Table 8. Variance between l-Day to10-Day Rainfalls Explained by Sectional Time Trend Curves Derived from Eight Frequency Distributions Based on Consecutive 10-Year Samples

	Variance explained (r^2) for given recurrence interval (yrs)			
	l-day rainfall		*Median for 1- to 10-day rainfall*	
Section	*2 yrs*	*5 yrs*	*2 yrs*	*5 yrs*
NW	0.30	0.65	0.46	0.55
NE	0.41	0.31	0.43	0.47
W	0.05	0.15	0.04	0.08
C	0.47	0.50	0.45	0.47
E	0.20	0.40	0.24	0.33
w s w	0.10	0.42	0.03	0.10
ESE	0.01	0.20	0.04	0.11
SW	0.22	0.19	0.14	0.25
SE	0.29	0.54	0.29	0.17
S	0.01	0.04	0.01	0.02
Median	0.21	0.35	0.19	0.21

3. FREQUENCY DISTRIBUTIONS OF HEAVY RAINFALL EVENTS

Data Used

The data used in developing the frequency relations consisted of both daily and hourly precipitation records from Illinois and from nearby stations in surrounding states. The daily data, mostly from nonrecording raingages, spanned the 83-year period from 1901 through 1983. They included data from the 61 precipitation-reporting stations discussed previously (figure 7), whose records had been carefully edited in previous Water Survey studies and were considered of acceptable accuracy for the frequency study. Records for most stations were complete for the 83-year period, but several did not begin until 1902 to 1908, one (Kankakee) did not start until 1917, and another (New Burnside) was terminated in 1957. These stations were used to ensure adequate coverage in certain areas.

The daily data were supplemented by hourly data for 34 recording-gage stations in Illinois and 21 stations in surrounding states for the 36-year period, 1948-1983 (figure 8). These data were used primarily in developing frequency distributions for rain periods of less than 24-hour durations. The recording stations are not as uniformly distributed as the daily reporting stations, and the quality of the data obtained from some of them was questionable. The 61-station, 83-year sample from the daily reporting stations was the primary database used in developing the Illinois frequency relations, because of both the length and quality of these records. The need to provide estimates of 50-year to 100-year recurrences dictated the use of records as long as possible.

Analytical Approach

Frequency relations were developed for rain periods varying from 5 minutes to 10 days and for recurrence intervals ranging from 2 months to 100 years. These durations and recurrence intervals should encompass the various needs of hydrologists and other users of rainfall frequency information for heavy storm occurrences. Initially, frequency distributions were determined for each of the 61 stations, and they are presented in the appendices of this report.

However, as pointed out by Huff and Neil1 (1959), the most reliable estimate of rainfall frequency relations can be obtained by combining all data within an area of relatively homogeneous precipitation climate with respect to the occurrence of heavy rainstorms. The analyses then yield area1 mean relationships applicable to all locations within a specific climatic section of the state. These area1 mean relationships moderate effects from the natural variability factor (random variations) somewhat and are less affected by measurement or computational errors in specific station data.

