Rainfall-Runoff-Hydrograph Relations

for Northern Louisiana

A technique for converting storm rainfall to a direct-runoff hydrograph
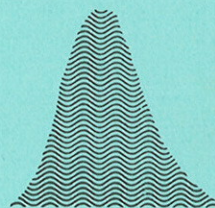
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SYMBOLS AND DEFINITIONS

A, drainage area, in square miles. The total surface area contributing to the surface drainage of a basin.

d, unit duration, in hours. The time during which rainfall excess occurs to produce a unit hydrograph. Sometimes referred to as unit time.

L, basin length, in miles. The distance from a designated point on a stream to the surface-drainage divide. Basin length is measured along the main stem and follows the general trend of the flood plain rather than the meandering low-water channel.

L_{ca}, basin mean length, in miles. The average distance which flood water must travel within a basin to reach the outlet. The distance is measured along the general path of the flood plain of all streams in a basin and is not representative of low-water channel distances.

$\emptyset$, infiltration index, in inches per hour. The rate at which the combined effects of infiltration, evapotranspiration, and surface detentions are abstracted from total rainfall. The balance of total rainfall is surface runoff.

Q, discharge, in cubic feet per second (cfs). The rate of flow at a particular instant of time.

Q_p, peak discharge, in cubic feet per second (cfs). The maximum, instantaneous rate of flow during a flood period.

ΣQ, summation of discharge ordinates of a hydrograph, in cubic feet per second.

ΣQ_u, summation of discharge ordinates of a unit hydrograph, in cubic feet per second.

R_e, rainfall excess, in inches. The volume of rainfall available for direct runoff; the residual of rainfall after all losses such as interception, infiltration, evapotranspiration, and surface storage have been satisfied.

S, main channel slope, in feet per mile. The slope of the main channel measured between points 10 percent and 85 percent upstream from the gage.

s_e, standard error of estimate, generally in percent. The error which will not be exceeded two thirds of the time.

T, time, in hours. The number of hours measured from the beginning of direct runoff.

T_L', lag time, in hours. The time measured from the center of mass of rainfall excess to the center of mass of the resulting runoff hydrograph.

T_L, adjusted lag time, in hours, equals $T_L' + d/2$. The time measured from beginning of rainfall excess to the center of mass of runoff for the unit hydrograph.

T_p, time-to-peak, in hours. The time measured from the center of mass of rainfall excess to the resulting time of maximum instantaneous discharge (peak discharge).

Δt, computation interval, in hours. The interval of time selected for successive computations of a particular problem.

STATE OF LOUISIANA

DEPARTMENT OF PUBLIC WORKS

In cooperation with the

UNITED STATES GEOLOGICAL SURVEY

TECHNICAL REPORT NO. 3

RAINFALL-RUNOFF-HYDROGRAPH RELATIONS FOR NORTHERN LOUISIANA

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RAINFALL-RUNOFF-HYDROGRAPH RELATIONS FOR NORTHERN LOUISIANA

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ABSTRACT

Streamflow records from 22 gaging stations and more than 90 rain gages were used to study the relation between rainfall, rainfall excess, and runoff hydrographs in northern Louisiana. Rainfall excess can be estimated from rainfall by the use of an infiltration index, $\emptyset$, which varies seasonally from 0.24 inch per hour in the winter to 0.7 inch per hour in the summer. The results are not precise; however, studies of more complicated techniques using various measures of antecedent conditions and storm duration did not offer significant improvements.

Unit hydrographs were developed from the streamflow records and regionalized for use at any site in the study area. The regionalized dimensionless unit hydrograph can be converted to a specific unit hydrograph for a site from known values of drainage basin size and length and an estimated value of lag time. Basin lag time, a critical factor, is related to basin characteristics and, inversely, to total volume of rainfall excess for a given storm. The recommended procedure for estimating lag time is based on the general equation

$$T_L' = aL^b ,$$

where T_L' is lag time, L is basin length, and a and b are coefficients which vary with rainfall excess. Coefficients are given for rainfall excess ranging from 1 to 5 inches.

The peak discharge from a known amount of rainfall excess occurring within two or three unit durations can be approximated from the equation

$$Q_p = \frac{645.3 \, AR_e}{T_L} ,$$

where Q_p is the peak discharge rate, A is the drainage basin size, R_e is the rainfall excess, and T_L is the adjusted lag time.

The accuracy of the lag time and unit-hydrograph relations is fairly good if the true amount of rainfall excess is known. A random test indicated a standard error of estimate of 22 percent.

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INTRODUCTION

The optimum design of waterway structures, such as dams, bridges, and levees, requires an accurate knowledge of streamflow so that the initial cost plus maintenance costs will be a minimum, and the structures will serve their purpose safely and effectively. The efficient operation of a reservoir requires an accurate prediction of inflow during floods. Accurate flood forecasting is becoming increasingly important as more people occupy the flood plains of our rivers and streams. These and other related problems can be solved in various ways depending on the particular situation; however, in many instances the flood hydrograph resulting from an actual or hypothetical storm is required. It is the purpose of this report to provide a method whereby flood hydrographs for streams in northern Louisiana can be synthesized from rainfall data and basin characteristics.

This report presents a method for estimating rainfall excess from direct rainfall by the use of an infiltration index. The rainfall excess can then be converted to a direct-runoff hydrograph through the use of a unit hydrograph. Methods are presented for defining the unit hydrograph for all streams in the study area. Examples and step-by-step procedures of the computations are given.

This report was prepared in the Baton Rouge district of the Water Resources Division of the U.S. Geological Survey as part of a cooperative agreement with the Louisiana Department of Public Works. Similar reports for southeastern and southwestern Louisiana have been published as Technical Reports Nos. 2a, (Calandro, 1967), 2b, (Sauer, 1967), 2c, (Lee, 1969), and 2d, (Sauer, 1969).

DESCRIPTION OF THE AREA

The study area, referred to as northern Louisiana in this report, is an area (fig. 1) of about 10,500 square miles bounded on the east by the Ouachita River, on the south by the Red River, on the west by the Louisiana-Texas border, and on the north by the northern periphery of Bayou Dorcheat and Corney Creek basins. The north boundary extends into southern Arkansas.

The study area is entirely within the Coastal Plain province (Fenneman, 1938). Topography ranges from flat land to rolling hills, with channel slopes ranging from 2 feet per mile on the large streams to over 30 feet per mile on the small streams. Channel slopes are closely related to basin size. Mixed stands of hardwood and softwood trees cover most of the area; however, some basins may have as much as 50 percent open land used for small farms and for pastures. A variety of soils occurs in the area, the general soil areas being the Coastal Plain, Flatwoods, and Recent (Holocene) alluvium (Lytle and Sturgis, 1962). The Coastal Plain soil area is the predominant grouping and ranges from fine sandy loam surface soils to sandy clay subsoils. The subsoils are defined as permeable to slowly permeable.

Figure 1. The study area, rain gages, and streamflow stations.

The semitropical climate of the area results in a mean annual temperature of about 66° F and mean annual precipitation of about 50 inches. Thunderstorms are the source of the most intense rainfall but are usually of short duration. Tropical storms in the late summer and fall sometimes cause prolonged heavy rainfall. During the winter, high-pressure systems moving into Louisiana from the northwest cause a simultaneous shift in the wind and a temperature drop that sometimes results in heavy rainfall over large areas. Snow and ice are rare and have no effect on streamflow in northern Louisiana.

DATA AVAILABLE

The two main types of data required for the development of techniques described in this report are rainfall and streamflow. Topographic maps were used to determine basin characteristics such as stream length, mean length, slope, and basin size.

Rainfall

A total of 94 U.S. Weather Bureau rain gages, most of which are shown on figure 1, were used as the source of all rainfall data for the analyses in this report. Some of these rain gages have been discontinued. About 80 gages in and around the study area are presently active, some of which are in Texas and Arkansas.

The density of the active rain-gage network is about one gage per 130 square miles. About 25 of the 80 active gages are recording type. The density of the recording gage network is one gage per 420 square miles.

Areal rainfall of individual storms over a basin was computed using the Thiessen polygon method. Hourly distribution of the rainfall was made on the basis of the nearest recording rain gage or gages. The error of areal rainfall for individual storms will vary from storm to storm and for the individual basins studied. This error is directly related to the density of rain gages in each basin. Quantitative evaluation of the magnitude of error is not available for northern Louisiana, but an estimate can be obtained by applying the results of the Muskingum basin study published by the U.S. Department of Commerce (1947). Using the results of that study, a curve (fig. 2) relating standard error to basin size was developed for a rain-gage density of 1:130 square miles (average for northern Louisiana). The curve applies to a random spacing of rain gages.

