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Time Distributions of Heavy Rainstorms in Illinois

by FLOYD A. HUFF

ILLINOIS STATE WATER SURVEY
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CIRCULAR 173

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Abstract: This document provides the best available in formation on the time-distribution characteristics of heavy rainstorms at a point and on small basins in Illinois and the Midwest. It is recommended for use in conjunction with Illinois State Water Survey Bulletin 70 and Circular 172 for runoff computations related to the design and operation of runoff control structures. It is also useful for post-storm assessment of individual storm events in weather modification operations. Information is presented in the form of families of curves derived for groups of storms categorized according to whether the greatest percentage of total storm rainfall occurred in the first, second, third, or fourth quarter of the storm period. The time distributions are expressed as cumulative percentages of storm rainfall and storm duration to enable comparisons between storms. The individual curves for each storm type provide estimates of the time-distribution characteristics at probability levels ranging from 10% to 90% of the total storm occurrences. Explanations arc provided of how to use the results in design problems.

Reference: Huff, Floyd A. Time Distributions of Heavy Rain storms in Illinois. Illinois State Water Survey, Champaign, Circular 173, 1990.

Indexing Terms: Climatology, heavy rainstorms, hydroclimatology, hydrometeorology, Illinois, rainfall, storm duration, time distributions.

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TIME DISTRIBUTIONS OF HEAVY RAINSTORMS IN ILLINOIS

by Floyd A. Huff

USER SUMMARY

• This document provides the best available information on the time-distribution characteristics of heavy rainstorms at a point and on small basins encompassing areas of up to 400 square miles in Illinois and the Midwest. It is recommended for use in conjunction with Illinois State Water Survey Bulletin 70 (Huff and Angel, 1989a) and Circular 172 (Huff and Angel, 1989b) for runoff computations related to the design and operation of runoff control structures. It is also useful for post-storm assessment of individual storm events in weather modification operations.

• Information is presented in the form of families of curves derived for groups of storms categorized as first-, second-, third-, or fourth-quartile storms depending on whether the greatest percentage of total storm rainfall occurred in the first, second, third, or fourth quarter of the storm period. The time distributions are expressed as cumulative percentages of storm rainfall and storm duration to enable comparisons between storms.

• The individual curves for each storm type (quartile group) provide estimates of the time-distribution characteristics at probability levels ranging from 10% to 90% of the total storm occurrences. Although the median curve is the single most representative curve, the others allow users to determine basin runoff relations for various types of distributions that occur in nature with each of the four basic storm types (quartile groups). The 10% and 90% curves should be quite useful for estimating runoff relations in the more extreme types of time distributions.

• For mean rainfall on *small basins* (≤ 400 square miles), the first- and second-quartile storms were found to be most prevalent in Illinois (33% each), followed by third-quartile storms (23%) and fourth-quartile storms (11%). For *point rainfall,* first-quartile storms were most prevalent (37%), followed by second-quartile storms (27%), third-quartile storms (21%), and fourth-quartile storms (15%).

• Storms with durations of 6 hours or less showed a tendency to be associated more often with first-quartile distributions, and those lasting from 6.1 to 12 hours were most commonly the second-quartile type. Rainstorms having durations of 12.1 to 24 hours occurred most often with the third-quartile type of distribution. Those having durations greater than 24 hours were most frequently associated with the fourth-quartile distribution. However, it is stressed that specific storms among all durations may be associated with any of the four quartile types.

• For most design applications, we recommend using the quartile type occurring most often for the design duration under consideration. For example, use the first-quartile curves for design durations of 6 hours and less, and use the second-quartile distributions for designs involving storm durations of 6.1 to 12 hours.

INTRODUCTION

This report provides key information on the time distributions of rainfall in heavy storms in Illinois. It is complementary to Water Survey Bulletin 70 (Huff and Angel, 1989a) and Circular 172 (Huff and Angel, 1989b). It is intended to provide all the time-distribution information needed for use in conjunction with the Bulletin 70 and Circular 172 rainfall frequency relations. These time distributions can also be used in conjunction with other available rainfall frequency relations for the Midwest and other areas of similar precipitation climate.

These time-distribution relations have also been developed to provide information useful in assessing human effects on storm rainfall resulting from inadvertent or planned modification of the natural precipitation distribution. For example, it has been shown that urban influences alter the natural rainfall distributions at St. Louis and Chicago, and this change is reflected in the storm rainfall frequency relations in these urban regions (Huff and Changnon, 1973; Changnon et al., 1977; Huff and Angel, 1989a, 1989b).

Much of the material used in preparing this report has been condensed from publications by Huff (1967, 1980, 1986) and Huff and Schickedanz (1970).

Background

The advent of urban runoff models in the late 1960s and early 1970s brought new demands on hydroclimatologists. These models required definition of the time-distribution characteristics of rainfall during heavy storms. Since the previous demand had not been strong, this information was not readily available. Some limited work on storm rainfall profiles (time distributions) had been done by the U.S. Army Corps of Engineers (1952) and by Tholin and Keifer (1960), who developed storm profiles for use with frequency data such as provided by U.S. Weather Bureau Technical Paper 40 (Hershfield, 1961). In 1967, the Illinois State Water Survey published results of a more detailed time-distribution study based on data from heavy storms sampled during the 12-year operation of a dense raingage network in central Illinois (Huff, 1967). This study was undertaken primarily to provide information applicable to existing urban design problems.

Others became involved in the development of time-distribution relations. For example, during the early 1970s, the Soil Conservation Service (1972) published average time profiles which have become quite widely used for design purposes. Pani and Haragan (1981) used Huffs 1967 methodology to develop relations for Texas, based on data from a 1,700-square-mile raingage network. Bonta and Rao (1987) investigated application of the Huff curves in Ohio, and found them to have potential for more widespread practical use in design storms.

A logical question is, do variations in time-distribution models substantially affect the runoff computations in design models for urban or small basins? *Evidence in the literature indicates that differences can be significant (Huff 1986).* For example, Ward et al. (1980) compared results from several time-distribution models for a small Kentucky basin under various hydrologic conditions. Among five distributions tested, including the SCS Type-II (supposedly applicable to the central and eastern United

States) and two of the Illinois models, a maximum variation in peak runoff of nearly 30% was obtained.

