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100-Year Rainstorms in the Midwest: Design Characteristics

by Floyd A. Huff

Midwestern Climate Center
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Abstract: This document provides pertinent information on the spatial distribution characteristics of extremely heavy rainstorm events in Illinois and the Midwest. Relations were developed for those storms in which maximum rainfall at the center equaled or exceeded the point maximum experienced on the average of once in 100 years or longer. The study was limited to this group of storms because of existing needs for information on these extreme storm events in the design and operation of water control structures in small basins. It is recommended for use in conjunction with Illinois State Water Survey Bulletin 70, Bulletin 71 (Midwestern Climate Center Research Report 92-03), and Water Survey Circular 173 for runoff computations related to the design and operation of runoff control structures in small basins subject to extreme rainfall events.

Area-depth relations were derived from information obtained through operation of several dense raingage networks, detailed field surveys and analyses of severe rainstorms in Illinois, analyses of heavy rainstorms in a six-basin hydroclimatic study, and exceptional storms recorded by the climate network of the National Weather Service in Illinois. Using data and information from these sources, curves defining spatial distributions for storms of various areal extent were derived. Results are presented in a form readily adaptable for use by hydrologists or other interested users.

Reference: Huff, Floyd A. 100-Year Rainstorms in the Midwest: Design Characteristics. Illinois State Water Survey, Champaign, Circular 176. 1993.

Indexing Terms: Extreme rainfall events, hydrometeorology, hydroclimatology, storm runoff, Midwest rainfall, spatial distributions, storm size, rain intensity.

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100-YEAR RAINSTORMS IN THE MIDWEST: DESIGN CHARACTERISTICS

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USER SUMMARY

The analytical results presented in this report are applicable primarily for those storms with maximum rainfall $\geq$ the amount expected to occur once in 100 years or longer, on average. The study was limited to this group of storms because of existing needs for information on these extreme storm events in the design and operation of water control structures in small basins.

This document provides the best available information on the spatial characteristics of extreme rainfall events, as measured in Illinois. The findings are also considered applicable to storms elsewhere in the Midwest, including Iowa, Missouri, Minnesota, Wisconsin, Michigan, Indiana, Ohio, and Kentucky. Within this region, both the macroscale and mesoscale characteristics of severe rainstorms are very similar. These storms are associated with the same types of major weather systems throughout the Midwest, and they occur mostly in the warm season from mid-spring to mid-fall.

The results are based on data from four sources: several dense raingage networks operating in Illinois between 1948 and 1980, detailed field surveys and analyses of severe storm events as part of the hydrometeorological research program of the Illinois State Water Survey, analyses of heavy rainstorms in a six-basin hydroclimatic study, and analyses of all exceptional storm occurrences recorded in Illinois using data from the climatic network of the National Weather Service beginning in the late 1890s.

Based on areal extent of the storms, the 100-year events were divided into two groups: (1) small-medium storms in which the 1-inch isohyet encompassed no more than 2000 square miles (sq mi), and (2) large storms that extended over areas of 2000 to 10,000 sq mi. Analyses were limited to the inner 2000 sq mi of the large storms, however, since the major purpose of the study was to furnish spatial distribution characteristics for relatively small basins and urban areas that might become exposed to one of these rare events.

Area-depth curves were derived from the isohyetal analyses of the storm samples. Computations were then made of the ratio of sub-area and total area mean rainfall to maximum rainfall at the storm center. This conversion was necessary to combine data from individual storms and to present the results in convenient formats.

Median spatial distribution curves were then developed for each of the two storm groups. For large storms, curves were derived for 3-, 6-, 12-, 24-, and 48-hour storm periods from 124 storms qualifying for inclusion in this study. The raingage density of the climatic network was inadequate to define spatial characteristics in the 100-sq-mi area surrounding the storm center. Consequently, the median values in this central region were determined from the data obtained from the dense raingage networks and the field survey storm analyses.

Small-storm samples were obtained from network operations and field surveys. Because of limited sample size (nine storms), a single median curve combining all storm durations≤24 hours was derived for this group.

Extreme events, as defined here, appear to occur most frequently in conjunction with small-medium storms. Analyses of dense raingage data suggest that about 85 percent of the occurrences are likely to be associated with smaller storm systems (isolated rainstorm events). Of the 16 storms identified in this study that produced maximum rainfall > 10 inches, however, 14 were associated with large storms that extend over several thousand square miles and are associated with a major convective system lasting from 6 to 24 hours.

The choice of which median distribution to use depends on user needs and requirements. For example, to estimate the maximum volume of rainfall that could conceivably occur in a flood-producing storm, the relation for large storms is recommended, regardless of the size of the basin or other area of interest. This type of storm generates the greatest rainfall during its lifetime for all sub-areas within its area of effect. To estimate the most likely spatial distribution that will occur with an extreme event, however, the relation for the small-medium storms is most appropriate for areas≤1000 sq mi. Most small-medium storms are confined to relatively small areas and are of relatively short duration compared to large-storm systems. The spatial distributions indicate how mean rainfall varies with distance from the storm center. These distributions are not and should not be used as estimates of areal mean rainfall frequency relations, however.

Spatial distribution relations and other information on storm characteristics presented in this report can be used in conjunction with point rainfall frequency relations (Huff and Angel, 1989, 1992) and time distribution relations (Huff, 1990) to construct scenarios of extreme storm events on small basins or other areas≤2000 sq mi.

INTRODUCTION

Background

There has been a growing demand for hydrologic data and information concerning extreme rainfall events on small basins (≤2000 sq mi), particularly for storms with return intervals of 100 years or more. Much of this demand is related to environmental concerns that have resulted in stricter requirements imposed by federal and state agencies on the design and construction of water control structures, such as storm sewer systems and dams.

