   578.    27.    11.     9.     2.     1.     3.        730.   CFSD
   TOTAL        0.004  0.001  0.004  0.589  0.863  8.492  0.401  0.164  0.127  0.029  0.008  0.051     10.73  INCHES/DA
   INTERFLOW    0.000  0.000  0.002  0.503  0.747  4.950  0.215  0.054  0.083  0.009  0.000  0.052     6.614  INCHES/DA
   BASE         0.004  0.001  0.004  0.047  0.116  0.434  0.195  0.106  0.051  0.029  0.008  0.009     1.003  INCHES/DA
                                                                                                      1448.  ACFT

   RECORDED       0.     3.     2.    59.   117.   536.    30.    14.     8.     5.     0.    10.        786.   CFSD
                                                                                                     11.55  INCHES/DA
                                                                              (     1543.   )         1558.  ACFT
   PRECIP        0.33   1.81   0.81   2.79   2.55  10.28   2.86   1.68   3.55   3.99   1.96   4.90     37.51  INCHES/DA

   EVP/TRAN-NET 1.236  1.265  0.875  0.702  0.576  0.693  1.851  3.149  4.777  4.396  2.925  1.344    23.790  INCHES/DA
      -POTENTIAL 4.687  2.137  0.875  0.702  0.576  0.693  1.871  4.346  5.865  5.814  7.841  5.704    41.111  INCHES/DA

   STORAGES-UZS 0.050  0.761  0.371  0.440  0.454  0.348  0.854  0.947  0.000  0.000  0.000  2.485            INCHES/DA
            LZS 0.951  0.784  1.102  2.488  3.524  4.640  4.743  3.150  2.753  2.322  1.355  2.281            INCHES/DA
            SGW 0.001  0.001  0.002  0.024  0.077  0.164  0.120  0.032  0.019  0.008  0.002  0.050            INCHES/DA

   INDICES-UZSN 1.969  1.065  0.805  0.490  0.361  0.328  0.722  1.579  2.404  2.461  3.113  1.816
            GWS 0.014  0.006  0.005  0.042  0.126  0.329  0.249  0.113  0.067  0.036  0.015  0.058
            INF 1.605  0.899  0.474  0.330  0.330  0.330  0.537  1.191  1.832  1.965  2.421  1.958
   BALANCE       -0.0844  INCHES
```

TABLE 8

TYPICAL OUTPUT FROM STANFORD WATERSHED MODEL, COMPARING SYNTHESIZED WITH RECORDED FLOW

```
          DAILY FLOW DURATION AND ERROR TABLE
          FLOW INTERVAL      CASES   AV.ERROR    AVR. ABS. ERROR   STANDARD ERROR

                    0.0-     484.0         0.2          0.21          0.40
                    1.0-      62.0         0.6          0.85          1.04
                    1.6-      60.0         0.3          1.06          1.56
                    2.7-      25.0         0.4          1.82          2.82
                    4.5-      26.0        -0.4          2.14          2.74
                    7.4-      36.0        -1.8          3.58          4.04
                   12.2-      21.0         3.1          3.76          4.93
                   20.1-       8.0         2.0          7.30          9.32
                   33.1-       7.0        -0.2          4.73          7.03
                   54.6-       2.0         4.2          8.31         11.75
                   90.0-       0.0
                  148.4-       0.0
                  244.7-       0.0
                  403.4-       0.0
                  665.1-       0.0
                 1096.6-       0.0
                 1808.0-       0.0
                 2981.0-       0.0
                 4914.8-       0.0
                 8103.1-       0.0
                13359.7-       0.0
                22026.5-       0.0
                             731.0         0.2          0.87         45.65
          CORRELATION COEFFICIENT (DAILY)         0.9805
          TWENTY HIGHEST CLOCKHOUR RAINFALL EVENTS IN THE WATER YEAR
      0.980 0.950 0.950 0.750 0.560 0.520 0.490 0.490 0.420 0.400 0.380 0.370 0.350 0.350 0.330 0.320 0.320 0.310 0.310 0.300
          TWENTY HIGHEST CLOCKHOUR OVERLAND FLOW RUNOFF EVENTS IN THE WATER YEAR
      0.495 0.283 0.200 0.163 0.152 0.147 0.083 0.078 0.076 0.057 0.050 0.047 0.042 0.039 0.034 0.031 0.029 0.023 0.020 0.020

  END-OF-DATA ENCOUNTERED ON SYSTEM INPUT FILE.
```

are described by end-of-month indices: soil moisture storage index, UZSN; groundwater storage index, GWS; and index of infiltration, INF. The output provides insight into occurences within the natural hydrologic cycle and serves as an aid in the process of trial and adjustment for evaluation of watershed parameters. Daily recorded flows may be compared with synthesized flows. Monthly synthesized and recorded flows may be compared to show the seasonal runoff distribution -- thereby, enabling one to determine seasonal adjustments that must be made in the input data. Daily or hourly flows describing synthetic and actual flood hydrographs may be compared in order to determine which parameters should be changed.

Table 8 shows the departure of daily, synthesized flows from daily recorded flows by group intervals of recorded flow. The daily correlation coefficient is computed by statistical analysis of synthesized and recorded flows. The correlation coefficient is governed primarily by how closely flood-peak flows are matched and gives little indication of how closely low flows are synthesized. Correlation is generally more accurate for large-scale winter storms than for localized summer thunderstorms wherein reliable basin rainfall data are difficult to obtain.

CHAPTER IV

RELATING INPUT PARAMETERS TO WATERSHED CHARACTERISTICS

Watershed Characteristics and the Runoff Cycle

The runoff cycle describes the processes wherein water falling onto the land surface travels through the watershed and eventually returns to the atmosphere by evapotranspiration or leaves the watershed as surface or subsurface flow. Routing of precipitation among the possible paths of travel is primarily governed by the nature of the watershed surface as expressed quantitatively by certain watershed characteristics. A review of the runoff cycle for those watershed characteristics particularly important in governing peak runoff rates is presented herein.

1. Interception - Precipitation initially contacts vegetative surfaces, and moisture stored on such surfaces is termed interception storage. Large interception storage capacities reduce flood peaks by holding water which would otherwise runoff. Interception is more effective in reducing small flood peaks than large flood peaks. Interception capacity is governed primarily by type and density of vegetative cover.
2. Depression Storage - Precipitation not held by the vegetative cover falls onto the ground surface. Portions of this moisture may be held in hollows and behind ridges on the soil surface and may not contribute to the flood peak. This moisture,

termed depression storage, is more effective in reducing small flood peaks than large flood peaks. Depression storage capacity is governed primarily by nature of the soil surface and slope. Steep slopes reduce the volume of moisture that may be stored behind a ridge of given height.

3. Infiltration - A portion of water contacted by the soil surface may infiltrate into the soil. Infiltrated water is slow in contributing to runoff but eventually enters the stream as interflow or base flow. High infiltration rates may substantially attenuate large flood peaks. Infiltration rates are primarily governed by soil permeability and the volume of moisture that may be stored within the soil. Soil typically contains layers of varying permeability at various depths below the surface. Groundwater may saturate soil which would otherwise have capacity to store moisture.
4. Evapotranspiration - A portion of the water stored on the surface or within the soil may return to the atmosphere by evaporation or by transpiration from vegetation. High evapotranspiration rates will deplete the soil moisture between storms and thereby increase subsequent infiltration rates. The quantity of vegetative cover is the primary factor governing the rate of transpiration.
5. Impervious Surface - Exposed surfaces such as buildings, roads, paved areas, rock outcrops, etc. appreciably decrease potential infiltration. Such areas short circuit previously discussed

portions of the hydrologic cycle and magnify flood peaks.

6. Runoff Routing - Water traveling from the point where it strikes the soil surface and thence to the stream may: 1) travel across the soil surface (overland flow), 2) travel partially through and partially above ground (interflow), or 3) travel down to the water table and later appear as base flow. Rate of overland flow is governed by the slope and roughness of the soil surface -- largely determined by the nature and density of the vegetative cover. Overland flow is normally more rapid over impervious surfaces. The rate of interflow is governed by the depth of impervious layers and by soil permeability. A shallow depth increases interflow by forcing the water back to the soil surface, whereas more permeable soil increases flow through the soil layers. The rate of groundwater or base flow is slow and has minor effect upon flood peaks.

7. Stream Routing - Basin shape is also an important factor affecting flood peaks. Water will arrive at the outlet of a compact basin in a shorter time than for a long, narrow basin of the same area. A long, narrow basin also has more channel capacity in which to store water and further attenuate flood peaks.

A review of factors mentioned thus far in the runoff cycle indicates six watershed characteristics to be particularly important in controlling flood peaks. There are:

a. Volume of moisture that may be stored within the soil--roughly proportional to the depth of soil available for moisture storage -- referred to herein as depth of hydrologic activity.

b. Rate at which moisture may enter soil -- indicated by soil permeability.

c. Type and amount of vegetative cover on soil surface -- may be measured in an inverse manner by lack of vegetative cover as soil exposure.

d. Fraction of the watershed surface which is impervious.

e. Slope of the watershed surface perpendicular to the channel.

f. Shape of the watershed -- indexed by the time-of-concentration for watersheds of same area.

Specific values for each of the watershed characteristics may vary from point to point within a given basin, and it is important that a weighted mean value be selected for each characteristic in order that values may be more representative of the entire basin. The specific value selected for a given watershed, as applicable to the Stanford Watershed Model computer program, is an index or measure of the effect of that characteristic upon the overall hydrologic cycle. Procedures are presented herein for use in estimating values of the watershed characteristics. The basic computer program has been developed in such a manner as to allow for refinement of values for the characteristics; in the event more accurate or reliable means are developed for determining the values, the basic program may be used for development of revised design curves.

