EFFECTS OF FOREST AND AGRICULTURAL LAND USE ON FLOOD UNIT HYDROGRAPHS

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ABSTRACT

The effects of forest and agricultural land uses on flood unit hydrographs of small catchments is the subject of this paper. A total of 105 floods from small catchments have been used in the study, of which eight are predominantly forest and 14 predominantly agricultural land-use catchments, with areas ranging from 0.12 to 7.19 square miles, situated in the eastern and central United States. Floods were caused by rainstorms of less than six hours duration.

The study is based on the unit hydrograph approach, supplemented by the regression analysis. The unit hydrograph is described by the two-parameter incomplete gamma function, enabling the computation of peak values. The regression analysis is used for the relationships among the selected hydrologic variables, and between the unit hydrograph parameters and the dominant catchment physiographic factors.

Derived unit hydrographs of flood events are affected by non-uniform distribution of rainfall. It is found that the same representative, unit hydrograph peak flow equation is applicable to both the forest and agricultural land-use catchments. The average rise time, T_a , is mainly dependent on land use and catchment physiographic factors A (area), S_2 or S_h (slopes), H (total fall), F_1 and C_f (percentage of forest cover). A concept of representative catchment, equal for all the studied river basins, is introduced, to separate the effects of geometry from those of land use.

The comparison indicates that the unit hydrographs of small catchments are significantly affected by the biological type of land use. For a given small catchment the agricultural land use means a greater flood peak with a faster surface runoff, while the forest land use means a smaller flood peak with a surface runoff. The catchments with the predominantly agricultural land use have unit hydrograph peaks approximately 2 to 4 times greater than the predominantly forest land-use catchments, with the values within the range 2-4 depending on the percent of catchment forest cover.

FOREWORD

The basis for this paper is the material contained in the Ph.D. dissertation of Dr. Wiroj Sangvaree entitled "Land-Use Effects on Flood Peaks," submitted to Colorado State University in August 1969. The results of the study have been further checked by several investigations and when necessary corrected. In the last two years, all the material presented in the thesis has been rechecked, and the results recomputed, under the supervision of the second author, V. Yevjevich. The graduate students, Shih-Min Tung, Janet Herrin, and Tat L. Wai, have cooperated in this check and revision of figures and results.

The study is based mainly on literature before the year 1969. Though several advanced studies have been produced on the subject in the last eight years, the paper was not revised in function of those results, because they have been found not to be taking into question the basic premises of this study. The major effort in the study was to separate the effects of geometry, or the geometry related parameters of catchments, from the effects of their vegetation land use, with the objective of a better discrimination of influence of the forest and agricultural land use on floods of small catchments. The results of this study clearly present that there are substantial effects of vegetation land use on the unit hydrograph characteristics.

Whenever the forest land use is replaced by the small vegetation cover, or by the agricultural land use, an increase in the flood peak of hydrographs from the same rainfall should be expected for the same flood return periods. The other aspects of flood hydrographs, such as the total volume of flood water from a given rainfall for forest land-use catchments as opposed to agricultural land-use catchments, and similar flood characteristics, were not investigated in this paper.

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Chapter I
INTRODUCTION

1-1 Estimation of Flood Characteristics for Small Catchments

The determination and prediction of flood peaks for small catchments is in great demand for comprehensive water resources planning, flood flow forecast, adequate design of various drainage systems, flood control, design of hydraulic structures, and so forth. Whenever sufficient and reliable records on stream flow are available, the characteristics of flood peak discharge should be determined directly from data. In other cases they should be determined by a combined use of the runoff and rainfall data. Only a tiny percentage of runoff from small catchments has been gaged (Giusti, 1963). Therefore, the flood peak discharges of ungaged small catchments must be estimated by using data on climatologic, physiographic and other factors of these catchments.

Estimation of flood peaks from small rural catchments. The currently used methods for the estimation of flood peak flows from small catchments are:

(1) Empirical or semi-empirical, developed by experience and judgment;

(2) Statistical, which can be further classified into flood frequency analysis by using regional data, and regression and correlation analysis in establishing the relationships of flood peak flows to rainfall and catchment factors;

(3) Rational or modified rational; and

(4) Those based on composition of flood hydrographs by using the various approaches related to the concept of unit hydrograph.

Flood flow formulas as the empirical or semi-empirical estimation methods of flood peaks were mostly originated during the period 1850 to 1890; they continued to proliferate until recently. These formulas give often satisfactory but occasionally very crude results. The approach relies heavily on experience and judgment of practitioners. At present, they are considered inadequate engineering techniques of a relatively small accuracy.

The flood frequency analysis is a good method for predicting floods whenever sufficient data are available. The accuracy depends on the size and reliability of available samples. Results are subject to significant uncertainties in case of small catchments, especially those with less reliable data.

Regression and correlation analysis is used mainly to establish relationships between hydrologic variables (Chow, 1964, Section 8-II). Many investigation results are available from the correlation of hydrograph peak flows and various hydrologic factors (Dickinson, et al, 1967). The prediction equations are often based on limited amount of data, and they disregard the effect of land use.

Rational methods and the unit hydrograph methods are currently used by engineers and hydrologists, because their physical meaning is reasonably clear. The rational methods should be used with an extreme caution. The five methods currently either used or recommended for estimating floods from extreme rainfall are: Rational Formula (Kuichling, 1889; Lloyd-Davis, 1906); the US Soil Conservation Service method (Hydrology, SCS Handbook, 1957); the Bureau of Public Roads method (Potter, BPR Hydraulic Design Series, 1961); Chow's method (Chow, 1962); and Tacitly Maximized Peaks method (Reich and Hiemstra, 1965). Results of their comparisons indicate that none of the five methods is reliable.

Effects of vegetation cover on components of hydrologic cycle. It has been recognized for some time that the vegetation cover influences a number of components in the hydrologic cycle (Chow, 1964, Section 21-22; Bruce and Clark, 1966). These components include direct interception of a part of precipitation by vegetation, reduction of evaporation from soil, increase of infiltration by opening up soil channels through development of roots, depletion of soil moisture by evapotranspiration, trapping and shading of snowpack, binding the soil against erosion, factors affecting the hydraulic characteristics of overland flow, and so forth.

Beneficial effects of vegetation are: (1) Ground shading, minimizing wind influence; (2) Spreading of water flow over the land surface and thus retarding the surface runoff and increasing the infiltration; (3) Developing of a more porous soil texture within the root zone as the result of building up and maintaining the organic content of the soil; (4) Establishing and maintaining the undecomposed or partly decomposed organic matter at or near the soil surface; and (5) Increasing of storage capacity and infiltration of the soil, resulting in lesser erosion and lesser gully formation.

Forest versus agricultural catchments. Forest catchments in the United States are predominantly covered by deciduous or coniferous trees associated with other small trees, shrubby species and grassland. Forest catchments are mostly located on rough, poor soil mountainous area (Sopper and Lull, 1967, p.99). Forest land is generally regarded as an area of optimum infiltration and negligible overland flow (Sopper and Lull, 1967, pp. 247 and 545). Soils under undisturbed forests have characteristics that are favorable for infiltration, such as porous channels caused by roots and activity by soil organisms, organic matter in the surface layers, and accumulation of organic debris (Auten, 1933; Lassen et al, 1951). Forest vegetation has deep root zone development that increases the amount of detained water in the soil storage. They reduce the overland flow and affect the surface-runoff hydrograph resulting from a storm rainfall (Sopper and Lull, 1967, p. 545). The removal of forest vegetation affects interception, snowmelt, soil moisture and infiltration rate, and increases the total runoff (Hoover, 1944; Love, 1955; Garstka et al, 1958; Anderson and Gleason, 1960). The amount of increased surface runoff and peak flows caused by heavy rainstorm of the forested catchments, whose vegetation has been removed, vary according to the rainstorm and catchment characteristics (Sopper and Lull, 1967, p. 551).

Agricultural catchments are mainly covered by small plants, crops and herbaceous vegetation, which have shallow root zone, and intercept lesser amounts of precipitation than forest trees (Chow, 1964, Section 6). Agricultural areas possess smaller water storage capacities. A larger surface runoff is expected from high intensity rainfall. The runoff from agricultural catchments is regarded sometimes as nonvirgin flow, because it is influenced by man's works, such as land-use practices, farm practices and small water diversions. The study of the effects of vegetation cover and land-use practices, especially the use of terraces in conjunction with rotation contour cropping, on peak flows of short return period floods from small agricultural catchments indicates that they decrease the number and the average magnitude of peak flows (Hobbs, 1946).

An exploratory study of the effects of land use upon the hydrograph rise time (Om Kar, 1967) showed a general trend of the rise time being longer for the forested catchments and shorter for the others. Bell (1967) also found that the representative lag time or the median lag time of small catchments covered by forest and good-wood land is longer than those of small catchments covered by crops and poor to fair pasture. Therefore, an agricultural land-use catchment is expected to have a greater unit hydrograph peak flow than the forested catchment.

1-2 Needs for Study of Land-Use Effects on Flood Peaks

Various developments have brought into focus the need for accurate techniques related to flood control design practices for small catchments. Usually a large number of small or moderate-size relatively unexpensive structures are involved in these developments. However, the total expenditure is substantial for a region. Advanced techniques are needed for the economical and accurate designs of typical flood control and drainage structures, which are used many times along the channels of small catchments.

A need exists for detailed investigations of effects of various catchment factors on flood hydrograph parameters. This should be paralleled by studies for a proper understanding of hydrologic physical processes of small catchments, leading to a more accurate prediction of flood peak discharges by the appropriate methods.

A classical hydrologic problem of the past has been the determination of effects of forests on floods in comparison with the flood characteristics of small catchments with the agricultural land use. The more detailed ramifications of the problem are: (a) Do forest land use produces smaller flood peaks than the agricultural land use for all the other flood-affecting factors being the same at a small catchment? (b) Do substantial differences exist in the catchment responses of these two land uses? (c) Are these responses linear or non-linear, and in such a way that the forest land use produces smaller flood peaks for moderate flood return periods and approximately the same or even greater flood peaks for the large return periods (extreme floods) than the agricultural land use? (d) How do the flood characteristics change when the small catchments undergo various modifications in the forest and agricultural land uses?

It is somewhat easier to study the effects of urbanization on floods, because of the relatively simple effects of urban impervious areas on surface runoff, drainage, evaporation, soil moisture and groundwater replenishments, water quality, etc., than to study the effects of vegetation covers, and changes in them, on floods. Significant attention has been given to hydrologic effects of urbanization in recent years. Because of complexities in the effects, however, the classical hydrologic problems of biological land-use effects on runoff cycle in general, and on floods in particular, seem to have been somewhat neglected. Therefore, the study presented in this paper represents an attempt to revive some aspects of research of these classical problems.

1-3 Study Objectives

Past investigations show that land use is an important factor which affects the runoff hydrograph. Because of complex interactions of different aspects of land use, it is difficult to discriminate their effects individually. Two basic reasons are responsible for it. First, the shape of hydrographs of small catchments is not solely dependent on land use; it is affected by a large number of other factors, primarily climatic and physiographic. These hydrologic factors are more or less mutually dependent. All the physical relations which govern their behavior are not yet well understood. A separation of these individual effects on the runoff hydrograph most often is not a simple task. Second, differences in effects of various types of land use are of the same order of magnitudes as the errors in observations of rainfall, runoff, and some climatic and physiographic factors.

The objective of this paper is to develop a method to discriminate the effects of forest and agricultural land uses on flood hydrographs from small catchments. In more details, this objective translates into:

(1) An investigation of relations between the dominant physiographic factors which affect the flood hydrographs of small catchments;

(2) A determination of relations between the parameters of unit hydrographs and the dominant physiographic factors and rainstorm variables of small catchments; and

(3) A comparison of flood flow responses of forest and agricultural land-use catchments.

1-4 Procedures to be Used in Investigations

The unit hydrograph concept, supplemented by the use of correlation and regression analysis, is the basis of the study. A mathematical expression for the unit hydrograph, in the form of the two-parameter incomplete gamma function as developed theoretically by using the systems approach (Edison, 1951), is applied in derivation of the general flood peak discharge equation.

Correlation and regression are used to investigate the relations between the hydrologic variables, namely:

(1) Relations between the dominant physiographic factors of small catchments;

(2) Equations for the prediction of unit hydrograph peak discharges; and

(3) Relations between the unit hydrograph parameters and the dominant physiographic factors and rainstorm variables.

Chapter II
ANALYTICAL CONSIDERATIONS

2-1 Unit Hydrograph Theory

The basic assumptions of the unit hydrograph theory are: (i) Effective rainfall occurs at a uniform time rate during the selected unit hydrograph interval; (ii) Effective rainfall is uniformly distributed over the whole catchment for which the unit hydrograph is developed and applied; (iii) Ordinates of the direct-runoff hydrographs are proportional to those of the unit hydrograph, or the total direct runoff of each hydrograph is proportional to the volume of unit hydrograph; and (iv) Unit hydrograph reflects the combined effects of all the physical characteristics of a catchment.

These assumptions are only approximately satisfied for any catchment. It is often claimed, and practiced, that in case of flood events carefully selected for small catchments these assumptions are not significantly violated, with approximations acceptable for practical purposes (Chow, 1964, Section 14).

2-2 Linear Catchment Systems

The systems approach to unit hydrograph has given an impetus to advanced theoretical analysis (Dooge, 1959, 1967). In this approach the catchment is considered without taking into account the complexity and details of physical laws involved in its response.

An ideal system is one that has constant parameters (all fundamental properties of the system are invariant with respect to time) and linear characteristics (the response characteristics are homogeneous and additive). Naturally, all real physical systems display nonlinear response characteristics under sufficiently extreme input conditions and common nonlinearities usually occur gradually rather than abruptly (Bendat and Piersol, 1966). The response characteristics of many catchments have been assumed to be linear, at least over some limited range of inputs, without large errors.

2-3 Equations of Unit Hydrograph

Mathematical expressions proposed by Edson (1951) for the unit hydrograph lead to a generalized gamma function

$$U_t = \frac{\beta^{\alpha+1}}{\Gamma(\alpha+1)}\, t^{\alpha}\, e^{-\beta t} \qquad (2\text{-}1)$$

The quantities $m = \alpha$ and $k = \beta$ are the unit hydrograph parameters given by Edson. Equation 2-1 gives for the peak discharge, or for $t = T_r$ = the time to peak and $dU_t/dt = 0$, $\beta = \alpha/T_r$, so that it becomes

$$U_t = \frac{1}{\Gamma(\alpha+1)}\left(\frac{\alpha}{T_r}\right)^{\alpha+1} t^{\alpha}\, e^{-\left(\frac{\alpha}{T_r}\right)t}, \qquad (2\text{-}2)$$

with the peak ordinate

$$U_p = \frac{1}{\Gamma(\alpha+1)}\, \alpha^{\alpha+1}\, e^{-\alpha}\, \frac{1}{T_r}\ . \qquad (2\text{-}3)$$

Approximations in Eq. 2-3 are

$$C_\alpha = \frac{1}{\Gamma(\alpha+1)}\, \alpha^{\alpha+1}\, e^{-\alpha} = \frac{1}{\Gamma(\alpha)}\, \alpha^{\alpha} e^{-\alpha} \approx 0.3989\alpha^{0.5},$$

for $\alpha \geq 2$, and

$$C_\alpha \approx 0.3549\ \alpha^{0.615} \text{ for } 1 \leq \alpha < 2. \qquad (2\text{-}4)$$

A comparison between the estimated values by these approximations of C_α and the exact values of C_α, with deviations smaller than 5%, is given in Fig. 2-1. Multiplying both sides of Eq. 2-3 by T_e = the effective rainfall duration, and combining it with C_α, the peak flow U_pT_e, expressed per unit effective rainfall intensity I_e and per unit area as $q_p/I_e = U_pT_e/A\,I_e$, with A = the catchment area, can then be estimated by

$$\frac{q_p}{I_e} = C_\alpha \frac{T_e}{T_r}\ . \qquad (2\text{-}5)$$

With the two approximations of C_α, Eq. 2-5 becomes

$$\frac{q_p}{I_e} = 0.3989\ \alpha^{0.5}\ \frac{T_e}{T_r}\ ,\quad \alpha \geq 2 \qquad (2\text{-}6)$$

and

$$\frac{q_p}{I_e} = 0.3549\ \alpha^{0.615}\ \frac{T_e}{T_r}\ ,\ 0.1 \leq \alpha < 2\ , \qquad (2\text{-}7)$$

with q_p = the peak flow per unit area, I_e = the average effective rainfall intensity, and T_e = the effective rainfall duration.