In an Illinois study of reservoir design floods on 20 small basins, Knapp and Terstriep (1981) compared the Illinois family of distributions, the SCS Type-II distribution, and the Corps of Engineers standard project storm distribution. They found substantial differences among the three types of distributions in computing peak runoff from probable maximum precipitation and 100-year storm events. For example, over most of the state maximum reservoir discharges averaged 20% to 25% greater for 100-year storm events when the Huff 1967 distributions were used.

Thus it is apparent that we must strive to provide the most accurate time-distribution models possible from comprehensive analyses of all available data on a regional basis, using logical meteorological and statistical techniques. Our major goal in developing the relationships presented in this report was to provide reliable information for Illinois design applications.

Acknowledgments

This report was prepared under the direction of Richard G. Semonin, Chief, Illinois State Water Survey, and with the general guidance of Peter J. Lamb, Head of the Water Survey's Climate and Meteorology Section. The many helpful comments and suggestions of Stanley A. Changnon, Jr., and Peter J. Lamb, who thoroughly reviewed the document, are greatly appreciated. Rebecca Runge typed the original manuscript, Gail Taylor edited the report, and illustrations were prepared by John Brother and Dave Cox. Support for preparation of the report was provided by NOAA grant COMM-NA89 RAH 09086.

DATA USED IN DEVELOPING TIME DISTRIBUTIONS

Huff (1967) investigated time distributions for the 12-year period 1955-1966 on the basis of data from 261 storms on a 400-square-mile network of 49 recording raingages in east-central Illinois (figure 1). This network is located in extremely flat prairie land; therefore no significant topographic or urban influences on local precipitation occur. The 261 storms yielded comprehensive time-distribution relations for point rainfall and for areas of 50 to 400 square miles. A storm was defined as a rain period separated from preceding and succeeding rainfall by 6 hours or more. All storms were used in which the network mean rainfall exceeded 0.50 inch and/or one or more gages recorded more than 1 inch. Within the data period, storms having total durations from 1 to 48 hours qualified for the study. Among the 261 storms, 110 (42%) had durations less than or equal to 12 hours, 86 (33%) lasted from 12.1 to 24 hours, and 65 (25%) had durations exceeding 24 hours.

Data from an urban network of 12 recording gages covering 10 square miles in the Champaign-Urbana area in east-central Illinois (Huff and Neill, 1957) (figure 2) were also used in the study. Data for the 50 heaviest storms during 1954-1963 were used to develop relations for this network. Later, Huff and Vogel (1976) used data from

