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RUNOFF FROM FOREST AND AGRICULTURAL WATERSHEDS

by

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RUNOFF FROM FOREST AND AGRICULTURAL WATERSHEDS

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ABSTRACT

The dichotomy between forest and agricultural watersheds with areas less than 40 square miles has been studied by looking at the time distribution of runoff from storm rainfall events. The direct investigation of rise times for hydrographs gave inconclusive results, but led to a more fruitful second approach.

The second part of the investigation focused on the unit hydrograph as the characteristic response of the watershed. The unit hydrograph can be represented mathematically by two-parameter incomplete gamma function. The rise time for the unit hydrograph is a convenient and significant parameter in determining the shape of the unit hydrograph.

The effects of the physiographic parameters of watersheds were removed by determining a hypothetical median watershed and varying the cover characteristics from forest to agricultural. The influences of steeper slopes that are common in forest watersheds were thus eliminated. The results clearly indicate the significant damping that forest cover causes in the watershed response to rainfall.

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*unit hydrograph/ peak flow/ *rainfall-runoff relationships.

Completion Report

Project A-002-Colo. SURFACE WATER MANAGEMENT

Sub-project C. FLOODS FROM FORESTS COMPARED TO THOSE FROM FARMLAND

Sub-project Leader: M. E. Holland

Isolated studies have indicated that forests may have a strong damping influence on flood peaks. This influence is often compensated for by the fact that forest watersheds are frequently located in upstream areas that have physiographic features, such as steep slopes, that tend to increase the flood peak. The purpose of this research study was to isolate the effect of the difference between forest cover and agricultural cover in determining the distribution in time of excess storm rainfall.

One condition that has made it difficult to study small watershed response in general and the forest-agriculture dichotomy in particular is the lack of sufficient data. A considerable quantity of hydrologic data has been collected by a number of federal, state and local agencies. However, the data had not been assembled at a single location in a readily usable form. The data required for the research described in this report was available only because Colorado State University had begun a Research Data Assembly Program for Small Watershed Floods (1,2) shortly before this project was initiated. During the first one and one-half years of this project, the major emphasis was on the assembly of data in co-operation with the overall program. The selection and inclusion of forest and agricultural watersheds was assured by this cooperation.

The shift in emphasis from the data assembly phase to the pursuit of the research objectives occurred early in 1967. Additional data were still being added to the file, but at a slower rate. The research objectives and results are discussed briefly in this report. The more detailed presentation of the research results will appear in a Ph.D. dissertation by a student supported by this project. The dissertation was not completed in time to be included in this report. It will be sent as a supplement when it is completed this summer.

OBJECTIVES

The objectives of this research study are

1. To examine the dichotomy between floods from small forest watersheds and those from small agricultural watersheds;
2. Compare observed peak flow rates and timing of runoff from forest and agricultural watersheds; and
3. Analyze the effects and influences of topographic and storm features to isolate the effects of the watershed cover.

In addition to the study of the peak flow rate and the timing of runoff, an investigation of the volume of runoff was also planned. However, the specific effects of the type of cover on the volume of storm runoff did not appear to be significantly distinguished for the watersheds included in this study. Therefore, the study of runoff volumes was dropped.

RESEARCH RESULTS

A preliminary analysis of the data from 51 small watersheds was reported in the 1967 progress report (3). The 51 watersheds were divided into four classes based on cover: forest, cultivated, grass and desert. Regression equations were obtained for the hydrograph rise times (Table 1) and for the flood peak with a return period of 10 years (Table 2). The equations were different for the different classes, but the enexplained variance was too large in all cases to be acceptable. Thus, the results of the preliminary study were inconclusive.

