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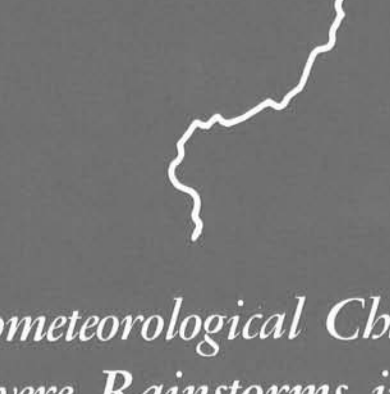
REPORT OF INVESTIGATION 90

LLINOIS

STITUTE OF NATURAL RESOURCES

Hydrometeorological Characteristics of Severe Rainstorms in Illinois

by FLOYD A. HUFF



ILLINOIS STATE WATER SURVEY

URBANA

1979

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Reference: Huff, Floyd A. Hydrometeorological Characteristics of Severe Rainstorms in Illinois. Illinois State Water Survey, Urbana, Report of Investigation 90, 1979.

Indexing Terms: Climatology, heavy rainstorms, hydrometeorology, rainfall frequency distributions, rainfall intensity, storm characteristics.

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CONTENTS

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Floyd A. Huff

ABSTRACT

This report provides a summary of available information on heavy rainstorms in Illinois obtained from analyses of data from various sources. These include climatological records of the National Weather Service, field surveys of severe rainstorms by the State Water Survey, and data collected from operation of several dense raingage networks in the state beginning in 1948. The major objective is to provide information useful in hydrologic design projects. Primary emphasis is placed on the frequency distribution of areal mean rainfall in severe rainstorms having durations of 6 to 48 hours and producing excessive amounts over areas of 25 to 10,000 square miles. However, information is also provided on other important storm factors, such as their shape, orientation, movement, and time distribution characteristics.

INTRODUCTION

The primary purpose of this report is to provide heavy rainfall information which may serve as a guide in hydrologic design projects in Illinois. A major problem of the design engineers is to determine a practical value for the design storm where maximum protection against structural failure is required. Structures whose design is based on the extremely large values of 'probable maximum rainfall' in Illinois, as calculated by the U. S. Weather Bureau (Riedel et al., 1956), are extremely costly, at least for the type of structures required for most purposes. One pertinent question, then, is what is the probability of occurrence of the 'probable maximum rainstorm' — is it a logical basis for design of high risk structures? This report is devoted primarily to presentation of data which may be used as a guide in answering this question, and others confronting hydrologists.

Results of several research studies concerned with the distribution of severe rainstorms in Illinois are presented in this report. These studies were made to provide refinement of hydrometeorological relations that are pertinent to hydrological applications in Illinois. Relationships presented are subject to modification as additional data are collected and further research conducted.

Metric units have not been used in this report because all of the analyses, carried out over a considerable span of years, were made in English units. Furthermore, much of the hydrologic design work in the United States is still carried out with the familiar English system of measurements. Conversion to metric units is a simple task for the reader who may prefer that system.

Acknowledgments

This report was prepared under the direction of Stanley A. Changnon, Jr., Head, Atmospheric Sciences Section, and William C. Ackermann, Chief, Illinois State Water Survey. Drafting of the illustrations was performed by John Brother and technical editing by J. Loreena Ivens; Marilyn J. Innes prepared the camera copy. Numerous research assistants helped with the routine analysis of the large amounts of data involved in preparation of the report.

PROBABLE MAXIMUM RAINFALL

For later comparisons with results of Water Survey research studies, values of probable maximum rainfall in Illinois, calculated by the U. S. Weather Bureau (Riedel et al., 1956), are shown in table 1 for storm periods of 6 to 48 hours and areas of 10 to 1000 square miles. Data are presented for each of the four sections shown in figure 1, which represent regions of similar rainfall climate in the state as determined by previous studies (Huff and Neill, 1959).

By Weather Bureau definition, the probable maximum precipitation represents the critical depth-duration-area relations that would result if conditions during an actual storm were increased to represent the most critical meteorological conditions that are considered probable of occurrence. The critical meteorological conditions are based upon evaluation of air mass properties (precipitable water, depth of inflow layer, wind, temperature, etc.), synoptic situations which might exist, topography, season of occurrence, and location of region. All factors are maximized for the given region to determine the maximum rainfall intensity; that is, the most effective combination of the various factors controlling rainfall intensity is selected. As will be shown later, studies of all available rainfall records in Illinois beginning in 1887 indicate that the probable maximum rainfall has not been closely approached within the state.

Relation of 100-Year Storm to Probable Maximum Storm

In Bulletin 46 and Technical Letter 13 of the Water Survey (Huff and Neill, 1959; Ackermann, 1970), estimates of the point rainfall frequency distribution for each of the four sections of figure 1 have been provided. As a guide in evaluating the rarity of the probable maximum storm, the mag-

Table 1. Probable Maximum Precipitation in Illinois*

Storm duration (hours)	*Average depth (inches) for given area (mi^2)*						
	10	*25*	*50*	*100*	*200*	*500*	*1000*
Northwest Section							
6	25.0	22.9	21.2	19.5	17.8	15.7	14.0
12	27.9	25.6	23.8	22.1	20.3	17.9	16.1
24	30.6	28.2	26.3	24.4	22.5	20.0	18.1
48	32.8	30.4	28.5	26.7	24.7	22.2	20.2
North Central Section							
6	24.2	22.1	20.5	18.9	17.3	15.2	13.7
12	28.5	26.3	24.5	22.8	21.1	18.8	17.2
24	31.3	29.0	27.3	25.6	23.9	21.6	19.9
48	33.6	31.5	29.9	28.3	26.6	24.5	22.9
South Central Section							
6	26.0	23.7	21.9	20.2	18.5	16.2	14.5
12	30.1	27.7	25.9	24.1	22.8	19.8	18.0
24	32.5	30.3	28.5	26.8	25.1	22.7	21.0
48	35.0	32.8	31.2	29.5	27.8	25.7	24.0
Southeast Section							
6	26.5	24.4	22.7	21.0	19.3	17.0	15.3
12	31.4	29.0	27.1	25.2	23.3	20.7	18.9
24	34.1	31.8	30.0	28.2	26.4	24.0	22.1
48	36.7	34.4	32.7	30.9	29.1	26.8	25.1

