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FINAL REPORT

DYNAMICS OF RUNOFF FROM HIGH-INTENSITY, SHORT-DURATION STORMS

by

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and

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(The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.)

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SUMMARY

In a previous study entitled "Temporal Distribution of Rainfall in Virginia" conducted by the Research Council, some 1,400 Virginia rainstorms were statistically analyzed and design rainfall time distribution curves, or hyetographs, were developed. In the present study, the effects of several parameters on the behavior of the runoff hydrograph were analyzed. These parameters included:

- o Temporal distribution of the rainfall
- o Antecedent soil moisture condition
- o Severity of the storm

The temporal distribution of the rainfall was simulated using three synthetic storm patterns where the temporal location of the maximum burst was modified; the antecedent soil moisture condition was simulated using three infiltration capacity curves (Horton's Equation); and the severity of the storm was simulated through return periods of 2, 25, and 100 years.

The resulting hydrographs from the Virginia distribution and the national distributions were analyzed.

The correlation between the SCS- AMC I, II, III and the infiltration capacity curves used to simulate antecedent soil moisture conditions are presented in the report, and the curves for correcting runoff estimates for different antecedent soil moisture conditions, storm durations, and return periods are suggested. Also, the intensity-duration-frequency curves developed using the one-minute rainfall data base are presented and compared with national curves.

Finally, an interactive computer program giving the hyetographs for storms less than one hour given the return period and the location of the storm is presented. This program uses the national IDF curves and the Virginia temporal distributions for storms less than or equal to one hour in duration.

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To Convert From	To	Multiply By

Length:

in	cm	2.54
in	m	0.025 4
ft	m	0.304 8
yd	m	0.914 4
mi	km	1 . 609 344

Area:

in^2	cm^2	6.451 600 E+00
ft^2	m^2	9.290 304 E-02
yd^2	m^2	8.361 274 E-01
mi^2	Hectares	2.589 988 E+02
acre (a)	Hectares	4.046 856 E-01

Volume:

oz	m^3	2.957 353 E-05
pt	m^3	4.731 765 E-04
qt	m^3	9.463 529 E-04
gal	m^3	3.785 412 E-03
in^3	m^3	1.638 706 E-05
ft^3	m^3	2.831 685 E-02
yd^3	m^3	7.645 549 E-01

NOTE: $1m^3$ = 1,000 L

Volume per Unit Time:

ft^3/min	m^3/sec	4.719 474 E-04
ft^3/s	m^3/sec	2.831 685 E-02
in^3/min	m^3/sec	2.731 177 E-07
yd^3/min	m^3/sec	1.274 258 E-02
gal/min	m^3/sec	6.309 020 E-05

Mass:

oz	kg	2.834 952 E-02
dwt	kg	1.555 174 E-03
lb	kg	4.535 924 E-01
ton (2000 lb)	kg	9.071 847 E+02

Mass per Unit Volume:

lb/yd^2	kg/m^2	4.394 185 E+01
lb/in^3	kg/m^3	2.767 990 E+04
lb/ft^3	kg/m^3	1.601 846 E+01
lb/yd^3	kg/m^3	5.932 764 E-01

Velocity: (Includes Speed)

ft/s	m/s	3.048 000 E-01
mi/h	m/s	4.470 400 E-01
knot	m/s	5.144 444 E-01
mi/h	km/h	1.609 344 E+00

Force Per Unit Area:

lbf/in^2	Pa	6.894 757 E+03
lbf/ft^2	Pa	4.788 026 E+01

Viscosity:

cS_t	m^2/s	1.000 000 E-06
P	Pa·s	1.000 000 E-01

Temperature: °F-32) 5/9 = °C

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INTRODUCTION

Highway drainage facilities are important components contributing to the service life of a highway system. To properly design a drainage system it is necessary to estimate the peak discharge resulting from a specific design storm. The choice of an appropriate design storm hyetograph has been found to be very important in estimating the shape and peak discharge of the resulting runoff hydrograph.

In an earlier study entitled "Temporal Distribution of Rainfall in Virginia" (Yu et al. 1984), storm data recorded at stations throughout the state were analyzed to determine the representative temporal distribution pattern, or hyetograph. Design curves and equations were prepared for use by engineers of the Virginia Department of Highways and Transportation in designing highway drainage. The current study is an extension of that earlier project.

It was believed that the determination of runoff resulting from high-intensity, short-duration storms would be of great value because of the increasing highway construction activities in urban and suburban areas. Specifically, the effects of storm intensity and duration, hyetograph selection criteria, and antecedent soil moisture condition were to be examined. The study benefited from the fact that a large volume of data on storm events was in hand from the previous project.

PURPOSE

The purpose of the study was to determine a method for selecting design storm temporal distributions, to study the intensity-duration-frequency relationship for rainfall of 30 minutes or less in duration, and to examine the effects on the runoff hydrograph of such factors as temporal distribution, antecedent moisture conditions, loss parameters, and the duration and severity of the storm.

METHODOLOGY

The major tasks and work elements in the project are outlined below.

I. Data Assembly

1. Selection of representative rainfall and stream flow gages
2. Selection of representative storm and runoff events
3. Preparation of data for analysis

II. Rainfall Frequency Analysis

1. Preparation of statistical computer packages
2. Analysis of the frequency of rainfall events
3. Derivation of rainfall frequency-intensity-duration curves

III. Rainfall-runoff Simulation

1. Selection of runoff models
2. Determination of the effects of hyetograph selection
3. Determination of the effects of storm intensity and duration, loss parameters, etc.
4. Determination of the effects of model selection

IV. Preparation of Final Report

EFFECTS OF RAINFALL TEMPORAL DISTRIBUTION

The Rio Road Watershed in Charlottesville, Virginia, was selected for the study of the effect of temporal rainfall distribution on the resulting hydrograph. Runoff was simulated using the Environmental Protection Agency Storm Water Management Model (SWMM) developed by Metcalf and Eddy et al. (1971). Only the runoff simulation routine was used in this study. Data on the Rio Road Watershed are given in Table 1.

Table 1

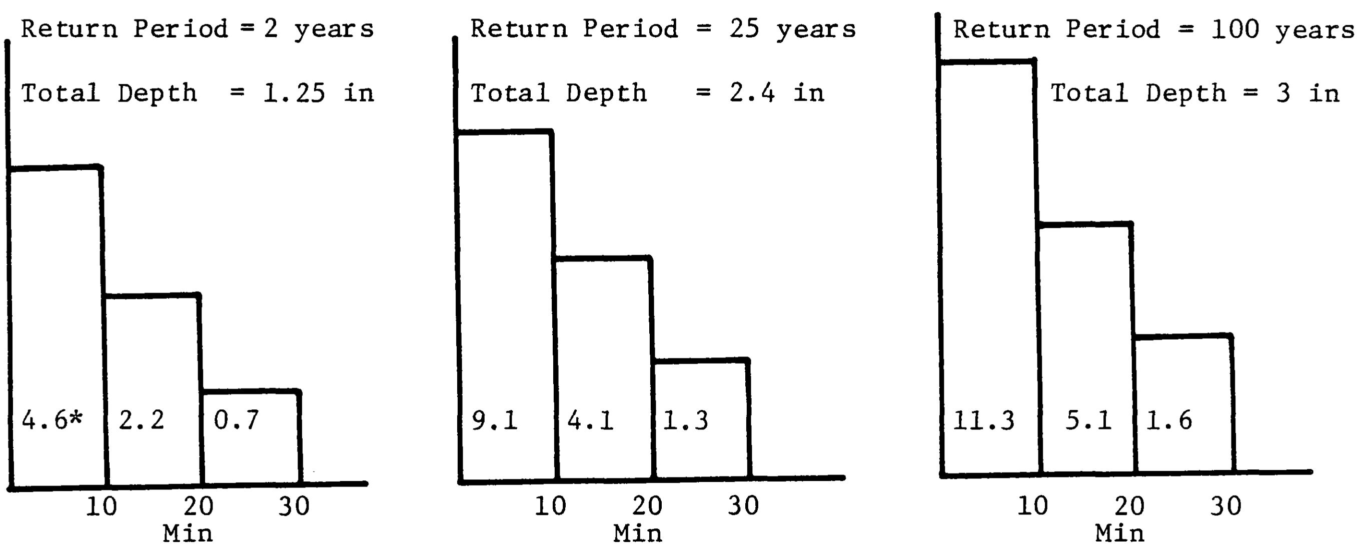
Characteristics of the Rio Road Watershed

Area	20.8 acres
Total Width of Overland flow	1,100 ft
Slope	0.15
Manning's Roughness Coefficient	0.30
Percent Impervious	24

Three storm temporal distributions were compared to illustrate the effect of the location of the maximum intensity on the runoff hydrograph. Storms with durations of 30 minutes and 3 hours and return periods of 2, 25, and 100 years were selected for the analysis.

The distributions shown in Figure 1 were developed from the temporal distribution for storms with durations of less than 1 hour for the piedmont region of Virginia. (Figure 19, Yu et al. 1984). Figure 1 gives the hyetographs for 2, 25 and 100 year return periods To examine the effect of peak rainfall location, the hyetographs were modified to have, in addition to the early-peaked pattern, centrally-peaked and late-peaked patterns. For each return period there were three storm patterns as shown in Figure 2.

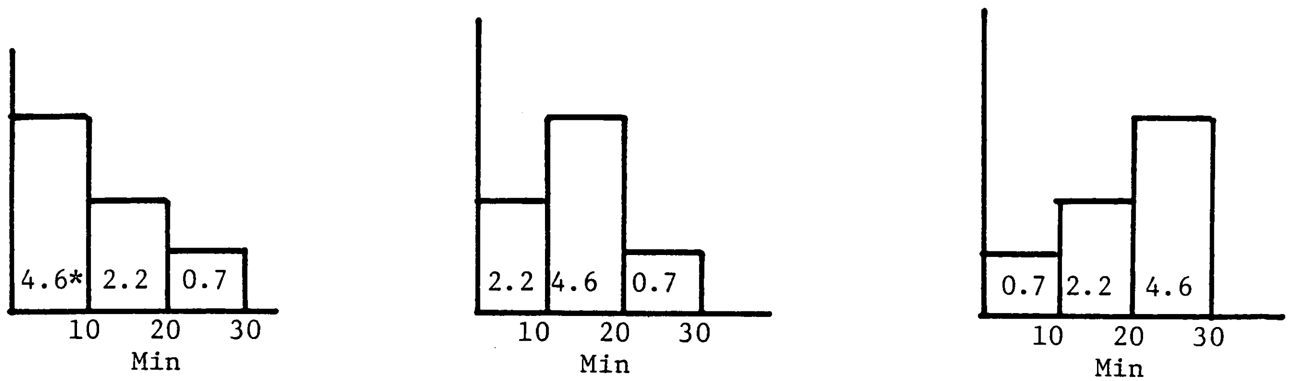
The resulting hydrographs are shown in Figures 3, 4, 5 and in tabulated form in Table 2. The infiltration capacity curve used for these runs was for normal antecedent soil moisture condition and is shown later on page 16.



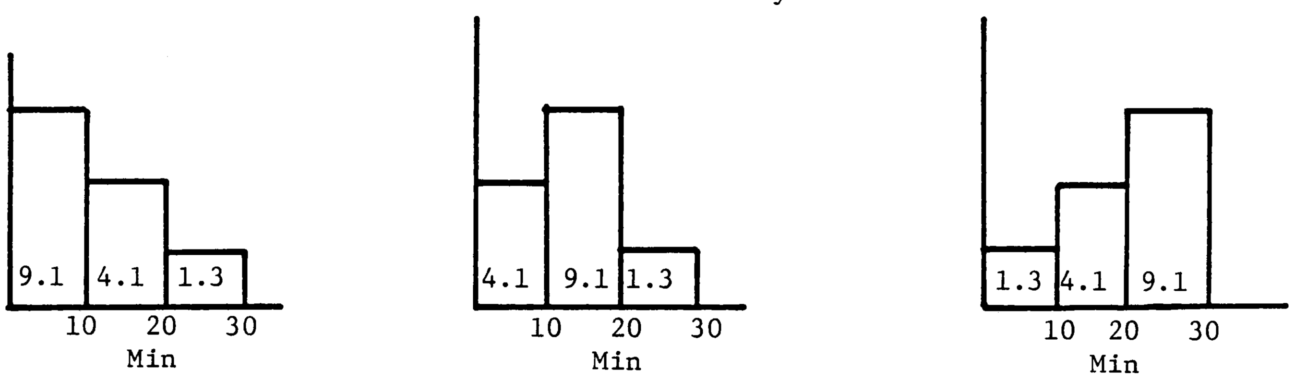
*Numbers represent rainfall intensity in in/hr.

Figure 1. Patterns for storms of 30-minute duration in the piedmont region.

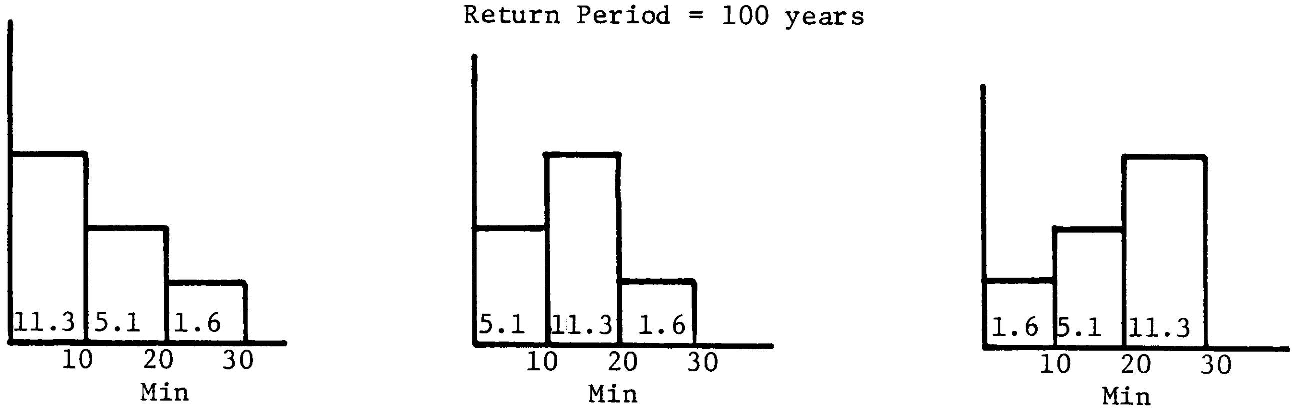
Return Period = 2 years



Return Period = 25 years



Return Period = 100 years



*Numbers represent rainfall intensity in in/hr.

Figure 2. Patterns for storms of 30-minute duration in piedmont region.

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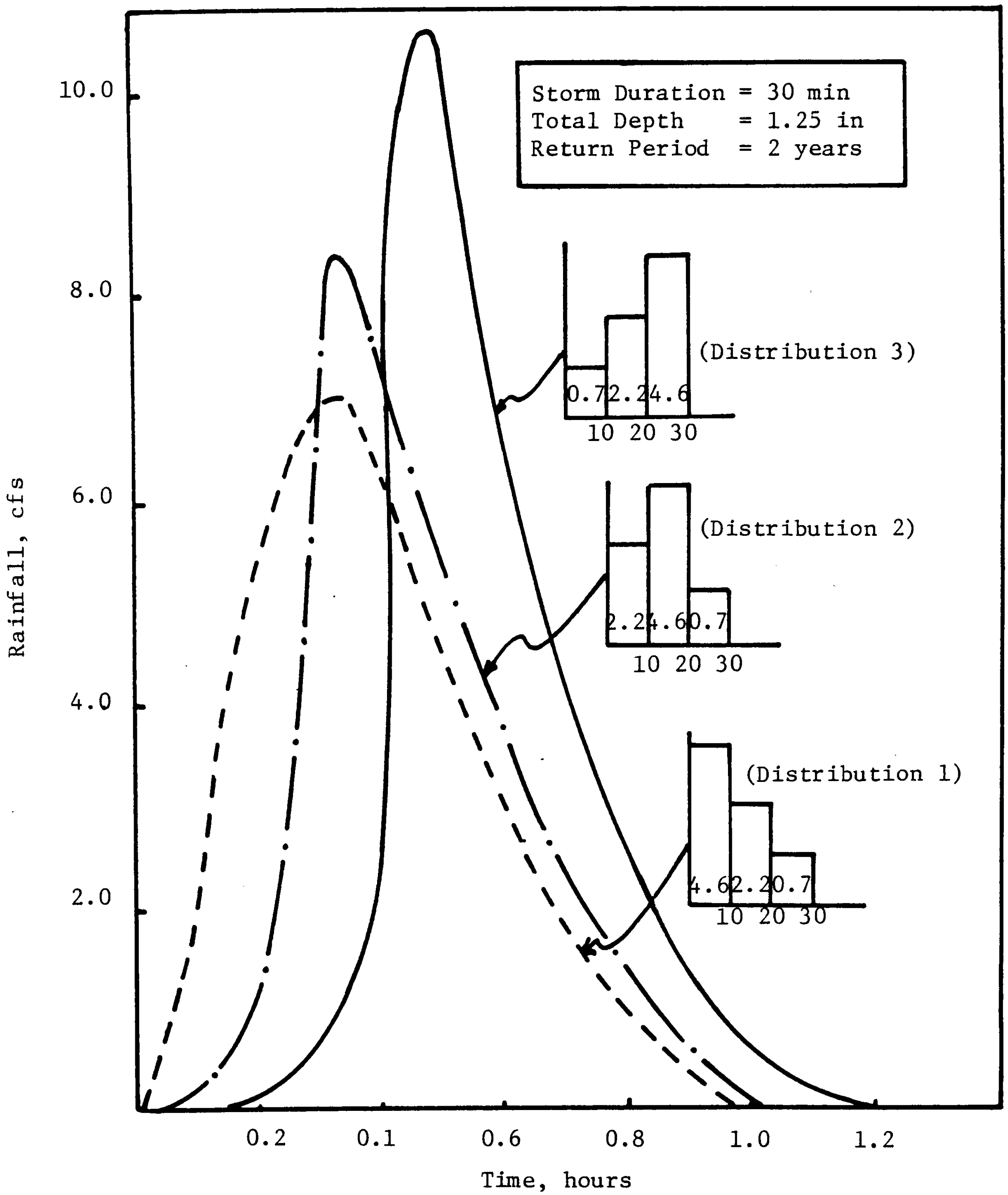


Figure 3. Hydrographs for storm of 30-minute duration with normal antecedent soil moisture condition. (Note: cfs is used for ft^2/s throughout this report.)