Evaluation of Watershed Characteristics

In order to quantify the relationship between the characteristics and flood peaks, it was necessary to develop a quantitative index for expressing the magnitude of each characteristic. The range of values each characteristic index might be expected to acquire was prejudged in order to limit correlation between the characteristics and flood peaks to values of practical concern. Ranges of expected values for five of the six watershed characteristics were predetermined through review of available soil surveys, topographic maps, and aerial photographs for all sections of Kentucky. The sixth characteristic, basin shape, which was indexed by time-of-concentration, presented a special case. All computer runs were based on the Cave Creek drainage area (2.53 square miles), and the range of indices required for that situation was equivalent to a range in time-of-concentration expected from a steep and compact area to that for a flat and elongated area of 2.53 square miles. Initial correlations between flood peaks and watershed characteristics were determined for excess rainfall from a 2.53-square-mile watershed, and then procedures were developed for adjusting the results to watersheds having different sizes. Procedures used to quantify each of the six indices and ranges of values for each index follow.

1. Depth of Hydrologic Activity - The depth of hydrologic activity may be estimated as depth of soil above an impending stratum, bedrock, or water table, whichever is least. The depth of soil above an impending stratum constitutes the zone of hydrologic

activity (5, p. 38). An impending layer may be characterized by a platy structure, firmness, or other morphological properties which control seepage. Inasmuch as the impending stratum controls the final infiltration rate, its depth is primarily determinative of the soil storage capacity.

Assuming that infiltrated moisture will percolate downward through the profile and replenish each soil layer before seeping to underlying layers, this moisture will percolate to a depth at which the total moisture stored equals the volume of gravitational water. Gravitational water is the volume of moisture that would drain freely under the influence of gravity from a saturated soil.

Examination of soil types described in various soil surveys (cf. 2, pp. 29-120) provided values for the depth of zone of hydrologic activity and were in the order of 10 to 70 inches. It was assumed that depths greater than 60 inches would have minor effect upon flood peaks; therefore, 60 inches was selected as the maximum depth; 10 inches through 60 inches was used in the program.

2. Soil Permeability - Soil permeability may be estimated as the mean permeability of soils within the zone of hydrologic activity. The range of soil permeability was determined from examination of values for soil types common to Kentucky (2, pp. 29-120). Average values of permeability for Kentucky soils varied from 1.5 to 6.5 inches per hour.

3. Soil Exposure - The soil-exposure index was quantified by assigning arbiturary weights to principal soil-cover types. Barren ground was assumed as the most exposed soil and forest was assumed as the most effective vegetative cover. Grassland was assumed to be intermediate between the two. Weighting factors used for evaluation of soil exposure were:

    Barren ground---------100
    Grassland --------- 50
    Forest --------- 0

   Soil exposure for a given watershed is estimated as the sum of products of given weighting factors times the watershed fraction in respective cover type. The range of values may vary from 0 to 100.

4. Impervious Cover - For this study, impervious cover is equal to the percent of the basin area which is impervious and drains directly into the channel. This variable was assigned a normal range of variation from 0 to 45 percent. A rural watershed may generally be assigned a value of 0 percent. The 45 percent represents the normal maximum value, but it may be exceeded in the downtown portions of large cities or small paved watersheds (6, pp. 223-234).

5. Overland Slope - The normal range in overland slope (perpendicular to channel) was obtained from topographic maps. Flat portions of Western Kentucky produced a minimum value of 0.01 and steep mountains of Eastern Kentucky produced a maximum value of 0.41.

6. <u>Time-of-Concentration</u> - Time-of-concentration is controlled by stream slope and basin compactness and therefore serves as an index for varying basin shapes. Two watershed shapes were theorized to include extreme variations likely to be encountered and are shown in Fig. 26. Values of stream slope were theorized to range from 0.001 to 0.05. Minimum travel time is associated with a circular watershed having a steep slope, and

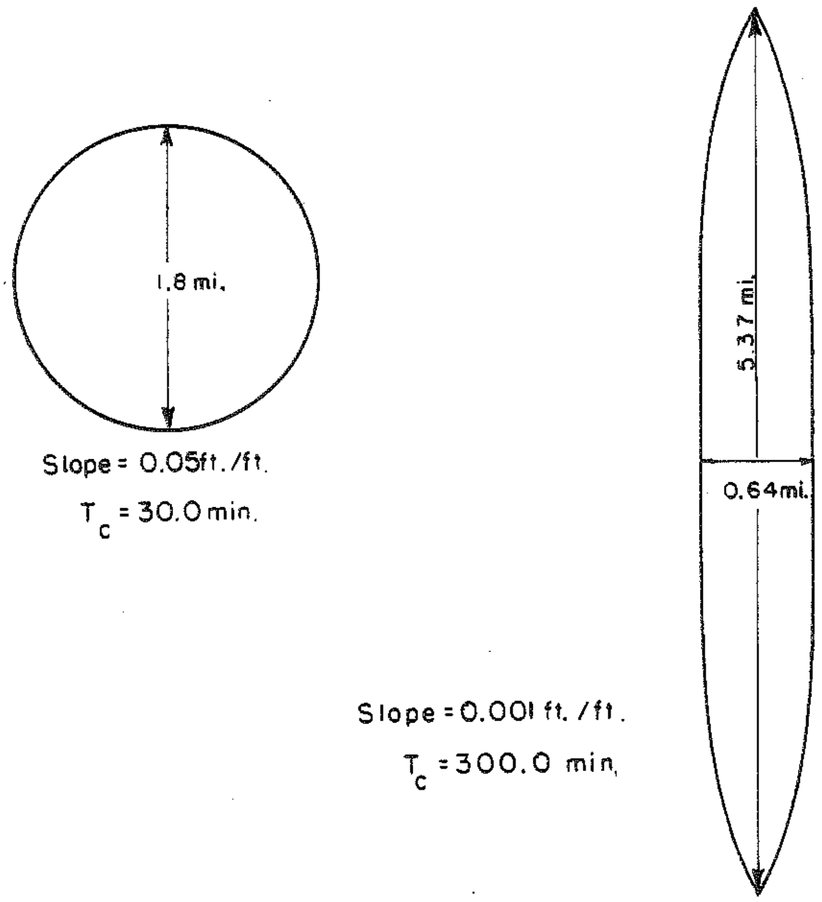


Fig. 26. Hypothetical Drainage Basins for Deriving Range for Time-of-Consideration

maximum travel time is associated with a long, narrow watershed having a shallow slope. Ramser's approach (Equation 12) yielded values of 30 to 300 minutes for the 2.53-square-mile watershed for these extremes of slope and shape.

A key step in use of the Stanford Watershed Model as an aid in relating watershed characteristics to a runoff coefficient was the determination of values for the six selected watershed characteristics for the Cave Creek watershed. The evaluation provides a known set of watershed characteristics for a watershed, for which a set of Stanford Watershed Model input parameters had previously been determined, and also provides an illustration as to how watershed characteristics might be quantified for any watershed under study. The following values were established for the Cave Creek watershed.

1. Depth of Hydrologic Activity - The volume of gravitational water (in the Stanford Watershed Model) is defined by LZSN and was found to be 4.85 inches for the Cave Creek watershed. From this information in conjunction with the soil characteristics for Cave Creek listed in Table 9 (*cf.* 13, p. 37), it was possible to evaluate the thickness of soil required to store 4.85 inches of moisture. A soil thickness of 24.5 inches was computed as that depth required to store the gravitational water.

   Boring records for an interchange under construction within the Cave Creek watershed were obtained in order to check the derived soil thickness. Laboratory test results for the soil samples indicated a significant increase in bulk density and

TABLE 9

PHYSICAL PROPERTIES OF CAVE CREEK SOILS

Available Water Capacity		Soil Profile		Soil Permeability
Per inch of soil (inches)	Per horison (inches)	Depth (inches)	Texture	(inches per hour)
0.22	3.08	1-14	Silt Loam	2.0 -6.3
0.19	1.33	14-21	Silt Clay Loam	0.63-2.0
0.18	1.98	21-32	Silt Clay Loam	0.63-2.0
0.17	2.72	32-48	Silt Clay Loam	0.63-2.0
0.15	1.80	48-60	Clay	0.63-2.0

percentage of clay and colloids occured at a depth of 24 inches. Porosity decreased at that depth.

2. Soil Permeability - A mean value of 3.25 inches per hour was established for soil permeability by use of information presented in the preceeding discussion and reference to Table 10 (*cf.* (13, p. 37).

TABLE 10

COMPUTATIONS FOR MEAN SOIL PERMEABILITY

Horizon	Thickness (inches)	Permeability (inches/hour)	Permeability x Thickness
A	14.0	4.15	58.0
B	7.0	2.00	14.0
C	3.25	2.00	6.5
	Σ = 24.25		Σ = 78.5

$$\text{Average Permeability} = \frac{78.5}{24.25} = 3.25 \text{ in./hr.}$$

3. Soil Exposure - Field inspection and examination of aerial photographs and soil surveys for Fayette County (13) indicated the Cave Creek watershed was used predominantly for pasturing, and a value of 56 was assigned to soil exposure.

4. Impervious Cover - Cave Creek is entirely rural without urban development, 0.0 was chosen for impervious cover.

5. Average Overland Slope - The average slope was obtained from a series of slope measurements from a topographic map. A mean value of 0.075 was computed.

6. Time-of-Concentration - The time-of-concentration was computed by the Ramser formula (Equation 12). Required measurements for using Ramser's formula were stream length and stream slope; substitution of these values provided a time-of-concentration of 67 minutes; however 60 minutes was used in the program for convenience, as previously explained.