**Based on U. S. Weather Bureau Hydrometeorology Report 33*

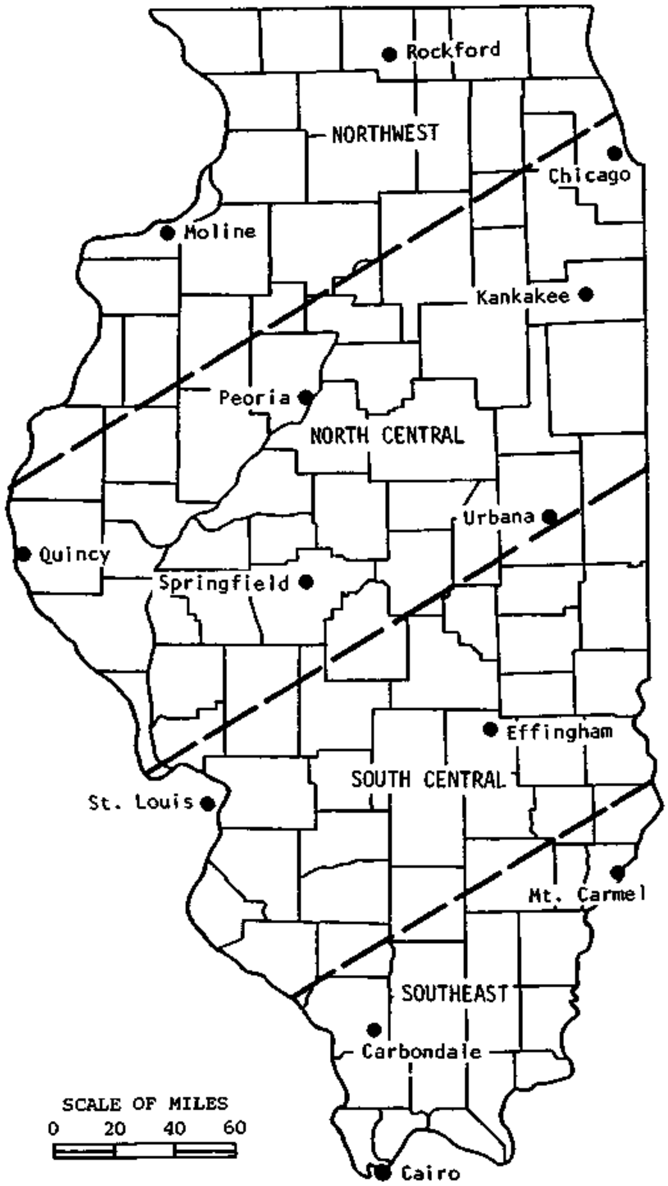

Figure 1. Section locations

nitude of the 100-year rainstorm, based upon Water Survey studies, is presented in table 2 for several storm durations and areas of 10 to 500 square miles. The 100-year areal values were determined from Water Survey data on point rainfall frequencies, using transformation factors developed by the Weather Bureau (Hershfield, 1961) and verified by Illinois network studies.

In table 3, the ratio of the 100-year storm to the probable maximum storm is shown for selected areas and several storm durations. This table shows that the 100-year storm values are only 20 to 32% of the probable maximum estimates. The percentages would be still smaller if Weather Bureau estimates (Hershfield, 1961) of 100-year storms in Illinois were used in place of the Water Survey data (Huff and Neill, 1959).

Table 2. 100-Year Rainstorm Estimates

Storm duration (hours)	*Depth (inches) for given area (mi^{1})* 10	25	50	100	200	500
Northwest Section						
6	5.8	5.5	5.3	5.1	5.0	4.7
12	6.8	6.6	6.4	6.3	6.1	5.9
24	8.3	8.2	8.0	7.8	7.7	7.5
48	9.1	9.0	8.8	8.7	8.6	8.4
North Central Section						
6	5.0	4.7	4.6	4.4	4.2	4.0
12	5.8	5.7	5.5	5.4	5.3	5.0
24	7.1	7.0	6.8	6.7	6.6	6.4
48	7.8	7.7	7.5	7.3	7.2	7.0
South Central Section						
6	5.8	5.6	5.4	5.2	5.0	4.8
12	6.9	6.8	6.6	6.4	6.3	6.0
24	8.3	8.1	8.0	7.9	7.7	7.5
48	9.0	8.9	8.7	8.5	8.4	8.2
Southeast Section						
6	6.1	5.9	5.7	5.6	5.4	5.2
12	7.3	7.1	6.9	6.8	6.6	6.3
24	8.6	8.5	8.4	8.3	8.1	7.9
48	9.3	9.2	9.0	8.9	8.8	8.5

Table 3. Ratio of 100-Year Rainstorm to Probable Maximum Storm in Illinois

Storm area (mi^{2})	*Average ratio for given duration (hours)* 6	12	24	48
10	0.22	0.23	0.25	0.25
50	0.24	0.25	0.28	0.28
100	0.26	0.27	0.29	0.29
200	0.27	0.29	0.30	0.30
500	0.30	0.32	0.32	0.32

Relation between Maximum Observed and Probable Maximum Storms

As part of its research program, the Atmospheric Sciences Section of the Water Survey made a comprehensive study of all heavy rainstorms recorded in Illinois during the 75-year period, 1887-1961. Before 1887, records are too sparse to carry out such storm studies. Beginning in 1948, extensive field surveys of severe rainstorms in Illinois were initiated by the Water Survey, and these have provided much information on the spatial, temporal, and synoptic weather characteristics of such storms. For storms prior to 1948, analysis was based primarily on data recorded by the climatological network of the Weather Bureau. Area-depth relations were computed for each storm. These were then adjusted for gage density differences (variations in sampling density) by use of empirical transformation factors developed from the field-surveyed storms (Huff and Semonin, 1960).

Table 4 shows the area-depth envelope values (mean rainfall maxima) observed in Illinois storms for storm periods of 6 to 48 hours and areas of 10 to 1000 square miles, based upon storm studies by the Water Survey and Corps of Engineers (U. S. Army, 1945). Comparison of tables

Table 4. Area-Depth Envelope of Illinois Storms

Storm period (hours)	*Depth (inches) for given area (mi^2)*						
	10	*25*	*50*	*100*	*200*	*500*	*1000*
6	13.4	12.6	11.8	10.9	9.8	8.5	7.5
12	16.7	16.3	15.7	14.7	13.8	12.0	10.4
24	17.0	16.5	16.0	15.1	14.2	12.5	11.0
48	17.6	17.4	17.1	16.7	16.3	15.6	14.8

Table 5. Ratio*of Observed Maximum to Probable Maximum Precipitation in Illinois

Storm duration (hours)	*Ratio for given area (mi^2)*				
	10	*50*	*200*	*1000*	*Average*
6	0.53	0.56	0.56	0.56	0.55
12	0.57	0.62	0.63	0.60	0.61
24	0.53	0.57	0.59	0.55	0.56
48	0.51	0.56	0.61	0.65	0.58
Average	0.54	0.58	0.60	0.59	0.58

* *Average of four sections of the state*

1 and 4 indicates that the maximum rainfall values experienced in Illinois are far below the estimated probable maximum values. In table 5, the average ratio of observed maximum to probable maximum rainfall in Illinois is presented for selected durations and areas. This computation indicates that the maximum rainfall experienced in the past 91 years is about 50 to 65% of the calculated probable maxima. The state maxima of table 4 exceed the 100-year amounts for fixed subareas in table 2. This is a normal occurrence. For a given recurrence interval, such as 100 years, some parts of a large area (such as a state) will exceed the *average* recurrence value and other parts will be below this average value.