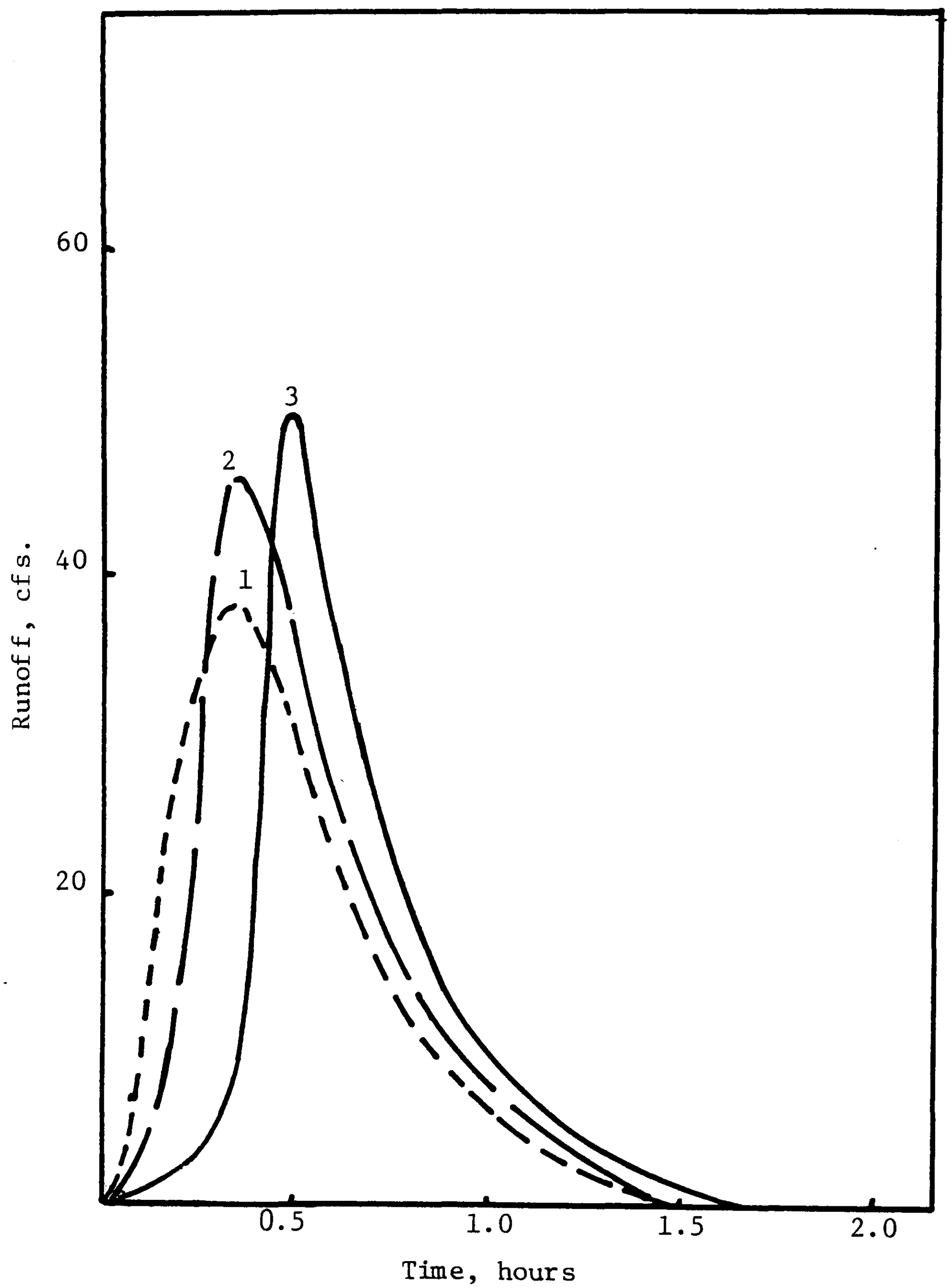


Figure 4. Hydrographs for storm of 30-min duration with normal antecedent soil moisture condition. Return period = 25 years.

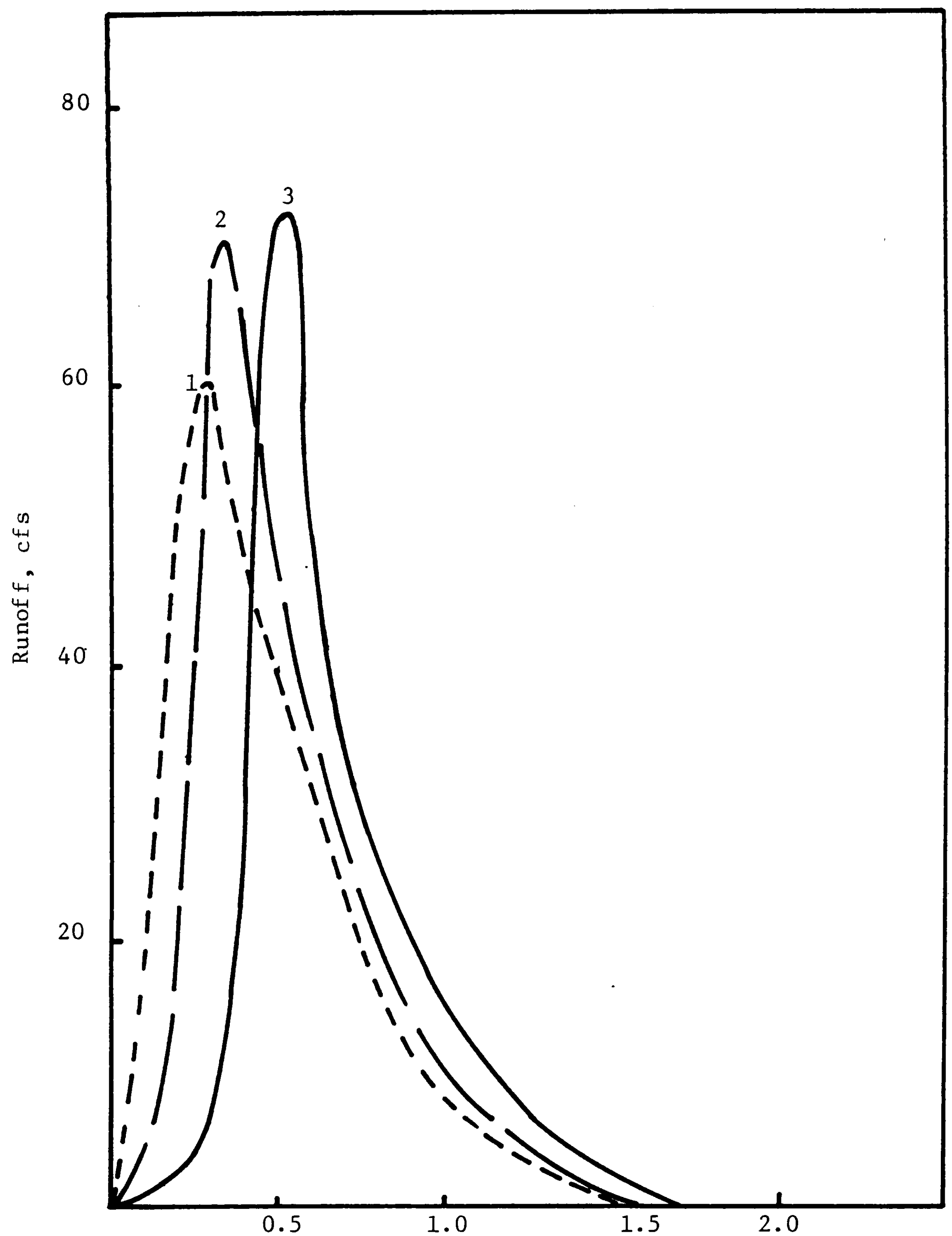


Figure 5. Hydrographs for storm of 30-min duration with normal antecedent soil moisture condition. Return period = 100 years.

Table 2

Effect of Temporal Rainfall Distribution on Peak Discharge
Storm Duration = 30 minutes
Normal Antecedent Soil Moisture Condition

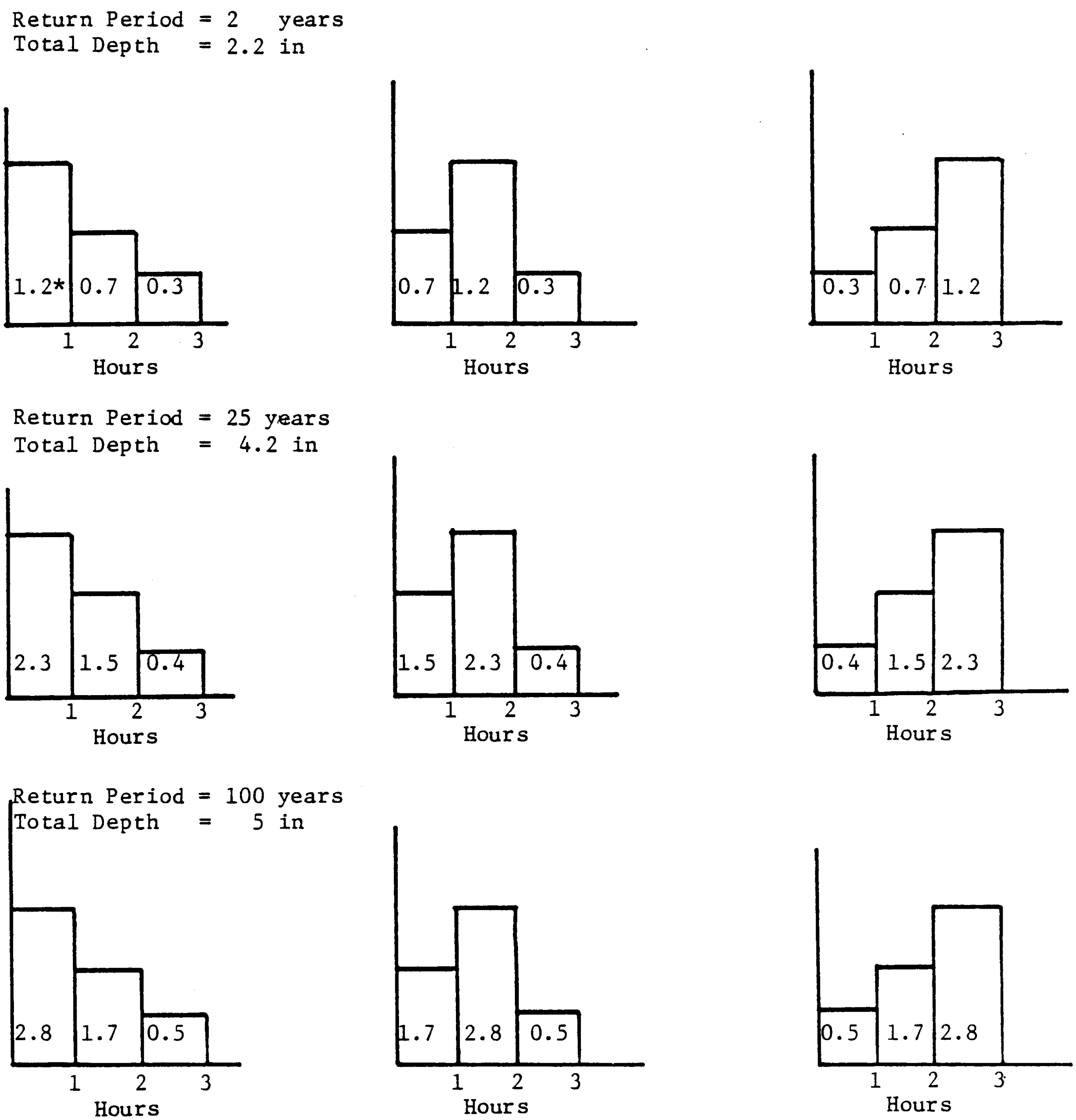
Distribution	2-Yr. Storm		25-Yr. Storm		100-Yr. Storm	
	Peak Flow, CFS	% Incr. over Dist. 1	Peak Flow, CFS	% Incr. over Dist. 1	Peak Flow, CFS	% Incr. over Dist. 1
1	6.8	-	38.4	0	60	-
2	9.0	32.3	47.0	22.4	70	16.7
3	10.4	52.9	52.0	35.4	72	20.0

Distribution 1: Highest intensity burst in the beginning of the storm.
Distribution 2: Highest intensity burst in the middle of the storm.
Distribution 3: Highest intensity burst at the end of the storm.

The resulting hydrographs indicate that under normal antecedent moisture conditions, the peak discharge is greatest for a distribution in which the peak is late in the storm. The distribution with the rainfall intensity at the beginning of the storm gives the lowest peak discharge. These extremes result from the fact that the abstractions are important at the beginning of the storm, and when they coincide with the highest intensity, the effect of the burst is lessened.

Table 2 shows that the storm distribution is more critical for a frequent storm than it is for a severe storm. This can be seen in the difference between the percentage increase in the peak discharge for distribution 1 (burst at the beginning of the storm) and that for distribution 2 (burst at the end of the storm). The percentage increase is dampened as the return period increases. The percentage augmentation in the peak discharge is 53% for a 2-year storm, 35% for a 25-year storm, and 20% for a 100-year storm. The reason for this decrease is that the effects of the abstractions during a major storm are greatly reduced. On the other hand, the same effects are important during a small storm.

That the peak discharge is greatest for a storm having its maximum burst late in the storm and that the 2-year storm is more critical are verified by the storm patterns for a 3-hour rainfall shown in Figures 6 through 9. The normal antecedent soil moisture condition was used for these runs.



*Numbers represent rainfall intensity in in/hr.

Figure 6. Storm pattern for storm of 3-hour duration.

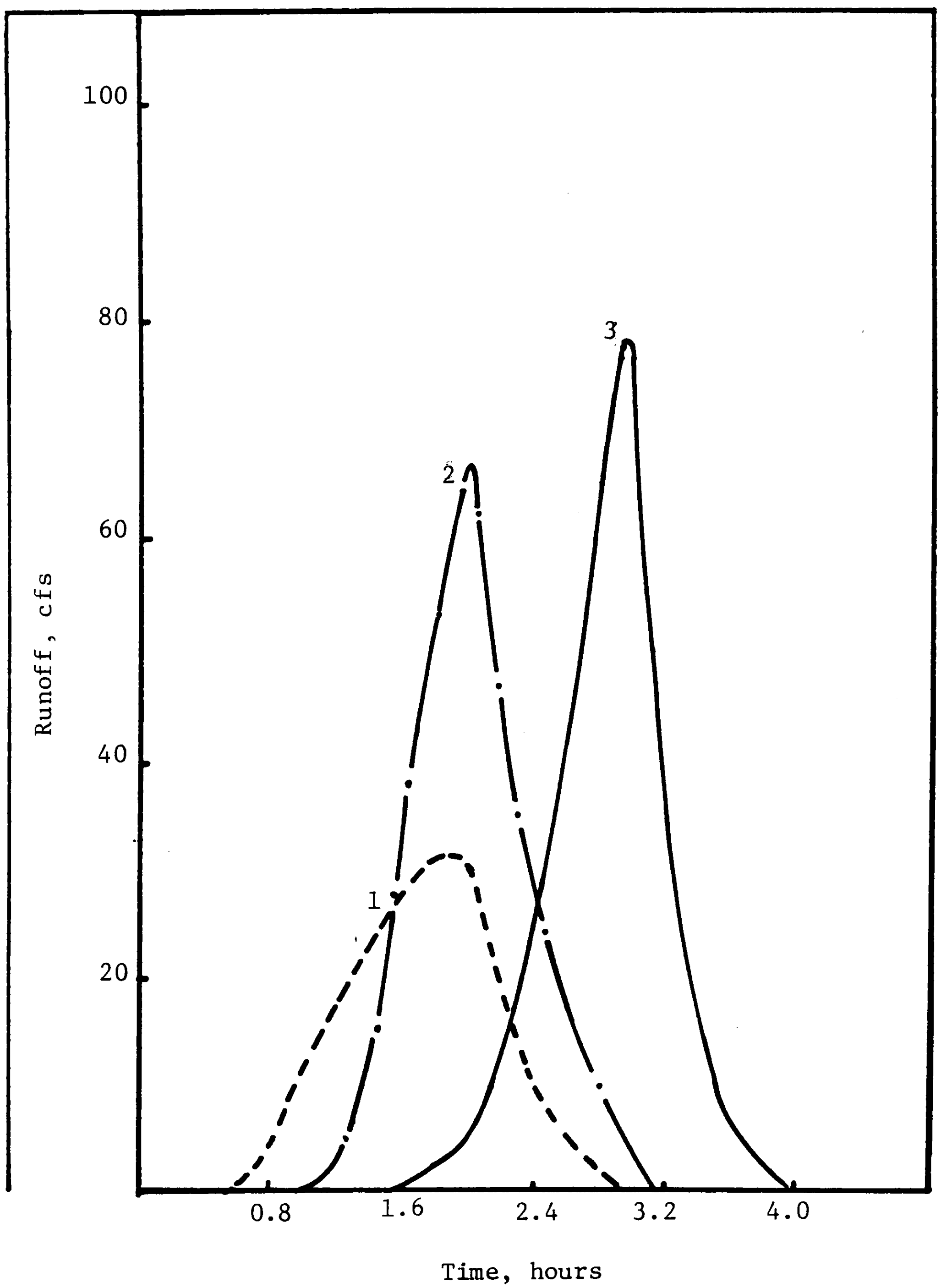


Figure 7. Hydrograph for storm of 3-hour duration with normal antecedent soil moisture conditon. Return period = 2 years.

