7. SPATIAL AND TEMPORAL CHARACTERISTICS OF HEAVY RAINSTORMS IN ILLINOIS

Data from dense raingage networks operated by the Illinois State Water Survey have supported numerous studies of the spatial and temporal distribution of heavy rainstorms of the type discussed in this report. Key results from several of these studies have been abstracted from published reports and technical papers and included here for the convenience of the user. They provide pertinent information for both the hydrologic designer and the hydrologic systems operator.

Relations between Point and Areal Mean Rainfall Frequencies

Knowledge of the frequency distributions of areal mean rainfall is pertinent to the efficient design of hydraulic structures such as dams, urban storm sewers, highway culverts, and water-supply facilities. In the United States, a relatively large amount of data is available on the frequency distributions of point rainfall, but there is little information on the frequency distributions of areal mean rainfall. Consequently, there was a need for determining how the mean rainfall frequency distributions for small areas about a point are related to the point frequency distributions.

Data from two dense raingage networks in east central Illinois (Huff, 1970) were used to determine the relationships between the frequency distributions of point and areal mean rainfall in areas ranging from 10 to 400 square miles and for storm periods of 30 minutes to 48 hours. A 10-year sample (1950-1959) from an urban network of 11 recording raingages in Champaign-Urbana provided data for 10 square miles. A network of 49 recording raingages on 400 square miles in east central Illinois provided a 12-year sample (1955-1966) for determination of relationships in areas of 50, 100, 200, and 400 square miles.

Point rainfall at the central gage in each area was used in developing the point-areal relationship. Areal mean rainfall was obtained from the arithmetic average of all gages in each of the sampling areas. For each storm period (30 minutes to 48 hours), the study was restricted to storms in which the central gage recorded rainfall that equaled or exceeded the amount expected to occur on the average of once in 2 years.

Table 35 was constructed to show the average ratios of areal mean to point rainfall for selected storm periods. These ratios can be used with available frequency distributions of point rainfall to estimate the frequency distributions of areal mean rainfall for small areas. The ratios are considered to be applicable throughout Illinois and most of the Midwest (see Huff and Vogel [1976] and Huff [1980] for a more detailed discussion of the point-areal relations).

Time Distributions of Rainfall (Storm Profiles)

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 in the design type of storms; that is, the time profile of storm rainfall as developed from "mass" curves of storm rainfall. Because the previous demand for this information had not been strong, it was not readily available. Some limited work on storm "profiles" was done by the 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 Water Survey published results of a more detailed time-distribution study based on data from heavy storms sampled in an 11-year operation of a dense raingage network in central Illinois (Huff, 1967). The present study was undertaken primarily to provide information applicable to the existing urban design problems (Huff, 1986).

In the present study, 260 storms were used in which mean rainfall on a 49-gage, 400-square-mile network exceeded 0.50 inch. Appraisal of this sample led to development of four basic types of curves, showing time distributions of rainfall in storms categorized as first-, second-, third-, or fourth-quartile storms depending on whether the maximum rainfall occurred in the first, second, third, or fourth quarter of the storm (Huff, 1967). Families of curves were then computed for each storm type to provide the user with a measure of variability that would occur about any average curve derived from the data. Curves were determined for point rainfall and areas up to 400 square miles.

Table 35. Relations between Areal Mean and Point Rainfall Frequency Distributions

Storm period (hours)	*Ratio of areal to point rainfall for given area*					
	10 sq mi	*25 sq mi*	*50 sq mi*	*100 sq mi*	*200 sq mi*	*400 sq mi*
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 analyses indicated that areas from 50 to 400 square miles, durations of up to 24 hours, and mean rainfall of more than 0.50 inch could be combined into a single family when the model was derived in terms of cumulative percent of storm time versus cumulative percent of rainfall.

Tables 36 and 37, abstracted from Huff (1980), show average areal and point rainfall distributions derived from the original Huff curves (Huff, 1967; Huff, 1980). The reader is referred to the foregoing publications and to that of Huff and Vogel (1976) for more details on time-distribution characteristics of heavy rainstorms in Illinois.

Storm Shape

Runoff characteristics in heavy storms are influenced by the shape and movement of the storms. 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 in Illinois having durations of up to 72 hours were used in a shape study of large-scale, flood-producing rain events. These were 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). The storms encompassed areas ranging from a few hundred 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 became more elongated. Within the 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.

In the network study, elliptical patterns also were found 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 curve is shown in figure 29 for areas of 20 to 1,000 square miles. For those interested, the curve can be continued to 10,000 square miles because storms up to this size were included in the historical storm study.

The foregoing discussion of shape factor was abstracted from Huff and Vogel (1976).

