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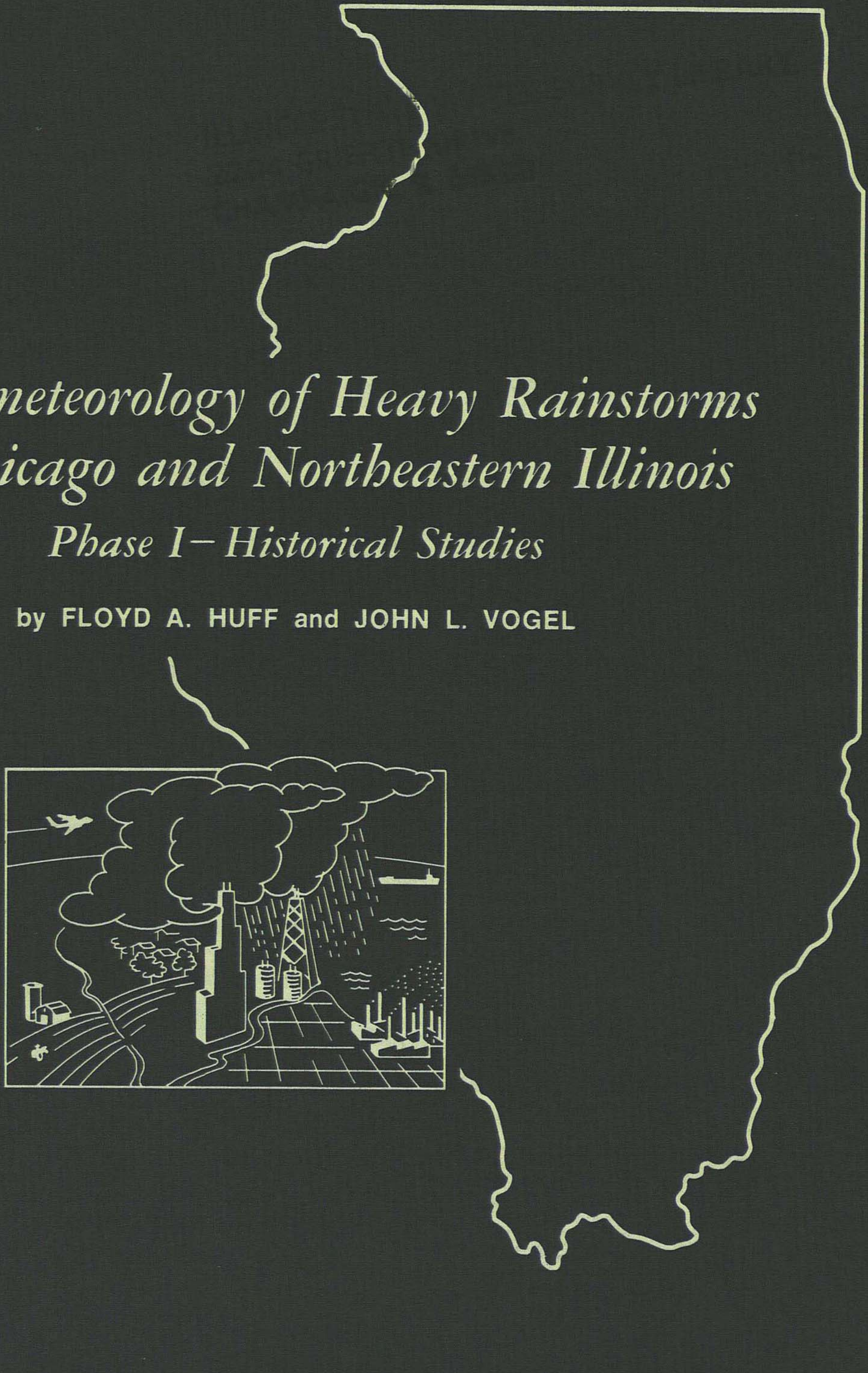

Hydrometeorology of Heavy Rainstorms in Chicago and Northeastern Illinois

Phase I – Historical Studies

by FLOYD A. HUFF and JOHN L. VOGEL

ILLINOIS STATE WATER SURVEY
URBANA
1976

REPORT OF INVESTIGATION 82

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Phase I—Historical Studies

by FLOYD A. HUFF and JOHN L. VOGEL

Title: Hydrometeorology of Heavy Rainstorms in Chicago and Northeastern Illinois, Phase I — Historical Studies.

Abstract: This report presents the results of an investigation of the distribution of heavy rainstorms in the Chicago urban area and the surrounding six counties, based on available historical rain data (primarily 1949-1974). The six counties are Cook, Du Page, Kane, Will, Lake, and McHenry. Presented are frequency distributions of point rainfall for rain periods from 5 minutes to 72 hours and recurrence intervals of 6 months to 50 years. Also presented are point-area relationships, frequency distribution of storm centers, diurnal and seasonal distribution of heavy storms, orientation of heavy storms, storm shapes, synoptic weather conditions associated with severe rainstorms, time between heavy rain occurrences, and time distribution characteristics of rainfall during heavy storms. Results are pertinent to design of hydraulic structures such as storm sewers. This historical study is the first phase of a comprehensive hydrometeorological research program for northeastern Illinois that will include, as the next phase, an extensive field measurement project in the area.

Reference: Huff, Floyd A., and John L. Vogel. Hydrometeorology of Heavy Rainstorms in Chicago and Northeastern Illinois, Phase I — Historical Studies. Illinois State Water Survey, Urbana, Report of Investigation 82, 1976.

Indexing Terms: Climatology, heavy rainstorms, hydrometeorology, local precipitation, rainfall frequency distributions, rainfall intensity, storm characteristics, urban weather.

STATE OF ILLINOIS
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Floyd A. Huff and John L. Vogel

ABSTRACT

This report presents the results of an investigation of heavy rainstorms in the Chicago urban area and the surrounding six counties, based on available historical data of rainfall and associated weather conditions. The six counties are Cook, Du Page, Kane, Will, Lake, and McHenry. Frequency distributions of point rainfall are presented for rain periods from 5 minutes to 72 hours and recurrence intervals of 6 months to SO years. Also presented are the relationship between point and areal mean rainfall frequencies, time and space distribution characteristics of heavy rains, orientation and movement of storms, the frequency distribution of storm centers, synoptic weather conditions associated with severe rainstorms, and the diurnal, monthly, and seasonal distribution of flood-producing storms. Results of this investigation are particularly useful in hydrologic design problems, such as in the design of urban storm sewer systems, but have application also in agriculture, environmental problems, and various phases of climatology and hydrometeorology.

This historical study is the first phase of a comprehensive hydrometeorological research program for northeastern Illinois. The second phase will involve an extensive field and analysis program utilizing a large raingage network, weather radars, and other meteorological equipment to acquire the hydrometeorological knowledge needed to optimize the design and operation of sophisticated water resources systems.

INTRODUCTION

Background

Previous investigators (Hershfield, 1961; Huff and Neill, 1959; Ackermann, 1970) have evaluated data to determine the frequency of point rainfall amounts of various intensity and duration in Illinois. These studies did not attempt to determine differences which might exist over small areas due to local weather anomalies, but rather gave broad indications of the frequency distribution of various precipitation events. However, recent research has indicated that inadvertent weather modification produced by urban environments can produce significant increases in the frequency of severe weather events such as hail, thunderstorms, and heavy rainstorms.

For example, Changnon (1968) found strong evidence that the Chicago urban-industrial complex was producing a significant increase in total precipitation, hail, and thunderstorms at La Porte, Indiana, approximately 35 miles to the east. A later study by Huff and Changnon (1970) showed that heavy rainstorms were apparently more frequent over and downwind of Chicago and St. Louis than in the surrounding suburban and rural areas. These and other findings led to a comprehensive climatological study of urban effects on precipitation at 8 major cities in the United States (Huff and Changnon, 1972, 1973). The results provided further verification of the urban influence on precipitation. This inadvertent modification apparently leads to important spatial variations in heavy, short-duration rainfalls that produce excessive storm runoff. Consequently, there appears to be a need to incorporate these variations in the design of hydraulic structures in large urban areas.

The growing interest in urban effects on regional weather by meteorologists, hydrologists, environmentalists, city planners, and others then led to the establishment of a comprehensive, 5-year field program in the St. Louis area during 1971 (Changnon et al., 1971). The major purpose of the research (Project METROMEX) was to define accurately the magnitude of urban environmental effects on precipitation in a large metropolitan area, the location of such effects with respect to the urban-industrial complex, and the meteorological causes of the urban anomaly.