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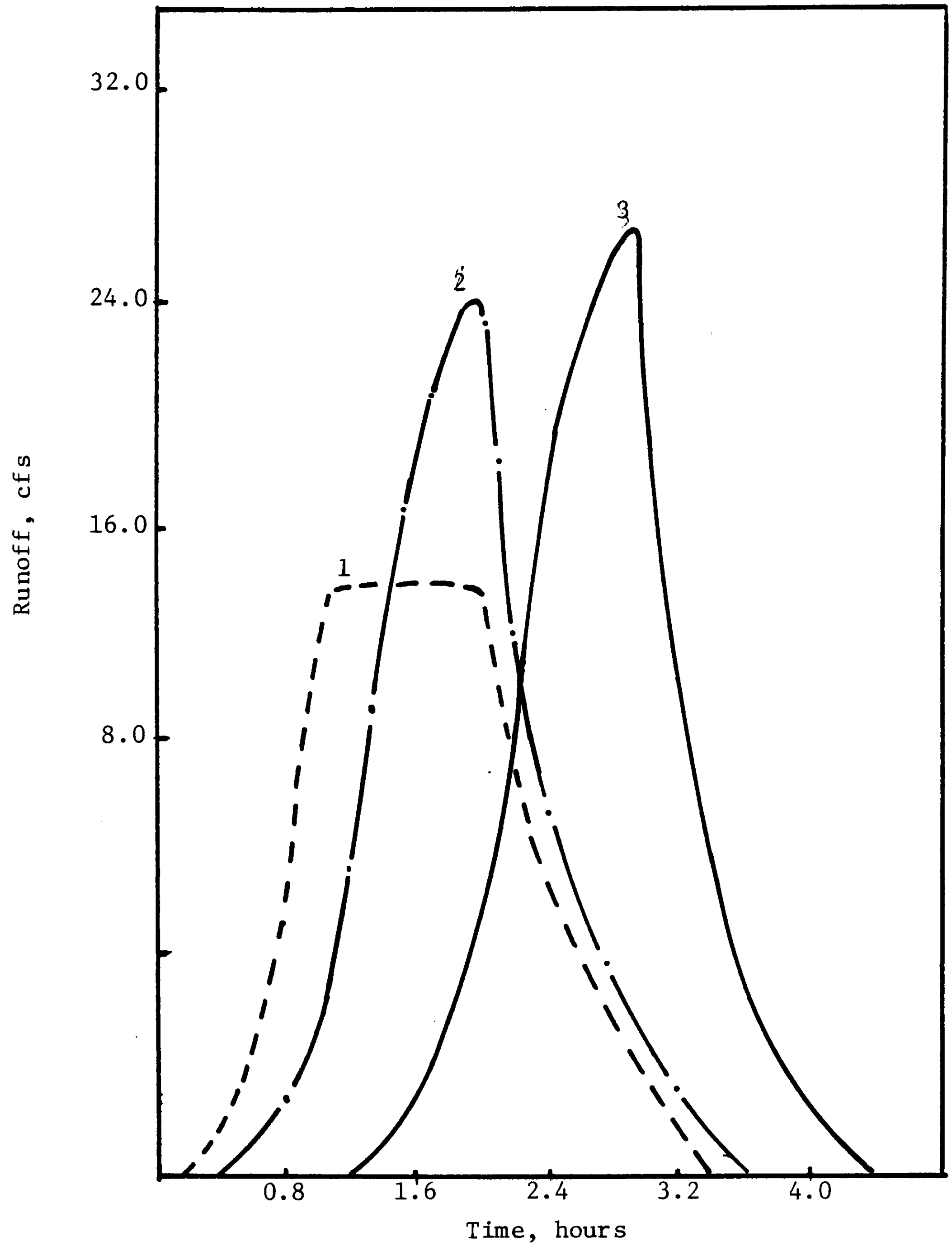

Figure 8. Hydrograph for storm of 3-hour duration with normal antecedent soil moisture conditon. Return period = 25 years.

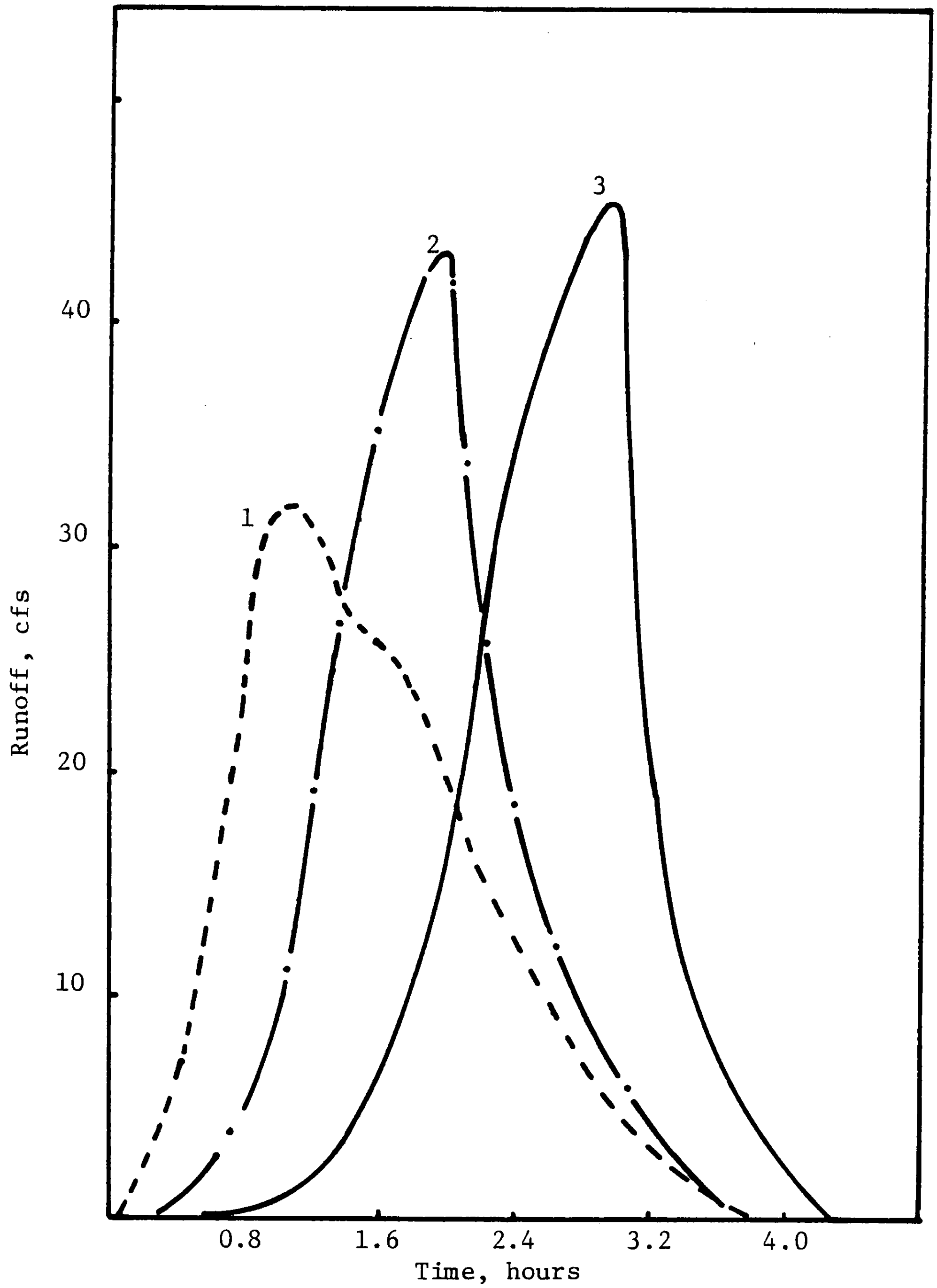

Figure 9. Hydrograph for storms of 3-hour duration with normal antecedent soil moisture condition. Return period = 100 years.

Table 3

Effect of Temporal Rainfall Distribution on
Peak Discharge
Storm Duration = 3 hours
Normal Antecedent Soil Moisture Condition

	2-Yr. Storm		25-Yr. Storm		100-Yr. Storm	
Distribution	Peak Flow, CFS	% Incr. over Dist. 1	Peak Flow, CFS	% Incr. over Dist. 1	Peak Flow, CFS	% Incr. over Dist. 1
1	3.2	-	22	-	32	-
2	6.6	106	32	45	43	34.4
3	8.0	150	34.5	56.8	45	40.6

Table 3 shows that the effect of the temporal distribution is more pronounced for the 3-hour storm than for the 30-minute storm. This is due to the long duration of the high intensity burst (1 hour). The influence of the antecedent moisture condition is, as expected, lessened due to the larger total volume of rainfall.

EFFECT OF ANTECEDENT SOIL MOISTURE

In the SWMM the infiltration capacity is simulated using the classical Horton's Equation

$$f = fc + (fo-fc)e^{-kt},$$

where

f = infiltration capacity (in/hr),

fo = initial infiltration capacity,

fc = final infiltration capacity, and

k = constant representing rate of decrease in infiltration capacity.

To study the effect of the antecedent soil moisture condition on the runoff hydrograph, four infiltration capacity curves ranging from a very low antecedent soil moisture to a complete saturation, or 100% imperviousness, were used. The curves are presented in Figure 10 and then commented upon.

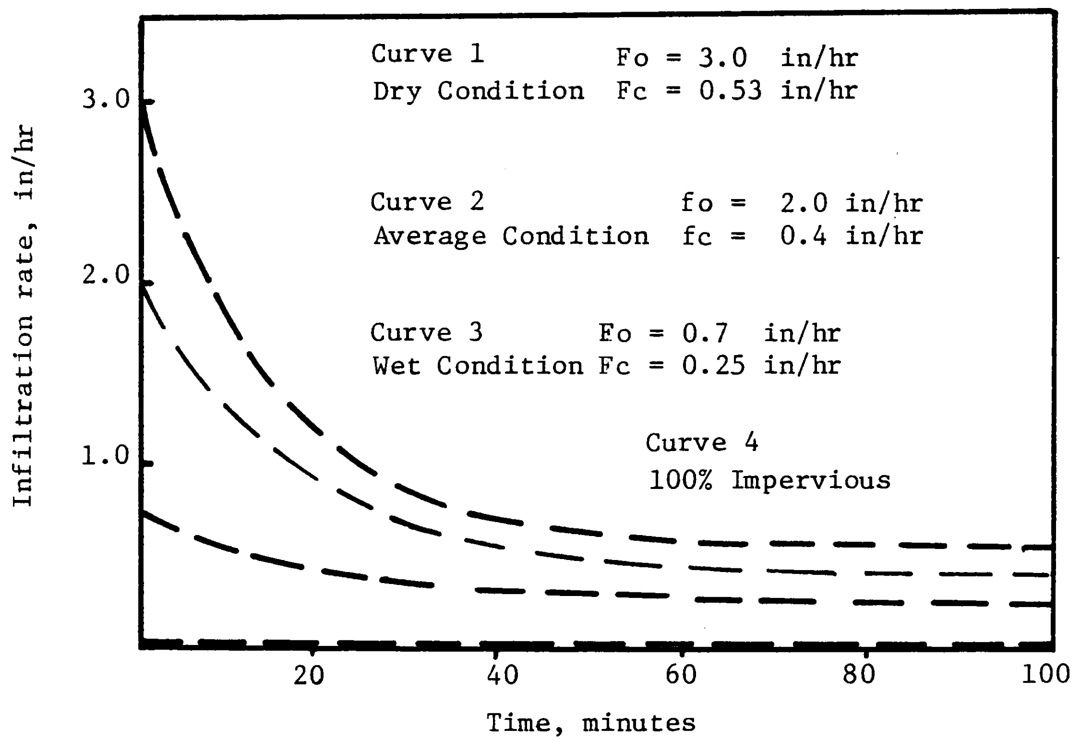

Figure 10. Infiltration capacity curves.

Curve 1: fo = 3.0 in/hr fc = 0.53 in/hr

This curve is considered to represent a typical infiltration capacity curve under a dry antecedent soil moisture condition for a summer month. It was chosen because it represents a very low moisture concentration in the soil.

Curve 2: fo = 2.0 in/hr fc = 0.4 in/hr

This curve can be considered to represent an "average" antecedent soil moisture condition.

Curve 3: fo = 0.7 in/hr fc = 0.25 in/hr

This infiltration capacity curve can be considered to represent a wet antecedent soil moisture condition.

Curve 4: fo = 0.0 in/hr fc = 0.0 in/hr

This curve represents the completely saturated soil. It can also be considered as simulating a watershed with 100% imperviousness.

These curves can be related to the Soil Conservation Service (SCS) AMC types used to estimate runoff from precipitation by the SCS method (Soil Conservation Service 1973). The SCS-AMC II is considered to represent the average soil cover and soil moisture condition, the SCS-AMC I a below average moisture condition (dry), and the SCS-AMC III an above average moisture condition (wet).

Curve No. 1 (fo = 3.0 in/hr, fo = 0.53 in/hr) used in this study can be considered to be equivalent to the SCS-AMC I, Curve No. 2 (fo = 2.0 in/hr, fo = 0.4 in/hr) to the AMC II, and Curve No. 3 to the SCS-AMC III.

The SCS suggests correction factors for adjusting runoff peaks from normal (AMC II) to other antecedent soil moisture conditions. Table 4 shows these correction factors.

Table 4

SCS Correction Factors

Curve	Factor
AMC I	0.80
AMC II	1.00
AMC III	1.25

Storms with a duration of 30 minutes were first used to study the effect of the antecedent soil moisture condition on the runoff hydrograph. These synthetic storm distribution patterns were presented in Figure 2. Tables 5 and 6 give the complete results for dry, wet, and completely saturated antecedent conditions.

Table 5 shows that for the more frequent storm (2-year storm), peak flow is more significantly affected when infiltration capacity curves representing a wet antecedent moisture condition and complete saturation are used. When the effect of the hyetograph shape was introduced, the percentage increased as the return period increased, as shown in Table 6. However, the same trend was not observed when a dry antecedent condition was used.

Table 5

Effect of Antecedent Soil Moisture Condition On Peak Discharge and Infiltration Capacity
(Distribution 1, 30-min. storm)

	2-Year Storm			25-Year Storm			100-Year Storm		
	Infiltr., in	Peak Disch., cfs	% Increase over normal conditions	Infiltr., in	Peak Disch., cfs	% Increase over normal conditions	Infiltr., in	Peak Disch., cfs	% Increase over normal conditions
Dry Condition	1.1	6.8	---	1.42	38.4	---	1.52	60	---
Wet Condition	0.45	18.5	172	0.75	56.0	46	0.78	76	27
Complete Saturation, (Impervious)	0.0	24.0	252	0.00	60.0	56	0.00	82	37

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Table 6

Percentage Increase in Peak Discharge
On the Impervious Area (30-min. storms)

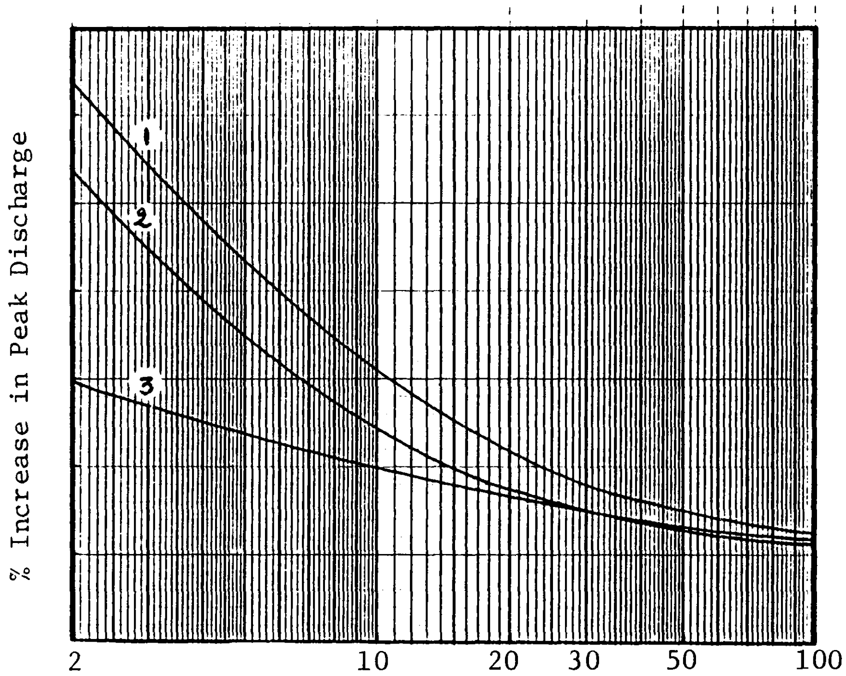
Distrib.	2-Yr. Storm Normal Cond.	2-Yr. Storm Comp. Satur.	2-Yr. Storm % Incr. In Peak	25-Yr. Storm Normal Cond.	25-Yr. Storm Comp. Satur.	25-Yr. Storm % Incr. In Peak	100-Yr. Storm Normal Cond.	100-Yr. Storm Comp. Satur.	100-Yr. Storm % Incr. In Peak
1	6.8	24.0	252	38.4	60.0	56	60	82	37
2	9.0	27.0	200	47.0	71.0	51	70	104	49
3	10.4	29.6	185	52.0	80.0	53	72	112	56

Table 6 indicates that the increase in peak discharge from the dry antecedent soil moisture condition to the completely saturated soil is a function of the temporal distribution of the rainfall and the storm return period. The percentage increase in peak flow for the impervious area is 252% for a 2-year storm, 56% for a 25-year storm, and 37% for a 100-year storm.