The three most pressing hydroclimatic needs in the Midwest are information on rainfall frequency distributions and other pertinent data not previously available, reliable time distribution models, and reliable spatial distribution characteristics for heavy storms. Recent studies and associated publications have provided answers to two of these needs. Huff and Angel (1989) published results of a very extensive study on the frequency distributions and hydroclimatic characteristics of heavy rainstorms in Illinois. That report updates information on rainfall frequency distributions, and provides other pertinent data not previously available, such as the seasonal distribution of heavy rainfall events, urban effects on the frequency distributions, temporal changes in heavy rainfall frequencies in the state, frequency distributions encompassing all rainfall periods from 5 minutes to 10 days, and return periods ranging from 2 months to 100 years. A similar report (Huff and Angel, 1992) extends the Illinois study to eight other states in the Midwest (Iowa, Missouri, Minnesota, Wisconsin, Michigan, Indiana, Ohio, and Kentucky).

The advent of urban runoff models in the late 1960s and early 1970s placed new demands on hydroclimatologists. These models required definitions of the time distribution characteristics of rainfall during heavy storms. Reliable time distribution models appropriate for use on small basins in Illinois and the rest of the Midwest were not available until data from dense networks operated by the Water Survey were applied to the problem (Huff, 1967). In 1990, this initial small basin study was updated and expanded (Huff, 1990).

The third major hydroclimatic need is reliable information about the spatial distribution characteristics of heavy storms, especially those extremely severe storms that produce central amounts corresponding to rainfall intensities to be expected on the average of once in 100 years or more. This report provides information on this subject, and also addresses the need for storm information in the Midwest. The results should also be applicable to other geographic regions that experience heavy rainfall climates similar to those experienced in the Midwest.

Research in recent years has shown that most heavy rainstorms in the Midwest, and much of the rest of the nation, are directly associated with convective complexes, which are mesoscale storm entities that develop circulation patterns separate from the macroscale air mass in which they are embedded (Maddox et al., 1979; Maddox, 1980; Maddox and Deitrich, 1981; Huff, 1978). The mesoscale systems are usually integral parts of larger-scale storm systems. In the Midwest, the mesoscale systems are most commonly squall lines or extensive squall areas that develop in conjunction with stationary fronts, activity preceding cold fronts, and organized instability zones in moisture-laden air originating in the Gulf of Mexico (Huff, 1978). Because they have similar origins, extreme rainstorm events throughout the Midwest tend to have similar properties with respect to intensity, duration, area1 extent, rainfall volume, rainfall gradients, and temporal distribution of precipitation within the storms. They occur most commonly from mid-spring to mid-fall.

Acknowledgments

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DATA USED IN STUDY

As part of the hydroclimatic research of the Illinois State Water Survey, area-depth relations have been determined for the most intense Illinois storms in the twentieth century. Area-depth curves provide a method of investigating the spatial characteristics of rainstorms. The curve intercept provides an estimate of the maximum point rainfall, the slope indicates the rainfall gradient in the storm, and the endpoint of the curve shows the storm mean rainfall within a basin or other area of interest.

The study used information from the Water Survey's data bank, which contains information from four sources. The first source consists of detailed field surveys that were made during storms in which central amounts of rainfall usually exceeded the 100-year recurrence-interval amount for the location and duration of the storm. Detailed analyses were made of the surface characteristics of these storms and the synoptic weather conditions under which they occurred (Huff et al., 1958; Huff and Changnon, 1961). From this source, 31 storm samples were obtained from storms having recurrence intervals ≥100 years.

The second source of data was a detailed study (Huff, 1981) of hydroclimatic characteristics in major storms on six Illinois basins: the Kaskaskia, Sangamon, Big Muddy, Little Wabash, Embarras, and Spoon River basins. Of 85 storms analyzed in that study, 36 storms had rainfall amounts at one or more stations ≥ the 100-year frequency value and were included in the present study.

The third source of data was heavy storms occurring within the climatic network of the National Weather Service, formerly the U.S. Weather Bureau. From historical records, the Water Survey has analyzed a total of 330 storms over a period starting in the 1890s. Of these storms, 57 included maximum rainfall amounts ≥ the 100-year frequency value. These data have proven useful in the spatial distribution study. The data quality is not as good as that obtained from the two previous sources, however, primarily due to rather sparse raingage densities in the early records. Original observer records (W.B. Form 1009) were made available to the Water Survey by the State Climatologist of the National Weather Service. These records were very helpful in determining storm duration; the rainfall's beginning, end, and greatest intensity; and other useful information.

The fourth source of data was the dense raingage networks operated by the Water Survey since 1949. At various times, seven networks have been operated for periods ranging from 3 to 11 years in various parts of the state (Changnon and Huff, 1980). Network size varied from 10 to 4000 sq mi. Because of the networks' limited size and period of operation, only seven 100-year events were sampled at one or more raingages within the networks. This limited sample provided details of the spatial patterns that could not be obtained from records of the other sources, however. The network data have been especially helpful in determining spatial distribution characteristics in a 50-to 100-sq-mi area surrounding the storm center. Detailed measurements in this region were not possible with the data from the other sources.

Based on the area enclosed by the 1-inch isohyet, Huff (1978) divided extreme rainfall events into three groups: small storms (<600 sq mi), medium storms (600 to 2000 sq mi), and large storms (>2000 sq mi). Initially, these same divisions were used in grouping data for the present study. The small- and medium-storm samples were later combined into one group because of the small samples in each of these two groups.

Because they produced major property damage, interruption of normal activities, and related problems over relatively large regions, large storms received the most attention in the field survey. For example, the storm of August 16-17, 1959, was centered on the Little Egypt dense raingage network in southern Illinois, and its rainfall exceeded the 100-year, 25-year, and 5-year frequencies over areas of 250 sq mi, 1600 sq mi, and 3350 sq mi, respectively. The large-storm group (124 storms) also constituted the largest sample of storms qualifying for inclusion in the present study. The raingage spacing (15-20 miles apart) in the basin and in climatic network storms was not dense enough to adequately measure the spatial distribution of rainfall in smaller storms. Consequently, relatively few small and medium storms were available, and they were either centered on one of the dense raingage networks or within one of the large storms for which extensive field surveys had been performed.