Range of Input Parameters Encountered

Thirteen input parameters were found to be dependent on the six watershed characteristics. The remaining 11 parameters were not related to the watershed characteristics and were assumed constant for this study. Tables 11 and 12 present input parameters adjacent to watershed characteristics with which each is associated. The ranges over which input parameters might vary were determined in various manners. Parameters A and SS are identical to watershed characteristics and have the same range in values as those characteristics they represent. Extreme values of Z were calculated from the two hypothetical watersheds.

TABLE 11

SELECTION OF RANDOM WATERSHED CHARACTERISTICS USING RANDOM NUMBERS

(1)	(2)	(3)	(4)	(5)	(6)
Watershed Characteristics	Stanford Watershed Model Parameter	Range	Random Number Table 13	Interval	Random Watershed
Depth of Hydrologic Activity		60"-10"	0.25	50.0"	22.5"
	LZSN	12.0-2.0		10.0	4.5
	CY	1.0-4.5		3.5	3.63
Soil Permeability		6.5-1.5"/hr	0.47	5.0"/hr	3.85"/hr
	CB	1.3-0.3		1.0	0.77
	IRC	0.62-0.82		0.2	0.726
Soil Exposure		100.-0.	0.85	100.0	85.0
	K3	0.2-0.3		0.1	0.215
	NN	0.1-0.4		0.3	0.10
Impervious Cover		45.-0.	0.44	45.0	19.8
	A	0.45-0.0		0.45	0.198
Overland Slope		.41-0.01	0.27	0.40	0.118
	SS	.41-0.01		0.40	0.118
Time-of-Concentration		300.-30.	0.42	270.0	143.0
	Z	20.-2.		18.0	10.0
	KS	0.989-0.889		0.09	0.931

TABLE 12

RANDOM WATERSHED CHARACTERISTICS SELECTED THROUGH INDIRECT INTERPOLATION

	Minimum Values	Cave Creek Values	Maximum Values
Product of Slope and Soil Exposure	0.0	4.20	40.0
Stanford Watershed Model Parameters			
CX	1.65	0.815	0.100
EDF	2.00	1.165	0.450

Products of Slope
and Soil Exposure

(A.) S*xSE = 10.0 CX = 0.702; EDF = 1.052
(B.) S xSE = 0.9 CX = 1.471; EDF = 1.821

*S = Slope
SE = Soil Exposure

Ranges of values corresponding to ranges of watershed characteristics for the other parameters were set by indirect methods. Basic guidelines for starting values suggested by Crawford and Linsley (4), published data listing parameter values for watersheds of described characteristics (6, 7, 4, 10, 11), and experience gained in application of the model to various Kentucky watersheds (Bear Branch, Breathitt County; Elkhorn Creek, Franklin County; Pond Creek, Jefferson County; and Cave Creek, Fayette County) were used in establishing ranges for the other parameters.

It was recognized that each relationship derived could be verified only through a more extensive analysis of more watersheds than was possible as part of this study; however, a realistic series of relationships through which runoff coefficients may be approximated more closely than was possible by other methods has been established. Results of sensitivity studies conducted on the Elkhorn Creek basin (7) will be discussed in order to illustrate the role each parameter plays in the total runoff cycle. A discussion of the watershed characteristics and their related Stanford Watershed Model parameters is presented.

1. Depth of Hydrologic Activity - Increased depth of hydrologically active soil increases soil moisture storage capacity and reduces interflow.
    a. LZSN - Analysis of several soil surveys provided average soil moisture storages from which LZSN was hypothesized to equal approximately 20 percent of the soil depth. Twenty percent of the depth of hydrologic activity provided values of 2.0 to 12.0 inches for LZSN. The percentage is representative of the ratio of the volume of water that will drain freely from most soils and the volume of soil solids. Fig. 27 depicts the effect of increased values of LZSN within the model. Increased soil moisture storage reduces flood peaks.
    b. CY - A range for the parameter CY was determined from results of various sensitivity studies (7; 4, pp.69-71). The range of CY varied inversely with the depth of hydrologic activity as noted on Table 11. Increased values of CY reduce flood peaks as noted on Fig. 28 -- more moisture enters into interflow. Slower routing causes the watershed to respond sluggishly to rainfall and slightly reduces runoff volume through increased moisture losses.

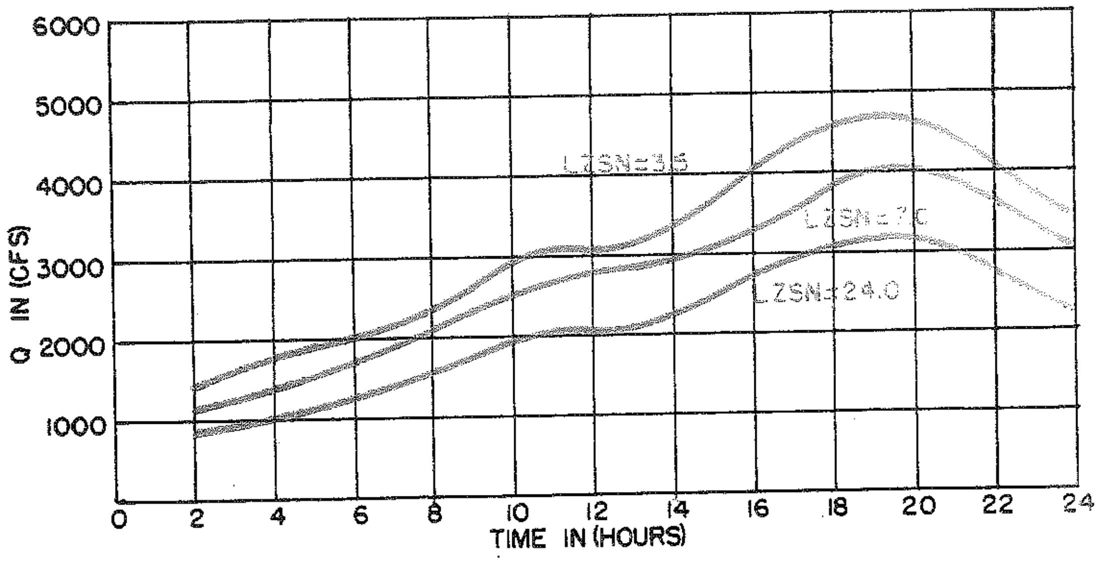


Fig. 27. Sensitivity of Model Response to the Soil Moisture Storage Parameter

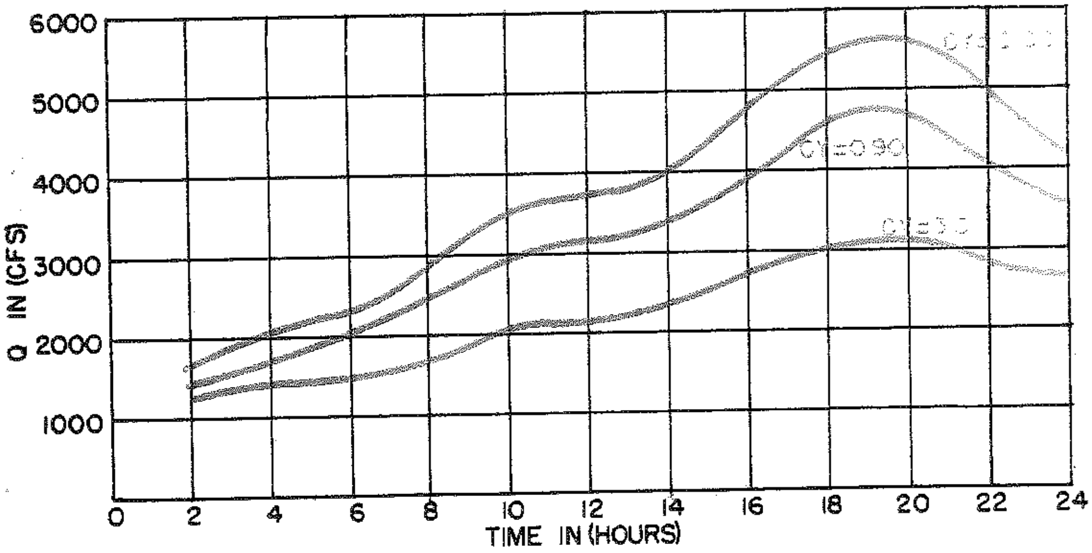


Fig. 28. Sensitivity of Model Response to Interflow Parameter

2. Soil Permeability - Soil permeability influences the rate of infiltration into the soil and transmission of interflow.

   a. CB - From the conclusions of studies by Crawford and Linsley (4, p. 76), it was hypothesized that CB is approximately equal to 20 percent of the soil permeability. Increased values of CB result in increased infiltration and thereby decreases direct runoff and interflow, as noted in Fig. 29.

   b. IRC - The range of IRC noted in Table 11 from results of sensitivity studies (7) and several hydrograph recession analyses was established. Increasing IRC, shown in Fig. 30, produces a decrease in flows during the storm and reduces the hydrograph-recession rate.

3. Soil Exposure - Increased soil exposure decreases moisture losses through evapotranspiration and retardance to overland flow. Each effect reduces runoff peaks.

