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FINAL REPORT

TEMPORAL DISTRIBUTION OF RAINFALL IN VIRGINIA

by

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Virginia Highway & Transportation Research Council
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SUMMARY

The temporal distribution of Virginia rainstorms was examined by statistically analyzing approximately 1,400 storm events recorded throughout the state. Rainfall time distribution curves were constructed and were compared with several nationally recognized curves such as the Huff quartile curves and the Soil Conservation Service Type II curves. Significant differences were found between the Virginia distribution and the national curves. No regional variation was observed in rainfall distribution for storms of six hours or longer duration. However, regional variation was appreciable for short duration storms. Design rainfall distribution curves, as well as equations describing the curves, are presented in this report.

SI CONVERSION FACTORS

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: $1m^3 = 1,000\ \ell$

To Convert From	To	Multiply By
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

In designing highway drainage facilities, knowledge of the time distribution of rainfall, or the hyetograph, is required before the design storm hydrograph can be obtained. The choice of an appropriate design hyetograph is very important because of its significant effect on the shape and peak magnitude of the resulting hydrograph, as demonstrated by Akan and Yen (1984).

The temporal distribution of rainfall is highly variable from location to location and from storm to storm. The commonly used distribution patterns, therefore, have been obtained mostly by statistical analysis of storm records or by subjective designation. These distribution patterns include, for example, the Soil Conservation Service Types I and II curves (SCS 1973), the Army Corps of Engineers' (1975) balanced hyetograph method, the Chicago method (Keifer and Chu 1957), and the Huff (1967) quartile distributions.

Recently Yen and Chow (1983) proposed the use of the statistical means of the first and second moments to construct the design hyetograph. Their study was based on statistical analyses of a large number of storm events for locations throughout the United States.

Since most of the nationally recognized distribution patterns were derived with storm data recorded in other parts of the country, they may or may not be representative for Virginia conditions. The primary purpose of this study was, therefore, to determine which of these patterns is most appropriate for Virginia, or whether a "localized" distribution for Virginia needs to be derived. In addition, it was expected that the results of the study would generate information that would further the understanding of the physical and statistical characteristics of the storm processes in this region.

Major tasks and work elements in this project were:

I. Select rainfall stations and inventory data

1. Select rainfall stations in Virginia
2. Select representative gages
3. Select representative storm events
4. Prepare data for statistical analysis

II. Evaluate National Rainfall Distribution Curves

1. Soil Conservation Service Type I and Type II curves
2. Corps of Engineers' balanced hyetograph method
3. FHWA RD-81/061 XSRAIN Huff quartiles
4. Other curves

III. Analyze Virginia Rainfall Data

1. Determinations of actual rainfall distribution patterns
2. Regional variations
3. Seasonal variations
4. Storm characteristics and other factors
5. Derivation of "design" curves for Virginia
6. Comparison with national curves
7. Discussions and recommendations

IV. Prepare Final Report

ACQUISITION OF STORM DATA

In order to examine whether there are differences in regional rainfall temporal distributions, the state was divided into three geographical regions, (Figure 1); namely, mountain, piedmont plateau, and coastal. Storm data were then obtained from the National Oceanic and Atmospheric Administration (NOAA 1961; 1962-82) and other sources, as described below.

Hourly Rainfall Data

Hourly precipitation data were retrieved from NOAA records through the Virginia State Climatology Office. These data, available on magnetic tape, include hourly rainfall for 87 gaging stations throughout Virginia. The locations of these stations were plotted on a Virginia map (Figure 2).

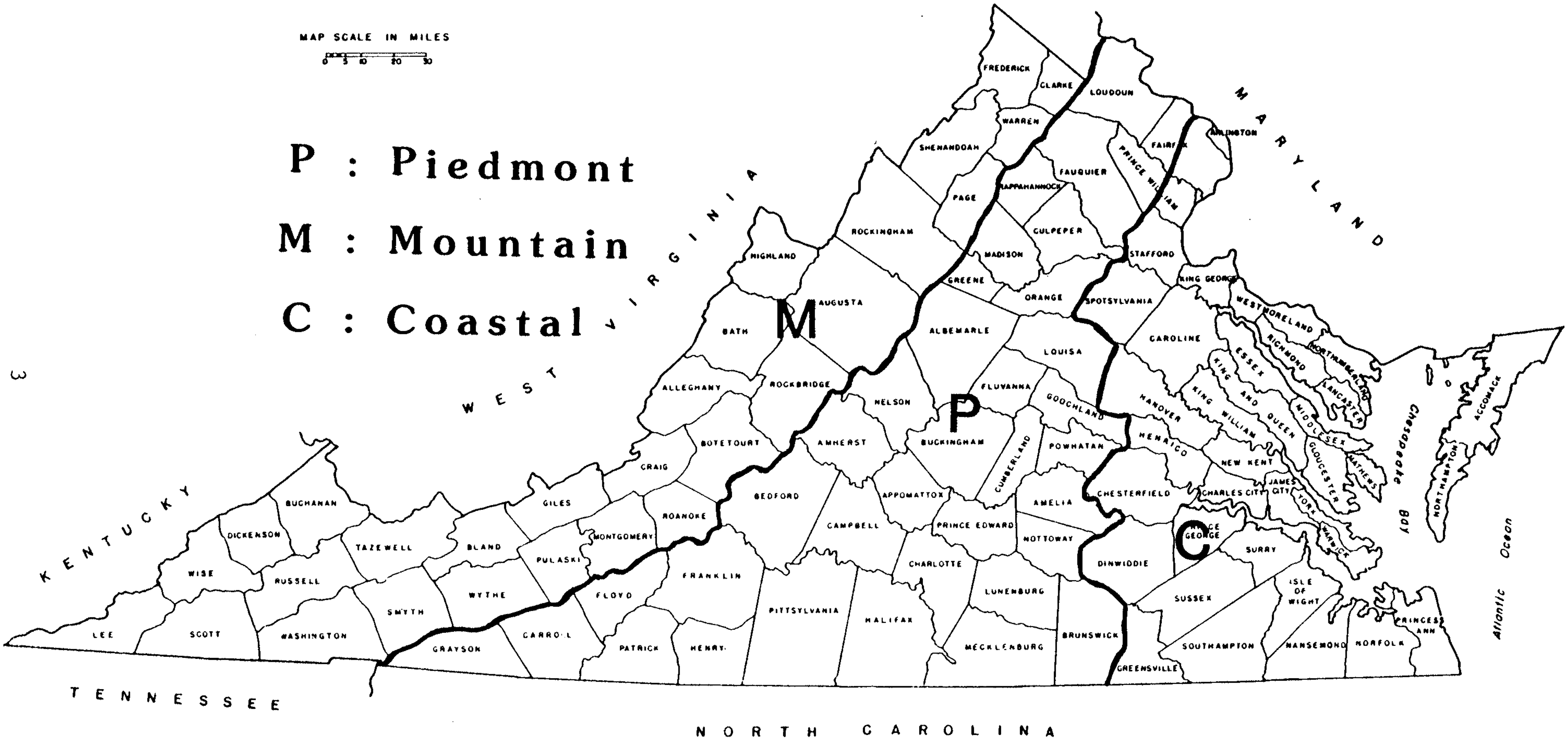


Figure 1. Three geographical regions of Virginia.

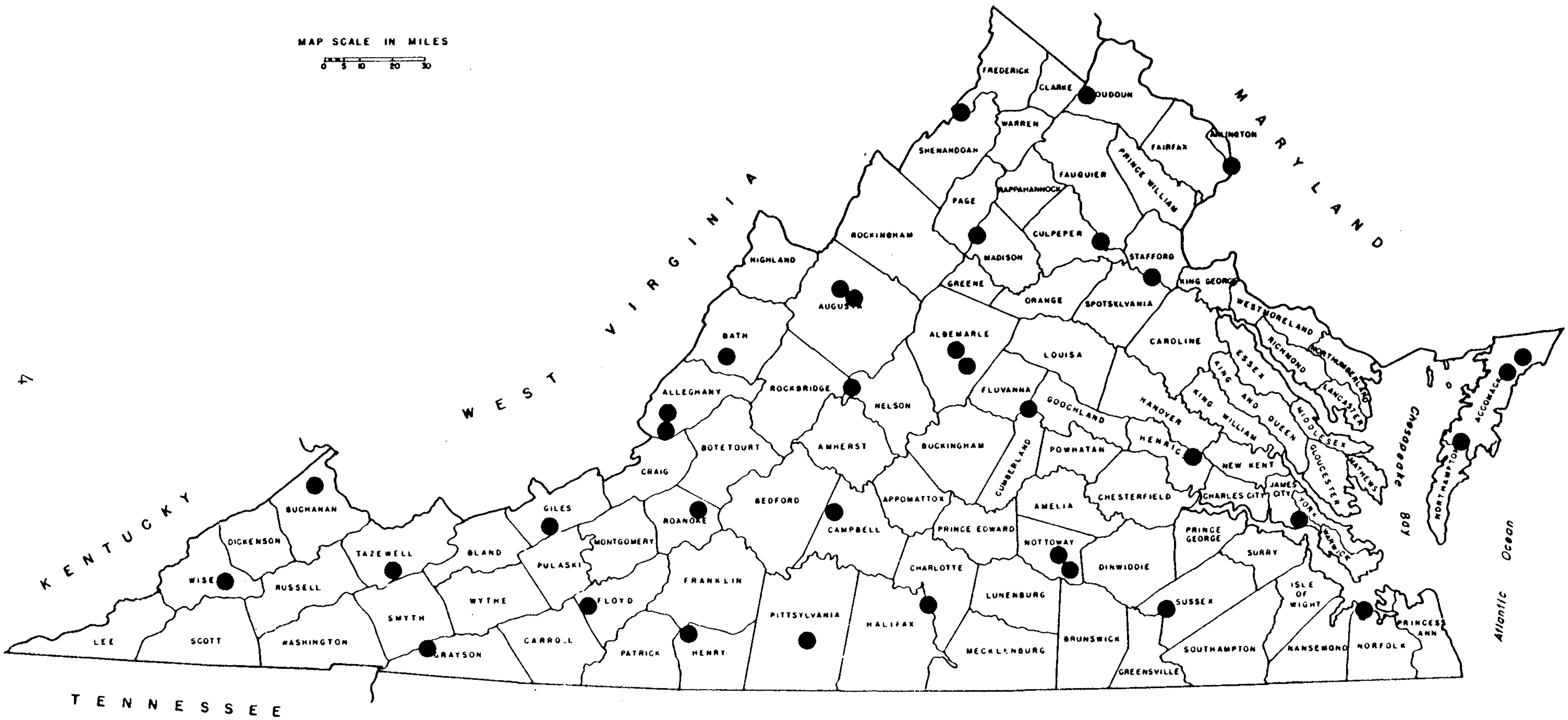


Figure 2. Locations of selected rain gaging stations for medium to long duration storms.

Selection of Rain Gage Stations

Representative stations were selected to provide an appropriate, uniform statewide, distribution throughout Virginia so that rainfall events were not unevenly weighted in the analyses. Only stations with complete records for the 23-yr period 1960-1982 were used. Thirty gages were selected: 13 in the mountain region, 9 in the piedmont, and 8 in the coastal area (see Figure 2). As shown in the figure, four gaging locations involved two recording stations within a few miles of each other. Periods of record do not overlap with these stations; the original gaging station in these areas was apparently relocated. A listing of the 30 stations with their periods of record and zone is presented in Table 1.

Selection of Representative Storm Events

A storm was defined as a period of rain separated from preceeding and succeeding rain by six or more hours. A minimum total accumulation of 0.50 in was required.

A computer program (FORTRAN V) was written to retrieve all storms that met these basic criteria during the selected 23-yr period. Then, storms with durations of 6, 9, 12, 15, 18, or 20 to 40 hr were selected for detailed analyses. A total of 1,000 storms (440 mountain, 270 coastal, and 290 piedmont) were selected.

Fifteen-Minute Data

To obtain a finer resolution on the time scale, data from 15-min gaging stations were obtained from the NOAA, again through the Virginia State Climatology Office. These stations measure accumulated rainfall at each 15-min interval to the nearest 0.10 in. The accuracy of the time measurement is enhanced, therefore, but the rainfall measurement is less accurate, since the stations which measure to the nearest 0.01 in are eliminated from this data set. Only the 15-min periods in which rainfall actually occurred are recorded in this data set; there are no zero records.

This data set was used to study storms lasting from 1 hr to 6 hr. Two groups were studied: from 1.0 to 1.75 hr and from 2.0 to 5.75 hr. Since for each storm there was a minimum of four records and each record was for a minimum of 0.1 in, the minimum total accumulation was 0.4 in for this phase of the study. There were 39 stations included in this data set, and 38 of these were selected for analysis (Figure 3). There were records for approximately 11 yr (1971-1982) for each station.

Table 1

Selected Rain Gage Stations Supplying Hourly Data

Station Name	Begin	End	Zone
Big Meadows	11/49	8/76	P
Blackstone	11/51	4/74	P
Camp Pickett	4/74	12/77	P
Chatham	2/48	1/61	P
Charlottesville	8/48	4/71	P
North Garden	6/71	12/77	P
Churchville	5/48	12/72	M
Staunton	1/73	12/77	P
Elkwood	5/48	12/77	P
Fredericksburg	5/48	8/69	C
	9/69	12/77	
Hot Springs	48	77	M
Hurley	8/48	3/67	M
	10/64	12/77	
Indian Valley	8/48	77	M
Jorden Mines	8/48	12/72	M
Covington F	1/73	12/77	
Lynchburg	8/48	12/77	P
Montebello	8/48	12/77	M
Mount Weather	5/48	12/77	M
Norfolk Airport	8/48	77	C
Painter	2/59	77	C
Philpott	10/53	12/77	P
Randolph	8/48	77	P
Richmond Air.	8/48	77	C
Roanoke Air	8/48	77	M
Spring Creek	11/50	12/77	M
Star Tannery	5/48	12/77	M
Stony Creek	8/48	12/77	C
Troutdale	8/48	12/77	M
Wallops Island	10/66	12/77	C
Washington Nat.	5/48	12/77	C
White Gate	8/48	12/77	M
Williamsburg	8/48	12/77	C
Wise	11/55	12/77	M

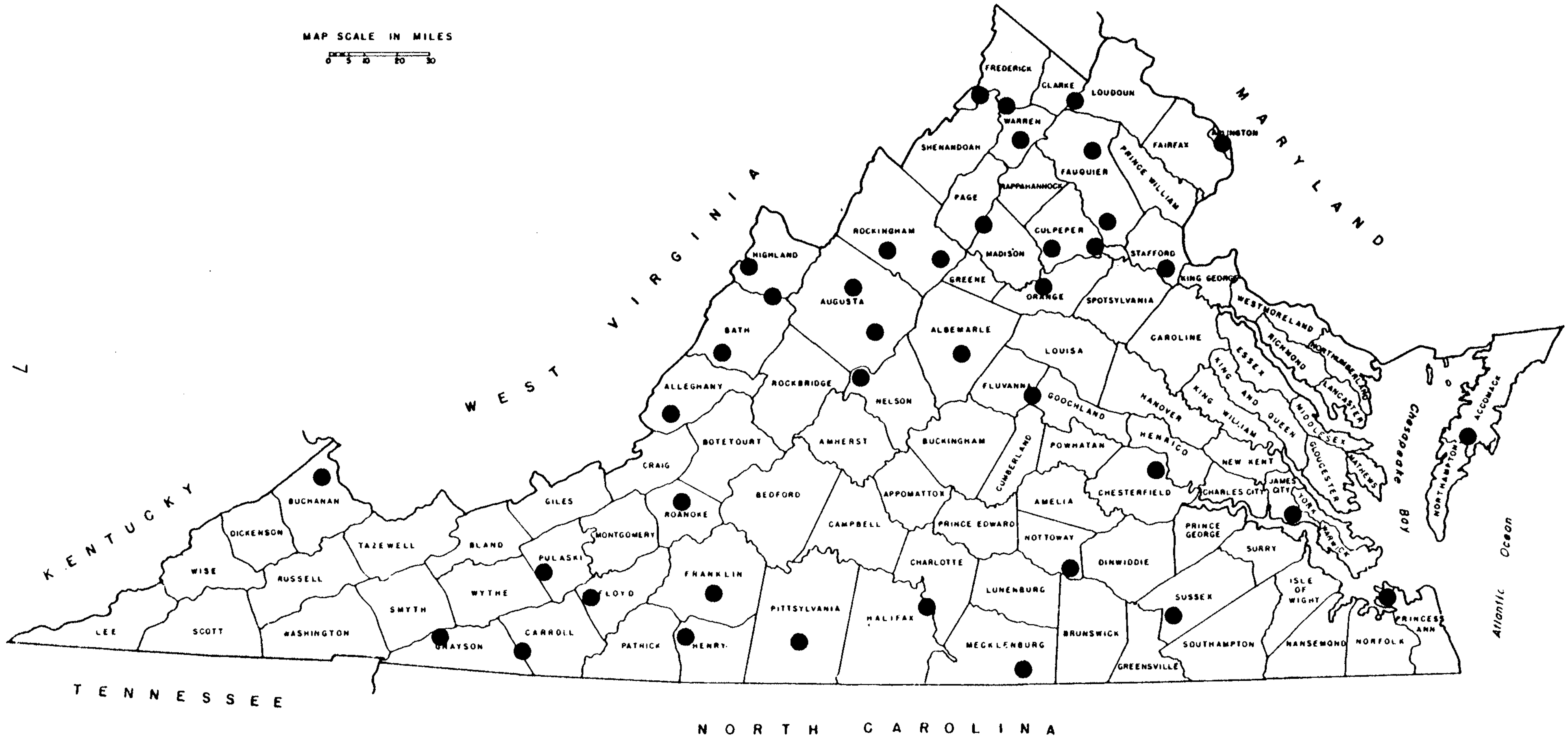


Figure 3. Fifteen-min gaging stations.

Various criteria were applied to the raw data to obtain candidate storms; for the 1.0 to 1.75 hr set the final storm definition was "continuous" rainfall to the accuracy of the gages, that is, no zero records within the storm, and 2 hr preceding and following the storm with no recorded rainfall. For the 2.0 to 5.75 hr storms, two consecutive zero records (30 min with no rainfall) within a storm disqualified that storm from consideration, and it was required that a storm be preceded and followed by at least 6 hr of no rainfall. These criteria were met by approximately 200 storms, approximately 40 in the 2.0 to 5.75 hr group and approximately 160 in the 1.0 to 1.75 hr group.

Five-Minute (or less) Data

Reference made by Yen and Chow (1983) to 5-min time interval rainfall data obtained from an Agricultural Research Service gaging station in Blacksburg, Virginia, led to personal contact with the Hydrology Research group in the Agriculture Engineering Department of Virginia Polytechnic Institute. They provided very short interval "break-point" rainfall data from ten gaging station locations in the mountain (5 stations) and piedmont (5 stations) areas of Virginia (Figure 4). The Hydrology Research group had also written a computer program to reduce the raw data from the gaging stations to a form with accumulations and storm durations more easily accessible. Approximately 120 record years of data were analyzed from this data set, for an average of about 12 yr per station. The new data give the intensity of rainfall and the time when the intensity changes. The "reduced" data have accumulated values since the last zero reading, along with daily, monthly, and yearly accumulation, and a complete description of the time to the nearest minute. Rainfall values are to the nearest minute. Rainfall values are to the nearest 0.01 in. With this data set the time resolution and the precipitation resolution are very fine scale, but there is some limitation in the geographical locations of the stations; there are no stations within the coastal plain, for example.

The reduced data were used to locate storms of between 10 min and 60 min duration, with a minimum of four records within the storm and with two hr preceding and following the storm with no rainfall.