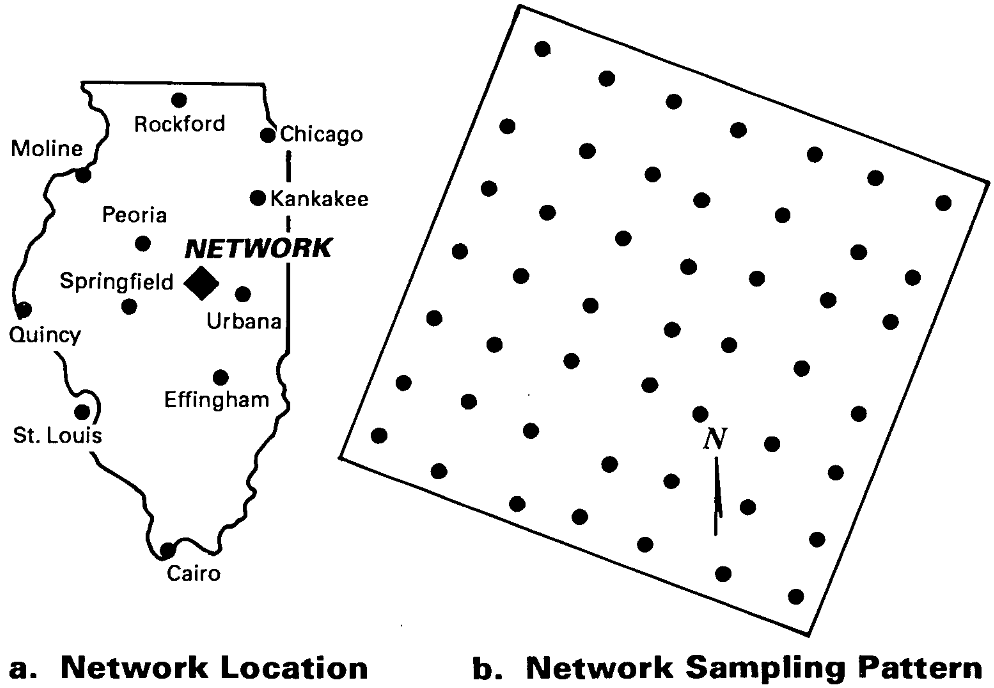


Figure 1. Location of east-central Illinois raingage network

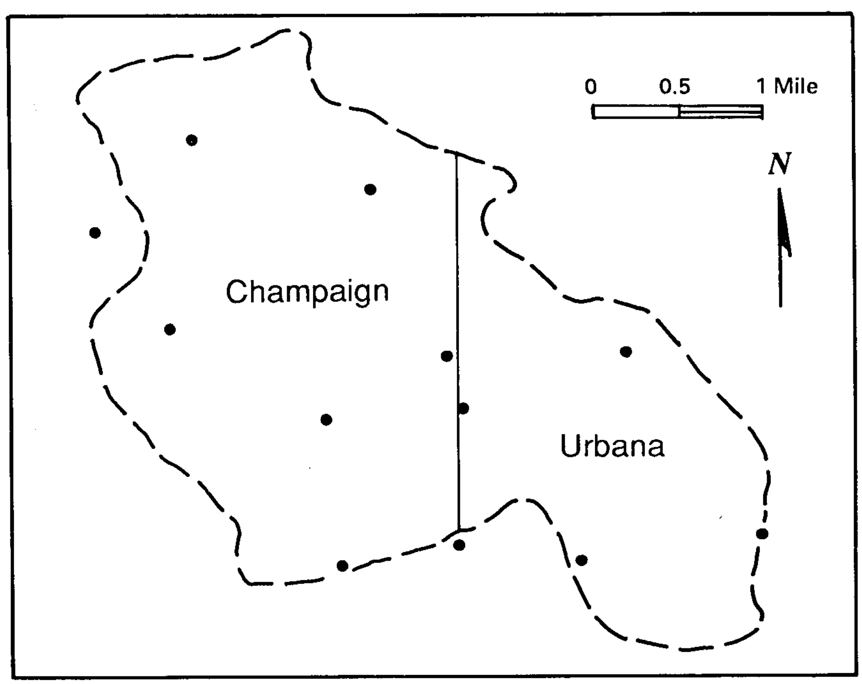


Figure 2. Location of Champaign-Urbana raingage network

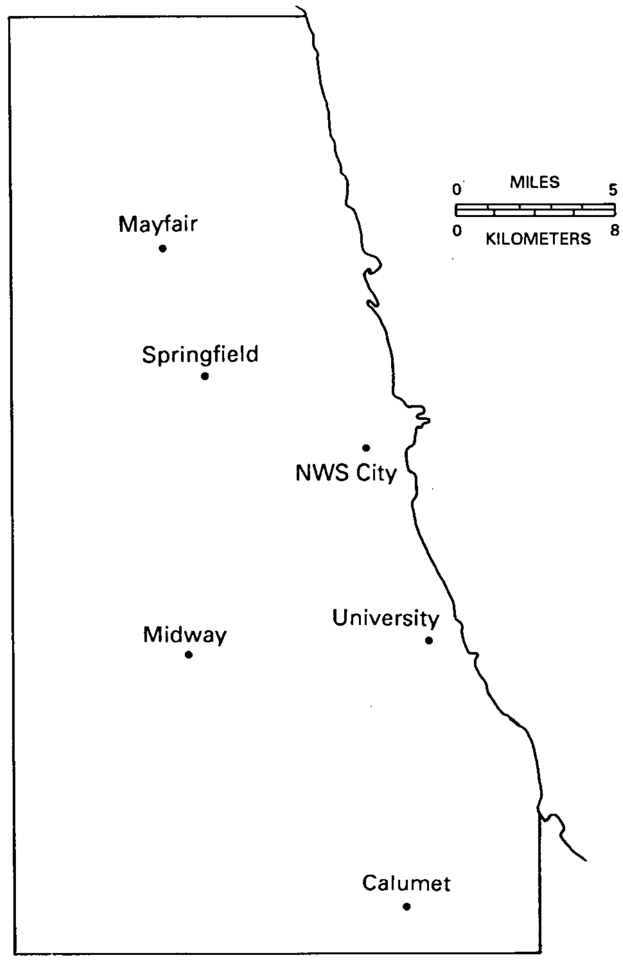


Figure 3. Locations of raingages used in the Chicago urban area

six recording gages in Chicago operated during 1932-1966 (figure 3) to develop point rainfall relations for comparison with the east-central Illinois findings. A total of 417 storms in which total rainfall exceeded 0.50 inch were used to derive the Chicago time-distribution curves, following the same procedures used in the Huff 1967 network study. The *time distributions* were not significantly affected by the urban and lake environments. However, *spatial distributions* of heavy storm rainfall were influenced (Huff and Vogel, 1976).

METHOD OF ANALYSIS

The time distributions were expressed as cumulative percentages of storm rainfall and storm duration to enable valid comparisons between storms and to simplify analyses and presentation of data. In Huff's 1967 study, relations were developed for point rainfall and for areal mean rainfall on areas of 50 to 400 square miles. Areal groupings showed only small changes in the time distribution with increasing size of sampling area. Therefore an average relationship for these combined areas was determined. Rainfall distributions were grouped according to whether the heaviest rainfall occurred in the first, second, third, or fourth quarter of a storm. For each quartile grouping, a family of curves was then derived to provide a quantitative measure of the interstorm variability expected to occur within that group. The interstorm variability was expressed in probability terms, as discussed later.

Before proceeding further, it is pertinent to discuss some basic differences between the methods of developing time distributions in this study and some others that have been widely used in the past. Most importantly, *the results are based strictly on Illinois data — not on a combination of data collected over an extensive portion of the country*. As pointed out by Huff (1986), time-distribution relations will vary between regions of the country having different precipitation climate regimes. Thus, for example, the Illinois-derived relations should closely approximate time-distribution characteristics in St. Louis and Indianapolis, but not those in Miami, Denver, Phoenix, Seattle, or other areas that experience substantially different climatic regimes than the midwestern United States.

Another important feature of this study is that the results are based strictly on real data. No assumptions were made concerning the characteristics of the distribution curves — the data determined the relationships. Furthermore, the data used were largely from the east-central Illinois network, in which extraordinary efforts were made to assure accurate sampling of storm systems. Careful attention was given to gage exposure, network operations, and data processing, all of which were performed by experienced personnel of the Water Survey.

Figure 4 is presented to stress further the importance of the approach that has been used. This illustration shows a median time-distribution curve obtained from combining all 261 storms from the Water Survey's central Illinois network. This curve has not been published previously, because it does not provide reliable information on the distribution characteristics of heavy-storm rainfall. It provides no measure of the varying types of storm profiles that occur in nature, or of the interstorm variability of a particular type of profile, both of which are important factors in application of temporal distributions. Figure 4 is a "crutch" curve of the type commonly used in the past — it is useful if nothing better exists, but it actually portrays a distribution that seldom occurs in nature. This weakness has been overcome in this study.

RESULTS OF ANALYSIS

Time Distributions of Storm Rainfall over Areas

Statistical models of time distributions for each quartile-type storm are shown in figures 5 through 8 for areas of 50 to 400 square miles combined. These are considered typical of heavy midwestern storms in which thunderstorms are the major rain producers. Combining all data, 33%, 33%, 23%, and 11%, respectively, of the storms were classified as first-, second-, third-, and fourth-quartile storms. No distinct trend was found for the quartile percentages to change with increasing area (from 50 to 400 square miles). The statistical models are smooth curves reflecting the average