   a. NN - Table 3 lists values of NN for various surface types from which a range of NN was established. Hydrographs produced for various values of NN are presented in terms of L in Fig. 31. L and NN are resulted in the model by the relationship (4):

$$\left[\frac{NN \times L}{\sqrt{SS}}\right]^{.60} \qquad 13$$

Increasing values of NN produced results similar to those

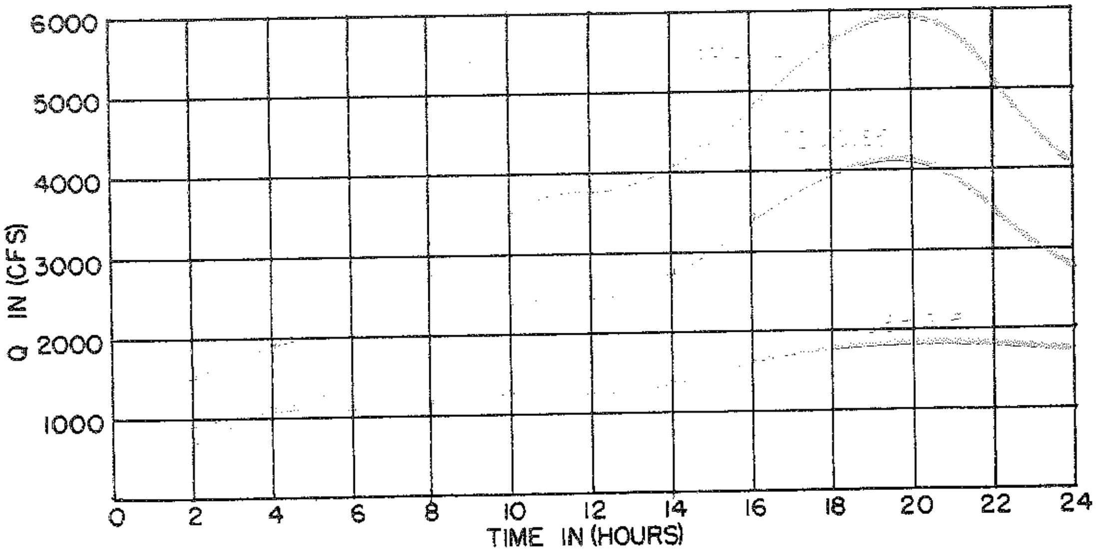


Fig. 29. Sensitivity of Model Response to Infiltration Parameter

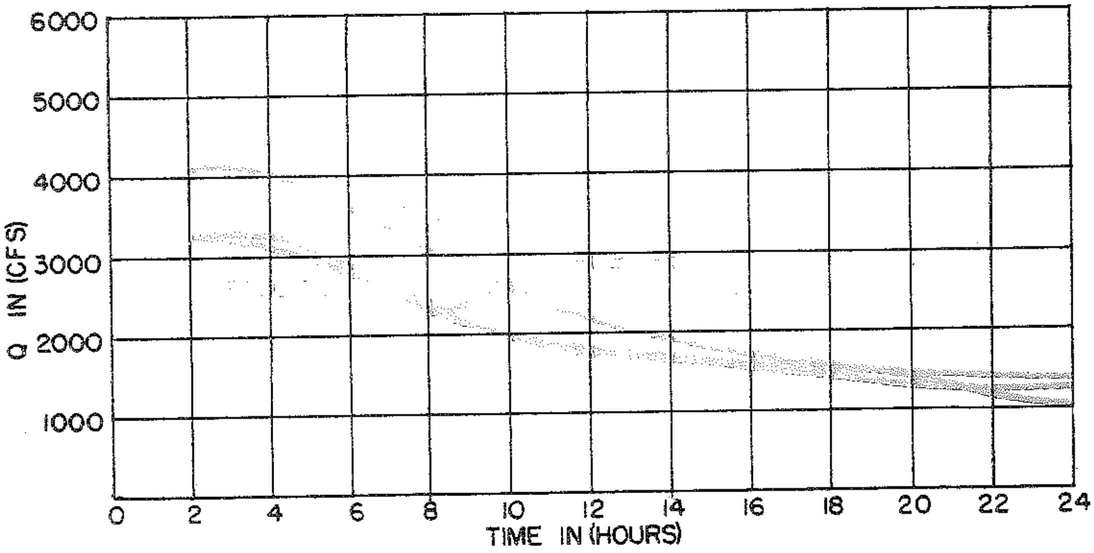


Fig. 30. Sensitivity of Model Response to Interflow-Recession Parameter

for increasing overland flow lengths. Increasing values of NN reduces runoff volumes and tends to attenuate the flood peaks by allowing more time for infiltration.

b. K3 - A range of K3 was obtained from Table 2. Increased evaporation reduces the peak of small storms or those storms immediately following a long dry period such as may occur in late summer or early fall. Increased values of K3 produced no significant change for the flood occurring in March.

4. Impervious Area - Increasing impervious area amplifies flood peaks and runoff volumes or it may extend or shift the flooding season from spring to summer months (6). The Stanford Watershed Model parameter A has the same range of values as impervious areas.

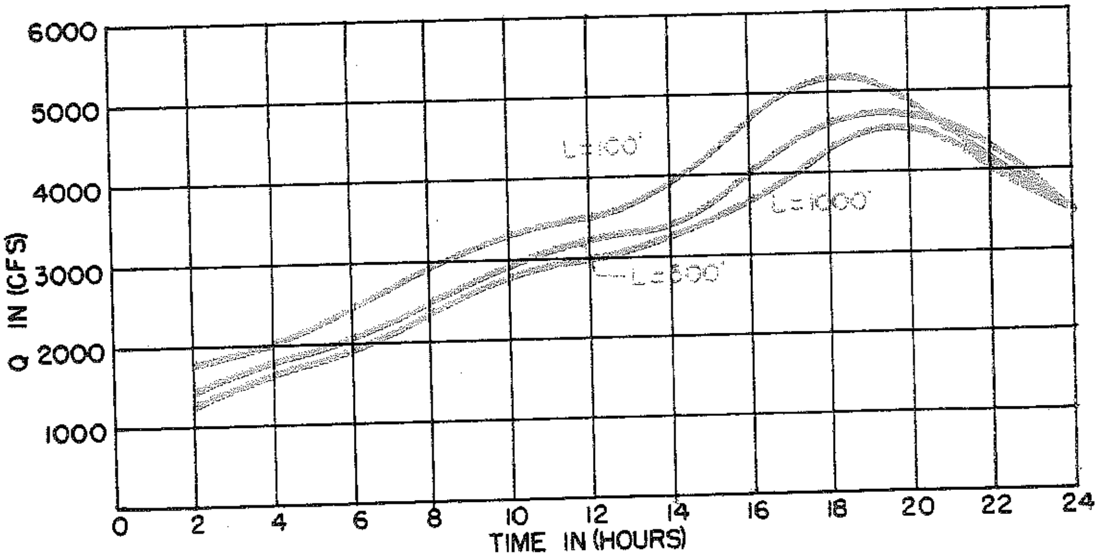


Fig. 31. Sensitivity of Model Response to the Length-of-Overland-Flow Parameter

5. Slope - The Stanford Watershed Model parameter SS has the same range of values as slope. The effect of SS on the flood hydrograph is inversely related to the effect of the length of overland flow, L, as noted by Equation 13. Hydrographs synthesized by increasing SS are illustrated in Fig. 31.

6. Slope and Soil Exposure Interaction - Exposure of the watershed surface and slope combine to control volume of moisture that may be stored on the surface. The range of soil-surface moisture storage suggested by Crawford and Linsley (4, p. 75) as well as values determined for various watersheds were used to evaluate the range of associated Stanford Watershed Model parameters CX and EDF.

    a. CX - A range for values of CX is presented in Table 12. Increasing values of CX reduce flows during the winter through increased surface-moisture storage capacity. Increasing CX had minor effect upon the flood hydrograph for the March storm.

    b. EDF - The range for EDF shown on Table 12 was established in a manner similar to that for CX. EDF represents the additional moisture-storage capacity available during warmer months. Runoff hydrographs generated by the Stanford Watershed Model using values of EDF are illustrated in Fig. 32.

7. Time-of-Concentration - Lower times-of-concentration designate more rapid passage of floods, less channel storage, and reduced values of KSC, KSF and Z.

a. Z - A 15-minute routing interval was selected for defining the range of Z values (Z is equal to the time-of-concentration divided by the routing interval). Representative flood hydrographs generated for values of Z are illustrated by Fig. 33.

b. KS - A value of KS of 0.90 was determined for Cave Creek and the range of variation was from 0.989 to 0.889. There was no clearly defined transition between the channel and flood plain for Cave Creek and no differentiation was made between the two available channel storage parameters. The undifferentiated value is designated as KS. Flood

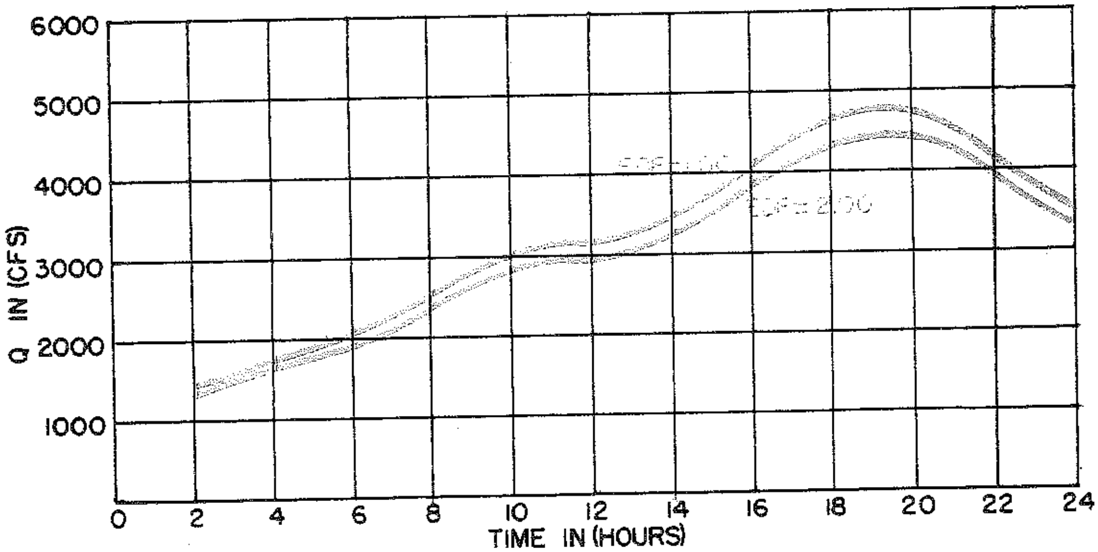


Fig. 32. Sensitivity of Model Response to the Soil-Surface Storage Parameter

hydrographs generated for values od KSC are illustrated in Fig. 34. KSF is the routing parameter for major floods and KSC applies to smaller floods. Since the March flood was not a major flood, there was no variation in the flood-hydrograph shape for increased values of KSF.