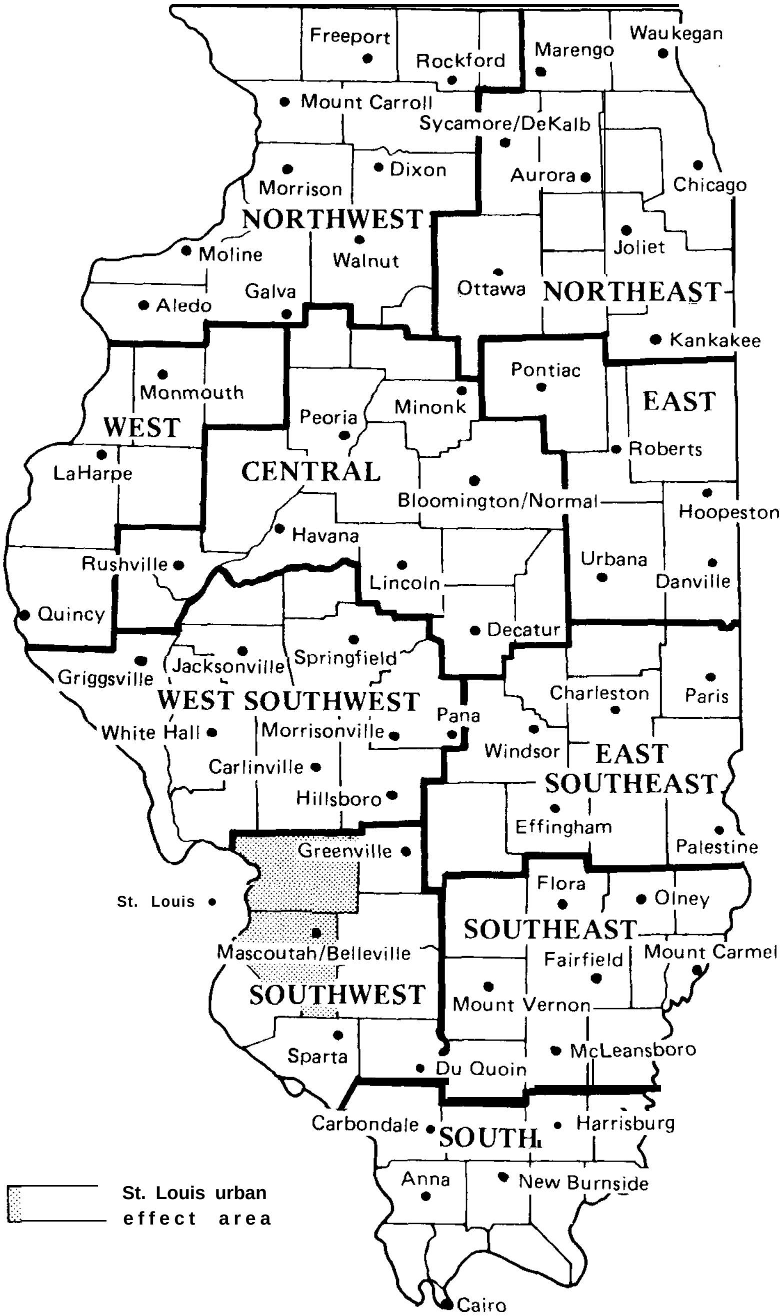

Figure 7. Precipitation-reporting stations and climatic sections used in developing Illinois frequency relations

The state was divided into ten sections of approximately homogeneous precipitation climate (figure 7). This was done through assessment of the heavy rainfall distributions for the 61 stations during the 1901-1983 sampling period, along with consideration of other pertinent meteorological and climatological information. Initially, an evaluation was made of the suitability of the nine climatic sections of the National Weather Service (NWS) (figure 3) for dividing the state into sections of approximately equivalent precipitation climate with respect to heavy rainstorms. Although the NWS sections are frequently used for climatic grouping of temperature and precipitation parameters (such as monthly or seasonal rainfall), adjustments were necessary in this grouping to adequately characterize the spatial and tem-