METHOD OF ANALYSIS

After selecting a storm that qualified for inclusion in the area-depth storm sample, an isohyetal pattern was drawn after plotting all available observations. A planimeter was then used to measure the area of the isohyetal pattern to obtain mean rainfall amounts over various sub-areas within the storm. These sub-area means, the maximum observed point rainfall, and the total area mean were then used to derive a storm area-depth curve. In the heavy rainfall studies with which we are concerned here, it was assumed that the outer boundary of the storm was the area within the 1-inch isohyet. Analyses were limited to a 2000-sq-mi area surrounding the storm center, since the study was primarily concerned with small-basin relations.

In deriving an area-depth curve, the data were fitted to specific mathematical distributions to obtain the best estimate possible for the storm's spatial distribution. This method was especially pertinent in obtaining the best possible estimates of the maximum point rainfall and sub-area means near the storm center. The number of observations used to establish points on the curve decreases from total-area mean to maximum point rainfall, thereby increasing potential sampling error.

For a storm area-depth curve, the mathematical distribution providing the best fit will differ substantially between storms. This is due to meteorological differences in storm system characteristics, which dictate the system's intensity, duration, rainfall gradient, areal extent, and other properties. Huff (1968) discussed this problem using data from a dense raingage network (1 gage/9 sq mi) on a 400-sq-mi area to investigate best-fit equations for deriving area-depthrelations. Eight different equations were found to contribute substantially to the best-fit curves in a sample of 562 network storms.

The foregoing curve-fitting procedure was applied in determining area-depth curves for each storm that qualified for the extreme event study (maximum rainfall ≥ 100-year frequency). To facilitate further analyses, individual area-depth relations were then converted to area-depth ratios. The ratios were calculated by dividing the sub-area means and the maximum point rainfall by the total area mean. In storms for which data were adequate to perform the analysis, the above procedure was also applied to partial storm periods (3-hour, 6-hour, etc.) within the total storm period. The partial storm analysis was performed primarily on data from the field survey and network data for which more accurate time distribution information was available.

For most hydrologic applications, users prefer to relate the spatial distribution characteristics to rainfall at the storm center. The original area-depth ratio curves are easily converted to this form. The spatial distribution relations provided in this report are expressed as ratios of sub-area and total area means to maximum point (storm center) rainfall.

Initially, area-depth ratio relations were developed separately for the field survey, six basins, and climatic network samples. The network sample was too small for separate treatment, however. For sub-areas >100 sq mi, there were no significant differences between the three sets of relations. The field-survey sample, for which more detailed information was available, however, indicated computed values of storm-center rainfall that exceeded the values for the other two samples. Because the field-survey values were supported by 100-year events available from the dense raingage operations, the four sets of data were combined. The field-survey and network ratios were used to determine means and medians for sub-areas

≤100 sq mi, however. Water Survey studies have indicated no preferential geographic location for these storms, so they were included in a single sample.

In the large-storm analyses, the resulting regression curves for 3- to 48-hour storm periods were found to be closely approximated by an expression in which the area-depth ratio was related to the cube root of the area. The general form is therefore:

$$Y = a + b X^{0.33} \tag{1}$$

where Y is the area-depth ratio, X is area, and a and b are regression coefficients.

Figure 1 shows the application of the above cube root curve to median sub-area values for 12-hour storm periods. Similar curves (not shown) were derived for other selected storm periods (3, 6, 24, and 48 hours). In deriving the curves, storm periods of 3 to 9 hours were used for the 6-hour relation. Similarly, storm periods of 9 to 15 hours were used for the 12-hour relation, 18 to 30 hours for the 24-hour relation, and 36 to 60 hours for the 48-hour relation. The 48-hour sample was small. Extreme events usually last <36 hours, and the majority <24 hours.