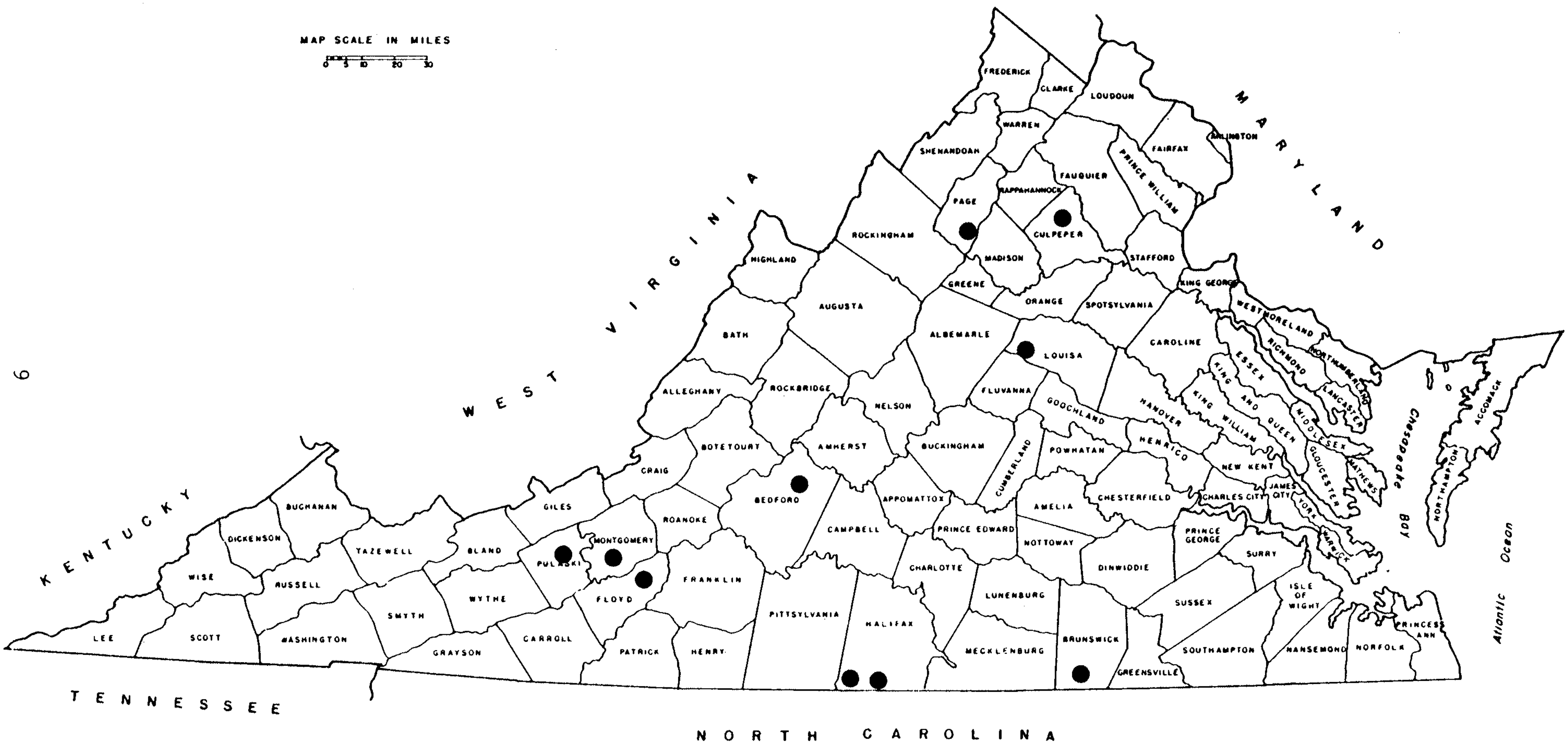


Figure 4. Break-point data gaging stations.

EVALUATION OF NATIONAL RAINFALL DISTRIBUTION CURVES

The Huff Procedure

The Huff method was based on a study in central Illinois involving 261 heavy storms (exceeding 0.50 in) with durations of 3 to 48 hr (Huff 1967). The storms were divided into four groups on the basis of the time quartile in which the heaviest rainfall occurred, with 10% to 90% probability levels determined for each quartile. These levels represent the percentage of storms having that particular time distribution or one above it; the 50% level is the median curve (see Figure 5). The time distributions are expressed in probability terms because of the variability of the distribution from storm to storm, and they can be used to design for various levels of risks. The median curve, however, is recommended for most applications (Huff 1967).

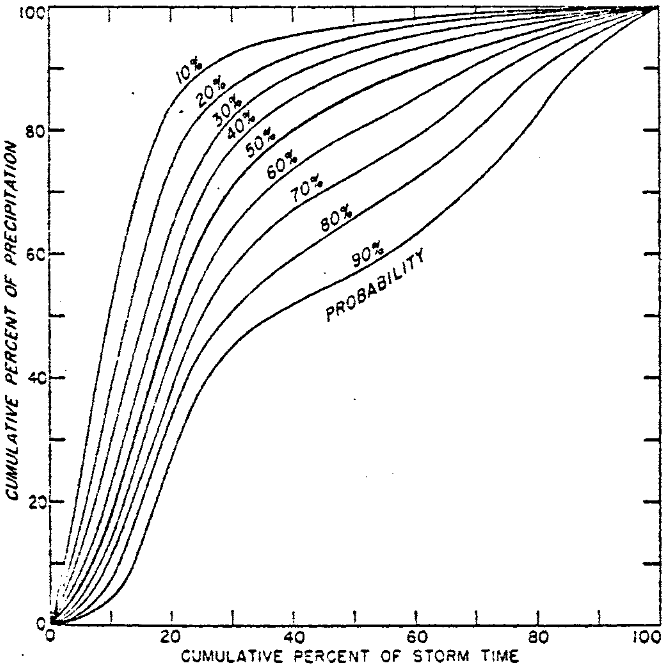
The probability levels represent particular storm types. For example, with the 10% level in first quartile storms, 80% of the total storm occurs in the first 20% of the storm duration. Huff associates this condition with short duration storms, such as the passage of an intense prefrontal squall line in which light rain falls for substantial periods following the initial major rain burst.

Within each quartile, the time distributions are expressed as cumulative percentages of storm rainfall and cumulative percentages of total storm duration. This technique was used by Huff to allow valid comparisons between storms and to simplify analyses of data. He did not distinguish storms on the basis of their duration when calculating the probability curves or the quartile divisions.

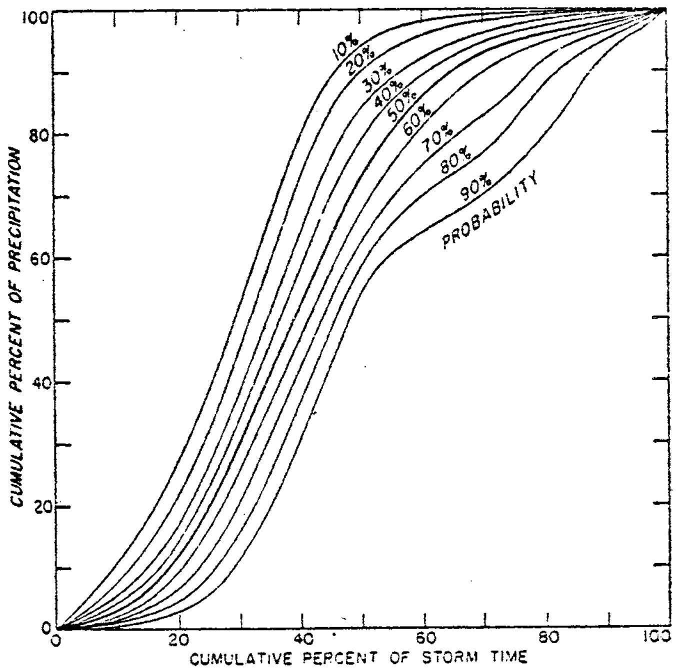
Huff did suggest a trend in regard to the relation between storm duration and quartiles. The long duration storms tended to have a fourth-quartile classification, whereas short duration storms fell predominately in the first and second quartiles. Overall, however, the effect of storm duration was minor and somewhat inconsistent. Statistical analyses indicated that total storm time explained only 7% of the variance in temporal distribution for all storms in his 400-mi^2 research area. Huff suggested that a larger data base might stabilize the effects and allow a quartile classification according to duration.

Analysis of Virginia Hourly Storm Data Using the Huff Procedure

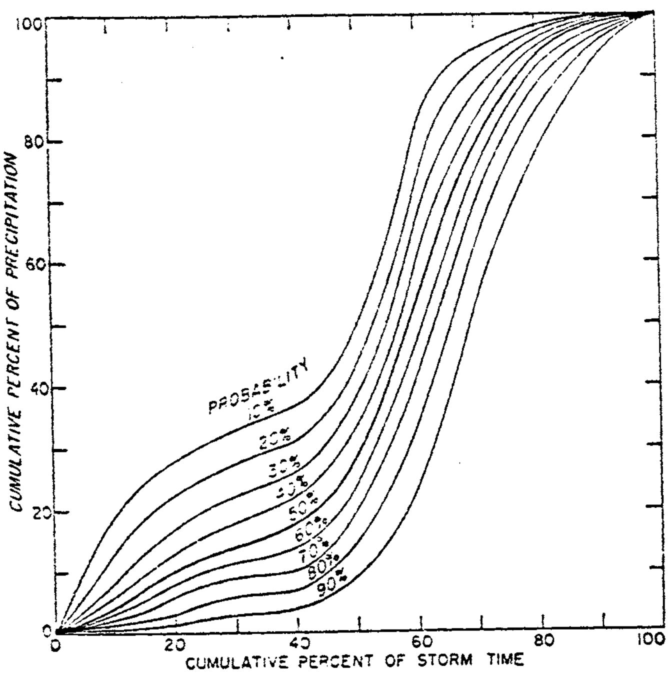
The 1,000 Virginia storms were analyzed using the Huff method to determine time distribution curves for the mountain, piedmont, and coastal regions. Storms were divided into four groups depending on the quartile in which the most rain occurred. Table 2 shows the percentage frequency of the quartiles for each region compared to Huff's results.



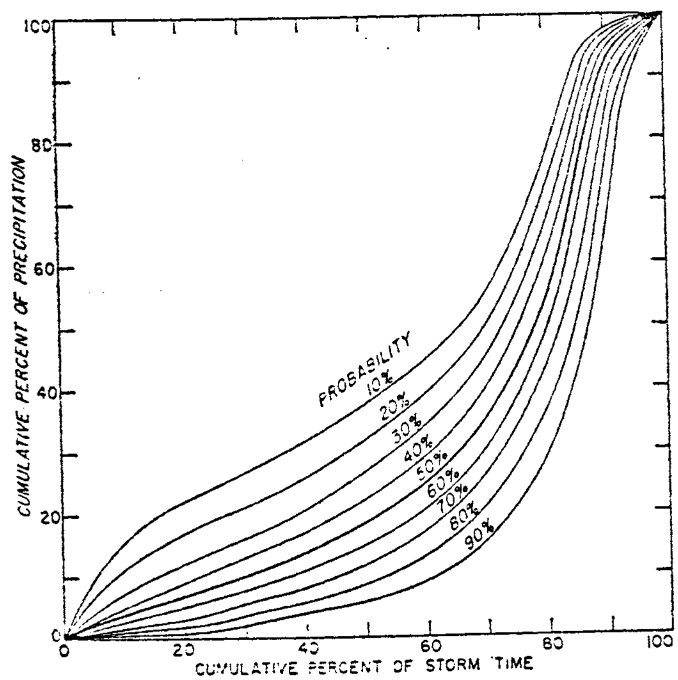
Time distribution of first-quartile storms.



Time distribution of second-quartile storms.



Time distribution of third-quartile storms.



Time distribution of fourth-quartile storms.

Figure 5. Time distribution of storms (Huff 1967).

A significant difference between the Virginia data and those from the Huff quartile curves was recognized for all three regions. Second and third quartiles predominated for Virginia storms in all three regions, while Huff's storms fell more often in the first quartile. Fourth quartile storms occurred least frequently in both studies (see Table 2).

These frequencies can be used to determine the probability of occurrence of a particular storm type associated with one of the probability levels. For example, the probability of a first quartile storm in the mountains is 0.18 (see Table 2). Within first quartile storms, the overall probability of 50% distribution is, therefore, 9% (0.18 x 0.50 = 0.09). The return period is thus 11 yr (1/0.09).

Table 2

Percentage Frequency of Quartile Storms

Quartile	Number of Storms	Frequency (%)	Overall Probability of 50% Curve	Return Period (years)	Huff Frequency	Huff Return Period (Years)
Mountain Region (440 storms)						
1	80	18.2	9.1	11.0	30	6.7
2	150	34.1	17.1	5.8	36	5.6
3	150	34.1	17.1	5.8	19	10.5
4	60	13.6	6.8	14.7	15	13.3
Coastal Region (270 storms)						
1	50	18.5	9.25	10.8	30	6.7
2	100	37.0	18.5	5.4	36	5.6
3	90	33.3	16.7	6.0	19	10.5
4	30	11.1	5.6	18.0	15	13.3
Piedmont Region (290 storms)						
1	50	17.2	8.6	11.6	30	6.7
2	90	31.0	15.5	6.5	36	5.6
3	110	37.9	19.0	5.3	19	10.5
4	40	18.8	6.9	14.5	15	13.3

As shown in Figures 6 through 9, there was little regional difference in the temporal distribution of rainfall amoung the regions of Virginia for storms of 6 hr or longer duration. The maximum difference in the 50% probability curves is approximately 5% for the first and the fourth quartile storms. Since about 68% of the Virginia storms are in the second and third quartiles (see Table 2), one "statewide" rainfall distribution curve should be adequate for Virginia.

To compare the Virginia and the Huff data at different probability levels, the 10%, 50%, and 90% probability curves for the Virginia mountain region (chosen as the representative one) were plotted together with the corresponding Huff curves for each quartile and are shown in Figures 10 through 13. In general, the Virginia curves are less variable. One consequence of the reduced variability is that more rainfall is predicted to fall in the first half of the storm. In this sense, the curves are more "conservative" than those of Huff. (Two exceptions are the 10% and 50% levels in the first-quartile storms).

The differences in the Virginia and Huff curves may be explained by the use of different time increments in the data. Because the rainfall data used in this research were hourly, a uniform distribution of rainfall was assumed within each hour when developing the 10% to 90% probability curves. Such uniformity may be responsible for the smoother, less variable curves. Huff developed his curves using 5-, 15-, and 30-min as well as hourly data, which obviously permits more accurate calculations of cumulative rainfall percentages. In any case, the results from this phase of the study are different enough to suggest that the Huff curves do not suitably represent Virginia rainfall patterns. They may apply exclusively to the Midwest or other areas of similar climate and topography.

As mentioned, Huff found that longer duration storms (over 24 hr) predominated in the fourth quartile, storms of moderate length (12 to 24 hr) predominated in the third quartile, and short duration storms predominated in the first and second quartiles.

Trends were not always consistent, however, and no strong correlation was present. Similarly for Virginia storms, there was no clear relation between duration and quartile. The mountain region distribution most closely simulated Huff's findings: the 6-hr storms predominated in the first and second quartiles and the longer storms (>18 hr) predominated in the fourth. However, in the remaining two regions, longer storms did not dominate the fourth-quartile group as they did in Huff's study, nor did shorter storms dominate first quartiles. These differences could be due in part to the smaller range of durations studied here (6 to 39 hr) compared to Huff's (3 to 48 hr). Both studies were consistent, however, in indicating no clear relation between storm duration and quartile classification.

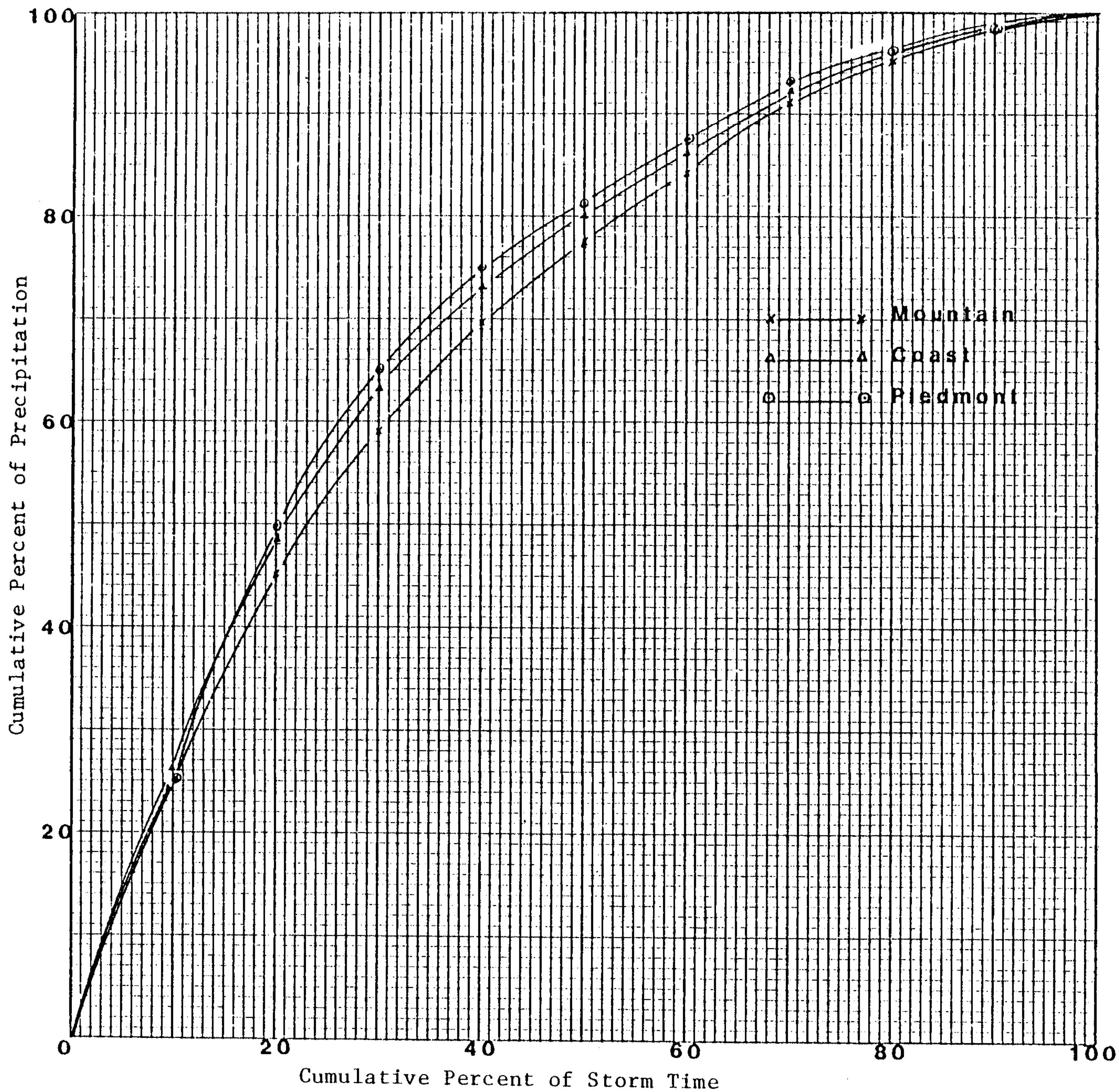


Figure 6. Time distribution of first quartile storms — 50% probability curves.

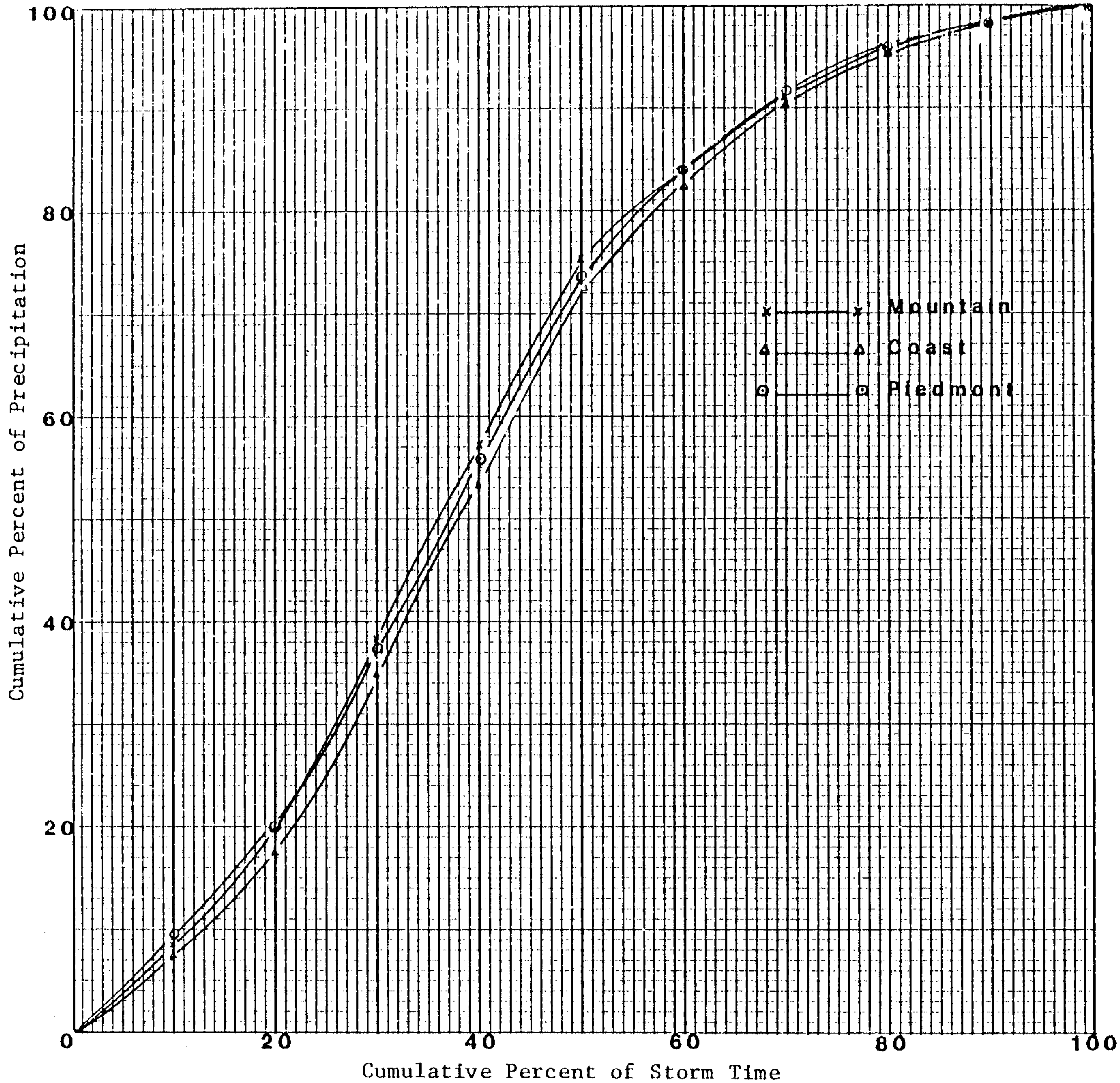


Figure 7. Time distribution of second quartile storms — 50% probability curves.