TABLE 1 EQUATIONS FOR PREDICTION OF HYDROGRAPH RISE TIMES

Class	n	Problem No.	Correlation	Equation	R^2	S_{ey}	Predicted Rise Time, hours	
							Watershed A	Watershed B
Forest	9	T_{M2}- 2	Simple	$T_M = 0.790 + 0.105\ L$	0.418	0.285	1.217	0.905
Cultivated	17	T_{M1}- 1	Simple	$T_M = 0.689 + 0.144\ A$	0.895	0.331	1.606	0.752
Grass	13	T_{M2}- 2	Simple	$T_M = 0.440 + 0.078\ L$	0.643	0.204	0.757	0.526
Desert	12			None				

TABLE 2 EQUATIONS FOR PREDICTION OF TEN-YEAR FLOOD PEAKS

Class	n	Problem No.	Correlation	Equation	R^2	S_{ey}	Predicted 10 Year Flood Peak, in./hr.	
							Watershed A	Watershed B
Forest	8	q-4	Multiple	$q = -0.066 - 0.027\ A + 0.482\ P$	0.267	0.567	0.726	0.886
Cultivated	16	q-7	Multiple	$q = -3.442 - 0.188\ A + 1.766\ P + 0.008\ S_1$	0.716	0.597	1.020	2.782
Grass	13	q-7	Multiple	$q = -6.933 - 0.039\ A + 3.125\ P + 0.007\ S_1$	0.486	1.014	0.797	1.558
Desert	12	q-7	Multiple	$q = -0.164 - 0.011\ A + 0.599\ P + 0.0015\ S_1$	0.276	0.429	1.334	1.512

A more detailed study has been carried on for the past two years. The small watersheds were screened more selectively by eliminating the grass and desert watersheds and by including in the forest and agricultural classes only watersheds with more than 50% of the area in the respective class. Twenty-two watersheds were found with 3 or more flood events. Eight were predominatly forest watersheds and fourteen were predominantly agricultural. A total of 105 flood event records were available for these watersheds and were used in the analysis. This study will be described in the next section. The major conclusions are presented here:

1. The unit hydrograph concept, together with regression and correlation analysis, affords a sound method of investigating the effects of land use upon the direct runoff from small watersheds.
2. The unit hydrographs of small watersheds are strongly affected by land use. The unit peak discharge from a small basin with predominantly agricultural cover can be 2 to 4 times as great as that from a forest-covered basin.
3. The average rise time may be regarded as the watershed time characteristic which is independent of rainfall. The most significant physiographic factor in determining the average rise time is the basin area. The average mainstream slope is the second most important.
4. The unit hydrographs due to short duration storms are affected more by a nonuniform time distribution of rainfall intensity than by the effective rainfall duration.

STUDY OF LAND USE ON FLOOD PEAKS

The study described in this section is being presented as a Ph.D. dissertation. The dissertation will be sent as a supplement to this report when it is completed.

This study is based on the unit hydrograph concept combined with regression and correlation analysis. Mathematical expression of the unit hydrograph in the form of a two-parameter incomplete gamma function, developed theoretically from both the parametric and stochastic approaches, is used in deriving the general unit peak flow equation. The method of regression and correlation analysis is used to investigate the correlation between the selected hydrologic variables in order to:

1. Study the relationships of the dominant physiographic factors of small watersheds.
2. Establish the relationships between the unit hydrograph parameters and the dominant physiographic factors and rainstorm variables.
3. Determine the best-fitted unit peak flow equations.

THEORETICAL AND ANALYTICAL CONSIDERATIONS

Consider the effective rainfall input to a watershed is composed of N distinguishable raindrops and the direct runoff hydrograph output can be interpreted in terms of the number of raindrops N_i, $i = 1,2,3,\ldots$, passing the gaging station during a time interval, $t_{i-1} - t_i$, of the hydrograph. Assume:

1. Each raindrop has the same a priori probability of reaching the gaging station during the <u>ith</u> time increment and is independent of the other raindrops.