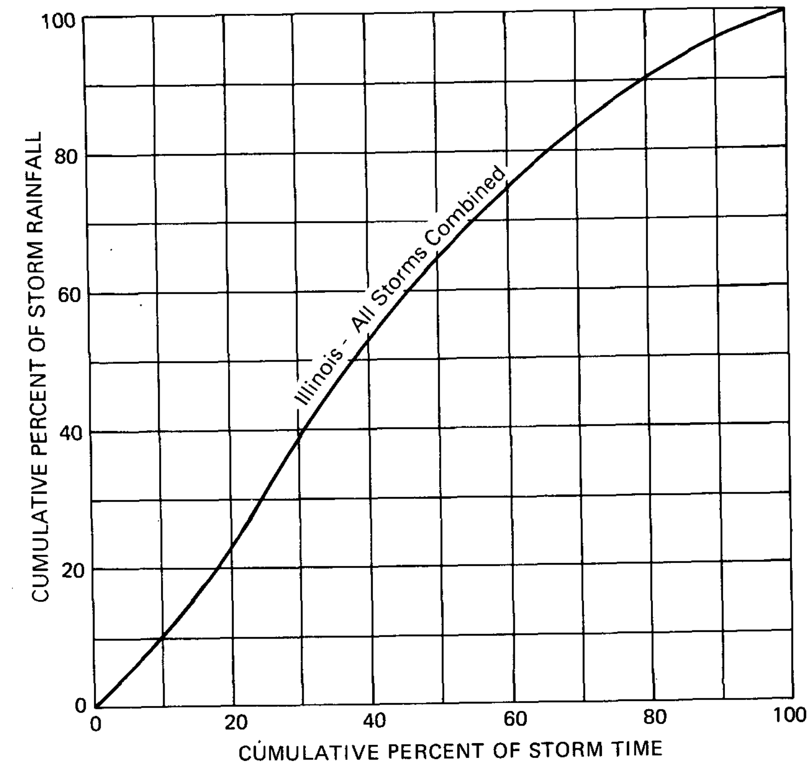


Figure 4. Median time distribution derived from combining all 261 storms from the central Illinois network