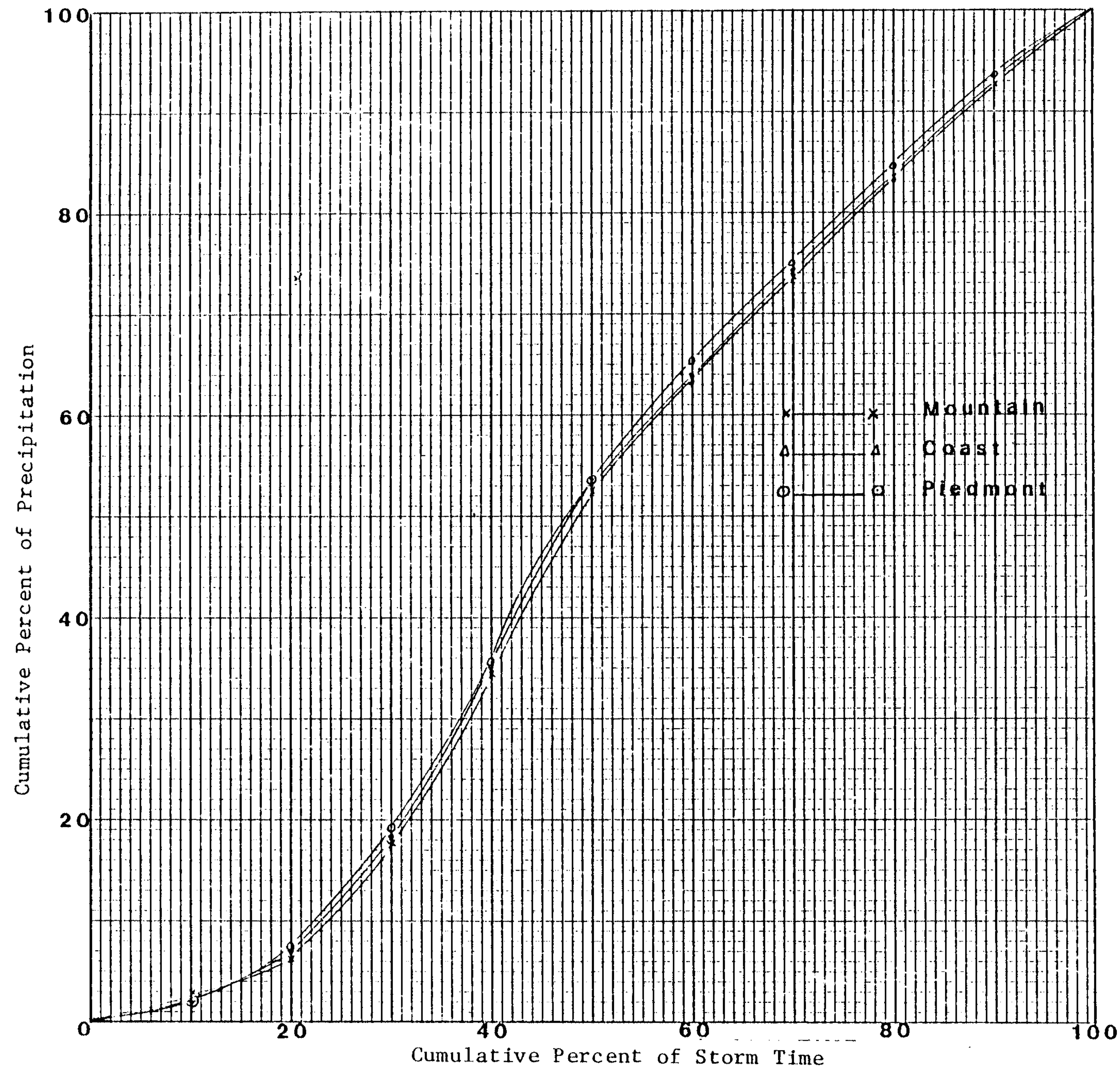


Figure 8. Time distribution of third quartile storms — 50% probability curves.

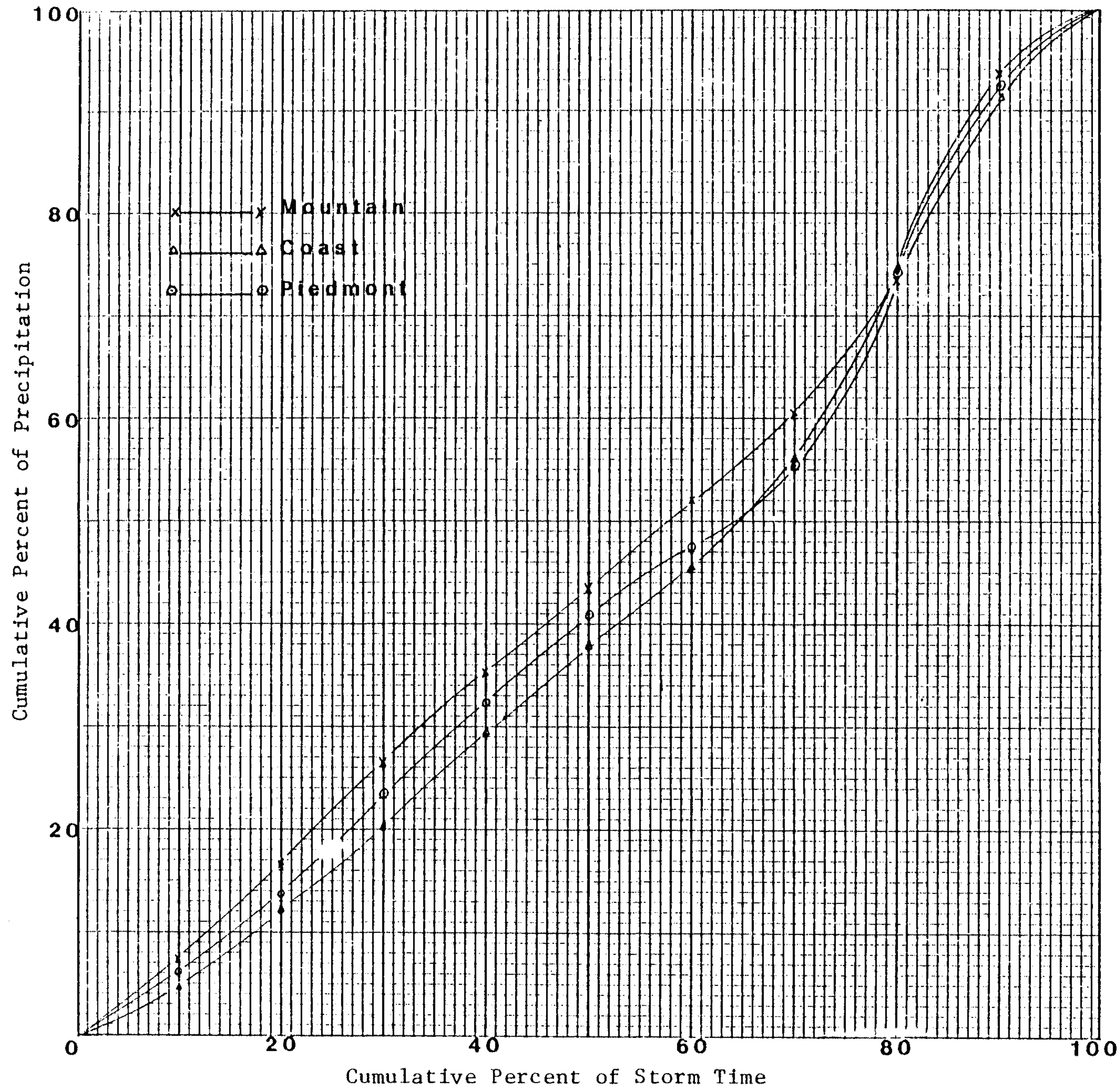


Figure 9. Time distribution of fourth quartile storms — 50% probability curves.

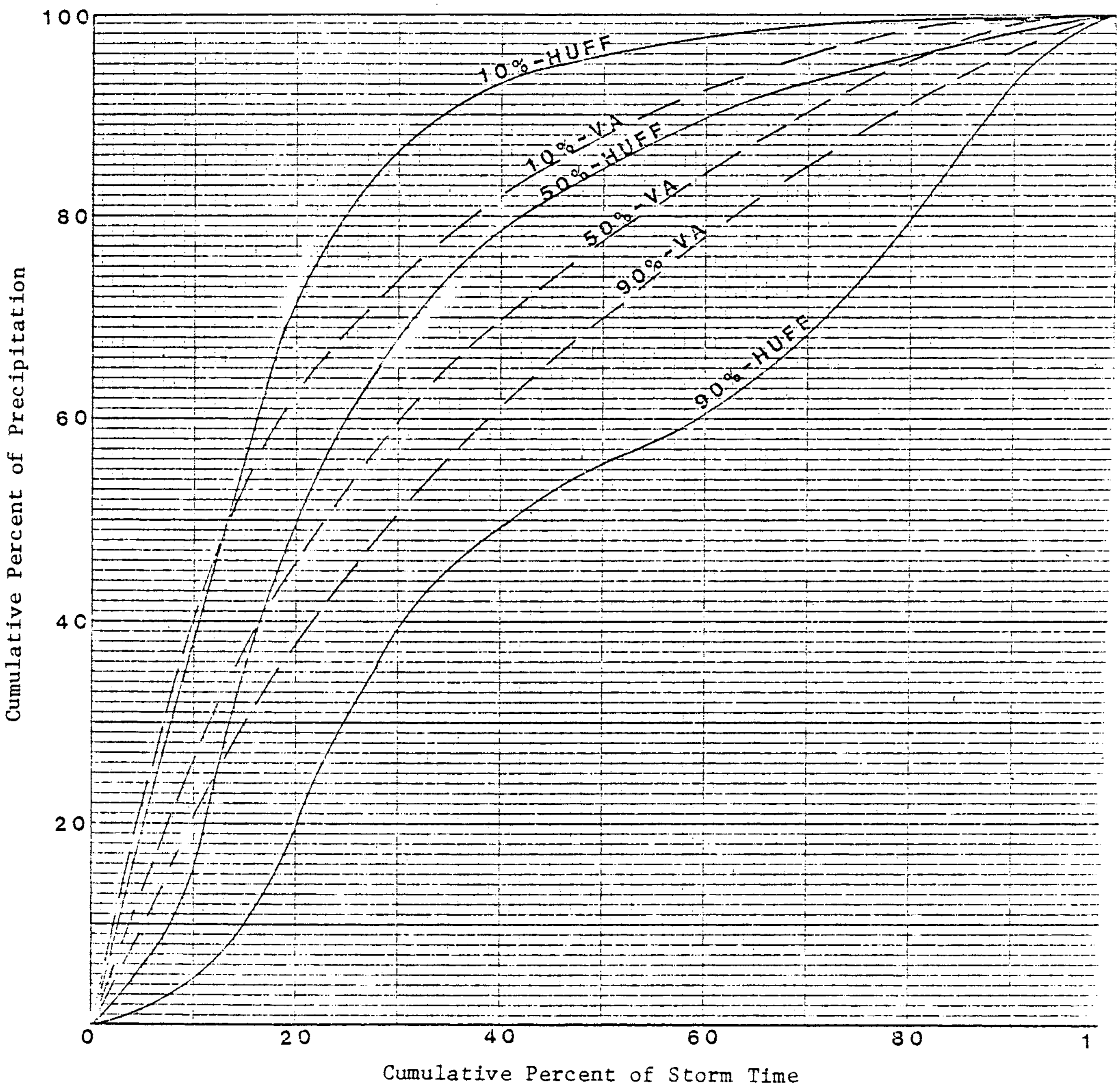


Figure 10. Time distribution of first quartile storms.

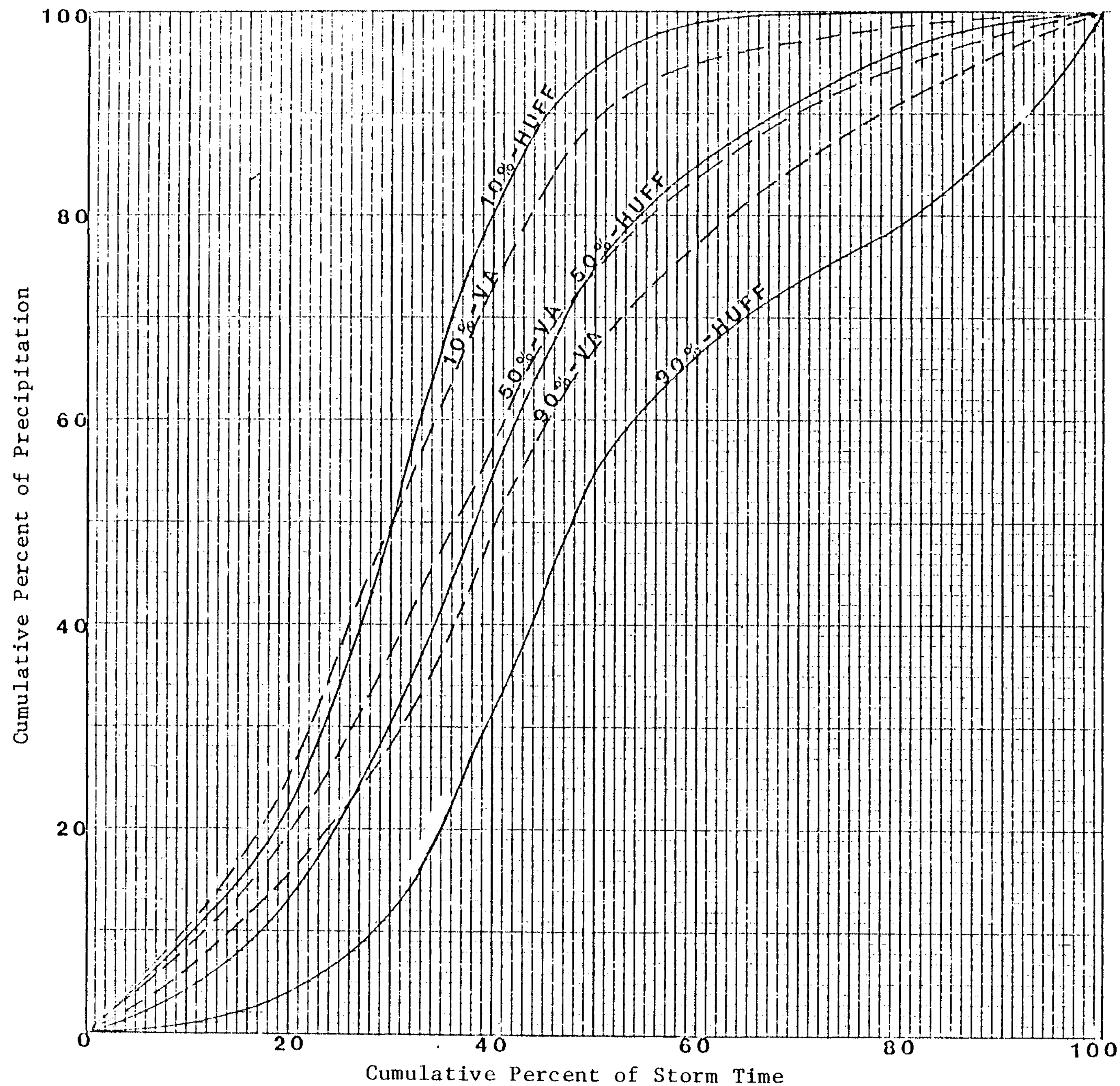


Figure 11. Time distribution of second quartile storms.

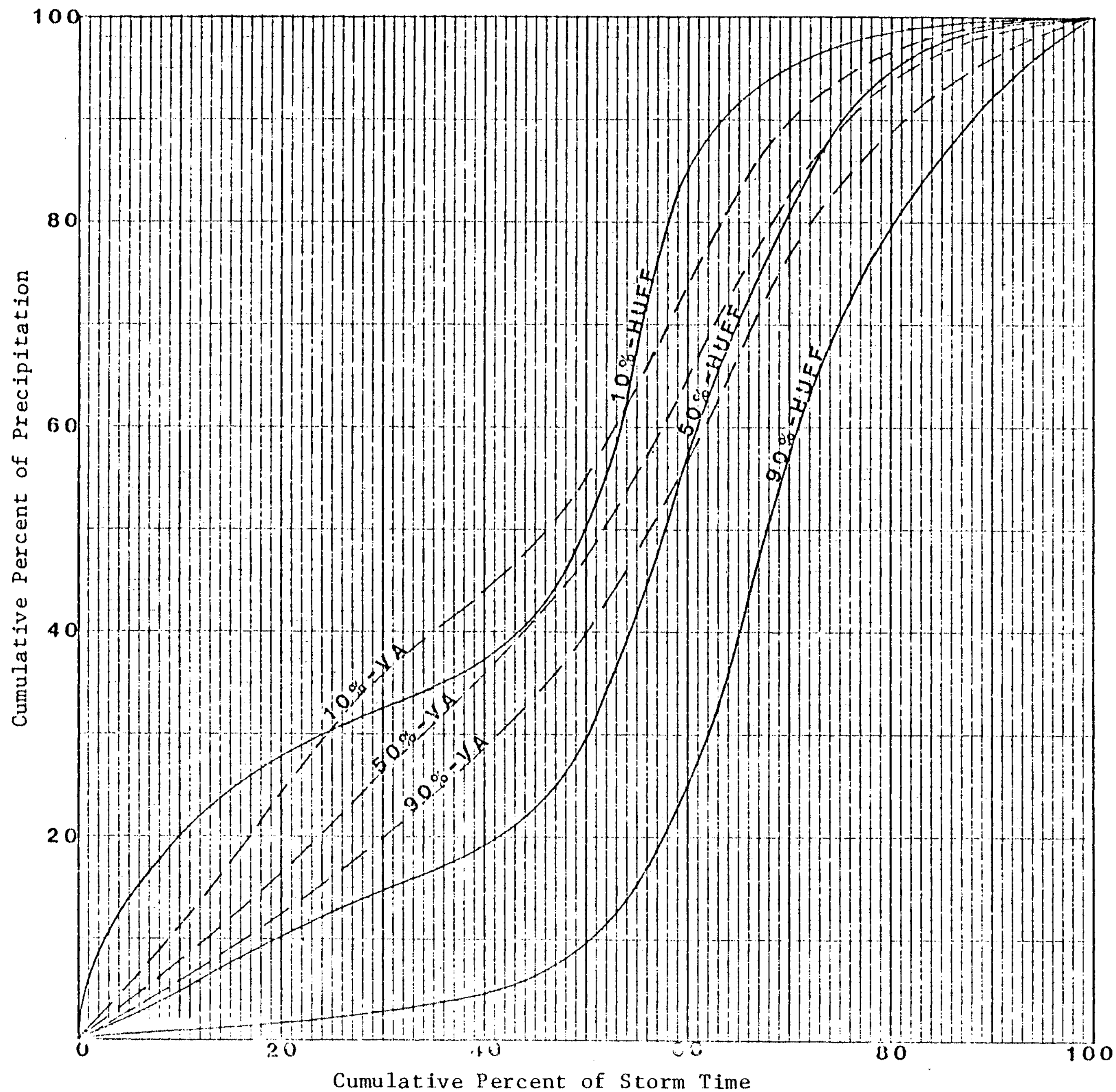


Figure 12. Time distribution of third quartile storms.

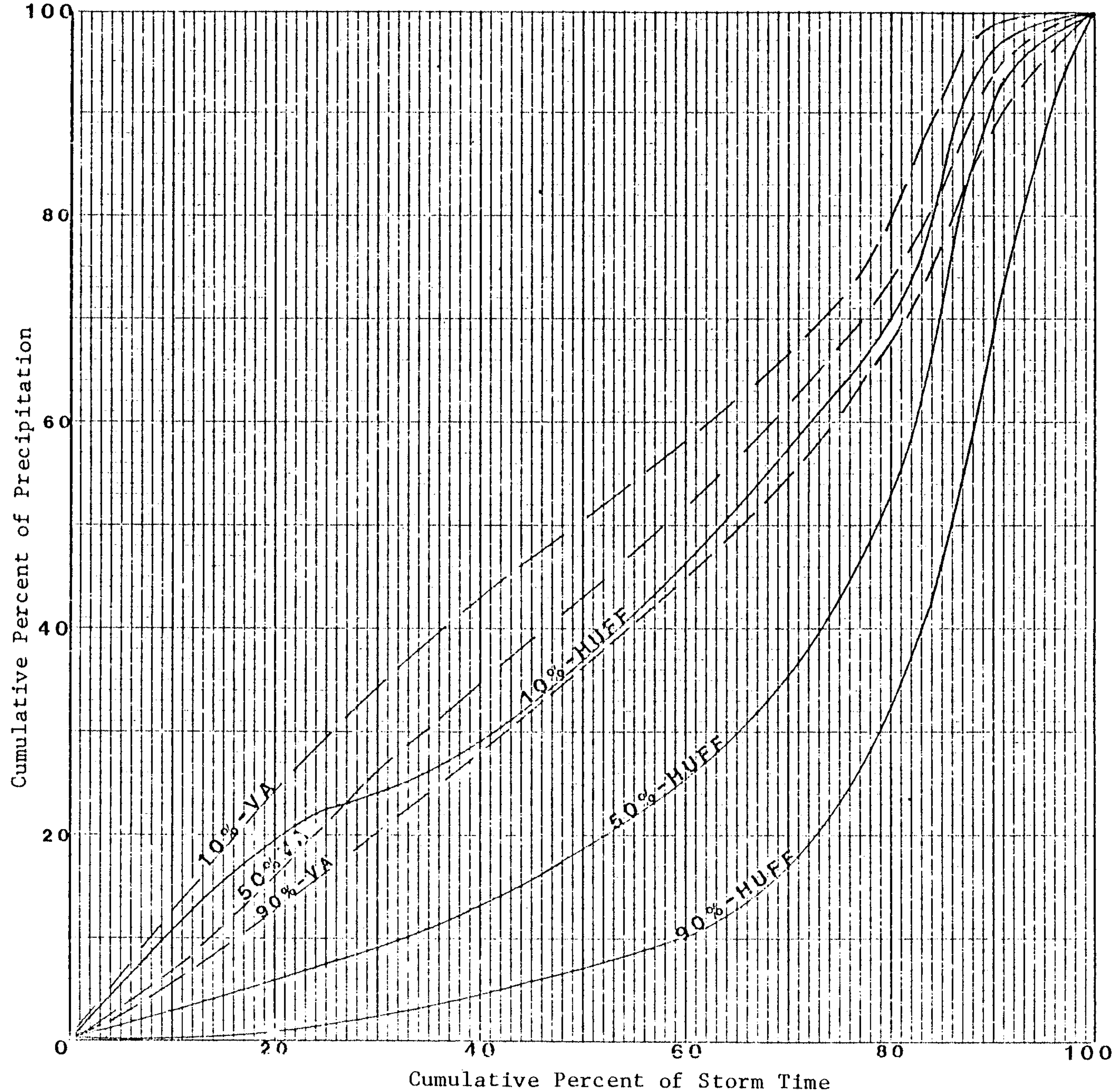


Figure 13. Time distribution of fourth quartile storms.