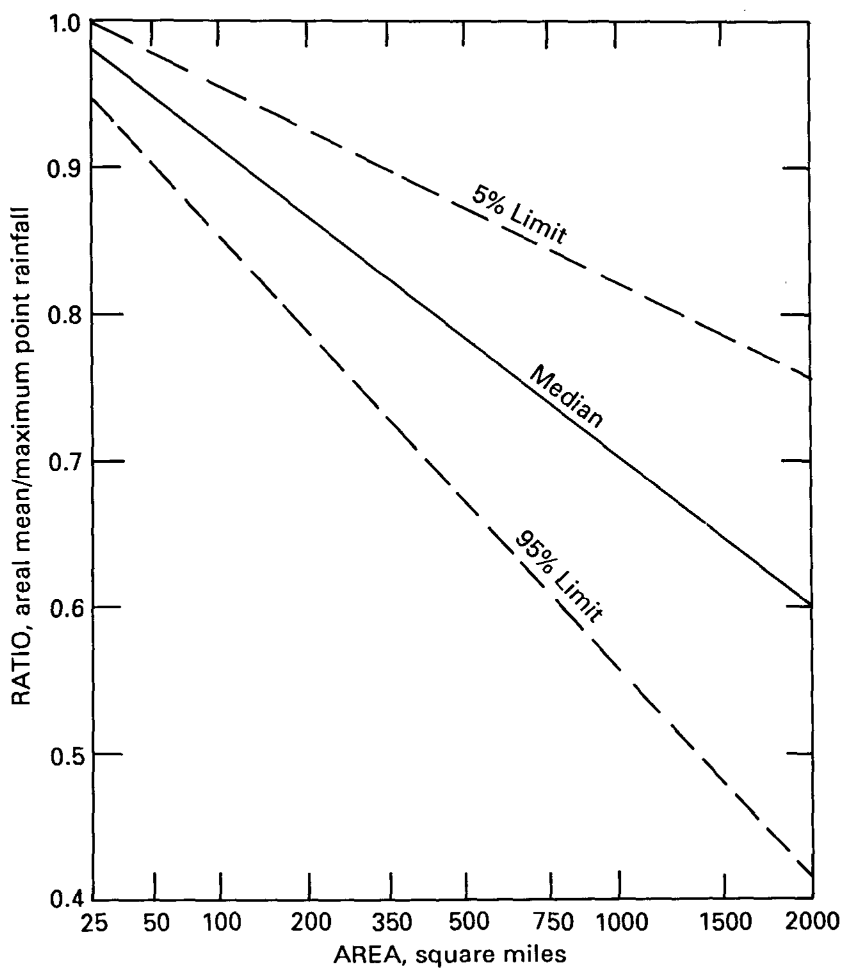

Figure 1. Median curve and curves enveloping 90 percent of all storms in the sample for 12-hour, large storms

RESULTS OF SPATIAL ANALYSES

Large Storms

Following the procedure discussed in the previous section, regression curves were determined for 3-, 6-, 12-, 24-, and 48-hour storm periods. Table 1 was then constructed from the curves for the median spatial distribution. The mean was also determined from the data samples, but differences from the median curves were minor. Table 1 can be used in hydrologic problems in which an estimate of the spatial distribution is required for extreme rainstorms with central (maximum) amounts ≥ the 100-year frequency value. Users should realize that considerable variation in the spatial distribution characteristics may exist between individual storms. This is illustrated in figure 1, which shows the median curve for 12-hour storm periods, along with curves that incorporate 90 percent of all storms in the sample.

Tables 2-5 provide examples of variations in spatial distributions for 24-, 12-, 6-, and 3-hour storm periods, respectively. All examples are from the field-survey group of storms, which is considered best from the standpoint of spatial detail and computation accuracy. At the bottom of these tables, a comparison is given between the medians of the table examples and those obtained for the total storm sample (124 storms). In general, the differences are very small.

Table 1. Median Spatial Distribution in Extreme Rainfall Events for Large Storms with Recurrence Intervals ≥ 100 Years

	Ratio, areal mean/point maximum rainfall for given storm period				
Sub-area (sq mi)	*3-hour*	*6-hour*	*12-hour*	*24-hour*	*48-hour*
25	0.95	0.97	0.98	0.98	0.99
50	0.92	0.93	0.95	0.95	0.97
100	0.88	0.90	0.92	0.92	0.94
200	0.83	0.85	0.87	0.88	0.91
350	0.78	0.81	0.83	0.85	0.88
500	0.74	0.76	0.78	0.81	0.85
1000	0.65	0.67	0.70	0.74	0.79
1500	0.60	0.62	0.65	0.69	0.75
2000	0.55	0.57	0.60	0.65	0.72

Table 2. Examples of Ratio Relation in 24-Hour Storm Periods with Point Maxima ≥ 100-Year Frequency

Date	*Point maximum (in.)*	*100-year frequency (in.)*	*Ratio, area1 mean/point maximum rainfall for given area (sq mi)* 25	50	100	200	500	100	1500	2000
8/16/59	10.5	8.3	0.98	0.96	0.93	0.90	0.84	0.76	0.73	0.70
6/l4/57	16.8	8.2	0.98	0.95	0.90	0.85	0.74	0.65	0.60	0.55
6/27/57	12.8	7.4	0.97	0.94	0.90	0.87	0.80	0.73	0.70	0.66
7/12/57	11.6	7.6	0.97	0.95	0.92	0.89	0.82	0.75	0.71	0.66
5/21/57	8.2	7.7	0.96	0.95	0.93	0.89	0.83	0.77	0.73	0.70
10/9/54	11.8	7.6	0.99	0.98	0.96	0.92	0.87	0.84	0.80	0.76
8/l4/46	16.5	8.2	0.98	0.96	0.93	0.90	0.82	0.77	0.70	0.65
7-storm median	-	-	0.98	0.95	0.93	0.89	0.82	0.76	0.71	0.66
Table 1 estimates	-	-	0.98	0.95	0.92	0.88	0.81	0.74	0.69	0.65

Table 3. Examples of Ratio Relation in 12-Hour Storm Periods with Point Maxima ≥100-Year Frequeny

Date	*Point maximum (in.)*	*100-year frequency (in.)*	*Ratio, area1 mean/point maximum rainfall for given area (sq mi)* 25	50	100	200	500	1000	1500	2000
8/16/59	9.5	7.2	0.98	0.96	0.93	0.88	0.82	0.74	0.69	0.65
6/14/57	16.6	7.1	0.98	0.95	0.89	0.83	0.72	0.63	0.58	0.52
6/27/57	12.4	6.5	0.97	0.93	0.88	0.83	0.75	0.68	0.64	0.60
7/12/57	10.4	6.6	0.97	0.95	0.92	0.88	0.82	0.72	0.68	0.64
7/8/51	12.6	6.0	0.9	0.90	0.84	0.78	0.70	0.62	0.57	0.53
5-storm median	-	-	0.97	0.95	0.89	0.83	0.75	0.6	0.64	0.60
Table 1 estimates	-	-	0.98	0.95	0.92	0.87	0.78	0.70	0.65	0.59

Table 4. Examples of Ratio Relation in Q-Hour Storm Periods with Point Maxima ≥100-Year Frequency

Date	*Point Maximum (in.)*	*100-year frequency (in.)*	*Ratio, area1 mean/point maximum for given area (sq mi)* 25	50	100	200	500	1000	1500	2000
6/14/57	12.9	6.2	0.98	0.91	0.84	0.76	0.63	0.51	0.45	0.39
6/27/57	9.0	5.6	0.96	0.92	0.88	0.84	0.76	0.69	0.65	0.60
7/12/57	7.1	5.7	0.98	0.96	0.93	0.88	0.82	0.72	0.67	0.62
7/8/51	12.4	5.2	0.95	0.88	0.83	0.76	0.69	0.60	0.56	0.52
4-storm median	-	-	0.97	0.92	0.86	0.80	0.73	0.65	0.61	0.60
Table 1 estimates	-	-	0.97	0.93	0.90	0.85	0.76	0.67	0.62	0.61