By the end of the 1973 field operations, it was apparent from the METROMEX network of 225 recording raingages in 2000 mi^2 that the St. Louis urban-industrial complex was indeed producing a substantial increase in warm season rainfall east and northeast of the city (Huff and Schlessman, 1974). By this time also, numerous inquiries had been received at the Water Survey from both private and governmental groups concerning information on the distribution of heavy rainstorms in the urban and suburban areas of Chicago.

The problems and needs at Chicago were explored further, and resulted in a conference on May 21, 1974, be-

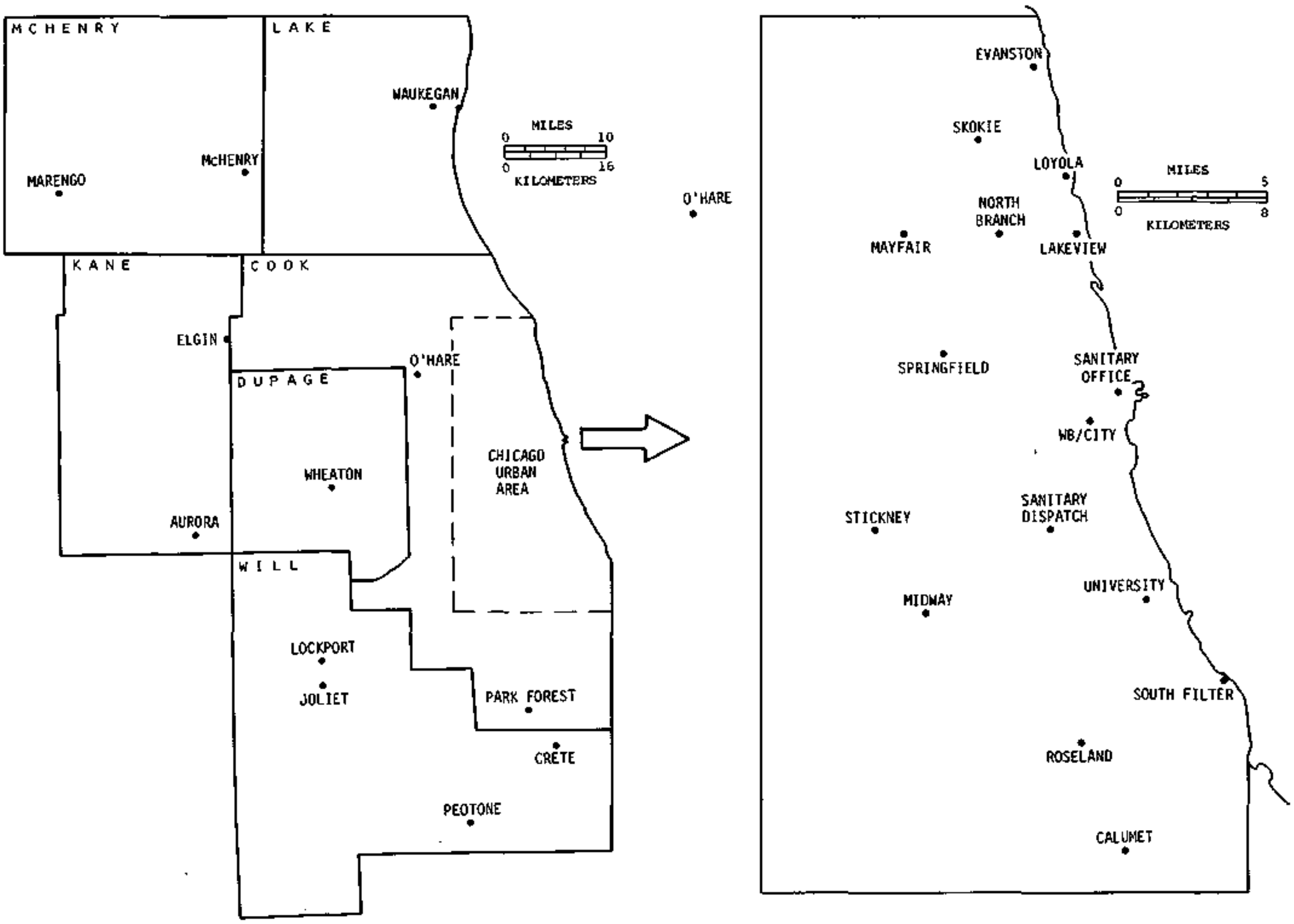


Figure 1. Location maps

tween representatives of the Water Survey and interested users of rainfall data in the metropolitan area, including the Metropolitan Sanitary District of Greater Chicago, the Bureau of Engineering of the City of Chicago, Northeast Illinois Planning Commission, the U.S. Army Crops of Engineers, and several consulting engineer firms. As a result of the interest expressed and needs outlined at this conference, a study was initiated to investigate the distribution of heavy rainstorms in the Chicago urban area and the surrounding six counties in the most comprehensive manner permitted by available data. The six counties selected for study were Cook, Du Page, Kane, Will, Lake, and McHenry (figure 1).

Fortunately, a network of recording raingages has been operated in Chicago since 1949. Data were available from 16 gages for all or most of the period from 1949 through 1974. Most of these were operated by the Metropolitan Sanitary District. These gages sampled an area of approximately 430 mi^2 within Cook County (figure 1). Furthermore, rainstorm data from the recording gages for 1949-1968 had been tabulated, edited, and placed on computer tape by the Chicago Bureau of Engineering. Only 12 raingages were available in the 3700 mi^2 that included the remainder of Cook County and the other five counties (figure 1), and only four of these were recording gages. The other eight were standard, non-recording gages from which only daily totals were available. Thus, detailed temporal analyses of heavy rainstorm patterns had to be confined largely to the urban area.

As part of the study, the raingage sites were visited and photographed, so that their exposures could be rated for use in interpreting results. Unfortunately, several gages had been moved during the sampling period so that a complete exposure record was not always available. Most of the sites were found to have satisfactory exposures that were equivalent to the exposures found in the climatic network of the National Weather Service in Illinois. Thus, it was concluded that the urban network data should be accepted as reliable in establishing urban patterns of rainfall distribution during the 26-year sampling period.

Scope of Study

All available data from the urban network and the climatic stations of the National Weather Service were used to develop frequency distributions of point rainfall. This was done for recurrence intervals of 0.5 to 50 years, and for rain periods ranging from 5 minutes to 72 hours. Other analyses were performed to determine the:

- point-area relationships
- frequency distribution of storm centers
- diurnal and seasonal distribution of heavy storms
- orientation of flood-producing storms
- shape characteristics of major storms
- synoptic weather conditions associated with severe rainstorms
- time between successive heavy storms
- time distribution characteristics of the rainfall during heavy storms
- area-depth relationships in outstanding storms both in the urban area and in the remainder of the 6-county area

This report is the culmination of the first phase of a comprehensive hydrometeorological research program for Chicago and northeastern Illinois. As indicated by the title, results presented here summarize our studies of historical weather data. At this time, we are initiating an extensive hydrometeorological field project that is being jointly sponsored by the State of Illinois and the National Science Foundation (NSF/RANN Grant ENV76-01447). The major objectives of the research in this second phase of the program are to 1) optimize methods of collecting and analyzing precipitation data for hydrologic design problems, 2) provide better areal detail of heavy rain events than was possible in the present study, 3) develop an operational rain prediction-monitoring system for the area utilizing a combination of radar and raingage data output, and 4) establish methods and techniques for transferring the research findings to other urban areas. As various phases of this program are completed, research reports will be published. The advent of a network of 300 recording raingages in 1976 with a 3- to 5-year period of data collection will provide considerably more information on the spatial variations of heavy rainfall rates in northeastern Illinois than the historical data herein can provide.

Analytical results in this report have been expressed in the English system of units in preference to the metric system. It is expected that hydrologists and other major users of the information will still be using the English system for computational purposes in the foreseeable future. Furthermore, all sources of data used in the study were in English units, and nearly all existing reference material on heavy rainfall, such as Technical Paper No. 40 of the U.S. Weather Bureau (Hershfield, 1961), is published in inches.

Acknowledgments

This report was prepared under the general direction of Dr. William C. Ackermann, Chief of the Illinois State Water Survey, and the guidance of Stanley A. Changnon, Jr., Head of the Atmospheric Sciences Section. A portion of the effort was performed as part of the research under NSF/RANN Grant ENV76-01447.

The authors are indebted to Ganji Tanaka and Joseph Harrison, City of Chicago, Bureau of Engineering, and William Eyre, Russell Harrup, and Dan Wnek of the Metropolitan Sanitary District of Greater Chicago for furnishing much of the data upon which the study was based and for their suggestions relating to the work.