Combining Eqs. 2-2 and 2-3, the dimensionless unit hydrograph becomes

$$\frac{U_t}{U_p} = e^{\alpha}\left(\frac{t}{T_r}\right)^{\alpha} e^{-\alpha\frac{t}{T_r}}\ , \qquad (2\text{-}8)$$

with U_t/U_p = the ordinates and t/T_r the abscissa of the dimensionless unit hydrograph.

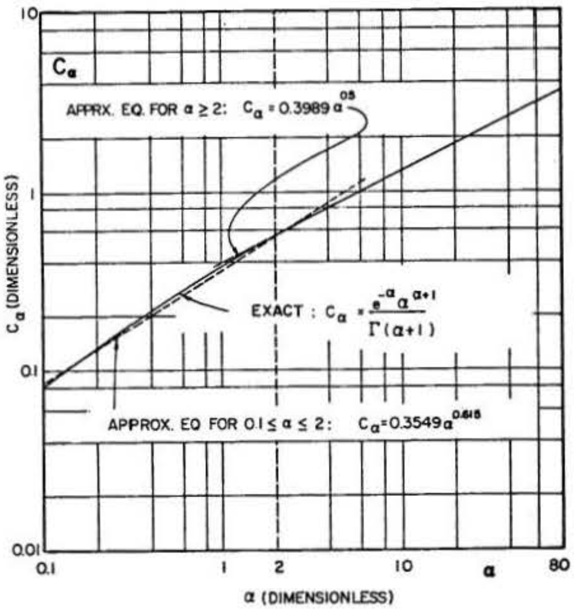


Fig. 2-1. Comparison of approximate and exact values of C_α for the ranges: $\alpha \geq 2$, and $1 \leq \alpha < 2$.

Chapter III
RESEARCH DATA ASSEMBLY

3-1 Selection of Catchments and Flood Events for Investigation

Catchments having areas smaller than 10 square miles were chosen for this study in order to minimize the effects caused by areal variation of rainfall and to avoid the heterogeneity in properties of large catchments. A distinct characteristic of most small catchments is that the overland flow rather than the channel flow is a dominating factor which affects the peak flow. They are very sensitive to high intensity rainfall of short duration and to the land use (Chow, et al, 1957). The total contribution to runoff by groundwater, channel interception and interflow is usually small for small catchments (Gray, 1962), with hydrographs mainly produced by surface runoff.

The small catchments of 100% forest cover and 100% agricultural land use were considered most desirable for this study. However, it was not feasible to find a sufficient number of such ideal catchments with pertinent data available. Therefore, the experimental small catchments of areas between 0.1 to 10 square miles, with 50% or more forest and/or agricultural land use were selected as study catchments. Selection is limited to those small catchments that have been assembled in a prescribed manner at Colorado State University as the part of the current program of hydrology of small catchments.

Eight forested and fourteen agricultural land use small catchments of areas ranging from 0.12 to 7.19 square miles, located throughout the eastern and central United States, were chosen. The 105 selected flood events from these catchments were mainly caused by rainstorms of short duration, all of a shorter duration than six hours. A detailed description and location of selected catchments are presented in Tables 3-1 through 3-3, and in Fig. 3-1.

Table 3-1. Small Catchments and Their Flood Events Selected for Investigation.

Type of Catchment	Range of Areas (sq. mi.)	Number of Catchment	Number of Flood Events
Forest	0.30 - 7.19	8	32
Agricultural	0.12 - 3.01	14	73
Combined	0.12 - 7.19	22	100

3-2 Selection of Hydrologic Variables

A large number of rainfall variables, basin physiographic factors and unit hydrograph parameters have been advanced in various investigations of their relationships in hydrologic literature. The selection of dominant variables is mostly based on experience on how they may be interrelated. The factors which most affect the flood peak discharge of small catchments, used in this study, are first given, namely:

A. *Unit hydrograph parameters*

(1) U_p , the peak flow

(2) T_r , the rise time

(3) T_a , the average rise time

(4) α , the shape factor.

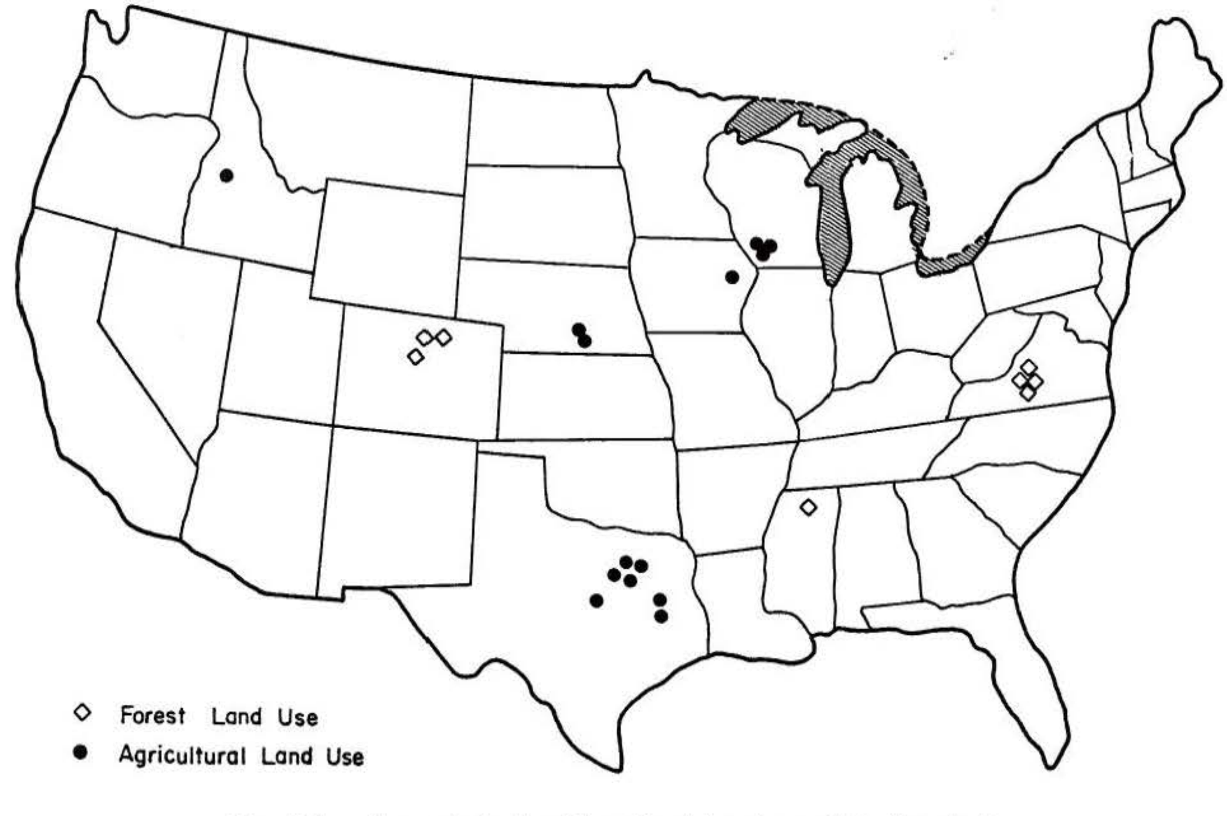


Fig. 3-1. Approximate location of catchments used in the study.

Table 3-2. Description and Location of Selected Small Catchments, and the Number of Flood Events Used for Each of Them

Order No.	Catchment No.	Name and location	State	Area Sq. mi.	Number of Events	Classification
1	10606104	Lower Fool Creek at Fraser Exp. Forest	Colorado	1.12	3	F
2	10606105	East St. Louis Creek at Fraser Exp. Forest	Colorado	3.10	5	F
3	10608004	Lower Missouri Gulch Manitou Exp. Forest	Colorado	7.19	3	F
4	11204004	Moscow, W-2	Idaho	0.11	3	A
5	11511001	Ralston Creek at Iowa City	Iowa	3.01	4	A
6	12412006	Oxford, W-24	Mississippi	0.80	3	F
7	12707001	Hastings, W-3	Nebraska	0.74	5	A
8	12707002	Hastings, W-5	Nebraska	0.64	5	A
9	14309001	Riesel, C, (Waco)	Texas	0.90	6	A
10	14309002	Riesel, D, (Waco)	Texas	1.74	6	A
11	14309005	Riesel, W-1, (Waco)	Texas	0.28	6	A
12	14309006	Riesel, W-2, (Waco)	Texas	0.20	6	A
13	14309007	Riesel, Y, (Waco)	Texas	0.48	5	A
14	14309008	Riesel, Y-2, (Waco)	Texas	0.21	7	A
15	14309009	Riesel, Y-4, (Waco)	Texas	0.12	6	A
16	14618008	Fosters Creek, W-1, Blacksburg	Virginia	0.61	3	F
17	14618007	Little Winns Creek, W-1, Blacksburg	Virginia	2.30	5	F
18	14618008	Pony Mountain Branch, W-1, Blacksburg	Virginia	0.30	5	F
19	14618010	Rocky Run Branch, W-1, Blacksburg	Virginia	0.87	5	F
20	14911001	Fennimore, W-1	Wisconsin	0.52	5	A
21	14911002	Fennimore, W-4	Wisconsin	0.27	6	A
22	14911003	Colby, W-1	Wisconsin	0.54	3	A

F = Forested, A = Agricultural

Table 3-3. Percentages of Areal Coverage by Each Land Use for Selected Catchments

Order No.	Catchment No.	State	Bare or Idle %	Grass or Pasture %	Cultivated %	Wood land or Forest %	Impervious %	Classification
1	10606104	Colorado				100		F
2	10606105	Colorado				100		F
3	10608004	Colorado				100		F
4	11204004	Idaho		49	51			A
5	11511001	Iowa		35	45	20		A
6	12412006	Mississippi	35	3	3	59		F
7	12707001	Nebraska		15	82		3	A
8	12707002	Naebrska		10	87		3	A
9	14309001	Texas		28	69		3	A
10	14309002	Texas		24	73		3	A
11	14309005	Texas		17	78		5	A
12	14309006	Texas		30	65		5	A
13	14309007	Texas		41	57		2	A
14	14309008	Texas		31	68		1	A
15	14309009	Texas		31	68		1	A
16	14618006	Virginia	11	26	15	46	2	F
17	14618007	Virginia	11	9	22	58		F
18	14618008	Virginia		30	17	52	1	F
19	14618010	Virginia	19	9	18	54	1	F
20	14911001	Wisconsin		16	79		5	A
21	14911002	Wisconsin		13	81		6	A
22	14911003	Wisconsin		21	65	11	3	A

Table 3-4. Physiographic Factors of Selected Catchments

Order No.	Catchment No.	A sq. mi.	H ft.	L mi.	L_c mi.	S_1 ft./mi.	S_2 ft./mi.	C_f %	F_1	$S_h \times 10^5$ $(ft./mi.)^2$
					Forested Catchments					
1	10606104	1.12	1965	2.38	1.02	826	781	100	2.168	34.475
2	10606105	3.10	3263	4.57	2.00	714	588	100	2.948	34.346
3	10608004	7.19	1484	5.62	2.92	264	237	100	2.282	3.063
4	12412006	0.80	217	1.40	0.81	155	85	59	1.418	0.589
5	14618006	0.61	101	0.61	0.42	101	69	46	0.420	0.167
6	14618007	2.30	167	2.30	1.39	73	43	58	1.390	0.121
7	14618008	0.30	451	0.86	0.45	663	276	52	1.290	6.780
8	14618010	0.87	109	1.70	0.76	64	47	54	1.485	0.137
					Agricultural Catchments					
1	11204004	0.28	106	0.86	0.41	123	65	51	1.259	0.4013
2	11511001	3.01	149	3.99	2.07	37	27	45	2.744	0.0738
3	12707001	0.74	75	1.64	0.48	46	40	82	1.064	0.0760
4	12707002	0.64	112	1.45	0.78	77	37	87	1.767	0.1960
5	14309001	0.90	51	1.70	0.67	30	26	69	1.266	0.0289
6	14309002	1.74	64	2.66	1.21	23	17	73	1.850	0.0235
7	14309005	0.28	50	1.02	0.47	49	50	78	1.712	0.0893
8	14309006	0.20	46	0.57	0.24	81	80	65	0.684	0.1058
9	14309007	0.48	52	0.91	0.47	57	54	57	0.891	0.0563
10	14309008	0.21	51	0.66	0.30	77	60	68	0.943	0.1239
11	14309009	0.12	45	0.51	0.24	88	72	68	1.020	0.1688
12	14911001	0.52	133	1.09	0.52	122	102	79	1.090	0.3402
13	14911002	0.27	90	0.60	0.27	150	134	81	0.600	0.3000
14	14911003	0.54	78	1.29	0.68	60	47	65	1.624	0.1128

Table 3-5. Mean, Median and Standard Deviation of Physiographic Factors of Selected Catchments

Type of Catchment	Statistical Parameters	A sq. mi.	H ft.	L mi.	L_c mi.	S_1 ft./mi.	S_2 ft./mi.	C_f %	F_1	$S_h \times 10^5$ $H^2/mi.^2$
Forest	Mean	2.036	970	2.430	1.221	358	266	71	1.675	9.960
	Median	0.995	334	2.000	0.915	210	161	59	1.415	1.826
	St. Deviation	2.285	1164	1.779	0.860	321	278	24	0.769	15.261
Agri-cultural	Mean	0.709	79	1.354	0.629	73	58	71	1.322	0.150
	Median	0.500	70	1.175	0.475	68	52	71	1.175	0.109
	St. Deviation	0.781	34	0.955	0.489	38	32	14	0.570	0.119
Combined	Mean	1.192	403	1.745	0.845	176	134	71	1.451	3.717
	Median	0.590	104	1.345	0.595	79	63	68	1.340	0.152
	St. Deviation	1.595	803	1.379	0.693	234	192	18	0.654	10.049

B. *Rainstorm variables*

(1) T_e , the effective rainfall duration

(2) I_e , the average effective rainfall intensity

(3) M_1 , the first moment of effective hyetograph

(4) M_2 , the second moment of effective hyetograph

(5) M_2' , the second central moment of effective hyetograph

(6) R_1 , the first moment of observed hyetograph

(7) R_2 , the second moment of observed hyetograph

(8) R_2' , the second central moment of observed hyetograph.

C. *Catchment physiographic factor*

(1) A , the area

(2) H , the total fall

(3) L , the main stream length

(4) L_c , the length to centroid of area

(5) S_1 , the main stream slope

(6) S_2 , the average main slope

(7) Forest and agricultural types of land uses

(8) C_f , the percentage of forest or agricultural cover

(9) F_1 , or LL_c/A , the shape factor

(10) S_h , or H^2/A , the relief factor.

The values of these physiographic factors for the selected catchments are shown in Table 3-4 and their statistical parameters are given in Table 3-5.