2. There are G_i ways in which N_i raindrops could have found their way to the gaging station during the time interval, $t_{i-1}-t_i$, and G_i is proportional to the travel distance L_i from a given location in the watershed to the outlet, which is in turn proportional to the travel time t_i. Accordingly,

$$G_i = C\, t_i^B$$

The problem is equivalent to the distribution of N distinguishable balls in n urns and each ith urn has G_i ways of placing N_i balls. The total number of ways, W, therefore follows the multinomial distribution. The limiting distribution, Fig. 1, in which Δt approaches zero is given by,

$$W = N \prod_{i=1}^{\infty} (Ct_i)\, N_i/N_i! \qquad (1)$$

The particular set of numbers N_i for which W is maximum will be the most probable one. The first constraint is a simple conservation statement,

$$N = \sum_{i=1}^{\infty} N_i$$

The second constraint is one which characterizes the watershed by T_m, the mean travel time:

$$T_m N = \sum_{i=1}^{\infty} t_i N_i$$

By maximizing Equation (1) subject to the two constraints, the unit hydrograph equation is found. The equation has the form of a two-parameter-incomplete gamma function with the parameters B and T_m. This equation can be expressed in terms of B and T_r, the rise time,

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

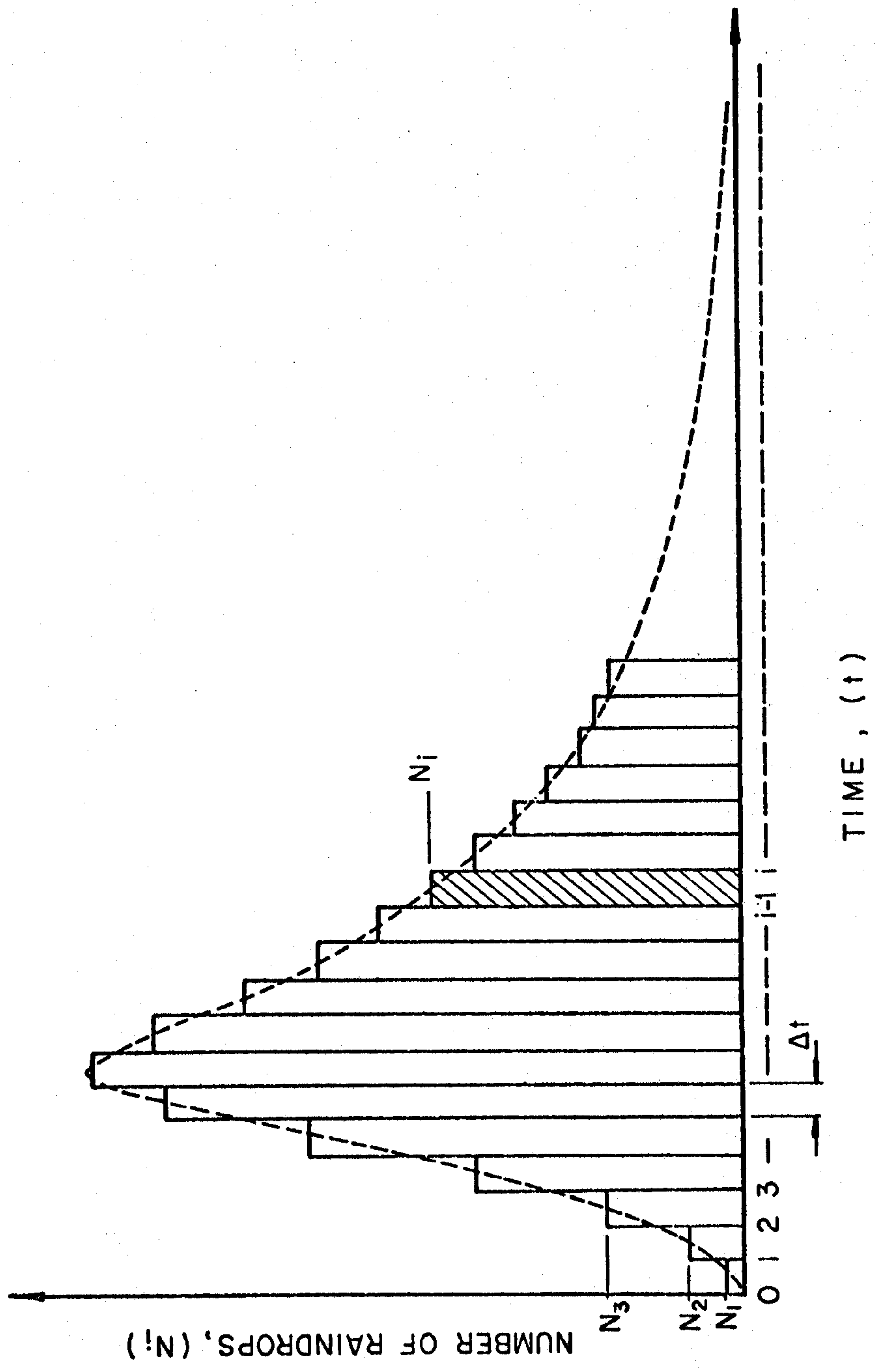

Figure 1. Hydrograph interpreted as a raindrop histogram

The unit peak flow equation is therefore,

$$U_p T_r = \frac{1}{\Gamma(B+1)} \quad B^{B+1} \quad e^{-B} \quad = f(B) \tag{3}$$

which can be approximated with error less than 5% by the equations for $B \geq 2.0$

$$f(B) = 0.3989 \; B^{0.5} \tag{4}$$

and for $0.1 \leq B \leq 2.0$

$$f(B) = 0.3549 \; B^{0.615} \tag{5}$$

The three equations are compared in Fig. 2.

By multiplying both sides of Equation (3) by T_e, the effective rainfall duration, and rearranging, we obtain

$$\frac{q_p}{I_e} = f(B) \left(\frac{T_e}{T_r}\right) \tag{6}$$

where q_p is the peak flow per unit area and I_e is the effective rainfall intensity.

SELECTION OF WATERSHEDS AND FLOOD EVENTS

The small watersheds (areas from 0.1 to 10 square miles) having 50% or more forest and agricultural cover, containing 3 or more flood events were selected from Research Data Assembly for Small Watershed Floods, Part 2, Colorado State University (2). There are 8 predominantly forest and 14 predominantly agricultural watersheds having areas ranging from 0.12 to 7.19 square miles and located throughout the eastern and central United States. The 105 selected flood events are mainly caused by rainstorms of short duration (less than 6 hours).