Table 5. Examples of Ratio Relation in 3-Hour Storm Periods with Point Maxima ≥ 100-Year Frequency

Date	Point maximum (in.)	100-year frequency (in.)	Ratio, areal mean/point maximum rainfall for given area (sq mi)							
			25	50	100	200	500	1000	1500	2000
6/14/57	9.0	5.2	0.97	0.91	0.83	0.74	0.61	0.49	0.43	0.38
6/27/57	4.7	4.7	0.95	0.91	0.89	0.85	0.78	0.72	0.69	0.66
7/l2/57	5.3	4.8	0.96	0.94	0.90	0.85	0.75	0.68	0.62	0.56
7/8/51	7.9	4.4	0.96	0.91	0.86	0.79	0.67	0.57	0.52	0.47
4-storm median	-	-	0.96	0.91	0.88	0.83	0.71	0.63	0.57	0.51
Table 1 estimates	-	-	0.95	0.92	0.88	0.83	0.74	0.65	0.60	0.55

Small-Medium Storms

Table 6 shows the spatial distribution in nine small-medium storms, along with the unadjusted group median, the group mean, and the adjusted median distribution. The unadjusted median was obtained from use of only those storms with maximum rainfall ≥ the 100-year frequency. When spatial distributions were derived for storms of lesser intensity (tables 7-8), it was found that the spatial distribution characteristics changed very slowly with increased storm intensity (longer recurrence-interval values). To take advantage of the much larger samples from less intense storms, a weighting procedure was used to adjust the small-medium sample. This resulted in the *adjusted median distribution* in table 6, which should be employed by users of the information in this report. No discernible trend was indicated for the spatial distribution characteristics to change with increasing duration among storms ≤ 24 hours. Therefore, in deriving tables 6-8, all small-medium storms were combined to calculate the median distributions. These storms usually have durations of <12 hours, and the majority last <6 hours. They are not associated with major synoptic systems, but rather with mesoscale disturbances that normally dissipate within several hours.

The medians were found to fit a regression curve in which the spatial ratios (sub-area mean/ maximum point rainfall) were related to the 0.25 root of the area:

$$Y = a + b\,X^{0.25} \qquad (2)$$

Small-medium storms are normally more skewed than large storms, as is reflected in best-fit equations (1) and (2). Huff (1978) has pointed out that small storms are usually much shorter in duration (2 to 8 hours) than large storms (6 to 48 hours), and they have steeper rainfall gradients than large storms.

There is also considerable interest in the spatial distribution in other heavy rainstorms on urban areas and very small watersheds yielding amounts that occur more frequently than at 100-year intervals. In response to this need, tables 7 and 8 have been derived from analyses of all the relatively heavy storms on the various dense networks that have been operated in Illinois in the past. In these tables, the underlined numbers represent total basin area. Ratios of areal mean to maximum point rainfall are provided for selected sub-areas in each basin and for the total basin area. Thus, in table 7 for the 400-sq-mi basin, the sub-areas

Table 6. Spatial Distribution of Rainfall in Small to Medium Storms with Maximum Rainfall ≥100-Year Frequency

Date	*Point maximum (in)*	*100-year frequency (in)*	*Median ratio, sub-area mean/point maximum rainfall for given area (sq mi)*						*Storm duration (hours)*
			25	*50*	*100*	*200*	*500*	*1000*	
7/19/76	8.5	6.3	0.97	0.94	0.88	0.82	0.69	0.58	8
5/7/61	115	5.2	0.82	0.73	0.64	0.55	0.43	0.35	6
5/26/56	9.2	5.0	0.93	0.86	0.76	0.65	0.48	0.34	6
7/18/52	10.5	5.7	0.91	0.83	0.74	0.65	0.51	-	6
8/1/58	3.7	3.1	0.88	0.76	0.60	0.44	-	-	1
6/6/61	4.8	4.5	0.81	0.65	0.52	0.38	0.22	-	4
6/13/67	7.5	4.5	0.88	0.82	0.73	0.63	-	-	4
6/2067	5.2	3.2	0.85	0.73	0.59	0.41	-	-	2
6/13/76	6.4	5.1	0.96	0.94	0.84	0.78	-	-	4
Median (unadjusted)	-	-	0.88	0.82	0.73	0.63	0.48	0.35	4
Mean	-	-	0.88	0.81	0.70	0.59	0.47	0.42	5
Median (unadjusted)	-	-	0.91	0.83	0.75	0.66	0.49	0.34	

Table 7. Spatial Distribution of Heavy Rainfall on Small Basins (50 to 400 sq mi) in Storms with Maximum Point Rainfall ≥2-Year Frequency, Basin Mean Rainfall >1 Inch, and Storm Periods ≤24 Hours

Median ratio, sub-area mean/point maximum rainfall for given area (sq mi)					
25	*50*	*100*	*200*	*300*	*400*
0.96	0.88	0.81	0.73	0.65	<u>0.59</u>
0.93	0.86	0.78	<u>0.67</u>		
0.93	0.85	<u>0.74</u>			
0.91	<u>0.82</u>				

Note: The median values were derived from 67 storm samples. Underlined numbers represent total basin area.