Several runs were then made using different storm durations, return periods, and dry, wet, and average antecedent soil moisture conditions.

Figures 11 and 12 show the results from this analysis. Figure 11 gives the percentage decrease in peak discharge from the average soil moisture condition to the dry condition. It shows that this decrease is a function of the storm duration and return period. For instance, the percentage decrease for a 3-hour storm is 54% for a 2 year-return period and 16% for a 25 year-storm. Figure 12 shows the percentage increase in peak discharge from the average soil condition to the wet antecedent soil moisture condition. It should be noted that these curves were developed using the Virginia rainfall distributions.

It is interesting to note that when compared with results obtained in this study, the correction factors suggested by the SCS are for return periods ranging between 20 and 30 years. These results suggest that the SCS antecedent moisture condition and adjustment factor should be a function of the return period of the storm. For more frequent (less than 10 years return period) storms, a higher adjustment factor should be used.

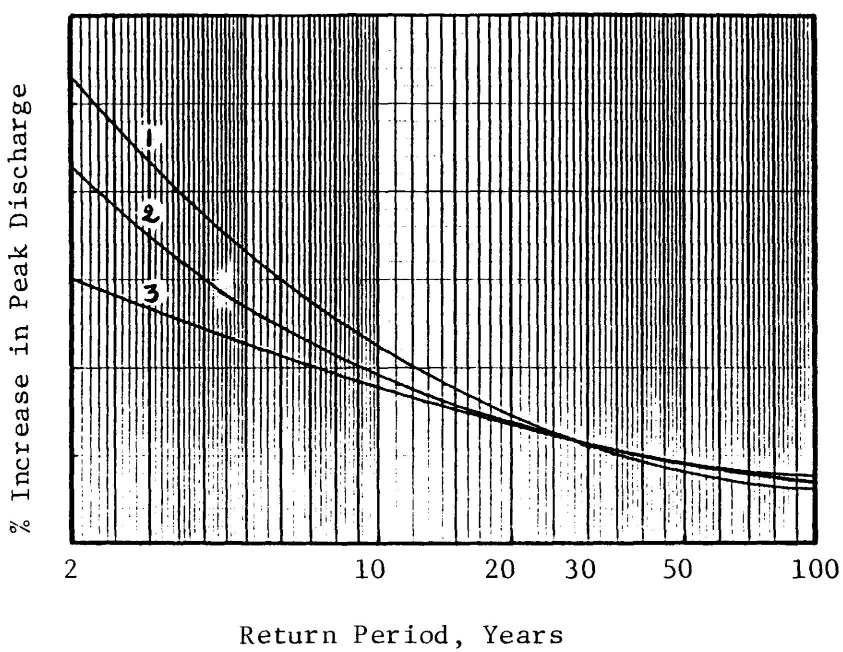


1 - D > 6 hours

2 - 1 ≤ D ≤ 6 hours

3 - D < 1 hour

Figure 11. Percentage decrease in peak discharge from average antecedent soil moisture to dry condition.



1 - 1 ≤ D ≤ 6 hours

2 - D > 6 hours

3 - D < 1 hour

Figure 12. Percentage increase in peak discharge from average antecedent soil moisture condition to wet condition.

The conclusion that can be drawn from these analyses is that the runoff hydrograph is significantly affected by such factors as the temporal distribution of the rainfall, the antecedent soil moisture condition, and the intensity of the storm. Each of these factors can be very important in estimations of the peak runoff and their influence may vary with the return period of the storm. The smaller the return period (more frequent), the larger the influence seems to be.

The results also suggest that in the design of drainage, when the storm hyetograph, the return period, and the duration are selected, it is very important that a proper antecedent soil moisture condition be assumed. Even an "average" soil moisture can mean different values in different regions. Consequently, good field data for the determination of long-term average soil moisture in a region are needed for the proper estimation of peak discharges.

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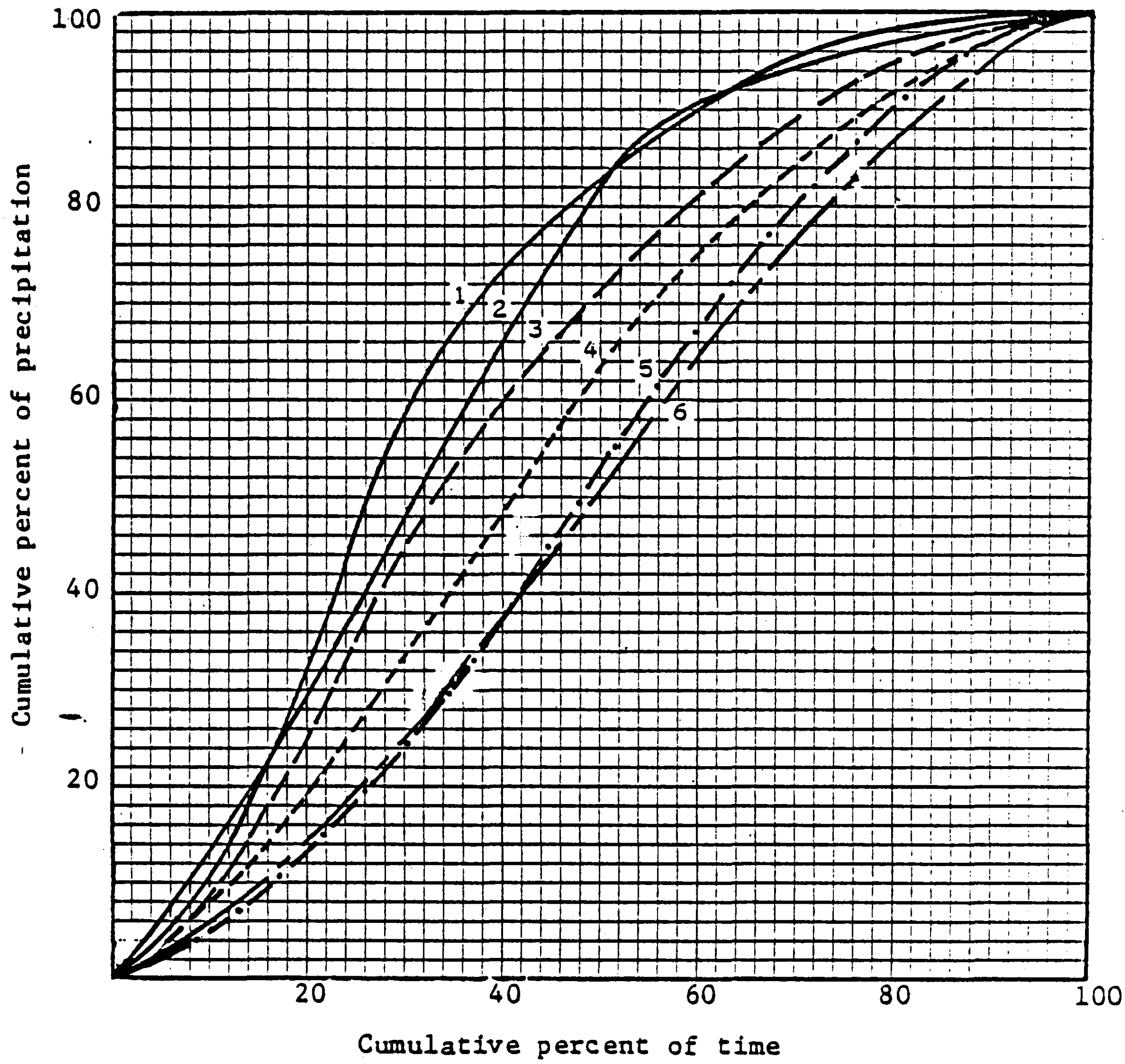
HYDROGRAPHS FROM THE VIRGINIA AND NATIONAL TEMPORAL DISTRIBUTIONS FOR VERY SHORT DURATION (LESS THAN OR EQUAL TO 1 HOUR) STORMS

The two Virginia temporal distributions (piedmont and mountain), the Huff (1967) and the FHWA triangular distributions (Yen and Chow 1983) were used to compare the resulting hydrographs. A 1-hour storm with different return periods and different infiltration capacity curves was used in the analysis. Figure 13 presents the different Virginia mass curves developed in a previous study (Yu et al. 1984).

Figures 14, 15, and 16 show the resulting hydrographs for the 25-year return period. The complete results are shown in Table 7.

The first observation from the analysis of very short duration storms is that the Huff 10%, second quartile storm gives a higher peak discharge than do the Virginia and the FHWA distributions. It should be noted that the Huff 10%, second quartile storm is used in the comparison because it was found to closely resemble the Virginia curves as compared with other quartile curves.

The piedmont and mountain distributions give a higher peak than does the FHWA distribution. The peak discharge is on the average 10% higher for the piedmont distribution and 20% higher for the mountain distribution. The two Virginia hydrographs peaked earlier than the FHWA hydrograph.



1. D ≤ 1 hr — Piedmont Region
2. D ≤ 1 hr — Mountain Region
3. 1 hr < D <6 hr — Piedmont Region
4. 1 hr < D <6 hr — Mountain Region
5. 6 hr < D <18 hr — Statewide
6. D > 18 hr — Statewide

Figure 13. Mean dimensionless rainfall mass curves (Yu et al. 1984).

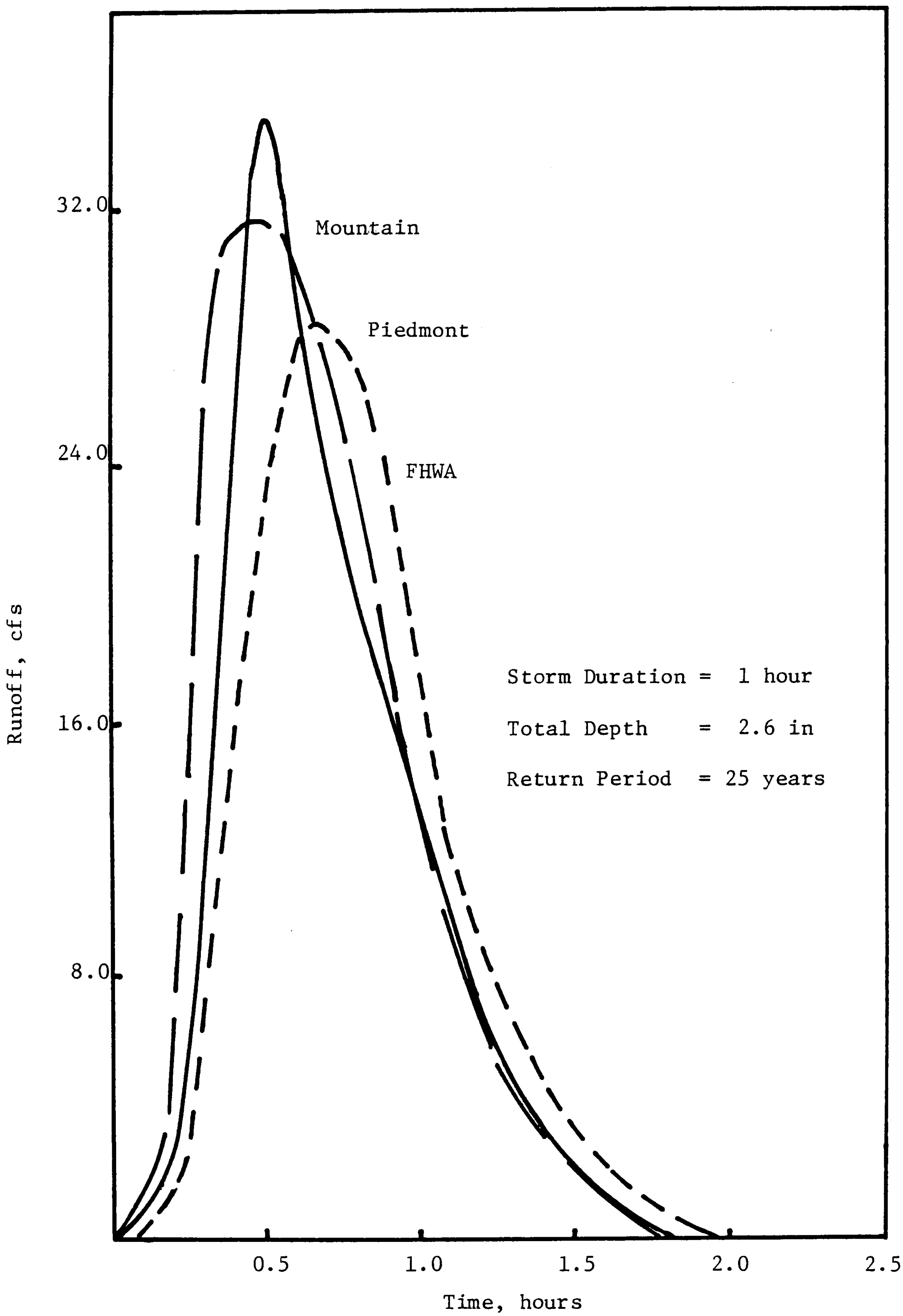


Figure 14. Hydrographs from the 1-hour storm with normal antecedent soil moisture condition.

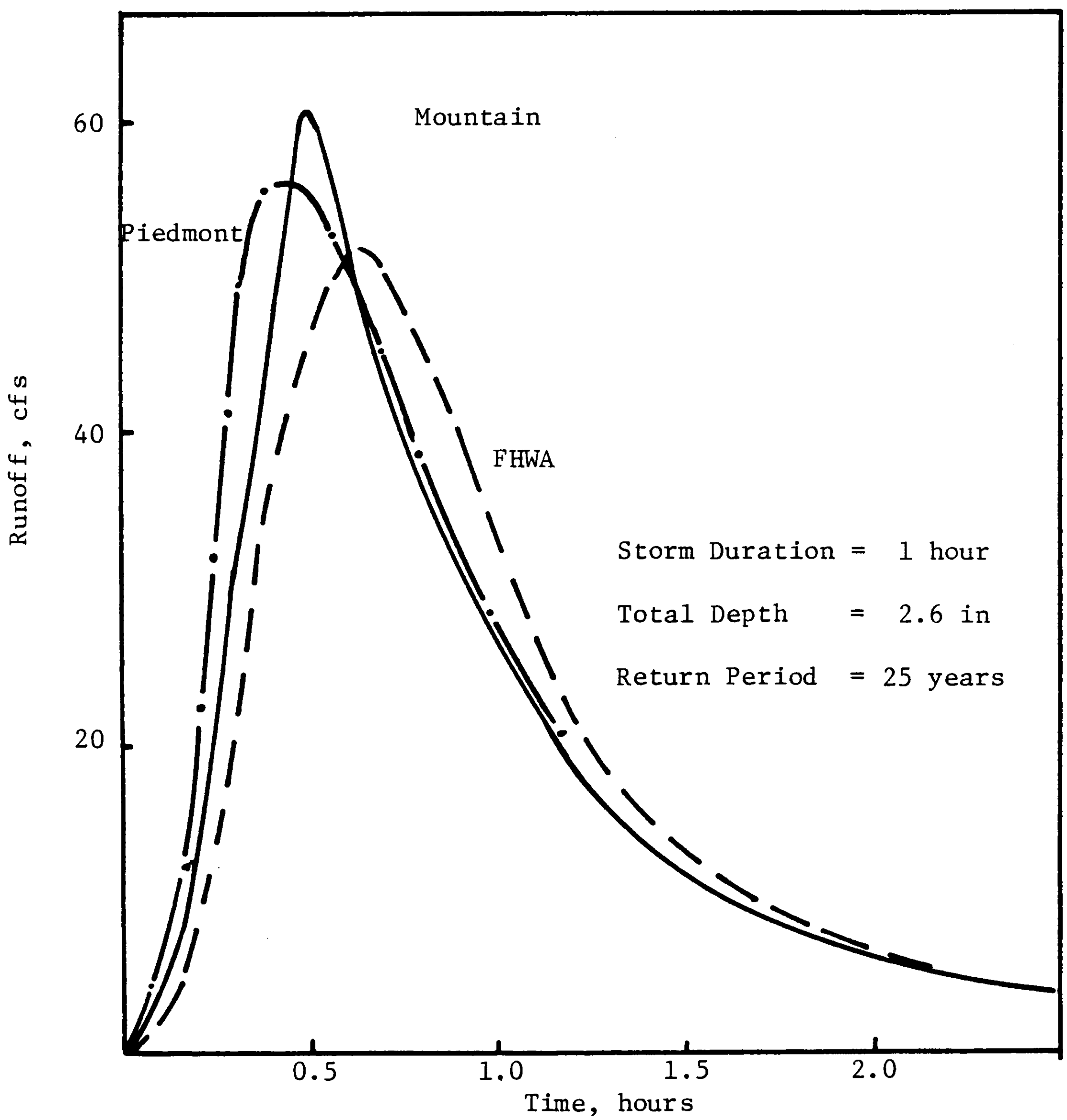


Figure 15. Hydrographs from the 1-hour storm with wet antecedent soil moisture condition.