The Soil Conservation Service (SCS) Method

The Soil Conservation Service (SCS) developed temporal rainfall distribution curves based on the 24-hr rainfall depth for a given frequency (SCS 1973). These curves include the following:

Type I Curve -- Recommended for use in Alaska, Hawaii, and the coastal side of the Sierra Nevada and the Cascade Range.

Type II Curve -- Recommended for use in the remaining part of the United States and in Puerto Rico and the Virgin Islands.

The SCS curves were developed based on generalized rainfall depth-duration-frequency curves obtained from U.S. Weather Bureau data (NOAA 1963). Figure 14 depicts the SCS 24-hr types I and II curves which can be used to derive design storm hyetographs of any duration. For example, the temporal distribution of a 6-hr design storm can be obtained by taking the most intense 6-hr rainfall rates on the 24-hr curve.

A preliminary comparison was made between the SCS type II curve and a similar distribution curve derived from Virginia 24-hr rainfall data. A 6-hr, 10-yr rainfall event for Richmond, Virginia, was used as an example.

The procedure used to derive the SCS 10-yr, 6-hr time distribution curve for Richmond is illustrated in Table 3. The 24-hr, 10-yr rainfall determined from the depth-duration-frequency curves for Richmond was 5.5 in. The most intense 6 hr on the 24-hr type II curve were selected to derive the representative 6-hr rainstorm (hours 9 through 15). This SCS 6-hour rainstorm is illustrated in Figure 15.

As shown in Table 3, the total rainfall for this storm in Richmond was 3.89 in. This figure closely approximates the depth of rain read directly from the depth-duration-frequency curves for a 6-hr, 10-yr storm (intensity 0.675 in/hr, total rainfall 4.05 in). The SCS derived the types I and II curves so that the resulting time distribution curve and total precipitation would approximate the total rainfall determined by the U.S. Weather Bureau T.P.-40 (1963). An average 24-hr rainfall curve was determined using all 24-hr Virginia storms. No regional distinction was made because there was a small 24-hr storm sample in each region, and little regional variation was apparent to justify any distinction.

This 24-hr average curve was used in place of the type II curve in the SCS procedure to determine a 10-yr, 6-hr temporal distribution curve. The procedure and results are presented in Table 4. Hours 14 through 20 were selected as most intense and, as before, the 10-yr, 24-hr rainfall read from the depth-duration-frequency curves was 5.5 in. The total precipitation for this average synthetic storm was 1.8 in. This 6-hr design storm is illustrated in Figure 15. Obviously, the average 24-hr curve produces a much less severe 6-hr storm.

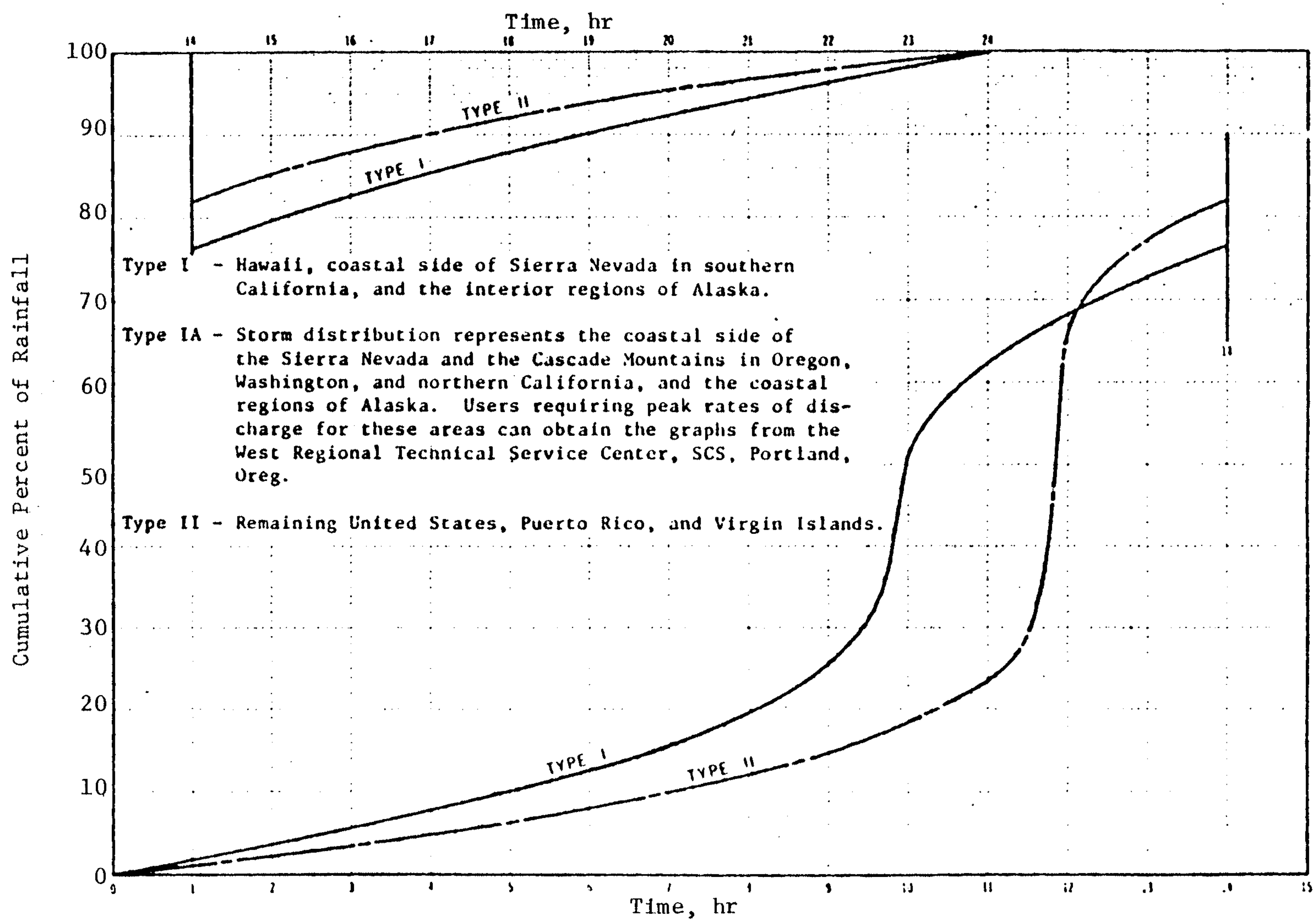


Figure 14. SCS 24-hr types I and II curves (SCS 1973).

The average 6-hr distributions for the three regions of Virginia are presented in Figure 16. As expected, these average curves are less steep than the synthetic SCS 6-hr design storm developed for more extreme cases as illustrated in Figure 15. These average curves further confirm the absence of regional variability in Virginia storm patterns for durations greater than 6 hr.

Table 3

Synthetic 10-yr, 6-hr Rainstorm for Richmond

10-yr, 24-hr rainfall = 5.50 in*

Time (hr) (1)	Type II Curve Ordinate (2)	Increment Curve Value (3)	Rainfall Depth (in) (4)
9	0.145	---	---
10	0.18	0.035	0.193 (5.0%)
11	0.24	0.06	0.33 (13.4%)
12	0.65	0.41	2.26 (71.5%)
13	0.775	0.125	0.668 (89.2%)
14	0.82	0.045	0.248 (95.6%)
15	0.85	0.03	0.165 (100.0%)

Precipitation Total = 3.89 in

*From depth-duration-frequency curves for Richmond

(1) From Type II curve, most intense 6 hours

(2) From Type II curve

(3) By subtraction of successive values in (2)

(4) (3) x 5.50

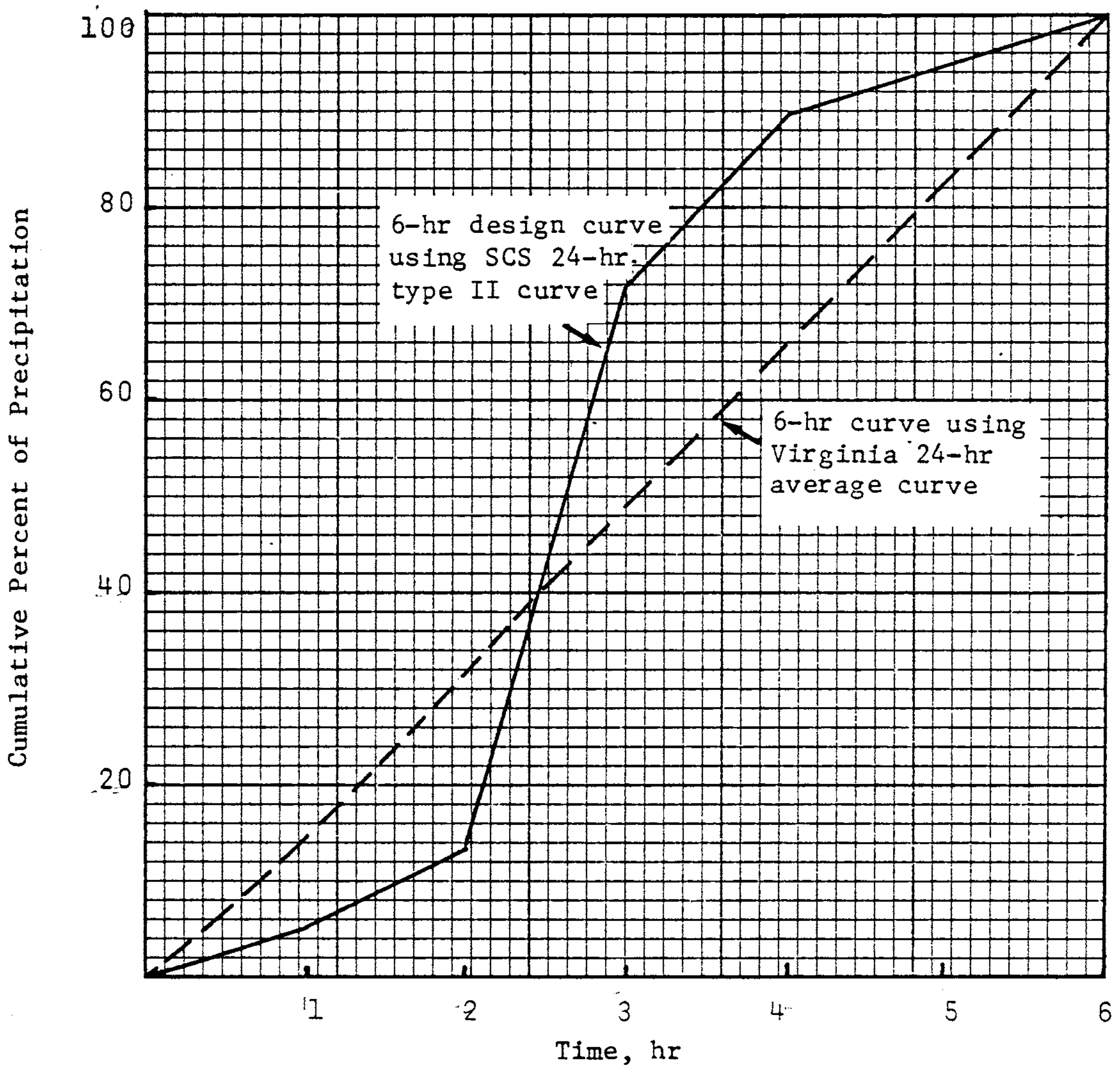


Figure 15. SCS 6-hr design storm and Virginia 6-hr average storm.

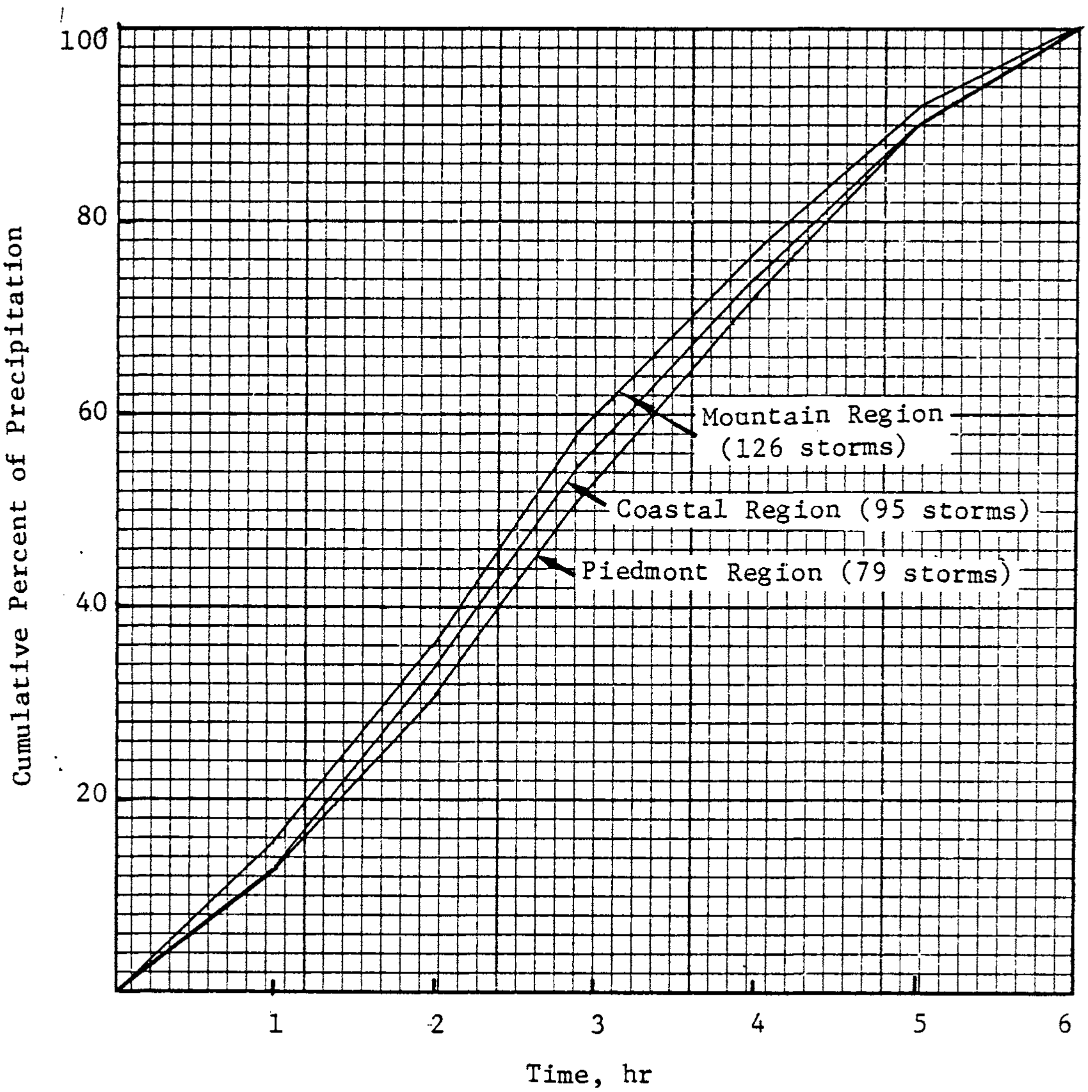


Figure 16. Six-hr rainfall distributions for mountain, coastal and piedmont regions of Virginia.

Table 4

Synthetic Average 10-yr, 6-hr Curve for Richmond

10-yr, 6-hr rainfall = 5.50 in*

Time (hr) (1)	24-hr Average Curve Ordinate (2)	Increment Curve Value (3)	Rainfall Depth (in) (4)
14	0.542	---	---
15	0.588	0.046	0.253 (14.3%)
16	0.644	0.056	0.308 (31.7%)
17	0.699	0.055	0.303 (48.8%)
18	0.749	0.050	0.275 (64.3%)
19	0.814	0.065	0.358 (84.5%)
20	0.864	0.050	0.275 (100.0%)

Precipitation Total = 1.77 in

*From depth-duration-frequency curves for Richmond

(1) From 24-hr average curve, most intense 6 hours

(2) From 24-hr average curve

(3) By subtraction of successive values in (2)

(4) (3) x 5.50

The results of the evaluation of national rainfall distribution curves with the Virginia hourly rainfall data can be summarized as follows:

- There appears to be little regional variability in the temporal distribution of Virginia storms with medium or longer durations (greater than 6 hr).

- Virginia storms with 6-hr or longer durations are predominately classified as second and third quartile types according to Huff's classification.

- No clear relation between storm duration and quartile groups was observed for medium or longer duration storms.

The evaluation of the balanced hyetograph method of the Corps of Engineers (1975) with Virginia data was not made due to its similarity with the SCS type II curve, in that both are center-peaked distribution curves.

The results of the hourly data analysis led to the conclusion that distribution curves should be developed with Virginia data and more comparison with national curves should be made with shorter time incremental data, i.e., 15-min and 5-min rainfall data as described in the previous section.

DERIVATION OF DESIGN CURVES

Results of the evaluation of nationally recognized curves as described in the previous section suggest the need for deriving design curves for rainfall temporal distribution using the Virginia data. It was also found that no regional difference was evident for rainfall durations of 6 hr or longer. However, for shorter duration storms, a regional difference may be significant and storm duration may have a strong effect on the temporal rainfall distribution.

Storm Definition and Classification

As described previously, magnetic tapes containing hourly and 15-minute precipitation data were obtained from the NOAA, and 5-min or less time interval data, also on a tape, were acquired from the Hydrology Research Group at Virginia Tech. Computer programs were written to search these tapes for storm events according to certain criteria. Close to 1,200 storms were extracted from the data tapes and were classified into 4 categories: very short duration (1 hr and less), short duration (greater than 1 and less than 6 hr), medium duration (6 hr to 18 hr), and long duration (longer than 18 hr). Table 5 provides a summary of storm definition and classification used in this study.

It should be mentioned that of the 10 "break-point" rainfall stations providing 1-min interval data, 5 were in the mountain region, 5 in the piedmont, and none in the coastal region.

Table 5

Storm Definition and Classification

1. Very Short Duration $D \leq 1$ hr (1-min Data)

   (Thunderstorms)

   - Preceded and followed by 2 hr of zero rainfall
   - Duration from 10 min to 60 min
   - Minimum of 4 records within the storm

2. Short Duration $1 \text{ hr} < D < 6$ hr (15-min Data)

   (Thunderstorms)

   - Preceded and followed by at least 2D (up to 6 hr) of zero rainfall
   - At least 0.4 in cumulated rainfall volume
   - Definition of rainfall intensity

     Light to Moderate - less than 1 in rain for 1-hr and 2-hr storms; less than 1.5 in for 3-hr and 4-hr storms.

     Heavy - 1 in or more 1- and 2-hr storms; 1.5 in or more for 3- and 4-hr storms.

3. Medium Duration $6 \text{ hr} \leq D \leq 18$ hr (Hourly Data)

   - Preceded and followed by at least 6 hr of zero rainfall
   - At least 0.5 in cumulated rainfall volume

4. Long Duration $D < 18$ hr (Hourly Data)

   (Same as in 3)

Construction of Design Curves

The selected storms were first hand-checked for anomalies before being entered into computer data files. A computer program was then written to process all the storm data to obtain cumulative percentages of total rainfall at 10 time percentage intervals (5% for the very short duration storms). The cumulative values at each 10% of time were then sorted using a computer program to produce a file containing ranked cumulative rainfall percentages at each 10% of total time division. The ranked data were used to generate mass rainfall curves at selected probability levels. Mean curves (taken at the 50% probability level) were then obtained for each category of storms.

Unlike the temporal distribution for medium to long duration storms (6 hr and up), the dimensionless rainfall mass curves for short duration storms (less than 6 hr) exhibited a significant regional difference as well as a dependence on storm duration. The results suggest the following:

- For storms with durations of 6 hr or longer, one statewide design curve would be adequate, as no significant difference in rainfall temporal distributions based on region or duration was found. As can be seen in Figure 17, the mass curves for the two duration category storms are almost identical.