Selection of Input Parameters for Computer Runs

The flood peak produced by a given storm on a given watershed is ascertainable from the watershed characteristics. Each of the characteristics varies continuously over a given range, and each individual set of characteristics produces a flood peak which may be determined by translating the 6 watershed characteristics into input parameters and by assuming proportionality within the ranges noted on Tables 11 and 12. The loci of points established in this manner represents a response surface. The problem is to select input-parameter sets which will adequately define the response surface with a minimum of computational effort. Statistical methods are available for examination of response surface; however, the random grid method (16, p.253) was selected for this study. A series of hypothetical watersheds was developed by use of random numbers in order to select intermediate points within the range perscribed for each watershed characteristic. A set of six, two-digit, random numbers were selected for each hypothetical watershed from standard tables (one for each characteristic) and were used to interpolate between extreme values of corresponding watershed characteristic in order to select a random value for that characteristic. The

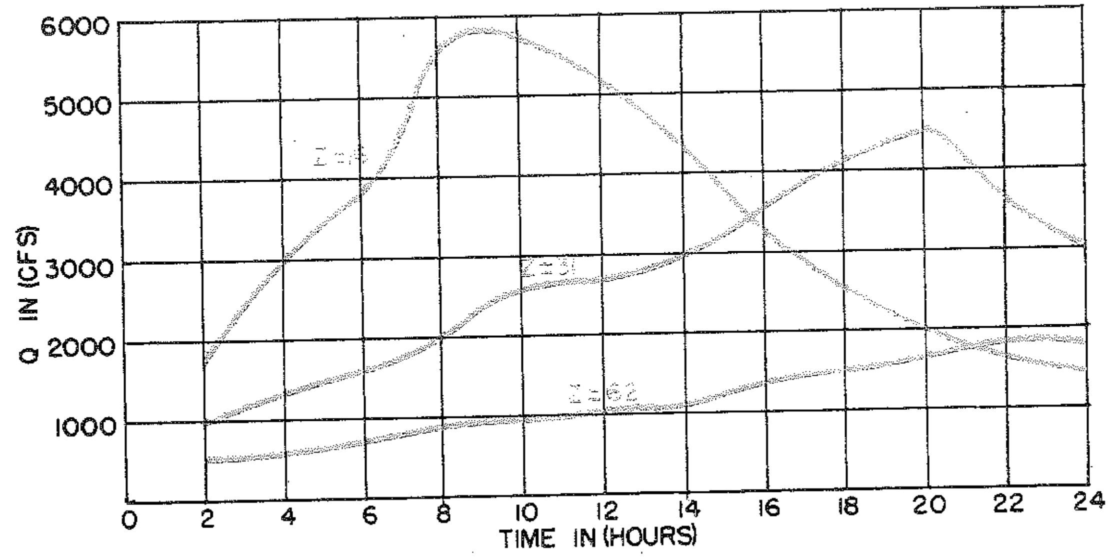


Fig. 33. Sensitivity of Model Response to the Time-Area Histogram Elements

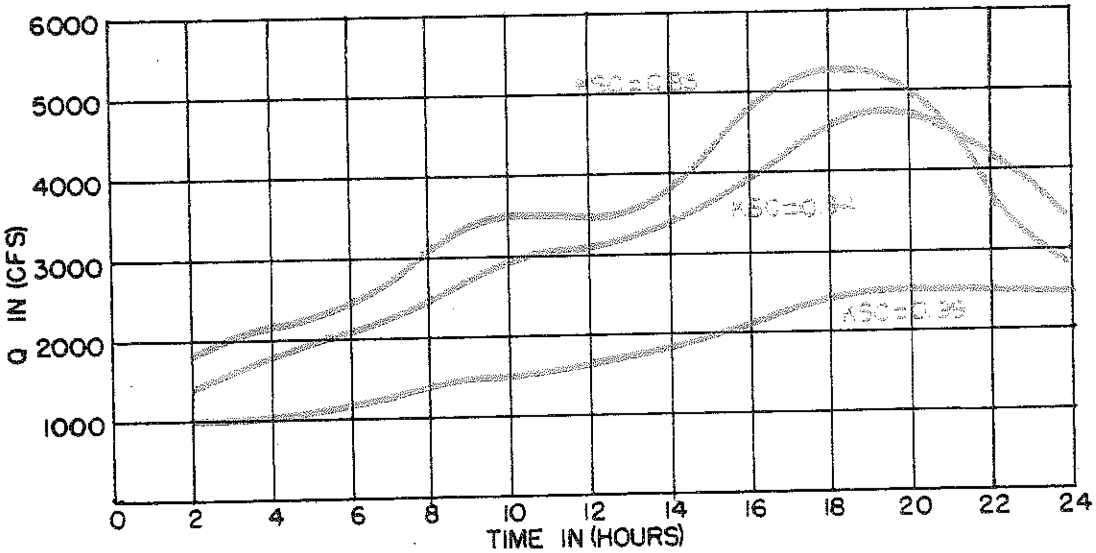


Fig. 34. Sensitivity of Model Response to the Channel-Routing Parameter

randomly selected characteristics were translated into comparable input parameters by assuming direct proportionality, as indicated in Table 11, between the watershed characteristics and the Stanford Watershed Model parameters. Several watershed interactions are complex and must be determined by a somewhat indirect manner. Soil exposure and slope interactions were interpolated between the maximum, Cave Creek, and the minimum parameter values. To accomplish this translation, the arithmetic product of slope and soil exposure was used as an index for interpolating random parameter values. Products greater than Cave Creek parameters were interpolated between the Cave Creek and the maximum values. Parameters were interpolated between Cave Creek and minimum values for products less than Cave Creek. Values used for this interpolation are presented in Table 12. A complete presentation of twenty, random watersheds analyzed in this study is presented in Table 13.

Flood Peaks From Hypothetical Watersheds

The model was then used to reproduce a continuous runoff hydrograph from 50 years of input climatological data. It was assumed that the input parameters as established for Cave Creek would remain constant. The generated hydrograph estimates flows which would have been recorded had the stream gage been installed earlier. The 50 years of synthesized flow provide a more refined basis than the 13 years of recorded flows for estimating desired design flood peaks because many of the larger floods were recorded in the earlier years.

TABLE 13

WATERSHEDS DEFINED BY RANDOM SELECTION

Watershed Variable	Variable Range	Stanford Watershed Model Parameter	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Depth of Hydrologic Activity	60-10 in.		22.5	13.0	39.5	57.0	17.5	50.0	55.0	42.5	30.0	34.0	33.5	44.0	20.5	31.5	48.0	32.0	50.5	24.5	23.5	52.0
	12- 2 in.	LZSN	4.5	2.6	7.9	11.4	3.5	10.0	11.0	8.5	6.0	6.8	6.7	8.8	4.1	6.3	9.6	6.4	10.1	4.9	4.7	10.4
	1.0-4.5 in.	CY	3.63	4.29	2.44	1.21	3.98	1.70	1.35	2.22	3.10	2.82	2.86	2.12	3.76	3.00	1.84	2.96	1.66	3.48	3.56	1.56
RANDOM NUMBER			0.25	0.06	0.59	0.94	0.15	0.80	0.90	0.65	0.40	0.48	0.47	0.68	0.21	0.43	0.76	0.44	0.81	0.29	0.27	0.84
Soil Permeability	6.5-1.5 in/hr		3.85	5.15	3.65	3.25	5.85	4.10	2.55	3.20	6.00	4.95	3.25	4.75	2.50	4.45	1.80	3.55	4.15	6.05	2.50	1.60
	1.3-0.3	CB	0.77	1.03	0.73	0.65	1.17	0.82	0.51	0.64	1.20	0.99	0.65	0.95	0.50	0.89	0.36	0.71	0.83	1.21	0.50	0.32
	0.62-0.82	IRC	.726	.674	.734	.750	.646	.716	.778	.752	.640	.682	.750	.690	.780	.702	.808	.738	.714	.638	.780	.816
RANDOM NUMBER			0.47	0.73	0.43	0.35	0.87	0.52	0.21	0.34	0.90	0.69	0.35	0.65	0.20	0.59	0.06	0.41	0.53	0.91	0.20	0.02
Soil Exposure	100.-0.		85.0	18.0	66.0	49.0	87.0	48.0	14.0	82.0	90.0	77.0	71.0	36.0	12.0	74.0	25.0	7.0	6.0	38.0	46.0	15.0
	0.2-0.3	K3	.215	.272	.234	.251	.213	.252	.286	.218	.210	.223	.229	.264	.288	.226	.274	.293	.294	.262	.254	.285
	0.1-0.4	NN[1]	0.10	.292	.10	.103	.10	.112	.316	.10	.10	.10	.10	.184	.328	.10	.244	.358	.364	.172	.124	.310
RANDOM NUMBER			0.85	0.18	0.66	0.49	0.87	0.48	0.14	0.82	0.90	0.77	0.71	0.36	0.12	0.74	0.25	0.07	0.06	0.38	0.46	0.15
Impervious Cover	45.-0.		19.8	41.8	03.6	33.8	35.6	29.3	28.4	05.4	30.6	21.6	21.2	41.0	34.2	23.4	05.4	29.2	43.7	37.8	19.3	12.6
	.45-0.0	A	.198	.418	.036	.338	.356	.293	.284	.054	.306	.216	.212	.410	.342	.234	.054	.292	.437	.378	.193	.216
RANDOM NUMBER			0.44	0.93	0.08	0.75	0.79	0.65	0.63	0.12	0.68	0.48	0.47	0.91	0.76	0.52	0.12	0.65	0.97	0.84	0.43	0.48
Overland Slope	.41-.0.		0.118	0.334	0.102	0.358	0.186	0.154	0.342	0.250	0.402	0.038	0.378	0.150	0.062	0.314	0.230	0.130	0.038	0.082	0.122	0.206
	.41-.01		0.118	0.334	0.102	0.358	0.186	0.154	0.342	0.250	0.402	0.038	0.378	0.150	0.062	0.314	0.230	0.130	0.038	0.082	0.122	0.206
RANDOM NUMBER			0.27	0.81	0.23	0.87	0.44	0.36	0.83	0.60	0.98	0.07	0.92	0.35	0.13	0.76	0.55	0.30	0.07	0.18	0.28	0.49
Time-of-Concentration	300-30 min.		143	278	162	106	124	184	233	203	38	60	162	187	49	249	241	149	81	44	170	151
	20-2	Z	10	19	11	7	8	12	16	13	3	4	11	12	3	18	16	10	5	3	11	10
	.989-.889	KS	0.931	0.981	0.938	0.917	0.924	0.946	0.964	0.953	0.890	0.900	0.938	0.947	0.896	0.976	0.967	0.933	0.908	0.894	0.941	0.934
RANDOM NUMBER			0.42	0.92	0.49	0.28	0.35	0.57	0.75	0.64	0.03	0.11	0.49	0.58	0.07	0.87	0.78	0.44	0.19	0.05	0.52	0.45
Slope and Soil		CX[2]	0.699	0.779	0.765	0.549	0.574	0.752	0.804	0.490	0.174	1.068	0.363	0.792	1.503	0.435	0.785	1.469	1.605	1.030	0.788	1.036
Exposure Interaction		EDF[2]	1.049	1.129	1.115	0.899	0.924	1.102	1.154	0.840	0.524	1.418	0.613	1.142	1.853	0.785	1.135	1.819	1.955	1.380	1.138	1.386

[1] For Soil Exposure greater than 50.0, an average NN of 0.10 was assumed.