3-3 Research Data

Hydrologic data assembled for this study are from the *Small Watershed Program* of Department of Civil Engineering of Colorado State University (Yevjevich and Holland, 1967). High-quality hydrologic data, previously recorded and complied by various US federal and state agencies, have been further processed, punched on data processing cards, and mounted on magnetic tape for permanent storage and continuous use. The type of data of interest consists of stream discharge obtained from continuous stage records, rainfall from both recording and non-recording gages, and topographic features of catchments. The types of catchments selected can be described as predominantly rural or forested with areas less than 40 square miles, drained by natural channels.

3-4 Preliminary Data Processing

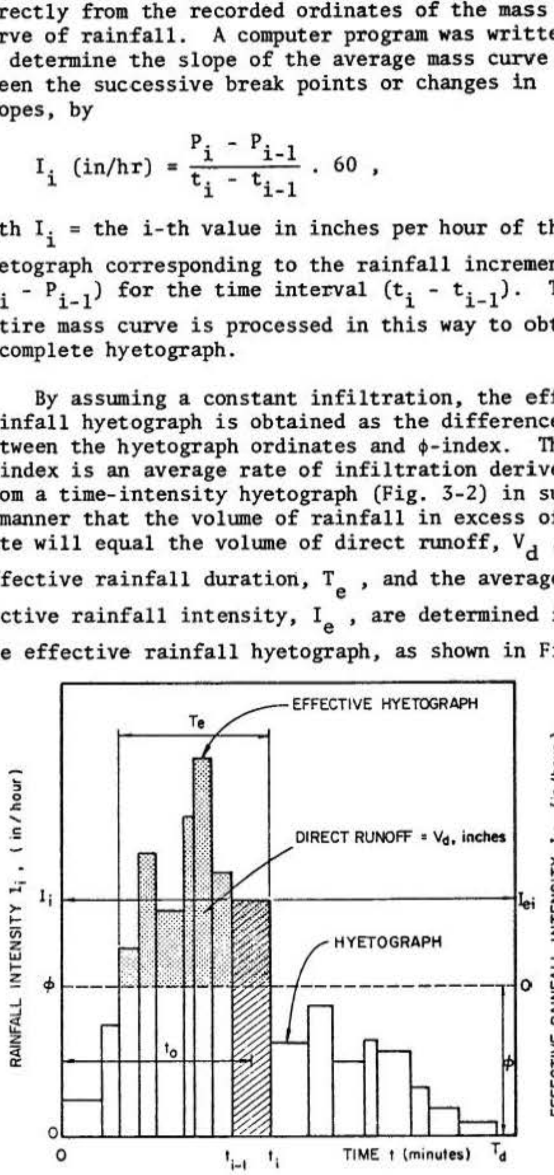
The physiographic factors of selected small catchments were computed from topographic maps and mounted on a magnetic tape. The types of land use and the percentage of cover were obtained from the original data as determined by the US federal and state agencies, responsible for experimental catchments. The parameters of unit hydrographs and rainfall variables were determined from the recorded discharge hydrographs and rainfall mass-curves, respectively. Methods of data processing are discussed briefly, and the results for the 105 flood hydrographs and rainfall hyetographs are summarized in Appendix C.

Derivation of average hyetographs and average effective hyetographs. The hyetograph is determined directly from the recorded ordinates of the mass curve of rainfall. A computer program was written to determine the slope of the average mass curve between the successive break points or changes in slopes, by

$$I_i \text{ (in/hr)} = \frac{P_i - P_{i-1}}{t_i - t_{i-1}} \cdot 60 , \qquad (3\text{-}1)$$

with I_i = the i-th value in inches per hour of the hyetograph corresponding to the rainfall increment $(P_i - P_{i-1})$ for the time interval $(t_i - t_{i-1})$. The entire mass curve is processed in this way to obtain a complete hyetograph.

By assuming a constant infiltration, the effective rainfall hyetograph is obtained as the differences between the hyetograph ordinates and ϕ-index. The ϕ-index is an average rate of infiltration derived from a time-intensity hyetograph (Fig. 3-2) in such a manner that the volume of rainfall in excess of this rate will equal the volume of direct runoff, V_d . The effective rainfall duration, T_e , and the average effective rainfall intensity, I_e , are determined from the effective rainfall hyetograph, as shown in Fig. 3-2.



$$I_{ei} = I_i - \phi \text{, in./hour; } I_e = \frac{V_d \times 60}{T_e} \text{, in./hour;}$$

$$t_o = t_i - \frac{t_i - t_{i-1} - 1}{2} \text{ minutes}$$

Fig. 3-2. Definition of hyetograph and effective hyetograph

Calculations of hyetograph moments. The weighted moments of the hyetograph and the effective hyetograph are computed by

$$M_n = \frac{\sum_{i=1}^{n} I_i \cdot (t_i - t_{i-1}) \cdot [t_i - (t_i - t_{i-1})/2]^n}{\sum_{i=1}^{n} I_i \cdot (t_i - t_{i-1})} \tag{3-2}$$

where M_n = the n-th moment about the beginning of the hydrograph, I_i for the hyetograph and I_{ei} for the effective hyetograph = the rainfall intensity which occurs over the interval $t_i - t_{i-1}$, and $t_i - (t_i - t_{i-1})/2$ = the distance from the beginning to the center of the interval in question.

The second central moment is calculated by

$$M_2' = M_2 - M_1^2 \ , \tag{3-3}$$

where M_2' = the second central moment.

Determination of unit hydrograph. Assuming a constant base flow for the initial discharge Q_o greater than zero (in most cases the initial discharge was approximately zero), the ordinates of the unit hydrograph are calculated by

$$U_t = \frac{Q_t - Q_o}{V_d} \ , \text{ with } V_d = V - V_b \ , \tag{3-4}$$

where U_t = the unit hydrograph ordinate at time t, Q_t = the corresponding hydrograph ordinate, V = the total runoff, V_d = the direct runoff, and V_b = the assumed groundwater runoff. Once the unit hydrograph is calculated, its peak flow, U_p , and its time to peak (the rise time), T_r , are determined as shown in Fig. 3-3. The approximate values of C_α of Eq. 2-4 are used for $\alpha \geq 2$, $0.1 \leq \alpha < 2$, respectively.

3-5 Research Approach in Discrimination of Land-Use Effects on Unit Hydrograph

The shapes of unit hydrographs of small catchments are affected by a large number of climatic and physiographic factors. To discriminate the effect of land use on peak flows of the unit hydrograph, all the effects which are due to the other hydrologic factors should be removed. This is not feasible in case the original data of flood hydrographs are used.

In this study, only the effects of the dominant physiographic factors of small watersheds, as well as of some rainstorm and other hydrologic factors, are removed by the following procedure:

(1) Catchments are selected with small variations of area and shape factor;

(2) Flood events are selected for short duration rainstorm so that the unit hydrograph method was easy to apply, with some hydrologic variables not necessary to include into relations;

(3) Relations between the selected physiographic factors and rainstorm variables are established by the correlation and regression analysis, so that the highly correlated variables could be excluded when their effects have been taken into account by the included variables;

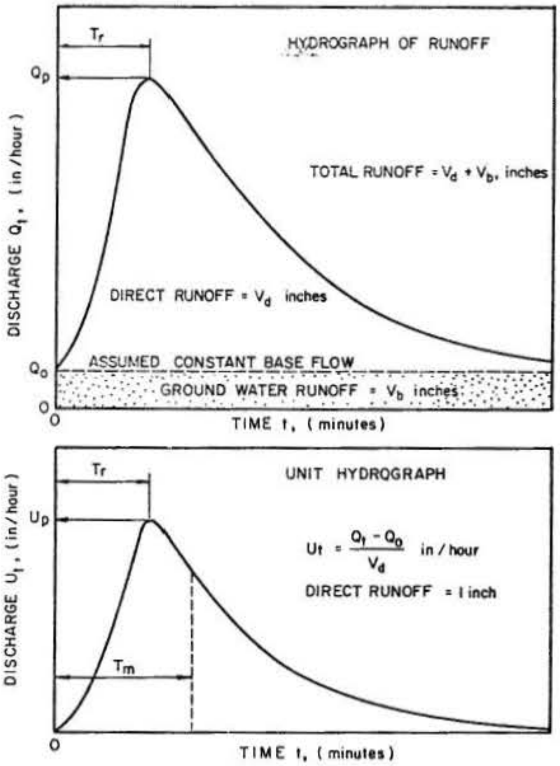


Fig. 3-3. Definition of hydrograph and unit hydrograph

(4) The use of the representative unit hydrograph and of the peak flow equations of the hydrograph reduces much of the effects of climatic and physiographic factors of small catchments to a typical small catchment; in other words, the effects of dominant rainfall and physiographic factors on the unit hydrograph are represented by its rise time and shape factor;

(5) The use of prediction equation for the average rise time by applying the correlation and regression analysis reduces the effects of representative physiographic factors of small catchments to the catchment time characteristic factor (T_a), which is equivalent to the average rise time (not significantly affected by the selected rainstorm variables), with the unit hydrograph and its peak flow for given T_a dependent mainly on catchment characteristics; and

(6) The selection of a representative small catchment, by using the median values of dominant physiographic factors of all the small catchments studied, removes the effects of dominant physiographic factors of individual catchments, thus leaving the effects of land use only.

All the unit hydrographs and their peak flows can then be reduced to the characteristics of the selected, representative small catchment. A comparison of so modified unit hydrographs of small catchments with different land uses then permits the discrimination of the effects of forest and agricultural land uses on flood peaks.

Chapter IV
ANALYSIS OF SELECTED DATA

4-1 Dependence Among Catchment Factors and Among Rainstorm Variables

Correlation among the selected catchment factors and among the rainfall variables were investigated so that some of the highly correlated factors or variables, say with the correlation coefficients of $|R| > 0.9$, can be excluded with their effects taken into account by the included factors or variables. This approach reduced the number of *independent* variables in the relations between the unit hydrograph parameters and the selected factors or variables by the regression analysis. Both the original values and their logarithms of the catchment factors and rainstorm variables were analyzed in this correlation. A stepwise multiple linear regression program was used to estimate the relations among the catchment factors and among the rainstorm variables.

Results of the correlation analysis are shown in Tables 4.1 through 4.12, with $|R| \geq 0.90$ designated with an asterisk. They indicate that many factors or variables are highly mutually correlated, therefore dependent. From the highly correlated factors or variables, a single variable may represent the effects of other factors or variables. The following factors or variables are selected as representative:

(1) In case of the geometric factors of catchments (Tables 4-1 through 4-6):

$$A,\ H,\ S_2 \text{ or } S_h\ ,\ F_1 \text{ and } C_f\ ,$$

with A representing A, L, and L_c ; and either S_2 or S_h to represent S_1 , S_2 and S_h ; and

(2) In case of the rainstorm variables (Tables 4-7 through 4-12):

$$M_1\ ,\ M_2' \text{ and } T_e\ ,$$

with M_1 representing M_1 , M_2 , R_1 and R_2 , and M_2' representing R_2' and M_2' .

Relations between the catchment physiographic factors of combined catchments (both forest and agricultural land-use catchments) are given in Table 4-13 and plotted in Figs. 4-1 through 4-4. Regression equations presented in Table 4-13 are designated by Eqs. 4-1 through 4-4. Equation 4-4 offers a way of determining S_2 from S_h and F_1 , or indirectly by Eqs. 4-1 through 4-4 from A, H, L and L_c . Table 4-13 provides the multiple correlation coefficient (R), the the square of the multiple correlation coefficient (R^2), and the standard error of estimates (S_{ey}).

4-2 Prediction Equation for Peak Flow of Unit Hydrographs

To develop the peak flow equation of unit hydrographs for a particular group of small catchments, their C_α values must be estimated. The flow equation is then obtained by using these C_α values. Three

Table 4-1. Correlation Matrix of Physiographic Factors for Forest Catchments

A	L	L_c	H	S_1	S_2	F_1	S_h	C_f
A	.920*	.970*	.432	-.035	.091	.565	.032	.654
L		.981*	.718	.222	.373	.832	.368	.845
L_c			.589	.085	.231	.728	.211	.763
H				.738	.843	.893	.887	.891
S_1					.924*	.591	.872	.604
S_2						.697	.965*	.785
F_1							.725	.901*
S_h								.746

Table 4-2 Correlation Matrix of Logarithms of Physiographic Factors for Forest Catchments

log A	log L	log L_c	log H	log S_1	log S_2	log F_1	log S_h	log C_f
log A	.911*	.967*	.516	.020	.181	.582	.172	.724
log L		.978*	.715	.278	.419	.862	.438	.871
log L_c			.638	.175	.312	.763	.326	.811
log H				.859	.928*	.779	.932*	.927*
log S_1					.970*	.529	.979*	.633
log S_2						.592	.991*	.771
log F_1							.650	.824
log S_h								.761

Table 4-3. Correlation Matrix of Physiographic Factors for Agricultural Catchments

A	L	L_c	H	S_1	S_2	F_1	S_h	C_f
A	.986*	.979*	.518	-.540	-.552	.817	-.387	-.395
L		.976*	.508	-.605	-.638	.860	-.415	-.320
L_c			.571	-.527	-.581	.902*	-.343	-.394
H				.283	.086	.505	.497	-.138
S_1					.906*	-.551	.914*	.147
S_2						-.672	.692	.222
F_1							-.295	-.295
S_h								.068

Table 4-4 Correlation Matrix of Logarithms of Physiographic Factors for Agricultural Catchments

	log A	log L	log L_c	log H	log S_1	log S_2	log F_1	log S_h	log C_f
log A		.975*	.948*	.501	-.695	-.760	.697	-.534	-.223
log L			.968*	.473	-.743	-.826	.917	-.544	-.213
log L_c				.528	-.668	-.785	.874	-.464	-.292
log H					.238	.015	.406	.454	-.152
log S_1						.924	-.594	.946	.119
log S_2							-.748	.797	.164
log F_1								-.324	-.270
log S_h									.082

Table 4-5. Correlation Matrix of Physiographic Factors for Combined (Forest-Agricultural) Catchments

	A	L	L_c	H	S_1	S_2	F_1	S_h	C_f
A		.931*	.957*	.529	.196	.254	.642	.219	.384
L			.981*	.667	.319	.392	.844	.423	.443
L_c				.594	.263	.321	.809	.333	.352
H					.817	.881	.664	.914*	.644
S_1						.945*	.428	.894	.439
S_2							.477	.965*	.588
F_1								.557	.406
S_h									.567

Table 4-6. Correlation Matrix of Logarithms of Physiographic Factors for Combined (Forest-Agricultural) Catchments

	log A	log L	log L_c	log H	log S_1	log S_2	log F_1	log S_h	log C_f
log A		.949*	.965*	.618	.106	.110	.646	.253	.228
log L			.971*	.643	.127	.140	.936	.309	.344
log L_c				.656	.154	.138	.802	.318	.230
log H					.836	.821	.567	.917*	.437
log S_1						.969*	.183	.975*	.338
log S_2							.167	.955*	.453
log F_1								.370	.346
log S_h									.422

Table 4-7. Correlation Matrix of Rainstorm Variables for Forest Catchments

	M_1	M_2	M_2'	R_1	R_2	R_2'	T_e
M_1		0.947*	0.461	0.993*	0.939*	0.429	0.428
M_2			0.379	0.942*	0.986*	0.331	0.307
M_2'				0.484	0.416	0.848	0.844
R_1					0.952*	0.486	0.482
R_2						0.438	0.407
R_2'							0.979*