The error involved in making a time distribution of rainfall is even greater than that for areal distribution because of the relatively sparse network of recording rain gages.
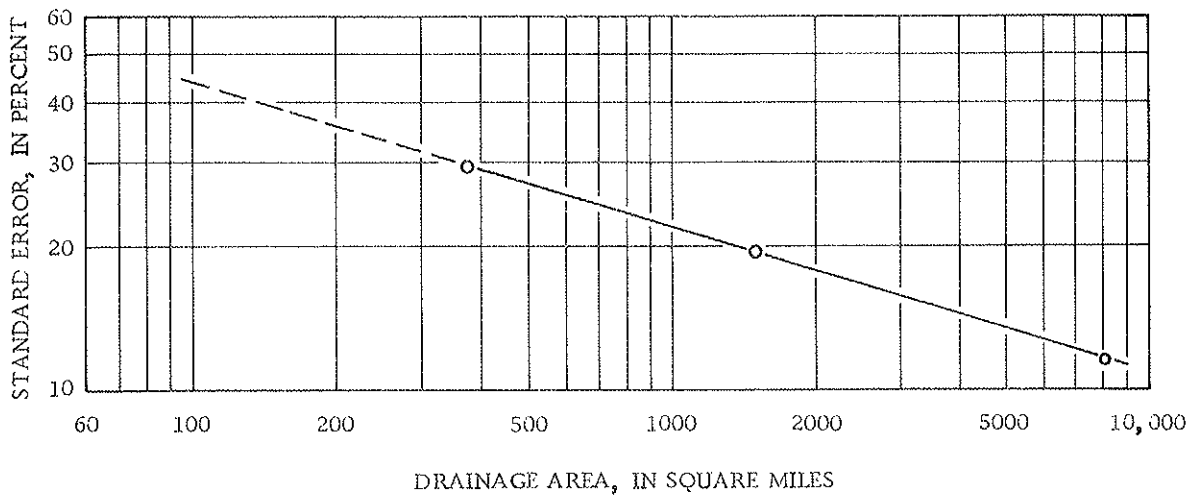
Figure 2. Standard error of areal rainfall as determined from a
random rain-gage network of one gage per 130 square miles.

Streamflow

Streamflow data were obtained from U.S. Geological Survey records
of 22 gaging stations in northern Louisiana. The locations of these
stations are shown in figure 1. One station (7-3525) was not used in
the rainfall-runoff analyses because of insufficient data, but it was
used in the study of unit hydrographs. Another station (7-3655) was not
used in the unit-hydrograph derivations, but it was used to develop an
infiltration index.

Runoff and hydrographs for individual storms were computed directly
from the original data, which are generally accurate to within 10 or 15
percent. Base flow during storm periods was deducted from the total
runoff to obtain the direct storm runoff. This deduction was made by
assuming a linear variation of base flow from the beginning of storm
runoff to a point on the recession of the hydrograph where direct runoff
was estimated to end. The error involved in estimating base flow in this
manner may be large, but because this is only a small part of the total
runoff, it will not cause significant error in the computation of storm-
runoff volumes and direct-runoff hydrographs.

RAINFALL EXCESS

Rainfall excess, as defined for this report, is that part of rain-
fall resulting in overland runoff, which eventually becomes streamflow.
The balance of rainfall either infiltrates to the soil and to ground-
water reservoirs or returns to the atmosphere by evapotranspiration.

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Infiltration and evapotranspiration are usually regarded as abstractions or losses, when the primary concern is the computation of rainfall excess. Because evapotranspiration is usually the smaller part of the total abstraction during a storm period, the further discussions in this report will refer to the difference between rainfall and rainfall excess for a given storm as an infiltration loss. The rate of loss will be referred to as the $\emptyset$ index. Likewise, rainfall excess and total direct runoff for a storm are considered synonymous.

Rainfall excess was computed for about 500 storms, each having 1.5 inches of rainfall or more. The calculation of rainfall excess within a basin for each of these storms was made from streamflow records at 21 gaging stations. The station, Black Lake Bayou near Castor, was not used because of insufficient data. Base flow was subtracted from the total runoff at a gage to compute the direct runoff, or rainfall excess. The process is complicated when individual storms are so close in time that resulting runoff from the storms merge. Graphical separation techniques were used for such instances, if possible; otherwise, the storms were not used.

The results of various attempts to relate rainfall excess to total storm rainfall, storm duration, rainfall intensities, and various antecedent indices were not satisfactory. Similar correlations using an average infiltration index, $\emptyset$, as dependent variable were made, but no satisfactory relations could be found.

Failure to define significant rainfall-runoff relations is attributed largely to the inaccuracies in computing total rainfall or a storm over a basin. As noted in the "Data Available" section on rainfall, the average density of the rain-gage network is one gage per 130 square miles. According to figure 2, rainfall computed for most basins used for this report (those less than 350 square miles) would have a standard error greater than 30 percent. When the primary cause of rainfall excess can be in error by this amount, it is not likely that the true effects of secondary factors such as antecedent conditions, duration, and intensity can be defined.

The median infiltration rate, $\emptyset$, was studied for each basin to see if it might be used on an areal basis. The 99-percent confidence interval of $\emptyset$, for each basin, indicates that only three basins have significantly different $\emptyset$ values from the median of the entire study area. The difference, however, is small and the three basins are widely separated; therefore, they were not singled out for individual study.

The $\emptyset$ values for all basins were grouped by months, and the median value was computed for each month. The results of this study are shown graphically in figure 3. The dashed lines in figure 3 encompass two-thirds of the data. That is, one-sixth of the $\emptyset$ values were less than the lower dashed curve and one-sixth were greater than the upper dashed curve.

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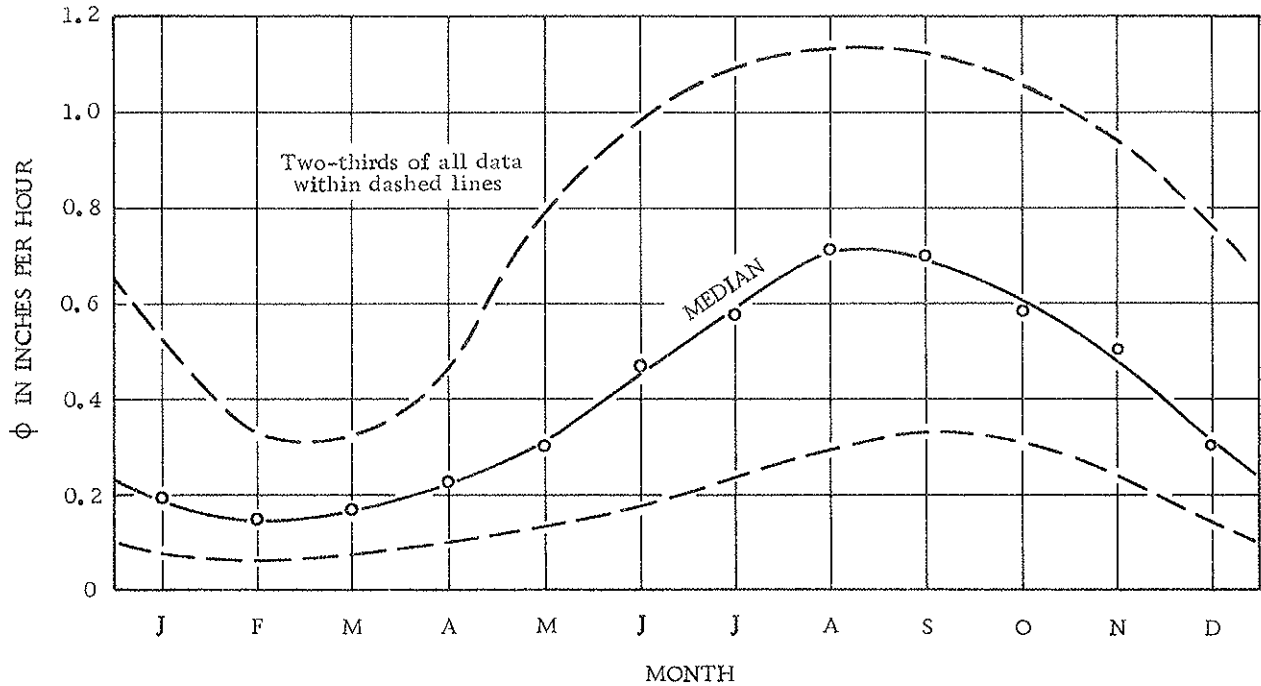
Figure 3.   Seasonal variation of infiltration index, $\emptyset$.

The median curve of figure 3 can be used to estimate the infiltration rate for a storm. The application of this $\emptyset$ value to storm rainfall will give an estimate of the rainfall excess for that storm. The dashed curves in figure 3 are indicative of the error to be expected in the computation of rainfall excess. An example of the application of $\emptyset$ is given in the section "Practical Application."

UNIT HYDROGRAPHS

The unit hydrograph for a site is a hydrograph of direct runoff (not including base flow) resulting from 1 inch of rainfall excess uniformly distributed over the drainage basin during a unit time. Such a hydrograph seldom occurs in nature; however, it can usually be derived from streamflow records if several storms which approximate the prescribed conditions are available for analysis.