FREQUENCY DISTRIBUTION OF AREAL MEAN RAINFALL IN SEVERE STORMS

Area-depth data compiled for severe rainstorms during the 75-year period 1887-1961 were used to obtain first estimates of the frequency of areal mean rainfall in Illinois for areas of 25 to 10,000 square miles. No attempt was made to subdivide the state in this study of severe storm events, since other analyses indicated these unusually severe storms may develop in any region of Illinois. Furthermore, subdividing would have reduced sample size to questionable proportions. With the exception of field-surveyed storms during 1948-1961, the rainfall depths for areas of less than 200 square miles had to be obtained primarily by extrapolation of the area-depth curves. These curves were obtained from fitting of the storm rainfall data to whatever mathematical distribution fitted the spatial distribution of storm rainfall best in a particular storm. This fitting procedure minimizes the extrapolation error.

Much of the historical data, especially prior to 1940 when recording raingages were sparse, provided only total storm rainfall data. Area-depth relations for partial storm periods in these cases were obtained through use of transformation factors derived from detailed storm studies by the U. S. Army Corps of Engineers (1945) and by the Water Survey. These transformation factors were average ratios of total storm rainfall (48-hr, 24-hr) to partial storm rainfall (6-hr, 12-hr, 18-hr) derived from area-depth relations in the detailed storm studies.

As the density of raingages has increased substantially over the period of historical records, a method was devised to adjust the storm area-depth curves for gage density variations. This was done by making comparisons between 1) area-depth relations in storms for which detailed field survey data were available, and 2) the relations obtained for the same storms using only the hydro-climatic network data available at various times when major flood-producing storms were recorded (Huff and Semonin, 1960). By this procedure, gage-density adjustments were derived for each decade and applied to the area-depth curves for that decade.

The modified data were then used to obtain the relations summarized in table 6. The values in table 6 are considered the best estimates which can be derived from existing records, but it should be clearly understood that sampling inadequacies existed during the period of record. The values in the table should, therefore, be treated as close approximations of the ‘true’ distributions, which can serve as a guide to the design or operational hydrologist having need for such information. The relations in table 6 should not be in error by more than 20% in any case, and, in most cases, should represent the 'true distribution' within 10%.

The values in table 6 represent envelope values for the state, not a specific location within the state. For example, the table shows a value of 16.8 inches for a 100-year frequency, 24-hour storm period, and an area of 25 square miles. The correct interpretation is that a maximum mean rainfall of 16.8 inches or greater over a contiguous area of 25 square miles is expected to occur somewhere in Illinois in an average 100-year period. The chance of occurrence over a particular 25-square-mile area would be far more remote. Similarly, a 24-hour mean rainfall of 12.8 inches or more is expected over a 25-square-mile area somewhere in the state on an average of once in 10 years or 10 times in an average 100-year period.

Table 6 may serve as a guide in evaluating 'practical maximum' rainstorms in Illinois in design problems by comparison with the probable maximum data in table 1. For example, the ratio of 100-year Illinois envelope values (table 6) to probable maximum values (table 1) is shown in table 7 for storm durations of 6 to 48 hours and areas of 25 to 1000 square miles. The 100-year envelope storm is approximately 56% of the probable maximum storm.

Analysis of all available data, including that compiled by the Weather Bureau and the Corps of Engineers, indicates that the storm of June 14-15, 1957, was the most intense 12-hour storm period recorded during the past 90 years in Illinois. In the core of that storm 24-hour and 6-hour amounts also established records. However, the record values established in the June 1957 storm are far below the probable maximum values of table 1.

The location, shape, and core values in the storm of June 14-15, 1957, are shown in figure 2, along with those for three other unusually severe rainstorms in 1957. Analyses indicate that more of these storms occurred in 1957 than in any other year in the 91 years of available records (1887-1978).

FIELD-SURVEYED AND NETWORK STORMS

Depth-Duration-Area Relations

Beginning in 1948, the Water Survey undertook comprehensive studies of outstanding flood-producing storms in Illinois. This was done through a field survey program (Huff et al., 1958) and the operation of several dense raingage networks in the state (Huff and Changnon, 1965).

Table 6. Frequency of Areal Mean Rainfall — Illinois Envelope Values

Area (mi^2)	*Average depth (inches) for given storm period (hours)* 6	12	18	24	48
10-Year Frequency					
25	9.4	11.2	12.1	12.8	13.7
50	8.7	10.4	11.3	12.1	13.1
100	8.0	9.7	10.6	11.3	12.5
200	7.3	8.9	9.7	10.4	11.5
500	6.2	7.9	8.6	9.3	10.3
1000	5.4	6.9	7.7	8.4	9.5
2000	4.5	5.9	6.6	7.3	8.3
5000	3.4	4.7	5.3	5.8	6.8
10,000	2.7	3.7	4.2	4.7	5.7
25-Year Frequency					
25	10.7	12.7	13.8	14.5	15.7
50	9.8	11.8	12.8	13.6	15.0
100	9.1	11.0	12.0	12.8	14.3
200	8.2	10.0	11.0	11.8	13.2
500	7.1	8.9	9.8	10.6	11.7
1000	6.2	7.8	8.8	9.4	10.8
2000	5.1	6.7	7.5	8.2	9.5
5000	3.9	5.2	6.0	6.6	7.8
10,000	3.0	4.2	4.8	5.4	6.5
50-Year Frequency					
25	11.6	13.8	15.1	15.6	17.1
50	10.6	12.6	14.1	14.7	16.3
100	9.9	12.1	13.3	13.7	15.7
200	9.0	11.0	12.1	12.8	14.4
500	7.7	9.7	10.7	11.5	12.9
1000	6.7	8.5	9.6	10.2	11.9
2000	5.6	7.2	8.2	8.9	10.3
5000	4.3	5.7	6.6	7.2	8.6
10,000	3.3	4.6	5.3	5.9	7.1
100-Year Frequency					
25	12.7	15.0	16.3	16.8	18.3
50	11.7	13.8	15.3	15.7	17.4
100	10.8	13.0	14.3	14.8	16.8
200	9.9	11.9	13.2	13.8	15.5
500	8.4	10.5	11.7	12.3	13.5
1000	7.4	9.3	10.4	11.0	12.8
2000	6.2	7.9	9.0	9.1	11.1
5000	4.7	6.3	7.2	7.7	9.3
10,000	3.6	5.0	5.8	6.3	7.7