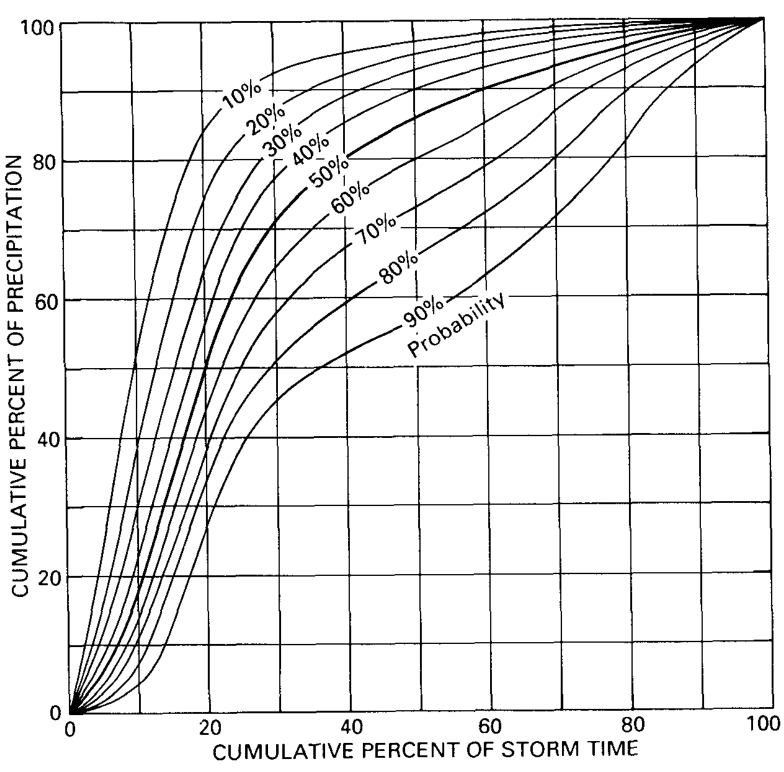


Figure 5. Time distribution of areal mean rainfall in first-quartile storms

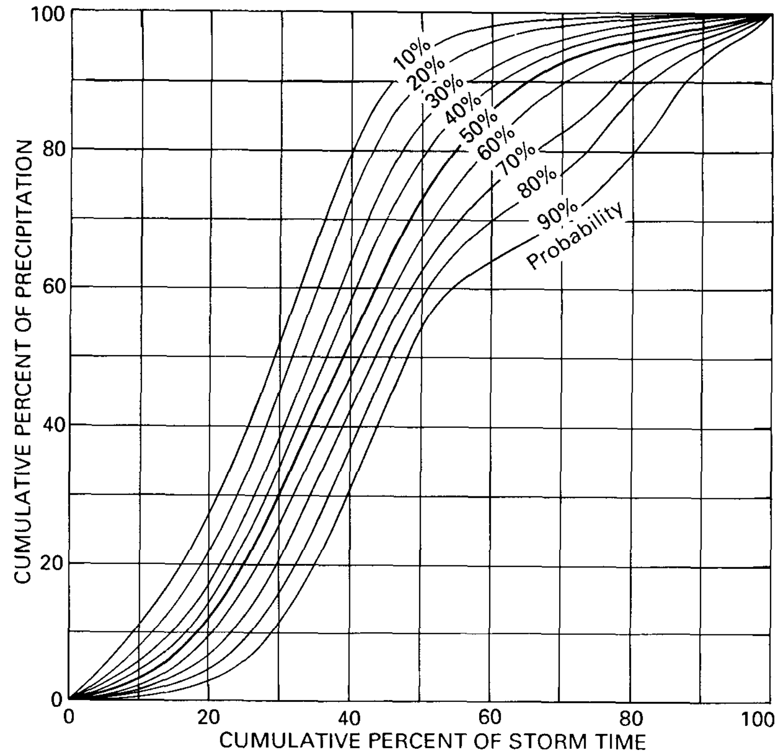


Figure 6. Time distribution of areal mean rainfall in second-quartile storms

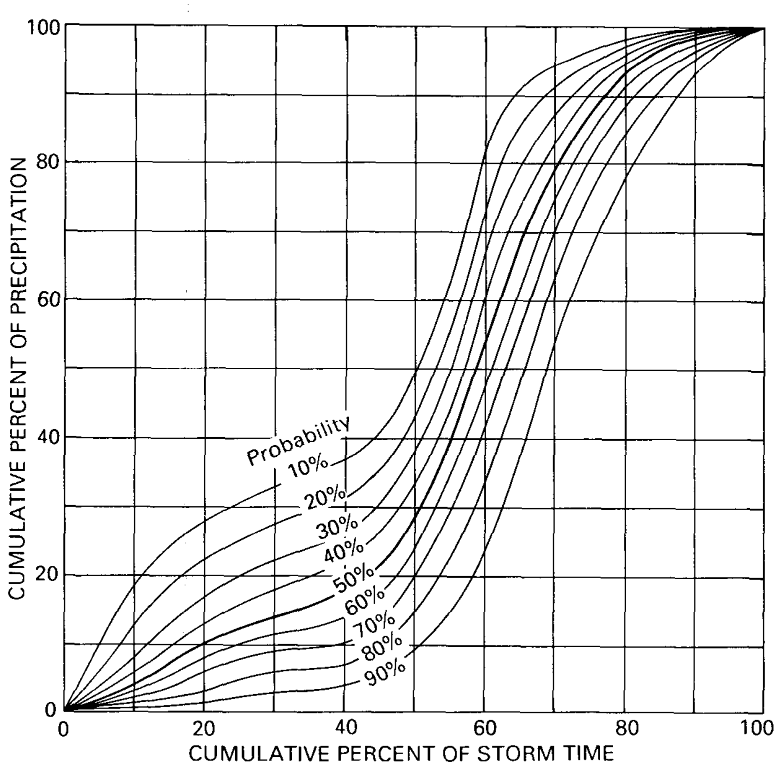


Figure 7. Time distribution of areal mean rainfall in third-quartile storms

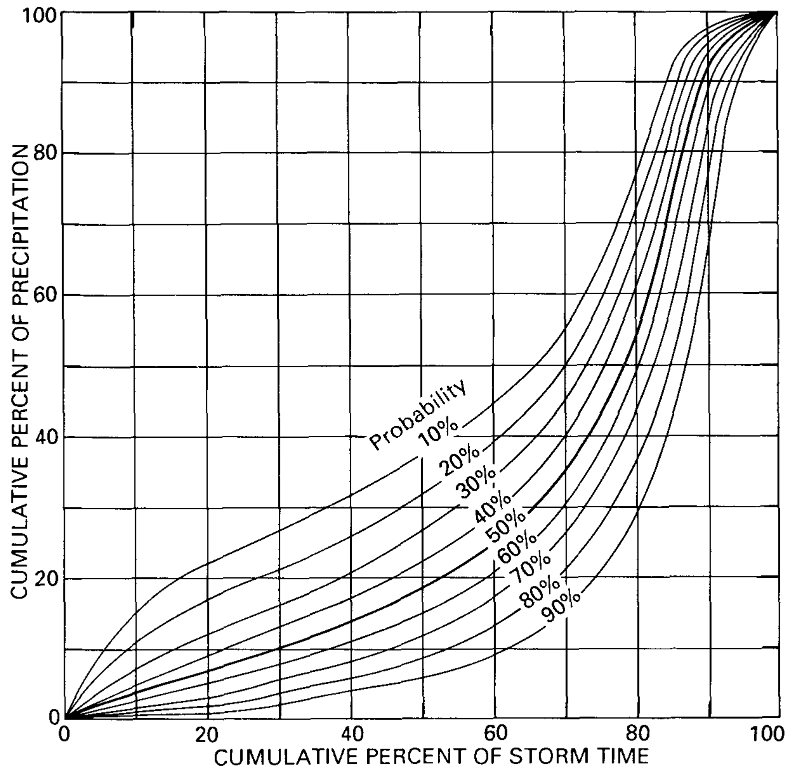


Figure 8. Time distribution of areal mean rainfall in fourth-quartile storms

rainfall distribution with time, and therefore the burst characteristics of a mass rainfall curve are not exhibited. Probability levels from 10% to 90% are shown, but the 50% level (median) has been stressed by a heavier line, since it is probably the most useful statistic. Table 1 provides median time distributions for each quartile-type storm in the combined areas.

Interpretation of the curves can be illustrated by referring to the first-quartile storm distributions in figure 5. The 10% curve is typical of storms in which the rainfall is concentrated in an unusually short portion of a storm (10% of all storms). It indicates that, on the average, one first-quartile storm out of every ten will have at least 89% of its rainfall in the first quarter of the storm period. More than 95% of it will occur in the first half of the storm.

The 50% curve (median) shows 63% and 86% of the rainfall at 25% and 50% of the storm period, respectively. The 90% curve reflects an unusually uniform distribution for first-quartile storms, which occurs in 10% or less of the storms. Thus this curve shows that in 10% of the storms, 39% or less of the rain will occur in the first quarter of the storm and 57% in the first one-half of the storm. To further illustrate the difference between the median curve and the 10% and 90% curves, table 2 shows the time distributions of rainfall for first-quartile storms on areas of 50 to 400 square miles at the 10%, 50%, and 90% probability levels.

Table 1. Median Time Distributions of Heavy Storm Rainfall on Areas of 50 to 400 Square Miles

Cumulative percent of storm time	*Cumulative percent of storm rainfall for given storm type*			
	First-quartile	*Second-quartile*	*Third-quartile*	*Fourth-quartile*
5	8	2	2	2
10	17	4	4	3
15	34	8	7	5
20	50	12	10	7
25	63	21	12	9
30	71	31	14	10
35	76	42	16	12
40	80	53	19	14
45	83	64	22	16
50	86	73	29	19
55	88	80	39	21
60	90	86	54	25
65	92	89	68	29
70	93	92	79	35
75	95	94	87	43
80	96	96	92	54
85	97	97	95	75
90	98	98	97	92
95	99	99	99	97

Table 2. Median Time Distributions of Area1 Mean Rainfall in First-Quartile Storms at 10%, 50%, and 90% Probability Levels

Cumulative percent of storm time	*Cumulative percent of storm rainfall for given storm probability*		
	10%	*50%*	*90%*
5	24	8	2
10	50	17	4
15	71	34	13
20	84	50	28
25	89	63	39
30	92	71	46
35	94	76	49
40	95	80	52
45	96	83	55
50	97	86	57
55	98	88	60
60	98	90	63
65	98	92	67
70	99	93	72
75	99	95	76
80	99	96	82
85	99	97	89
90	99	98	94
95	99	99	97

Time Distributions of Point Rainfall

Figures 9 through 12 provide time-distribution curves for point rainfall. These were obtained from averaging the point relations from the central Illinois study (Huff, 1967) and those obtained from the Chicago-area study (Huff and Vogel, 1976). Differences between the two sets of analyses were insignificant in view of the natural variability in storm rainfall. Therefore they were combined to incorporate a larger sample into the point relationships. Curves for the 10%, 50% (median), and 90% probability levels (figure 9) provide a measure of the interstorm variability that occurs with point rainfall distributions. Table 3 is similar to table 1 and shows the median time distributions that are applicable to point rainfall for each quartile-type storm.