Figure 4 is a definition sketch of a unit hydrograph showing various dimensions and their relation to rainfall excess. Definitions of the various symbols are given on the inside front cover.
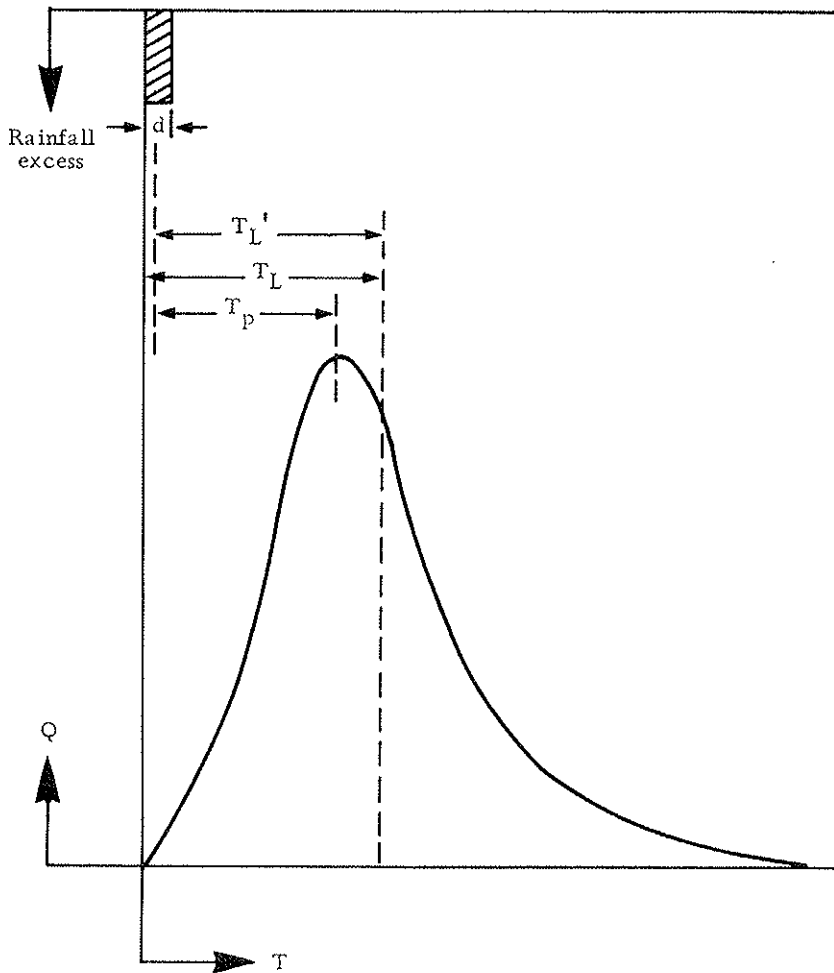
Figure 4.   Typical unit hydrograph.

The unit hydrograph for a site can be used to compute direct-runoff
hydrographs at the same site for various amounts of rainfall excess.
The necessary assumptions are derived from the basic unit-hydrograph
definition and are as follows:

(1)   It is assumed that the rainfall excess of a particular storm
can be determined with reasonable accuracy. Not only must the volume of
rainfall excess be determined, but, just as important, the time distribu-
tion must be known. Rainfall excess can be computed as explained in
this report, although the basic principles of the unit-hydrograph theory
do not depend on the manner in which rainfall excess is computed. Any
method which gives reasonable accurate approximations of rainfall excess
will do. It should be pointed out that the unit hydrograph is not a
tool for computing rainfall excess but only a method by which rainfall
excess can be converted into a discharge hydrograph.

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(2) It is assumed that the runoff-producing rainfall is distributed
fairly uniformly over the basin. This assumption limits, to some extent,
the maximum size of basins that can be used in such computations. For
the basins in the study area (all less than 1,500 square miles and most
less than 350 square miles), it can generally be assumed that fairly
uniform distribution will occur for the large storms; however, the user
should assure himself of uniform areal distribution for any storm to be
computed because in some instances rainfall may be concentrated over one
part of a basin, or the storm may move upstream or downstream, all of
which tend to distort the hydrograph resulting from that storm. It cannot
be expected that exact reproductions will be obtained because there are
always some nonuniformities, and rainfall excess is difficult to compute
with accuracy. If it is desired to compute the flood hydrograph for an
outstanding storm over one of the larger basins and it is known that
this storm is not uniformly distributed, the basin can be subdivided into
smaller basins, and the hydrographs computed for each. After this has
been done, flood-routing procedures can be used to combine the various
subbasin hydrographs at the desired location. Carter and Godfrey (1960)
provide a suitable method of routing floods.

(3) It is assumed that the discharge ordinates of a direct-runoff
hydrograph are in the same ratio to the unit hydrograph as the rainfall
excess is to one. That is, the ordinates of a unit hydrograph multiplied
by the rainfall excess, in inches, equals the ordinates of the direct-
runoff hydrograph for that amount of rainfall excess. It will be shown
later in this report that the unit hydrograph for a site is variable,
depending on the amount of rainfall excess. This variability accounts
to some extent for nonlinear storage.

The basic use of the unit hydrograph is derived from assumption (3)
of the preceding discussion. Through this assumption it is possible to
convert any amount of rainfall excess to a runoff hydrograph. The simple
case is one in which all rainfall excess occurs during the unit time, or
unit duration, d. Each ordinate of the unit hydrograph is multiplied by
the rainfall excess, in inches; and the resulting hydrograph is the hydro-
graph of direct runoff expected from that amount of rainfall excess.

The more complex and more common case is one in which rainfall excess
occurs during more than one unit duration. When this occurs, each period
of unit duration is computed separately; the individual hydrographs are
placed (lagged) in their proper time position; and the sum of the ordi-
nates at a given time will yield the total discharge at that time. Figure
5 is a graphic example illustrating the computation of a direct-runoff
hydrograph when rainfall excess occurs during several unit-time periods.
To complete the runoff hydrograph, base flow must be included.

Unit hydrographs were derived from streamflow records at 21 gaging
stations in the study area. Five or six storms were used to define lag
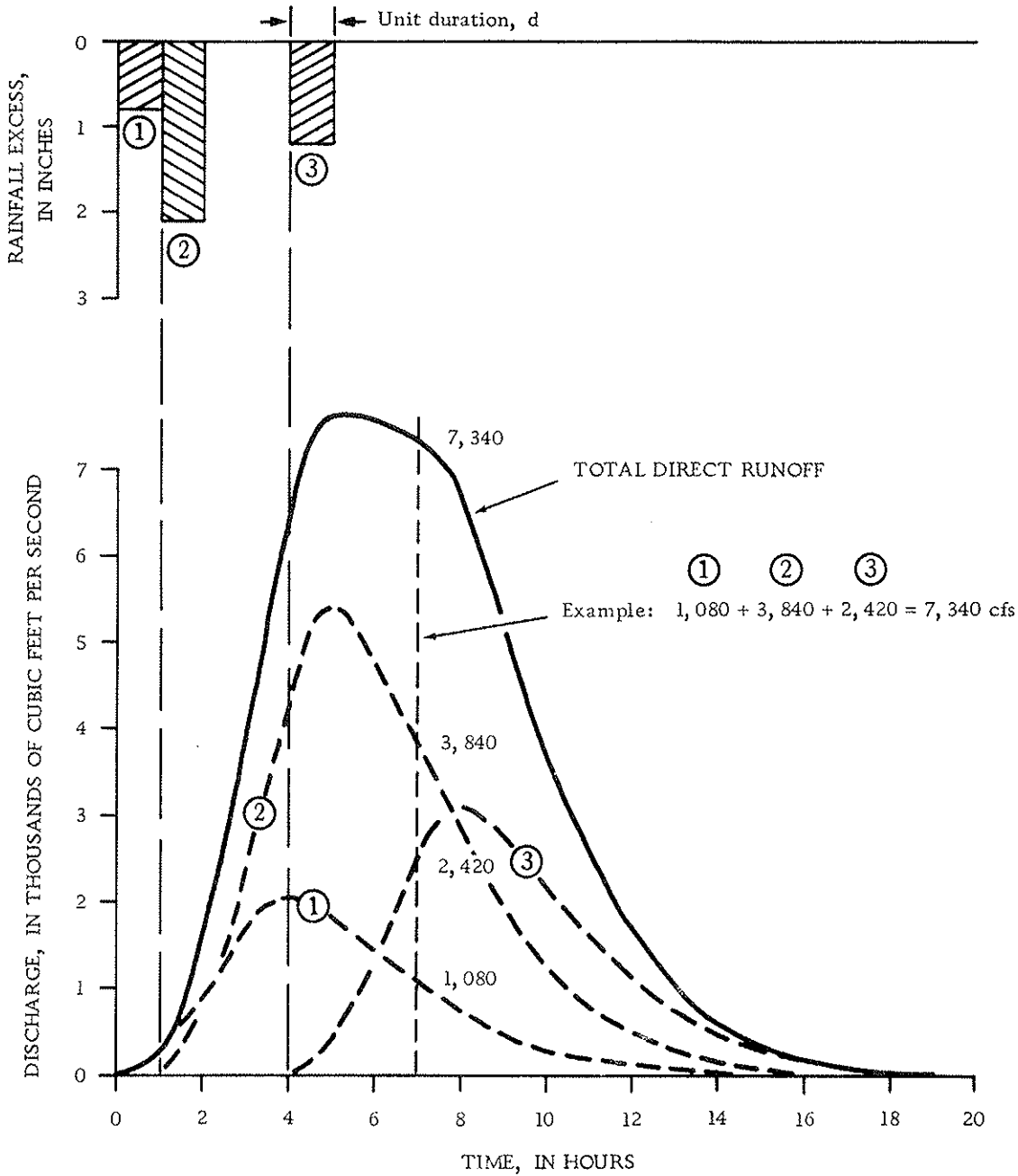time, T_L', and the dimensionless unit hydrograph at each station.