Table 8. Spatial Distribution of Heavy Rainfall on Small Basins (50 to 400 sq mi) in Storms with Maximum Point Rainfall ≥10-Year Frequency, Basin Mean Rainfall >1 Inch, and Storm Periods ≤24 Hours

Median ratio, sub-area mean/point maximum rainfall for given area (sq mi)					
25	*50*	*100*	*200*	*300*	*400*
0.93	0.85	0.76	0.65	0.60	<u>0.55</u>
0.91	0.80	0.70	<u>0.60</u>		
0.88	0.75	<u>0.60</u>			
0.85	<u>0.68</u>				

Note: The median values were derived from 67 storm samples. Underlined numbers represent total basin area.

are 25, 50, 100, 200, and 300 sq mi. The ratios on the areas of heaviest rainfall decrease gradually from 0.96, 0.88, 0.81, 0.73, and 0.65, respectively, to 0.59 for 400 sq mi (entire basin).

Table 7 shows the median spatial distribution on 50- to 400-sq-mi areas by combining all storms having central amounts ≥ the 2-year frequency, areal mean rainfall > l inch, and durations ≤ 24 hours. The median values were derived from approximately 220 storm samples. This table is applicable to isolated severe rainstorms described by Changnon and Vogel (1981). Typically, these storms produce storm center amounts in a range from 3 to 8 inches, with most of the heavy rain occurring within two to three hours. It is estimated that these storms, causing localized flash floods and producing substantial damage to property and crops, occur, on the average, of once per 1500 sq mi per year.

Table 8 is similar to table 7, but it is based on 67 storms with maximum rainfall ≥ the 10-year frequency. Comparing tables 7 and 8, rainfall intensity decreases faster with distance from the storm center as the overall intensity of storms increases (≥2-year to ≥10-year frequency). However, in comparing tables 6 and 8, there appears to be only a relatively small difference in the rate of rainfall decrease near the storm centers (25- to 200-sq-mi sub-area). Reference to table 1 shows that rainfall decreases with distance from the storm center at a much slower rate than for large storms.

Application of Results

Tables 1 and 6 provide information on the spatial distribution characteristics of individual storms. They *do not* provide estimates of the frequency distribution of areal mean rainfall for various basin sizes. Such estimates for 10- to 400-sq-mi areas are given in Water Survey Bulletin 71 (Huff and Angel, 1992).

Tables 1 and 6 were derived to show how the area1 mean rainfall decreases from the storm center outward to the boundaries of the basin or other area of interest in extremely heavy rainfall events. It was necessary to derive two separate relations, one for large storms and another for small storms, because 100 year point rainfall values can occur with either storm type, and the spatial distribution characteristics vary significantly between them. In fact, the two separate relations represent two meteorologically different types of storm systems. Median relations are shown in tables 1 and 6, since hydrologists are usually most interested in applying a typical sequence of storm values. The median and mean values do not vary significantly. The median was selected because it is more amenable to statistical computations; for example, computation of the variance in the distributions, as illustrated in figure 1.

The applications of tables 1 and 6 are illustrated by the examples in table 9. First, assume that a hydrologist or other user is interested in the spatial distribution of rainfall in a 12-hour large storm centered at Peoria, Illinois, in which the maximum rainfall in the storm center is equal to that for the 100-year frequency. Reference to Water Survey Bulletin 70 (Huff and Angel, 1989) indicates that the value for the 100-year frequency is 6.44 inches. After applying the median ratios of table 1, the area-depth relation indicated in table 9 is obtained.

Next, assume a user is interested in the spatial distribution (area-depth relation) in a small storm enveloping 500 sq mi, in which the 6-hour rainfall is equal to that for the 100-year frequency at Peoria, 5.55 inches. Use of the adjusted median ratios shown in table 6, gives the area-depth relation in table 9.

Table 9. Application of Tables 1 and 6 Using 100-year Frequency Amounts at Peoria, Illinois

Storm type	Duration (hours)	Point maximum (in.)	Mean rainfall (in.) for given sub-area (sq mi) 25	50	100	200	500	1000	1500	2000
Large	12	6.44	6.31	6.12	5.92	5.68	5.02	4.51	4.19	3.86
Small	6	5.55	5.05	4.61	4.16	3.56	2.72			
Large	6	5.55	5.38	5.16	4.99	4.72	4.22	3.72	3.44	3.16

The third example shows the area-depth relation obtained for a 6-hour large storm centered at Peoria. Note the more rapid rate of decrease in mean rainfall in the small storm as distance from the storm center increases. As indicated previously, the rainfall gradient is steeper in small rather than large extreme events.

The three previous examples illustrate how to use the tables to determine typical spatial distributions in extreme rainstorm events. The user's next decision is whether to use table 1 or table 6 in specific situations; Use of table 1 is recommended if the basin of interest encompasses ≥ 1000 sq mi. Small-medium storms are usually contained within 1000 sq mi. This table was obtained from analysis of those storms producing maximum amounts≥the 100-year recurrence-interval value and ≥1 inch in an area ≥ 2000 sq mi surrounding the storm center.

As indicated previously, table 6 was primarily derived from events that extended over areas ≤ 2000 sq mi, with intervals ≥ 100-year frequency. However, two-thirds of the sampled storms were limited to areas ≤500 sq mi. Approximately 80 percent were contained within 1000 sq mi. The small-medium storm relations had to be derived from a much smaller sample than table 1, because the climatic network does not have sufficient gage density to identify and define the spatial distribution characteristics in these relatively small extreme rainfall events. Although the values in table 6 are not as well established as the values in table 1, table 6 provides the best estimate for ascertaining typical or average spatial properties in *small storms* extending over basins ≤1000 sq mi.

The rainfall gradient is greater in the small-medium storm model than in the large-storm model. In some cases, the user may want to calculate differences obtained with the two tables when applied to a small basin or urban area. For example, assume that a design project requires estimates for a 400-sq-mi basin (about the size of the central urban area of Chicago), in which the basin mean rainfall in a 6-hour storm produces a maximum rainfall of 10 inches. Table 6 indicates a typical mean of 5.5 inches. However, by assuming that this storm is part of a large-storm event, use of table 1 is indicated, which shows a mean of 7.9 inches for a 6-hour storm encompassing 400 sq mi. The difference, approximately 44 percent, will produce substantially different values of storm runoff. Unfortunately, it is not possible to predict whether a large or a small storm would prevail if a 10-inch point rainfall occurs.