Point-to-Area Relations

Except for data from the 10-square-mile urban area at Champaign-Urbana, suitable data were not available for deriving time-distribution relations for intermediate areas between a point and 50 square miles. The 10-square-mile results were in close agreement with those for point rainfall, so the point values can be used for areas up to 10 square miles.

For areas of 10 to 50 square miles, it is suggested that the point and areal relations in figures 5 through 12 be averaged. For example, if users are interested in a first-quartile storm over a 25-square-mile area and are using a median or average distribution, they should tabulate the median distribution values from the point and areal curves and average them to obtain the desired time distribution. This procedure has been illustrated in table 4 and figure 13, in which median distributions are shown for each quartile-type storm for areas of 10 to 50 square miles.

Figure 14 illustrates how the first-quartile point values differ from those for the largest area studied (400 square miles) in Illinois. The point curve indicates larger percentages of the total rainfall at the start of the storms. This tendency appears logical for rain on very small areas. If one assumes a storm of given intensity and areal extent moving across two areas of appreciably different sizes, the smaller area will tend to receive a larger percentage of its areal mean rainfall in the early part of the rain period, particularly if the storm is smaller than the network in areal extent.

How to Use the Time Distributions

Fourth-quartile storms occurred most often with durations greater than 24 hours; *first-quartile and second-quartile storms* occurred most frequently with durations less than or equal to 12 hours; and *third-quartile storms* most often had durations of 12.1 to 24 hours (Huff, 1967). Among all storms combined, 42% fell into the duration grouping of 12 hours or less, 33% fell in the 12.1- to 24-hour group, and 25% exceeded 24 hours in duration. Recommended uses of the curves and tables are indicated below.

- For durations of 12 hours or less, it is recommended that first- and second-quartile relations be used to establish typical time distributions. Statistically, first-quartile distributions were slightly more prevalent in storms having durations of 6 hours and less, and second-quartile distributions were more prevalent in those lasting from 6.1 to 12 hours.