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Figure 5. Example of hydrograph computed from rainfall excess occurring in several unit-time periods.

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Unit hydrographs for different sites appear, at first glance, to have quite different shapes, and one might doubt that a group of unit hydrographs, such as those defined for northern Louisiana, could be combined into a single hydrograph representing all. However, certain mathematical manipulations can be used to change the unit hydrograph into a dimensionless form. Dimensionless unit hydrographs are similar in shape and magnitude and can be averaged into a single unit hydrograph that can be used to reproduce synthetic unit hydrographs at any site. The method of reducing a unit hydrograph to dimensionless form involves, first, a transformation of the time scale by dividing each unit of time by the adjusted lag time of the unit hydrograph. Adjusted lag time, T_L, is defined as the time from beginning of rainfall excess to center of mass of the runoff hydrograph (fig. 4). Second, ordinates of discharge are determined at equal intervals of the transformed time scale, and these ordinates of discharge are reduced to dimensionless values by dividing each by the summation of all. A group of unit hydrographs reduced to dimensionless form in this manner can be averaged into one dimensionless hydrograph that will be representative of all. Such a procedure is referred to as regionalization. The results of this regionalization are given in the following sections.

Lag Time

Lag time, a critical factor used in the derivation of dimensionless unit hydrographs, is defined as the time from center of mass of rainfall excess to the center of mass of the resulting runoff hydrograph. It is usually considered to be a constant for a given basin; however, the results of this report indicate that in northern Louisiana lag time for a basin varies significantly with the magnitude of rainfall excess.

The variation of lag time for each basin used in this report is defined by the plots shown in figure 6. Although the scatter of some points may seem excessive, there is definite indication that runoff from large storms concentrates more quickly than runoff from small storms.

The primary reason for the variable lag time in each basin is attributed to the type of main channel and flood plain existing in northern Louisiana. The main channels are small, tortuous, and generally overflow during all except the small floods. Flood plains are usually wide and shallow with numerous slough channels. As a flood increases in magnitude, the effective distance it must travel is shortened, and the travel time is shortened by corresponding amounts. Also, the larger floods travel faster than small floods because of greater depths.

The curves of figure 6 are considered a better indication of lag time in a basin than the lag time computed for individual storms. This is so because each storm tends to have some nonuniformity caused by variable areal coverage or time distribution. On this basis, lag time was read from the curves for each station for storms of 1, 2, 3, 4, and 5 inches of rainfall excess. These values are given in table 1 along
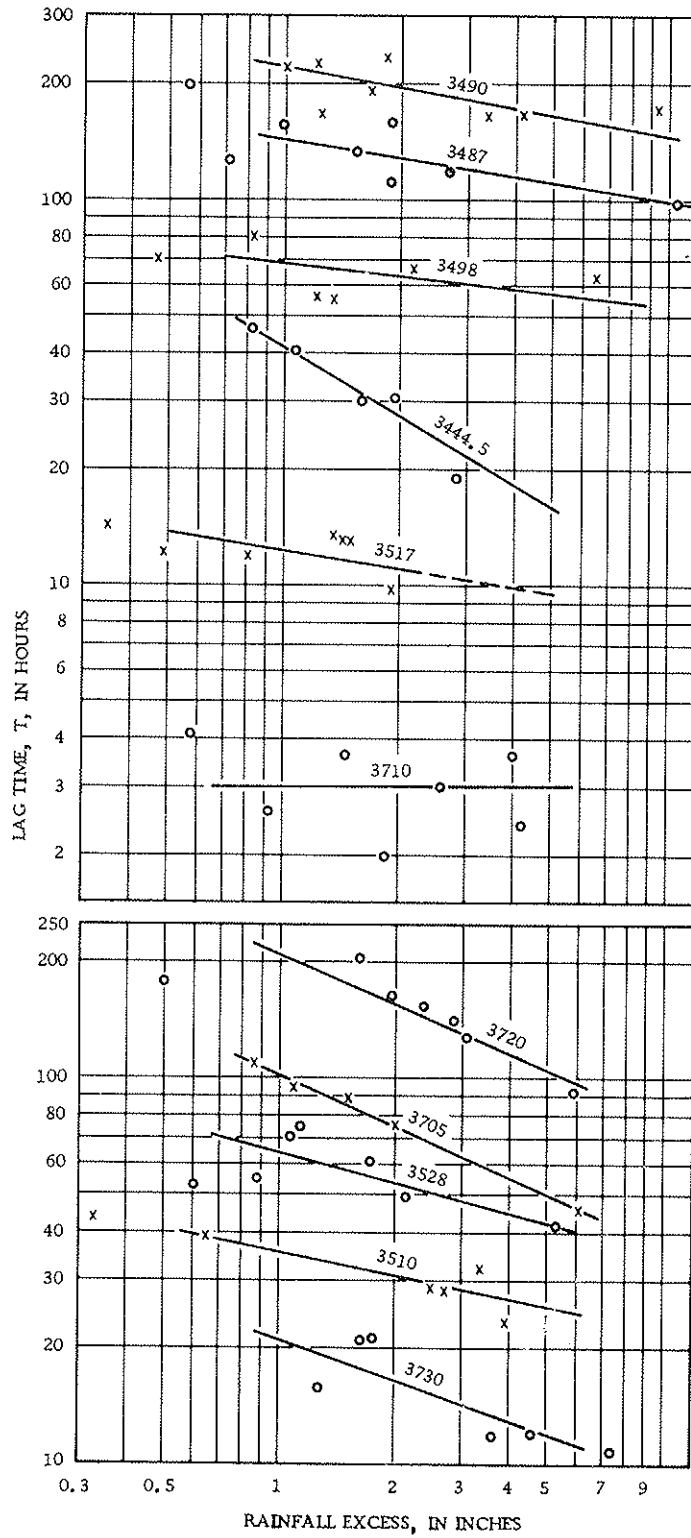
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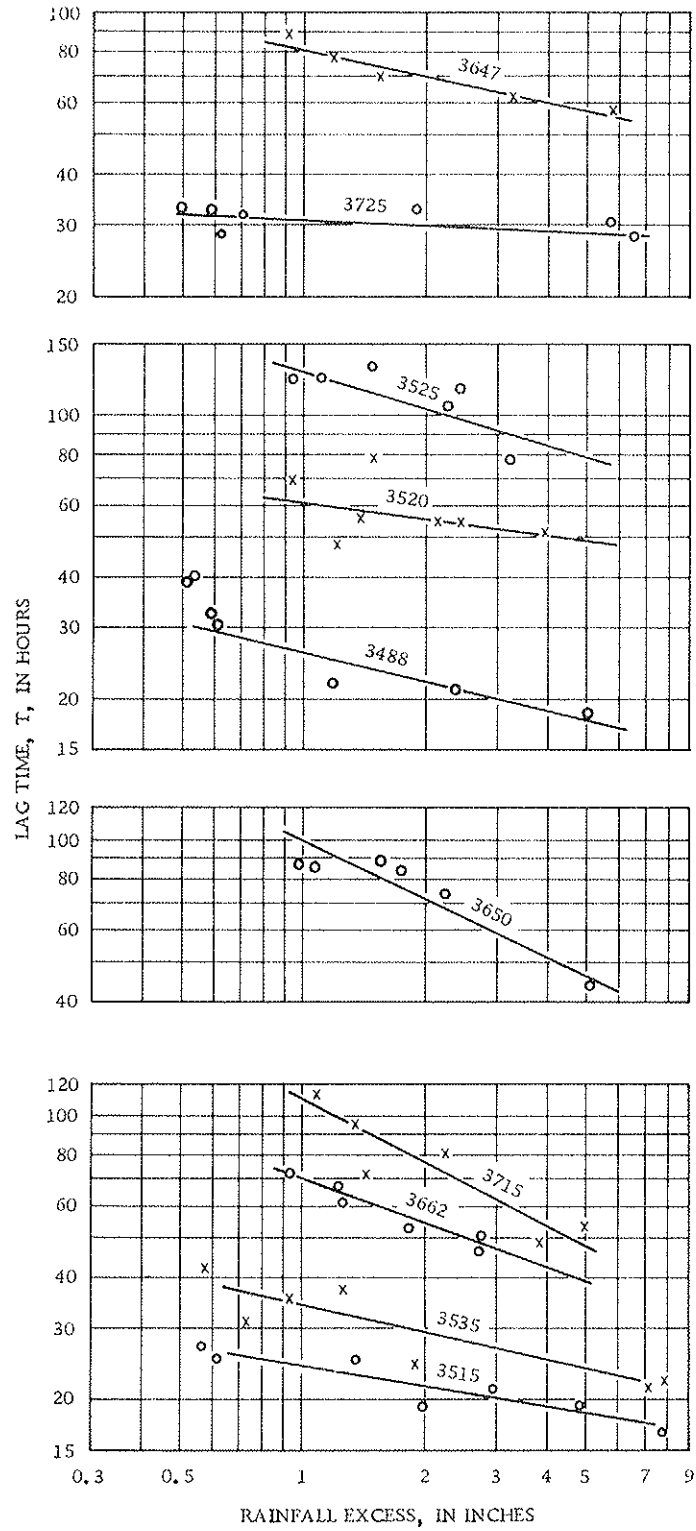Figure 6. Relation of lag time to rainfall excess

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Figure 6. Relation of lag time to rainfall excess--Continued

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Table 1.--Streamflow stations, basin characteristics, and lag time

Basin characteristics: A, drainage basin size, in square miles; L, drainage basin length, in miles; L_{ca}, drainage basin mean length, in miles; S, main channel slope, in feet per mile.