Table 4-8. Correlation Matrix of Logarithms of Rainstorm Variables for Forest Catchments

	log M_1	log M_2	log M_2'	log R_1	log R_2	log R_2'	log T_e
log M_1		0.998*	0.295	0.997*	0.995*	0.359	0.501
log M_2			0.329	0.997*	0.998*	0.393	0.528
log M_2'				0.297	0.327	0.900*	0.697
log R_1					0.999*	0.361	0.515
log R_2						0.391	0.542
log R_2'							0.639

Table 4-9. Correlation Matrix of Rainstorm Variables for Agricultural Catchments

	M_1	M_2	M_2'	R_1	R_2	R_2'	T_e
M_1		0.961*	0.661	0.977*	0.942*	0.701	0.698
M_2			0.677	0.948*	0.982*	0.732	0.690
M_2'				0.715	0.732	0.956*	0.803
R_1					0.966*	0.779	0.763
R_2						0.809	0.755
R_2'							0.898

Table 4-10. Correlation Matrix of Logarithms of Rainstorm Variables for Agricultural Catchments

	log M_1	log M_2	log M_2'	log R_1	log R_2	log R_2'	log T_e
log M_1		0.995*	0.403	0.965*	0.953*	0.248	0.665
log M_2			0.451	0.969*	0.966*	0.290	0.716
log M_2'				0.409	0.452	0.816	0.695
log R_1					0.995*	0.293	0.724
log R_2						0.355	0.772
log R_2'							0.721

Table 4-11. Correlation Matrix of Rainstorm Variables for Combined (Forest-Agricultural) Catchments

	M_1	M_2	M_2'	R_1	R_2	R_2'	T_e
M_1		0.935*	0.524	0.992*	0.927*	0.503	0.453
M_2			0.430	0.934*	0.988*	0.400	0.307
M_2'				0.548	0.463	0.869	0.807
R_1					0.941*	0.557	0.502
R_2						0.491	0.384
R_2'							0.913*

Table 4-12. Correlation Matrix of Logarithms of Rainstorm Variables for Combined (Forest-Agricultural) Catchments

	$\log M_1$	$\log M_2$	$\log M_2'$	$\log R_1$	$\log R_2$	$\log R_2'$	$\log T_e$
$\log M_1$		0.996*	0.299	0.984*	0.976*	0.214	0.516
$\log M_2$			0.345	0.985*	0.984*	0.255	0.562
$\log M_2'$				0.311	0.354	0.834	0.680
$\log R_1$					0.997*	0.244	0.553
$\log R_2$						0.285	0.599
$\log R_2'$							0.650

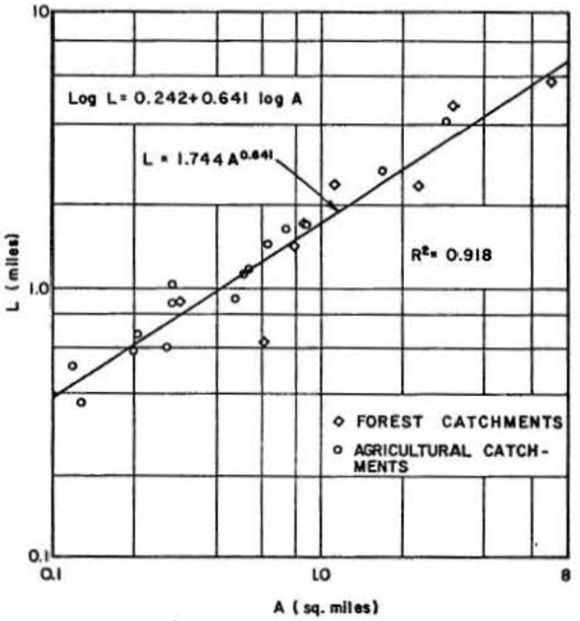


Fig. 4-1. Relationship of the length of main stream (L) to catchment area (A), as given by Eq. 4-1.

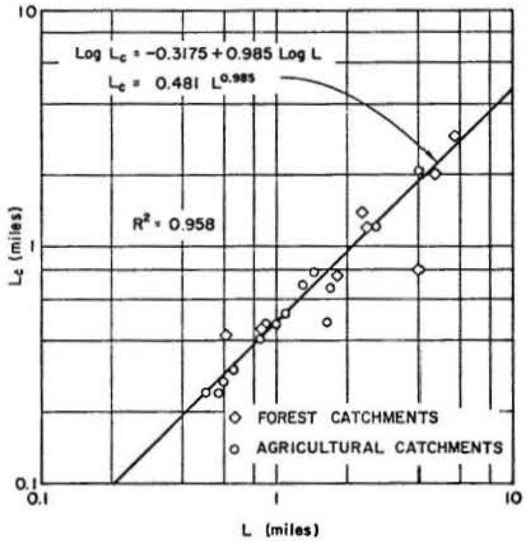


Fig. 4-2. Relationship of the length to the centroid of area (L_c) to the length of the main stream (L), as given by Eq. 4-2

Table 4-13. Relations among Physiographic Factors of Selected, Combined (Forest-Agricultural) Catchments

	Regression Equation	R	R^2	S_{ey}
(4.1)	$\log L = 0.2416 + 0.6411 \log A$	0.958	0.918	0.097
(4.2)	$\log L_c = -0.3175 + 0.9846 \log L$	0.979	0.958	0.075
(4.3)	$\log S_2 = -0.038 + 0.9564 \log S_1$	0.999	0.998	0.107
(4.4)	$\log S_2 = -0.2735 + 0.4942 \log S_h - 0.4351 \log F_1$	0.999	0.998	0.096

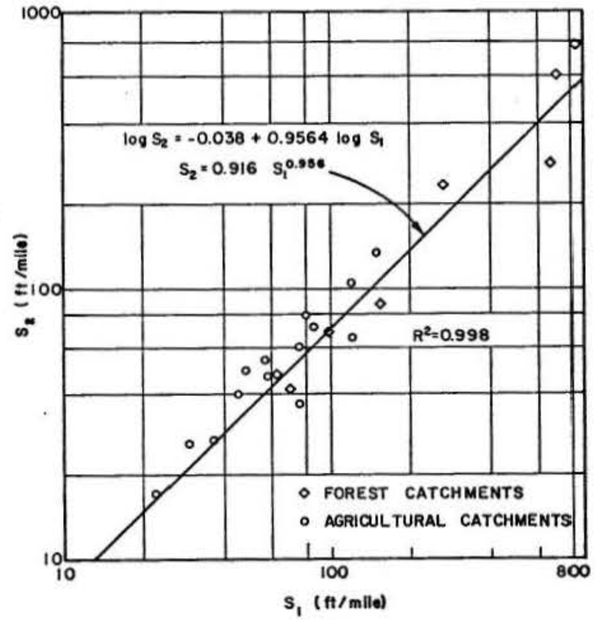


Fig. 4-3. Relationship of the slope of main stream (S_1) and the average slope of main stream (S_2), as given by Eq. 4-3.

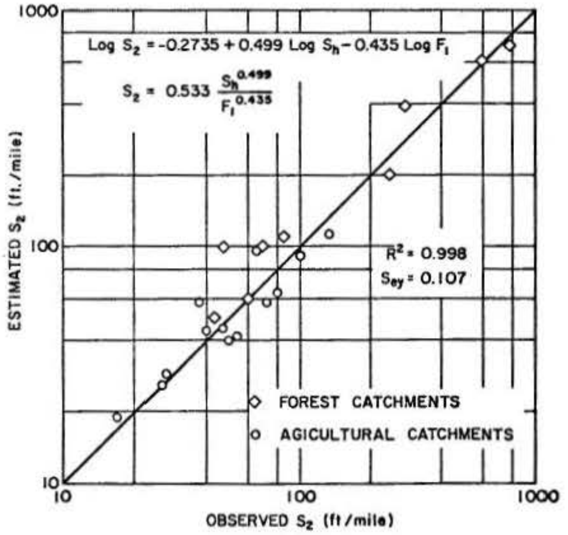


Fig. 4-4. Relationship of the observed versus the estimated values of the average slope of main stream (S_2), as given by Eq. 4-4.

separate sets of data are used: forest, agricultural, and combined (forest-agricultural) catchments.

The C_α values are not constant for a catchment, because they vary from one storm to another (Table C-1, Appendix C). They are determined from the peak flows and rise times of unit hydrographs computed from the observed flood hydrographs. The shape of these unit hydrographs, on which C_α depends, vary from one unit hydrograph to another, because these shapes are affected by the nonuniformity in rainfall distribution. Though the main reason for variation in the C_α values seems to be the nonuniformity of rainfall, the changes of roughness of catchment surface with seasons may be still another reason for it. Contributing to these variations in the shape are the variations in rainfall duration of storms, errors in separation of the base flow on hydrographs, the use of the constant infiltration index on hydrographs, as well as the approximate validity of the principle of superposition of the unit hydrograph concept.

For the selected drainage basin, a representative C_α value is required for the construction of unit hydrograph peak flow prediction equations. Two approaches are used here to estimate the representative values of C_α .

Use of the least square method for estimation of C_α . The representative values of C_α of unit hydrographs are estimated for forest, agricultural and combined forest-agricultural catchments by the least square method. Their peak flow prediction equations are then obtained from these C_α values. As seen in Fig. 4-5, a discrimination of the land-use effects by comparing the three peak flow prediction equations for given T_r shows small differences, because the parameter T_r accounts for the land use to a considerable extent.

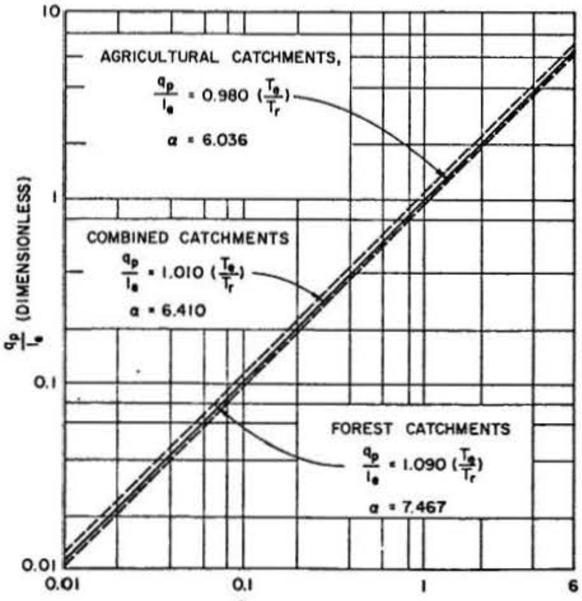


Fig. 4-5. Comparison of the peak flow equations of unit hydrographs

An alternative approach to the least square method is to assume the general peak flow equations of unit hydrograph in the form

$$\frac{q_p}{I_e} = C\left(\frac{T_e}{T_r}\right)^n \tag{4-8}$$

with

$$C_\alpha = C\left(\frac{T_e}{T_r}\right)^{n-1} \tag{4-9}$$

where C and n are constants. The parameters are estimated by the least square method in using the stepwise linear regression program. For combined forest-agricultural catchments, the elimination of data points which deviate significantly from the line of the best fit and those having (T_e/T_r) greater than two, resulted in a small increase of R^2 . Results of this analysis are summarized in Table 4-15 and presented in Figs. 4-6 and 4-7. The estimated values of n are slightly different from the theoretical value of one. In most cases, the n values are larger than one, which indicates that, on the average, C_α increases slightly with an increase of T_e/T_r . The n value for agricultural catchments is somewhat smaller than unity, which should not be. The q_p/I_e values deviate from the prediction equation for the T_e/T_r values greater than one, and approach the constant values as T_e/T_r becomes large. The error in the estimated n for the

Table 4-14. Peak Flow Equations of Unit Hydrographs

Type of Catchment	Equation Number	Peak Flow Equation	R	R^2
Forest (32 Events)	(4-5)	$\frac{q_p}{I_e} = 1.090\ (\frac{T_e}{T_r})$	0.839	0.699
Agricultural (73 Events)	(4-6)	$\frac{q_p}{I_e} = 0.980\ (\frac{T_e}{T_r})$	0.730	0.533
Combined (105 Events)	(4-7)	$\frac{q_p}{I_e} = 1.010\ (\frac{T_e}{T_r})$	0.824	0.679

Table 4-15. Peak Flow Equations of the Best Fit for Unit Hydrographs

Type of Catchment	Equation Number	Peak Flow Equation	R	R^2
Forest (32 Events)	(4-10)	$\frac{q_p}{I_e} = 1.085\left(\frac{T_e}{T_r}\right)^{1.100}$	0.921	0.847
Agricultural (73 Events)	(4-11)	$\frac{q_p}{I_e} = 0.805\left(\frac{T_e}{T_r}\right)^{0.969}$	0.828	0.685
Combined (105 Events)	(4-12)	$\frac{q_p}{I_e} = 0.848\left(\frac{T_e}{T_r}\right)^{0.997}$	0.885	0.784

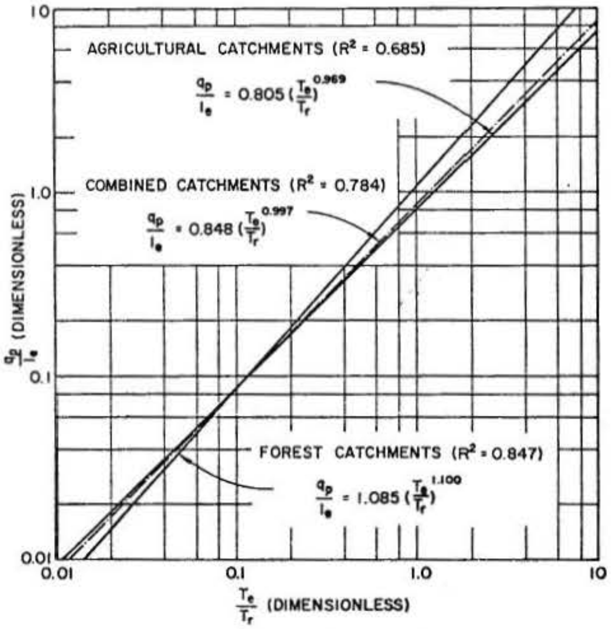


Fig. 4-6. Comparison of the peak flow equations of the best fit for unit hydrographs

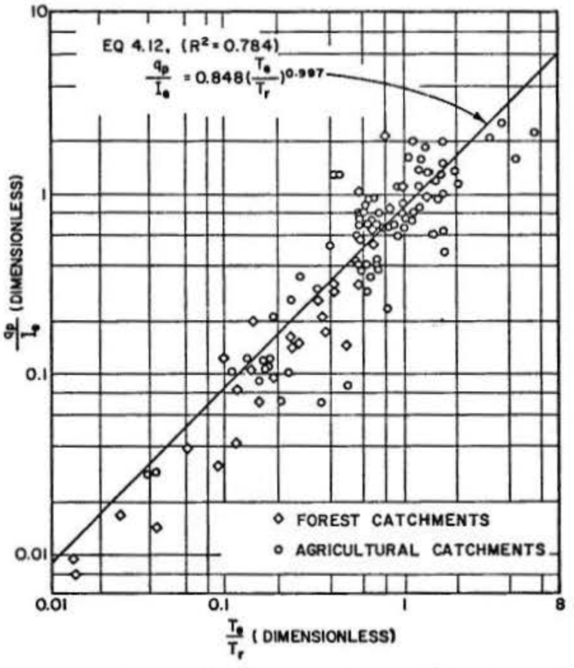


Fig. 4-7. The peak flow equations of the best fit for unit hydrographs for combined forest-agricultural catchments

agricultural catchments results from flood data with $(T_e/T_r) > 1$ and insufficient data for the small (T_e/T_r). A higher R^2 value is obtained for the prediction equation of forest catchments (Eq. 4-10) than for the agricultural catchments (Eq. 4-11). The explanation for it is that the flood hydrographs of forest catchments mainly result from the relatively uniform effective rainfall of short duration, while the smaller R^2 values of agricultural catchments can be explained by the nonuniformity in effective rainfall and flood events with $(T_e/T_r) > 1$, with the large differences between the peak flow equations of the best fit for unit hydrographs of forest and agricultural catchments, thus explained. The peak flow equation of the best fit for unit hydrographs of combined forest-agricultural catchments is then representative for all the catchments because of a large total number of catchments included.