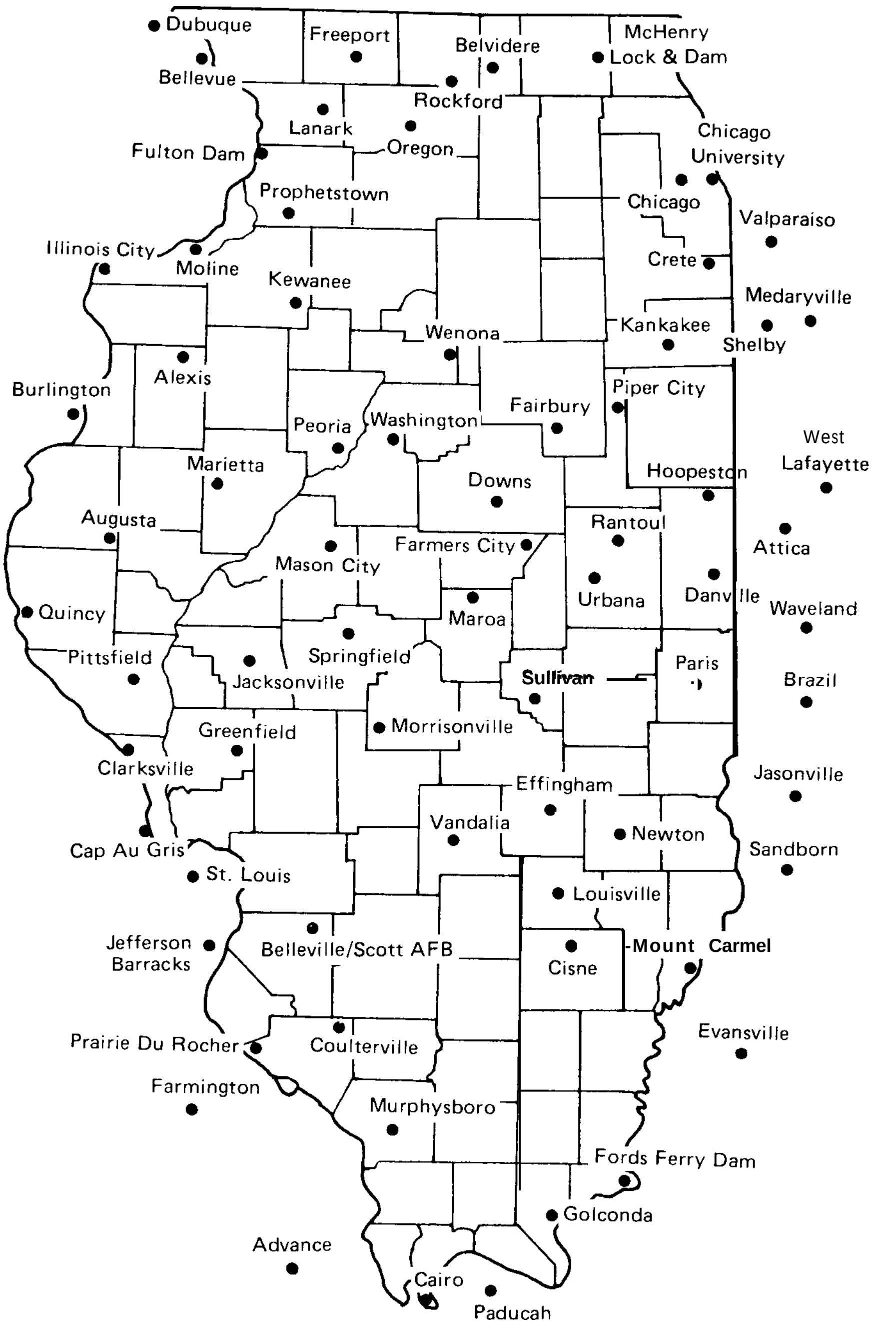

Figure 8. Locations of recording-gage stations

poral distribution characteristics of heavy rainstorms in Illinois.

In modifying the NWS grouping, major emphasis was placed on two types of information: the frequency distributions of heavy storm rainfall derived for each of the 61 stations for the 1901-1983 sampling period, and the pertinent meteorological and climatological factors influencing the frequency, intensity, and spatial distribution of extreme storm rainfall events in Illinois. Frequency distributions for rain periods of 24 hours to 10 days were used in specifying the regions (sections) having similar distribution characteristics.

Major emphasis was placed on the spatial distribution of rainfall amounts for recurrence intervals of 2 to 10 years because these values are more accurately defined than those for longer intervals. For example, for the 1901-1983 data, there are 41, 16, and 8 independent samples available for each station for the 2-year, 5year, and lo-year recurrence intervals, respectively, whereas only three samples define the 25-year recurrence interval. Major emphasis was also placed on rain periods of 24 to 72 hours in designating the climatic sections, because these durations are of primary interest to most users of Illinois frequency relations.

Important meteorological and climatological factors were involved in the decision making. These included the length of the convective rainfall season, which increases considerably within Illinois from north to south. Extreme rainfall events, especially those having durations of 72 hours or less, are nearly always associated with thunderstorms, and these occur most frequently in the extreme southern and western parts of the state. Another pertinent factor is the spatial distribution of major synoptic weather conditions, such as fronts and low-center passages within the state (Chiang, 1961). These weather events usually generate the storms that occasionally develop into severe rain events. Inadvertent weather modification resulting from topographic and urban influences can also affect the distribution characteristics of heavy rainstorms. All of these factors have been studied in previous Water Survey research (Changnon, 1957; Huff and Changnon, 1972; Changnon et al., 1977; Chiang, 1961; Huff and Vogel, 1976; Huff and Vogel, 1978; Huff, Changnon, and Jones, 1975).