Station No. (Part 7)	Station name	Basin characteristics				Rainfall excess, in inches				
		A	L	L_{ca}	S	1	2	3	4	5
						Lag time, in hours				
3444.5	Paw Paw Bayou near Greenwood	78	14.5	8.0	9.4	41	27	21	18	16
3487	Bayou Dorcheat near Springhill	605	47.8	26.1	3.5	142	127	119	113	110
3488	Flat Lick Bayou near Leton	66.9	12.5	6.6	8.4	26	22	20	19	18
3490	Bayou Dorcheat near Minden	1097	79.0	38.4	2.2	220	193	180	171	165
3498	Cypress Bayou near Benton	133	22.5	11.8	5.9	68	63	60	58	57
3510	Boggy Bayou near Keithville	79	15.0	7.8	8.6	36	31	28	27	26
3515	Cypress Bayou near Keithville	66	11.5	6.2	12.0	24	22	20	19	18
3517	Bayou Na Bonchasse near Mansfield	19.5	6.0	4.0	18.2	12	11	10.2	9.8	9.5
3520	Saline Bayou near Lucky	154	27.1	11.3	6.1	60	55	52	50	49
3525	Black Lake Bayou near Castor	423	39.6	21.6	3.9	128	103	91	84	78
3528	Grand Bayou near Coushatta	93.9	24.0	11.9	5.3	64	53	48	44	42
3535	Nantachie Creek near Montgomery	47	13.1	8.2	6.2	34	29	27	25	24
3647	Bayou De Loutre near Laran	141	23.3	12.0	3.6	80	69	63	60	57
3650	Bayou D'Arbonne near Dubach	355	38.4	16.2	4.7	99	72	60	52	47
3655	Middle Fork Bayou D'Arbonne nr Bernice	178	35.6	16.2	4.4	--	--	--	--	--
3662	Little Corney Bayou near Lillie	208	29.5	13.7	4.3	69	54	55	47	43
3705	Castor Creek near Grayson	271	38.2	18.5	3.0	101	75	62	55	50
3710	Garrett Creek at Jonesboro	2.14	2.2	1.07	63.5	3.0	3.0	3.0	3.0	3.0
3715	Dugdemona River near Jonesboro	347	28.9	15.1	4.6	110	77	63	54	48
3720	Dugdemona River near Winnfield	654	53.2	27.2	2.4	208	156	132	118	106
3725	Bayou Funny Louis near Trout	92	21.9	8.5	7.1	31	30	29	29	29
3730	Big Creek at Pollock	51	10.2	6.4	11.3	21	16	14	13	12

with the basin characteristics for each station. Lag times for one station (7-3655--Middle Fork Bayou D'Arbonne near Bernice) are not given because data for that station were insufficient to define the relation.

The data in table 1, with logarithmic transformation, were used in a linear multiple regression study to relate lag time to basin characteristics. The relations defined by these analyses can be used to estimate lag time for ungaged sites in northern Louisiana. Lag time, in hours, for 1, 2, 3, 4, and 5 inches of rainfall excess is denoted as T'_{L1}, T'_{L2}, T'_{L3}, T'_{L4}, and T'_{L5}, respectively, in the following equations. Other parameters used are:

(1)   A, drainage basin size, in square miles;

(2)   L, drainage basin length, in miles, measured along the general path of the flood plain from the point of outlet to the fartherst point on the basin divide;

(3) L_{ca}, drainage basin mean length, in miles, also measured along the general path of the flood plain; and

(4)   S, the main channel slope, in feet per mile, measured as the slope between points at a distance 10 percent upstream from the gage and 85 percent upstream from the gage.

The following equations give lag time in terms of:

Mean length (s_e=19 percent)

$$T'_{L1}=2.48\ L_{ca}^{1.28}$$

$$T'_{L2}=2.29\ L_{ca}^{1.24}$$

$$T'_{L3}=2.22\ L_{ca}^{1.21}$$

$$T'_{L4}=2.21\ L_{ca}^{1.18}$$

$$T'_{L5}=2.19\ L_{ca}^{1.16}$$

Length (s_e=20 percent)

$$T'_{L1}=1.32\ L^{1.21}$$

$$T'_{L2}=1.22\ L^{1.18}$$

$$T'_{L3}=1.19\ L^{1.15}$$

$$T'_{L4}=1.20\ L^{1.12}$$

$$T'_{L5}=1.19\ L^{1.10}$$

Area (s_e=25 percent)

$$T'_{L1}=1.64\ A^{.72}$$

$$T'_{L2}=1.56\ A^{.69}$$

$$T'_{L3}=1.54\ A^{.67}$$

$$T'_{L4}=1.55\ A^{.65}$$

$$T'_{L5}=1.56\ A^{.64}$$

Area and slope (s_e=21 percent)

$$T'_{L1}=18.7\ A^{.42}S^{.56}$$

$$T'_{L2}=21.8\ A^{.38}S^{.60}$$

$$T'_{L3}=22.4\ A^{.35}S^{.61}$$

$$T'_{L4}=22.2\ A^{.33}S^{.61}$$

$$T'_{L5}=22.0\ A^{.32}S^{.61}$$

s_e is the average standard error, in percent, for each group of equations.

All of the regression coefficients in the preceding equations are significant at either the 95-percent or 99-percent level of significance. Slope did not prove significant when used with length and mean length, and the resulting equations are not given.

Based on standard error, the best results (s_e=19 percent) were obtained using mean length. It is suggested, however, that the "length" regression be used for making estimates of lag time in northern Louisiana. The small sacrifice in standard error is more than compensated for by the ease of computation. Basin length can be easily and quickly determined from topographic maps using dividers, rolling map measure, or by other simple means. The equations of lag time versus length are shown graphically in figure 7.

Significance of Variable Lag Time

A significant aspect of this study is the evidence that indicates lag time is not always constant for a basin, and that it shows a definite relation with the magnitude of storm runoff. This gains importance when lag time is used to define the unit hydrograph. Assume, for instance, that lag time for a basin is not variable but constant for all storms regardless of size. The unit hydrograph for this basin then takes on the same shape and magnitude for all storms. The application of this unit hydrograph to small storms as well as large storms results in linear proportionality of the hydrograph ordinates.

Assume for the same basin, however, that lag time varies with magnitude of storm runoff. Now, because of the direct relationship between lag time and the unit hydrograph, there will result unit hydrographs of different shapes and magnitude for the various size storms. Unit hydrographs developed for large storms, because of shorter lag times, will have earlier and higher peaks than unit hydrographs developed for small storms. The application of these unit hydrographs to their respective storm runoffs will have the affect of a nonlinear relationship between various storms. In many areas such as the study area in northern Louisiana, this nonlinear relation is typical.

It should be emphasized that the unit hydrograph for a particular storm is applied with the assumption of linear proportionality. The variable lag time in a basin simply yields a family of unit hydrographs for that basin, which will account for the nonlinear relation between various size storms.