Figures 4-7 and 4-8 show the fit of the peak flow equation for unit hydrographs of combined forest-agricultural catchments. A comparison between the estimated values of peak flow equations, Eqs. 4-7 and 4-12, for the combined catchments shows in Fig. 4-9 the

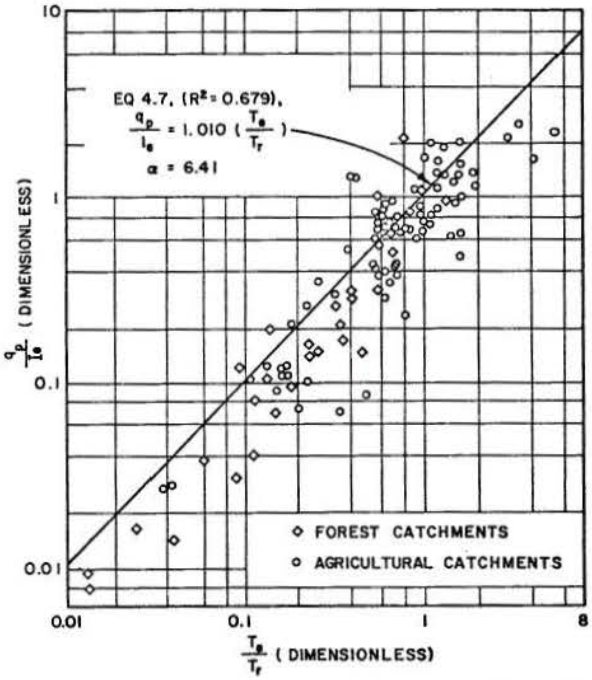


Fig. 4-8. Peak flow equations of unit hydrographs for the combined forest-agricultural catchments

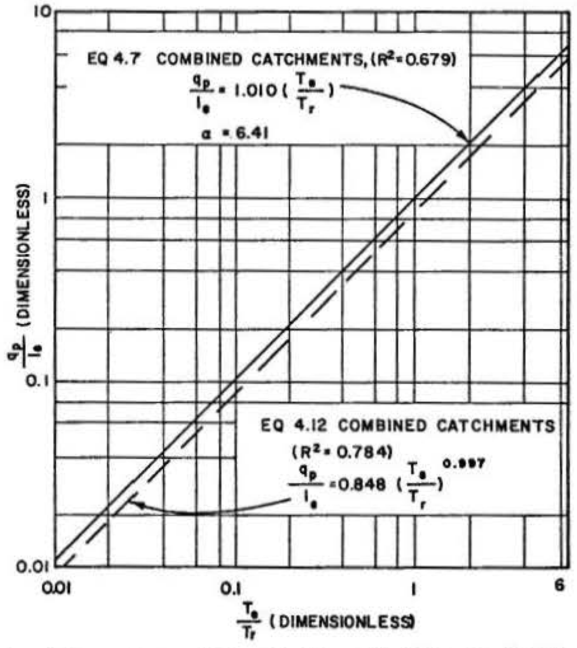


Fig. 4-9. Comparison of the peak flow prediction equations for unit hydrographs of combined forest-agricultural watersheds

relatively small differences, so Eq. 4-12 is selected as representative for catchments of this study. The above peak flow prediction equation for unit hydrographs is compared with the other equations available in Table 4-16, with the differences in coefficients relatively small in most cases.

Table 4-16. Comparison of Peak Flow Prediction Equations for Unit Hydrographs

Snyder, (1938, 1943)	$q_p = 442\ T_1^{-1}$
SCS, (1957)	$q_p = 484\ T_r^{-1}$
Hickok, et al., (1959)	$q_p = 475\ T_1^{-1}$
Espey, et al., (1968)	$Q_p = 473\ A^{0.988}\ T_r^{-1.26}$
This study	$q_p = 492\ T_r^{-1}$

q_p in cfs/sq mi, T_1 (hydrograph lag time) and T_r(hydrograph rise time) in hours, Q_p in cfs, and A in sq mi.

4-3 Derivation of Average Rise Time Equations

The average rise time, T_a , of unit hydrographs is investigated as a dependent variable by using the correlation and repression analysis. The independent variables studied are: the basin area, A; the total fall, H; the average main stream slope, S_2 ; the basin relief factor, S_h ; the catchment shape factor, F_1 ; and the percentage of dominant land-use cover, C_f . Both the observed and logarithmic values of variables were used in computations. The prediction equations of average rise time are found by the stepwise multiple linear regression method for: (a) forest catchments, (b) agricultural catchments, and (c) combined forest-agricultural catchments.

In case of agricultural catchments, the much higher R^2 values resulted because of the exclusion of data on catchment W-3, Hastings, Nebraska (catchment No. 12707001). The reason for excluding this catchment was the fact that its five flood events have values of the effective rainfall duration, T_e , greater than the hydrograph rise time, T_r , with the sample average rise time, T_a , underestimated because of sampling errors. For combined forest-agricultural catchments the developed prediction equations had very small R^2 values; they are not presented herein. The selection of prediction equations for the average rise time, T_a , as presented in Tables 4-17 through 4-19, is based on the following two conditions:

(1) That value of R^2 (or R) increases for each additional independent variable, or each additional variable given by its logarithms; and

(2) That there is a physical justification for including each independent variable into the regression equation, with the correct sign.

Figures 4-10 through 4-14 show the fit of prediction equations for the average rise time by comparing the observed and the estimated values by these equations.

The most significant independent variable in prediction equations of average rise time in flood hydrographs of forest catchments was the area, A. In most equations, it explained about 70% of the variance. The catchment total fall, H, and the relief factor, S_h , were the next most significant independent variables. The percent forest coverage, C_f , appeared to be the least significant independent variable. The effects of S_2 on T_a in Eq. 4-13 was small. This is because S_2 and H are highly correlated and the effect of S_2 has been taken into account by H. All equations show the increase in T_a with an increase of percentage forest cover, C_f .

Table 4-17. Regression Prediction Equations for the Average Rise Time of Forest Catchments (C_f in percents)

Eq. 4-13	$T_a = -86.63$	$+\ 17.05\ A$	$-\ 0.051\ H$	$+\ 40.39\ F_1$	$+\ 278.9\ C_f$	$-\ 0.126\ S_2$
	R:	0.922	0.948	0.992	0.993	0.994
	R^2:	0.851	0.969	0.984	0.986	0.989
	ΔR^2:	0.851	0.010	0.015	0.002	0.003
	S_{ey} in minutes	17.0	0.032	45.6	298.6	0.187
Eq. 4-14	$\log T_a = 3.258$	$+\ 0.1271 \log A$	$-\ 0.289 \log S_h$	$+\ 0.4287 \log F_1$	$+\ 1.1698 \log C_f$	
	R:	0.999	0.999	0.999	0.999	
	R^2:	0.997	0.998	0.999	0.999	
	ΔR^2:	0.008	0.0004	0.001	0.0003	
	S_{ey} in minutes	0.248	0.112	0.277	1.202	

Table 4-18. Regression Prediction Equations for the Average Rise Time of Agricultural Catchments (Including Catchment No. 12707001) [C_f in percents]

$$T_a = 57.99 - 0.120\ S_2 + 14.92\ A - 0.150\ H + 9.03\ F_1 \quad (4\text{-}15)$$

$$T_a = 73.73 - 0.124\ S_2 + 13.22\ A - 0.142\ H + 9.15\ F_1 - 21.91\ C_f \quad (4\text{-}16)$$

R:	0.988	0.992	0.993	0.970	0.994
R^2:	0.977	0.984	0.986	0.942	0.988
ΔR^2:	0.001	0.007	0.002	0.942	0.001
S_{ey} in minutes	0.153	6.32	0.123	10.60	23.54

$$\log T_a = 2.289 - 0.3574 \log S_2 - 0.5089 \log C_f + 0.0890 \log F_1 \quad (4\text{-}17)$$

R:	0.999	0.999	0.999
R^2:	0.998	0.999	0.999
ΔR^2:	0.003	0.0006	0.000
S_{ey} in minutes	0.111	0.227	0.153

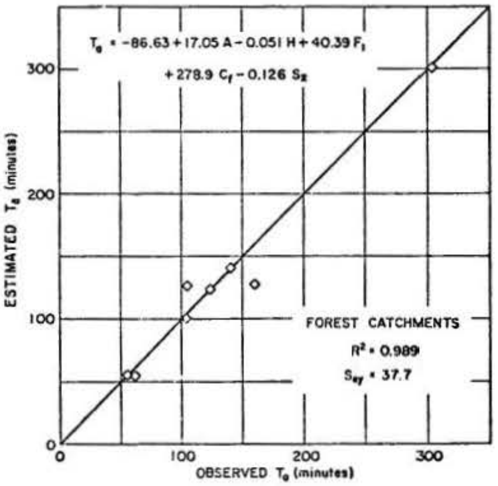


Fig. 4-10. Correlation of observed versus estimated values of the average rise time (T_a), given by Eq. 4-13.

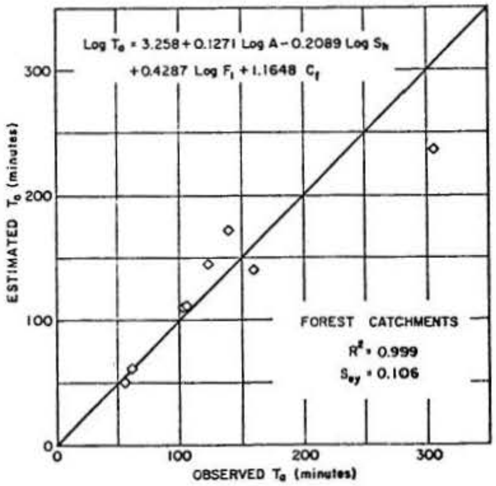


Fig. 4-11. Correlation of observed versus estimated values of the average rise time (T_a), given by Eq. 4-14.

Table 4-19. Regression Prediction Equations for the Average Rise Time of Agricultural Catchments (Excluding Catchment No. 12707001) [C_f in percents]

$$T_a = 74.2 - 0.269\ S_2 + 15.393\ A - 0.0753\ H \quad (4\text{-}18)$$

R:	0.998	0.990	0.998
R^2:	0.996	0.981	0.977
ΔR^2:	0.015	0.054	0.0008
S_{ey} in minutes	0.054	2.520	0.048

$$\log T_a = 2.577 - 0.463 \log S_2 \quad (4\text{-}19)$$

$$\log T_a = 2.475 - 0.4349 \log S_2 - 0.3523\ C_f \quad (4\text{-}20)$$

R:	0.999	0.999
R^2:	0.999	0.999
ΔR^2:	0.004	0.0002
S_{ey} in minutes	0.141	0.046

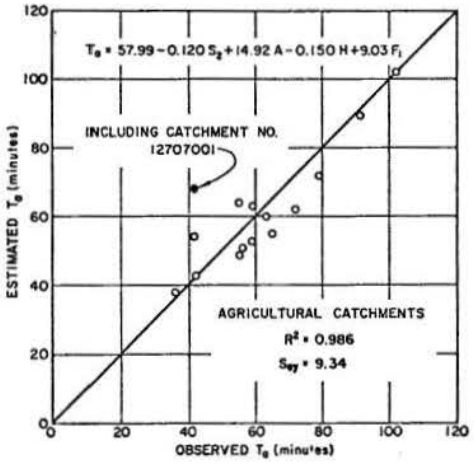


Fig. 4-12. Correlation of observed versus estimated values of the average rise time (T_a), given by Eq. 4-15.

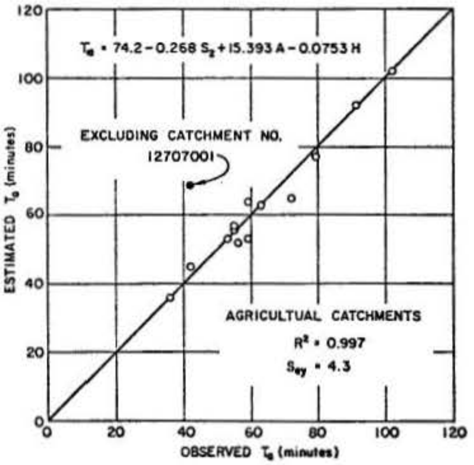


Fig. 4-13. Correlation of observed versus estimated values of the average rise time (T_a), given by Eq. 4-18.

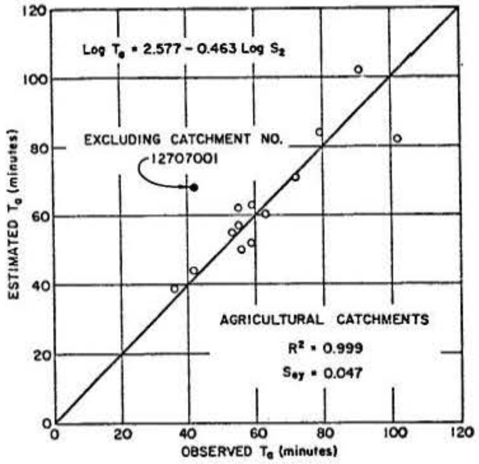


Fig. 4-14. Correlation of observed versus estimated values of the average rise time (T_a), given by Eq. 4-19.

The most significant independent variable for agricultural catchments was the average main stream slope, S_2 . This may result from a small variation in A values of the selected catchments. Generally, A comes out to be the most significant independent variable for a large range of variation of catchment areas. All the equations indicate the decreases in the average rise time, T_a , with an increase in the percentage of agricultural land use, C_f .

Differences between the observed values and the estimated values of T_a by their prediction equations for catchments with 50% agricultural land use and 100% agricultural land use are small: less than 5 minutes for estimates by the linear regression equations and less than 10 minutes for estimates by the logarithmic regression equations. These differences are therefore negligible in practical applications. Equation 4-14 for forest catchments and Eq. 4-20 for agricultural catchments are selected as the prediction equations for the average hydrograph rise time, T_a ; they have each a high value of R^2, with all the independent variables being of the expected sign.

4-4 Derivation of Prediction Equation for the Hydrograph Rise Time

To derive the prediction equation for the hydrograph rise time (or the time to hydrograph peak flow), T_r , the catchment time factor (or the average hydrograph rise time), T_a , and the selected rainstorm time variables in the form of the first moment M_1 of effective rainfall hyetograph, the second central moment M_2' of effective rainfall hyetograph and the effective rainfall duration T_e , were used. Their correlation matrices are given in Table 4-20. These matrices show:

(1) The effective rainfall duration, T_e , is influenced by the nonuniformity in time distribution of rainfall, expressed by M_1 and M_2';

(2) The hydrograph rise time, T_r , of selected flood events is affected by the first moment of effective rainfall hyetograph (or by the time nonuniformity of rainfall); it is less affected by the effective rainfall duration;

(3) Small correlation coefficients between the average rise time and the selected rainstorm variables indicate:

(a) The procedure of averaging the rise time eliminates much of the effect of nonuniformity of rainfall time distribution; and

(b) T_a mainly depends on catchment factors, as shown in Tables 4-17 through 4-19, but is independent of the effective rainfall duration, T_e ; therefore, it can be regarded as the catchment time factor. The corresponding unit hydrograph represents the average catchment response and does not depend on the effective rainfall duration, T_e .