Table 7. Ratio of Calculated 100-Year Envelope Storm to Probable Maximum Storm in Illinois

Storm duration (hours)	*Ratio for given area (mi^2)* 25	50	200	1000	*Average*
6	0.55	0.55	0.56	0.55	0.55
12	0.56	0.55	0.55	0.54	0.55
24	0.56	0.56	0.57	0.55	0.56
48	0.57	0.57	0.58	0.57	0.57
Average	0.56	0.56	0.56	0.55	0.56

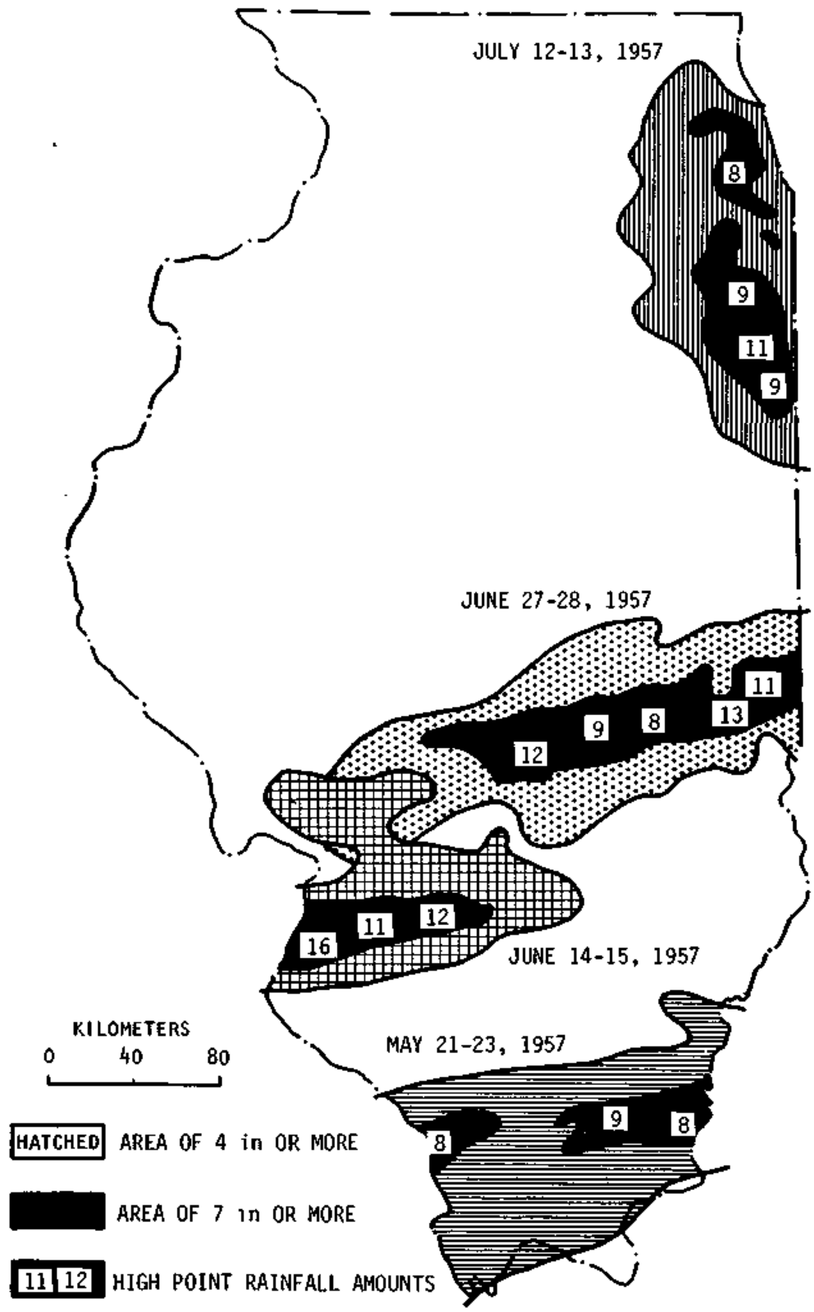

Figure 2. Major rainstorms in Illinois during 1957

These studies have yielded much knowledge concerning the characteristics of severe rainstorms in Illinois. As part of this research, depth-duration-area relations were determined in these storms. The previous sections have dealt with generalized relationships. However, it is sometimes desirable for the design hydrologist to have information relating to specific storms producing exceptionally heavy rainfall amounts over areas (basins) of various sizes.

Therefore, table 8 was compiled to provide such information on a group of outstanding storms occurring between 1948 and 1978. Table 8 shows area-depth relations for extremely heavy storms which encompassed areas of 5000 square miles or more. Data have been presented for storm periods of 3 to 24 hours. The fewer number in the 3-hour category was dictated by our inability to subdivide the storms into 3-hour increments in the majority of the field-surveyed storms. Most of the data in table 8 are from field surveys, since they are relatively large storms not contained within any raingage network. The last column in table 8 shows the section (figure 1) in which the storm was centered.