Within the Water Survey, special appreciation is expressed to John B. Stall, Head of the Hydrology Section, who consistently encouraged this undertaking and was instrumental in arranging conferences with potential users in northeast Illinois and in locating sources of data for the project. Much of the data processing and routine analysis of the data was supervised by E. E. Schlessman, Jr. John Brother supervised the drafting of the many illustrations contained in the report. G. Dzurisin and P. Lamb assisted in several phases of the analyses. Mrs. J. Loreena Ivens edited the final manuscript and Mrs. Suzi L. O'Connor prepared the camera-ready copy.

RAINFALL FREQUENCY RELATIONSHIPS

Frequency Distribution of Point Rainfall

The frequency distributions of point rainfall were derived from four sources of data and information. These include the Chicago urban network (figure 1) operated during 1949-1974, Technical Paper No. 40 of the U.S. Weather Bureau (Hershfield, 1961), and Technical Letter 13 of the Illinois State Water Survey (Ackermann, 1970), and publications of climatic data on hourly and daily precipitation by the National Weather Service. Originally, it was planned to derive frequency relations for the immediate urban area solely from the urban network data. However, analyses indicated that the 1949-1974 data were badly skewed and frequency relations derived from these data would provide fallaciously high estimates of heavy rainfall occurrences, particularly for longer recurrence intervals. This resulted from the presence of several unusually heavy storms during 1949-1974 that were not representative of an average 26-year period. Time trend analyses indicated that these unusual storms were random events, and not indicative of any significant change in the urban rainfall distribution in recent years. To overcome this sampling problem, data from earlier years were used to modify the 1949-1974 results.

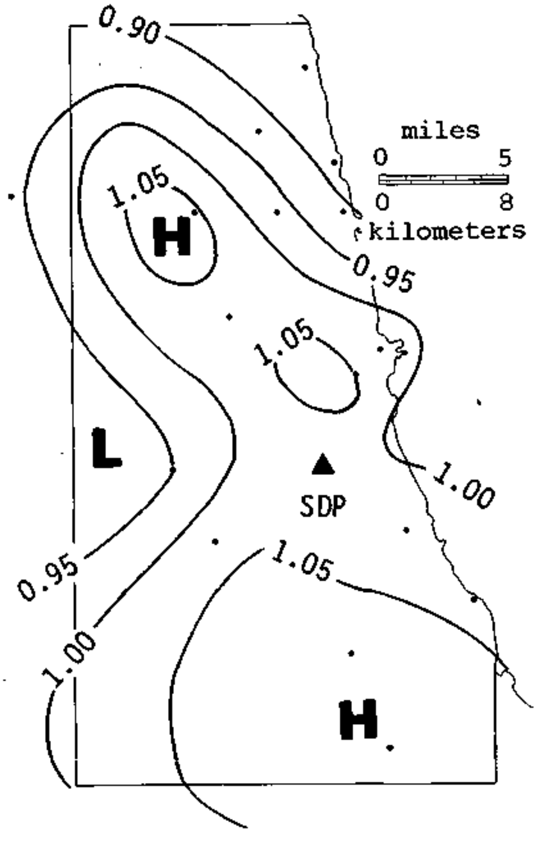


Figure 2. Ratio pattern for 24-hour, 2-year storms

Other analyses led to the conclusion that the spatial distribution characteristics of heavy rainfall in the urban area, as reflected by percentage differences between raingage stations, could be delineated satisfactorily by the frequency relations derived from the urban network data. The pattern of percentage differences (relative variability) between stations was found to remain stable for various levels of rain intensity and storm duration obtained from the station frequency curves. Furthermore, earlier studies by Huff and Changnon (1972, 1973) showed that the pattern of heavy rainfalls remained consistent for consecutive 10-year periods from 1949 to 1968 in northeast Illinois and northwest Indiana, as well as within the Chicago urban area.

Spatial distribution patterns for the urban area were derived from the 1949-1974 data by calculating the ratio of rainfall at each raingage station to the most central station, Sanitary Dispatch (figure 1). This station also is near the geometric center of the three urban stations [Midway, University, Weather Bureau City Station (WB/City) in figure 1] used in deriving the long-term frequency relations in Technical Paper No. 40. The ratios were obtained from station frequency curves computed for various rain durations ranging from 1 to 72 hours. These station ratios then established the spatial patterns.

An example of the derived patterns is shown in figure 2 for a 24-hour storm period having a recurrence interval of 2 years, based on 1949-1974 data. Ratios vary from 0.90 in the northeast part of the city to 1.08 at Calumet in the southern part. The ratio pattern indicates a trend for the heaviest rainfall to occur over the northwest, north central, and southern parts of the city and for storms to be less intense in the western suburbs and near the lake, particularly in the northeast part of the urban area.

In computing rainfall amounts from the urban ratio pattern, central values at Sanitary Dispatch for durations of 1 to 72 hours and recurrence intervals of 1 to 50 years were obtained from Technical Paper No. 40 and Technical Letter 13. These values were then multiplied by each station's ratio to obtain the appropriate rainfall amount. Recurrence interval values for 1 to 10 years were obtained primarily from Technical Paper 40 and those beyond 10 years from Technical Letter 13. Major differences occur in rainfall estimates for recurrence intervals of 25 to 100 years, and it is believed that Technical Letter 13 provides better estimates at the longer recurrence intervals.

Frequency relations for periods of less than 1 hour were obtained through use of transformation factors derived from the urban network data. This was done by computing the average ratios of x-minute to 60-minute rainfall from a large sample of heavy storms analyzed by the Metropolitan Sanitary District, in which maximum amounts for periods of 5 to 60 minutes had been tabulated. Multiplication of the 1-hour frequency values (previously determined) by these average ratios then provided the frequency distributions for rain periods of 5, 10, 15, and 30 minutes.

Frequency relations for rural stations in the surrounding counties were determined from analyses of all periods of record for each station by using the methods of Huff and Neill (1959) for analysis of non-recording raingage data from cooperative station data. These station frequency distributions were then used in conjunction with the regional patterns developed earlier by Hershfield (1961) and Huff and Neill (1959) to specify the 6-county distribution patterns outside of the urban area.

The frequency relations have been expressed in terms of the partial duration series, as opposed to the annual maxima series. The annual series consists of only the highest value for each year, whereas the partial duration series incorporates all of the highest values regardless of the year in which they occur. Thus, more than one value used in the frequency distribution can occur in a single year with thepartial duration series. The two series are equivalent for longer recurrence intervals but diverge usually for return periods of 10 years or less. For example, the partial duration can be converted to the annual series by multiplying the 2-year, 5-year, and 10-year partial duration amounts by 0.88, 0.95, and 0.99, respectively. Values in Technical Paper 40 are also expressed in partial duration terms, but those in Technical Letter 13 were derived from the annual series. The partial duration series is used here, since it appears to be the most applicable to hydrologic design problems in urban areas.

The spatial patterns of point rainfall frequencies for various durations and recurrence intervals are provided for the immediate urban area in figures 3 to 9, and for the surrounding suburban and rural areas in figures 10 to 16.

Separate maps were constructed because the urban raingage network provided much better spatial definition of the frequency distributions within the urban area.

The frequency distribution maps presented here provide the best estimates of point rainfall frequencies that could be obtained from consideration of the urban raingage network data and long-term records at both first-order and cooperative stations of the National Weather Service (formerly U.S. Weather Bureau). The comprehensive hydrometeorological study (Phase II) being undertaken by the Water Survey in the Chicago region beginning in 1976 will provide more detailed information on the characteristics of heavy rainfall distribution in the urban and surrounding regions. This may lead to modification of the "best-estimate" results presented in figures 3 to 16. However, these results will not be available until 1980 or 1981.

Relation between Point and Areal Mean Rainfall Frequency

Knowledge of the frequency distribution 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 there is a relatively large amount of data available on the frequency distribution of point rainfall, but very little information on the frequency distribution of areal mean rainfall. Consequently, there has been need for determining how the mean rainfall frequency distributions for small areas about a point are related to the point frequency distributions.

If a close relation exists between point and areal frequencies, then conversion factors can be developed from limited data on areal frequencies for transforming the abundant data on point frequencies to equivalent areal values, and provide a practical solution to a pertinent hydrologic problem. The problem has been investigated previously on a limited scale (Huff, 1956; Huff and Changnon, 1960; and U.S. Weather Bureau, 1955). The recent availability of a much larger sample of data from dense raingage networks in Illinois has provided the means for reliable definition of the midwestern relationship.