Unit Duration

The unit duration, d, by definition is the time during which rainfall excess occurs to produce a unit hydrograph. Unit duration should be selected so that an optimum number of points are computed to define the unit hydrograph. Selection of a unit duration that is too small will
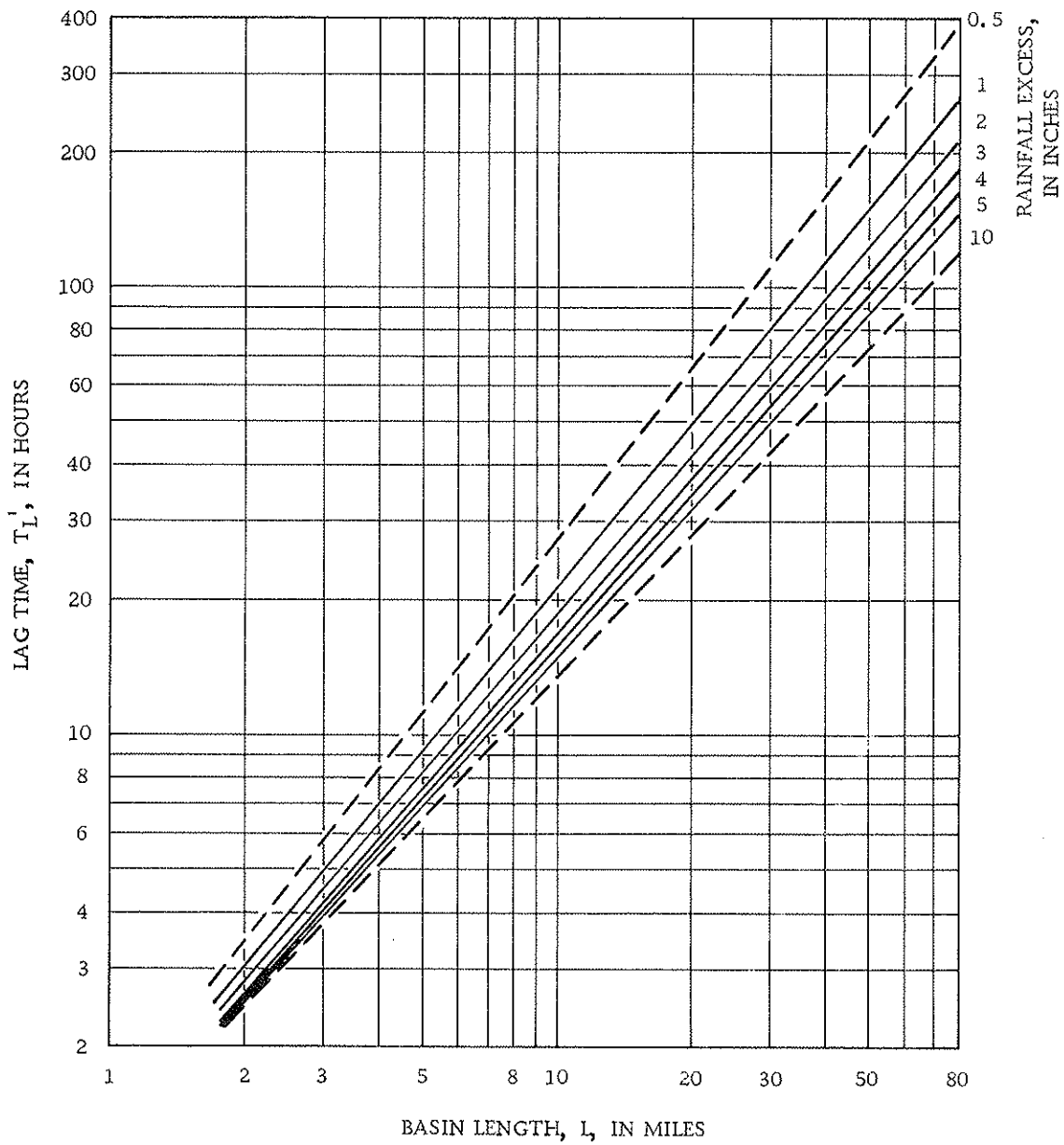
Figure 7. Relation of lag time to basin length.

result in excessive computations. This will not affect accuracy but will be laborious and time consuming. Selection of a unit duration that is too large will result in insufficient definition of the unit hydrograph and could lead to large errors.

Sufficient definition of the unit hydrograph can be obtained if unit duration, d, is computed as 10 percent of the lag time. The unit duration computed in this manner should then be rounded to the nearest whole number of hours evenly divisible into 24 hours. For example, if T'_L is 45 hours, then unit duration, d, equals 10 percent of 45, or 4.5 hours. For practical use, d should be used as 4 hours.

Derivation of Synthetic Unit Hydrographs

The individual unit hydrographs computed for each station were reduced to dimensionless terms according to the procedure described in the preceding explanation of "Unit Hydrographs." For each station a graphical average was drawn from a composite of the individual dimensionless graphs. Variations of the individual dimensionless unit hydrographs are primarily the result of nonuniformities of the storm, and the average is considered representative of uniform storm conditions.

All of the average dimensionless unit hydrographs for the 21 stations were similar in shape and magnitude, the standard deviation of the peaks being about 15 percent. An average of these results in a single, dimensionless unit hydrograph applicable to the study area. An accumulated summation of this average hydrograph is given, in percent, in table 2.

A synthetic unit hydrograph for any site in the study area can be derived from table 2. The variables necessary to make this derivation are drainage-area size, A; adjusted lag time, T_L ($T_L = T'_L + d/2$); unit duration, d; and computation interval, Δt. (Computation interval, Δt, is selected to be equal to unit duration, d.) Table 2 is tabulated at 0.01 intervals of T/T_L, but to derive a smooth unit hydrograph it is recommended that thousandths be used for values of T/T_L and that the table be interpolated. T is defined as the number of hours measured from beginning of direct runoff.

The procedure for deriving a synthetic unit hydrograph from table 2 is as follows:

1. Compute T/T_L for increments of T equal to Δt (d=Δt). The values of T/T_L should be listed up to and including 2.5.

2. Tabulate the corresponding percentages from the summation table. These are accumulated distribution percentages for the desired unit hydrograph at intervals equal to Δt.

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3. Take differences between succeeding values of the accumulated percentages. This gives the distribution, in percent, of the unit hydrograph for the selected unit duration and time interval. A plot of these values would yield a distribution graph.

4. To convert the distribution percentage to cubic feet per second, divide each by 100 and multiply by the summation of discharge ordinates, ΣQ_u, computed by the equation

$$\Sigma Q_u = \frac{645.3A}{\Delta t}$$

This equation represents a summation of the discharge ordinates of the unit hydrograph if these ordinates are spaced at intervals equal to Δt. It is derived as follows:

(1) The total volume of runoff, in cubic feet, from any rainfall excess, R_e, in inches, over a drainage area, A, in square miles, is

$$\text{Volume } (ft^3) = \frac{A(mi^2)(5280)^2(ft^2/mi^2)R_e(in.)}{12 \; in/ft}$$

$$= \frac{(5280)^2}{12} A \; R_e \; .$$

(2) The total volume of runoff is also equal to the area under the discharge hydrograph resulting from the rainfall excess, R_e. This area can be computed by summing incremental areas equal to $Q\Delta t$, where Q, in cubic feet per second, is the average discharge during the time interval, Δt, in hours. The total volume, in cubic feet per second hours is

$$\text{Volume } (ft^3 hr/sec) = Q_1 \Delta t + Q_2 \Delta t + \ldots .Q_n \Delta t.$$

$$= \Delta t (Q_1 + Q_2 + \ldots .Q_n)$$

$$= \Delta t (hrs) \Sigma Q (ft^3/sec).$$

This is converted to cubic feet by multiplying by 3600, the number of seconds per hour.

$$\text{Volume } (ft^3) = 3600(sec/hr) . \; \Delta t(hr) \Sigma Q(ft^3/sec).$$
$$= 3600 \; \Delta t \Sigma Q.$$

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(3) Combining the equations for volume as derived in (1) and (2), the equation for ΣQ can be derived as follows:

$$\frac{(5280)^2}{12} \; A \; R_e = 3600 \; \Delta t \; \Sigma Q$$

$$\Sigma Q = \frac{645.3 \; A \; R_e}{\Delta t}$$

(4) For a unit hydrograph, the rainfall excess, R_e, is equal to 1 inch, and the equation becomes

$$\Sigma Q_u = \frac{645.3A}{\Delta t} \;,$$

where ΣQ_u is the summation of discharge ordinates of the unit hydrograph.

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Table 2.--Summation table for synthetic unit hydrographs.

T/T_L	0	.01	.02	.03	.04	.05	.06	.07	.08	.09
	Accumulated Distribution, in percent									
0	0	.07	.14	.22	.31	.40	.50	.60	.71	.83
.1	.95	1.12	1.29	1.48	1.67	1.88	2.10	2.33	2.57	2.82
.2	3.08	3.36	3.65	3.96	4.28	4.61	4.97	5.33	5.71	6.11
.3	6.52	6.93	7.35	7.80	8.26	8.74	9.24	9.75	10.29	10.84
.4	11.41	11.99	12.58	13.20	13.83	11.49	15.16	15.85	16.56	17.28
.5	18.03	18.80	19.60	20.40	21.23	22.07	22.93	23.80	24.69	25.60
.6	26.52	27.48	28.44	29.41	30.39	31.39	32.39	33.40	34.42	35.44
.7	36.48	37.50	38.51	39.53	40.54	41.56	42.58	43.59	44.61	45.62
.8	46.64	47.59	48.53	49.46	50.39	51.31	52.22	53.13	54.02	54.92
.9	55.80	56.63	57.45	58.25	59.05	59.84	60.61	61.38	62.13	62.88
1.0	63.61	64.32	65.01	65.69	66.37	67.03	67.68	68.32	68.95	69.56
1.1	70.17	70.76	71.35	71.92	72.48	73.04	73.58	74.11	74.64	75.15
1.2	75.65	76.15	76.64	77.13	77.60	78.07	78.53	78.97	79.42	79.85
1.3	80.27	80.69	81.11	81.51	81.92	82.31	82.70	83.07	83.45	83.81
1.4	84.17	84.53	84.88	85.23	85.57	85.90	86.23	86.56	86.87	87.18
1.5	87.49	87.79	88.09	88.38	88.66	88.95	89.22	89.49	89.76	90.02
1.6	90.28	90.53	90.77	91.02	91.25	91.48	91.71	91.94	92.16	92.38
1.7	92.59	92.80	93.00	93.20	93.40	93.59	93.78	93.97	94.15	94.33
1.8	94.51	94.68	94.85	95.01	95.17	95.33	95.49	95.64	95.80	95.94
1.9	96.09	96.23	96.36	96.49	96.62	96.75	96.88	97.00	97.12	97.24
2.0	97.36	97.47	97.57	97.68	97.78	97.88	97.98	98.07	98.17	98.26
2.1	98.35	98.43	98.51	98.59	98.66	98.74	98.81	98.88	98.95	99.02
2.2	99.09	99.14	99.20	99.25	99.30	99.35	99.40	99.45	99.50	99.54
2.3	99.59	99.62	99.65	99.68	99.71	99.74	99.77	99.80	99.83	99.85
2.4	99.88	99.89	99.90	99.92	99.93	99.94	99.95	99.96	99.98	99.99
2.5	100.00									

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PEAK DISCHARGE

This report is designed mainly to provide a method of computing the flood hydrograph of a given rain storm. There are instances, however, when only the peak discharge from a storm is desired. To simplify this type of computation the following equation may be used:

$$Q_p = \frac{645.3 \ A \ R_e}{T_L},$$

where Q_p =peak discharge, in cfs;

A=drainage area, in square miles;

R_e =rainfall excess, in inches; and

T_L =adjusted lag time, in hours.