[2] Selected by indirect interpolation as outlined in Table 12.

The fifty, synthesized, annual, flood peaks are listed in Table 14. A shorter term of record was selected for analysis of the twenty, hypothetical watersheds having randomly varied characteristics in order to decrease computer time and expense. The fifty, yearly flood peaks (Table 14) were divided into ten continuous, 10-year periods of record. The mean and standard deviations of the ten annual floods were determined for each staggered 10-year period. Criteria for selecting a representative 10-year period of record were:

A. Contains both winter and summer peaks.

B. Has values for mean and standard deviations of annual floods approximately equal to those for the 50-year period.

Correction factors were developed for converting mean and standard deviations for the 10-year record to values appropriate for the entire 50 years once the representative 10-year period (1921--1930) had been selected for repetitive analysis. The method of correction was: multiply the standard deviation of annual flood peaks for the 10-year analysis of the hypothetical watershed by the ratio of the Cave Creek values for the entire 50 years to the Cave Creek value for the selected 10 years. Mean values were corrected by adding differences between the 10- and 50-year Cave Creek means to the 10-year synthesized mean for the hypothetical watershed.

The selected parameters are combined with the selected 10-year period of rainfall record within the Stanford Watershed Model to generate 10 years of runoff record. The mean and standard deviation of the 10 annual flood peaks were computed and corrected to a 50-year

TABLE 14

HISTORICAL FLOOD HYDROGRAPH

Water Year	Flood (cfs)	Water Year	Flood (cfs)	Water Year	Flood (cfs)
1916-1917	44.4	1933-1934	35.5	1950-1951	129.0
1917-1918	18.8	1934-1935	536.5	1951-1952	259.8
1918-1919	55.2	1935-1936	75.6	1952-1953	159.3
1919-1920	194.0	1936-1937	91.6	1953-1954	58.1
1920-1921	35.7	1937-1938	38.8	1954-1955	381.5
1921-1922	384.3	1938-1939	115.9	1955-1956	130.4
1922-1923	106.6	1939-1940	204.3	1956-1957	133.8
1923-1924	110.4	1940-1941	80.0	1957-1958	261.0
1924-1925	45.8	1941-1942	284.4	1958-1959	60.0
1925-1926	65.7	1942-1943	269.6	1959-1960	243.1
1926-1927	62.6	1943-1944	97.8	1960-1961	79.6
1927-1928	537.2	1944-1945	88.1	1961-1962	177.2
1928-1929	38.5	1945-1946	160.3	1962-1963	98.5
1929-1930	85.3	1946-1947	146.3	1963-1964	140.0
1930-1931	166.5	1947-1948	579.1	1964-1965	99.4
1931-1932	1055.2	1948-1949	114.4	1965-1966	98.0
1932-1933	130.4	1949-1950	106.2		

basis from results of each run based on randomly selected watershed characteristics. A computer program based on Gumbel's method of frequency analysis (15, pp. 250-257) was written for computation of 50-year return-period flood peaks utilizing corrected means and standard deviations. The 2.33- and 50-year floods were selected for evaluation. The points were plotted on extreme-probability paper from which flood magnitudes for various frequencies could be read.

CHAPTER V

CORRELATING FLOOD PEAKS TO WATERSHED CHARACTERISTICS

This chapter presents a procedure whereby designers may select an appropriate runoff coefficient for a measured set of watershed characteristics. The presentation is in two steps: 1) curves relating flood peaks to watershed characteristics are developed and presented, and 2) the procedure for use of the curves to estimate a flood peak of specified frequency for a particular watershed is described.

The Correlation Procedure

The Stanford Watershed Model was applied using Lexington, Kentucky rainfall on a drainage area equal to the 2.53-square-mile Cave Creek watershed and twenty sets of randomly selected watershed characteristics. Each characteristic was selected within the prescribed range by use of a table of two-digit random numbers and the procedure designated on Tables 11 and 12, as previously outlined in Chapter IV. The resultant sets of characteristics are noted in Table 15. Synthesized streamflows were entered into a Gumbel frequency analysis in order to determine the 50-year flood for each hypothetical watershed as shown on Table 15. The hypothetical watersheds each contained an area of 2.53 square miles and each 50-year storm represented a value of Q/A = CI according to the Rational Formula Equation 1. Each flood peak in

TABLE 15

WATERSHED CHARACTERISTICS FOR THE TWENTY RANDOM WATERSHEDS

Random Watershed	Time-of-Concentration (minutes)	Slope (feet/feet)	Depth of Hydrologic Activity (inches)	Soil Permeability (inches/hour)	Soil Exposure (percent)	Impervious Cover (percent)	50-year Flood (cfs/acre)	50-year Flood (curves) (cfs/acre)
1	143.0	0.118	22.5	3.85	85.0	19.8	0.393	0.487
2	278.0	0.335	13.0	5.15	18.0	41.8	0.217	0.240
3	162.0	0.102	39.5	3.65	66.0	3.6	0.353	0.284
4	106.0	0.358	57.0	3.25	49.0	33.8	0.722	0.679
5	124.0	0.186	17.5	5.85	87.0	35.6	0.477	0.636
6	184.0	0.154	50.0	4.10	48.0	29.3	0.450	0.444
7	233.0	0.342	55.0	2.55	14.0	28.4	0.361	0.401
8	203.0	0.250	42.5	3.20	82.0	5.4	0.367	0.364
9	38.0	0.402	30.0	6.00	90.0	30.6	0.972	0.882
10	60.0	0.038	34.0	4.95	77.0	21.6	0.483	0.432
11	162.0	0.378	33.5	3.25	71.0	21.2	0.474	0.518
12	187.0	0.150	44.0	4.75	36.0	41.0	0.451	0.333
13	49.0	0.062	20.5	2.50	12.0	34.2	0.602	0.599
14	265.0	0.314	31.5	4.45	74.0	23.4	0.224	0.494
15	241.0	0.230	48.0	1.80	26.0	4.5	0.235	0.172
16	149.0	0.130	32.0	3.55	7.0	29.2	0.314	0.333
17	81.0	0.038	51.0	4.15	6.0	43.7	0.472	0.327
18	44.0	0.082	24.5	6.05	38.0	37.8	0.210	0.216
19	170.0	0.122	23.5	2.50	46.0	19.3	0.321	0.426
20	151.0	0.206	52.0	1.60	15.0	21.6	0.399	0.364

cfs per acre, is the dependent variable to be determined, and the values in each set of watershed characteristics are the independent variables with which the flood peak was correlated.

Multiple regression was initially attempted in the correlation effort. Several trial calculations were made using the MULTR program obtained from the statistical library of the University of Kentucky Computing Center. The program incorporates a variance ratio test which was applied to each characteristic to measure its relative significance in determining runoff per acre. The regression proceeded in steps and started with the most significant characteristics, successively adding the next most significant characteristic -- thereby producing a number of intermediate regression equations. All variables having a prescribed level of significance were included in the final regression. A more detailed discussion of the procedure used in the program may be found in Ralston and Wilf (19).