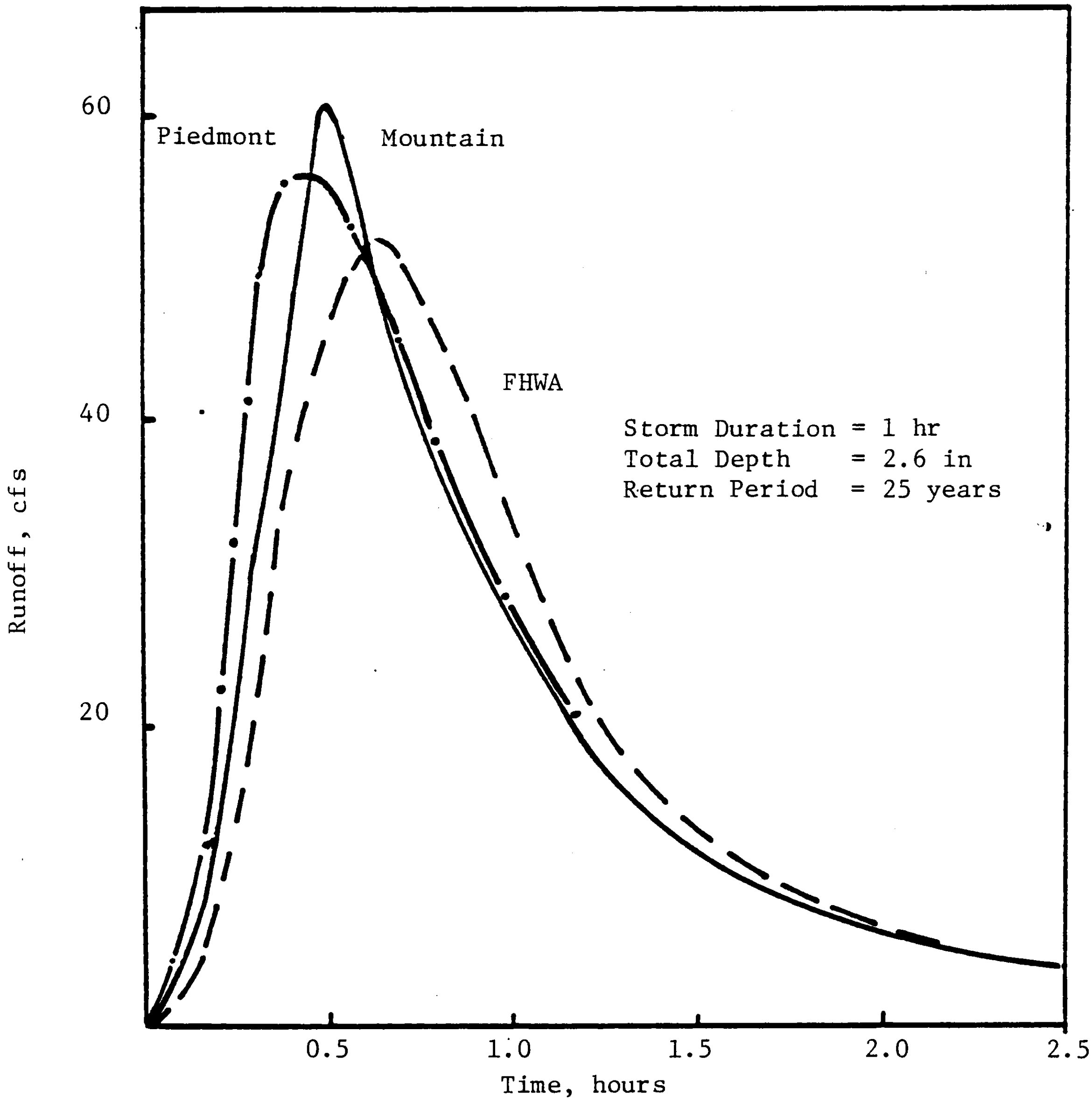


Figure 16. Hydrographs from the 1-hour storms.
100% impervious.

Table 7

Effect of Temporal Distribution, Antecedent Soil Moisture Condition, and Storm Frequency on Peak Discharge. Duration = 1 hour

Normal Antecedent Soil Moisture Condition

	Peak Flow, CFS		
	2-Yr.	25-Yr.	100-Yr.
FHWA	7.8	29	52
Piedmont	9.6	32	58
Mountain	10.8	36	64
Huff	12.0	40	74

Wet Antecedent Soil Moisture Condition

	Peak Flow, CFS		
	2-Yr.	25-Yr.	100-Yr.
FHWA	20.0	44	66
Piedmont	22.5	48	76
Mountain	24.5	54	84
Huff	26.4	60	94

100% Impervious

	Peak Flow, CFS		
	2-Yr.	25-Yr.	100-Yr.
FHWA	27.2	52	76
Piedmont	29.6	56	84
Mountain	31.2	61	94
Huff	32.8	68	108

The higher peak from the two Virginia distributions is due to the fact that more than 80% of the total rainfall fell in the first half of the storm. The piedmont hyetograph for a 1-hour storm has a much higher intensity burst than the FHWA hyetograph (7.25 in/hr for the piedmont distribution and 5.2 in/hr for the FHWA distribution). The piedmont and FHWA hyetographs are presented in Figure 17. This large difference in intensity bursts is dampened on the resulting hydrographs because the piedmont distribution is comparable to Distribution 1 introduced earlier (the distribution having the highest burst at the beginning of the storm). The mountain distribution gives a higher peak than do the piedmont and the FHWA distributions because it has the highest intensity burst at the middle of the storm. The mountain distribution is similar to distribution 2 introduced earlier, where the highest burst is at the middle of the storm.

The increase in peak discharge from a dry to an impervious condition is shown in Table 8. For a return period of 25 years, the increase is 74% on the average. The increase is 45% for a 100-year storm.

Since an "average" AMC condition is commonly assumed in drainage design, it is especially important to examine the increase in peak discharge from normal or an average AMC to a wet condition. From Figures 11 and 12 the results in Table 9 can be obtained.

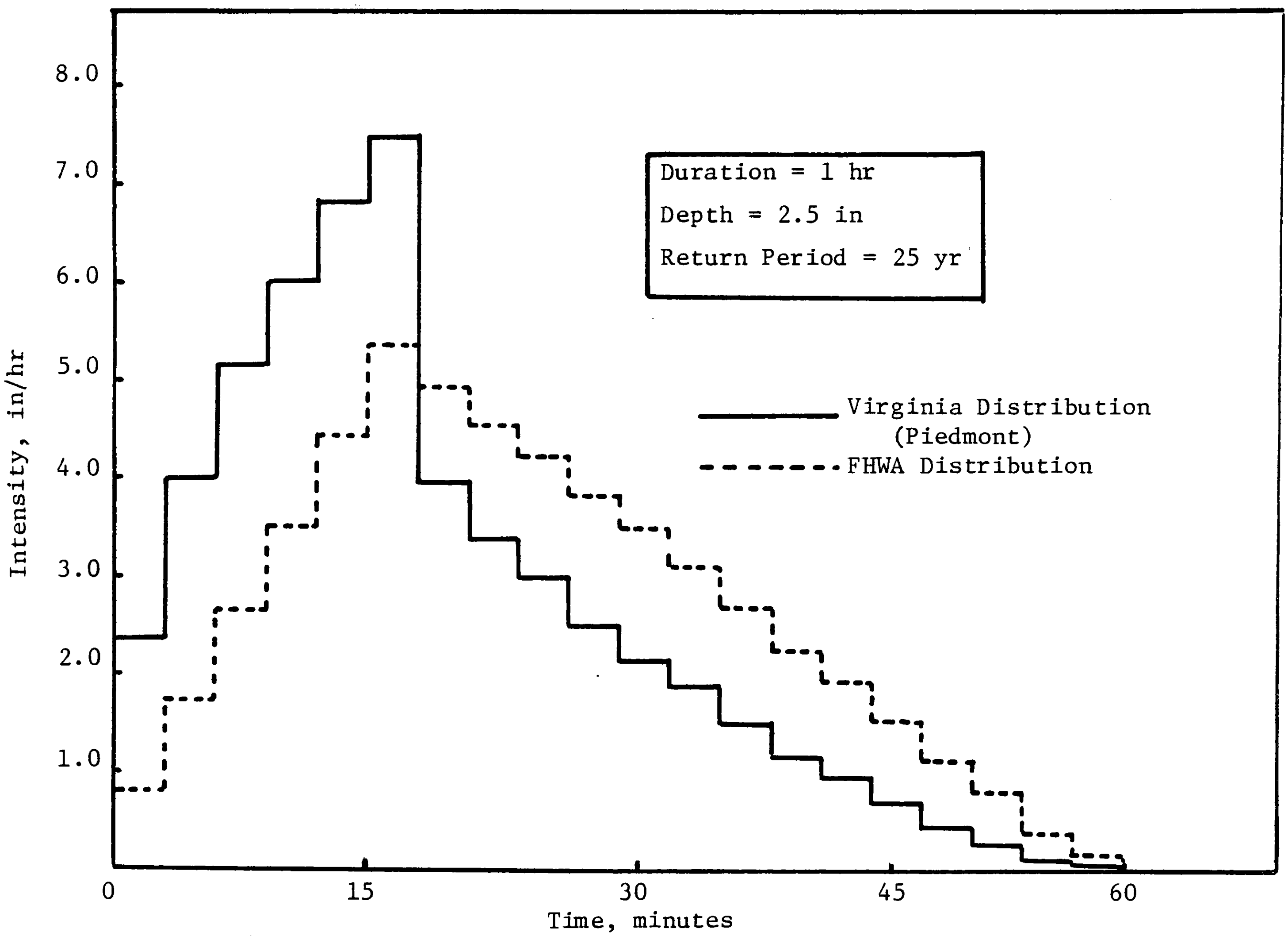


Figure 17. Hyetographs for the piedmont and FHWA distribution. Duration = 1 hour

Table 8

Increase in Peak Discharge on the Impervious Area
Storm Duration = 1 hour

	2-Yr. Storm			25-Yr. Storm			100-Yr. Storm		
	Dry Cond.	100% Imper.	Percent Incr.	Dry Cond.	100% Imper.	Percent Incr.	Dry Cond.	100% Imper.	Percent Incr.
FHWA	7.8	27.2	248	29	52	79	52	76	46.2
Piedmont	9.6	29.6	208	32	56	75	58	84	44.8
Mountain	10.8	31.2	188	36	62	72	64	94	46.9
Huff	12.0	32.8	173	40	68	70	74	108	45.9

Table 9

Average Increase in Peak Discharge as a Function of Return Period

Return Period, Years	Average Percentage in Peak Discharge
2	85
5	55
10	40
25	24
50	16
100	12

The results in Table 8 suggest an important observation. The commonly used SCS adjusting factor (e.g., 20% increase from AMC II to AMC III for CN = 70) is also a function of the return period of the storm. For more frequent (less than 10-year return period) storms, a higher adjustment factor should be used.

ANALYSIS OF SHORT DURATION STORMS

A storm of 3-hour duration was used for the analysis. The two Virginia distributions and the FHWA triangular distribution were compared. Figures 18 through 20 show the resulting hydrographs from a 25-year storm and Table 10 gives the complete results for different return periods and antecedent soil moisture conditions.

These results show that the Virginia distributions always gave a lower peak than did the FHWA distribution, except for a very severe storm (100-year). The mountain distribution is expected to give a slightly higher peak because the temporal location of the highest burst is at the middle of the storm (see Figure 7). The differences in peak flows for all three distributions were fairly small, however. As shown in Figure 17, the piedmont distribution has the highest burst and more than 70% of the rain fell in the first half of the storm. On the other hand, the FHWA distribution showed a slightly more uniform rainfall distribution than did the piedmont distribution and a less uniform one than that of the mountain distribution.

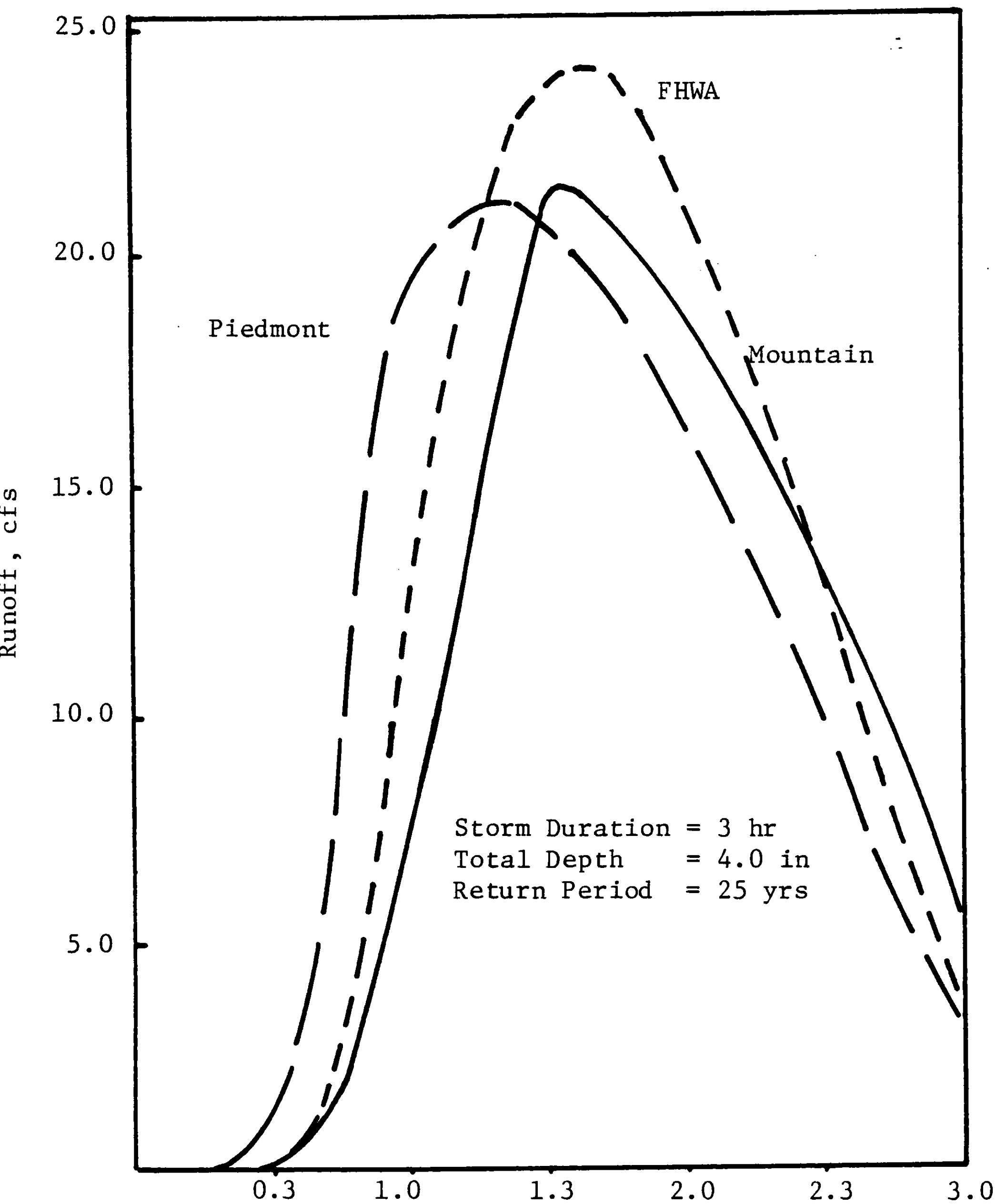


Figure 18. Hydrographs from the 3-hour storms during dry antecedent conditions.

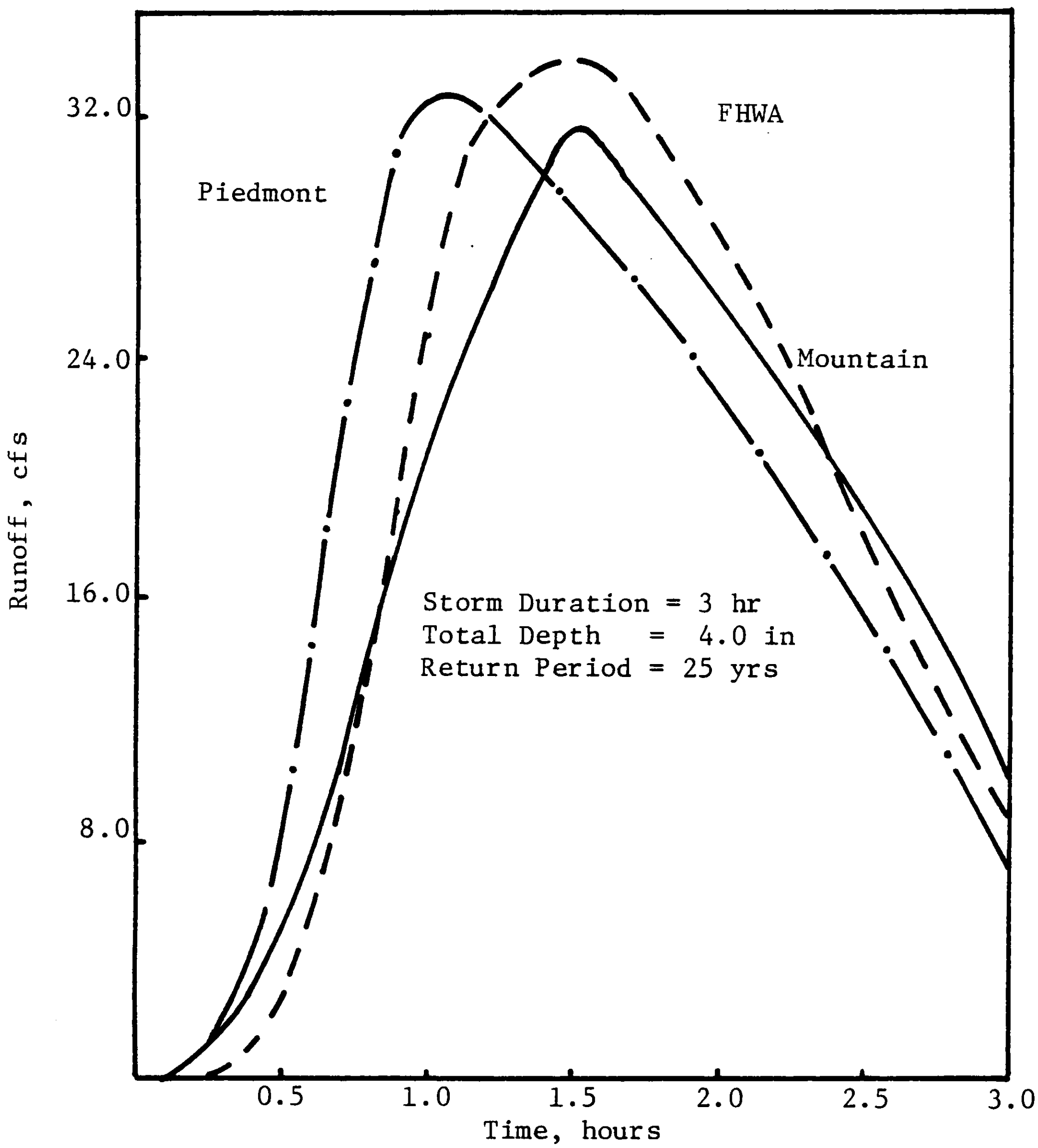


Figure 19. Hydrographs from the 3-hour storm duration with wet antecedent condition.