Analysis Procedure

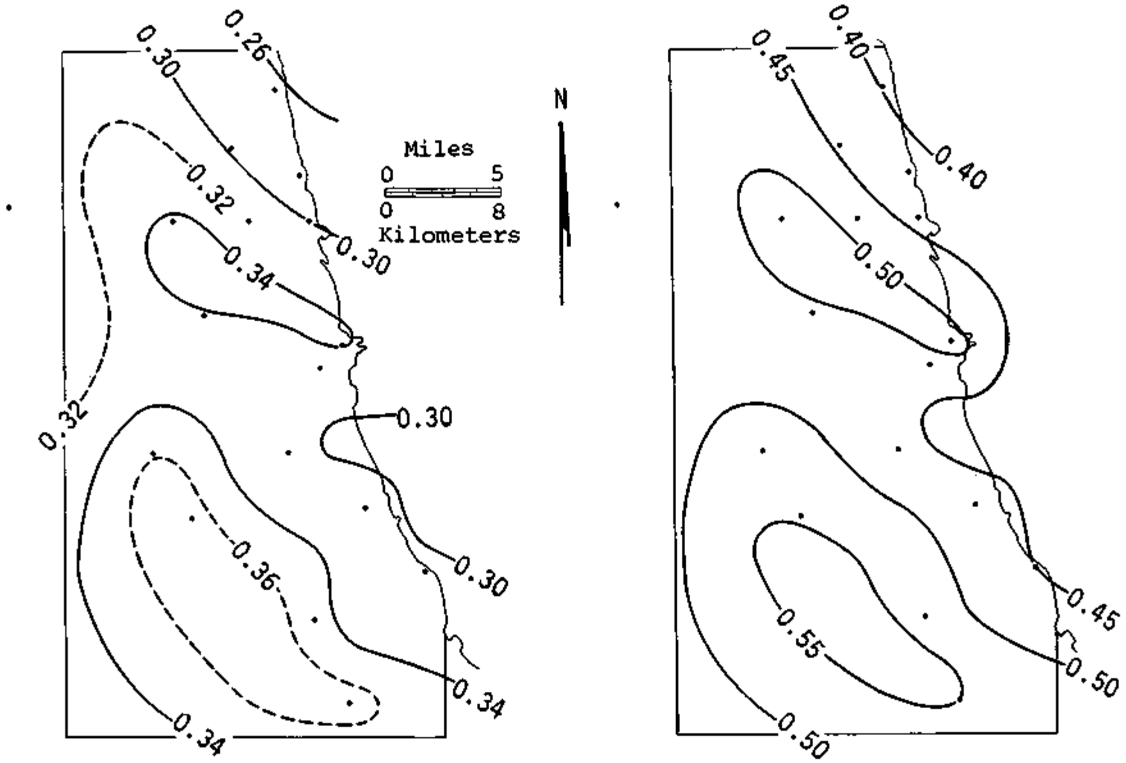
Data from two dense raingage networks in east central Illinois (Huff, 1970) were used to determine the relationship between the frequency distributions of point and areal mean rainfall on areas ranging from 10 to 400 mi^2 and for storm periods of 30 minutes to 48 hours. A 10-year sample (1950-1959) from an urban network of 11 recording raingages in Champaign-Urbana provided data for 10 mi^2. A network of 49 recording raingages on 400 mi^2 in east central Illinois provided a 11-year sample (1955-1966) for determination of relationships on areas of 50, 100, 200, and 400 mi^2.

Point rainfall at the central gage in each area was used in development of 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 — 48 hours), the study was restricted to storms in which the central gage recorded rainfall equaling or exceeding the amount expected to occur on the average of once in two years.

Point and areal mean rainfall for each specific area and storm period were ranked. Next, the ratio of areal mean to point rainfall was determined for each rank. No distinct trend was found for the ratio to vary with increasing rainfall amount. Therefore, average ratios for each area and storm period were used in the development of the relationship between the frequency distributions of point and areal mean rainfall.

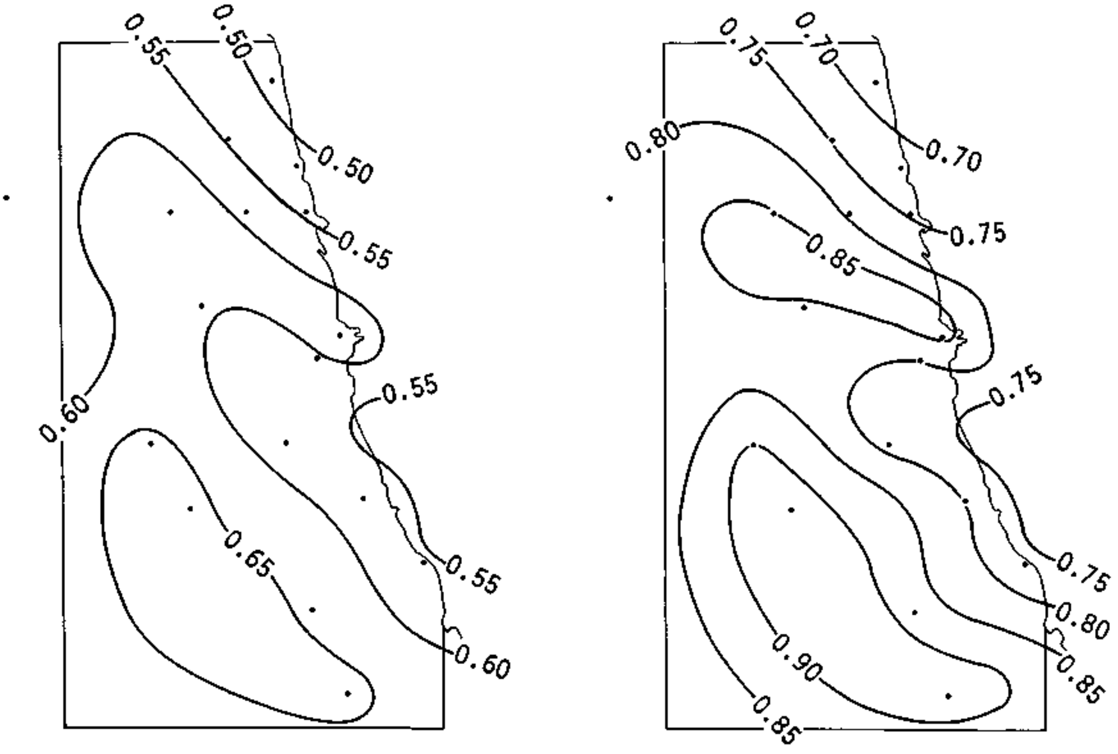
Analytical Results

For a given storm period, the relationship was found to be approximated closely by relating the average ratios to the logarithm of the area. By this curve-fitting procedure, table