- For storms with short durations (between 1 and 6 hr), and also very short durations (between 10 minutes and 1 hour), regional design curves are needed. As shown in Figure 18, the mass rainfall curve for the very short duration storms has a much steeper rise as compared to that of the short duration storms, which indicates a concentration of rainfall volume during early stages of very short duration storms. A regional difference was also evident when mass curves for the piedmont and mountain regions were compared. For lack of data, mass curves for the coastal region were not developed.

- All the mean rainfall mass curves are shown in Figure 19 for comparison. The longer duration storms show a fairly even distribution of rainfall amount over the duration, with the heaviest rainfall being near the middle. As storm duration decreases, more rainfall accumulates during the early stages of the storm. For the very short duration storms, on the average more than 80% of the total rainfall accumulates during the first half of the storm.

- Steeper rainfall mass curves were obtained for the piedmont region as compared to those of the mountain region. For the coastal region, it would be reasonable to apply the piedmont rainfall mass curves until enough data are available for developing coastal region curves.

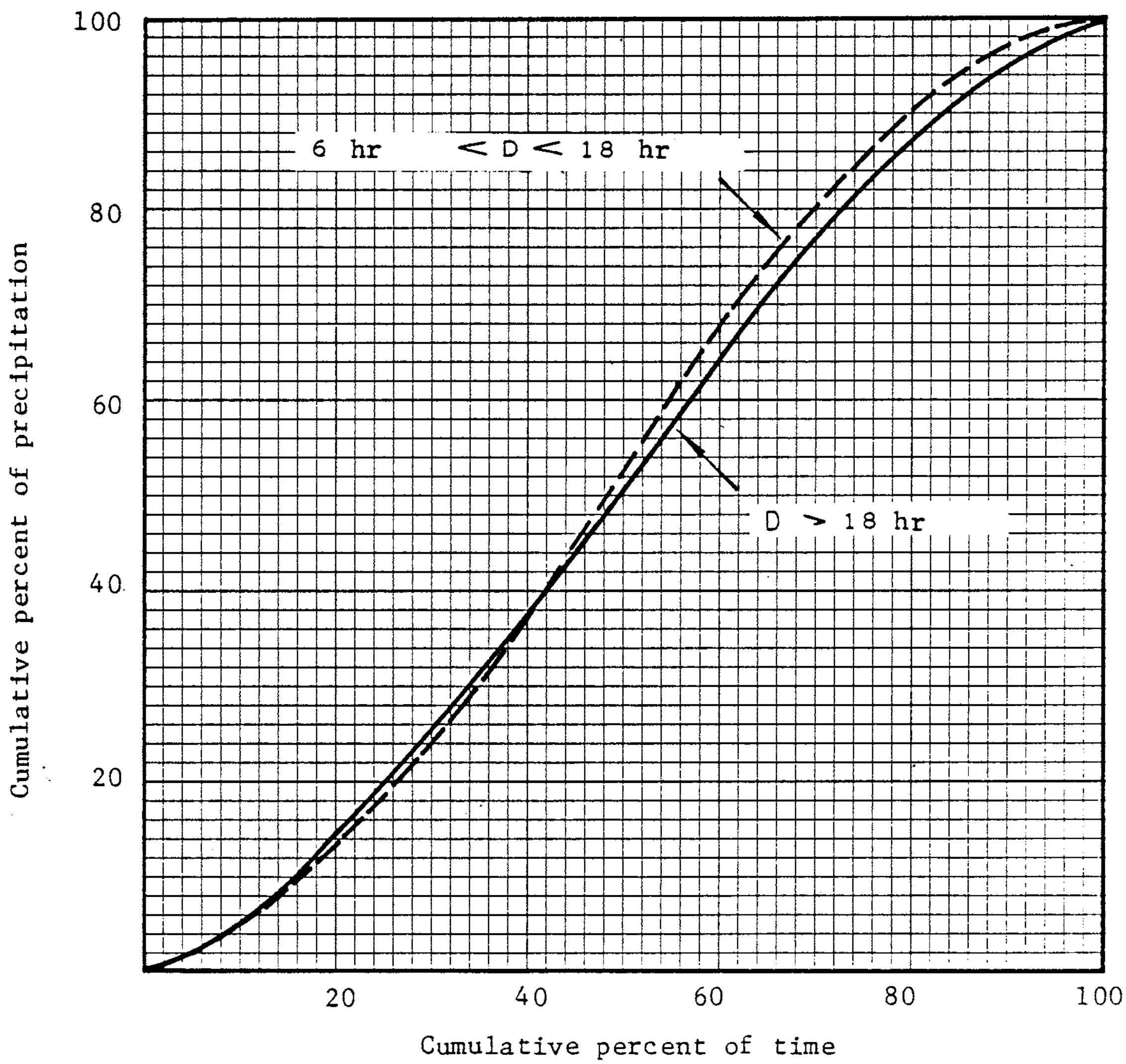


Figure 17. Statewide mean dimensionless curve for storms.

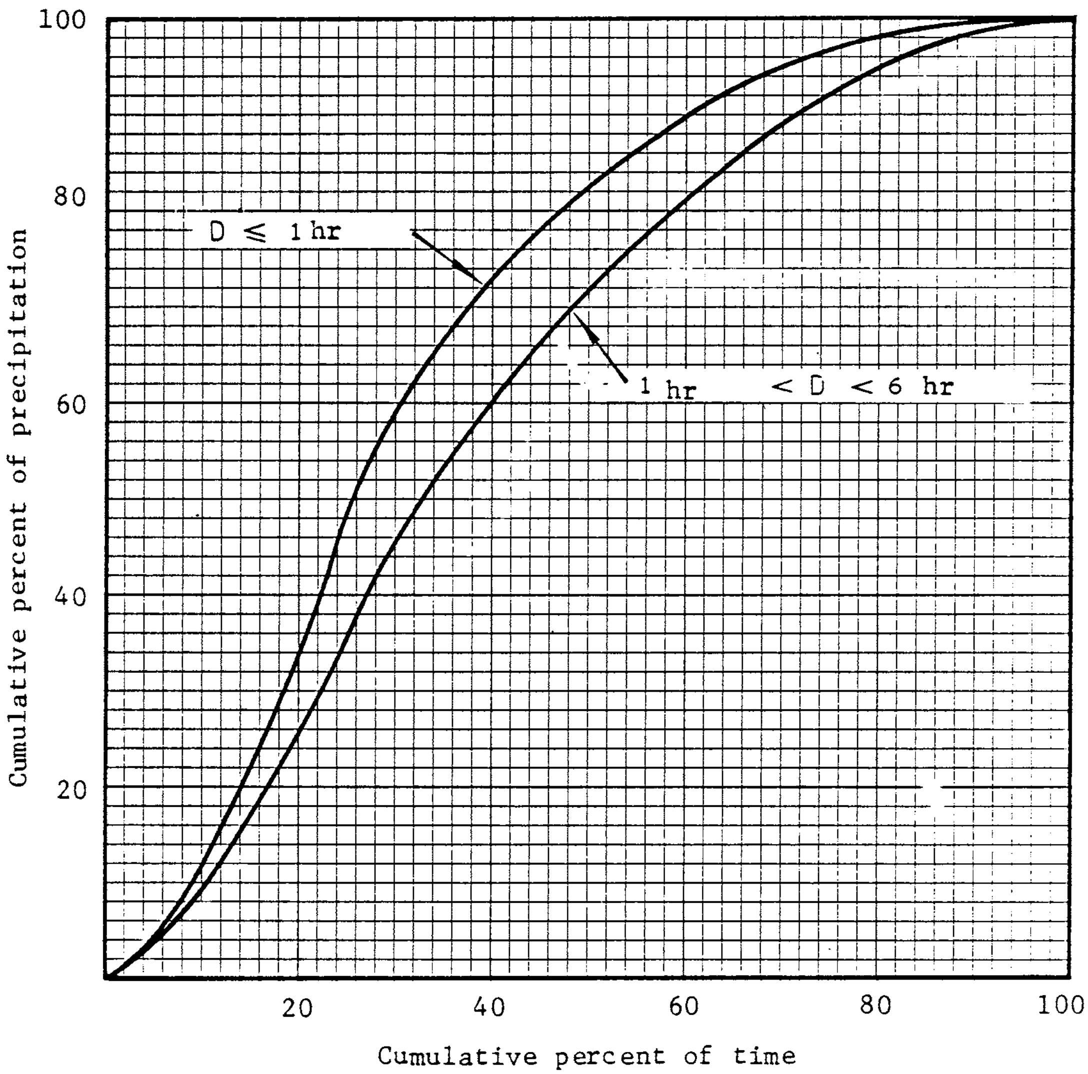
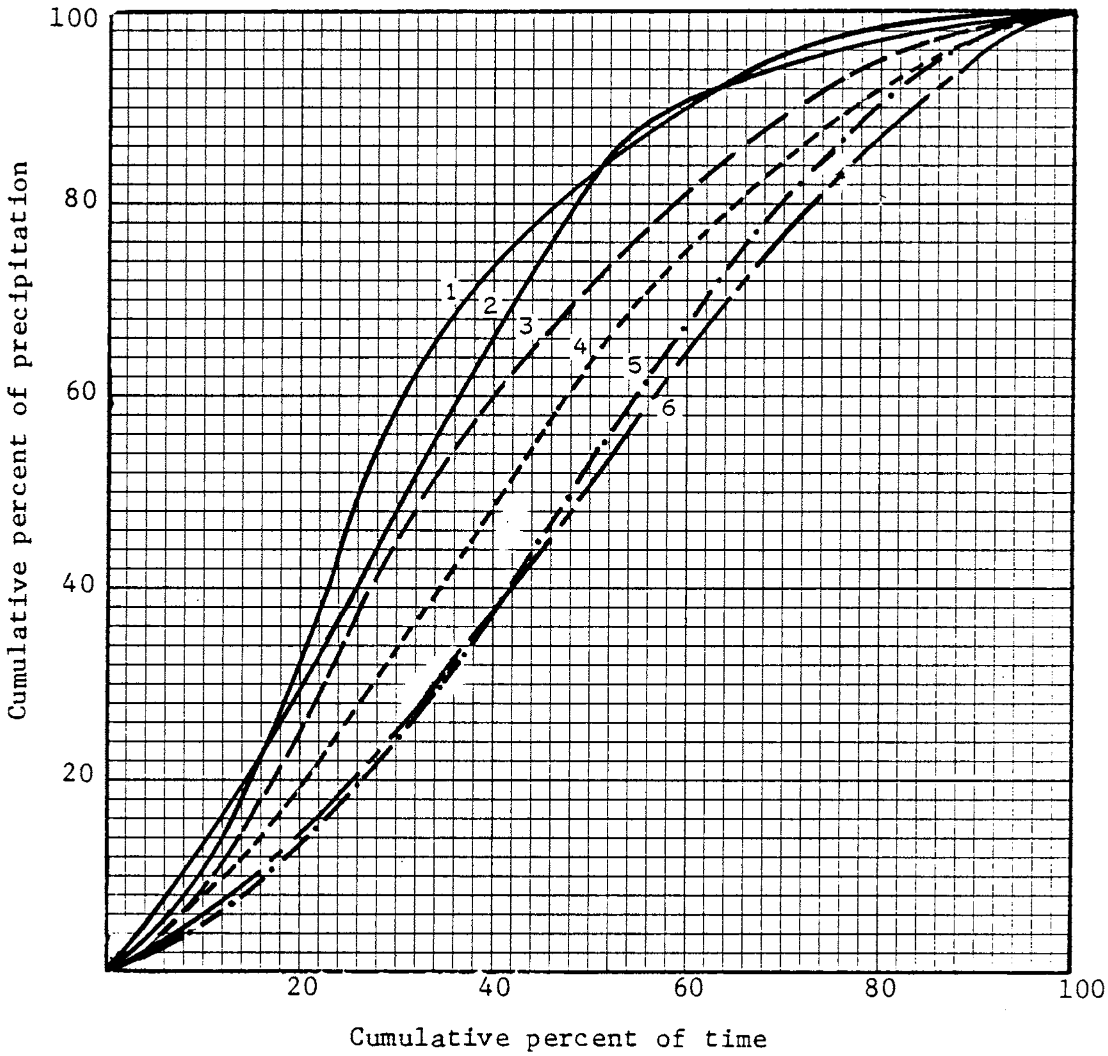


Figure 18. Mean dimensionless mass curve for storms — piedmont region.



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 19. Mean dimensionless mass curve for storms.

The entire set of design curves is shown in Figures 20 through 25, with the mean curves also plotted. It should be noted that the 10% curve represents the accumulated rainfall amounts in percentages of the total at certain times during the storm which are exceeded by 10% of all storms. On the other hand the 90% curve gives the amounts exceeded by 90% of all storms. These "envelop" curves permit the user flexibility to choose the design storm hyetograph. He may choose to select the mean curve or the 10% curve and compare the magnitudes of the design peak flows resulting from the two hyetographs.

To enhance clarity in reading the design curves, large graphs of these curves (Figures 20 through 25) have been prepared and are available upon request.

Derivation of Equations for the Design Curves

The design equations were developed using 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. The program uses a least-squares fit method and requires a user supplied FORTRAN subroutine and FORTRAN function. The subroutine defines the number of fitting parameters and the number of independent variables. The function is used to define the equation to be used in the curve fitting.

Since all the design curves giving the temporal rainfall distributions exhibit a double curvature, it was necessary to develop two equations for each curve. The cutoff point was chosen in the vicinity of the change in curvature.

The least-squares fit to the distribution function was slightly modified to assure a continuity at the cutoff point. This means that either equation can be used to determine the ordinate (cumulative percentage of rainfall) at this point.

The design equations giving the temporal rainfall distributions for storm durations of 6 to 18 hr and 18 hr and longer are presented in Tables 6 through 8 for the 10%, 50%, and 90% probability curves, respectively. These equations correspond to the design curves shown in Figures 20 and 21. As for the design curves for short and very short duration storms shown in Figures 22 through 25, the corresponding design equations are presented in Tables 9 through 14.

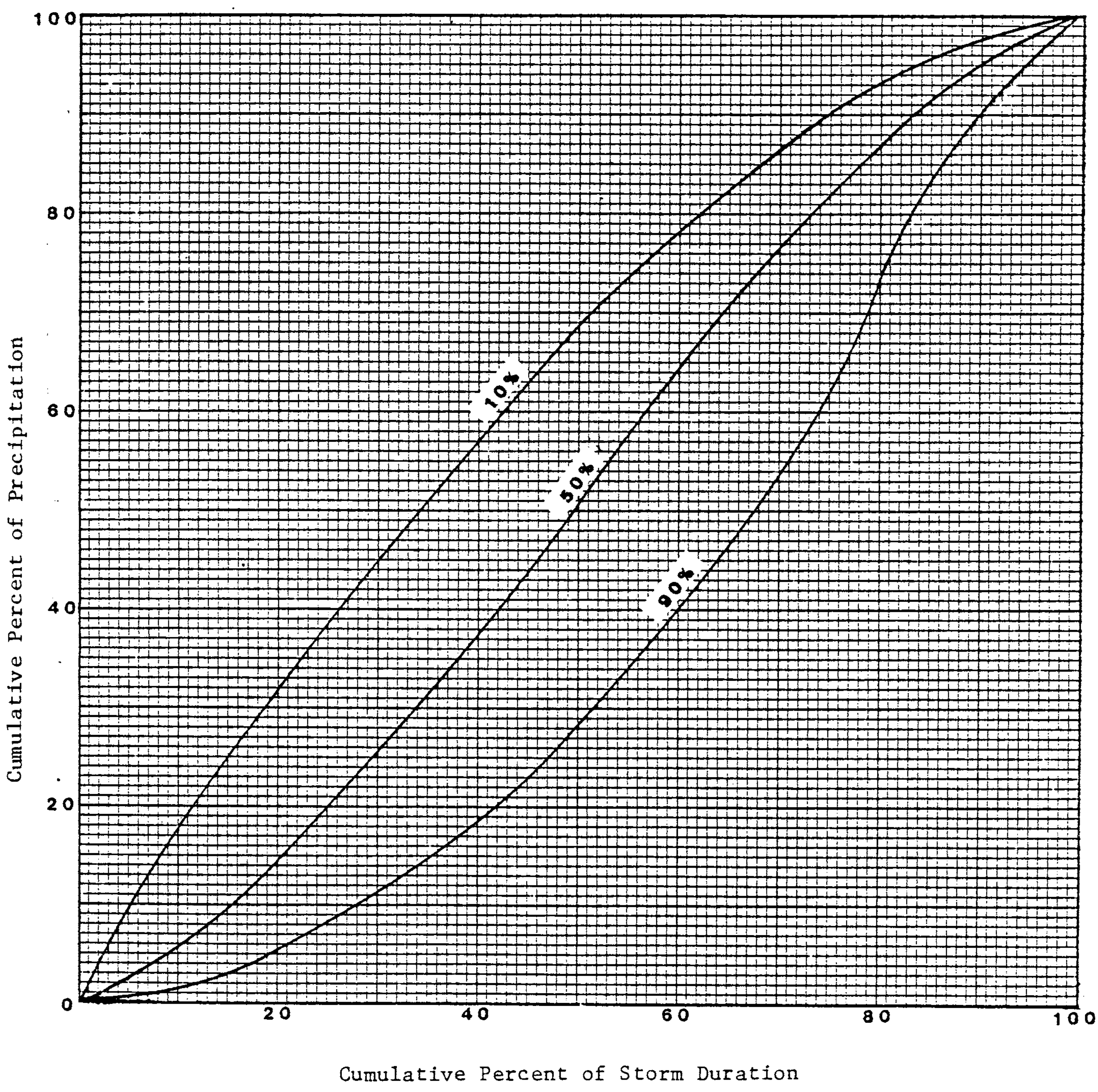


Figure 20. Time distribution of storms, duration > 18 hr.

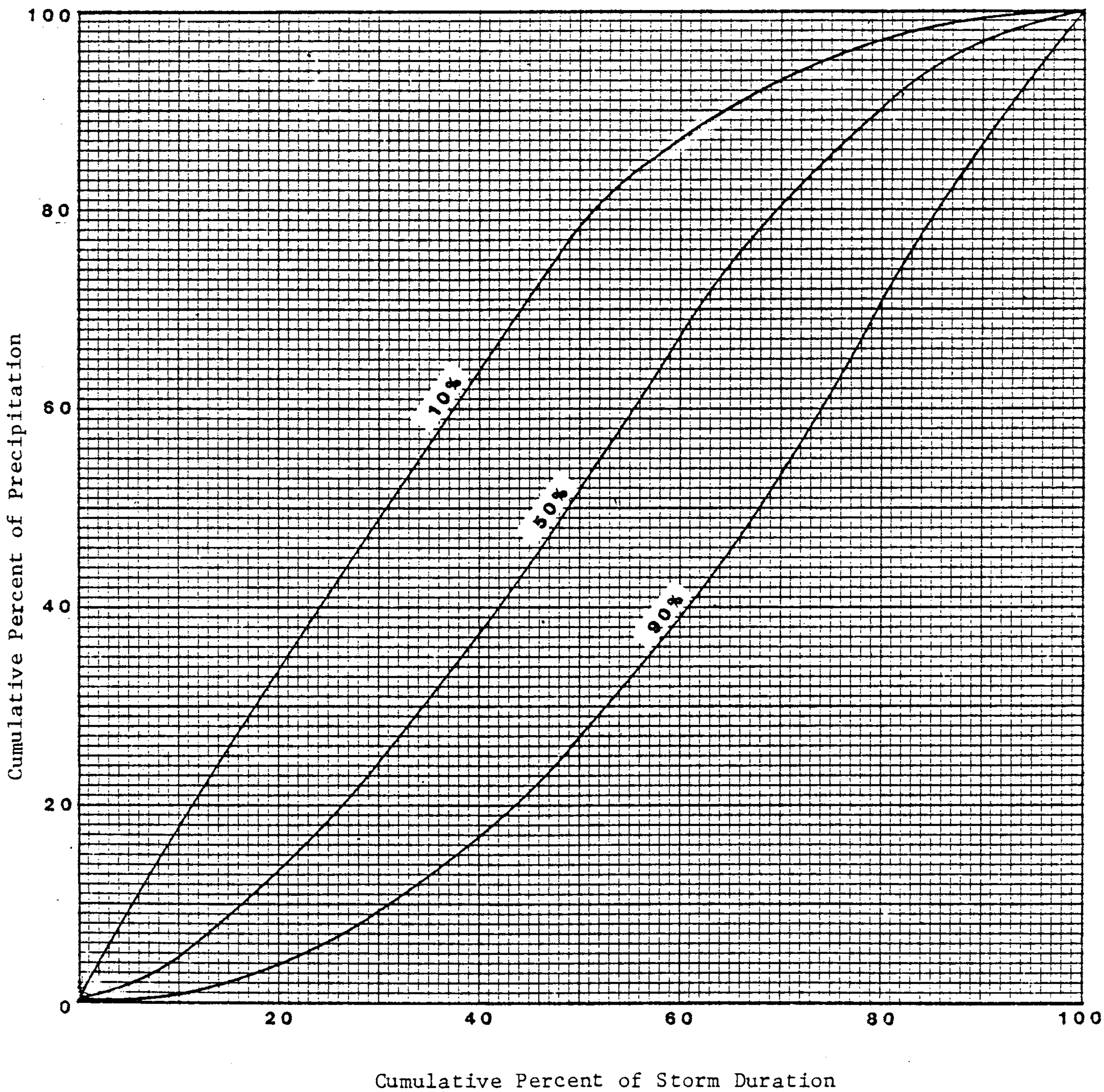


Figure 21. Time distribution of storms, 6 hr ≤ duration < hr.