Table 4-20. Correlation Matrices of Selected Hydrologic Variables

	Observed Variables			Logarithmic of Observed Variables		
	T_e	T_r	T_a	T_e	T_r	T_a
	Forest Catchments			*Forest Catchments*		
M_1	0.698	0.396	0.070	0.665	0.410	0.223
M_2'	0.803	0.429	0.200	0.695	0.017	0.076
T_e	1.000	0.389	0.200	1.000	0.379	0.264
T_r	0.386	1.000	0.625	0.379	1.000	0.631
T_a	0.200	0.625	1.000	0.264	0.631	1.000
	Agricultural Catchments			*Agricultural Catchments*		
M_1	0.428	0.561	0.280	0.501	0.293	0.054
M_2'	0.844	0.338	0.014	0.697	0.028	-0.198
T_e	1.000	0.234	-0.041	1.000	0.376	-0.004
T_r	0.234	1.000	0.680	0.376	1.000	0.659
T_a	-0.041	0.680	1.000	-0.004	0.659	1.000
	Combined Catchments			*Combined Catchments*		
M_1	0.453	0.624	0.432	0.516	0.426	0.216
M_2'	0.807	0.395	0.150	0.680	-0.087	-0.224
T_e	1.000	0.243	0.026	1.000	0.245	-0.069
T_r	0.243	1.000	0.755	0.245	1.000	0.709
T_a	0.026	0.755	1.000	-0.069	0.709	1.000

The prediction equation of hydrograph rise time for combined forest-agricultural catchments has the highest value of R^2, given by

$$T_r = 2.2071 + 0.7561\,T_a + 0.00324\,M_2' + 0.1734\,T_e \qquad (4\text{-}21)$$

R:	0.755	0.833	0.840
R^2:	0.570	0.694	0.706
ΔR^2:	0.570	0.124	0.012
S_{ey} in minutes	47	40	39

The greater values of R^2 may be obtained for prediction equations of rise time by adding a larger number of independent variables, such as the time to the maximum rainfall intensity, the soil moisture index, the seasonal variation index and others. However, the objective of this investigation is to show the effect of nonuniformity of rainfall distribution over a catchment on T_r , with T_a as the catchment characteristic time factor. Therefore, no attempt is made to further improve the prediction equations of hydrograph rise time by adding new variables.

Chapter V
LAND-USE EFFECTS ON UNIT HYDROGRAPHS

5-1 Selection of Regression Equations for Further Investigations

The expression selected to represent the relations of catchment parameters for the objectives of this study are:

(A) Relations between the selected physiographic factors of combined forest-agricultural catchments

$$L = 1.744\ A^{0.641} \qquad (5\text{-}1)$$

$$L_c = 0.481\ L^{0.985} \qquad (5\text{-}2)$$

$$S_2 = 0.916\ S_1^{0.956} \qquad (5\text{-}3)$$

$$S_2 = 0.533\ S_h^{0.499}\ F_1^{-0.435} \qquad (5\text{-}4)$$

(B) The prediction equations for the average rise time:

For forest land use catchments,

$$T_a = -86.63 + 17.05\ A - 0.051\ H + 40.39\ F_1 + 278.9\ C_f - 0.126\ S_2\ ; \qquad (5\text{-}5)$$

For agricultural land-use catchments,

$$T_a = 74.2 - 0.268 + 15.393 A + 0.0753\ H\ . \qquad (5\text{-}6)$$

(C) The unit hydrograph peak flow equation of combined forest-agricultural catchments

$$\frac{q_p}{I_e} = 1.010\ \left(\frac{T_e}{T_r}\right) \qquad (5\text{-}7)$$

and

$$U_p = 1.010\ \left(\frac{1}{T_r}\right) \qquad (5\text{-}8)$$

(D) The unit hydrograph equation

$$U_t = 612.9\ \left(\frac{1}{T_r}\right)^{7.41}\ t^{6.41}\ e^{-\left(\frac{6.41}{T_r}\right)t}\ , \qquad (5\text{-}9)$$

with $\alpha = 6.41$. The ranges and units of catchment physiographic factors are given in Table 5-1.

Table 5-1. Ranges and Units of Catchment Physiographic Factors for Representative Regression Equations

		Ranges of Parameters for Watersheds		
Variable	Unit	Forest	Agricultural	Combined
A	Sq. miles	0.30 - 7.19	0.12 - 3.01	0.12 - 7.19
L	Miles	0.61 - 5.62	0.51 - 3.99	0.51 - 5.62
L_c	Miles	0.42 - 2.92	0.24 - 2.07	0.24 - 2.92
H	Feet	101 - 3263	45 - 149	45 - 3263
S_1	Ft/miles	64 - 826	23 - 150	23 - 826
S_2	Ft/miles	43 - 781	17 - 134	17 - 781
$S_h x10^5$	$(ft/miles)^2$	0.12 - 34.5	0.024- 0.40	0.024-34.5
F_1	Dimensionless	0.420 - 2.948	0.600- 2.744	0.420- 2.948
C_f	Dimensionless	0.46 - 1.00	0.45 - 0.87	0.45 - 1.00

5-2 Selection of a Representative Catchment

Median values of the dominant physiographic factors of combined forest-agricultural watersheds, as given in Table 3.5, are used as factors of the representative catchment. They are reproduced in Table 5.2.

Table 5-2. Physiographic Factors of the Representative Catchment

A sq. mi.	H Feet	L Miles	L_c Miles	S_2 ft/mi	$S_h x10^5$ $(ft/mi)^2$	F_1 Dimensionless
0.590	104	1.345	0.595	63	0.152	1.340

The median values are used because they are within the range of values for which the average rise time, Eqs. 5.5 and 5.6, of both the forest and agricultural land-use catchments are applicable.

5.3 Comparison of Peak-Flow Responses

By using the physiographic factors of Table 5.2 of the representative catchment, the peak flows of unit hydrographs and the unit hydrographs themselves of the representative catchment, with 100% forest cover, with the 50% forest and 50% agricultural land use, and with the predominantly agricultural land use, are computed by applying Eqs. 5.1 through 5.9.

All the peak flows of unit hydrographs and the unit hydrographs themselves of catchments used in this study are in the above procedure reduced to the characteristics of the representative catchment. In other words, the effects of physiographic factors of individual catchments are removed--in the limit of accuracy of the developed regression equations--and only the effects of remaining factors, and particularly of the land-use factors have remained in the representative catchment. Thus, all the peak flows of unit hydrographs and all the unit hydrographs are sorted in three groups: 100% forest, 50% forest and 50% agricultural, and 100% agricultural land-use catchments, all reduced to the geometry of the representative catchment, with Eqs. 5.1 through 5.9 applied for that purpose. The parameters of the unit hydrographs of the representative catchment are then:

A. *The average rise time*

(1) 100% forest land use (Eq. 5.5)

$$T_a = -86.63 + (17.47 \times 0.59) - (0.051 \times 104) + (40.39 \times 1.34) + (278.9 \times 1) - (0.126 \times 63) = 243.21 \text{ minutes}$$

(2) 50% forest - 50 % agriculture land use (Eq. 5.5)

$$T_a = -86.63 + (17.47 \times 0.59) - (0.051 \times 104) + (40.39 \times 1.34) + (278.9 \times 0.5) - (0.144 \times 63) = 103.76 \text{ minutes}$$

(3) Predominantly agricultural land use (Eq. 5.6)

$$T_a = 74.21 - (0.268 \times 63) + (15.39 \times 0.590) - (0.075 \times 104) = 58.61 \text{ minutes}$$

B. *The unit hydrograph peak flows.* By using Eq. 5.8, the unit hydrograph peak flows are

(1) 100% forest land use, with T_a = 243.21 minutes = 4.05 hours,

$$U_p = 1.01 \times (4.05)^{-1} = 0.249 \text{ in./hr.}$$

(2) 50% forest and 50% agricultural land use, with T_a = 103.76 minutes = 1.73 hours,

$$U_p = 1.01 \times (1.73)^{-1} = 0.594 \text{ in./hr.}$$

(3) Predominantly agricultural land use, with T_a = 58.61 minutes = 0.977 hours,

$$U_p = 1.01 \times (0.977)^{-1} = 1.034 \text{ in./hr.}$$

C. *The unit hydrographs.* Equation 5.9 may be written as

$$U_t = 612.92 \; X \; Y_t \; Z_t \tag{5.10}$$

with

$$X = T_r^{-7.41}, \tag{5.11}$$

$$Y_t = t^{6.41}, \tag{5.12}$$

and

$$Z_t = e^{-(6.41/T_r)t} \tag{5.13}$$

For given values of T_r and t, the values of X, Y_t and Z_t may then be determined either analytically or graphically. Equations 5.11 and 5.12 plot as straight lines on the log-log graph paper, while Eq. 5.13 becomes a straight line on a semi-log paper.

The unit hydrographs for the 100% forest land use (T_r = 4.05), the 50% forest and 50% agricultural land use (T_r = 1.73), and the predominantly agricultural land use (T_r = 0.977) are presented in Fig. 5.1.

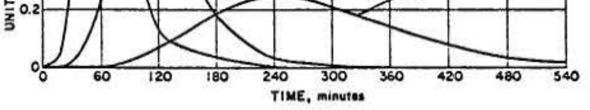


Fig. 5-1. Comparison of unit hydrographs of all the catchments, with their physiographic factors reduced to factors of the representative catchment (area 0.59 sq. miles): (1) agricultural land-use catchment; (2) 50% forest and 50% agricultural land-use catchment; and (3) 100% forest land-use catchment.

Table 5.3 shows a sample of calculations for the unit hydrograph of the predominantly agricultural land use catchment, reduced to the representative catchment. The values of Y_t and Z_t were determined graphically.

The final results are shown in Table 5.4, as the major results of this study.

Table 5-3. A Sample of Calculations of Unit Hydrograph Ordinates of Predominantly Agricultural Land-use Catchment, with Their Physiographic Factors Reduced to Factors of Representative Catchment

t hours	Y_t	Z_t	$Y_t Z_t$	$U_t = CXY_t Z_t$ in./hr
0.25	1.4×10^{-4}	1.9×10^{-1}	2.66×10^{-5}	0.0195
0.50	1.2×10^{-2}	3.8×10^{-2}	4.56×10^{-4}	0.322
0.75	1.6×10^{-1}	7.3×10^{-3}	1.17×10^{-3}	0.840
1.00	1.0	1.4×10^{-3}	1.40×10^{-3}	1.034
1.25	4.18	2.7×10^{-4}	1.15×10^{-3}	0.835
1.50	13.5	5.3×10^{-5}	7.18×10^{-4}	0.519
1.75	36.1	1.0×10^{-5}	3.61×10^{-4}	0.272
2.00	85.0	2.0×10^{-6}	1.70×10^{-4}	0.124
3.00	1.1×10^{3}	2.8×10^{-9}	3.08×10^{-6}	0.0024
4.00	7.2×10^{3}	4.0×10^{-12}	2.88×10^{-8}	0.00002

Constant C = 612.9, X = 1.18, CX = 724.5

Table 5-4. Comparison of Average Rise Time and Peak Flow Discharges for Various Types of Land Use of Catchments with Their Physiographic Factors, Reduced to Factors of Representative Catchment

Types of Catchment Cover	Average Rise Time Minutes	Unit Hydrograph Peak in./hr.
100% forest	243	0.249
50% forest and 50% agricultural	104	0.584
Predominantly agricultural	59	1.034

Table 5-4 demonstrates that forest catchments experience a much smaller peak flow of unit hydrographs than do the agricultural catchments. An increase in forest cover decreases the peak runoff, as the 50% forest and 50% agricultural land-use catchments show; they have the unit hydrograph peak flow about 2.38 times greater than the peak flow of unit hydrographs of the 100% forest catchments, on the average. The peak flow of unit hydrographs of agricultural catchments is about 4.34 times greater than for the 100% forest catchments, on the average. The average rise time or the average time to peak of the 100% forest catchment is, however, correspondingly much longer than the 50% forest and 50% agriculture, or the predominantly agricultural catchments, by approximately the same ratio as found for peak flows.

Chapter VI
CONCLUSIONS

The analysis of 105 flood events of eight forest and 14 agricultural land-use experimental catchments in the eastern and central United States, leads to these conclusions:

(1) The unit hydrograph approach, with the reduction of geometry (physiographic factors) of each of these catchments to geometry (physiographic factors) of a representative catchment by the use of regression and correlation analysis, represents an effective method in discriminating the effects of land use on the surface runoff hydrographs of small catchments. It is necessary to first remove the geometry effects in order to analyze the effects of land use. Because the geometry (topography) of small catchments affects the type and stability of land use, there is a high correlation between the geometry and the land use. This fact requires a separation of the effects of geometry prior to the study of the effects of land use.

(2) Unit hydrographs of small catchments are significantly affected by the land use. For a given small catchment, the agricultural land use increases the flood peaks while the forest land use has the opposite effect. The peak flows of unit hydrographs of catchments with the predominantly agricultural land use are approximately two to four times greater than the peak flows which result from catchments with the predominantly forest land use.

(3) Catchment factors, such as the length, L, L_c ; the area, A; or the slopes, S_1 , S_2 , and S_h, are highly mutually correlated variables. In regression and correlation analysis, the parameters A and, S_2 or S_h , should be selected as the representative physiographic factors.

(4) All the hydrologic variables of small catchments may be mutually correlated. Therefore, some variables can be excluded from the correlation analysis if they are highly correlated with the included variables into the regression equations. In doing so, the less mutually correlated variables included increase the number of degrees of freedom in correlation, thus permitting the inclusion of new independent regression variables, in order to further increase the coefficient of determination or the explained variance by the regression equations.

(5) Dominant physiographic factors of small catchments, that are found to affect the rise time parameter, T_a , of the unit hydrograph, are: land use, area A (accounted for not only through A, but also through L, L_c), head fall H, slopes S_2 or S_h (and also of S_1 through S_2), catchment shape factor F_1 , and the percent of land-use cover C_f (for forest catchments). The most significant factor came out to be the area A, while the slope S_2 became the second most significant factor. The parameter T_a is considered as the time characteristic of catchments, independent of effective rainfall.

(6) Unit hydrographs of short-duration storms of small catchments are more affected by the nonuniformity in time distribution of rainfall intensity than by the duration of effective rainfall. The estimated values of C_α (a shape factor of unit hydrographs) are constant for any catchment analyzed, but varying from one storm to another. The observed T_r values vary with the time characteristic T_a , the nonuniformity of rainfall in time (measured by M_2'), and some other factors.

(7) The representative C_α value of forest catchments is close to the representative value C_α of the agricultural land-use catchments. The average, dimensionless unit hydrographs, came out to be the same for all the catchments analyzed. The representative peak flow equations of unit hydrographs and the representative unit hydrograph equation may be applied to both the forest and the agricultural land-use catchments.

(8) The method outlined permits the study of effects of other land uses on flood hydrographs, such as for the catchments which are predominantly grass covered, desert catchments, urban catchments, as well as the types of land cover other than the forest or the classical agricultural land use.

(9) Results of effects of forest and agricultural land uses, as well as of the other land uses, on flood hydrographs should be further verified by using the catchments of a still wider range of geographic conditions than those used in this study. Such investigations should reveal whether the extrapolations are permitted beyond the ranges of catchment areas, flood peaks, and other factors studied herein, as well as whether the additional characteristics, such as geologic formations, water storage properties and other factors may be of significant effects on floods of small catchments as well.

REFERENCES

Amorocho, J., 1963, Measures of the linearity of hydrologic systems: Journal of Geophysical Research, Vol. 68, No. 8.