5-MINUTE, 6-MONTH RAINFALL

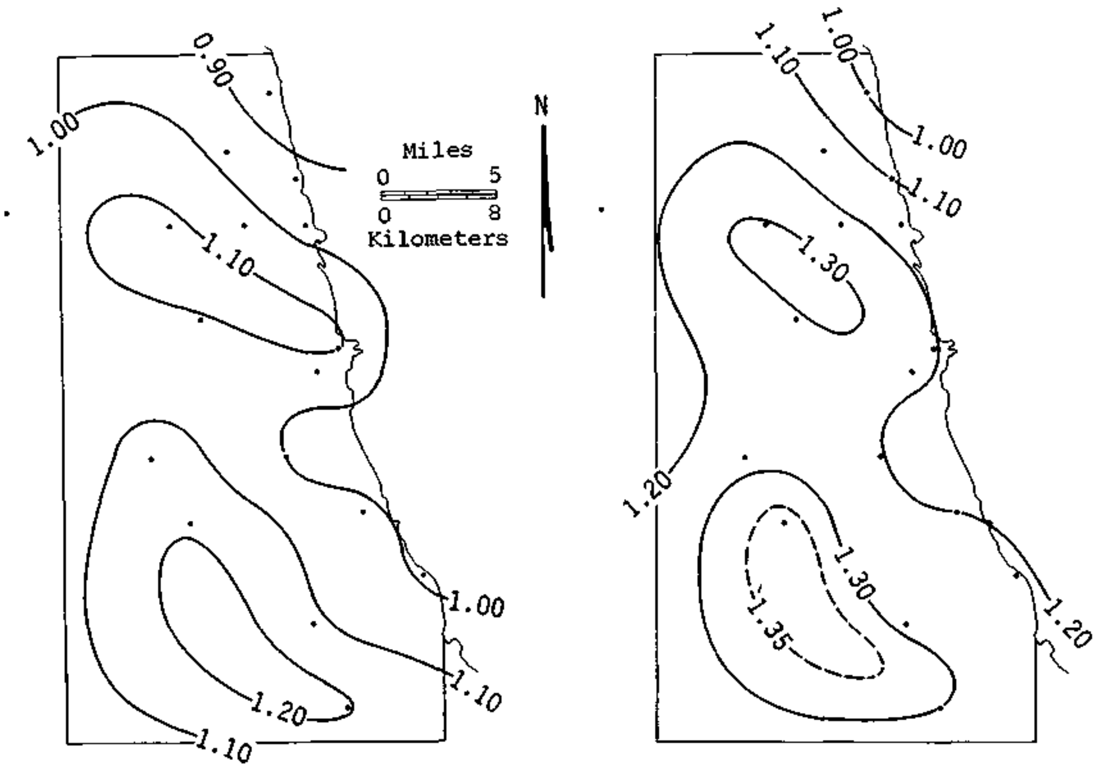
10-MINUTE, 6-MONTH RAINFALL



15-MINUTE, 6-MONTH RAINFALL

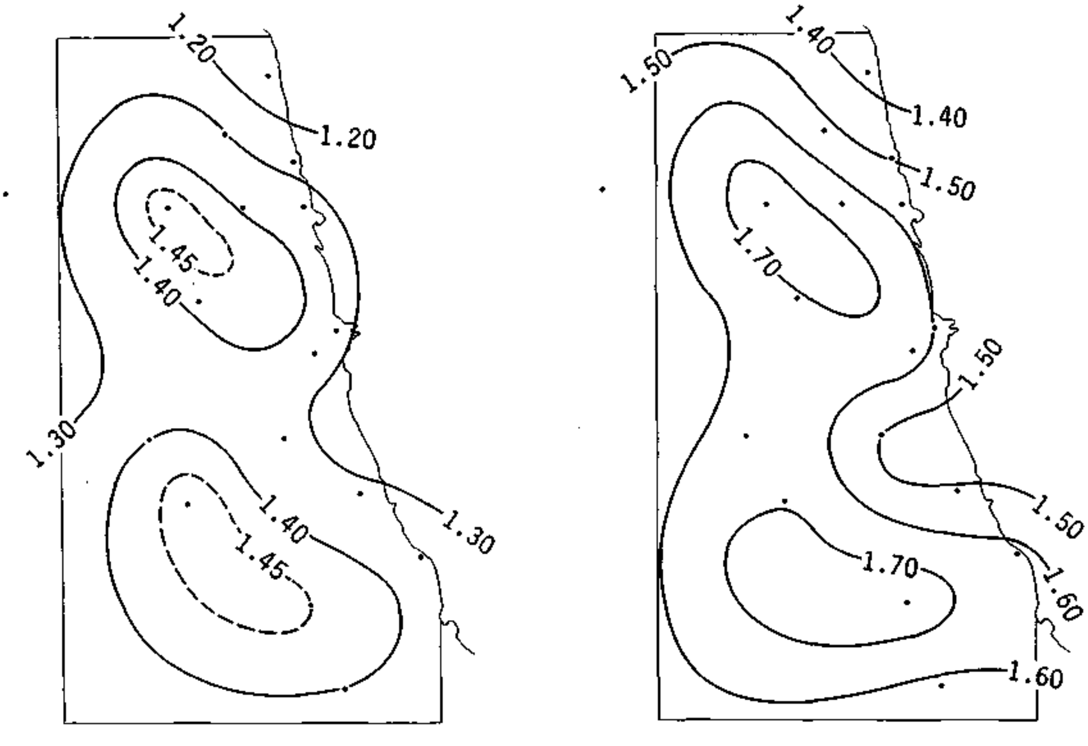
30-MINUTE, 6-MONTH RAINFALL

Figure 3. 0.5-year frequency of urban-area rainfall



1-HOUR, 6-MONTH RAINFALL

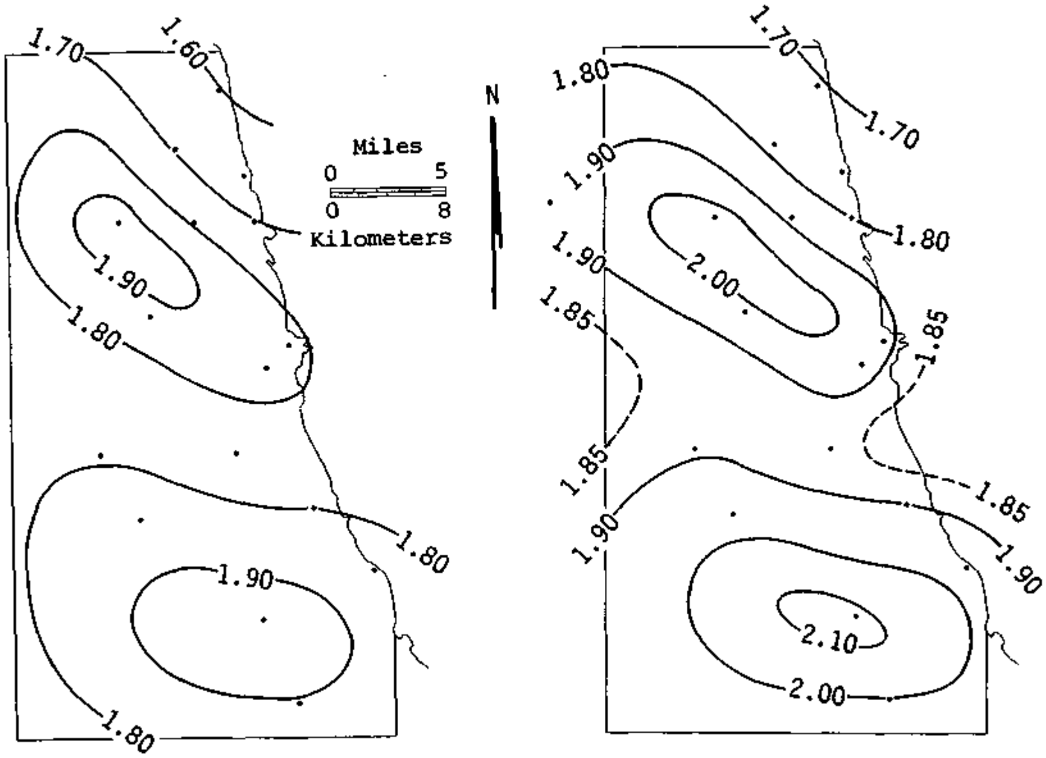
2-HOUR, 6-MONTH RAINFALL



3-HOUR, 6-MONTH RAINFALL

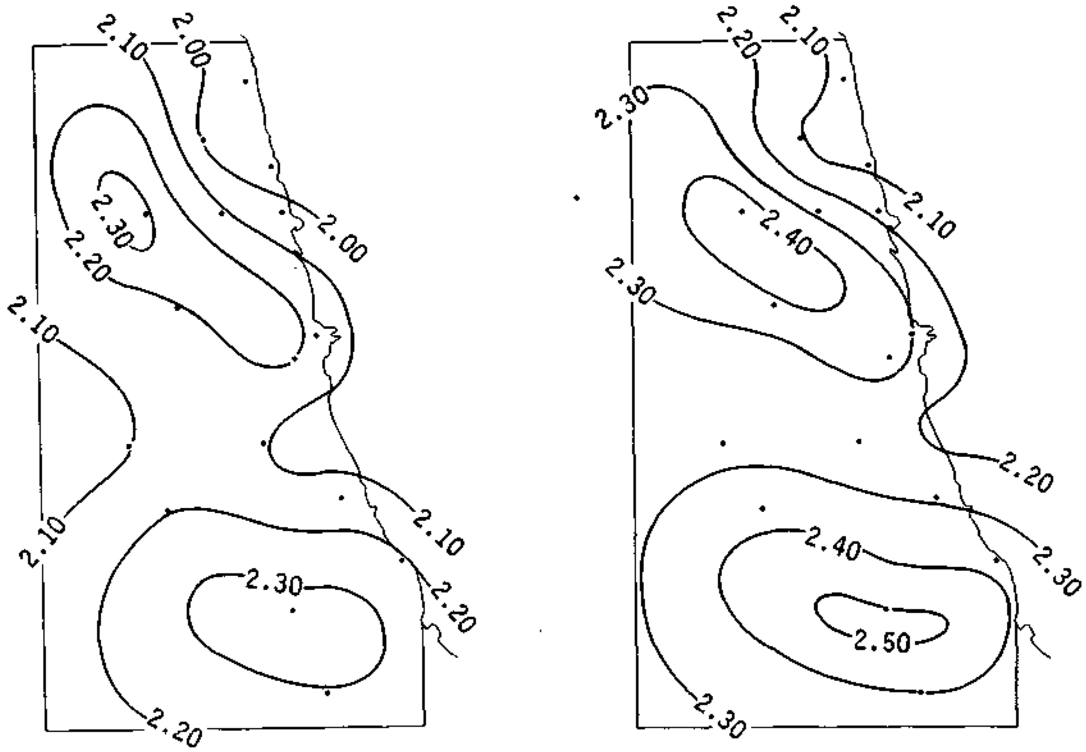
6-HOUR, 6-MONTH RAINFALL

Figure 3 (Continued)