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. Because 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 orienta-

Table 36. Average Time Distributions of Heavy Storm Rainfalls 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	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

**Storms were categorized as first-, second-, third-, or fourth-quartile storms depending on whether the maximum rainfall occurred in the first, second, third, or fourth quarter of the storm.*

Table 37. Average Time Distributions of Heavy Rainfall at a Point

Cumulative percent of storm time	*Cumulative percent of storm rainfall for given storm type**			
	First-quartile	*Second-quartile*	*Third-quartile*	*Fourth-quartile*
5	12	4	3	2
10	26	9	6	5
15	40	14	10	8
20	51	19	13	10
25	59	25	16	13
30	65	32	20	16
35	71	40	23	18
40	75	52	27	21
45	78	61	33	24
50	82	68	39	28
55	84	73	46	32
60	87	78	56	35
65	89	82	68	40
70	91	86	79	44
75	93	89	85	50
80	95	92	89	58
85	96	94	92	68
90	97	96	95	83
95	99	98	98	93

**Storms were categorized as first-, second-, third-, or fourth-quartile storms depending on whether the maximum rainfall occurred in the first, second, third, or fourth quarter of the storm.*

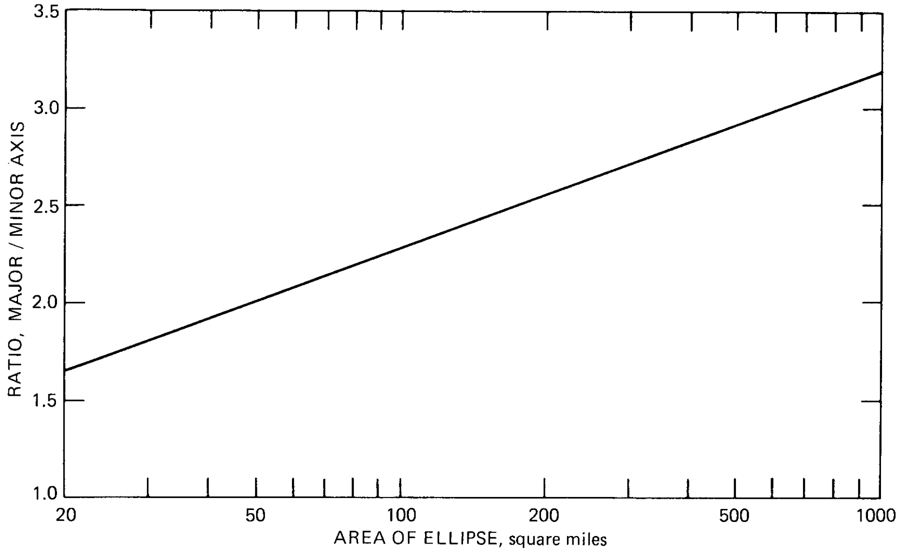

Figure 29. Mean shape factor for heavy storms

tion of 230°, the orientation was along a line from 230 to 050° (southwest to northeast). Network studies show it is 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 38 shows the distribution in heavy storms having mean rainfall exceeding 1 inch over a contiguous area of 10,000 square miles (Huff and Semonin, 1960). This distribution is considered typical for heavy storms in Illinois. Other studies have supported the results shown in table 38 (Huff and Vogel, 1976; Vogel and Huff, 1978).

Table 38. Orientations 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

Heavy rainstorms in Illinois are most frequently oriented from west-southwest to east-northeast, west to east, or west-northwest to east-southeast (236-295° in table 38). The median orientation of the storms used in deriving table 38 was 265° (nearly west to east). In general, it has been found that the very heavy storms tend to have nearly west-to-east orientations. Heavy but less severe storms are usually oriented west-southwest to east-northeast or west-northwest to east-southeast. Moderately heavy storms, especially those of short duration (1 to 3 hours) are frequently oriented west-southwest to east-northeast or southwest to northeast. 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) have provided the frequency distribution of cell move-

Table 39. 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

ments shown in table 39. The most frequent raincell movements are from west-southwest through west to west-northwest (240-299°), which accounted for 42% of the total number analyzed in Huff's 1975 study. Of the total, 84% exhibited motion with a westerly component.

The foregoing information on storm orientation and movement in Illinois was abstracted from Huff (1979). Other information for the Chicago urban area and the six-county region surrounding Chicago is presented by Huff and Vogel (1976).

Extreme Rainstorm Events (Outliers)

During the 1951-1960 period, an unusual number of severe rainstorms occurred in Illinois. Ten storms substantially exceeded the 100-year recurrence interval of storm rainfall for total or partial storm periods. All except the storm of May 21-23, 1957, produced amounts of nine inches or more at the storm core within periods of 24 hours or less and qualified as outliers by the Section 5 definition. The Water Survey carried out extensive field surveys and analyses of these major storm events in Illinois. Through this program, information was generated for each of the ten storms, the depth-duration-area relations for which are shown in table 40. Results were published in a number of technical reports (Huff, 1979; Huff and Changnon, 1961; Huff, Hiser, and Stout, 1955; Huff et al., 1958; Illinois State Water Survey, 1952; Larson, Hiser, and Daniels, 1955).