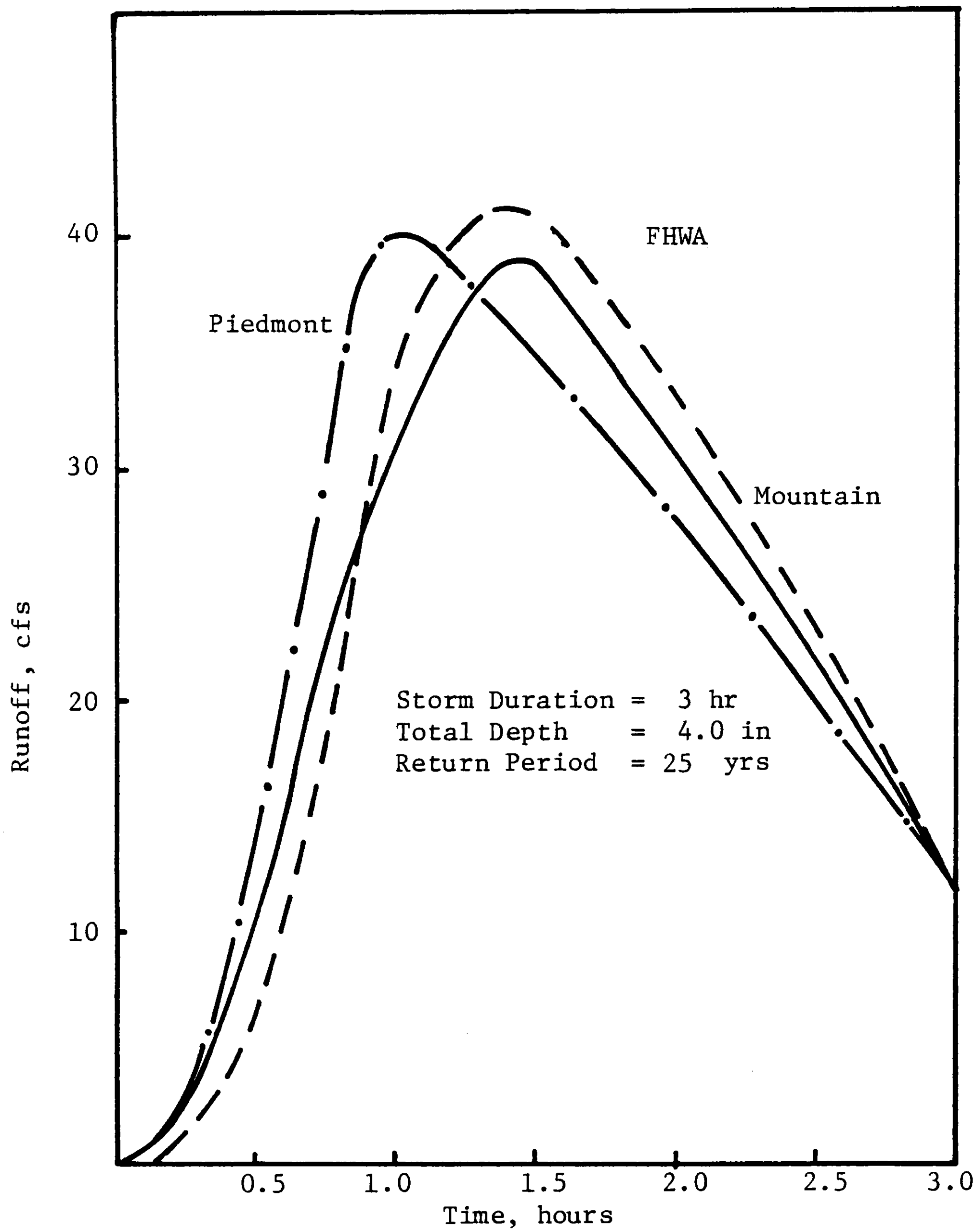


Figure 20. Hydrographs from the 3-hour storms. 100% impervious.

Table 10

Effect of Temporal Distribution, Antecedent Soil Moisture Condition, and Return Period on Peak Discharge. Storm duration = 3.0 hours

Normal Antecedent Moisture Condition

	2-Year Storm		25-Year Storm		100-Year Storm	
	Peak Disch., CFS	Time to Peak-Hr	Peak Disch., CFS	Time to Peak-Hr	Peak Disch., CFS	Time to Peak-Hr
Piedmont	1.92	1.65	21.0	1.3	32.8	1.1
Mountain	1.88	1.85	22.0	1.5	37.6	1.5
FHWA	3.44	1.85	24.0	1.6	36.0	1.5

Wet Antecedent Condition

	2-Year Storm		25-Year Storm		100-Year Storm	
	Peak Disch., CFS	Time to Peak- Hr.	Peak Disch., CFS	Time to Peak-Hr.	Peak Disch., CFS	Time to Peak-Hr.
Piedmont	10.4	1.40	32.8	1.1	42.0	0.90
Mountain	10.0	1.75	32.0	1.5	48.0	1.50
FHWA	12.0	1.90	34.0	1.5	46.0	1.35

100% Impervious

	2-Year Storm		25-Year Storm		100-Year Storm	
	Peak Disch., CFS	Time to Peak-Hr	Peak Disch., CFS	Time to Peak-Hr	Peak Disch., CFS	Time to Peak-Hr
Piedmont	16.0	1.20	40.0	1.0	54.0	0.9
Mountain	16.8	1.50	38.4	1.5	54.0	0.9
FHWA	18.0	1.55	42.0	1.4	53.0	1.35

The important difference is that the piedmont hydrograph peaks earlier than the other two.

For a 25-year storm the increase in peak discharge from a dry to 100% impervious condition is 90% for the piedmont distribution and 75% for the mountain and FHWA distributions. The piedmont distribution gives a higher increase in peak discharge because more rainfall falls early in the storm compared to the two other distributions. The results for the 3-hour, 25-year storm are shown in Table 11.

Results from the 1-hr and 3-hr storm analyses suggest that for very short duration (1 hour and less) storms, the Virginia rainfall loss curves would yield higher peak discharges than that obtained with the FHWA curves. However, the trend is reversed when the storm duration increases (3-hour storms), except for extremely severe storms (100-year return period).

Information on the average percentage increase in peak flow from a dry to impervious condition for very short storms (Table 7) and for short storms (Table 11) should be useful to the drainage design engineer in estimating runoff increases resulting from urbanization.

Table 11

Percentage Increase in Peak Discharge from a Dry to Impervious Condition
Storm Duration = 3 hours
Return Period = 25 Years

	Dry Condition	100% Impervious	Percentage Increase
Piedmont	21	40.0	90.5
Mountain	22	38.4	74.5
FHWA	24	42.0	75.0

FREQUENCY ANALYSIS OF SHORT-DURATION, HIGH-INTENSITY STORMS

The intensity-duration-frequency (IDF) curves for short duration storms were developed for Virginia using actual storm data. The storm duration selected varied from 5 minutes to 30 minutes. The data base used for this analysis was the 1-minute storm data provided by the Hydrologic Research Group in the Agriculture Engineering Department of Virginia Polytechnic Institute and State University (Yu et al. 1984). The IDF curves obtained were compared to the curves developed by the National Weather Service in the 5 to 60 minutes precipitation frequency for the eastern and central United States (NOAA 1977).

Discussion on TP40 and HYDRO 35

In TP40 and HYDRO 35 (NOAA 1961, 1977), the results are expressed in terms of partial duration frequencies. In TP40, first the annual series IDF's are developed, and then the resulting statistics are transformed to partial duration series using empirical factors.

The IDF curves in HYDRO 35 were developed using statistical extrapolation. Average relationships between rainfall depths for 60-minute and shorter duration storms for the same return period are shown in Table 13. With these ratios and the IDF for 60-minute rainfall, IDF curves for shorter duration storms can be developed. These ratios were derived from the data collected at 200 first order weather bureau stations.

Table 13

Rainfall Depth Ratio Between 60-Minute and Shorter Duration Storms For the Same Return Period

Duration, Minutes	Rainfall Depth Ratio
5	0.292
10	0.450
15	0.569
30	0.790

Procedure Used

Storms ranging from 5 to 60 minutes in duration were selected. These storms were extracted from the data base with the condition that the total depth of a storm would exceed 0.4 in. The data base covers ten stations located in the piedmont and mountain regions. Approximately 120 years of data were analyzed for the storm extraction with an average of 12 years of data per station.

Storms of a specific duration were ranked using the partial-duration series. The maximum occurrences would yield a curve as shown in Figure 21. A Gumbel extreme value distribution is fitted to these data using a computer program. This computer program uses a nonlinear, least-squares, curve-fitting method.

For each storm duration, a curve was obtained. The data were used to convert depth in inches to an intensity in in/hr and to obtain the IDF curves.

Figures 22 through 25 show the IDF curves developed and the one proposed in HYDRO 35 for return periods of 2, 5, 10, and 25 years. Figure 22 compares the IDF curves with the one developed by NOAA for Albemarle County in the piedmont region.

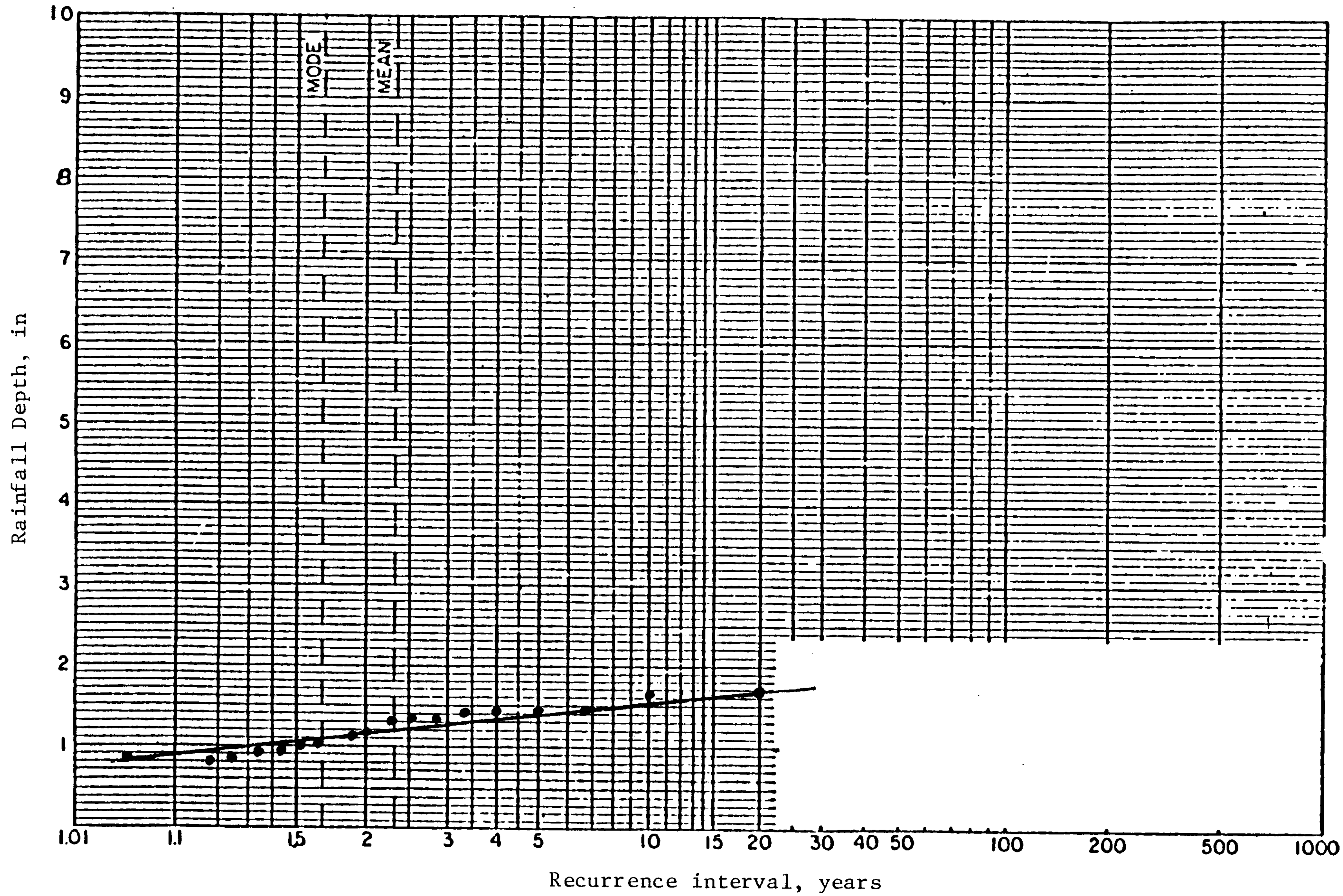


Figure 23. Gumbel extreme value distribution.

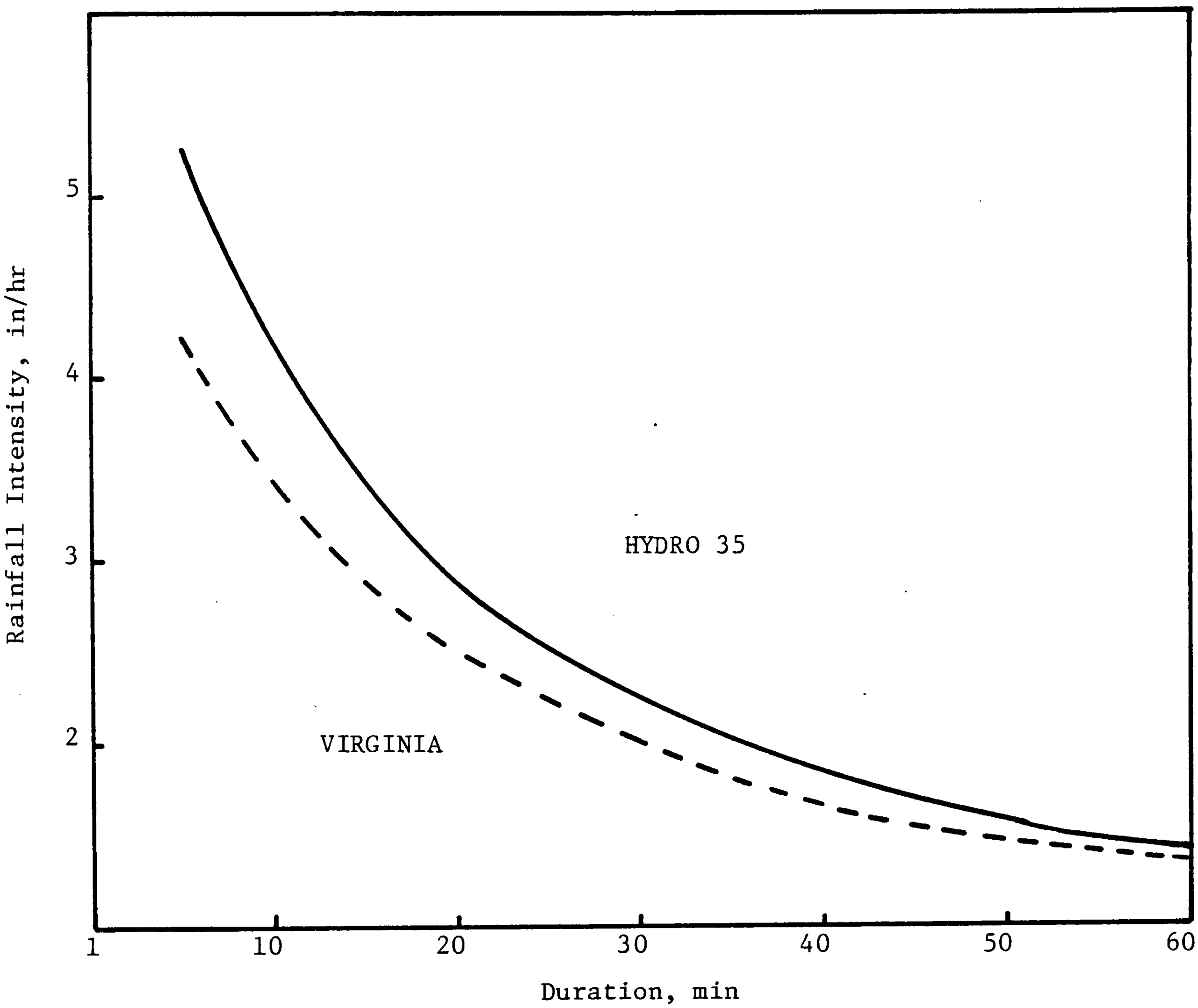


Figure 22. IDF curves for 2-year storm. Albemarle County, Virginia.