In designating the climatic sections, major emphasis was placed on minimizing the dispersion of individual (station) rainfall amounts at selected recurrence intervals about the area1 mean. Clusters of stations were selected for testing, with the NWS climatic sections used as initial guides. The initial computations were made for the stations within each of the nine NWS sections. Next, adjustments were gradually introduced that decreased the cluster variability and conformed better with known climatological factors such as thunderstorm frequency and length of the convective rainfall season (mentioned above). This involved both spatial movement and variations in the number of stations in the original NWS clusters.

This procedure was continued in a stepwise fashion until a group of sections was obtained that approached minimum possible dispersion and, at the same time, was compatible with the climatic background knowledge and information discussed earlier.

As an example, consider the relatively small section labeled "West" in figure 7, which contains only three stations (Quincy, LaHarpe, and Monmouth). Analyses indicated that these stations had very similar frequency distributions, which exhibited considerably larger rainfall values at various recurrence intervals than were found for stations located to the north, east, and south. To illustrate, the 2-year, 24-hour rainfall averaged 3.45 inches in the west compared with 3.11, 3.02, and 3.11 inches, respectively, in the northwest, central, and west southwest sections shown in figure 7.

Strictly from statistical considerations, one might conclude that the data for Quincy, LaHarpe, and Monmouth are not representative of the heavy rainfall distribution in their region because of the relatively large disagreement of these data with the data for numerous stations to the north, east, and south that incorporate a substantial portion of the state. However, Water Survey studies (Changnon, 1957) have shown that the area in question coincides closely with a region of relatively frequent thunderstorms in Illinois, and, as indicated previously, extreme rainfall events in Illinois nearly always occur in thunderstorm activity. In view of the climatic support for the statistical results, the Quincy-LaHarpe-Monmouth findings were deemed legitimate, and the west section was established to reflect the relatively heavy rainstorm climate in extreme western Illinois.

The preceding example illustrates the general procedure followed in establishing the ten sections of approximately homogeneous precipitation climate in Illinois. However, some compromise and some subjective judgment were involved in the final establishment of boundaries. This was necessary because results from efforts to minimize the dispersion of station clusters (potential climatic sections) were not always exactly the same for each of the recurrence intervals (2 to 100 years) and for each of the rainfall periods (24 hours to 10 days) used in the analyses. As indicated earlier, in these cases the shorter recurrence intervals (2 to 10 years) and rain periods of 24 to 72 hours were given the most weight in final definition of the areas because of data reliability (sample size) and the most frequent needs of Illinois users.

The ten-section grouping reflects certain spatial trends indicated in earlier national studies, such as those by Yarnell (1935) and Hershfield (1961), and in the earlier Illinois study by Huff and Neil1 (1959). Thus, a general trend is indicated for a west-to-east decrease in rainfall for a given recurrence interval and rain period. However, this trend is disrupted in northeastern Illinois by effects of the Chicago urban area and Lake Michigan, as shown by Huff and Vogel (1976). A general north-to-south increase in rainfall is indicated by the sectional grouping, except for a reversal in central and east central Illinois (central and east sections in figure 7). This reversal was first identified by Huff and Neil1 (1959). It appears to be related to the lack of any significant topographic influences in the region, as well as to its location north and east of the regions of maximum thunderstorm activity in Illinois (Changnon, 1957) but south of the region of most active frontal activity during the warm season (Chiang, 1961).

We recommend using area1 mean frequency relationships. However, some users seek an isohyetal presentation because it facilitates use of the frequency information in certain types of hydrologic problems; for example, in calculating the frequency distribution of storm rainfall in basins, especially when a basin overlaps two or more climatic regions. We have tried to meet this need by including isohyetal maps for the storm periods and recurrence intervals most commonly used by the hydrologic community. This includes maps for storm periods ranging from 1 to 72 hours and for recurrence intervals of 2 to 100 years. (See figures 10 through 17.)

Adjustment for Climatic Trend

The relatively strong climatic trend revealed in the comparison of the two 40-year periods (1901-1940 and 1941-1980) and described in Section 1 was incorporated through use of an adjustment factor in the frequency relations derived from the 1901-1983 data. This factor was obtained by calculating the ratio of 1941-1980 rainfall to that for the entire 1901-1983 period at each of the 61 stations for the various rain periods and recurrence intervals.