The probability of a small storm occurring is greater than that of a large storm, but it is still extremely small. For example, analysis of records from seven Illinois raingage networks together representing more than 40 data years of record, identified only seven storms ≥ the 100-year frequency. Six of these seven storms (about 85 percent) were small-medium storms. However, “super” storms with maximumrainfall amounts >10 inches were predominately large storms.

Changnon and Vogel (1981) analyzed 33 years of network records in their frequency study of isolated severe rainstorms. They selected storms ≤ the 48-hour duration with a 3-hour point rainfall maximum exceeding the 25-year frequency value, and a 12-hour point value exceeding the 10-year frequency value. They found 32 storms, among them the six small-medium storms and the one large storm that qualified for inclusion in the present study. From their study, Changnon and Vogel estimated that one of their qualifying storms occurs on the average of once per 1500 sq mi per year for a total of about 40 such storms per year in Illinois. The probability of such a storm is more than five times greater than the probability of a similar 100-year event, based on the network occurrences (6 out of 32 storms). This suggests as a rough approximation that one of the small extreme events may occur on the average of once per 8,000 sq mi, or about seven such storms per year in Illinois, compared with about one large storm per year in Illinois.

However, if the user is concerned with the maximum flood-producing storm that could conceivably occur on a specific basin, the large-storm model is the better choice, regardless of basin size. This model is more statistically reliable because it is based on a larger storm sample. It yields larger amounts of rainfall throughout the area of interest. It can also conceivably occur at a specific location even though the probability is very small. For example, among 16 storms identified in this study with maximum rainfall amounts >10 inches, 14 (87 percent) occurred in large storms. Tables 2-5 provide excellent examples of the spatial distribution characteristics in these relatively large storm systems. They also provide a measure of the variability between storms of the same duration. Table 6 provides similar information for small storms.

Related Storm Factors

In addition to the spatial distribution characteristics, other important factors in assessing the flood potential of extreme rainfall events include areal mean rainfall and the orientation, shape, and movement of storms. Time distribution characteristics, also very important, are provided in Water Survey Circular 173 (Huff, 1990). Information on the other related factors has appeared previously in various reports and papers, but it is briefly summarized here because of its importance in the spatial distribution processes of major storm systems.

Point-Areal Mean Rainfall Relations

Relations between point and areal mean rainfall on small basins have been discussed in several previous publications (Huff, 1956; Hershfield, 1961; Huff and Vogel, 1976; Huff and Angel, 1992). Relations for areas of 10 to 400 sq mi are presented in table 10. Although derived from Illinois dense network data for several hundred storms, they should also be representative of the Midwest in general.

Huff (1981) used data from isohyetal analyses of heavy storms on six basins to obtain approximations of the frequency distribution of areal mean rainfall on areas of 1000 to 5000 sq mi for recurrence intervals of 2 to 100 years. These approximations were then compared with the point rainfall frequencies to determine whether the relations shown in table 10 could be extended to larger areas. The results indicated only a weak correlation between point and areal mean rainfall frequencies in the larger areas. Thus, it appears that the relations shown in table 10 cannot be extended to areas ≥1000 sq mi. It is recommended that table 10 not be extrapolated beyond 600 sq mi when applied in water control design projects or

Table 10. Relation between Areal Mean and Point Rainfall Frequency Distributions

Storm period (hours)	Average ratio of areal to point rainfall for given area (sq mi)					
	10	25	50	100	200	400
0.5	0.88	0.80	0.74	0.68	0.62	0.56
1.0	0.92	0.87	0.83	0.78	0.74	0.70
2.0	0.95	0.91	0.88	0.84	0.81	0.78
3.0	0.96	0.93	0.90	0.87	0.84	0.81
6.0	0.97	0.94	0.92	0.89	0.87	0.84
12.0	0.98	0.96	0.94	0.92	0.90	0.88
24.0	0.99	0.97	0.95	0.94	0.93	0.91
48.0	0.99	0.98	0.97	0.96	0.95	0.94

other applications. Unfortunately, adequate data are not available for determining areal mean rainfall frequency relations on larger areas in the Midwest.

The user should recognize that table 10 does not provide reduction factors for use in runoff computations. Tables 1 and 6 do serve this purpose, however. Table 10 was derived from rankings of point and areal mean rainfall. Equivalent rank values do not necessarily come from the same storm system. That is, rank 1 for 50-, 100-, and 200-sq-mi areas may not have been associated with the same storm, but rather with different storms. Table 10 was developed to provide users a means for estimating mean rainfall frequency relations on small basins or other areas of interest. As indicated earlier, the point-areal relations apparently deteriorate when the storm-effect areas increase to 1000 sq mi or more.

Storm Orientation

An important factor in determining the flood potential of a specific storm event is the orientation of the rainfall pattern. For example, if the axes of heavy rainstorms tend to be parallel to a river basin or other area of concern, then the total runoff will be greater than in regions that are usually perpendicular to storm systems that pass. Storm orientation also provides an indication of the movement of the major precipitation-producing entities embedded in any large-scale weather system (Huff and Angel, 1989). The distribution of orientations in heavy rainstorms of various intensity is shown in table 11. The 16 storms with maximum rainfall ≥10 inches all exceeded the 100-year value of point rainfall for all storm periods ≤ 48 hours in Illinois and the other eight states (Iowa, Wisconsin, Minnesota, Michigan, Indiana, Ohio, Missouri, and Kentucky) comprising the Midwest climate region (Huff and Angel, 1992). The 16-storm sample was obtained from field surveys in Illinois and from long-term climatic records.