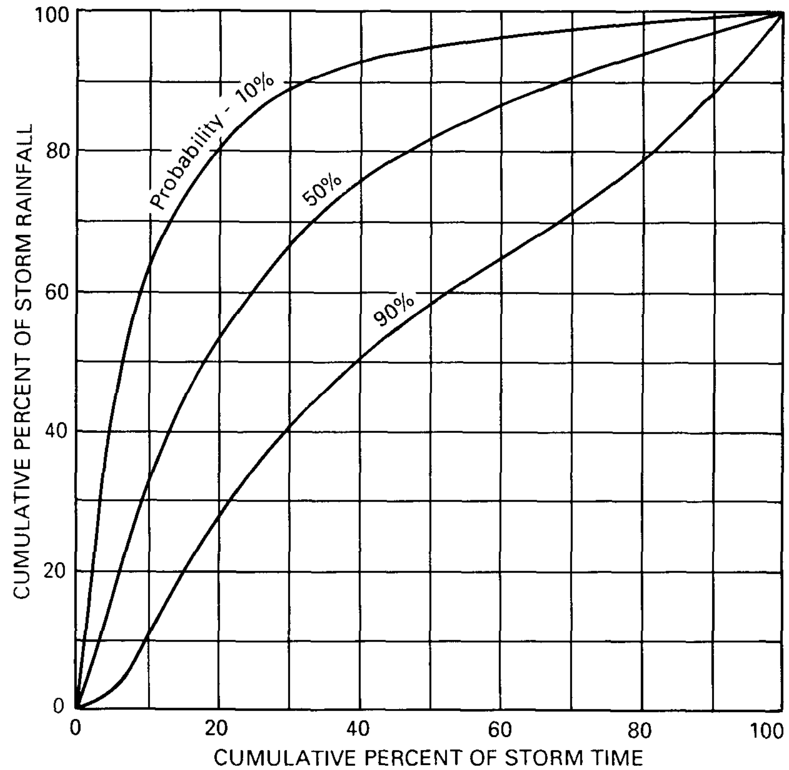


Figure 9. Time distribution of point rainfall in first-quartile storms

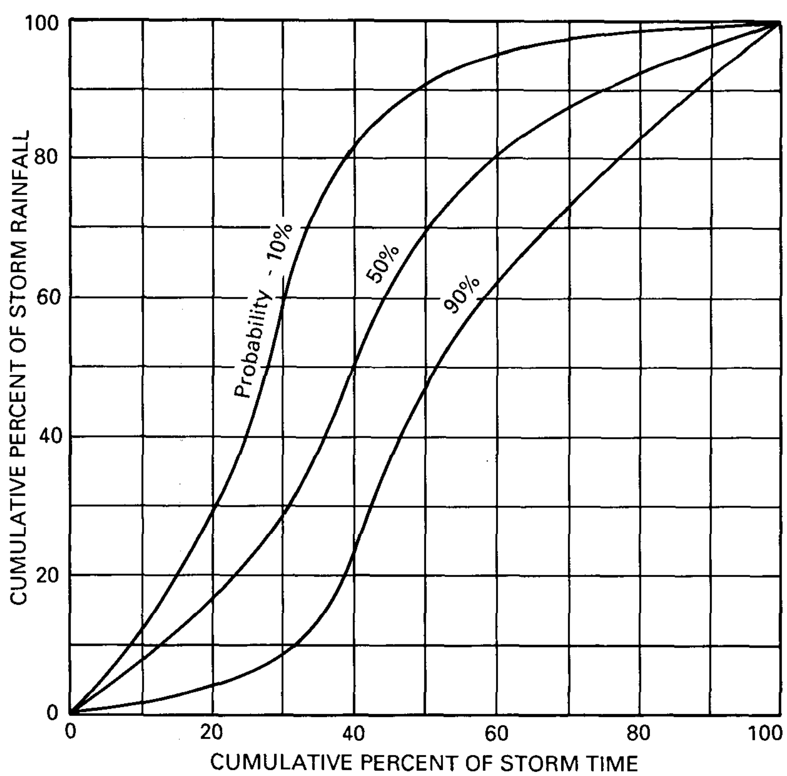


Figure 10. Time distribution of point rainfall in second-quartile storms

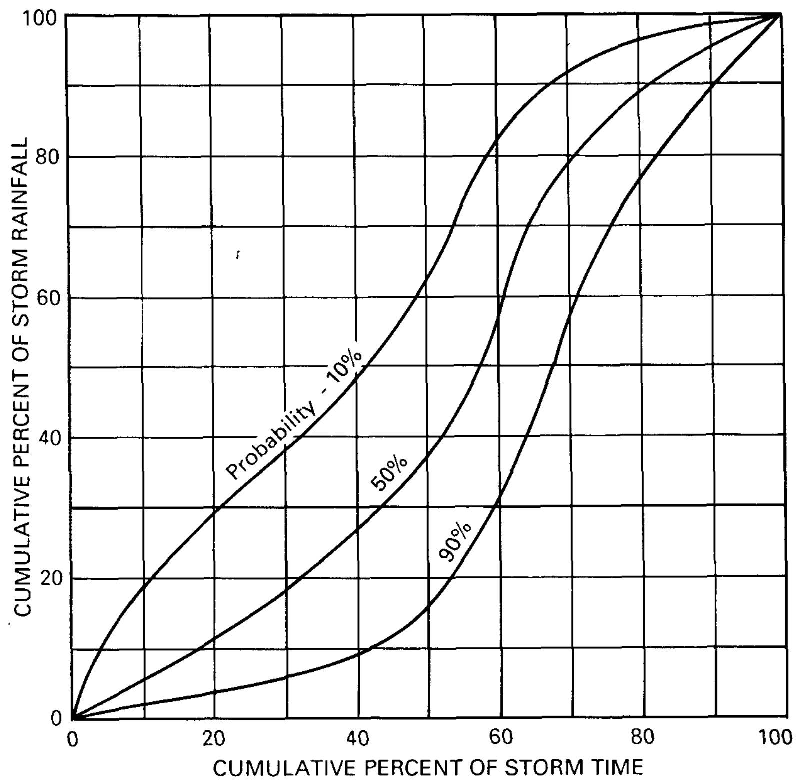


Figure 11. Time distribution of point rainfall in third-quartile storms

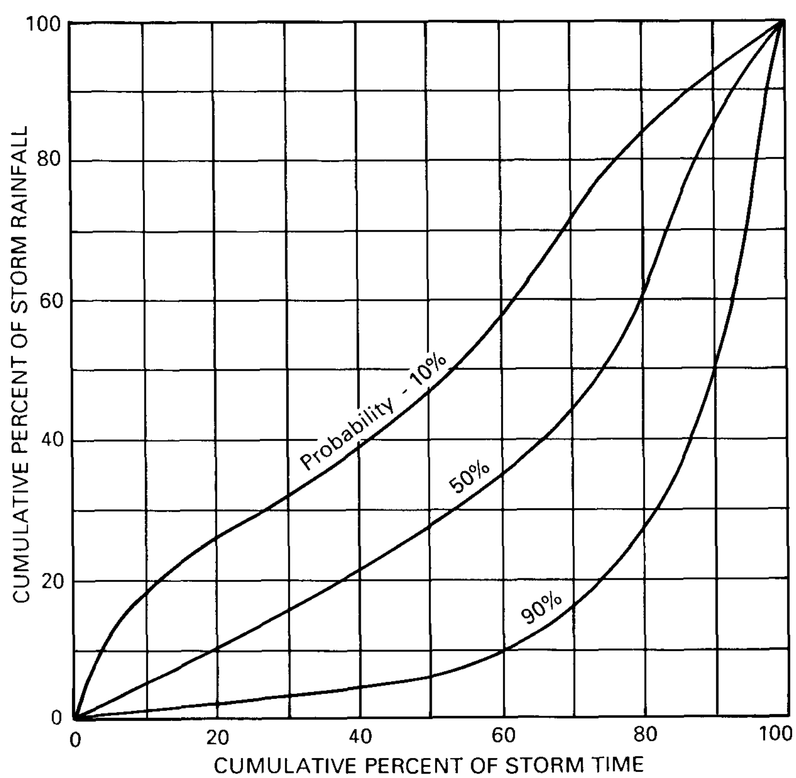


Figure 12. Time distribution of point rainfall in fourth-quartile storms

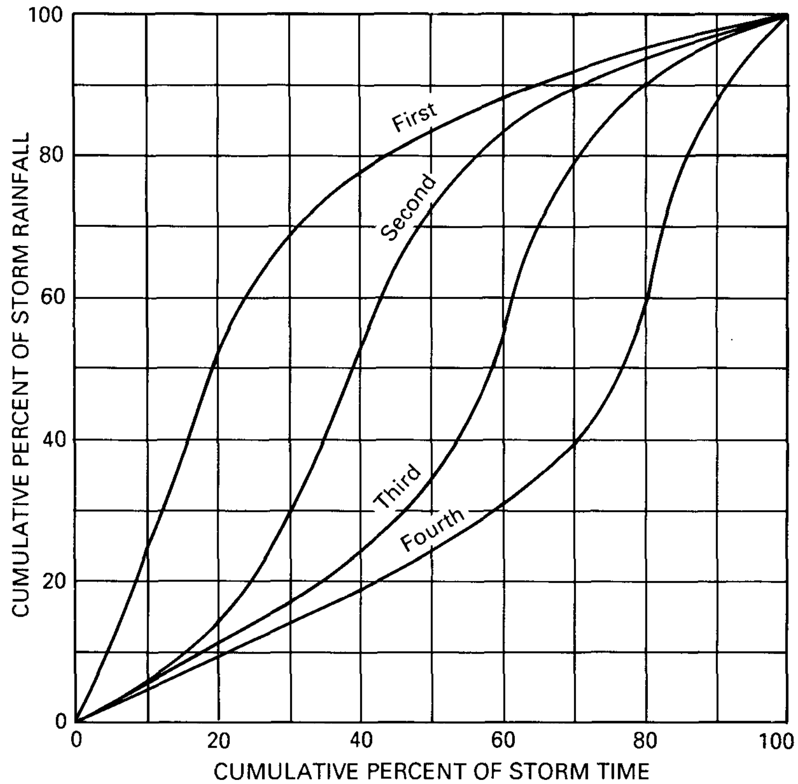
Table 3. Median Time Distributions of Heavy Storm Rainfall at a Point