Mean ratios were then calculated for each of the ten climatic sections, and these average values were used to adjust both the station and section frequency distributions derived from the 1901-1983 data. The average ratios were used in preference to station values to minimize the effects of random sampling fluctuations among the 61 individual stations. In effect, the adjustment ratios provide a weighting factor that gives more weight to the latter part of the sampling period. This was deemed appropriate in view of the findings by Lamb and Changnon (1981) and others with respect to temporal persistence in precipitation.

Table 9 shows the adjustment factors for each climatic section for storm periods of 24 hours to 10 days. No statistically significant trend was found for a change in the adjustment ratio (1941-1980/1901-1983) with increasing recurrence intervals, so the various recurrence-interval values for each storm period were averaged to obtain the average ratios in table 9. It is apparent that the most pronounced upward trend occurred in the northern part of the state, with a reversal to a slight downward trend in the southern part, as discussed in Section 1. These ratios are considerably smaller than those obtained **in** the **comparison** of the 1901-1940 and 1941-1980 periods because the 1941-1980 period is included in the denominator of the adjustment ratio. The 24-hour values were those used for the rain periods of less than 24-hour duration.

Ranking of Rainfall Data

Two methods of data ranking are commonly used in frequency analysis. In our study, the frequency relations have been developed from the partial-duration series, as opposed to the annual-maxima series. The annual series consists of only the highest values

Table 9. Adjustment Factors for Climatic Trend by Section and Storm Period

Climatic section	*Avemge ratio for given storm duration in each section*					
	24 hrs	*48 hrs*	*72 hrs*	*5 days*	*10 days*	*Combiried*
Northwest	**1.06**	**1.05**	**1.06**	**1.04**	**1.04**	**1.05**
Northeast	**1.07**	**1.04**	**1.05**	**1.03**	**1.02**	**1.04**
West	**1.05**	**1.03**	**1.05**	**1.05**	**1.05**	**1.05**
Central	**1.02**	**1.03**	**1.04**	**1.03**	**1.03**	**1.03**
East	**1.02**	**1.04**	**1.05**	**1.04**	**1.04**	**1.04**
West Southwest	**1.04**	**1.04**	**1.05**	**1.01**	**1.01**	**1.03**
East Southeast	**0.99**	**0.99**	**0.99**	**1.01**	**1.01**	**1.00**
Southwest	**0.98**	**0.98**	**0.98**	**0.99**	**0.99**	**0.98**
Southeast	**0.99**	**0.98**	**0.98**	**1.00**	**1.00**	**0.99**
South	**0.99**	**0.98**	**0.98**	**1.00**	**1.00**	**0.99**

for each year, whereas the partial-duration series incorporates all of the highest values regardless of the year in which they occur. Thus, with the partial-duration series, more than one value used in the frequency distribution can occur in a single year. The two series are equivalent for longer recurrence intervals but usually diverge for return periods of 10 years or less. For example, for 24-hour storms, the partial duration can be converted to the annual series by multiplying the a-year, &year, and lo-year partial-duration amounts by 0.88, 0.95, and 0.99, respectively (Huff and Neill, 1959).

Values in earlier major publications varied. In U.S. Weather Bureau Technical Paper 40 (Hershfield, 1961), values were expressed in partial-duration terms, but those used by Huff and Neill (1959) were derived from the annual series. The partial-duration series is used here because it appears to be the most applicable to hydrologic design problems.

Independence of Observations

As in any statistical analysis, the individual observations or data points should be independent of each other. With a partial-duration series, one must be careful that the observations used are not meteorologically dependent; that is, they must be from separate storm systems. In the present study, data for precipitation durations of 24 hours or less were obtained from individual precipitation events, defined as precipitation periods in which there was no precipitation for at least 6 hours before and 6 hours after the precipitation event (Huff, 1967); then, only the maximum value for the particular duration (6 hours, 12 hours, etc.) within such a precipitation event was used. This ensures that the precipitation values are independent of each other and are derived from individual storms. For precipitation durations of 2 to 10 days, no time separation criteria were needed.