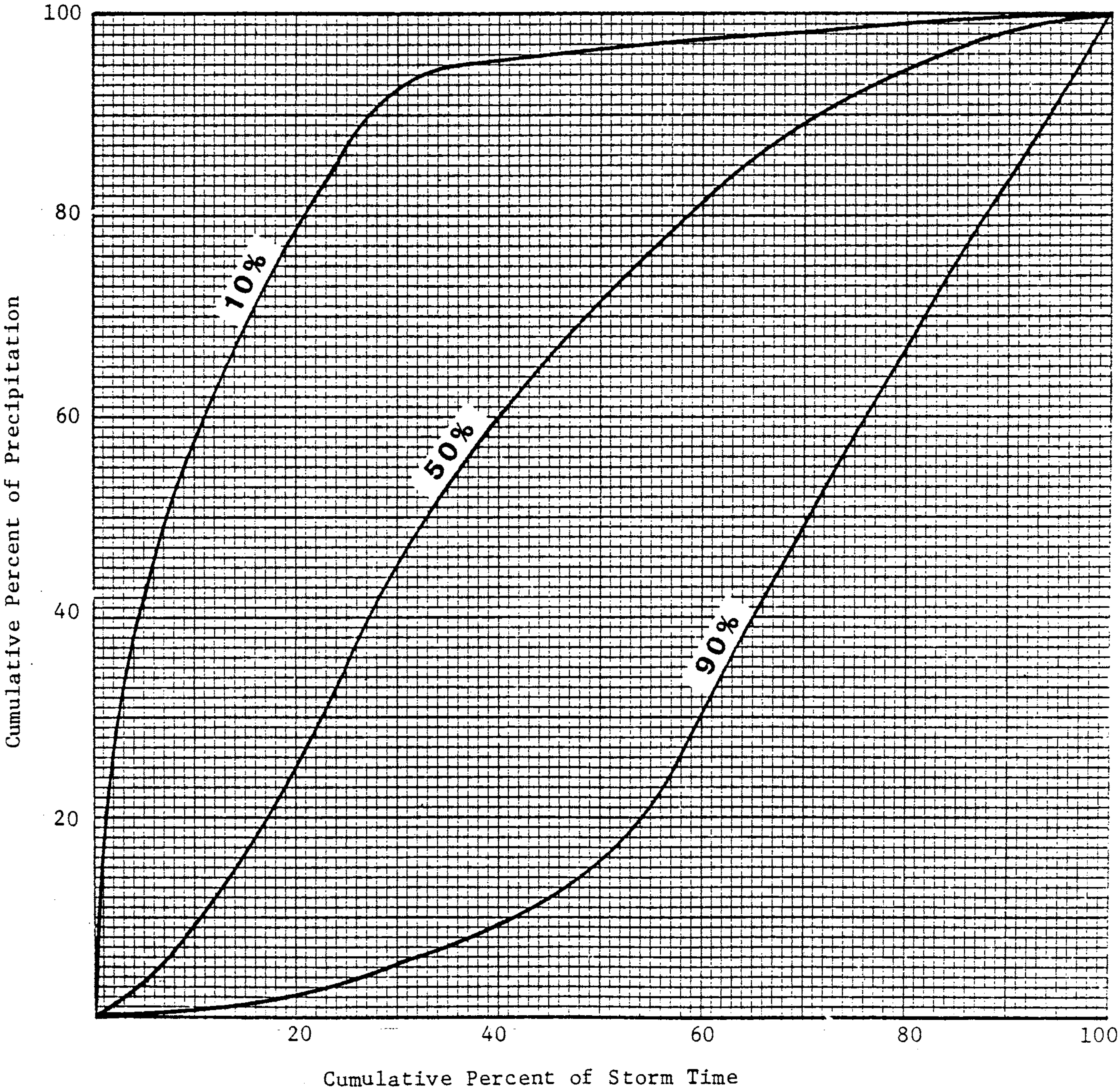


Figure 22. Time distribution of storms, piedmont region
1 hr < duration < 6 hr.

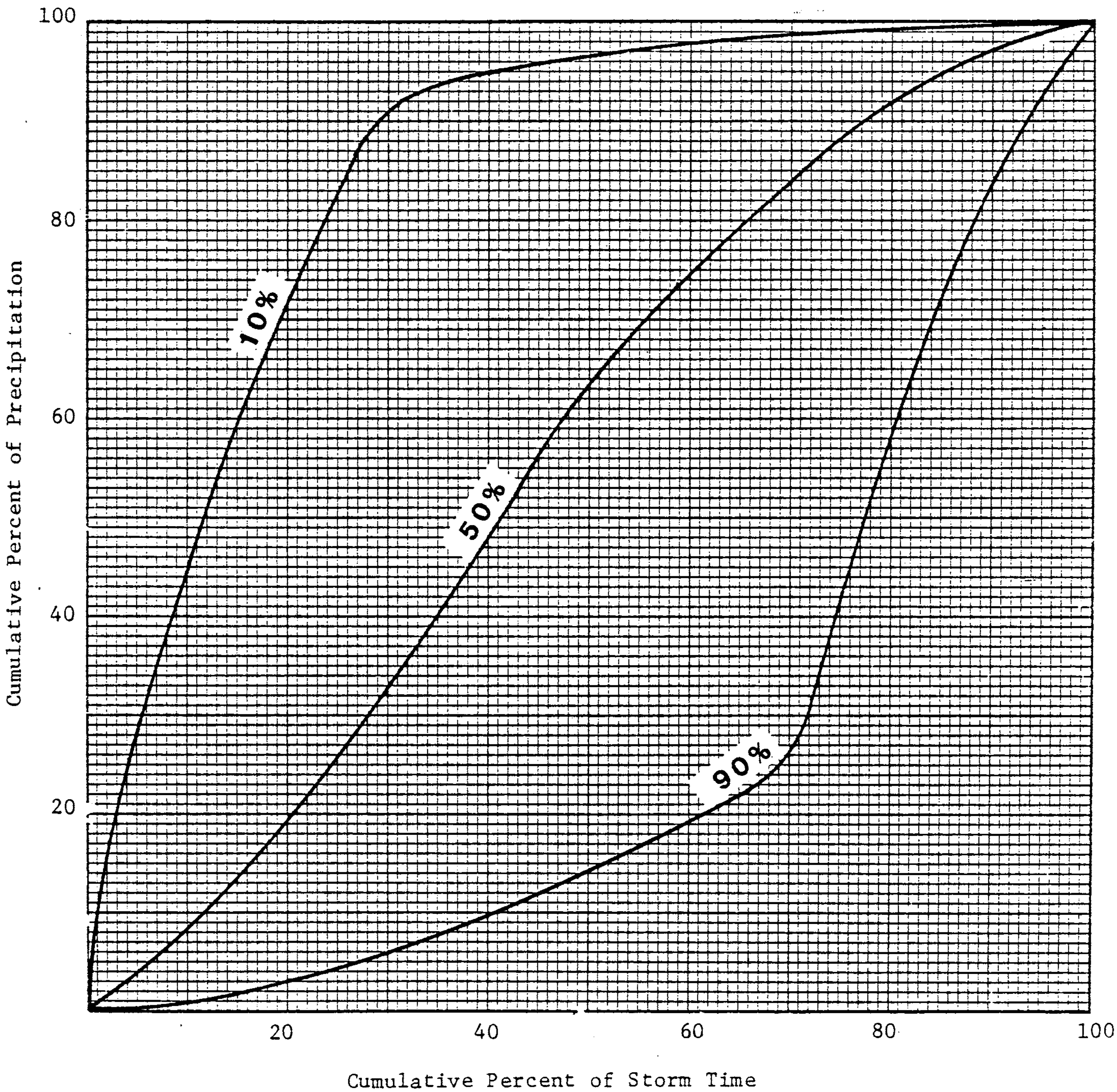


Figure 23. Time distribution of storms, mountain region
1 hr < duration < 6 hr.

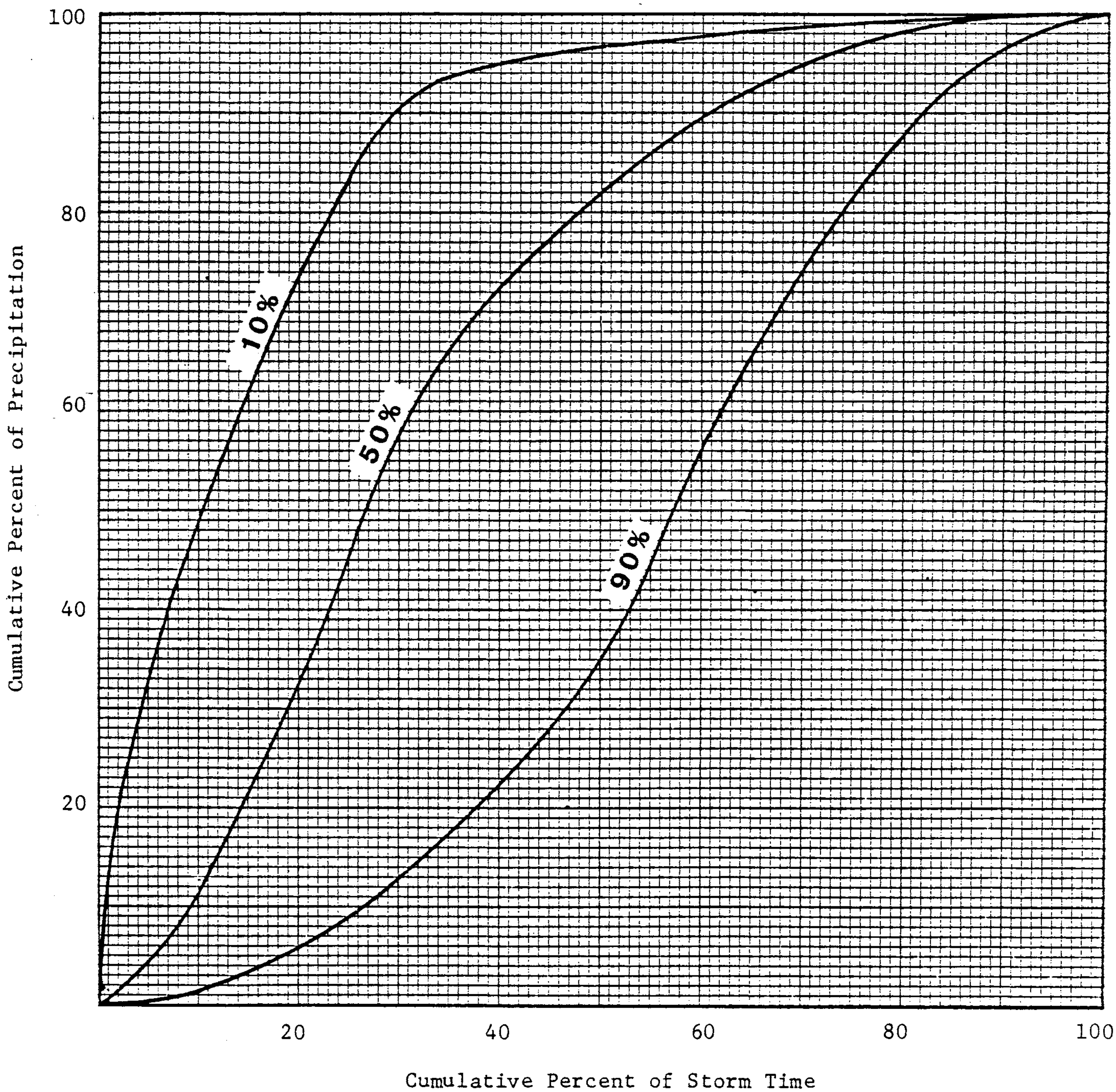


Figure 24. Time distribution of storms, piedmont region
Duration $\leq$ 1 hr

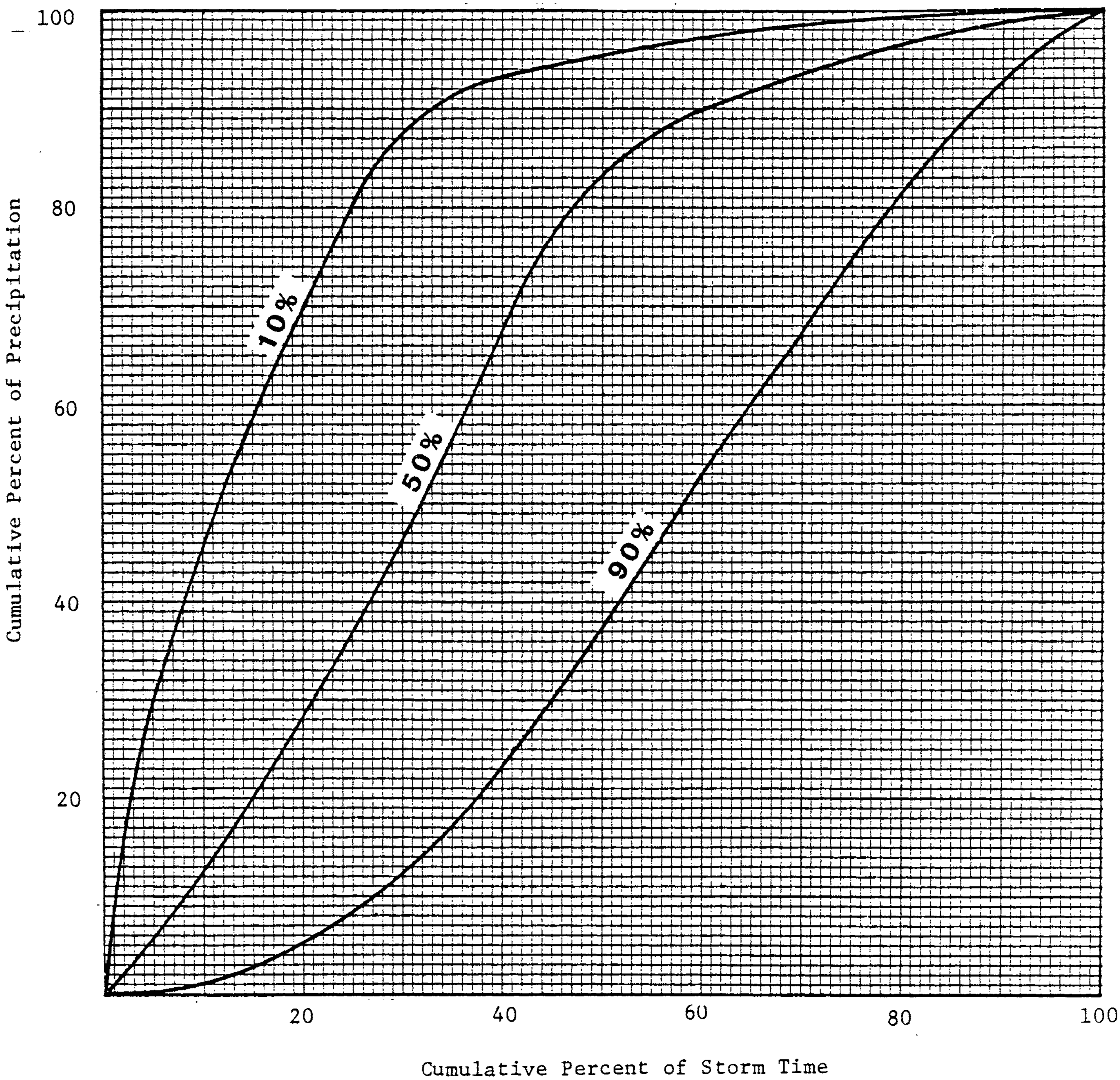


Figure 25. Time distribution of storms, mountain region
Duration < 1 hr.

Table 6

Equations for Temporal Rainfall Distribution — 10% Probability Distribution

Storm Duration	$0 \leq x \leq 50$	$50 \leq x \leq 100$
$6 \text{ hr} \leq D \leq 18 \text{ hr}$	$y = 2.017\, X^{0.937}$	$y = 100 - 0.004\, (100-x)^{2.192}$
$18 \text{ hr} < D$	$y = 2.537\, x^{0.844}$	$y = 100 - 0.047\, (100-x)^{1.660}$

General forms of the equations

For $0 \leq x \leq 50$ $\quad Y = ax^{b}$

For $50 \leq x \leq 100$ $\quad Y = 100 - c\, (100-x)^{d}$

where

y = cumulative percentage of precipitation

x = cumulative percentage of storm duration

a,b,c,d are regression coefficients

Table 7

Equations for Temporal Rainfall Distribution — 50% Probability Distribution

Storm Duration	$0 \leq x \leq 50$	$50 \leq x \leq 100$
6 hr $\leq$ D $\leq$ 18 hr	$y = 0.154\ x^{1.488}$	$y = 100 - 0.059(100-x)^{1.712}$
18 hr <D	$y = 0.249\ x^{1.359}$	$y = 100 - 0.1662(100-x)^{1.455}$

General formsof the equations

For $0 \leq x \leq 50$ $\quad y = ax^b$

For $50 \leq x \leq 100$ $\quad y = 100-c(100-x)^d$

where

y = cumulative percentage of precipitation

x = cumulative percentage of storm duration

a,b,c,d are regression coefficients

Table 8

Equations for Temporal Rainfall Distribution — 90% Probability Distribition

Storm Duration	$0 \leq x \leq 70$	$70 \leq x \leq 100$
6 hr $\leq$ D $\leq$ 18 hr	$y = 0.0086x^{2.057}$	$y = 100 - 0.992(100-x)^{1.130}$
18 hr <D	$y = 0.020x^{1.857}$	$y = 100 - 0.392(100-x)^{1.405}$

General forms of the equations

For $0 \leq x \leq 70$ $\quad y = ax^{b}$

For $70 \leq x \leq 100$ $\quad y = 100-c(100-x)^{d}$

where

y = cumulative percentage of precipitation

x = cumulative percentage of storm duration

a,b,c,d are regression coefficients

Table 9

Equations for Temporal Rainfall Distribution

1 hr <Duration<6 hr

10% Probability Distribution

Region	$0 \leq x \leq 30$	$30 \leq x \leq 100$
Piedmont	$y = 19.67\ x^{0.460}$	$y = 100 - 0.024(100-x)^{1.30}$
Mountain	$y = 9.557\ x^{0.669}$	$y = 100 - 0.00225(100-x)^{1.89}$

General forms of the equations

For $0 \leq x \leq 30$ $\quad y = ax^{b}$

For $30 \leq x \leq 100$ $\quad y = 100 - c(100-x)^{d}$

where

y = cumulative percentage of precipitation

x = cumulative percentage of storm duration

a,b,c,d are regression coefficients

Table 10

Equations for Temporal Rainfall Distribution — 50% Probability Distribution

1 hr < Duration < 6 hr

Region	$0 \leq x \leq 30$ (1)	$30 \leq x \leq 100$ (2)
Piedmont	$y = 0.336\ x^{1.451}$	$y = 100 - 0.0187\ (100 - x)^{1.8723}$

Region	$0 \leq x \leq 50$ (1)	$50 \leq x \leq 100$ (2)
Mountain	$y = 0.4454.\ x^{1.270}$	$y = 100 - 0.0688\ (100-x)^{1.60}$

For (1) $y = ax^{b}$

For (2) $y = 100 - c\ (100-x)^{d}$

where

y = cumulative percentage of precipitation

x = cumulative percentage of storm duration

a,b,c,d are regression coefficients.

Table 11

Equations for Temporal Rainfall Distribution — 90% Probability Distribution

1 hr < Duration < 6 hr

Region	$0 \leq x \leq 50$ (1)	$50 \leq x \leq 100$ (2)
Piedmont	$y = 0.0129\ x^{1.787}$	$y = 100 - 1.505\ (100-x)^{1.034}$

Region	$0 \leq x < 70$ (1)	$70 \leq x \leq 100$ (2)
Mountain	$y = 0.0195\ x^{1.684}$	$y = 100 - 0.628\ (100-x)^{1.406}$

For (1) $\quad y = ax^{b}$

For (2) $\quad y = 100-c\ (100-x)^{d}$

where

y = cumulative percentage of precipitation

x = cumulative percentage of storm duration

a,b,c,d are regression coefficients.

Table 12

Equations for Temporal Rainfall Distribution — 50% Probability Distribution

Duration $\leq$ 1 hr

Region	$0 \leq x \leq 30$ (1)	$30 \leq x \leq 100$ (2)
Piedmont	$y = 0.394\ x^{1.473}$	$y = 100 - 0.00107\ (100-x)^{2.484}$

Region	$0 \leq x \leq 50$ (1)	$50 \leq x \leq 100$ (2)
Mountain	$y = 0.780\ x^{1.202}$	$y = 100 - 0.0313\ (100-x)^{1.561}$

For (1) $y = ax^b$

For (2) $y = 100 - c\ (100-x)^d$

where

y = cumulative percentage of precipitation

x = cumulative percentage of storm duration

a,b,c,d are regression coefficients.

Table 13

Equations for Temporal Rainfall Distribution

Duration $\leq$ 1 hr

10% Probability Distribution

Region	$0 \leq x \leq 30$	$30 \leq x \leq 100$
Piedmont	$y = 12.83\, x^{0.5823}$	$y = 100 - 0.0007\, (100 - x)^{2.168}$
Mountain	$y = 10.888\, x^{0.621}$	$y = 100 - 0.00048\, (100 - x)^{2.34}$

General forms of the equations

for $0 \leq x\ 30$ $\qquad y = ax^{b}$

for $30 \leq x \leq 100$ $\qquad y = 100 - c\, (100 - x)^{d}$

where

y = cumulative percentage of precipitation

x = cumulative percentage of storm duration

a,b,c,d are regression coefficients.