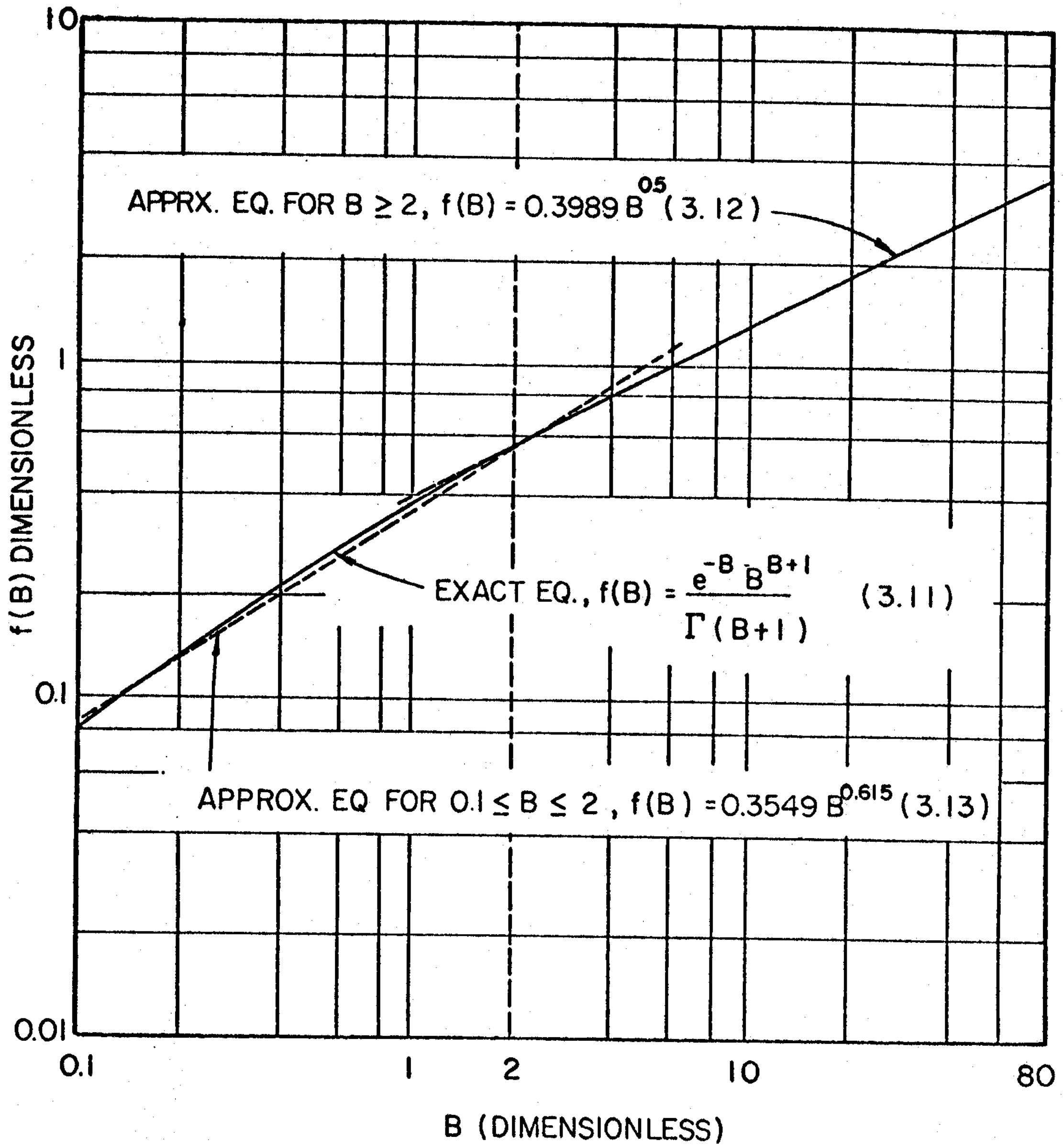

Figure 2. Goodness of fits of the approximate unit peak flow equations to the exact equation.

SELECTION OF HYDROLOGIC VARIABLES

A. Unit Hydrograph Parameters

1. U_p, the unit hydrograph peak flow
2. T_r, the rise time
3. T_{ra}, the average rise time
4. B, the unit hydrograph shape factors
5. Ba, the average unit hydrograph shape factors

B. Rainstorm Variables

1. T_e, the effective rainfall duration
2. I_e, the average effective rainfall intensity
3. ERM_1, the first effective hyetograph moment
4. ERM_2, the second effective hyetograph moment
5. $ERMM_2$, the second central effective hyetograph moment
6. TRM_1, the first hyetograph moment
7. TRM_2, the second hyetograph moment
8. $TRMM_2$, the second central hyetograph moment

C. Physiographic Factors of Watershed

1. A, the basin 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 stream slope
7. Types of land uses, forest and agriculture
8. C_f, the percentage of cover
9. LL_c/A, the basin shape factor
10. H^2/A, the basin relief factor.

COMPARISON OF PEAK FLOW RESPONSES

Selection of Representative Equations

After comparing the goodness of estimations and investigating the physical meaning of the regression equations, the following equations are selected to represent the watersheds used in this study.

A. Relationships between Physiographic Factors (all watersheds)

$$L = 1.766\ A^{0.643} \tag{7}$$

$$L_c = 0.470\ L^{0.991} \tag{8}$$

$$S_2 = 0.933\ S_1^{0.940} \tag{9}$$

$$S_2 = 162\ \frac{(H^2/A)^{0.494}}{(LL_c/A)^{0.506}} \tag{10}$$

B. The Average Rise Time Equations

Forest Watershed

$$T_{ra} = -\ 100.4 + 14.18\ A - 0.0552\ H + 52.0\ LL_c/A + 292.2\ C_f -).144\ S_2 \tag{11}$$