The 34-storm sample in table 11 was also obtained from field surveys and long-term climate records of the National Weather Service. These storms had central amounts ≥8 inches, which exceeds the 50-year recurrence interval value throughout the nine-state area. Those storms having maxima ≥5 inches all exceeded the 5-year frequency of point rainfall in the Midwest region.

The 262-storm sample for our study was obtained from dense raingage network operations, field surveys, and long-term climatic records. The median azimuths in table 11 show a slight veering from 270°

Table 11. Distribution of Orientations in Heavy Rainstorms with Durations ≤48 Hours

Azimuth (degrees)	*Total occurrences in storms with maximum point rainfall indicated (percent)* ≥*10 inches*	≥*8 inches*	≥*5 inches*
180-229	0	3	5
230-249	6	15	17
250-269	25	29	27
270-289	38	24	22
290-309	25	20	19
310-329	6	6	6
330-360	0	3	4
Median azimuth	280	275	270
Number of storms	16	34	262

(storms producing 5 inches of rainfall) to 280° (storms producing 10 inches of rainfall). This trend is believed to result from the greater influence of high-level winds on steering the stronger storms. The more intense storms tend to build to higher levels (Huff, 1967), and the wind tends to veer with height in Midwest storms.

Storm Shape

When viewed in their entirety, heavy rainstorms usually exhibit an elliptical shape. This shape tends to become more elongated (increasing ratio of major to minor axis) as the area encompassed by the storm increases. The elliptical shape has been found to be predominant in various Illinois studies involving rain-gage networks, field surveys, and long-term climatic records (Stout and Huff, 1962; Huff, 1967; 1975). Table 12 shows average shape patterns for heavy rainstorms on areas ranging from 50 to 5000 sq mi. The ratios are applicable for rainstorms having durations ≤48 hours. The ratios were determined for the storm area within the 1-inch isohyet. Maximum rainfall amounts for all storms exceeded the 2-year frequency of maximum point rainfall at the storm center.

Storm Movement

In Illinois and other Midwest states, extreme events are usually produced by one or more squall lines or squall areas traversing a basin or other area of interest. These mesoscale systems are most frequently spawned by macroscale weather systems, such as cold fronts or stationary fronts. The mesoscale systems consist of a number of individual convective entities, usually thunderstorms. These entities, often referred to as raincells, have a motion that is strongly related to the wind field in which they are embedded. The extreme rainfall events at the surface are then produced by a series of these unusually intense entities, which are maximized in the same general area. Network studies of the motion of heavy raincells (Huff, 1975) have provided the frequency distribution of cell movements shown in table 13. The most frequent cell movements, from west-southwest through west to west-northwest, were associated with 42 percent of the 659 cells analyzed. Note that the most frequent motion of the raincells corresponds closely with the predominant storm orientations in table 11. As might be expected, there is a relatively strong relation between orientation of the surface rainfall pattern and the movement through the atmosphere of the convective entities responsible for the heavy surface rainfall.

Table 12. Average Shape of Heavy Rainstorms

Area enclosed (sq mi)	*Ratio, major to minor axis*
50	2.14
100	2.27
200	2.56
500	2.92
1000	3.19
2000	3.47
5000	3.72

Table 13. Frequency Distribution of Heavy Raincell Movements

Azimuth (degrees)	*Storms (percent)*	*Azimuth (degrees)*	*Storms (percent)*
180-209	6	0-29	4
210-239	16	30-59	2
240-269	22	60-89	2
270-299	20	90-119	2
300-329	13	120-149	2
330-359	7	150-179	4

Statistical Models of Flash Flood Storms

From extensive field surveys and analyses of outstanding network storms, statistical characteristics of typical Midwest flash floods have been derived. These models provide a source of pertinent information for hydrological models used in the design of flood protection structures. In deriving the models, storms were divided initially into three types: large storms (area > 2000 sq mi), medium storms (area = 600 to 2000 sq mi), and small storms (area < 600 sq mi).

The large-storm model is described in table 14. Large storms produce most of their rainfall within a 12-hour period. They tend to start in early evening, reach maximum intensity before midnight, continue with intense rainfall for about six hours, and dissipate near sunrise. The rainfall pattern most often approaches a west-east orientation as indicated in table 11. The pattern is most frequently elliptical with a major-minor axis ratio of 3.80 (close to the 5000-sq-mi average in table 12). Squall line or squall areas tend to cross the storm location every two to three hours, and about five of these mesoscale systems will cross during the life of the storm.

Because of the relatively small number of samples, the small and medium storms were combined. A statistical model of these smaller storms with about a 4-hour average duration is provided in table 15. These storms tend to start in late afternoon and quickly reach maximum intensity. Their heavy intensities last about three hours, on the average. They commonly envelop an area of approximately 500 sq mi, have a west-southwest to east-northeast orientation, produce approximately six major bursts about 30 minutes apart, and have a shape ratio of 2.90. The foregoing statistical models were abstracted from Huff (1979).

Table 14. Storm Characteristics of Statistical Model of 12-Hour Maximum Rainfall in Large Severe Rainstorms

Starting time: 1900 CST
Start of heaviest rain intensities: 2200 CST
Duration of heaviest storm intensities: 6 hours
Area enveloped: 5000 sq mi
Orientation of surface rainfall pattern: 265-085 degrees
Ratio, major/minor axis of rainfall pattern: 5.80
Number of individual substorm elements
(squall lines or areas): 5
Average frequency of substorm elements: 24 hours

Note: CST is Central Standard Time.

Table 15. Storm Characteristics of Statistical Model of Small-Medium Severe Rainstorms

Storm duration: 4 hours
Starting time: 1600 CST
Start of heaviest rain intensities: 1630 CST
Duration of heavy rain intensities: 3 hours
Area enveloped: 500 sq mi
Orientation of surface rainfall pattern: 260-280 degrees
Ratio, major/minor axis of rainfall pattern: 2.90
Number of bursts or merging cells: 6
Average frequency of bursts: 0.5 hours

Note: CTS is Central Standard Time.

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