Cumulative percent of storm time	*First-quartile*	*Second-quartile*	*Third-quartile*	*Fourth-quartile*
	Cumulative percent of storm rainfall for given storm type			
5	16	3	3	2
10	33	8	6	5
15	43	12	9	8
20	52	16	12	10
25	60	22	15	13
30	66	29	19	16
35	71	39	23	19
40	75	51	27	22
45	79	62	32	25
50	82	70	38	28
55	84	76	45	32
60	86	81	57	35
65	88	85	70	39
70	90	88	79	45
75	92	91	85	51
80	94	93	89	59
85	96	95	92	72
90	97	97	95	84
95	98	98	97	92

Table 4. Median Time Distributions of Heavy Storm Rainfall on Areas of 10 to 50 Square Miles

Cumulative percent of storm time	*First-quartile*	*Second-quartile*	*Third-quartile*	*Fourth-quartile*
	Cumulative percent of storm rainfall for given storm type			
5	12	3	2	2
10	25	6	5	4
15	38	10	8	7
20	51	14	12	9
25	62	21	14	11
30	69	30	17	13
35	74	40	20	15
40	78	52	23	18
45	81	63	27	21
50	84	72	33	24
55	86	78	42	27
60	88	83	55	30
65	90	87	69	34
70	92	90	79	40
75	94	92	86	47
80	95	94	91	57
85	96	96	94	74
90	97	97	96	88
95	98	98	98	95

Figure 13. First-, second-, third-, and fourth-quartile median distributions of storm rainfall on areas of 10 to 50 square miles



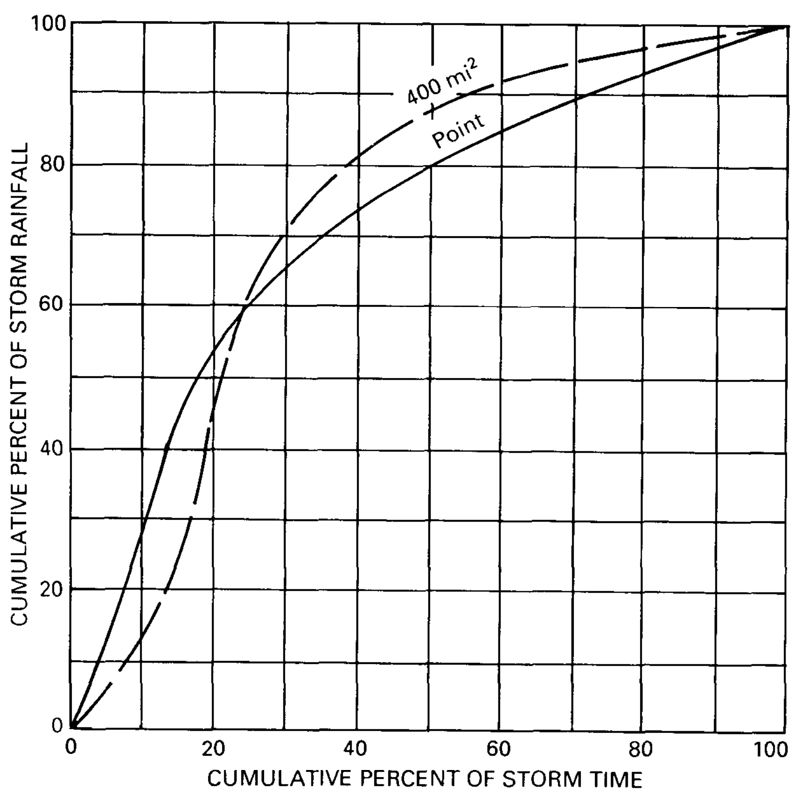


Figure 14. Differences between curves for point values and 400-square-mile values

- Time distributions for storms lasting from 12.1 to 24 hours are most likely to conform to a third-quartile distribution.

- For storms lasting longer than 24 hours, the fourth-quartile curves are recommended.

The above recommendations are based strictly on the frequency distributions of each of the four storm types with respect to storm duration. It should be remembered that a particular storm may fall into any of the four quartile types.

For most purposes, the median curves are probably most applicable to design. These curves are more firmly established than the more extreme curves, such as those for the 10% and 90% probability levels, which are determined from a relatively small portion of each quartile's sample. However, the extreme curves in figures 5 through 12 should be useful when runoff estimates are needed for the occurrence of unusual storm conditions, such as typified by the 10% curves.

Illustrations of How to Use the Results in Design Problems

Case One

First, assume that a design based on a 5-inch rainstorm of 6-hour duration is being determined for a given point, based on a median or average time distribution. In this case, a *first-quartile median curve* would be appropriate (based on the first recommendation above). Then, from figure 9 or table 3, one can determine that 1.67 inches would occur in the first 10% (36 minutes) of the storm. Similarly, 60% (3.00 inches) would be expected to occur in the first 25% (90 minutes) of the storm, and 82% (4.10 inches) in the first 50% (3 hours) of the rain period.

Case Two

Now, assume that the same design problem involves a 5-inch, 6-hour storm but on a basin encompassing 100 square miles. Then, refer to figure 5 or table 1. In this case, the median values indicate that the area1 average would be 0.85 inch in the first 10% (36 minutes) of a *first-quartile storm*. During the first 25% of the storm (90 minutes), 63% of the rain (3.15 inches) would fall, and during the first 50% (3 hours), 86% (4.30 inches) would occur.

Case Three

If a *second-quartile* instead of a *first-quartile storm* were used as the design basis for the 100 square miles, only 4% (0.20 inch) would occur in the first 10% of the storm. This would increase to 21% (1.05 inches) in the first 25% (90 minutes) of the storm period. Then a rapid increase to 73% of the total rainfall (3.65 inches) would occur by the halfway point of the storm event.

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