Several transformations of variables are available as program options for improving the correlation equations. Input data may be transformed by use of such functions as inverse, logarithmic, square root, etc. Several of these options were employed. None of the regression equations provided desirable results due to difficulty in incorporating the curvilinear nature of the correlation into a simple mathematical transformation. Nevertheless, multiple regression significance testing yielded an order of significance of watershed characteristics for use as a starting point for subsequent graphical correlation. A listing of watershed characteristics by order of significance follows:

1. Time-of-concentration
2. Slope
3. Depth of Hydrologic Activity
4. Soil Permeability
5. Soil Exposure
6. Impervious Cover

Graphical curve fitting was next attempted. Graphical curve fitting has been used by the U. S. Weather Bureau for correlating such meteorologic data as temperature, wind speed, and elevation with monthly pan coefficients (cf. 15, p. 120). An excellent discussion of coaxial correlation is presented by Linsley, Kohler, and Paulhus (15, pp. 311-321). A satisfactory set of curves was developed for estimating the 50-year rainfall excess for a 2.53-square-mile watershed subject to Lexington rainfall from quantitative measure of six watershed characteristics through application of the coaxial correlation process of curve fitting by trial and adjustment. Table 15 summarizes the twenty synthetically generated flood peaks and the twenty flood peaks which would be read from the coaxial correlation. The correlation is quite satisfactory.

Corrections to Coaxial Correlation

The coaxial correlation of Fig. 35 provides 50-year flood peaks for a drainage area of 2.53 square miles subject to Lexington, Kentucky rainfall patterns. It is possible to extend those results to predict floods of different frequencies, to drainage areas of different sizes,

and to locations having differing rainfall intensity-duration characteristics.

1. Predicting Peaks for Different Frequencies - The flood peak (cfs per acre) as estimated by the coaxial correlation equals the 50-year rainfall excess, CI, in the Rational Formula, Equation 1. The values of both C and I must be adjusted for rainfall excess for some other return period. Intensity may be adjusted according to the ratio of the value read from an intensity-duration curve for the required frequency to the value for the 50-year event. Runoff coefficients for the 50- and 25-year floods were determined in order to evaluate the effect of frequency on the coefficient. A Gumbel frequency analysis of flood peaks synthesized for the twenty hypothetical watersheds was used to predict 50- and 25-year events. The volumes were then converted to rainfall excess, CI, by dividing by the Cave Creek watershed area. Intensities corresponding to the basin time-of-concentration for the desired frequencies were read from intensity-duration plots for Lexington, Kentucky (Fig. 3). For times-of-concentration greater than 120 minutes, intensities were read from curves presented in the Manual of Instructions for Drainage Design (9). Runoff coefficients were obtained by dividing the values of CI, rainfall excess, by the respective rainfall intensity. Ratios of the 25- and the 50-year runoff coefficients were then computed. The 25- and 50-year runoff coefficients were related by an average ratio which was found

to be 0.970, as noted in Table 16. Scatter among individual values may be the result of difficulty in reading intensity-duration curves precisely.

A curve of the runoff coefficient correction by frequency as a fraction of the 50-year coefficient was plotted and is presented on Fig. 36. A 100-year runoff coefficient correction factor is 3.0 percent greater than that for a 50-year frequency as distinguished from the curve.

2. Application to Various Size Drainage Areas - Two factors required for converting rainfall excess estimated for the 2.53-square-mile watershed to flood peaks for other drainage areas are: 1) time-of-concentration, which was initially brought into the correlation as an index of basin shape and 2) difference in rainfall intensity for the two basins. A larger basin of the same shape will have a longer time-of-concentration because of its greater length. The first problem to be overcome in determining the flood peak for a different drainage area is that of selecting the index time-of-concentration for a 2.53-square-mile watershed of the same shape. This may be done by noting that L is the only term in Equation 12 affected by drainage area. For basins of the same shape, area is proportional to L^2. Therefore, the relationship

$$L = L_W \left[\frac{\sqrt{2.53}}{\sqrt{A_W}} \right] = 1.59 \left[\frac{L_W}{\sqrt{A_W}} \right] \qquad 14$$

TABLE 16

DATA FOR DEVELOPING THE RUNOFF COEFFICIENT CORRECTION CURVE

(1) Random Watershed	(2) Time-of-Concentration (minutes)	(3) 50-year Rainfall Intensity (inches/hour)	(4) 50-year Flood (cfs/acre)	(5) C_{50} = CI/I	(6) 25-year Rainfall Intensity (inches/hour)	(7) 25-year Flood (cfs/acre)	(8) C_{25} = CI/I	(9) C_{25}/C_{50}
1	143	1.64	.393	.240	1.55	.324	.209	.8708
2	278	1.07	.217	.203	0.95	.185	.195	.8986
3	162	1.64	.353	.215	1.42	.293	.206	.9581
4	106	1.90	.722	.380	1.67	.617	.369	.9710
5	124	1.73	.477	.276	1.55	.407	.263	.9529
6	184	1.50	.450	.300	1.29	.385	.299	.9967
7	233	1.25	.361	.289	1.08	.315	.292	1.0104
8	203	1.39	.367	.264	1.25	.309	.247	.9356
9	38	3.75	.972	.259	3.37	.852	.253	.9768
10	60	2.83	.483	.171	2.52	.414	.164	.9591
11	162	1.64	.474	.289	1.42	.387	.273	.9446
12	187	1.48	.451	.305	1.29	.401	.311	1.0196
13	49	3.22	.602	.187	2.90	.525	.181	.9679
14	249	1.14	.224	.196	0.99	.191	.193	.9847
15	241	1.21	.235	.194	1.06	.209	.197	1.0154
16	149	1.60	.314	.196	1.50	.302	.201	1.0265
17	81	2.30	.472	.205	2.05	.414	.202	.9854
18	44	3.44	.210	.061	3.10	.185	.059	.9672
19	170	1.60	.321	.200	1.39	.278	.201	1.0050
20	151	1.73	.399	.231	1.50	.352	.235	1.0173

$$\frac{C_{25}/C_{50}}{20.0000} = \frac{19.4636}{20.0000} = 0.8732$$

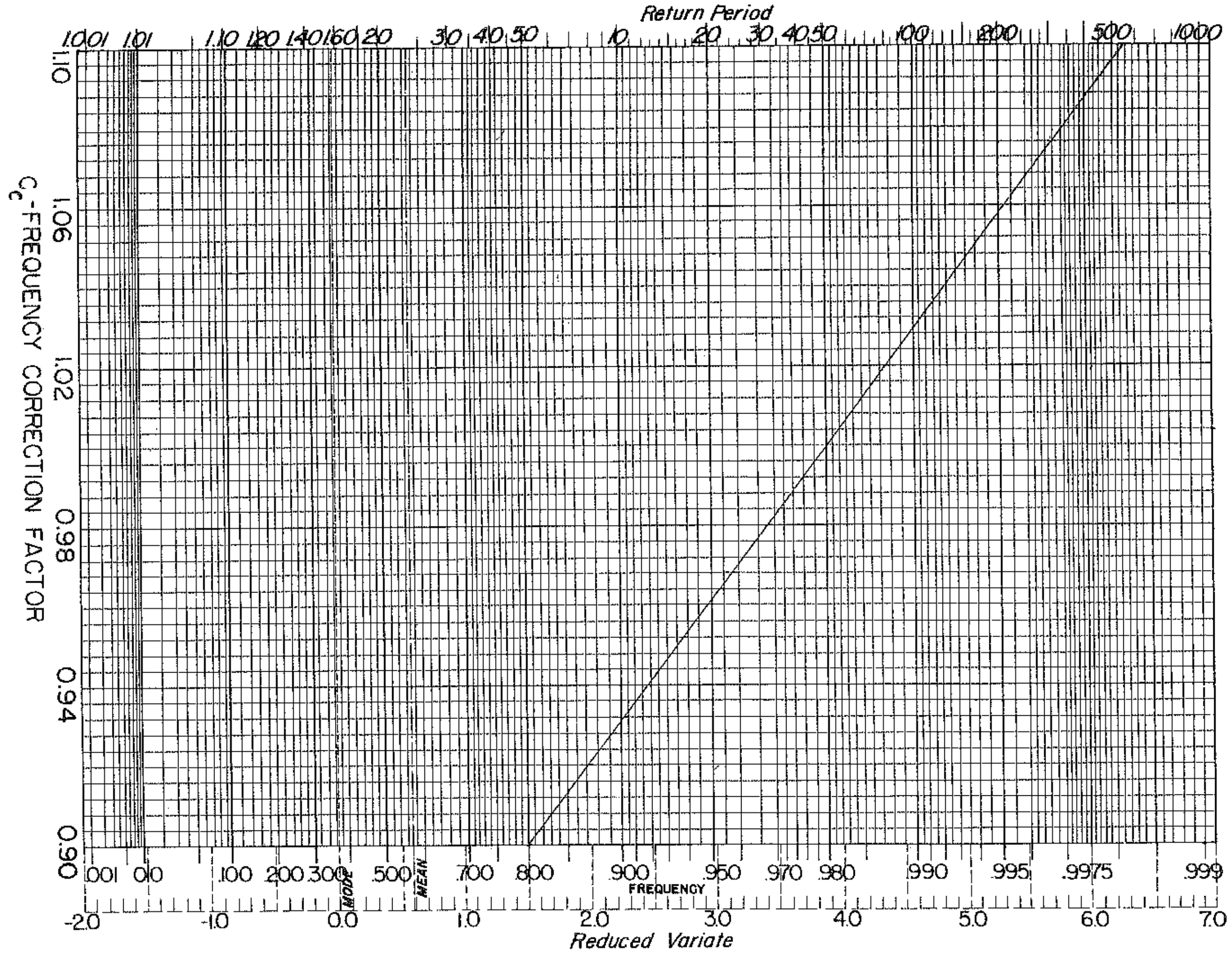


Fig. 36. Frequency Correction Factor for Runoff Coefficients

may be used to estimate L_w* from L_w for the watershed of area A_w square miles. This adjusted L and a channel slope based on L_w may then be used to estimate the index time of concentration for application in the coaxial correlation. After using the coaxial correlation to produce a value of rainfall excess, another correction is made to account for the difference in rainfall intensity between the two basin sizes. The ratio used is that of the rainfall intensity for the index time-of-concentration based on the value of L_w adjusted to the rainfall intensity for the true time-of-concentration for the basin of area A_w. Finally, the flood peak is computed by multiplying the corrected value of rainfall excess, CI, by the watershed area in acres. Caution is recommended against application of this procedure to areas in excess of 10 square miles.