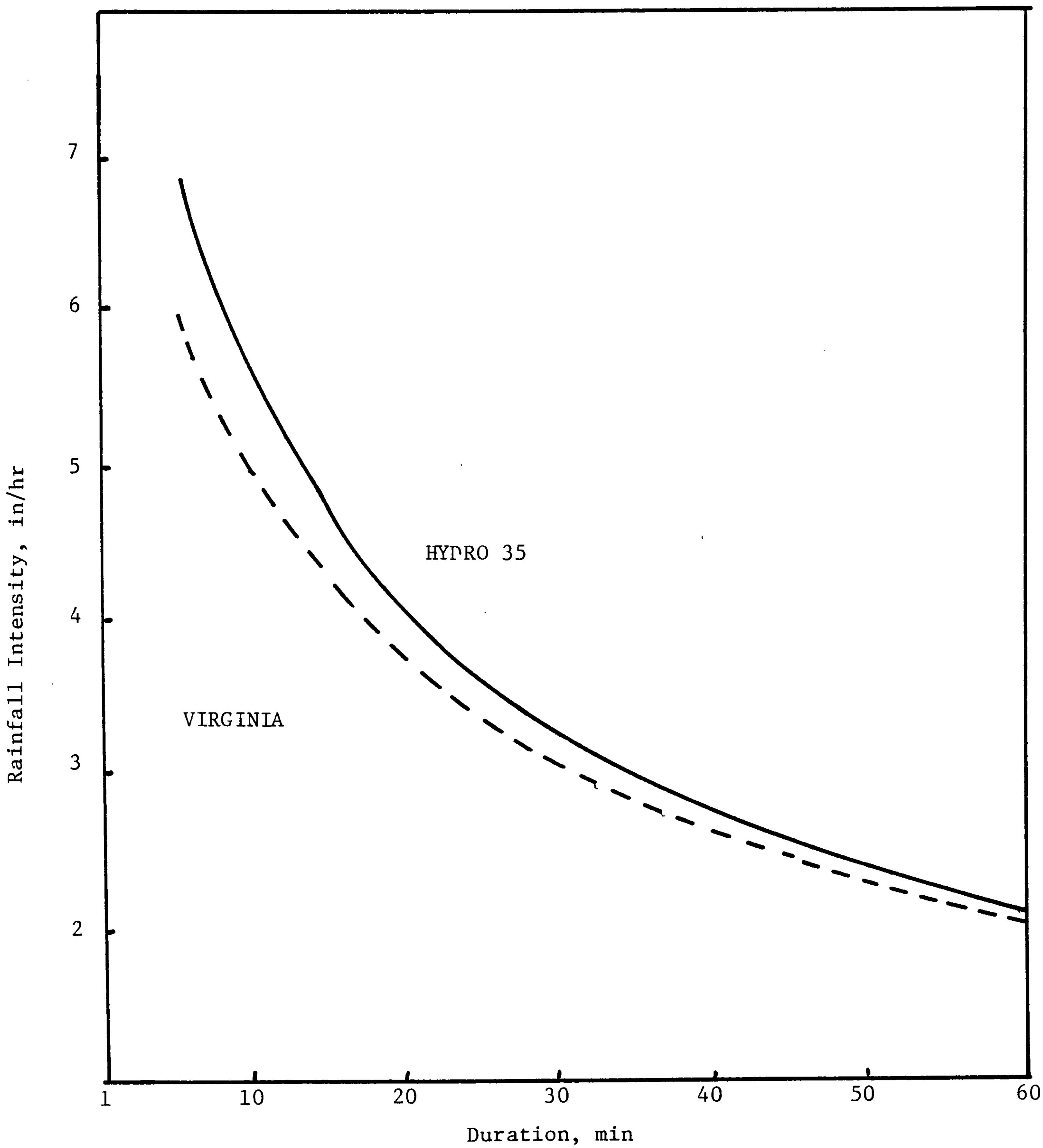


Figure 23. IDF curves for 5-year storm. Albemarle County, Virginia.

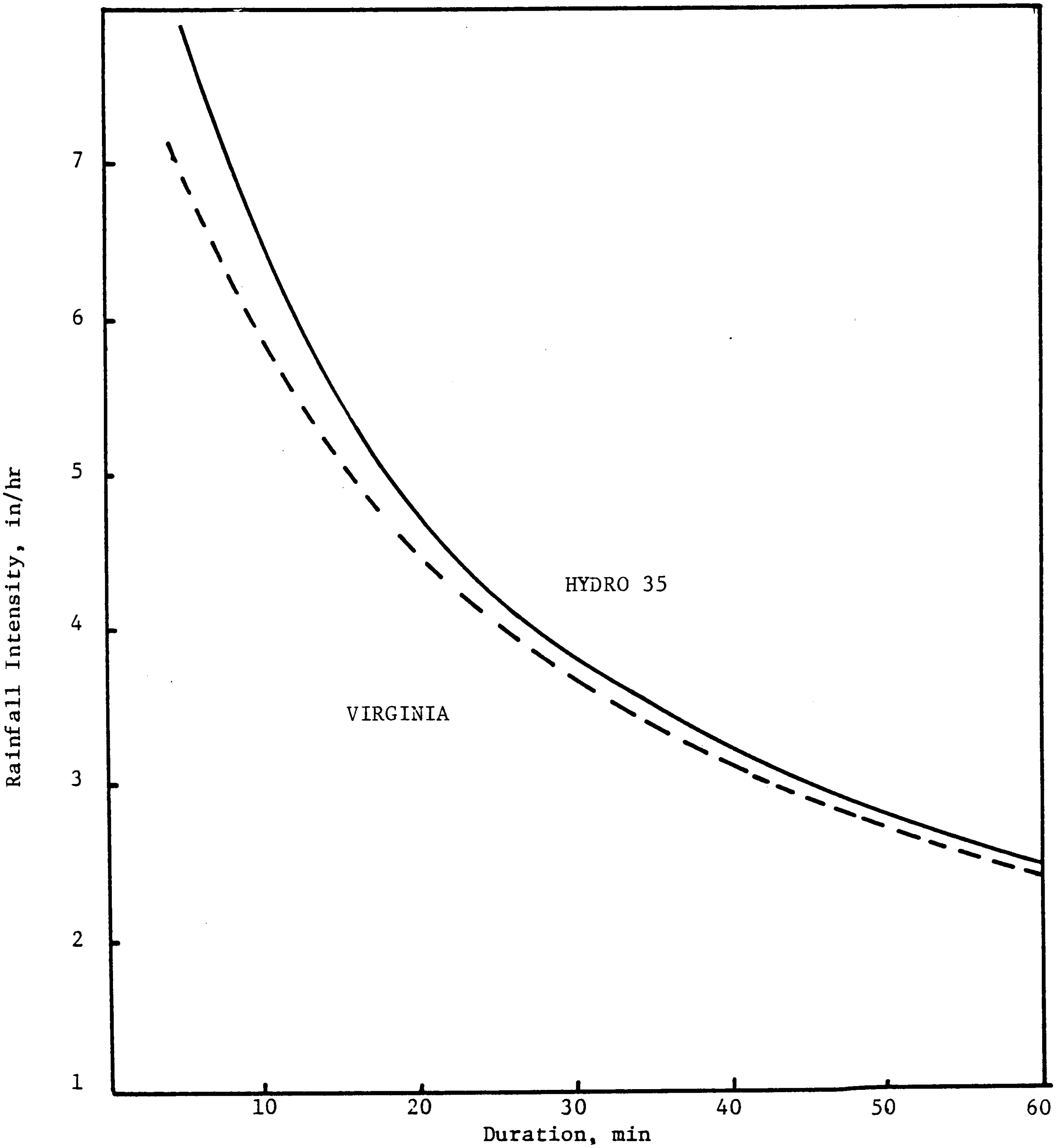


Figure 24. IDF curves for 10-year storm. Albemarle County, Virginia.

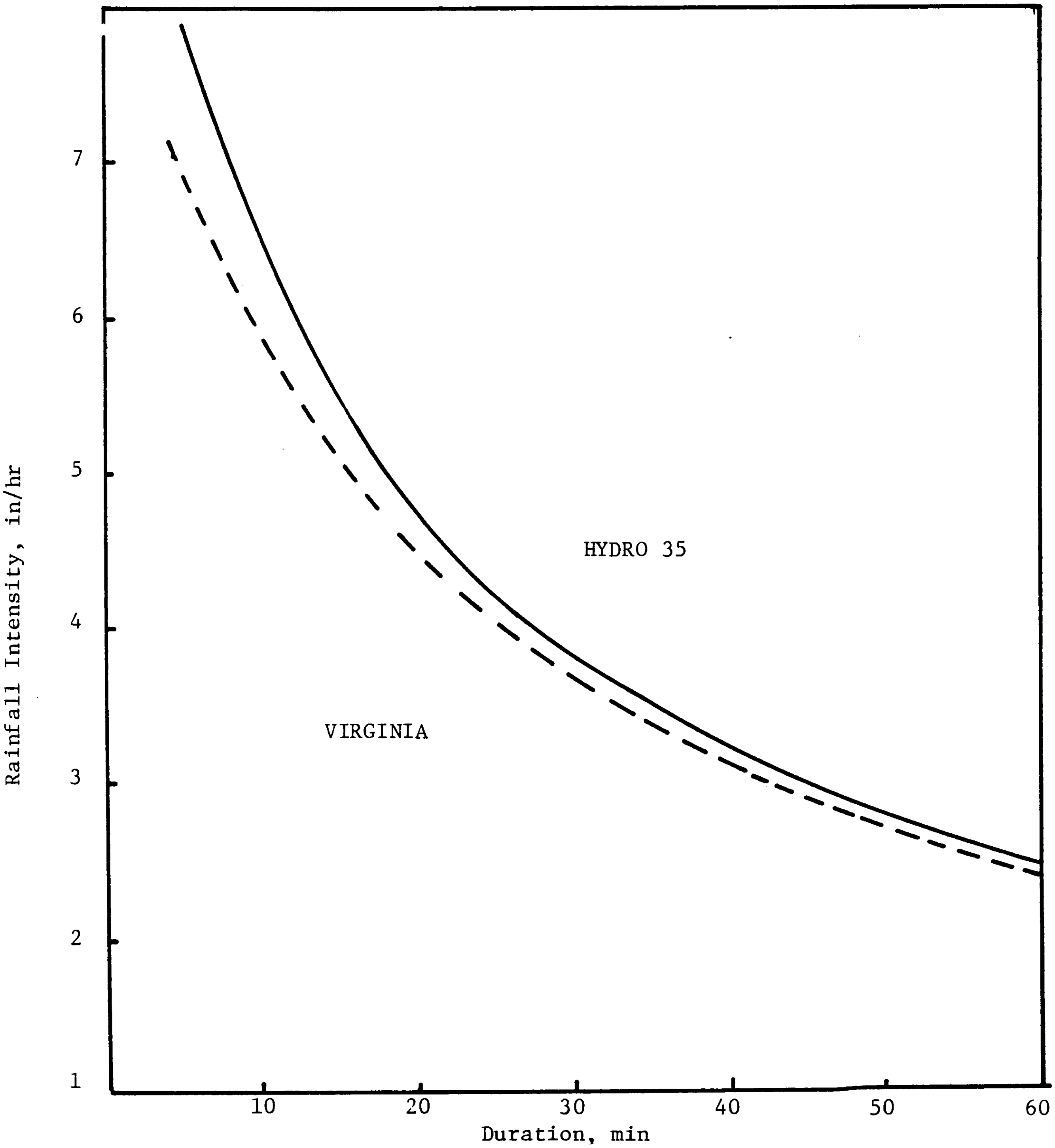


Figure 25. IDF curves for 25-year storm. Albemarle County, Virginia.

CONCLUSION FROM THE ANALYSIS

The results indicate that the IDF curves developed from the Virginia data base give a lower intensity for the same duration and return period for short duration storms. The difference in intensity in in/hr increases when the storm duration shortens. This implies that when using the Virginia IDF curves a smaller rainfall depth would be obtained than that obtained from the NOAA curves for the same duration and return period. These differences are shown in Figures 22, 23, 24, and 25.

It should be noted that the IDF curves developed using Virginia data agree with those from HYDRO 35 for the 60-minute duration storm. The deviation becomes larger as the duration and the return period decrease. This deviation might be attributable to the fact that actual storm data were used in this study whereas HYDRO 35 was based on annual series data and curves for shorter duration storms were extrapolated from 60-minute storm data. Since the data base used in this study was small, it is important to verify this deviation with additional storm data.

CONCLUSIONS

The following conclusions can be drawn from results obtained in the present study.

1. Hyetograph (or temporal rainfall distribution) selection is an extremely important step in drainage design. Under normal antecedent soil moisture conditions, peak discharges could differ by more than 50% for different hyetographs for design storms of the same duration and frequency. In general, late-peaked hyetographs result in a higher runoff than do the centrally-peaked hyetographs, which in turn result in a higher runoff than do the early-peaked hyetographs.

2. The effect of hyetograph selection is greatest for frequent (small) storm events. As the storm return period increases, the difference in peak discharge resulting from different hyetographs becomes smaller.

3. The effect of hyetograph selection seems to be related to the duration of the storm. More pronounced effects were observed when the storm duration increased from 60 minutes to 3 hours.

4. Antecedent soil moisture appears to be even more critical than hyetograph shape in determining peak discharge. Again, the effect is more pronounced for frequent (small) storms.

5. Relatively speaking, the antecedent moisture condition exerts a stronger influence on the early-peaked hyetographs than on the late-peaked ones in determining peak discharge.

6. For very short duration (less than or equal to 1 hour) storms, the Virginia distribution curves (piedmont and mountain) produced a higher peak runoff than that from the FHWA curve, but a slightly lower peak runoff than that from the Huff second quartile, 10% distribution curve.

7. For short duration storms (3-hour duration in this study), the difference in peak discharges resulting from use of the FHWA and the Virginia curves was small or insignificant. The piedmont curves appear to produce the shortest times to peak because of the higher amount of rainfall during the early stages of the storm.

8. It was observed that the peak discharge adjustment factor for antecedent moisture conditions is a function of the return period of the storm. The adjustments suggested by the SCS for AMC I and AMC III (approximately 20% decrease and 20% increase, respectively) seem to be for storm return periods between 20 and 30 years. As

the return period decreases, the adjustment factor increases (Figures 11 and 12).

9. For very short duration storms, the IDF curves derived from Virginia data generally show lower intensities than those from the NOAA curves. More data analyses are needed before definitive trends can be determined.

RECOMMENDATIONS

Based on the results obtained in the present study, the following recommendations are made.

1. In hyetograph selection it should be noted that the SCS Type II curves for medium and long duration storms (6 hours or longer) may produce higher peak discharges than those obtained with the Virginia curves. However, the reverse is true for short or very short (1 hour or less) duration storms. A computer program for determining and printing the hyetograph using Virginia curves is appended.

2. It may be preferable to compare a few hyetographs in peak runoff computations. The more widespread use of microcomputers by engineers should make the task of such comparisons quite straightforward.

3. Antecedent moisture condition (AMC) selection is still a subjective matter. The results from this study have shown the importance of the AMC and its relationship to storm return periods. However, at present it is not recommended that design engineers assume a condition other than the normal or average one. The relationship between the AMC and the HEC-1 loss parameters (or such parameters in other models) should be examined.

4. More data should be collected and analyzed to clarify further the question of deviations of Virginia IDF curves from the NOAA curves for very short duration storms.

ACKNOWLEDGEMENTS

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APPENDIX

INTERACTIVE COMPUTER PROGRAM VASH

Using the intensity duration frequency curves for storms of less than 1-hour duration and the Virginia temporal distribution, a computer program was developed to give the hyetographs.

The necessary inputs for this program are:

- Duration of the storm
- Frequency of the storm
- Location of the storm

The program accepts eleven counties scattered around the state of Virginia. Figure A-1 shows the counties that can be inputted.

A detailed User's Guide is provided.

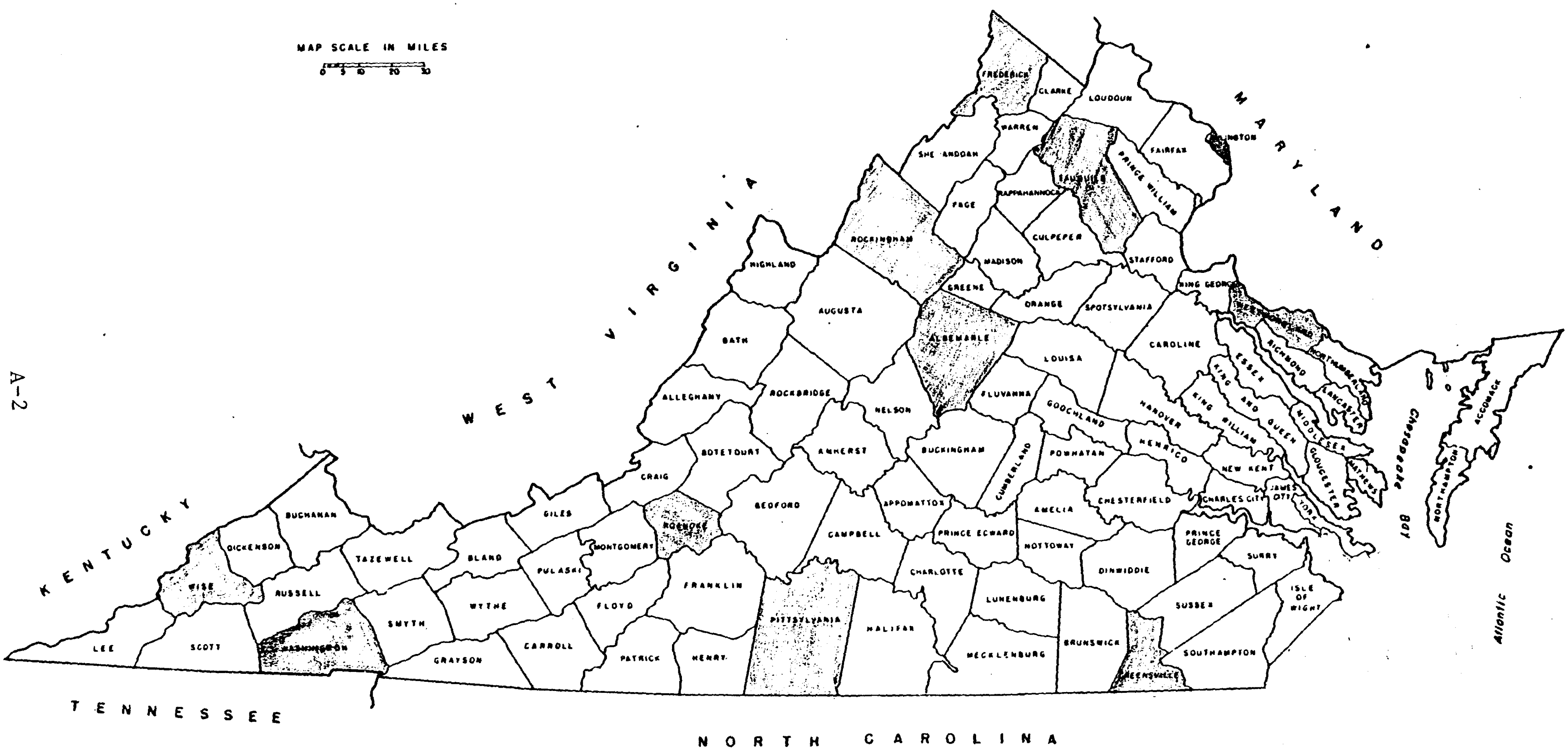


Figure A-1. Counties that can be used with the computer program VASH.