12-HOUR, 6-MONTH RAINFALL

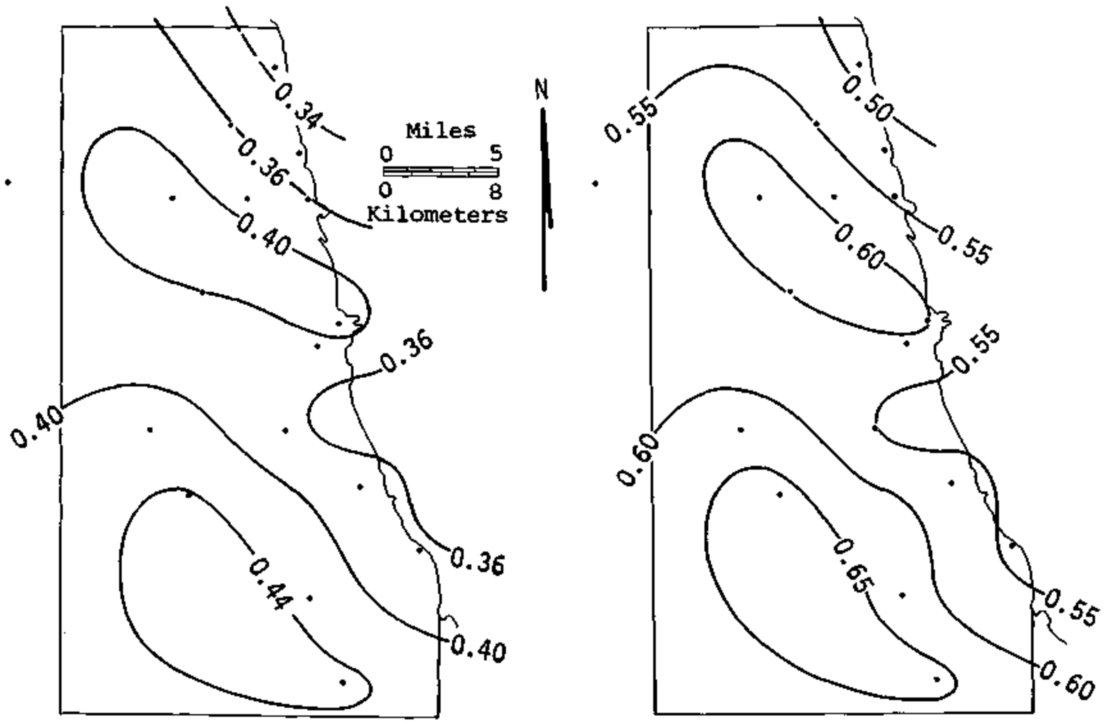
24-HOUR, 6-MONTH RAINFALL



48-HOUR, 6-MONTH RAINFALL

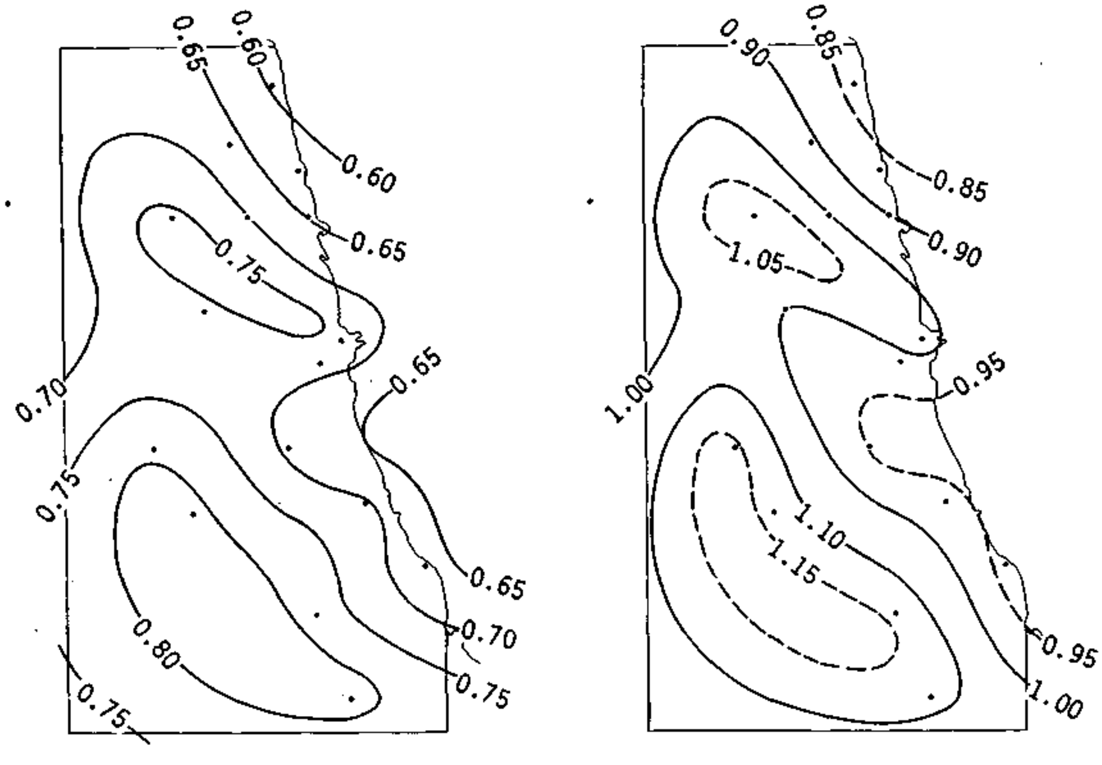
72-HOUR, 6-MONTH RAINFALL

Figure 3 (Concluded)