Table 14

Equations for Temporal Rainfall Distribution

Duration $\leq$ 1 hr

90% Probability Distribution

Region	$0 \leq x \leq 50$	$50 \leq x \leq 100$
Piedmont	$y = 0.0148\ x^{1.982}$	$y = 100 - 0.0477\ (100-x)^{1.851}$
Mountain	$y = 0.00933\ x^{2.119}$	$y = 100 - 0.316\ (100-x)^{1.353}$

General forms of the equations

for $0 \leq x \leq 50$ $\quad y = ax^{b}$

for $50 \leq x \leq 100$ $\quad y = 100 - c\ (100-x)^{d}$

where

y = cumulative percentage of precipitation

x = cumulative percentage of storm duration

a,b,c,d are regression coefficients.

EXAMPLE I

The illustrative example below shows how to develop the design hyetograph using either the cumulative mass curve or the equations.

Piedmont Region

Assume: Duration of the design storm = 1 hr

Design return period = 25 yr

The rainfall depth is determined from TP-40 (U.S. Weather Bureau Technical Paper #40 "Rainfall Frequency Atlas of the U.S. for Durations from 30 min to 24 Hours and Return Period from 1 to 100 Years"). We obtain:

Design rainfall depth = 2.6 in.

The design hyetograph can be developed using either the design curves or equations, or the "Slope-Intensity" method, as illustrated below.

A) <u>Design Curves or Equations</u> - Assumption: Uniform rainfall intensity during the time increment chosen.

Procedure: Shown in Table 15.

Table 15

Design Hyetograph Obtained from Desing Curves or Equations

Cumulative % of time (1)	Time (mm) (2)	Cumulative % of rainfall (3)*	Cumulative rainfall (in) (4)*	Incremental rainfall (in) (5)*	Intensity of precipitation (in/hr) (6)*
0	0	0	0	0.300	3.00
10	6	11.7	0.300	0.545	5.45
20	12	32.5	0.845	0.689	6.89
30	18	59.0	1.534	0.338	3.38
40	24	72.0	1.872	0.265	2.65
50	30	82.2	2.137	0.198	1.98
60	36	89.8	2.335	0.135	1.35
70	42	95.0	2.470	0.080	0.80
80	48	98.2	2.550	0.040	0.40
90	54	99.7	2.590	0.010	0.10
100	60	100.0	2.600		

(3)* Cumulative rainfall (in). It can be read directly from the 50% temporal distribution curve for the piedmont region and for duration $\leq$ 1 hr (Figure 24), or using the corresponding equations (Table 12). For some design curves there is at the cutoff point a slight difference between the cumulative percentage of rainfall from the curve and the cumulative percentage of rainfall from the equation, because some curves are smoothed at the separation point.

(4)* Cumulative rainfall (in). (Total rainfall depth) x (cumulative % of rainfall).

(5)* Incremental rainfall (in). (Δi). This is the difference of cumulative rainfall at tine N-1.

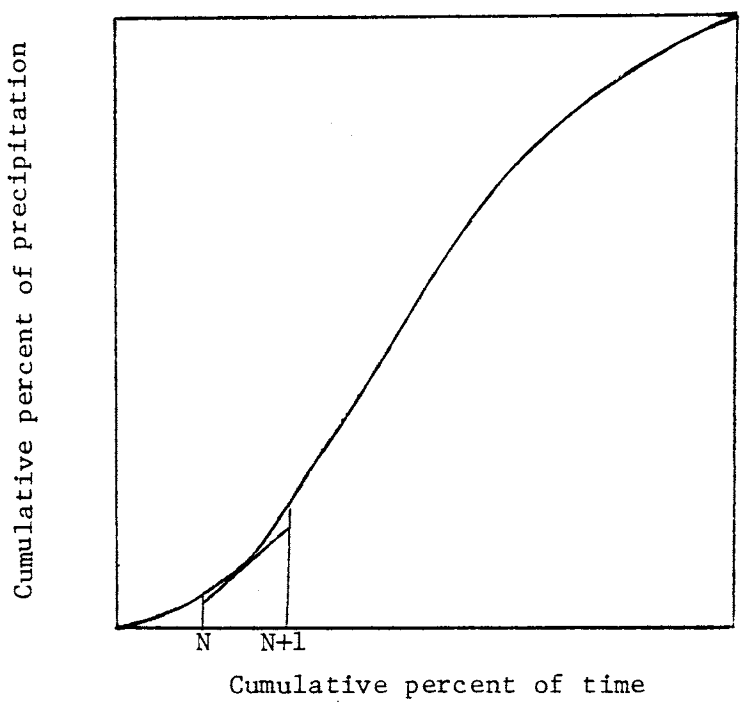
(6)* Intensity (in/hr). Can be computed from the incremental rainfall, Δi, and the incremental time Δt in min.

B) <u>Slope-Intensity Method Using Design Equations</u>

For our example the equations are for $D \leq 1$ hr and the piedmont region. From Table 11 we obtain the equations

$$Y = 0.394\ x^{1.473} \quad \text{for } 0 \leq x \leq 30$$

$$Y = 100 - 0.00107\ (100-x)^{2.484} \quad \text{for } 30 \leq x \leq 100$$



There the intensity of rainfall between time N and time N+1 is the slope of the tangent at the mid-point.

EXAMPLE II

Example II illustrates the use of slope of the rainfall mass curve to obtain intensity. Here the intensity of rainfall between time N and time N+1 is the slope of the tangent at the midpoint. The slope is the derivative dy/dx at this midpoint.

For $0 \leq x \leq 230$ $\qquad Y = 0.394\ x^{1.473}$

(Y = cumulative % of rainfall, X = cumulative % of time.)

$dy/dx = y' = 1.473 \times 0.394\ x^{1.473-1}$

$y' = 0.5804\ x^{0.473}$

To evaluate the intensity of rainfall between 0 and 10% of the cumulative time and the midpoint is 5%, plug 5 into the above equation.

$y' = 0.5804\ 5^{0.473} = 1.243$

This is a "dimensionless intensity" since x and y are dimensionless.

To get the intensity in in/hr, multiply 1.243 by the ratio of total rainfall/duration.

Total rainfall = 2.6 in.

Duration = 1 hr and Ratio = 2.6

Intensity between 0 and 10% = 2.6 x 1.243 = 3.23 in/hr. With the method described in A, 3 in/hr is obtained for the same time interval. The slope intensity method is a more accurate one and much more straightforward.

X	Midpoint	Dimensionless Slope	Intensity (in/hr)
0-10	5	1.243	3.230
10-20	15	2.089	5.430
20-30	25	2.660	6.910

For $30 \leq x \leq 100$, the equation is $y = 100 - .0.00/07\ (100-x)^{2.484}$

$dy/dx = y' = -(-0.00/07.2.484)(100-x)^{2.484-1}$

$y' = 0.00265(100 - x)^{1.484}$

X	Midpoint	Dimensionless Slope	Intensity (in/hr)
30- 40	35	1.290	3.370
40- 50	45	1.010	2.630
50- 60	55	0.750	1.960
60- 70	65	0.518	1.350
70- 80	75	0.315	0.820
80- 90	85	0.147	0.380
90-100	95	0.029	0.075

This method is straightforward and more accurate since one needs only to derive the appropriate equation, get the dimensionless slope corresponding at each time increment, and multiply this dimensionless slope by the ratio of the total rainfall over duration. A flowchart describing the procedure for applying this method is shown in Figure 27.

Figure 28 depicts the design hyetographs obtained by the two methods described above. The slope-intensity method gives a slightly higher rainfall intensity during the early stages of the storm.

Comparison of Virginia Design Curves with the SCS and the FHWA Curves

Comparison with the SCS Type II Curve

A preliminary comparison between the average Virginia rainfall temporal distribution and that described by the SCS type II curve was made earlier with the hourly data. As shown in Figure 15, the 6-hr rainfall mass curve derived from the average 24-hr Virginia curve is markedly different from the 6-hr curve derived from the SCS type II 24-hr rainfall curve. The SCS curve rises slowly during the early stages of the storm and increases sharply towards the middle of the storm duration. On the other hand, the Virginia data show a more rapid rise in the first part of the storm and a milder increase at the mid-portion of the storm duration.

Similar observations were made when comparing the SCS type II curves with the Virginia design curves derived from analyzing the entire data set; namely, the hourly, 15-min, and 1-min rainfall data.

In Figure 29, the SCS type II curves for 24-hr and 6-hr duration storms (obtained by using the most intense 6-hr rainfall from the 24-hr curve) are plotted against the corresponding Virginia curves. Again, the Virginia curves show higher concentrations of rainfall volume during the early part of the storm and less in the middle portion than do the SCS type II curves.

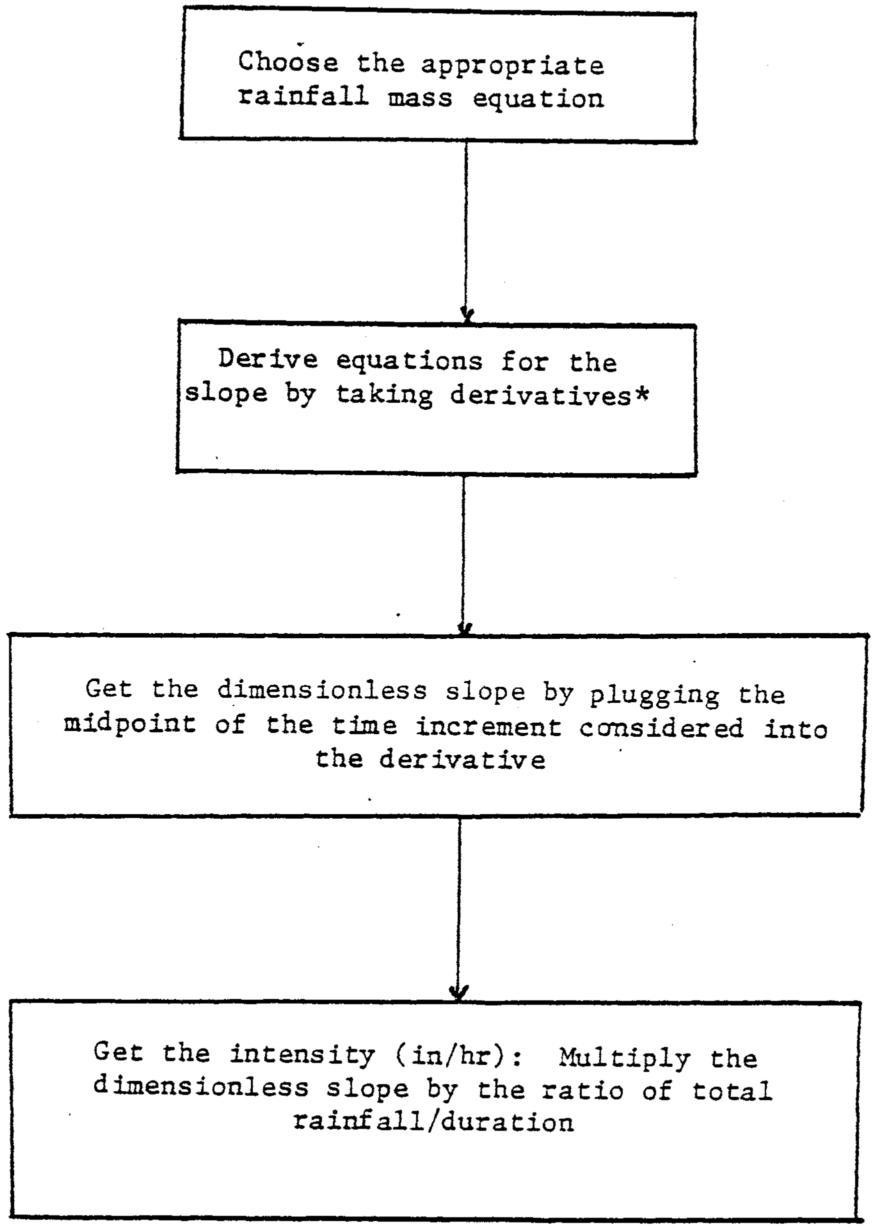


Figure 27. Procedure for applying the slope-intensity method.

* $y = a.x^b$ $\qquad y' = \frac{dy}{dx} = a.b.x^{b-1}$

$y = 100-c(100-x)^d$ $\qquad y' = \frac{dx}{dx} = c.d\ (100-x)^{d-1}$

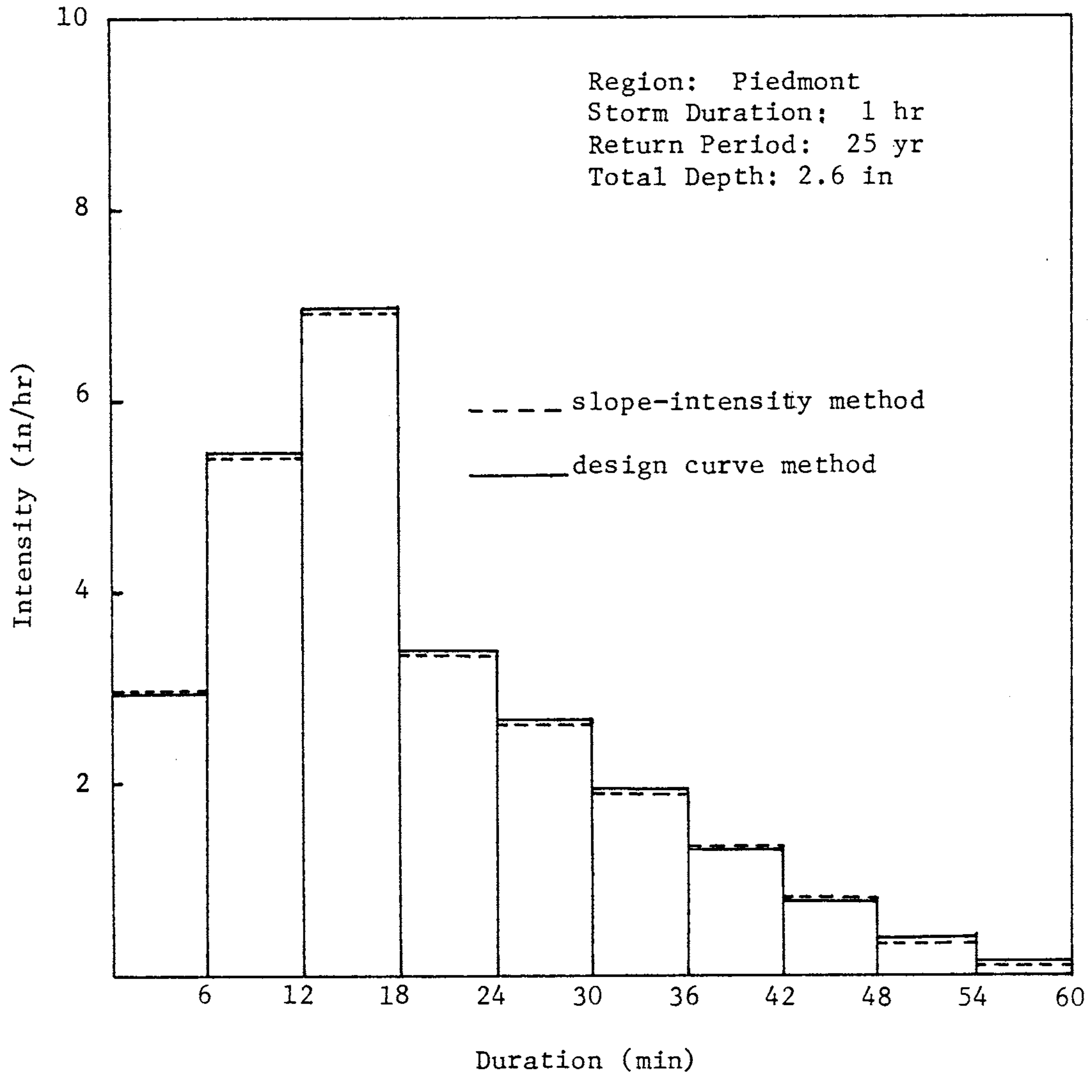


Figure 28. Example of derived design hyetographs.

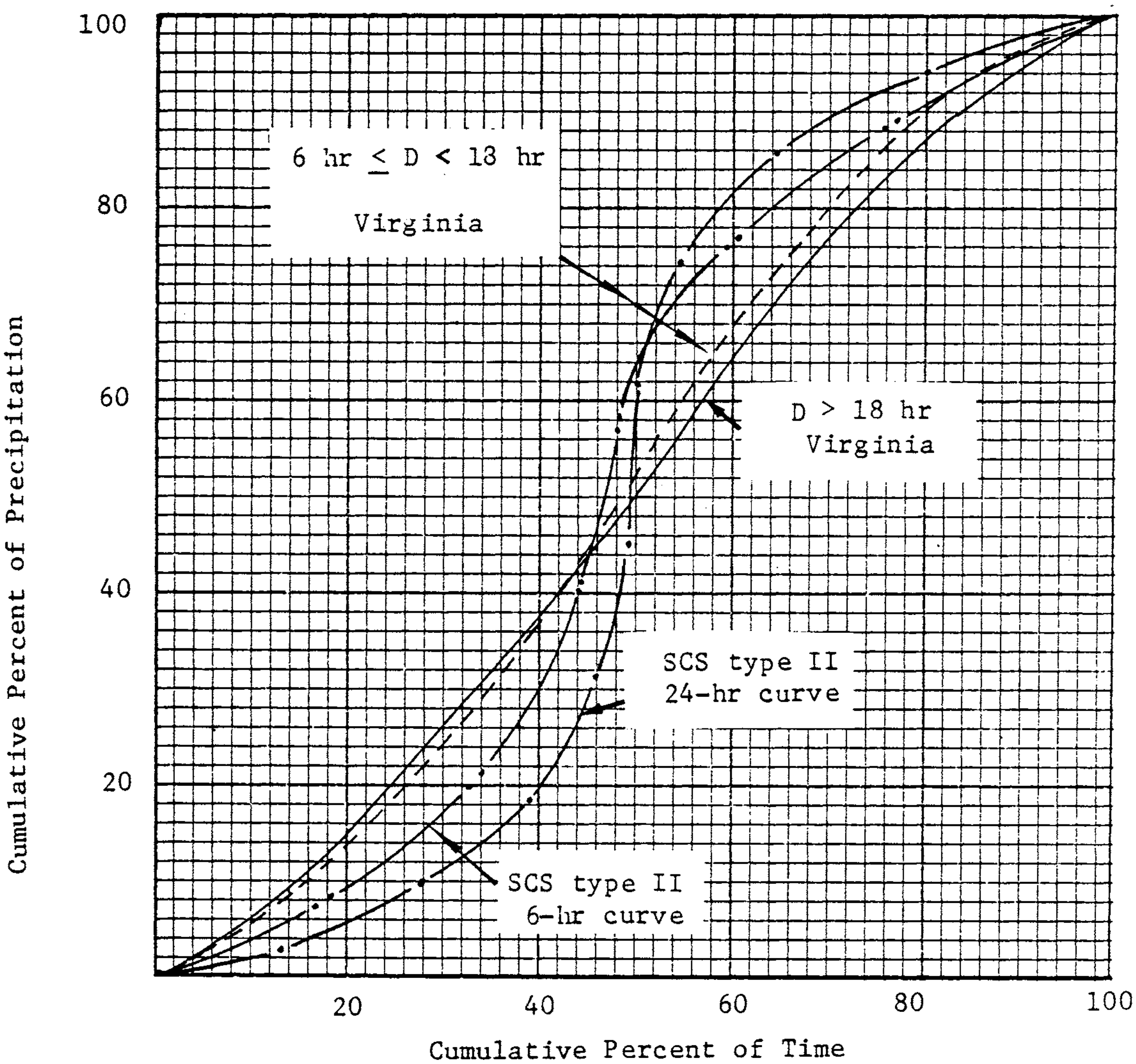


Figure 29. Comparison of Virginia rainfall curves with the SCS type II curves.

Table 16 lists the percent rainfall accumulation rates of the Virginia curves and the SCS type II curves for the 24-hr storm. Here, more than 30% of the total rainfall is seen to accumulate during the first 9 hr of the storm for the Virginia curve, whereas only 14% is estimated by the SCS type II curve. The difference between the two curves is smaller for the 6-hr storms.

Table 16

Comparison of Virginia Rainfall Cumulation Rate With the SCS Type II Rate

Hours	Cumulative Percent Rainfall, Virginia	Cumulative Percent Rainfall, SCS Type II
3	7	3
6	19	8
9	34	14
12	51	68
15	66	84
18	83	90
21	94	97
24	100	100

Hours	Cumulative Percent Rainfall, Virginia $6 \leq D < 18$	Cumulative Percent Rainfall, SCS Type II
1	10	7
2	28	20
3	52	68
4	76	82
5	93	91
6	100	100

Comparison with the FHWA Triangle Hyetographs

Yen and Chow (1983), in a report to the Federal Highway Administration (FHWA), reported results of statistical analyses of more than a quarter of a million rainstorms over three hundred locations in the United States. They proposed the use of triangular and trapezoidal hyetographs with "localized" parameters which can be obtained statistically.

They presented maps showing parameters for the triangular hyetograph for all parts of the United States. These parameter values were obtained by analyzing the moments of the aforementioned rainfall data, which included three sets from Virginia gaging stations.