Transformation Factors

Because the 61-station sample provided only daily rainfall totals, the calendar-day amounts had to be converted to maximum-period amounts. The transformation factors used for this purpose are shown for l-day to 10-day rainfalls in table 10. The factor for converting calendar-day rainfall to maximum 24-hour rainfall was derived by Hershfield (1961), using available recording raingage data throughout the United States. It is an average value that may vary considerably between storms, but it should result in only small errors when applied to a large sample of storms. The 1.13 transformation was verified by Huff and Neil1 (1959), using recording raingage data from Illinois stations. The transformation factors for 2- to 10-day periods were also derived by Huff and Neil1 from the Illinois data.

Table 10. Ratios of Maximum-Period to Calendar-Day Precipitation

Storm period (days)	Ratio
1	1.13
2	1.02
3	1.01
5	1.01
10	1.01

Computation of Short-Duration Rainfall

Recurrence-interval values for storm periods of less than 24 hours were obtained from average ratios of x-hour/24-hour rainfall. These ratios were determined primarily from the recording raingage data for 1948-1983 at 34 Illinois stations and at 21 stations in adjoining states. Results of a similar study, based on use of the Chicago urban network data for 1948-1974 (Huff and Vogel, 1976) and ratios derived by Hershfield (1961), were also taken into consideration in determining the values to be applied. All the sources of information provided ratios that were in close agreement.

In table 11, the derived ratios are shown for rain periods ranging from 5 minutes to 18 hours. Analyses indicated that the ratios do not vary significantly within Illinois or with variations in the length of recurrence intervals. Therefore, they could be used for all frequency computations involving rain periods of less than 24 hours. This permitted use of our longest and most reliable period of record (1901-1983) in the short-period frequency computations, and also helped smooth random sampling variations between points and/or areas in the state.

Recurrence Intervals of 2 to 9 Months

Frequency relations are usually developed for recurrence intervals of 1 year or longer. However, to meet some user needs in Illinois, it has been necessary to develop frequency relations for time periods shorter than 12 months. In analyzing the data, it was found that the 2-month to g-month frequency

Table 11. Average Ratios of X-Hour/ 24-Hour Rainfall for Illinois

Rain period (hours)	Ratio, x-hr /24-hr
0.08 (5 min.)	0.12
0.17 (10 min.)	0.21
0.25	0.27
0.50	0.37
1	0.47
2	0.58
3	0.64
6	0.75
12	0.87
18	0.94

values could be related to the l-year values. Further, we found that the x-month/12-month ratios are consistent throughout the state and for all recurrence intervals. These ratios are shown in table 12 for storm periods of 24 hours to 10 days. The 24-hour values are also applicable to storm periods of less than 24-hour duration.

Thus, in table 12, the 24-hour rainfall expected on the average of once in 6 months is equal to 81% (0.81) of the 24-hour rainfall expected once in 12 months at any station or in any climatic section of the state. This technique was used in extending the frequency curves below the l-year recurrence interval in the present study. Again, using the average values results in smoothing of the distributions and eliminates some of the irregularities due to random sampling variations unrelated to the long-term precipitation climate.

Areal Mean Frequency Distributions

The ten climatic sections used in computing area1 mean frequency distributions are shown in figure 7. County outlines, sampling point locations and names, and boundaries of the ten sections are indicated in this figure. The southern and western sections are subject to the greatest frequency of thunderstorm rainfall (Changnon, 1957) and, in general, have the highest rainfall amounts for given rain periods and recurrence intervals. The southern section also has the longest convective rainfall season and incorporates the Shawnee Hills, which, as previously noted, tend to increase the natural rainfall (Huff, Changnon, and Jones, 1975). The central section incorporates most of the Illinois River low discussed in Section 1.

The southwestern section has been the recipient of an unusual number of severe rainstorms in the last 40 to 45 years. This region is subject to topographic enhancement of storms by the Ozark Mountains, which lie to the west and southwest; to a relatively long convective season; and to influences of the St. Louis urban area effect under some storm conditions (Vogel and Huff, 1978). The eastern, east southeastern, and southeastern sections have no distinguishing topographic features or climatic anomalies. The same is true of the northwestern section. Variation in the length of the convective rainfall season is the major difference between these sections.