Anderson, H. W., and C. H. Gleason, 1960, Logging effects on snow, soil moisture, and water losses: Proc. Western Snow Conf., Reno, Nev., April 1959 (Colorado State University, Fort Collins, September 1960)

Anderson, H. W. and C. H. Gleason, 1960, Effects of logging and brush removal on snow water runoff: Int. Assoc. of Sci. Hydrology, General Assembly of Helsinki I.U.G.G. Publ. No. 51.

Auten, J. T., 1933, Porosity and water absorption of forest soils: Jour. Agr. Res. No. 46.

Bell, F. C. 1968, Estimating design floods from extreme rainfall: Hydrology Paper No. 29, Colorado State University, Fort Collins.

Bruce, J. P. and Clark, R.H., 1966, Introduction to hydrometeorology: Pergamon Press, London.

Bendat, J. S. and Piersol, A. G., 1966, Measurement and analysis of random data: John Wiley and Sons, Inc., New York.

Chow, Ven T., as chairman, and others, 1957, Report of the committee on runoff, 1955-1956: Trans. Am. Geophys. Union, Vol. 38, No. 3.

Chow, Ven. T., 1962, Hydrologic design of culverts: Jour. of Hydraulics Division, ASCE, Vol. 88, No. HY2, Proc. Paper 3071.

Chow, Ven T., 1964, Handbook of applied hydrology: McGraw-Hill Book Co., New York.

Dickinson, W. T., Holland, M. E. and Smith, G. L., 1967, An experimental rainfall-runoff facility: Hydrology Paper No. 25, Colorado State University, Fort Collins.

Dooge, J. C. I., 1959, A general theory of the unit hydrograph: Jour. Geoph. Res., Vol. 64, No. 2.

Dooge, J. C. I., 1967, The hydrologic system as a closed system: Int. Hydrology Symposium, Colorado State University, Fort Collins.

Edson, C. G., 1951, Parameter for relating unit hydrographs to watershed characteristics: Am. Geophys. Union Trans., Vol. 32, No. 4.

Garstka, W. U., Love, L. D., Goddell, B. C. and Bertle, F. A., 1958, Factors affecting snowmelt and streamflow: US Bureau of Reclamation and US Forest Service.

Giusti, E. V., 1963, Distribution of river basin area in the conterminous United States: Int. Assoc. of Scientific Hydrology, Vol. 7. No. 3.

Gray, D. M., 1962, Derivation of hydrographs for small watersheds from measurable physical characteristics: Res. Bulletin 506, Iowa State University, Ames.

Hiemstra, L. A. V. and Reich, B. M., 1967, Engineering judgment and small area flood peaks: Hydrology Paper No. 19, Colorado State University, Fort Collins.

Hobbs, H. W., 1946, Runoff behaviors of small agricultural watersheds under various land use practices: Trans. Am. Geophys. Union, Vol. 27.

Hoover, M. D., 1944, Effect of removal of forest vagetation upon water yield: Trans. Am. Geophys. Union, Vol. 25.

Hydrology, 1957, National engineering handbook: US Dept. of Agric., SCS, Washington, D.C., Section 4, Supplement A.

Kuichling, D., 1889, The relation between the rainfall and the discharge of sewers in populous district: Trans. ASCE, Vol. 20.

Langbein, W. B., 1940, Channel-storage and unit-hydrograph studies: Trans. A.G.U., Vol. 21.

Lasson, L., Lull, H. W. and Frank, B., 1951, Some fundamental plant-soil-water relation in watershed management: US Dept. Agr. Circ. 910.

Lloyd-Davis, D. E., 1906, The elimination of storm water from sewerage systems: Inst. of Civ. Engs., London, England, Minutes of Proceedings, Vol. 164.

Love, L. D., 1955, The effect on streamflow of the killing of spruce and pine by the engleman spruce beetle: Trans. MA. Geophys. Union, Vol. 36, No. 1.

Om Kar, Songthara, 1967, Hydrograph rise times: Interim Report, Water Resources Research, Colorado State University, Fort Collins.

Potter, 1961, Hydraulic design series, No. 2: Division of Hydraulic Research, Bureau of Public Roads, Washington D.C.

Reich, B. M. and Hiemstra, L. A. V., 1965, Tacitly maximized small watershed flood estimates: Jour. of Hydraulics Division, ASCE, Vol. 91, No. HY3, Proc. Paper 4339.

Sopper, W. E. and Lull, H. W., 1967, International symposium on forest hydrology: Pergamon Press Ltd., London.

Yevjevich, V. and Holland, M. E., 1967, Research data assembly for small watershed floods: Report, Part 2, Engineering Research Center, Colorado State University, Fort Collins, Colorado.

APPENDIX A

LIST OF SYMBOLS

A	Catchment area	Square miles
α	Unit hydrograph shape factor	Dimensionless
β	Unit hydrograph factor	--
C	Constant	--
C_α	Peak flow shape coefficient of unit hydrograph	Dimensionless
C_b	Coefficient	Dimensionless
C_f	Percentage of areal coverage	Dimensionless
C_i	i-th constant $(i = 1, 2, 3, \ldots)$	--
e	Base of natural, Naperian logarithms	--
F_1 or LL_c/A	Catchment shape factor	Dimensionless
H	Total catchment fall	Feet
I_e	Average effective rainfall intensity	inches/hour
I_{ei}	Effective rainfall intensity at time t_i	inches/hour
I_i	Rainfall intensity at time t_i	inches/hour
K	Constant	--
k	Nash's unit hydrograph factor	--
L	Length of main stream	miles
L_c	Distance to centroid of area	miles
L_i	Travel distance of raindrop at time t_i	miles
M_n	The n-th effective hyetograph moment about the beginning of the hydrograph	$(\text{minutes})^n$
M'_n	The n-th central effective hyetograph moment	$(\text{minutes})^n$
m	Edson's unit hydrograph factor	--
n	Constant	Dimensionless
P	Total precipitation	inches
P_i	Precipitation at time t_i	inches
Q_t	Hydrograph ordinate at time t	in./hr. or (cfs)
Q_o	Initial hydrograph discharge	in./hr. or (cfs)
Q_p	Hydrograph peak discharge	in./hr. or (cfs)
q_p	Areal average peak discharge	in./hr. or cfs/sq. mi.
R_n	The n-th moment of rainfall hyetograph about the beginning of the hydrograph	$(\text{minutes})^n$
R'_n	The n-th central moment of rainfall hyetograph	$(\text{minutes})^n$
S	Slope	--
S_1	Main stream slope	ft./mi
S_2	Average main stream slope	ft./mi
S_h or H^2/A	Catchment relief factor	sq.ft./sq.mi.
T_d	Rainfall duration	minutes or hrs.
T_e	Effective rainfall duration	minutes or hrs.
T_1	Hydrograph lag time	minutes or hrs.
T_m	Mean travel time	minutes or hrs.
T_r	Hydrograph rise time or the time to hydrograph peak flow	minutes or hrs.
T_a	Average hydrograph rise time	minutes or hrs.
t, t_i	Time variables	--
U_t	Unit hydrograph ordinate at time t	in./hr. or cfs
U_p	Unit hydrograph peak flow	in./hr. or cfs
V	Total runoff	inches
V_d	Direct runoff	inches
V_b	Base runoff	inches
ϕ	ϕ-index	in./hr.

APPENDIX B

METHOD OF COMPUTING CATCHMENT CHARACTERISTICS

Area, A. The area is usually given. When not, the catchment boundary is delineated and the planimeter used. Areas less than 64 acres (0.1 square mile) and greater than 25,600 acres (100 square miles) are omitted in this study.

Length of Main Stream, L. Extend all marked stream systems up to the catchment boundaries in accordance with the contours. Extension to the catchment boundary is not done for streams which appear to originate in springs or swamps. The main stream drains the greatest area. Using a paper strip, the total length of the main stream is marked off by a series of straight line segments on the strip. The total strip distance equals L when measured by the map scale. The label points where the main stream crosses a contour line are marked. The distance in miles to two decimal places between successive contours are calculated and recorded on the paper strip. The summation of these distances is the length of the main stream, L.

Length to Centroid of Area, L_c. The centroid of catchment can be found quickly and easily, and with a fairly high degree of accuracy, by centering over a map of the catchment a clear plastic overlay having a system of lines drawn on it at 45° angles to form a star-shaped design. L_c is the distance along the main stream from the outlet to a point adjacent to the centroid of area projected to the main stream. This distance can be found by using the paper strip used to measure the length of the main stream, L.

Total Fall, H. Using the strip of paper with the main stream marked off on it as the abscissas, a graph of distance vs. elevation along the main stream is plotted on 20 x 20 squares to the inch graph paper. After the profile is plotted, each of the ends of the profile is extrapolated. The minimum and maximum elevations of the main stream from these extended slopes are determined. The total fall can now be determined to the nearest foot, with the distances, in miles, between successive contour lines on the profile, recorded.

Stream Slope, S_1. S_1 is calculated by dividing the total fall, H, by the length of the main stream in miles, L , to the nearest foot per mile.

Stream Slope, S_2.

$$S_2 = \frac{2\Sigma l_i z_i}{(\Sigma l_i)^2} = \frac{2\Sigma l_i z_i}{L^2} \quad \text{, feet/mile}$$

with l_i = the distance along the main stream between successive contours and z_i = the average elevation above the outlet for each reach of length, l_i . The individual l_i can be easily determined from the plotted profile of the main stream or from the paper strip used to measure the length of the main stream.