These reports contain detailed information on the characteristics of these outlier storms, including isohyetal patterns, characteristics of the rainfall distribution, depth-area-duration relations, antecedent rainfall, synoptic weather conditions associated with the storms, and both partial and total storm isohyetal patterns. When possible, radar analyses were also made to help define the spatial-temporal characteristics of the storms and the triggering mechanisms for these rare events.

These individual storm studies should be helpful to hydrologists involved in the design and operation of hydraulic structures in areas where the risk to life and property from severe flash floods is a major concern. Large metropolitan areas, such as Chicago, are especially subject to massive property damage, interruption of normal activities, and, sometimes, creation of health hazards from severe rainstorms of the type discussed above.

Additional Information

Reports and papers that deal with various aspects of the temporal and spatial characteristics of heavy rainstorms in Illinois are identified in the reference list by asterisks. These publications provide much more detailed information than is presented in the brief summaries in this section. For example, additional information on the time distribution of heavy storm rainfall is provided in references 15, 20, 30, and 33.

Detailed information on the temporal-spatial characteristics of rare storm events that substantially exceed the 100-year recurrence-interval values is presented in references 19, 21, 23, 28, 32, 35, and 37. All of the references identified by asterisks contain important information on one or more of the various spatial-temporal characteristics of severe rainstorms in Illinois discussed in this section.

Table 40. Depth-Duration-Area Relations for Selected Storms

	Depth (inches) for given area (sq mi) and duration (hours)								
	25	*50*	*100*	*200*	*500*	*1000*	*2000*	*5000*	*Section*
24 hours									
8/16-17/59*	10.3	10.1	9.8	9.5	8.8	8.2	7.3	5.9	S
6/14-15/57*	16.5	16.0	15.1	14.2	12.5	11.0	9.3	6.7	SW
6/27-28/57*	12.4	12.0	11.5	11.1	10.2	9.4	8.5	7.1	ESE
7/12-13/57*	11.3	11.0	10.7	10.3	9.5	8.7	7.6	5.9	NE
5/21-23/57	7.9	7.8	7.6	7.3	6.8	6.3	5.7	4.8	S
5/26-28/56	10.9	10.1	9.3	8.2	6.2	4.7			C
10/9-10/54	11.7	11.6	11.3	10.9	10.3	9.5	8.6	7.0	NE
12 hours									
8/16-17/59†	9.3	9.1	8.8	8.4	7.8	7.0	6.2	4.8	S
7/14/58*	8.7	8.5	8.2	7.4	7.0	6.2	5.2	3.9	NE
6/14-15/57*	16.3	15.7	14.7	13.8	12.0	10.4	8.6	6.1	SW
6/27-28/57*	12.0	11.5	10.9	10.3	9.3	8.4	7.4	5.9	ESE
7/12-13/57*	9.8	9.6	9.3	8.9	8.2	7.3	6.5	4.9	NE
5/21-22/57**	7.3	7.1	6.8	6.5	5.9	5.3	4.6	3.6	S
5/26-28/56	9.2	8.5	7.6	6.5	4.8	3.5			C
10/9-10/54	7.3	7.2	7.0	6.8	6.3	5.9	5.3	4.2	NE
7/8-9/51	12.0	11.3	10.6	9.8	8.8	7.8	6.7	5.6	C
6 hours									
8/16-17/59†	5.1	5.0	4.8	4.7	4.3	4.0	3.6	2.9	S
6/14-15/57*	12.6	11.8	10.9	9.8	8.1	6.6	5.0	3.1	SW
6/27-28/57*	8.7	8.3	8.0	7.6	6.8	6.2	5.5	4.4	ESE
7/12-13/57*	6.9	6.8	6.6	6.2	5.8	5.1	4.4	3.2	NE
5/21-22/57**	7.0	6.7	6.4	6.1	5.5	4.8	4.2	3.2	S
5/26-28/56	8.5	7.9	7.0	6.0	4.4	3.1			C
10/9-10/54	5.3	5.2	5.0	4.8	4.4	4.0	3.6	2.8	NE
7/18-19/52	9.5	8.7	7.8	6.8	5.3				NW
7/8-9/51	11.9	11.0	10.3	9.5	8.5	7.5	6.5	5.3	C
3 hours									
8/16-17/59†	4.0	3.8	3.7	3.5	3.1	2.7	2.3	1.6	S
6/14-15/57*	8.7	8.2	7.5	6.7	5.5	4.4	3.4	2.0	SW
6/27-28/57*	4.5	4.3	4.2	4.0	3.7	3.4	3.1	2.6	ESE
7/12-13/57*	5.1	5.0	4.8	4.5	4.0	3.6	3.0	2.1	NE
7/8-9/51†	7.6	7.2	6.8	6.3	5.3	4.5	3.7	2.5	C

**Field survey was primary data source*

***Network supplied most of isohyetal information*

†Both field surveys and SWS networks provided key information