Table 8. Depth-Duration-Area Relations in Selected Storms

	Depth (inches) for given area (mi^2) and duration (hours)									
Date	*25*	*50*	*100*	*200*	*500*	*WOO*	*2000*	*5000*	*10,000*	*Section*
24 Hours										
8/16-17/59*	10.3	10.1	9.8	9.5	8.8	8.2	7.3	5.9	4.5	SE
6/14-15/57*	16.5	16.0	15.1	14.2	12.5	11.0	9.3	6.7	5.0	SC
6/27-28/57*	12.4	12.0	11.5	11.1	10.2	9.4	8.5	7.1	6.0	SC
7/12-13/57*	11.3	11.0	10.7	10.3	9.5	8.7	7.6	5.9	4.5	NC
5/21-22/57**	7.9	7.8	7.6	7.3	6.8	6.3	5.7	4.8	3.6	SE
10/9-10/54*	11.7	11.6	11.3	10.9	10.3	9.5	8.6	7.0	5.4	NW
12 Hours										
7/2/62t	5.2	4.8	4.5	4.0	3.4	2.9	2.3	1.4		NC
7/28-29/61*	10.1	9.7	9.2	8.6	7.4	6.3	5.5	4.2	3.1	SC
5/20/59+	6.7	6.2	5.7	5.2	4.0	3.3	2.5	1.5		NC
8/16-17/59+	9.3	9.1	8.8	8.4	7.8	7.0	6.2	4.8	3.5	SE
7/14/58*	8.7	8.5	8.2	7.4	7.0	6.2	5.2	3.9		NW
6/14-15/57*	16.3	15.7	14.7	13.8	12.0	10.4	8.6	6.1	4.3	SC
6/27-28/57*	12.0	11.5	10.9	10.3	9.3	8.4	7.4	5.9	4.7	SC
7/12-13/57*	9.8	9.6	9.3	8.9	8.2	7.3	6.5	4.9		NC
5/21-22/57**	7.3	7.1	6.8	6.5	5.9	5.3	4.6	3.6		SE
10/9-10/54*	7.3	7.2	7.0	6.8	6.3	5.9	5.3	4.2	3.3	NW
7/8-9/51+	12.0	11.3	10.6	9.8	8.8	7.8	6.7	5.6	4.5	NC
6 Hours										
8/16-17/59+	5.1	5.0	4.8	4.7	4.3	4.0	3.6	2.9	2.3	SE
6/14-15/57*	12.6	11.8	10.9	9.8	8.1	6.6	5.0	3.1		SC
6/27-28/57*	8.7	8.3	8.0	7.6	6.8	6.2	5.5	4.4	3.6	SC
7/12-13/57*	6.9	6.8	6.6	6.2	5.8	5.1	4.4	3.2		NC
5/21-22/57**	7.0	6.7	6.4	6.1	5.5	4.8	4.2	3.2		SE
10/9-10/54+	5.3	5.2	5.0	4.8	4.4	4.0	3.6	2.8	2.1	NW
7/8-9/51+	11.9	10.0	10.3	9.5	8.5	7.5	6.5	5.3	4.2	NC
3 Hours										
8/16-17/59+	4.0	3.8	3.7	3.5	3.1	2.7	2.3	1.6	1.1	SE
6/14-15/57*	8.7	8.2	7.5	6.7	5.5	4.4	3.4	2.0		SC
6/27-28/57*	4.5	4.3	4.2	4.0	3.7	3.4	3.1	2.6	2.2	SC
7/12-13/57*	5.1	5.0	4.8	4.5	4.0	3.6	3.0	2.1		NC
7/8-9/51+	7.6	7.2	6.8	6.3	5.3	4.5	3.7	2.5		NC

**Field survey was primary data source*
***Network supplied most of isobyetal information*
tBoth field surveys and SWS networks provided key information

Table 9. Area-Depth Relations in Selected Small-Area Storms Having Durations of 2 to 8 Hours

Date	Duration (hours)	Average depth (inches) for given area (mi^2) 10	25	50	100	200	500	1000	Section
7/18/52*	6	11.0	9.5	8.7	7.8	6.8	5.3	4.1	NW
5/26/56t	6	9.8	8.5	7.9	7.0	6.0	4.4	3.1	NC
5/7/61t	6	11.5	9.4	8.4	7.4	6.3	5.0	4.0	NC
6/6/61*	4	4.8	3.9	3.1	2.5	1.8			NC
6/13/67*	4	7.3	6.4	6.0	5.3	4.4	2.9	1.8	NC
6/20/67*	2	5.2	4.4	3.8	3.1	2.2			SC
8/11/72**	3	3.3	2.6	2.1	1.6	1.1			SC
7/25/73**	4	3.7	3.1	2.6	2.1	1.7			SC
6/13/76**	4	6.5	6.2	5.9	5.2	4.2	2.6	1.6	NC
7/19/76**	8	8.1	7.9	7.6	7.2	6.6	5.6	4.8	NC

**Field-surveyed storms*
***SWS network storms*
†Combination of field survey and network data sources

Table 9 shows area-depth relations for 6-hour rainfalls in smaller, intense storms that are contained within areas of 2000 square miles or less. Part of these are from network events and part from field surveys. These small-area, very intense storms should be of particular interest to the urban hydrologist. Two of the storms (August 11, 1972, July 25, 1973) were centered in the St. Louis metropolitan area, and two others (June 13, 1976, July 19, 1976) were centered in the Chicago region.

Statistical Models of Flash Flood Storms

From our extensive field surveys and analyses of outstanding network storms, statistical characteristics of typical flash flood storms in Illinois have been derived. These statistical models provide a source of pertinent input information for hydrologic models used in the design of flood protection structures. In performing the rainstorm analyses, storms were divided into two groups. Large mesoscale storms were defined as those extending over contiguous areas of 2000 square miles or more, but usually encompassing 5000 square miles or more. Similarly, small-scale storms were defined as those confined to areas of several hundred to 2000 square miles, but usually contained within 1000 square miles.

The large storms, such as those in table 8, were usually found to produce most of their rainfall in 12 hours. Relatively heavy rainfall, as defined by the area within the 1-inch isohyet, typically enclosed an area of about 5000 square miles. From the data provided by the field surveys and dense raingage networks, an area-depth model of a typical 12-hour storm was derived and is presented in figure 3. Curves are also shown for maximum 3-hour rainfall periods and for a 24-hour storm period. Figure 4 shows a similar curve for the small-area storm having durations of 2 to 8 hours over 500 square miles. Most of these storms last from 3 to 6 hours. In figures 3 and 4, area is plotted against the area-depth ratio, defined as the ratio of the heaviest mean rainfall on partial areas to the mean rainfall over the total area. This normalization was required in combining storms of varying intensity to obtain a statistical model.

The area-depth models were determined from medians for a group of storms, so that considerable deviation may occur about the models among storms. Consequently, the models are intended only to portray average or typical conditions, and to serve as a useful guide in hydrologic design problems in Illinois and the Midwest.