5-MINUTE, 1-YEAR RAINFALL

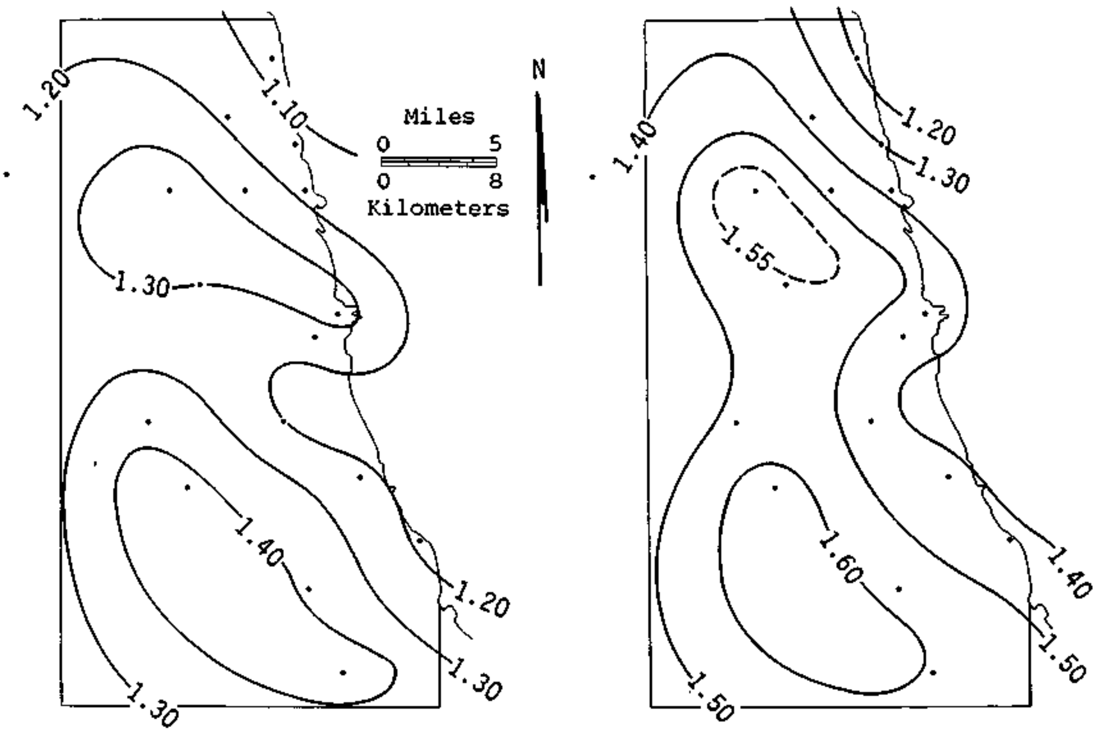
10-MINUTE, 1-YEAR RAINFALL



15-MINUTE, 1-YEAR RAINFALL

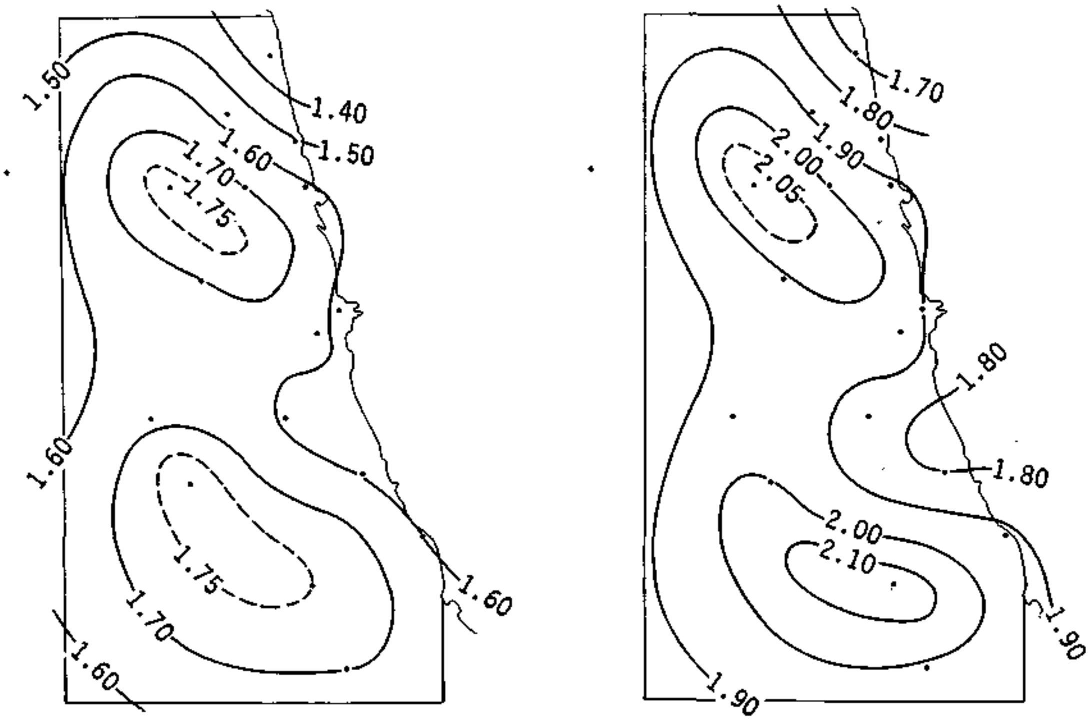
30-MINUTE, 1-YEAR RAINFALL

Figure 4. 1-year frequency of urban-area rainfall



1-HOUR, 1-YEAR RAINFALL

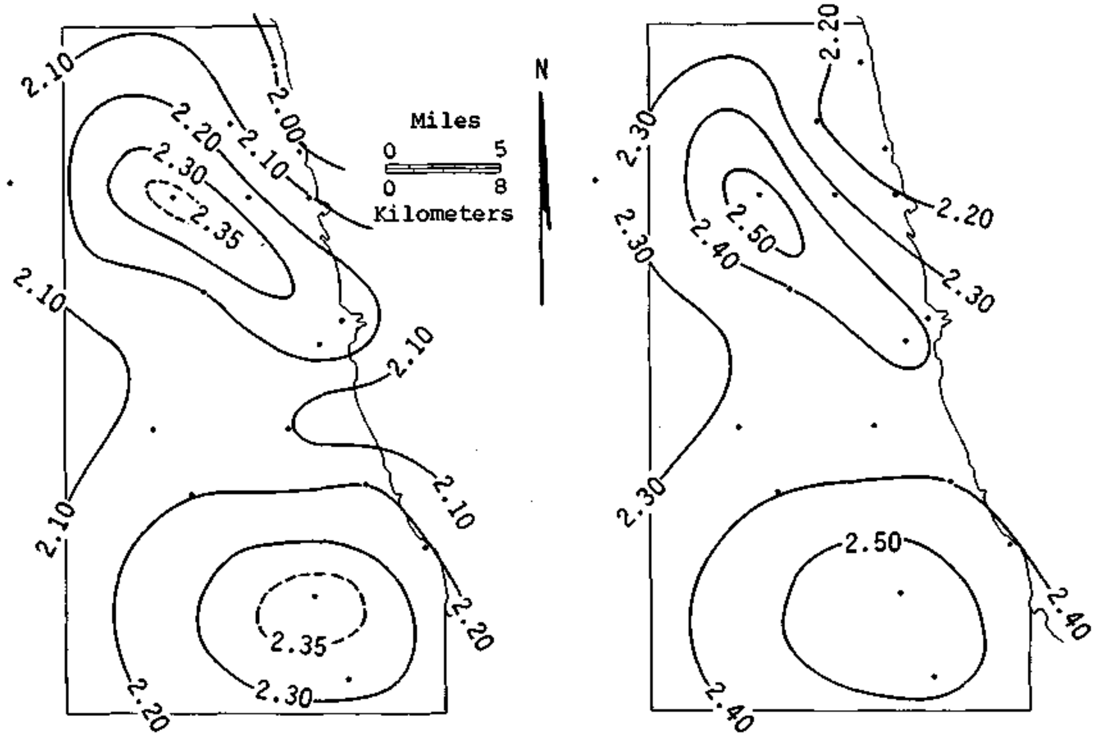
2-HOUR, 1-YEAR RAINFALL



3-HOUR, 1-YEAR RAINFALL

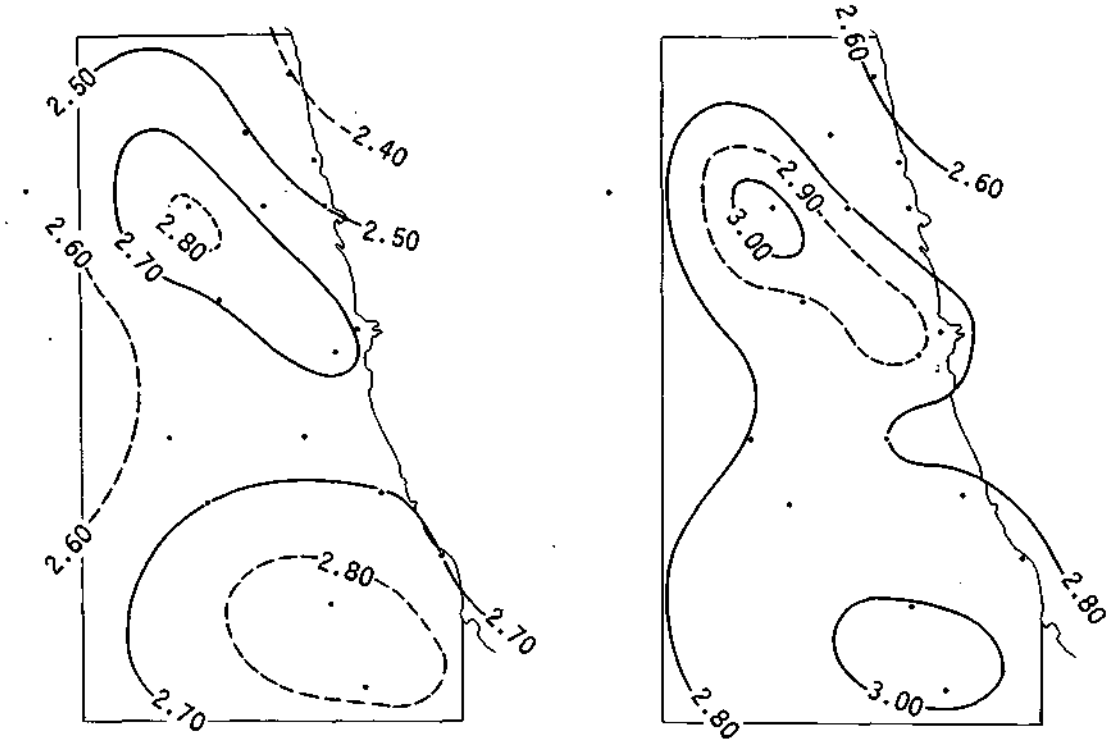
6-HOUR, 1-YEAR RAINFALL

Figure 4 (Continued)