3. <u>Application to Areas having Different Rainfall-Intensity Characteristics</u> - Since the coaxial correlation was based on Lexington rainfall values, the CI-value read from the curves would be applicable only to areas within the Lexington Thiessen polygon. The rainfall excess read from the curves may be transformed from the Lexington area to some other rainfall polygon by applying the ratio of rainfall intensity within the other polygon area to rainfall intensity at Lexington. These rainfall intensity values are read from the intensity-duration curves presented in Figs. 3 through 11. It is possible

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*Subscript "w" refers to watersheds other than Cave Creek.

to compensate for variation in rainfall patterns throughout the State of Kentucky by incorporating the rainfall-intensity factor in the design formula.

Procedure for Estimating Flood Peaks

The procedure developed herein for use in estimating the flood peak for a specified frequency and watershed of known area and characteristics is composed of two basic steps: 1) the watershed characteristics are evaluated and entered into the coaxial correlation, Fig. 35, to estimate the 50-year flood peak from a 2.53-square-mile area subject to the Lexington, Kentucky, rainfall intensity-duration relationship and 2) an equation is used to correct for differences in desired frequency, known area, and applicable rainfall intensity-duration relationships.

1. Use of the Coaxial Correlation - The coaxial curves are entered successively with the index time-of-concentration, slope, depth of hydrologic activity, soil permeability, soil exposure, and impervious cover.
2. Time-of-concentration - The index time-of-concentration to use in entering the curves may be computed as

$$T_c = 0.0078 \left[\frac{1.59 L_w}{\sqrt{A_w \; S_w}} \right]^{0.77} \qquad 15$$

This equation is based on the actual channel slope of the watershed and an adjusted stream length and is derived by combining Equations 12 and 14.

3. Slope of Overland Flow - The desired slope for use herein is the slope of those surfaces over which overland flow occurs in route to the stream. The value thereof is best estimated by measuring slopes perpendicular to stream channels for a number of representative watershed locations and computing a weighted average.
4. Depth of Hydrologic Activity - This value may be estimated as the depth to bedrock, soil layer of restricted permeability, or water table (whichever is nearer the ground surface). It may be approximated from soil surveys or from available boring data. A weighted value (according to the fraction of the watershed area having each value) would be used in the event the values vary widely within the given watershed.
5. Soil Permeability - An average value of soil permeability within the zone of hydrologic activity is used and may be estimated by averaging values obtained from soil surveys by depth (use weighted average by acres in each soil type). In the event soil surveys do not indicate values for permeability, an estimate may be made from values listed for the same soil classification for nearby soil surveys.
6. Soil Exposure - The fraction of pervious watershed surface in forest, grass, small vegetation, cropland, or bare surface may be estimated from aerial photographs, field inspection, or more approximately from topographic maps. The soil exposure index is then evaluated by using the surface factors of 0, 50, and 100 as tabulated on page 65.

7. Impervious Cover - For rural areas this value may be estimated from aerial photographs or topographic maps as the fraction of the watershed surface in paved areas, roof tops, and/or exposed rock. For urban areas, impervious cover may be estimated by using Fig. 21.

Application of Procedure to Other Situations

Application of the basic guidelines presented herein for use in estimating design discharges for areas within other regions of the State and for varying design frequencies may be accomplished through use of the equation

$$Q = CI\ C_c \left[\frac{I_w}{I_b}\right] A_w \qquad 16$$

where Q = design discharge in cfs,

CI = rainfall excess (obtained from Fig. 35),

C_c = frequency correction factor (obtained from Fig. 36),

I_w = rainfall intersity (inches/hour) for the watershed under study (obtained from Figs. 3 through 11 using T_c from Equation 12 for the actual watershed, using intensity-duration curve for area of influence in which the watershed is located, and using the return period for which design discharge is desired),

I_b = base rainfall intensity (inches/hour) for the actual watershed as adjusted and placed in the Lexington area of influence (obtained from Fig. 3 using T_c computed from Equation 15 for the actual watershed and the 50-year frequency curve), and

A_w = watershed area in acres.

Utilization of this procedure may best be illustrated by the following example: Compute the design discharge for a 100-year return period flood for an area within the Bear Branch basin near Noble in Breathitt County. The following values for the watershed were obtained from a review of topographic maps, aerial photographs, and soil reports for the area:

Area = 2.21 square miles (1415 acres)
L_w = 13,300 feet
H_w = 700 feet
Overland Slope = 0.35
Depth of Hydrologic Activity = 10.0 inches
Soil Permeability = 1.50 inches/hour
Soil Exposure = 13%
Impervious Cover = 3%

The solution is presented in the following steps:

1. Rainfall Excess - The index time-of-concentration for the area is computed from Equation 15 and is found to be 38 minutes. Using 38 minutes for T_c and previously listed values for the other watershed characteristics, the rainfall excess is obtained from Fig. 35 as indicated by the solid line. A value of 0.320 inches/hour was obtained and represents CI in Equation 16.
2. Runoff Frequency Factor - A frequency correction factor of 1.030 is obtained from Fig. 36. This value is for a 100-year return

period flood and represents C_c in Equation 16.

3. Rainfall Intensity Factor - The time-of-concentration for the watershed is 36 minutes as computed by Equation 12. An I_w of 4.30 inches/hour is obtained by entering Fig. 3 (since Breathitt County is in the Lexington area of influence) with T_c of 36 minutes and going up to the 100-year return curve. The value for I_b is obtained from Fig. 3 (Lexington) by entering with a 39-minute index T_c and going up to the 50-year return period curve. A value of 3.70 inches/hour was read.

4. Computation of Flood Peak - The design flood is then computed by Equation 16 as

$$
\begin{aligned}
Q &= 0.320 \times 1.030 \times \left[\frac{4.30}{3.70}\right] \times 1415 \\
&= 542 \text{ cfs.}
\end{aligned}
$$

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

A procedure has been established for relating flood peaks to measurable watershed characteristics; it is based on data from the Cave Creek watershed as analyzed by the Stanford Watershed Model. Also, a method has been formulated for estimating runoff coefficients for various basins when their watershed characteristics are known. Runoff coefficients are quite sensitive to variations in watershed characteristics and climatic conditions, and the development of a generalized relationship requires analysis of a multiplicity of interactions -- a requirement that has been satisfied through the use of the digital computer and the Stanford Watershed Model. At present, certain limitations are inherent in the study and result from the need to test the results against streamflow data from additional small watersheds.

Curves presented in this report were developed for an area having a mean annual rainfall of approximately 40 inches, which is rather evenly distributed throughout the year. The probability of a basin being in a desiccated condition at the time of occurrence of a rainfall intensity of given frequency is greater for areas having low, mean annual precipitation; and the procedure suggested herein may result in an overestimation of flood peaks. Flood peaks lower than actual might result in application of the method to areas more humid than the Lexington area of influence. The method is based upon data for a basin which is drained by natural channels having a capacity approximately equal to the mean annual flood. Water would overtop the channel and spread over the flood plains in the event of occurrence of larger storms, and flood-plain storage would mitigate the flood peak at the basin outlet. Improved channelization may contain the flood, reduce storage attenuation and result in greater flood peaks -- thus, the method may not be applicable to basins having improved channelization.

Furthermore, it is recommended that additional studies be initiated in order to better define the time-of-concentration. One approach might be the establishment of an experimental watershed with a system of instrumentation such that continuous measurement may be obtained for determining the time-of-concentration. An accurate measure of time-of-concentration is essential due to the fact that it is the basis on which design and intensity-duration curves were developed.

Further studies of the effects of basin size and time-of-concentration upon flood peaks would be beneficial and are suggested for verification of the relationships presented herein. The rates and quantities of runoff from small basins are largely dependent upon physical conditions of soil and cover within the areas, whereas channelization has the more pronounced effect for larger basins (3, p. 35). The relationship derived herein to illustrate the effect of time-of-concentration was not verified thoroughly -- due to the lack of rainfall data for durations less than one hour.

Urbanization may appreciably affect the watershed characteristics used in the basic correlation. Data relative to quantitative changes occasioned by urban development are limited at present. A more appropriate procedure for measuring the watershed characteristics within an urban environment may be forthcoming as more data becomes available. The procedure established herein does not consider snow-melt as an important factor, and certain modifications would be necessary for application to areas wherein snow-melt might produce design flood peaks.

It is also recommended that a frequency analysis be made of peak rainfall intensities noted at other recording gages in Kentucky. These additional stations have shorter periods of record than do the Weather Bureau stations analyzed in Chapter II but provide a basis for developing intensity-duration information for the many parts of the State located at a distance from a Weather Bureau station. This data would allow for further subdivision of the state and may yield greater accuracy for the overall approach developed herein (on a statewide basis). Development of such curves may also provide a means whereby the State may be subdivided more appropriately than by the Theissen network. Since much of the data is not published, recorder charts may have to be obtained and analyzed.

A modified procedure for estimating runoff from small watersheds has been presented in this report; it differs somewhat from that currently used by the Kentucky Department of Highways. In the recommended procedure, the runoff coefficients may be determined from the watershed characteristics rather than geographical location. The suggested procedure is straightforward and may readily be adapted to the procedure in current use by the Department. It is recommended that the revised intensity-duration curves and Theissen network be incorporated into the Department's drainage manual.

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