This equation is based on the dimensionless unit hydrograph where

$$\Delta t/_{T_L} \approx Q_p/_{\Sigma Q}.$$

By substituting the equation $\Sigma Q = \dfrac{645.3 \ A \ R_e}{\Delta t}$, the above equation for Q_p was developed.

It should be noted that this is an approximate relation. If the duration of rainfall excess greatly exceeds the value of d that would normally be selected, the equation for Q_p should not be used. However, if rainfall excess occurs within two or three unit durations, the peak computed by this method will be within 5 percent of the peak computed by the unit-hydrograph technique.

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PRACTICAL APPLICATION

Rainfall-runoff and unit-hydrograph techniques are useful at any site where a flood hydrograph is desired for preliminary design of waterway structures or channels and where it is not practical, either because of time or money, to obtain the flood hydrograph by conventional streamgaging procedures. It is useful for extending flood records by the use of long-term rainfall records. Flood forecasts from known amounts of rainfall can be made by rainfall-runoff and unit-hydrograph procedures.

The following step-by-step procedure will assist the user in applying the techniques described in this report. In addition, an example follows that illustrates most of the details involved in practical application.

Procedure for Application of Rainfall-Runoff and Unit Hydrographs

Following is a step-by-step procedure for the complete application of the rainfall-runoff and unit-hydrograph techniques. In some problems all of the steps will not be necessary, and the user should make necessary adjustments.

1. From the best available topographic maps, determine the drainage area and length of the basin.

2. Locate on a map all rainfall gages in or near the basin.

3. Determine Thiessen weight factors for each rain gage.

4. Determine the basinwide rainfall for each hour during the storm.

5. Compute rainfall excess. An appropriate estimate of average infiltration rate, $\emptyset$, can be made from figure 3 and subtracted from each hourly rainfall amount to obtain rainfall excess. Of course, where $\emptyset$ exceeds rainfall, rainfall excess equals zero. Compute the total amount of rainfall excess for each storm by summing the hourly values of rainfall excess.

   If other methods of computing rainfall excess are available they may be used without affecting the computations of the unit hydrograph and total storm hydrograph. This is at the discretion of the user and his ability to estimate rainfall excess. For actual storms, the unit hydrograph has little value without a good estimate of rainfall excess; therefore every effort should be made to make as reliable an estimate as possible. For hypothetical storms, the infiltration curves of figure 3 can be used to define average conditions with reliable accuracy.

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6. Determine lag time, T_L', from figure 7 for each individual storm
    to be compuced. Where direct runoff from two or more storms
    merges to form a hydrograph with a single peak, the total
    rainfall excess for all of these storms should be used to
    determine T_L'.

7. Select a unit duration, d, equal to 0.1 T_L', rounded to the
    nearest whole number of hours evenly divisible into 24. Use
    a computation interval, Δt, equal to d.

8. Compute adjusted lag time, T_L, equal to $T_L' + d/2$.

9. Derive the unit hydrograph from table 2 according to the pro-
    cedure given in the previous section, "Derivation of Synthetic
    Unit Hydrographs."

10. If all rainfall excess is in one unit-time increment equal to
    d, multiply each ordinate of the unit hydrograph by the rain-
    fall excess to obtain a hydrograph of direct runoff. If the
    rainfall excess occurs in more than one unit-time increment,
    the unit-hydrograph ordinates must be multiplied by each
    incremental rainfall excess, the resulting hydrographs lagged
    by the respective time differences, and summed. An example
    of such a computation is given in the following application.

11. Estimate base flow and add to the direct-runoff hydrograph to
    define the total flow hydrograph. This report does not pro-
    vide a procedure for making this estimate; however, it will
    usually be a small percentage of the direct runoff, probably
    less than 5 percent.

Example

    The procedures of this report are illustrated by computing the
direct runoff hydrograph for a hypothetical storm imposed on the Bayou
de Loutre basin. The point of outflow is at the gaging station near
Laran. The storm is derived from U.S. Weather Bureau Technical Paper
No. 40 by Hershfield (1961). All of the computation steps are listed in
the same order as those of the preceeding section, "Procedure for Appli-
cation of Rainfall-Runoff and Unit Hydrographs."

    1. The drainage area, A, is 141 square miles, and the length, L, is
        23.3 miles.

    2. and 3. This storm is derived from a rainfall-frequency atlas
        and is considered uniform in time and area; therefore, rain
        gages and Thiessen weights are not needed.

    4. The 100-year, 12-hour rain was selected for computation and is
        equal to 8.0 inches for a point in the Bayou de Loutre basin

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(Hershfield, 1961). To apply this to the entire basin (A=141 sq mi) it must be reduced by a factor of 0.89 (Hershfield, 1961); therefore, average rain over the basin is equal to 0.89 times 8.0, or 7.12 inches for a 12-hour period. It will be assumed that the rain is evenly distributed in time and area.

5. The most likely time of occurrence for this storm is in April or May of any year. From figure 3, the median infiltration rate, $\emptyset$, between April and May is 0.26 inch per hour. The average hourly rain is 7.12 divided by 12, or 0.593 inch. Rainfall excess is therefore equal to 0.593 minus 0.26, or 0.333 inch per hour for the 12-hour period. The total rainfall excess is 4.00 inches.

6. Lag time, T_L', is read from figure 7 by entering with basin length and total rainfall excess and found to be 41 hours.

7. Unit duration, d, and computation interval, Δt, is selected as 4 hours. This is computed as 0.1 T_L', rounded to the nearest whole number of hours evenly divisible into 24.

8. Adjusted lag time equals T_L' plus d/2, or 41 plus 2 equals 43 hours.

9. The unit hydrograph is derived from table 2 according to the procedure given in the section "Derivation of Synthetic Unit Hydrographs." These computations are shown in table 3. The summation of discharge ordinates for the unit hydrograph, at intervals of Δt equal to 4 hours, is

$$\Sigma Q_u = \frac{645.3 \ A}{\Delta t} = \frac{645.3 \,(141)}{4} = 22,747 \text{ cfs.}$$

10. The rainfall excess of 0.333 inch per hour is accumulated into 4-hour amounts equal to 1.33 inches. There will be three of these increments during the 12-hour storm period. The unit-hydrograph ordinates are multiplied by 1.33 for each 4-hour period and lagged accordingly. The summation of these hydrographs results in the total direct-runoff hydrograph. This is shown in table 4 and, graphically, in figure 8.

11. The direct-runoff hydrograph does not include base flow; therefore, an estimate of base flow should be added to complete the hydrograph.

It should not be implied that the peak discharge for this flood has a recurrence interval of 100 years. There is no direct relation between the recurrence interval of a rain and the corresponding peak discharge. Other factors of a variable nature will cause different peaks from storms of equal magnitude.