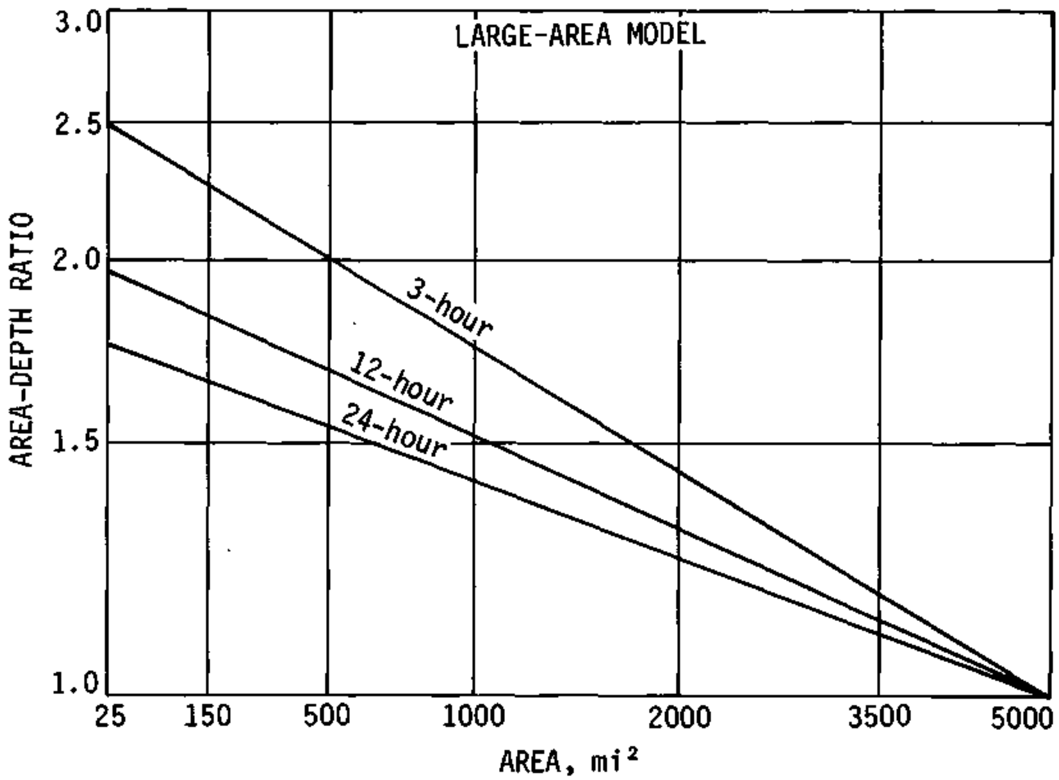

Figure 3. Area-depth model for large mesoscale storms

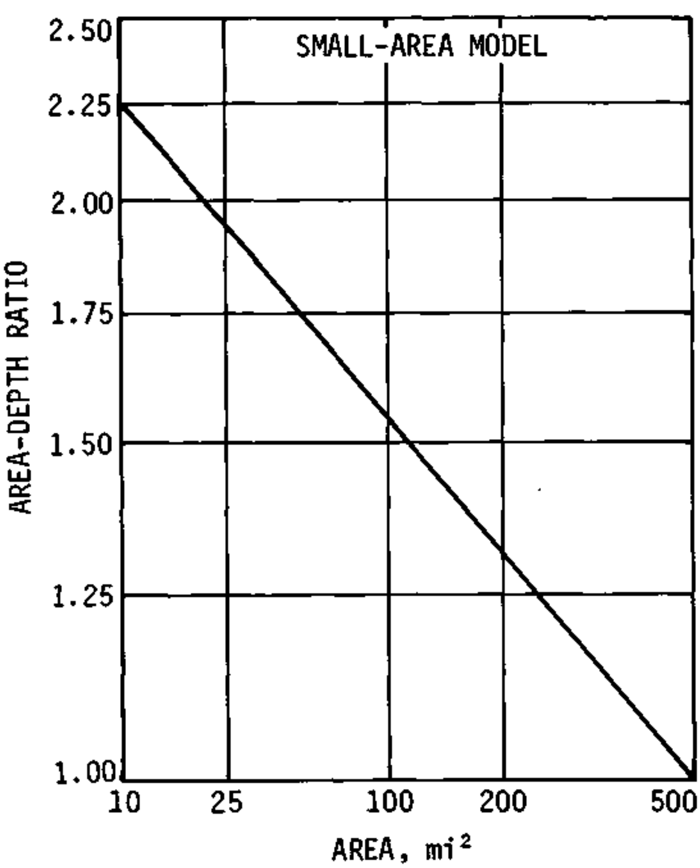

Figure 4. Area-depth model for small mesocale storms

Figure 3 shows that the rainfall gradient, indicated by the area-depth curve slope, decreases as storm duration increases and more convective entities cross the storm zone. Comparison of figures 3 and 4 shows a much steeper gradient in the small-area storms. This occurs because these storms are smaller in areal extent, last for a shorter time usually, are commonly associated with a single, quasi-stationary storm system, and are very intense at the storm core.

Various storm characteristics in addition to the area-depth relations were evaluated. From these, statistical models were derived for the large and small mesoscale storm systems. The models, based on median values, are summarized in tables 10 and 11.

TIME DISTRIBUTION

Seasonal Distribution

Seasonally, severe rainstorms occur most frequently in summer. A study of 260 heavy storms in Illinois (Huff and Semonin, 1960) showed that 51% occurred in summer (June-August), 20% in spring (March-May), 22% in fall (September-November), and 7% in winter (December-February). The winter storms occur almost exclusively in the southern part of the state. July had the most storms (19%), followed by August (17%), June (15%), and September (12%).

When the storm sample was stratified according to intensity, as indicated by the maximum recorded rainfall, the predominance of summer storms became even greater. Among the heaviest 50% of the storms, 63% occurred in summer, and over 70% in the June-September period. In northeastern Illinois, Huff and Vogel (1976) found that 30% of the heavy storms occur in July, 67% in summer, and 75% during June-September. The stronger predominance of summer storms in northeastern Illinois compared with the overall state distribution quoted above, is because of the larger number of heavy spring and fall storms in the southern half of the state.

Intra-Storm Distribution

Huff (1967) made an extensive study of the time distribution of rainfall in heavy storms on small basins. This study was based on data for a dense network of raingages on 400 square miles in central Illinois, and yielded information that should be very useful in hydrologic design problems on small basins. The results should be especially useful in urban design problems, since relationships were developed for point rainfall and for various sizes of areas up to 400 square miles.

In the 1967 study, it was found that the relations could be expressed best by relating percent of storm rainfall to percent of total storm time and grouping the data according to the quartile in which rainfall was heaviest. The individual effects of mean rainfall, storm duration, area, and other storm factors were small and erratic in behavior when the foregoing analytical technique was used.

Table 12 and figure 5 show median time distributions on areas of 50 to 400 square miles for each of the four storm types. This information was obtained from curves appearing in the 1967 paper. Much more information on the relations appear in that paper, and should be studied by those interested in more than average time distribution relations. Of the four quartile types, the first and second quartile storms occur most frequently. Long-duration storms (over 24 hours) predominate in fourth-quartile storms, storms of moderate length (12-24 hours) were most frequent with the third-quartile type, and short-duration storms were most common in the first-quartile and

Table 10. Statistical Model of 12-Hour Maximum Rainfall in Severe Rainstorms* of the Large Type

Characteristic	*Model*
Starting time of storm *(CST)*	1900
Start of heaviest rain intensities *(CST)*	2200
Duration of heaviest rain intensities *(hours)*	6
Area enveloped *(mi^2)*	5000
Orientation of surface rainfall pattern *(degrees)*	265-085
Ratio, major/minor axis of rainfall pattern	3.80
Number of individual substorm elements *(squall lines or areas)*	5
Average frequency of substorm elements *(hours)*	2.4

*As *used here and in table 11, a storm consists of a rainfall system clearly separated in time and space from other areas of precipitation. These are usually complex systems consisting of several substorm elements within the enveloping isohyet of the storm system. These substorm elements may be individual thunderstorms or rainshowers, an organized group of convective entities, or a squall line(s)*

Table 11. Statistical Model of Severe Rainstorms* of the Small Type

Characteristic	*Model*
Storm duration *(hours)*	4
Starting time of storms *(CST)*	1600
Start of heaviest rain intensities *(CST)*	1630
Duration of heavy rain intensities *(hours)*	3
Area enveloped *(mi^2)*	500
Orientation of surface rainfall pattern *(degrees)*	260-080
Ratio, major/minor axis of rainfall pattern	2.90
Number of bursts or merging cells	6
Average frequency of bursts *(hours)*	0.5

second-quartile groups. Approximately two-thirds of all storms fell into these two groups. Storms of less than 6 hours were predominately first-quartile storms.