Of the ten sections, the northeastern section has the greatest diversity in the distribution of heavy storm rainfall. If more station data were available, division of this section into two or three subsections would be desirable. It incorporates effects of three

Table 12. Ratios of Illinois Rainfall Amounts for Recurrence Intervals of Less than 1 Year to Rainfall Amounts for Recurrence Intervals of 1 Year, for Various Rainstorm Periods

Storm period	Mean ratio, x-month to 12-month rainfall amount for given rainstorm period				
	2 months	3 months	4 months	6 months	9 months
<=24 hours	0.55	0.64	0.70	0.81	0.92
48 hours	0.53	0.62	0.69	0.80	0.92
72 hours	0.52	0.61	0.69	0.80	0.92
5 days	0.51	0.61	0.69	0.80	0.92
10 days	0.49	0.59	0.69	0.80	0.92

important conditions that produce in-area variations in rainfall: a frontal maximum, Lake Michigan influences, and urban effects. The southern and southeastern parts of this section lie in a climatic high that extends northeastward from southwestern Illinois and is related to frequent frontal activity. The southwestern part of this northeastern section is between the Illinois River and the Waukegan-Marengo low (Lake and McHenry Counties). The large Chicago urban area is subject to both urban and lake effects on precipitation, and the Waukegan area north of the city and near the lake is subject to the suppressing influence that Lake Michigan has on convective season rainfall (Changnon, 198413).

Graphical Values

Figure 9 shows families of frequency curves for each of the ten climatic sections. Curves are shown for recurrence intervals of 2 months to 100 years and for rain periods of 5 minutes to 10 days. The sectional curves were derived by averaging rainfall amounts from the frequency curves for each individual station in the section. These families of curves illustrate the characteristics of the frequency distributions and the interrelationship between storm (rain) periods and recurrence intervals of various lengths.

Tabular Values

The relationships shown in figure 9 are presented in tabular form in table 13. The tabular values facilitate use of the information and provide more accurate rainfall values than can be read from the logarithmic plots of figure 9. Estimates of the dispersion of point rainfall amounts that can be expected to occur about the sectional curves are discussed and presented in Section 5 of this report.

In table 13, the first column (storm code) refers to the storm (rain) period. The codes are numbered consecutively from 1 to 15, with code 1 representing 10-day storm periods and code 15 representing 5-minute periods. The second column (zone code) refers to the ten climatic sections. Thus, zone 1 is the northwestern section, zone 2 is northeastern, etc., as indicated in the code explanations included with the table.

For each storm period, rainfall amounts are shown for each climatic section for recurrence intervals of 2 months to 100 years. For example, assume a user wishes to know the lo-year frequency of 24-hour rainfall in the central section. First, move to storm code 5 (24-hour rainfall). In the code 5 grouping, move to zone 4 (central section) and continue across the page to the column labeled "lo-year." At this point (storm code 5, zone 4) the rainfall amount is 4.45 inches, which is the 24-hour rainfall to be expected, on the average, once in 10 years at any given point in the central section.

Areal versus Isohyetal Presentations

The use of the areal frequency relations is favored over the use of isohyetal presentations generated from the frequency curves for individual stations in the region of interest. The areal approach lessens the effects of natural and human-induced variability between points in an area of approximately homogeneous precipitation climate with respect to heavy rainstorms. The averaging process allots equal weight to all station data in a specific climatic area (section). When data for a relatively large number of stations are available, such as the data for the 61 stations used in the present study, it is readily apparent that considerable variation in the frequency distributions of heavy rainfall may exist between nearby points (table 14), even in relatively long sampling periods such as the 83-year period used in the present study. Such variation occurs even when the sampling stations are selected after all available information pertaining to their operation is edited and reviewed.

Much of this areal variability is caused by random sampling variation. For example, the station at Urbana has been operated since 1888 in the same location, first by the University of Illinois and more recently (since 1948) by the Illinois State Water Survey. The raingage operation has been under the close supervision of University and Survey scientists throughout its history. There is probably no raingage station in the state with a more authentic record. Yet, in general, the frequency relationships for the Urbana station show smaller rain values for a given recurrence interval than do those for several surrounding stations located in the same or very similar climatic regimes.

The major cause apparently is that Urbana has not experienced the most extreme rain events that can occur in east central Illinois. A few examples resulting from extensive field surveys of heavy rains (Huff et al., 1958; Huff and Changnon, 1961) during the period since 1955 are a 10-inch rainfall in less than 24 hours about 25 miles north-northwest of Urbana (May 1956); a 12-hour storm of 13 inches about 40 miles southeast of the city (June 1957); a 6-inch storm in 4 hours 3 miles north (June 1961); a 7-