USER'S GUIDE

Program VASH (Va. Short Storm Hyetograph)

VASH is an interactive BASIC program written for the Va. Highway Transportation and Research Council by Donna Richardson and Djamel Benelmoufok. VASH performs two major tasks:

1) Given a specific location, a storm duration, and return period, the program computes the depth of rainfall.

2) The program uses the depth computed in part one, along with the Virginia IDF design equations developed in the previous VHTRC study, Temporal Distibution of Rainfall in Virginia, to compute a hyetograph for the specified storm.

Methods Used

1) Computing the depth of rainfall.

VASH uses the equation derived by Chen (1975) that approximates any intensity-duration-frequency curve:

$$r = a/(t_d + b)^c$$

r = avg.rainfall intensity (in/hr)

t_d = duration of rainfall (min.s)

a,b,c = storm constants that depend on the rainfall distibution in that particular area

The storm constants were derived from the IDF curves presented in the Virginia Highway Drainage Manual. An interactive, nonlinear curve fitting program, CNONLIN, developed at the UVA Medical School and available through the CDC Cyber computer of the University of Virginia, was used to fit the curves. The program uses a least squares fit method and requires a user supplied FORTRAN subroutine and function. The subroutine defines the number of fitting parameters and the number of independent variables. The function is the equation to be used in the curve fitting.

The program was run and the storm constant derived for the six different return periods and eleven representative counties described in the Drainage Manual. Therefore, the user needs only to input the desired county, return period, and storm duration, and VASH has the necessary coefficients to compute the intensity and depth of rainfall.

2) Computing the hyetograph

The previous report, Temporal Distribution of Rainfall in Virginia, describes a method for obtaining a design hyetograph from design mass curves or equations. The same study developed the design equations for the specific regions in Virginia. This program uses the method and Va. design equations to compute the hyetograph.

Running VASH

1) Type "basica" from your operating system to get into BASIC.

2) Type " load"VASH" " to get the program.

3) Type "run".

From this point, the user needs only to respond to prompts from the program. Four values are supplied by the user:

desired return period - can be 2, 5, 10, 25, 50 or 100 years

county - The program accepts eleven counties. These counties are scattered around the entire state and are felt to be representative of any conditions found in Virginia: ALBEMARLE, ARLINGTON, FAUQUIER, FREDERICK, GREENSVILLE, PITTSYLVANIA, ROANOKE, ROCKINGHAM, WASHINGTON, WISE, WESTMORELAND. The county must be entered in upper case letters.

desired storm duration - VASH was developed to handle short storms and therefore only accepts durations of 60 minutes and less.

number of increments in hyetograph - VASH allows the user the choice of having 5, 10, or 20 values in the hyetograph.

Enter return period of storm.
(possible values are 2,5,10,25,50,100): 50

Enter county in upper case letters.
(see user's guide for available counties) : ALBEMARLE

Enter duration of storm (min.s).
(value must be <= 60): 55
Would you like 5, 10 or 20 values in the hyetograph? 20

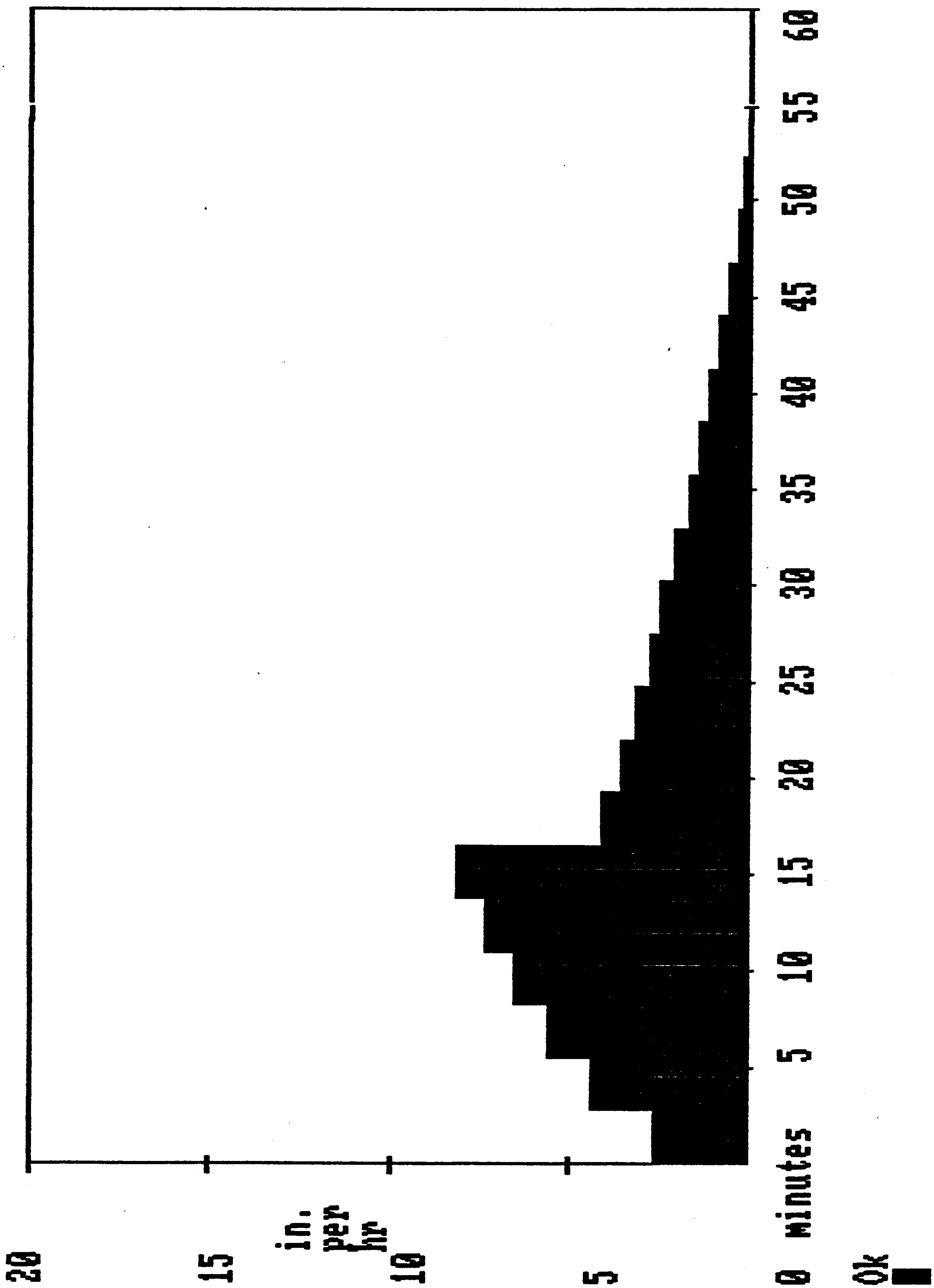
important variables :

storm duration (min.s) = 55
20 values in hyetograph
depth of rainfall = 2.649177

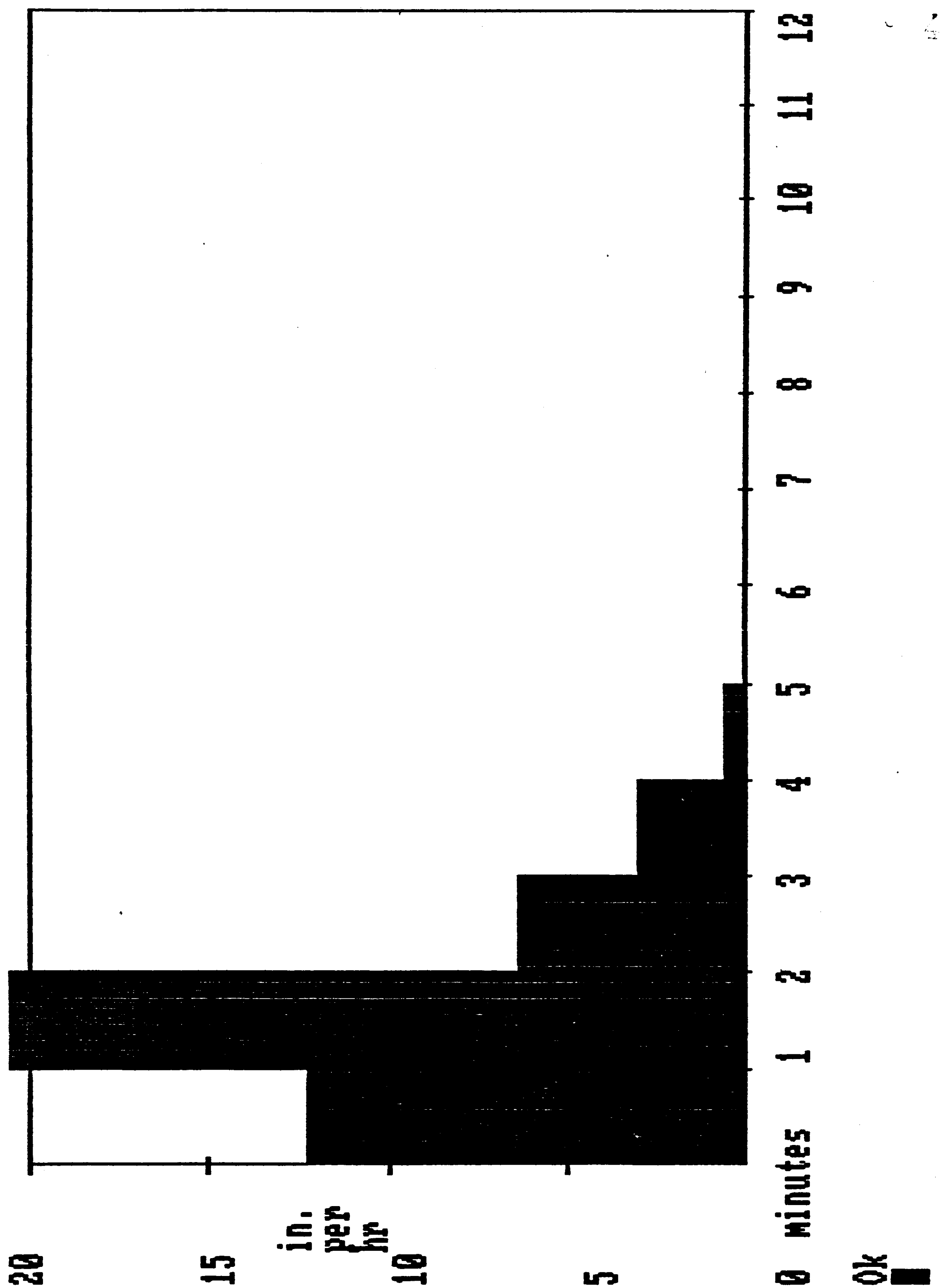
press any key to continue

duration (min.s)	intensity (in/hr)
2.75	2.5872
5.50	4.3501
8.25	5.5391
11.00	6.4946
13.75	7.3144
16.50	8.0427
19.25	3.9822
22.00	3.5524
24.75	3.1389
27.50	2.7425
30.25	2.3640
33.00	2.0043
35.75	1.6646
38.50	1.3461
41.25	1.0505
44.00	0.7800
46.75	0.5372
49.50	0.3260
52.25	0.1528
55.00	0.0299

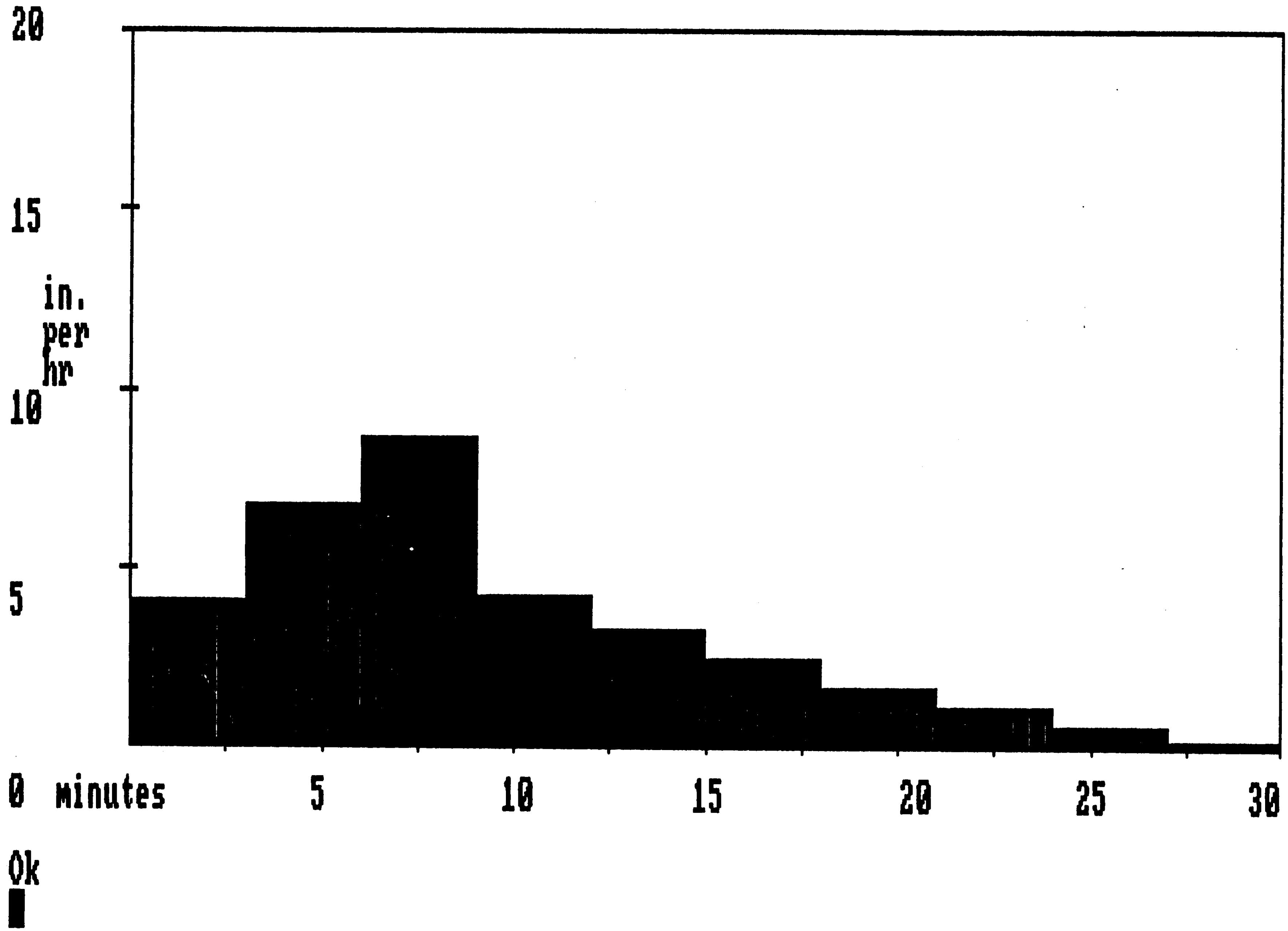
If your terminal has graphics capability, enter the word graph.
Otherwise, enter anything else to end program:


20
15
10
5
0
in.
per
hr
minutes
0
5
10
15
20
25
30
35
40
45
50
55
60
Ok

```
Enter return period of storm.
(possible values are 2,5,10,25,50,100): 20

Enter county in upper case letters.
(see user's guide for available counties) : aALBEMARLE

Enter duration of storm (min.s).
(value must be <= 60): 5
Would you like 5, 10 or 20 values in the hyetograph? 5


important variables :

storm duration (min.s) =  5
 5 values in hyetograph
depth of rainfall =     .6709013


press any key to continue
duration (min.s)        intensity (in/hr)
 1.00                   13.8848
 2.00                   23.3463
 3.00                    7.1063
 4.00                    3.3298
 5.00                    0.6522

If your terminal has graphics capability, enter the word graph.
```


20
15
in.
per
hr
10
5
0
minutes
1
2
3
4
5
6
7
8
9
10
11
12
Ok

```
Enter return period of storm.
(possible values are 2,5,10,25,50,100): 1010

Enter county in upper case letters.
(see user's guide for available counties) : ALBEMARLE

Enter duration of storm (min.s).
(value must be <= 60): 30
Would you like 5, 10 or 20 values in the hyetograph? 10


important variables :

storm duration (min.s) =  30
 10 values in hyetograph
depth of rainfall =     1.612679


press any key to continue
duration (min.s)      intensity (in/hr)
 3.00                  4.0076
 6.00                  6.7386
 9.00                  8.5803
12.00                  4.2022
15.00                  3.2795
18.00                  2.4349
21.00                  1.6769
24.00                  1.0178
27.00                  0.4769
30.00                  0.0934

If your terminal has graphics capability, enter the word graph.
 Otherwise, enter anything else to end program:
```


20
15
in.
per
hr
10
5
0 minutes
5
10
15
20
25
30
Ok

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