Antecedent Rainfall

The amount of rainfall preceding heavy storms is of major importance in both flood prediction on a real-time basis and in the design of hydrologic structures. For design purposes, the probability distribution of rainfall amounts for several days preceding a heavy storm event is of prime concern. Data for dense networks that have been operated by the Water Survey in Illinois in the past 25 years have been studied to provide an answer to this problem. Analyses were confined to the warm season from mid-April to mid-October when convective rainfall predominates and most of the flash-flood storms occur in Illinois and the Midwest. Probability distributions were derived for 1 to 10 days preceding all storms in which the network mean rainfall equaled or exceeded 1 inch. Distributions have been computed for areas ranging in size from 10 to 400 square miles. These are areas which are of major interest in urban and small watershed hydrology.

Table 12. Average Time Distribution of Heavy Storm Rainfall on Areas of 50 to 400 mi^2

Cumulative percent of storm time	*Cumulative percent of storm rainfall for given quartile storm*			
	First quartile	*Second quartile*	*Third quartile*	*Fourth quartile*
5	9	3	2	2
10	20	6	4	3
15	35	9	7	5
20	51	13	10	7
25	63	21	12	9
30	70	31	14	10
35	75	42	16	12
40	80	55	19	14
45	83	65	23	16
50	86	73	30	19
55	88	80	39	21
60	90	85	53	25
65	92	89	68	29
70	93	92	79	35
75	95	95	87	43
80	96	96	92	54
85	97	97	95	75
90	98	98	97	92
95	99	99	99	97

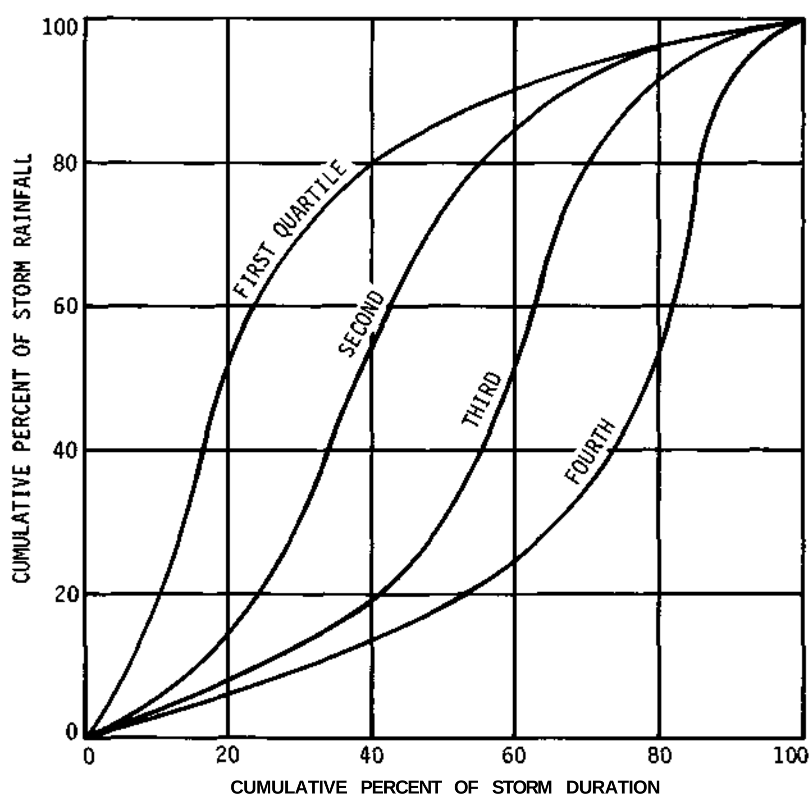

Figure 5. Time distribution of rainfall in heavy storms on areas of 50 to 400 square miles

Table 13. Probability Distributions of Antecedent Rainfall for 1 to 10 Days on Selected Areas in Storms Producing Rainfall of 1 Inch or More

	Average rainfall (inches) exceeded for given antecedent period and area (mi²)														
Probability	***1 Day***			***2 Days***			***3 Days***			***5 Days***			***10 Days***		
(percent)	***10***	***100***	***400***	***10***	***100***	***400***	***10***	***100***	***400***	***10***	***100***	***400***	***10***	***100***	***400***
5	1.05	1.40	1.80	1.50	1.70	2.00	1.65	1.90	2.15	2.00	2.30	2.50	3.10	3.40	3.55
10	0.60	0.83	1.15	0.96	1.22	1.42	1.12	1.37	1.60	1.48	1.70	2.00	2.40	2.65	2.85
20	0.22	0.34	0.57	0.41	0.67	0.83	0.57	0.80	0.99	0.97	1.15	1.45	1.70	1.90	2.20
30	0.08	0.12	0.28	0.14	0.37	0.52	0.29	0.46	0.63	0.66	0.81	1.00	1.30	1.42	1.72
40			0.11		0.14	0.30	0.13	0.24	0.39	0.42	0.56	0.70	1.00	1.09	1.38
50						0.17		0.10	0.22	0.24	0.36	0.47	0.75	0.83	1.10

Results are shown in table 13 which presents probabilities for selected areas of 10, 100, and 400 square miles during antecedent periods of 1 to 10 days. Amounts in the table were abstracted from probability curves derived for each specified situation.

Table 13 shows that the antecedent rainfall tends to be greater as the sampling area increases. This is related to a strong trend for heavy convective storms on the larger areas to be associated with organized convective activity of a macroscale nature and to occur during periods of relatively heavy rainfall in the general region. Whereas a single air mass shower of strong intensity could produce a 1-inch mean on 10 square miles, it would require a storm system of considerable areal extent to produce a mean of this magnitude over 400 square miles. Intense, isolated air mass showers frequently develop in summer during periods when rainfall is not widespread.

SHAPE, ORIENTATION, AND MOVEMENT OF HEAVY RAINSTORMS

Basin runoff characteristics in heavy storms are influenced by the shape, orientation, and movement of the storms. Several Water Survey studies utilizing network and historical storm data have yielded considerable information on this subject. Findings are summarized briefly in the following paragraphs.