APPENDIX C

TABLE C-1. RAINFALL AND RUNOFF DATA

Catchment No.	Event No.	Date	P in.	V in.	I_e in./hr.	ϕ in./min.	q_p in./hr.	U_p in./hr	T_e min.	T_r min.	T_a min.	C_α	T_e/T_r	q_p/I_e	Type of Catchment
10606104	1	7/15/47	0.52	0.036	0.032	0.013	0.007	0.398	15	80		1.167	0.1875	0.2168	F
	2	8/ 9/47	0.70	0.034	0.030	0.014	0.006	0.264	35	70		0.400	0.5000	0.2000	
	3	7/23/55	0.57	0.049	0.027	0.015	0.010	0.273	70	160	103.3	0.847	0.4375	0.3704	
10606105	1	7/17/57	0.07	0.054	0.007	0.002	0.009	0.361	55	130		3.039	0.4231	1.2857	F
	2	7/20/51	0.33	0.064	0.081	0.025	0.010	0.274	10	85		1.050	0.1176	0.1235	
	3	7/29/45	0.49	0.110	0.203	0.026	0.010	0.177	10	110		0.542	0.0909	0.0193	
	4	7/23/45	0.27	0.095	0.227	0.014	0.008	0.136	5	120		0.844	0.0417	0.0352	
	5	7/22/45	0.08	0.063	0.044	0.001	0.009	0.272	20	170	123.0	1.737	0.1177	0.2045	F
10608004	1	8/22/40	0.73	0.003	0.019	0.030	0.004	1.806	7	48		1.444	0.1458	0.2105	
	2	8/ 8/45	0.70	0.094	0.301	0.045	0.004	0.070	6	430		0.930	0.0143	0.0133	
	3	8/15/45	0.89	0.071	0.231	0.046	0.004	0.100	6	440	306.0	1.236	0.0140	0.0173	
11204004	1	3/26/40	0.09	0.011	0.237	0.007	0.008	1.104	2	55		0.929	0.0364	0.0338	A
	2	4/ 9/40	0.15	0.032	0.074	0.005	0.039	1.461	21	50		1.255	0.4200	0.5270	
	3	5/ 4/40	0.16	0.003	0.015	0.008	0.002	0.787	10	55	53.3	0.733	0.1818	0.1333	
11511001	1	6/ 1/43	1.96	1.126	1.221	0.017	0.489	0.453	53	90		0.680	0.5889	0.4005	A
	2	7/21/48	1.97	0.717	0.677	0.018	0.863	1.213	63	135		2.731	0.4667	1.2747	
	3	7/ 1/50	3.23	1.289	0.859	0.023	0.649	0.503	90	120		1.007	0.7500	0.7555	
	4	7/18/56	2.94	0.999	1.304	0.030	0.858	0.858	40	65	102.5	1.069	0.6154	0.6580	
12412006	1	5/ 9/58	0.59	0.143	0.177	0.009	0.110	0.811	45	65		0.898	0.6923	0.6215	F
	2	1/17/60	0.70	0.275	0.092	0.002	0.076	0.267	180	205		0.941	0.8781	0.8261	
	3	7/25/62	1.53	0.122	0.490	0.027	0.122	0.997	15	44	104.7	0.730	0.3409	0.2490	
12707001*	1	6/20/39	1.39	0.936	1.755	0.010	1.168	1.248	32	31		0.645	1.0323	0.6655	A
	2	6/ 7/53	1.56	0.897	0.841	0.009	0.729	0.813	64	40		0.542	1.6000	0.8668	
	3	6/15/57	1.95	1.352	1.229	0.009	1.848	1.367	66	62		1.412	1.0645	1.5037	
	4	5/15/60	2.26	0.878	1.098	0.025	0.947	1.078	48	47		0.844	1.0213	0.8625	
	5	8/11/61	1.70	0.257	0.643	0.053	0.146	0.569	24	28	41.6	0.265	0.8571	0.2271	
12707002	1	6/15/57	1.36	0.396	0.396	0.020	0.270	0.681	60	85		0.965	0.7059	0.6818	A
	2	6/12/58	2.18	0.362	2.716	0.087	0.324	0.895	8	60		0.895	0.1333	0.1193	
	3	7/ 3/59	2.10	1.395	1.861	0.014	1.154	0.827	45	58		0.799	0.7759	0.6201	
	4	5/15/60	2.17	1.042	0.672	0.017	0.646	0.620	93	54		0.558	1.7222	0.9613	
	5	6/14/61	2.54	0.682	0.350	0.013	0.249	0.366	117	102	71.8	0.620	1.1471	0.7114	
14309001	1	4/24/57	1.64	1.398	2.133	0.004	0.873	0.629	39	68		0.713	0.5735	0.4093	A
	2	5/ 9/57	1.38	0.322	1.280	0.025	0.113	0.353	15	100		0.589	0.1500	0.0883	
	3	5/13/57	1.36	1.071	0.556	0.002	0.569	0.534	101	89		0.902	1.1348	1.0234	
	4	6/23/59	0.79	1.488	0.937	0.000	0.627	0.426	86	50		0.389	1.7200	0.6692	
	5	7/ 9/61	1.43	0.169	0.596	0.039	0.050	0.296	17	33		0.163	0.5152	0.0839	
	6	7/16/61	1.54	0.501	1.307	0.026	0.149	0.297	23	133	78.8	0.659	0.1729	0.1140	
14309002	1	6/10/41	1.66	1.398	1.111	0.004	0.744	0.536	75	100		0.893	0.7500	0.6696	A
	2	6/15/42	1.01	0.798	1.152	0.004	0.321	0.407	41	65		0.441	0.6308	0.2786	
	3	7/15/50	1.81	0.852	0.720	0.016	0.277	0.325	71	96		0.520	0.7396	0.3847	
	4	6/23/59	2.64	1.710	0.921	0.009	0.602	0.353	111	130		0.765	0.8539	0.6536	
	5	7/16/61	1.60	0.574	0.983	0.025	0.163	0.285	35	82		0.389	0.4268	0.1658	
	6	7/23/61	0.94	0.123	0.461	0.042	0.046	0.374	16	72	90.8	0.449	0.2222	0.0998	
14309005	1	6/10/41	2.59	2.036	1.821	0.006	3.339	1.642	67	40		1.095	1.6750	1.8336	A
	2	3/26/46	0.84	0.465	2.775	0.017	0.926	2.001	10	37		1.234	0.2703	0.3337	
	3	4/24/57	1.83	1.661	1.776	0.002	2.161	1.304	56	132		2.868	0.4242	1.2168	
	4	6/15/61	0.87	0.148	0.729	0.045	0.270	1.846	12	16		0.494	0.7500	0.3704	
	5	7/16/61	1.16	0.157	1.289	0.060	0.130	0.855	7	62		0.881	0.1129	0.1009	
	6	6/ 9/62	2.06	1.193	2.386	0.023	2.141	1.795	30	42	54.8	1.256	0.7143	0.8973	
14309006	1	4/24/57	1.97	1.644	1.731	0.014	2.071	1.590	58	25		0.516	2.3200	1.1964	A
	2	5/13/57	1.65	1.439	0.640	0.002	1.540	1.076	43	37		2.070	1.1622	2.4063	
	3	6/23/59	2.13	1.151	1.135	0.018	1.420	1.308	59	43		0.912	1.3721	1.2511	
	4	5/22/61	1.90	0.068	0.228	0.060	0.047	0.687	18	94		1.076	0.1915	0.2061	
	5	6/25/61	1.39	0.274	0.328	0.030	0.204	0.760	49	89		1.130	0.5506	0.6220	
	6	6/ 9/62	2.03	0.720	1.524	0.035	0.957	1.346	28	50	56.3	1.121	0.5600	0.6280	
14309007	1	3/31/57	0.51	0.240	1.946	0.046	0.150	1.048	7	34		0.374	0.2059	0.0771	A
	2	6/ 4/57	1.85	1.069	1.665	0.020	1.438	1.363	38*	37		0.841	1.0270	0.8637	
	3	6/23/59	1.99	0.797	1.000	0.023	0.665	0.854	47	73		1.033	0.6438	0.6650	
	4	6/25/61	1.46	0.317	0.366	0.024	0.206	0.651	52	90		0.974	0.5778	0.5628	
	5	7/16/61	1.23	0.139	0.597	0.045	0.060	0.432	14	83	63.4	0.596	0.1687	0.1005	
14309008	1	4/24/57	1.79	1.618	2.018	0.002	1.650	1.022	48	37		0.630	1.2973	0.8176	A
	2	5/13/57	1.57	1.392	0.362	0.004	1.240	1.049	38	25		1.452	1.5200	2.2064	
	3	6/ 4/57	1.88	1.275	2.303	0.018	1.758	1.387	33	32		0.740	1.0313	0.7634	
	4	6/23/59	2.83	1.062	0.619	0.024	0.782	0.736	103	82		1.006	1.2561	1.2633	
	5	6/23/61	1.46	0.310	0.373	0.029	0.248	0.800	50	84		1.117	0.5952	0.6649	
	6	7/16/61	1.15	0.144	0.665	0.049	0.721	5.008	13	79	55.4	6.587	0.1646	1.0842	
	7	6/ 9/62	1.78	0.741	1.309	0.020	0.883	1.190	34	49		0.972	0.6939	0.6746	
14309009	1	4/24/57	1.77	1.721	1.309	0.001	1.674	0.983	78	48		0.787	1.6250	1.2788	A
	2	5/13/57	1.46	1.436	0.953	0.000	1.186	0.829	90	46		0.636	1.9565	1.2445	
	3	6/ 4/57	1.85	1.339	2.566	0.014	1.634	1.247	31	34		0.707	0.9118	0.6446	
	4	6/23/59	2.94	0.986	0.558	0.028	0.789	0.801	106	64		0.854	1.6563	1.4140	
	5	6/25/61	1.47	0.342	0.437	0.025	0.338	0.988	47	82		1.349	0.5732	0.7735	
	6	7/16/61	1.16	0.120	2.392	0.050	0.065	0.543	3	78	58.7	0.706	0.0385	0.0272	
14618006	1	9/ 5/60	0.92	0.070	0.300	0.082	0.043	1.019	14	54		0.553	0.2593	0.1433	F
	2	2/25/61	0.43	0.358	1.759	0.018	0.119	0.650	18	70		0.431	0.1571	0.0677	
	3	5/ 1/62	1.44	0.287	1.058	0.032	0.148	0.557	15	60	61.3	0.560	0.2500	0.1399	
14618007	1	10/10/59	3.61	1.704	0.430	0.015	1.155	0.684	186*	203		2.931	0.9163	2.6860	F
	2	8/26/60	2.43	0.736	0.138	0.008	0.256	0.374	115*	180		2.904	0.6389	1.8551	
	3	9/ 2/60	1.44	0.333	0.596	0.035	0.179	0.599	30	91		0.911	0.3297	0.3003	
	4	8/23/61	1.09	0.145	0.256	0.011	0.067	0.517	30	125		1.090	0.2400	0.2617	
	5	6/20/62	0.60	0.167	1.537	0.054	0.061	0.379	6	96	139.0	0.635	0.0625	0.0397	
14618008	1	6/ 9/58	1.25	0.084	0.903	0.049	0.092	1.220	5	36		0.734	0.1389	0.1019	F
	2	6/12/58	0.94	0.446	0.437	0.012	0.432	1.267	30*	43		1.414	0.6971	0.9863	
	3	6/ 2/59	2.35	0.777	0.522	0.014	0.284	0.439	86	144		0.911	0.5972	0.5441	
	4	9/30/59	1.17	0.034	0.892	0.062	0.037	1.305	2	18		0.374	0.1111	0.0415	
	5	5/26/62	1.57	0.034	0.149	0.037	0.025	0.753	13	36	55.4	0.465	0.3611	0.1678	
14618010	1	6/26/58	1.85	0.452	0.422	0.028	0.129	0.390	54	94		0.532	0.5745	0.3057	
	2	7/10/59	4.03	0.390	0.131	0.025	0.130	0.344	172	300		1.731	0.5735	0.9924	F
	3	9/30/59	1.45	0.068	1.724	0.088	0.028	0.624	2	78		0.633	0.0256	0.0162	
	4	6/ 7/61	2.22	0.490	0.213	0.027	0.223	0.456	138	144		1.092	0.9583	1.0469	
	5	6/20/62	1.71	0.211	0.643	0.032	0.077	0.394	18	188	160.8	1.252	0.0957	0.1198	
14911001	1	8/12/43	2.15	0.490	1.584	0.079	0.898	2.075	18	29		0.913	0.6207	0.5669	A
	2	6/28/45	1.09	0.489	3.418	0.051	1.002	2.356	8	24		0.880	0.3333	0.2932	
	3	6/24/49	2.00	0.430	1.218	0.048	0.723	1.749	21	21		0.594	1.0000	0.5936	
	4	7/15/50	1.84	0.292	0.531	0.056	0.438	1.501	33	53		1.325	0.6226	0.8249	
	5	8/ 5/51	6.98	1.853	0.803	0.033	1.690	0.940	113*	84	42.2	1.565	1.3452	2.1046	
14911002	1	8/12/43	2.05	0.436	3.143	0.080	1.210	2.977	8	13		0.626	0.6154	0.3850	A
	2	7/11/44	1.94	0.212	1.413	0.078	0.358	1.690	9	37		1.042	0.2432	0.2534	
	3	6/28/45	1.08	0.474	3.494	0.046	1.296	2.827	8	13		0.617	0.6154	0.3709	
	4	6/24/49	2.39	0.459	1.531	0.056	0.990	2.155	18	20		0.718	0.9000	0.6466	
	5	7/15/50	1.85	0.334	0.607	0.058	0.645	1.932	33	36		1.159	0.9167	1.0626	
	6	8/ 5/51	6.77	1.743	0.926	0.029	1.742	0.999	113	96	35.8	1.598	1.1771	1.8812	
14911003	1	5/13/56	0.86	0.419	2.141	0.027	0.151	0.386	11	30		0.192	0.3667	0.0705	A
	2	6/ 4/58	3.23	1.278	1.370	0.034	0.575	0.450	56	74		0.555	0.7568	0.4197	
	3	9/13/62	0.96	0.856	0.899	0.001	0.323	0.407	50	72	58.7	0.517	0.6944	0.3593	

T_e^* = adjusted T_e , F = forested, A = agricultural

TABLE C-2. RAINFALL VARIABLES

Catchment No.	Event No.	Date	T_e min	M_1 min	M_2 (min)^2	M_2' (min)^2	R_1 (min)	R_2 (min)^2	R_2' (min)^2
10606104	1	7/15/47	15	13	156	*	13	156	*
	2	8/ 9/47	35	54	3014	57	57	3370	75
	3	7/23/55	70	91	8892	616	68	5256	647
10606105	1	7/17/57	55	19	731	380	22	796	334
	2	7/20/51	10	5	25	*	5	25	--
	3	7/29/45	10	6	39	6	5	32	6
	4	7/23/45	5	3	6	*	3	6	*
	5	7/22/45	20	60	3600	0	60	3600	*
10608004	1	8/22/40	7	7	45	3	7	45	3
	2	8/ 8/45	6	243	59049	*	243	59049	0
	3	8/13/45	6	3	9	*	3	9	*
11204004	1	3/26/40	2	15	225	*	15	225	*
	2	4/ 9/40	21	5	29	2	9	115	27
	3	5/ 4/40	10	5	25	35	5	25	31
11511001	1	6/ 1/43	53	38	1763	351	37	1645	308
	2	7/21/48	63	39	1896	370	41	2027	350
	3	7/ 1/50	90	41	2628	986	42	2613	880
	4	7/18/56	40	28	906	110	28	903	147
12412006	1	5/ 9/58	45	19	547	171	22	619	147
	2	1/17/60	180	112	15744	3237	118	16911	3032
	3	7/25/62	15	68	4556	*	68	4556	*
12707001*	1	6/20/39	32	9	129	41	11	178	58
	2	6/ 7/53	64	19	508	152	23	772	238
	3	6/15/57	66	35	1582	333	34	1508	358
	4	5/15/60	48	67	4668	153	69	4896	181
	5	8/11/61	24	15	272	560	15	262	1000
12707002	1	6/15/57	60	33	1413	356	34	1473	340
	2	6/12/58	8	18	324	*	18	324	*
	3	7/ 3/59	45	23	727	178	23	708	174
	4	5/15/60	93	66	4648	326	62	4363	507
	5	6/14/61	117	40	2191	564	54	3920	1001
14309001	1	4/24/57	39	19	365	82	17	379	87
	2	5/ 9/57	15	10	105	14	8	88	17
	3	5/13/57	101	26	1090	426	32	1753	721
	4	6/23/59	86	36	1670	400	36	1670	400
	5	7/ 9/61	17	13	180	21	13	200	23
	6	7/16/61	23	16	275	32	16	297	38
14309002	1	6/10/41	75	31	1151	186	31	1227	225
	2	6/15/42	41	13	233	7	14	283	9
	3	7/15/50	71	46	2582	475	40	2148	524
	4	6/23/59	111	60	4630	1044	65	5402	1159
	5	7/16/61	35	12	215	63	15	318	89
	6	7/23/61	16	12	182	38	12	169	24
14309005	1	6/10/41	67	23	596	87	24	681	127
	2	3/26/46	10	40	1578	7	40	1607	7
	3	4/24/57	56	123	15337	120	124	15381	130
	4	6/15/61	12	8	64	3	10	100	9
	5	7/16/61	7	5	55	6	5	35	5
	6	6/ 1/62	30	22	549	71	23	598	68
14309006	1	4/24/57	58	25	737	114	25	773	139
	2	5/13/57	43*	26	1333	643	32	1973	956
	3	6/23/59	59	30	1163	255	30	1146	268
	4	5/22/61	18	41	1698	30	36	1291	28
	5	6/25/61	49	38	1690	242	33	1351	265
	6	6/ 9/62	28	18	393	74	19	408	64
14309007	1	3/31/57	7	4	19	6	4	18	5
	2	6/ 4/57	38	18	381	65	18	423	88
	3	6/23/59	47	22	685	216	23	720	207
	4	6/25/61	52	11	157	48	26	952	283
	5	7/16/61	14	10	106	6	10	106	6
14309008	1	4/24/57	48	22	589	112	22	599	116
	2	5/13/57	38*	20	787	370	29	1808	940
	3	6/ 4/57	33	15	311	81	15	321	83
	4	6/23/59	103	51	4048	1405	55	4297	1264
	5	6/25/61	50	13	320	140	26	957	294
	6	7/16/61	13	5	20	*	9	84	10
	7	6/ 9/62	34	24	682	109	22	586	103
14309009	1	4/24/57	78	22	641	159	23	695	183
	2	5/13/57	90	23	843	319	23	888	339
	3	6/ 4/57	31	14	245	56	14	264	62
	4	6/23/59	106	48	3595	1278	56	4373	1275
	5	6/25/61	47	14	322	114	25	835	228
	6	7/16/61	3	15	210	*	15	210	*
14618006	1	9/ 5/60	14	6	69	32	7	65	22
	2	2/25/61	18	4	24	6	4	26	7
	3	5/ 1/62	15	11	179	38	12	157	25
14618007	1	10/10/59	186*	129	19465	*	132	20873	*
	2	8/26/60	115*	125	17540	1862	152	28518	5409
	3	9/ 2/60	30	20	452	48	18	368	55
	4	8/23/61	30	139	19317	107	136	18569	82
	5	6/20/62	6	44	1936	*	44	1936	*
14618008	1	6/ 9/58	5	11	117	1	11	113	2
	2	6/12/58	30*	33	1116	56	138	1677	200
	3	6/ 2/59	86	105	11624	529	108	12198	595
	4	9/30/59	2	67	4489	*	67	4489	*
	5	5/26/62	13	26	685	3	24	576	12
14618010	1	6/26/58	54	40	1756	191	41	1944	252
	2	7/10/59	172	163	30172	3448	165	30071	2924
	3	9/30/59	2	14	196	--	14	196	--
	4	6/ 7/61	138	110	13882	1715	103	12844	2208
	5	6/20/62	18	153	23292	17	151	22846	23
14911001	1	8/12/43	18	9	60	14	9	111	24
	2	6/28/45	8	3	13	4	4	16	4
	3	6/24/49	21	13	200	23	13	209	29
	4	7/15/50	33	21	553	133	18	420	112
	5	8/ 5/51	113*	89	8698	781	87	8664	1126
14911002	1	8/12/43	8	5	32	4	6	37	4
	2	7/11/44	9	17	280	88	18	332	5
	3	6/28/49	8	3	14	4	4	16	4
	4	6/24/49	18	14	209	12	15	258	21
	5	7/15/50	33	21	584	123	18	425	109
	6	8/ 5/51	113	89	8421	534	83	7716	804
14911003	1	5/13/56	11	18	337	*	18	312	*
	2	6/ 4/58	56	45	2334	333	47	2489	291
	3	9/13/62	50	19	581	229	19	615	238

T_e^* = adjusted T_e , * = very small value, -- = negative value

Key Words: Unit hydrograph, land-use effect on unit hydrographs, forest land-use catchments, agricultural land-use catchments.

The effects of forest and agricultural land uses on flood unit hydrographs of small catchments (up to 10 sq. mi.) is the subject of this paper. The unit hydrograph approach is used, supplemented by the regression analysis. The unit hydrograph is approximated by the two-parameter incomplete gamma function. The regression analysis is used for relationships among hydrologic variables, and between the unit hydrograph parameters and physiographic factors. The average rise time is dependent on land use and catchment physiographic factors. A concept of representative catchment, equal for all the river basins studied, is introduced in order to separate the effects of geometry from the effects of land use.

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The study indicates that for a given small catchment the agricultural land use means a smaller flood peak with a faster surface runoff, while the forest land use means a smaller flood peak with a slower surface runoff. Catchments with predominantly agricultural land use have unit hydrograph peaks approximately 2 to 4 times greater than the predominantly forest land-use catchments.

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