Using parameter values suggested by Yen and Chow, a triangular hyetograph was constructed for the piedmont region in Virginia. Figure 30 shows the FHWA hyetograph for Virginia with the peak occurring at 30% of the rainfall duration. Since the FHWA method was designed basically for short duration storms, a Virginia hyetograph with a duration of 1 hr for the same region was plotted in the same figure for comparison.

The Virginia data indicate a storm peak after approximately 26% of the total duration, with the peak period having approximately 13% of the rainfall. The FHWA hyetograph indicates a lower, or 10%, peak rate with the peak occurring slightly later than the Virginia data indicate. The Virginia data also have a linear rise to the peak, but the decline is substantially curved, indicating that the decrease in intensity following the peak is more rapid than for the FHWA hyetograph.

Similar results were obtained when a 2-hr FHWA storm mass curve was compared with the corresponding Virginia curve (Figure 31).

Comparison with the Huff Hyetographs

As described earlier, significant differences were found between the Huff rainfall time distributions and those derived with Virginia hourly rainfall data. In general, the Virginia data showed more concentrations of storms in the second and third quartiles as opposed to concentrations in the first and second quartiles for the Illinois storms. Also, in comparisons of the dimensionless rainfall time distribution curves for medium to long duration storms (6 hr or longer), the Virginia curves indicated more accumulation of rainfall during the first half of the storm and a smaller rate of accumulation during the middle portion of the storm.

A comparison was made for the short (between 1- and 6-hr) and very short (less than 1-hr) duration storms. The Huff second quartile curves were chosen because they were found to closely resemble the Virginia curves as compared with other quartile curves. Figure 32 illustrates the second quartile Huff curves.

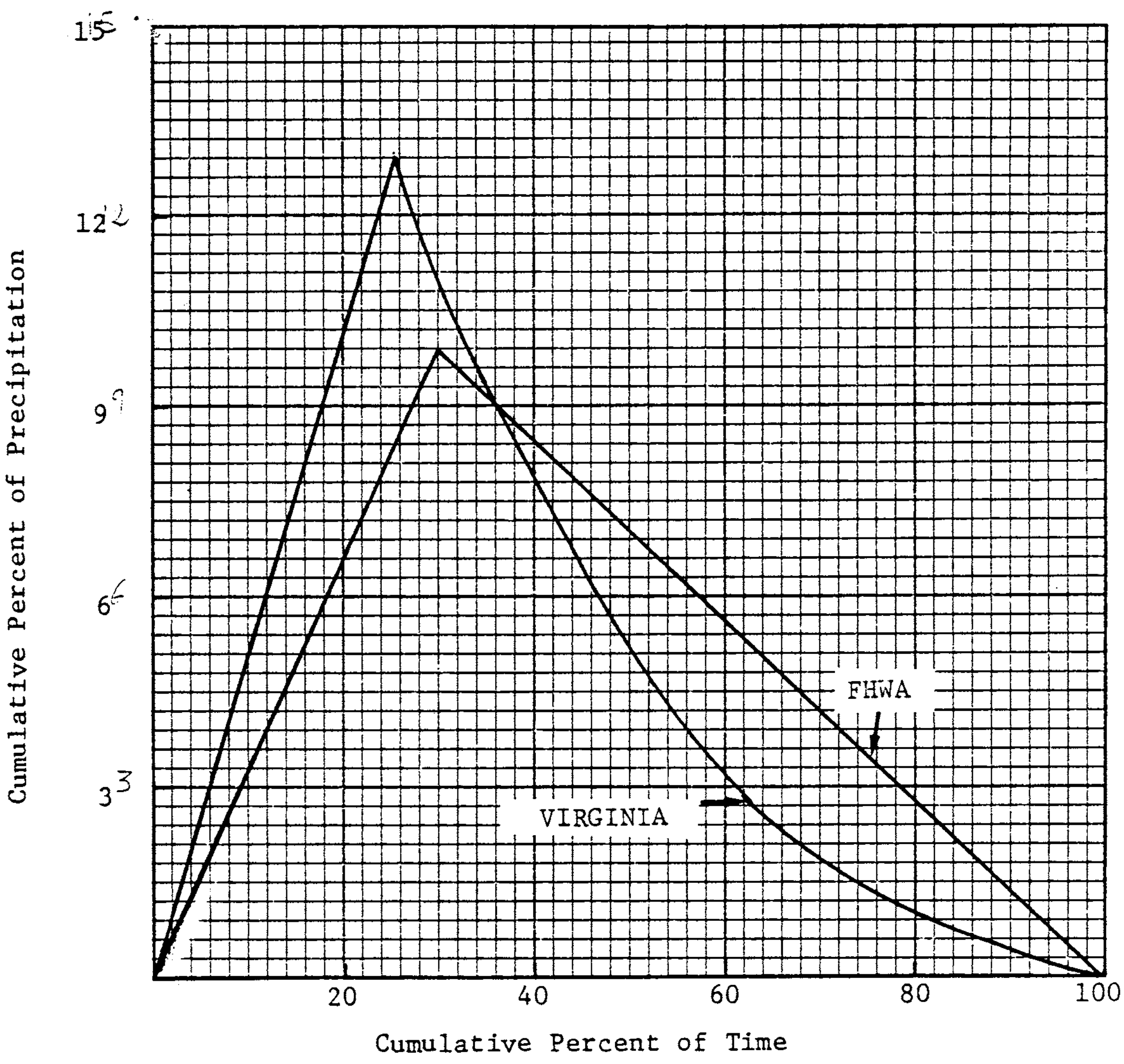


Figure 30. Comparison of the FHWA triangular hyetograph and the Virginia hyetograph.

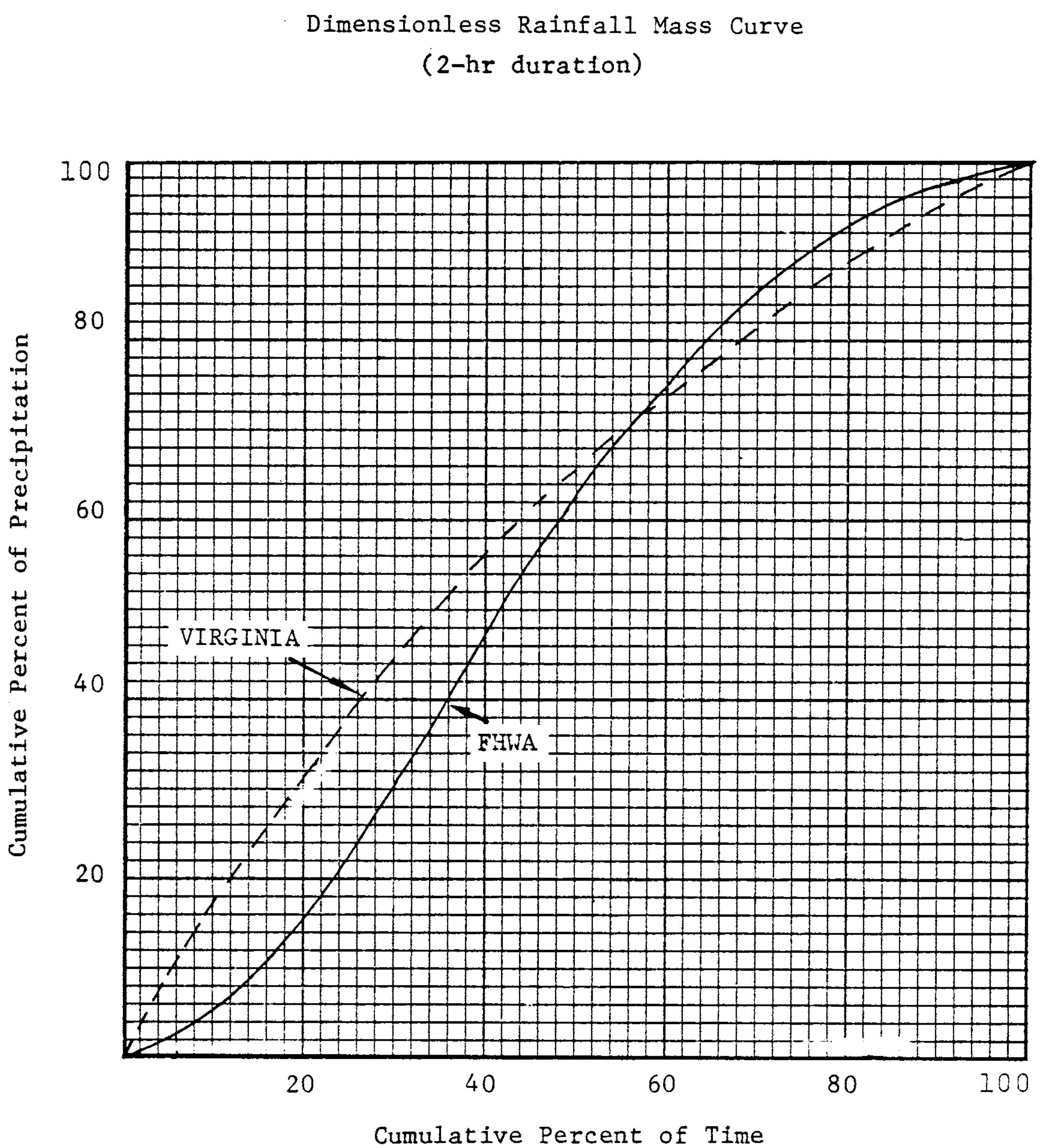


Figure 31. Comparison of FHWA and Virginia rainfall mass curves.

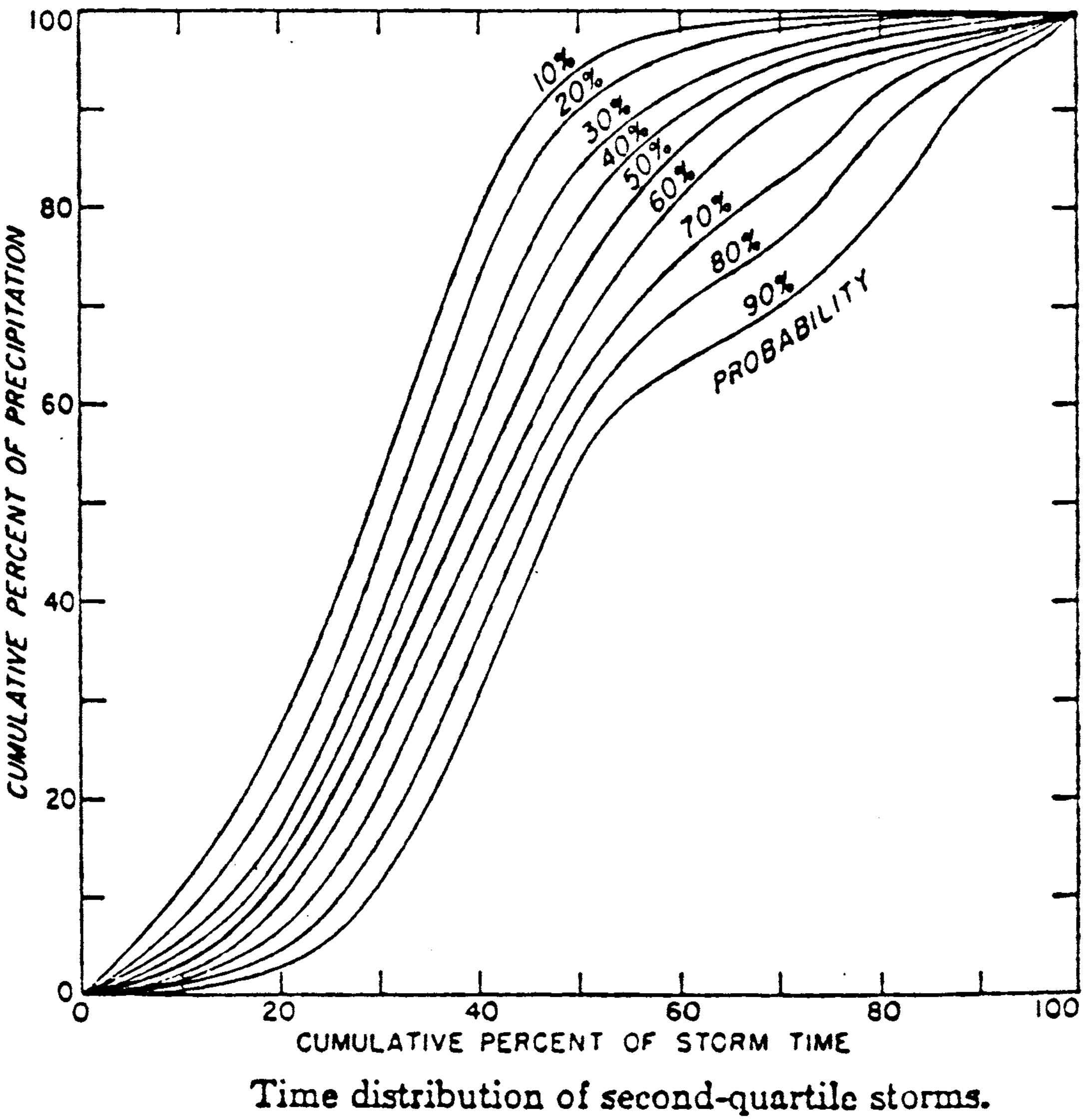


Figure 32. Time distribution of second quartile storms (after Huff 1967).

As shown in Figure 33, the Virginia curve for storms of less than 1-hr duration was compared with the 10% probability curve of Huff, while the curve for between 1-hr and 6-hr duration was compared with the 50% Huff curve. It can be seen that although the comparison is reasonably close, significant differences do exist. Again, the Virginia data show more rainfall accumulations during the first half of the storm and a lower rate of accumulations during the middle portion of the storm.

Implications on Runoff Estimation

It has been demonstrated that for a given total depth and duration of rainfall and antecedent basin conditions, the peak discharge and its time of occurrence can vary significantly with the temporal distribution of rainfall (Akan and Yen 1984). Different hyetographs produce different runoff hydrographs, even for the same design frequency and duration.

Akan and Yen found that the Huff first quartile, 50% hyetograph, having a short time to the peak rainfall, soon saturates the soil surface. Thus, it causes an early decline in infiltration capacity and results in the earliest peak flow among the hyetographs they tested. On the other hand, the SCS hyetograph, having a longer time to the peak rainfall, satisfies the infiltration demand in a more gradual way. Consequently, the hydrograph obtained from the SCS curve had a later but higher peak flow because of the higher rain intensity available at a later time.

The Virginia rainfall distribution curves show a general characteristic of having a shorter time to the peak rainfall when compared with the Huff and the SCS curves. Therefore, the Virginia hyetograph may be expected to produce an earlier hydrograph peak which may be lower than that obtained with the SCS curve. However, for a highly impervious area such as a parking lot, the effect of infiltration is minimal so the runoff peak may be the same regardless of the hyetograph used.

Another important consideration is that if the design location is at a downstream point which receives flows from a number of subbasins, the hydrographs from these subbasins must be combined to provide the overall design peak flow. In this case, the time to peak flow becomes very important when the hydrographs are combined and routed downstream.

In summary, the impact of hyetograph selection on runoff estimation varies, depending upon factors such as basin infiltration capacity and rainfall duration, among others. For long or medium duration storms, the Virginia curves may produce a late peak runoff that may be smaller than that produced by the SCS curve. Nevertheless, the reverse may be true for short duration storms or highly impervious watersheds. The relative effects of these factors and others, such as antecedent moisture condition, time of concentration selection, use of runoff models, etc., will be examined in a later study.

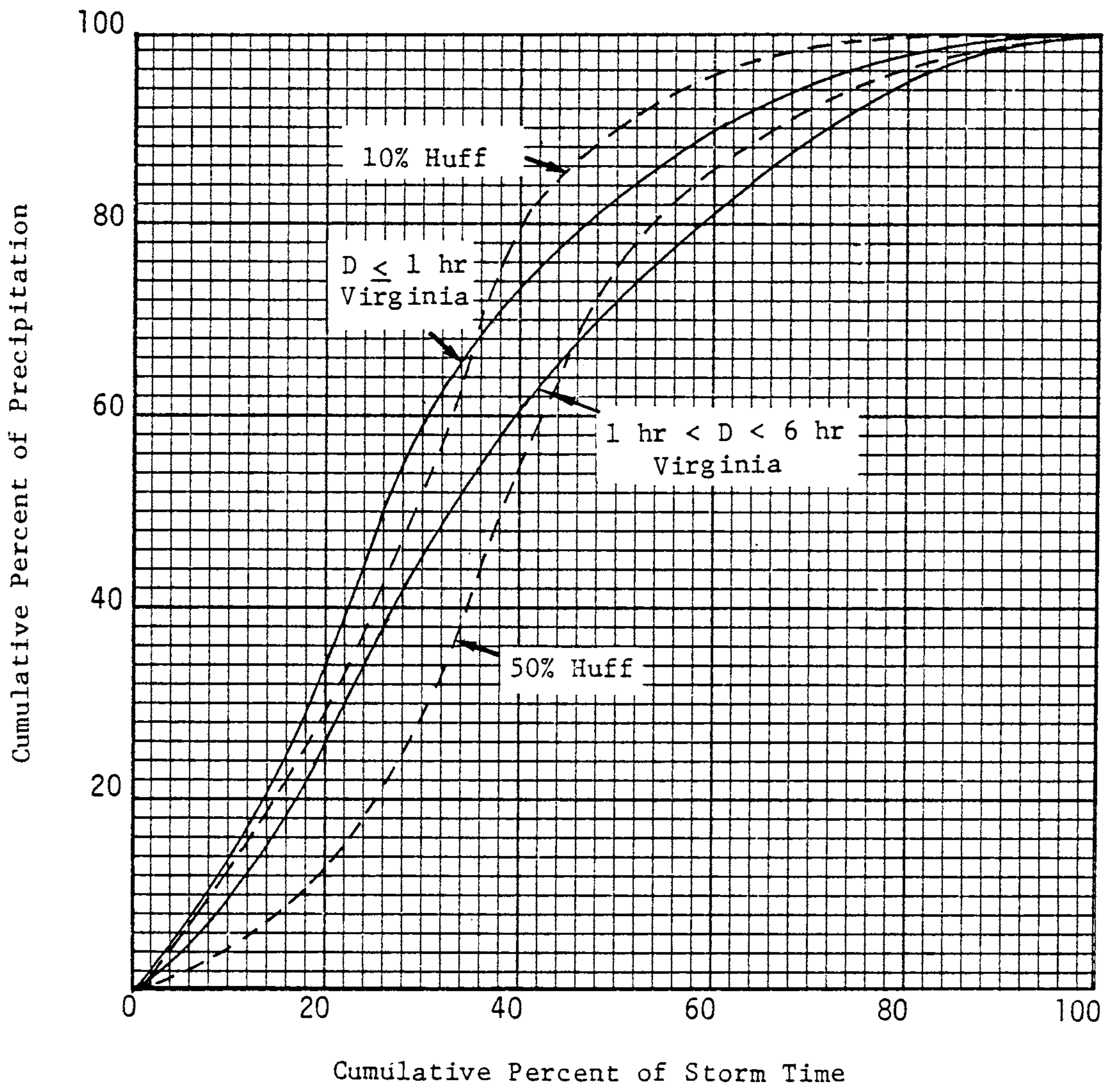


Figure 33. Comparison between Virginia and Huff curves.

CONCLUSIONS

Based on results obtained from statistical analyses of some 1,400 storms recorded throughout the state of Virginia, the following conclusions can be made:

1. The temporal distribution of Virginia storms differs significantly from the commonly recognized distribution curves such as the Huff quartile curves and the SCS curves. In general, the Virginia curves show a shorter time to the peak rainfall and a lower rate of increase near the mid-portion of the storm duration.

2. One statewide rainfall time distribution curve is adequate for Virginia for storms of 6-hr or longer durations.

3. Virginia storms of 6-hr or longer durations are predominantly second and third quartile types according to Huff's classification. Shorter duration storms are mostly first and second quartile types.

4. No regional difference was observed for storms of medium or long durations (6-hr or longer). However, for short duration storms (mostly thunderstorms), there were significant regional differences in rainfall time distributions, so regional curves are needed.

5. The impact of hyetograph selection on runoff estimation depends upon factors such as infiltration capacity, storm duration, and antecedent moisture condition. Further study is needed.

RECOMMENDATIONS

Based on the information gathered for this study and the results obtained from the data analyses, the following recommendations are made regarding the selection of rainfall temporal distribution curves for Virginia.

1. A statewide curve should be used for medium and long duration storms. See Figure 20 for storm durations between 6 and 18 hr, and Figure 21 for durations longer than 18 hr.

2. Regional curves should be used for short duration (greater than 1 hr and less than 6 hr) storms as well as very short (less than 1 hr duration) storms. See Figures 22 and 23 for short duration storms, and Figures 24 and 25 for very short duration storms. No data were available for the derivation of design curves for the coastal region; however, it is suggested the piedmont curves be used for the coastal region until data for that region become available.

3. All the above figures have been enlarged for clarity and are available upon request.

4. For normal situations, the 50% curves are recommended; however, any distribution between 10% and 90% may be used in accordance with the storm severity desired.

5. Equations describing the design curves have been derived and are listed in Tables 6 through 14. These equations can be incorporated in computers or programmable calculators for the computation of rainfall mass distributions.

6. For medium to long duration storms, the SCS type II curve may produce a higher flow peak than that obtained from the Virginia curves. Therefore, it is recommended that comparison be made between results from the Virginia hyetograph and those from the SCS curve before a final choice is made.

7. Further study is needed to examine the impact of hyetograph selection on peak runoff estimation.

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