Storm Shape

Two studies have been made to determine the shape characteristics of heavy rainstorms in Illinois. In one study, data from 260 storms on a dense raingage network in east central Illinois were used to investigate shapes on areas of 50 to 400 square miles (Huff, 1967). Storms were used in which areal mean rainfall exceeded 0.50 inch. In the other study, historical data for 350 heavy storms having durations up to 72 hours were used in a shape study of large-scale, flood-producing rain events. These were Illinois storms in which maximum 1-day amounts exceeded 4 inches or in which 2-day and 3-day amounts exceeded 5 inches (Stout and Huff, 1962). Storms encompassed areas ranging from a few hundred miles to 10,000 square miles.

The study of historical storms indicated that the rain intensity centers most frequently had an elliptical shape. The ratio of major to minor axis tended to increase with increasing area enclosed within a given isohyet; that is, the ellipse becomes more elongated. Within limits employed in the study, no significant difference in the shape factor occurred with increasing storm magnitude or with durations ranging from a few hours to 72 hours.

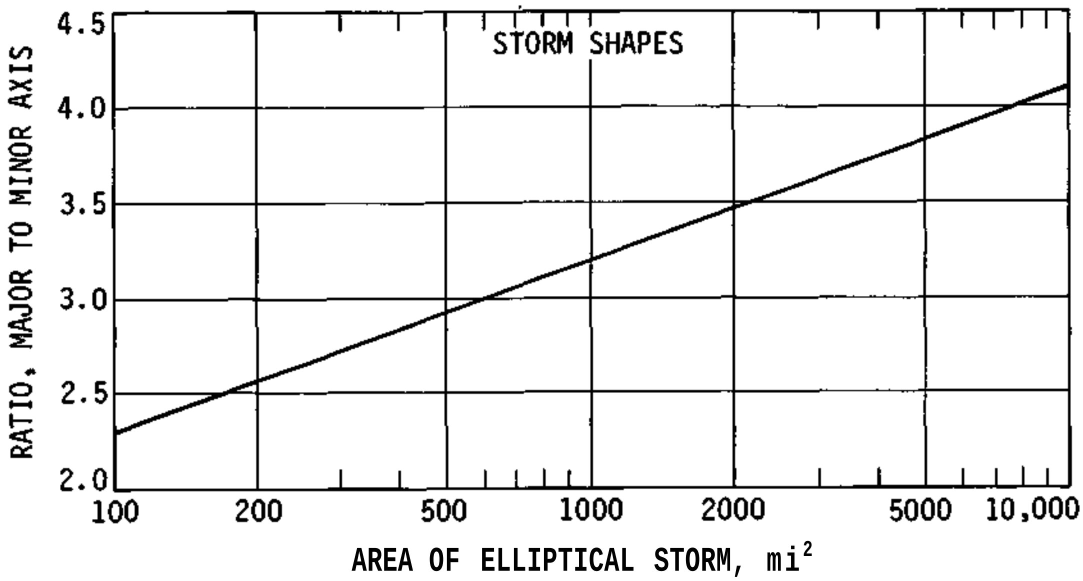

Figure 6. Shape factor for heavy rainstorms

In the network study, elliptical patterns were found also to be the most prevalent type, but the heaviest storms tended to be made up of a series of rainfall bands. However, intensity centers within these bands were most frequently elliptical. From these two studies, a mean shape factor has been determined that can be used as guidance in hydrologic problems in which storm shape is a significant design factor.

The shape relation is shown in figure 6 for storm areas of 100 to 10,000 square miles. The isohyetal shape factor has been expressed as a function of the area enclosed by the isohyet. The ordinate represents the median ratio of major to minor axis of the elliptical isohyet enclosing the area given on the abscissa. Figure 6 is applicable for all Illinois storms with durations up to 72 hours, and should be useful where it is pertinent to incorporate a storm shape factor into hydrologic models.

Storm Orientation

An important consideration in any region is the orientation of the major axis of heavy rainstorms. 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 in this region will be greater, on the average, than in a region perpendicular to most storm axes. The orientation of the storm axis also provides an indication of the movement of the major precipitation-producing entities embedded in any large-scale weather system. Since most individual storm elements have a component of motion from the west, an azimuth angle ranging from 180 to 360° was ascribed to each storm. Thus, if a storm had an orientation of 230°, the orientation was along a line from 230 to 050° (SW-NE). Network studies show it is then very likely that the major rain-producing cells within a storm with this orientation moved from the southwest to the northeast.

No significant difference was found between the orientation of storms when they were stratified according to mean rainfall and areal extent. Table 14 shows the distribution in 260 heavy storms having mean rainfall exceeding 1 inch over a contiguous area of 10,000 square miles

Table 14. Orientation of Heavy Rainstorms in Illinois

Azimuth (degrees)	*Percent of storms*	*Azimuth (degrees)*	*Percent of storms*
180-215	4	276-295	20
216-235	6	296-315	12
236-255	30	316-335	6
256-275	21	336-360	1

(Huff and Semonin, 1960). This distribution is considered typical for heavy storms in Illinois. Other studies have supported the results shown in table 14 (Huff and Vogel, 1976; Vogel and Huff, 1977).

Heavy rainstorms in Illinois are most frequently oriented from WSW-ENE through W-E to WNW-ESE (236-295° in table 14). The median orientation of the 260 storms used in deriving table 14 was 265° (nearly W-E). The median for the extremely heavy storms in tables 8 and 9 was 260°. In general, it has been found that the very heavy storms (such as those in table 8) tend to have nearly W-E orientations. Heavy, but less severe storms, are usually oriented WSW-ENE or WNW-ESE. Moderately heavy storms, especially those of short duration (1 to 3 hours) are frequently oriented WSW-ENE or SW-NE. It is quite fortunate that the orientations of the major drainage basins in Illinois are closer to a north-south than to a west-east orientation.

Storm Movement

In Illinois, heavy rainstorms are usually produced by one or more squall lines or squall areas traversing a basin or other area of interest. Each system (squall line or squall area) consists of a number of individual convective entities, usually thunderstorms, and these entities have a motion that is strongly related to the wind field in which they are imbedded. These entities are often referred to as raincells. Network studies of the motion of heavy raincells (Huff, 1975) has provided the frequency distribution of cell movements shown in table 15. The most frequent raincell movements are from WSW through W to WNW (240-299°) which accounted for 42% of the total number analyzed in the Huff study. Of the total, 84% exhibited motion with a westerly component.

Table 15. Frequency Distribution of Heavy Raincell Movements

Azimuth (degrees)	*Percent of storms*	*Azimuth (degrees)*	*Percent of storms*
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

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