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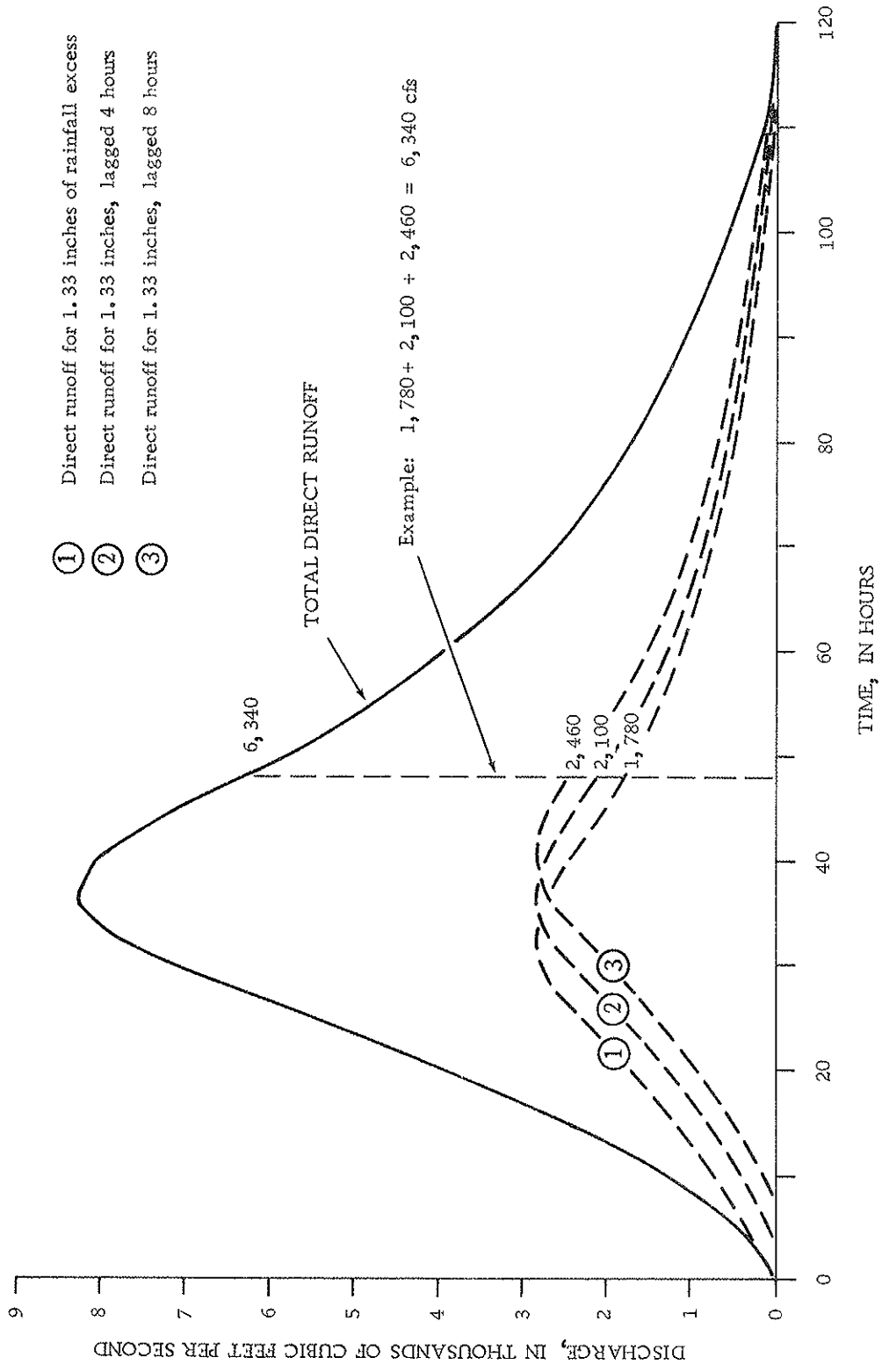
Figure 8. Direct-runoff hydrograph for 100-year, 12-hour storm, Bayou de Loutre near Laran.

① Direct runoff for 1.33 inches of rainfall excess

② Direct runoff for 1.33 inches, lagged 4 hours

③ Direct runoff for 1.33 inches, lagged 8 hours

TOTAL DIRECT RUNOFF

Example: 1,780 + 2,100 + 2,460 = 6,340 cfs

Table 3.--Derivation of unit hydrograph for
Bayou de Loutre near Laran

Time T hours	T/T_L	Acc. distr. % from table 2	Diff. %	Unit hydrog. cfs = $\frac{diff}{100} \times \Sigma Q$
0	------	-------	------	-------
4	0.093	0.87	0.87	198
8	.186	2.72	1.85	421
12	.279	5.67	2.95	671
16	.372	9.86	4.19	953
20	.465	15.50	5.64	1,280
24	.558	22.76	7.26	1,650
28	.651	31.49	8.73	1,990
32	.744	40.95	9.46	2,150
36	.837	50.11	9.16	2,080
40	.930	58.25	8.14	1,850
44	1.023	65.21	6.96	1,580
48	1.116	71.11	5.90	1,340
52	1.209	76.10	4.99	1,140
56	1.302	80.35	4.25	967
60	1.395	83.99	3.64	828
64	1.488	87.12	3.13	712
68	1.581	89.79	2.67	607
72	1.674	92.03	2.24	510
76	1.767	93.91	1.88	428
80	1.860	95.49	1.58	359
84	1.953	96.79	1.30	296
88	2.047	97.85	1.06	241
92	2.140	98.66	.81	184
96	2.233	99.27	.61	139
100	2.326	99.67	.40	91
104	2.419	99.90	.23	52
108	2.512	100.00	.10	23

Table 4.--Computation of direct-runoff hydrograph for
100-year, 12-hour rainfall,
Bayou de Loutre near Laran

Time, in hours	Rainfall excess, in inches (Multiply each times unit hydrograph)			Total direct runoff (cfs)
	1.33	1.33	1.33	
	Direct runoff, in cfs			
0	0	-----	-----	0
4	263	0		263
8	560	263	0	823
12	892	560	263	1,720
16	1,270	892	560	2,720
20	1,700	1,270	892	3,860
24	2,190	1,700	1,270	5,160
28	2,650	2,190	1,700	6,540
32	2,860	2,650	2,190	7,700
36	2,770	2,860	2,650	8,280
40	2,460	2,770	2,860	8,090
44	2,100	2,460	2,770	7,330
48	1,780	2,100	2,460	6,340
52	1,520	1,780	2,100	5,400
56	1,290	1,520	1,780	4,590
60	1,100	1,290	1,520	3,910
64	947	1,100	1,290	3,340
68	807	947	1,100	2,850
72	678	807	947	2,430
76	569	678	807	2,050
80	477	569	678	1,720
84	394	477	569	1,440
88	321	394	477	1,190
92	245	321	394	960
96	185	245	321	751
100	121	185	245	551
104	69	121	185	375
108	31	69	121	221
112	------	31	69	100
116	------	------	31	31

ACCURACY AND LIMITATIONS

The accuracy of final hydrographs resulting from the application of methods described in this report is difficult to evaluate because of the interaction of the various factors that enter into the computations. Each factor, such as areal rainfall, rainfall excess, time distribution, lag time, and unit hydrograph, introduces error inherent in that particular item. Some of these errors tend to cancel, while others are accumulative. The standard error of some of these factors is given in the preceding sections, but no attempt has been made to mathematically combine them into a single standard error representative of the entire procedure. Instead, a random selection of storms was used to estimate the standard error.

The random selection of 42 storms was made from all storms having 3 inches or more of rainfall. Hydrographs for each storm were then computed according to the procedures of this report, and the peak discharge compared to the actual peak to obtain a graphical measure of the standard error of estimate. This error, 135 percent, is rather large and would indicate the procedures of this report are of little use. However, examination of the various sources of this error indicates the largest part of it is caused by error in computing rainfall excess. The standard error of the rainfall-excess computations is 94 percent. By adjusting the rainfall excess to the true values, thus eliminating the 94-percent error, the standard error of the peaks is reduced from 135 percent to 22 percent. This indicates that the combined effects of the lag time and unit-hydrograph relations have a standard error of 22 percent, an acceptable accuracy.

In summary, it can be said that the largest part of the error occurs in the computation of rainfall and rainfall excess. This conclusion is not new but simply points to the fact that more adequate means are necessary for defining rainfall excess from a storm. A large part of this deficiency can be overcome by the addition of more rain gages in a basin. The conversion of rainfall excess into a hydrograph can be accomplished with reasonable accuracy.

It should be noted that the errors described above are for computations of actual storms. Where the methods are used for hypothetical storms, such as might be defined in a rainfall-frequency atlas, a large part, if not all, rainfall and rainfall-excess error is eliminated, and the results will be of acceptable accuracy. Also, if the methods are used to compute an annual series of peak discharges, the large errors of individual flood peaks will be random, and a frequency curve defined by these peaks will not be greatly in error.

The practical application of the methods of this report are subject
to the following limitations:

1. Before using the unit-hydrograph method it should be ascertained
   that the general assumptions are met reasonable well. As a
   general rule, it can be assumed that the greater the deviation
   from the basic assumptions, the greater the error in the final
   hydrograph. Adjustments for these deviations should be made
   if possible. Basic assumptions are described in the section
   "Unit Hydrographs."

2. The method has not been tested for sites of less than about 2
   square miles drainage area.

3. The regionalized data should be used only within the study area.
   The synthetic unit hydrographs are similar to those for south-
   western and southeastern Louisiana, and those in southeastern
   Louisiana were found similar to those of Mitchell (1948) for
   Illinois streams. This would indicate that, if lag time is
   known, synthetic unit hydrographs could be computed for streams
   outside the study area; however, there is no conclusive evi-
   dence in this regard.

4. The methods of computing lag time and rainfall excess should
   definitely not be used outside the study area. These methods
   were derived strictly for streams within the study area, and
   streams outside the area will undoubtedly have different
   characteristics. In fact, some streams in the study area that
   have not been gaged, may have altogether different character-
   istics from those defined in this report.

5. The methods are not applicable downstream from large reservoirs
   or swamps. Flood hydrographs should be computed upstream
   from the reservoir or swamp and routed through it to account
   for storage effects.

6. The methods are not applicable for urban areas, particularly the
   methods of computing lag time and rainfall excess.

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