Agricultural watershed

$$T_{ra} = 75.6 - 0.277\ S_2 + 14.76\ A - 0.0739\ H \tag{12}$$

C. The Unit Peak Flow Equation (all watersheds)

$$\frac{q_p}{I_e} = 0.817 \left(\frac{T_e}{T_r}\right) \tag{13}$$

$$U_p = 0.817 \left(\frac{1}{T_r}\right) \tag{14}$$

D. The Unit Hydrograph Equation

$$U_t = 54.5 \left(\frac{1}{T_r}\right)^{5.2} t^{4.2}\ e^{-\left(\frac{4.2}{T_r}\right) t} \tag{15}$$

Selection of Median Watershed

Median Values of the dominant physiographic factors of all watersheds are chosen to represent the physiographic factors of the median watershed and are summarized in Table 3.

TABLE 3. PHYSIOGRAPHIC FACTORS OF MEDIAN WATERSHED

A	H	L	L_c	S_2	LL_c/A	H^2/A
Sq. Miles	Feet	Miles	Miles	Ft./Miles	Dimension-less	$\times 10^5$ (Ft./Miles)^2
0.590	104	1.345	0.595	63	1.340	0.152

Comparison of Peak-flow Responses

Using the physiographic factors of the median watershed (Table 3), the unit peak flows and the unit hydrographs of the median watersheds having 50% forest cover, 100% forest cover and agricultural cover are obtained by applying the representative equations of Section 3. The results are shown in Table 4 and Figure 3.

TABLE 4. COMPARISON OF PEAK FLOW RESPONSES

Types of watershed	Average rise time Minutes	Unit peak discharge In./Hours
Agricultural	59	0.817
50% Forest	109	0.450
100% Forest	255	0.192

The results indicate that the forest watersheds have smaller unit peak flows than the agricultural watershed. Increase in forest cover will decrease the peak runoff and the 50% forest watershed has unit peak flow 2.34 times the unit peak flow of the 100% forest watershed (in average). The unit peak flow of the agricultural watershed is about 4.26 times that of the 100% forest watershed. The average time to peak or the average rise time of the 100% forest watershed is longer than the others by approximately the same ratio as the peak flow.

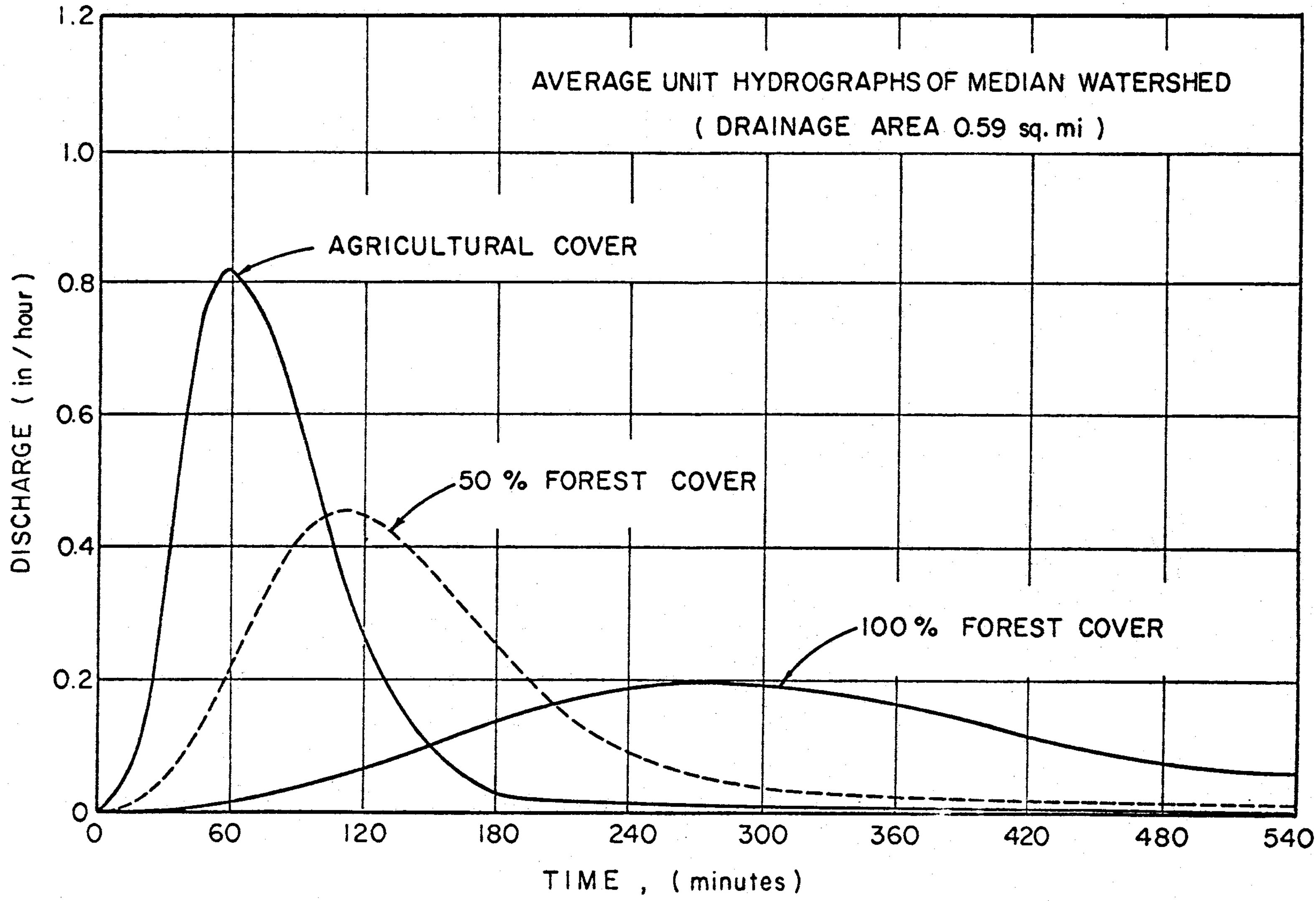

Figure 3 Comparision of the unit hydrographs of the median watershed of predominant forest and agricultural covers

CONCLUSIONS

The following conclusions have been drawn from the study and the analysis of 105 flood events of 8 forest and 14 agricultural watershed throughout the eastern and central United States:

1. The unit hydrograph approach, together with the method of regression and correlation analysis, affords a sound method of investigating the effects of land uses upon the direct runoff resulting from small watersheds.
2. The unit hydrographs of small watersheds are strongly affected by land uses. For a given small watershed, agricultural cover will enhance the flood potential compared to forest cover. The unit peak discharge from small basins with predominantly agricultural cover is approximately 2 to 4 times as great as that resulting from small basins with predominant forest cover.
3. The watershed factors L, L_c and A are highly correlated and so are S_1 and S_2. In regression and correlation analysis, A, and S_2 can be chosen to represent the others.
4. The dominant physiographic factors of small watersheds that affect the unit hydrograph parameter, T_{ra}, are A (and L and L_c), H, S_2 (and S_1), H^2/A, LL_c/A and C_f (forest watersheds). The most significant factor is the basin area (A), and S_2 can be considered to be the second significant factor. T_{ra} may be regarded as the watershed time characteristic which is independent of rainfall.

5. The unit hydrographs due to short duration storms of small watersheds are more affected by nonuniform time distribution of rainfall intensity than by the effective rainfall duration. Larger effects upon the unit hydrographs were observed for agricultural watersheds.
6. The values of B are not constant for any of the watersheds analyzed, but vary from storm to storm. The values of T_r also vary with T_{ra} (watershed characteristics), $ERMM_2$ (nonuniform rainfall) and T_e and other hydrologic factors.
7. The mean Ba of the forest watersheds is very close to the mean Ba of the agricultural watersheds. This implies that the average dimensionless unit hydrographs of all watersheds analyzed are similar and the same average unit peak flow equations (Equation 13 and Equation 14) and average unit hydrograph equation (Equation 15) are applicable for both forest and agricultural watersheds used in this study.
8. The stochastic systems approach afforded a sound method of determining the unit hydrograph equations.

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