12-HOUR, 1-YEAR RAINFALL

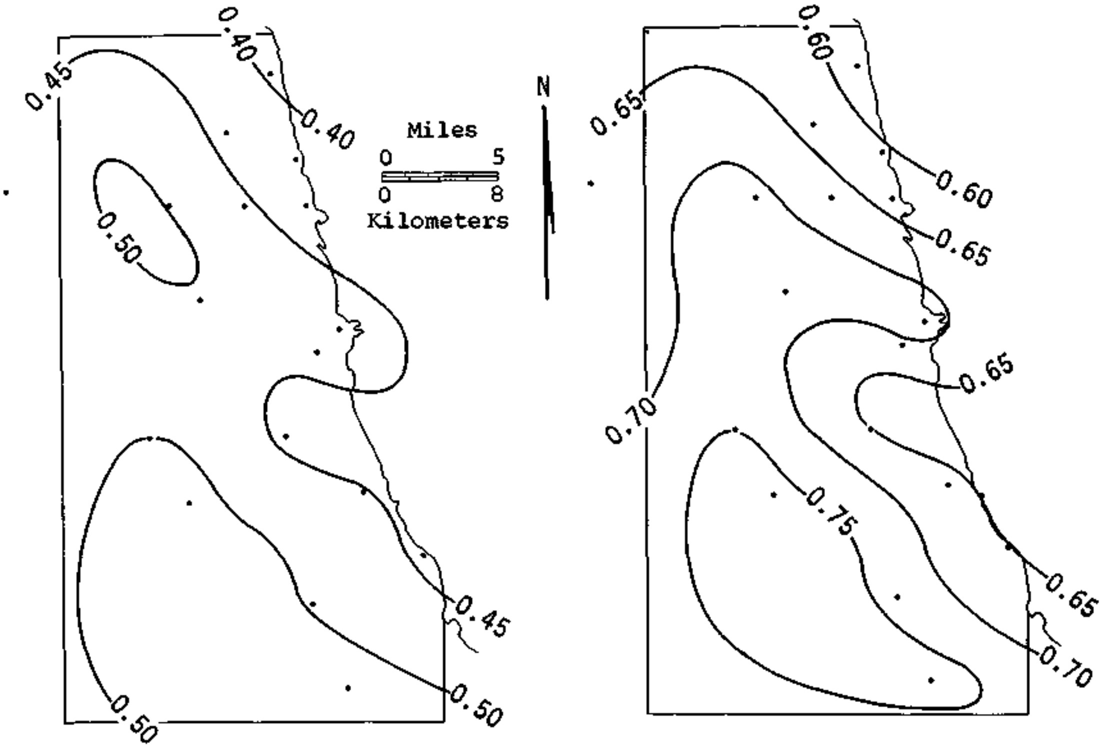
24-HOUR, 1-YEAR RAINFALL



48-HOUR, 1-YEAR RAINFALL

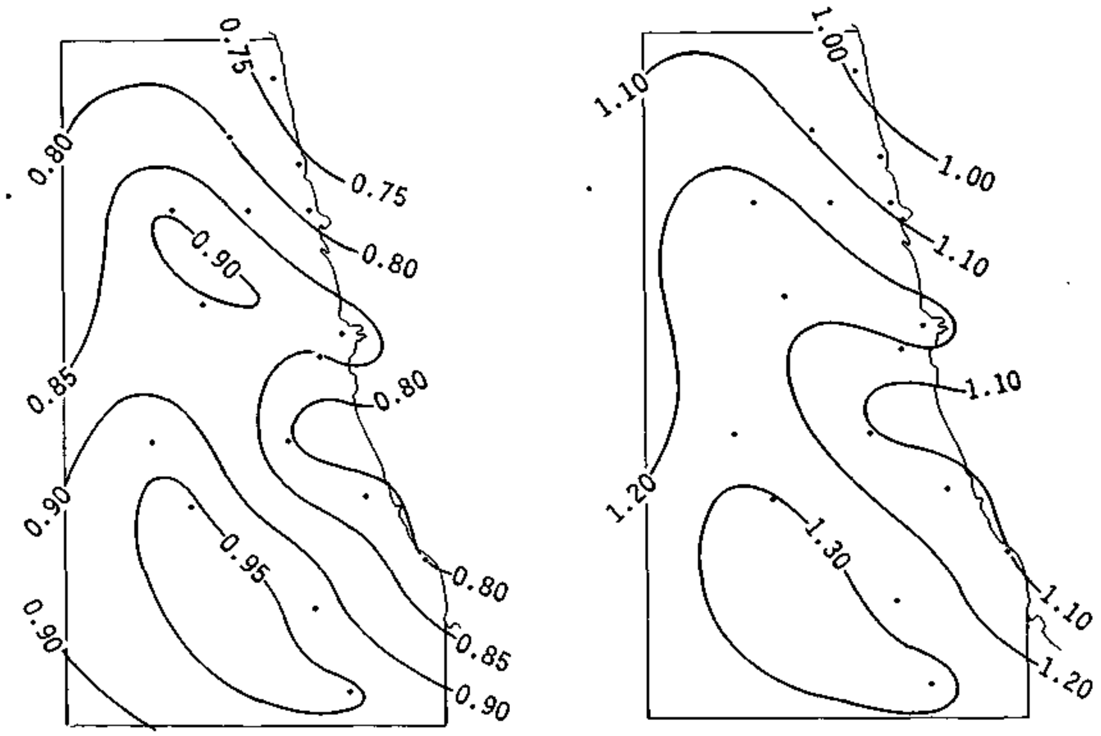
72-HOUR, 1-YEAR RAINFALL

Figure 4 (Concluded)



5-MINUTE, 2-YEAR RAINFALL

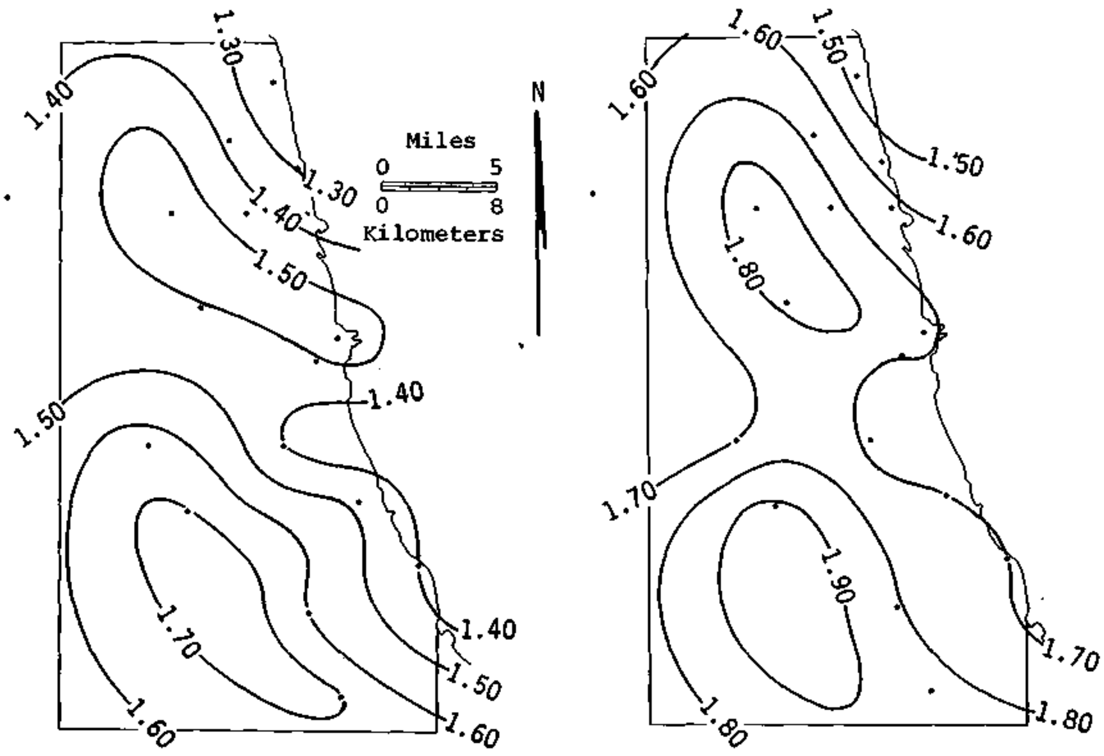
10-MINUTE, 2-YEAR RAINFALL



15-MINUTE, 2-YEAR RAINFALL

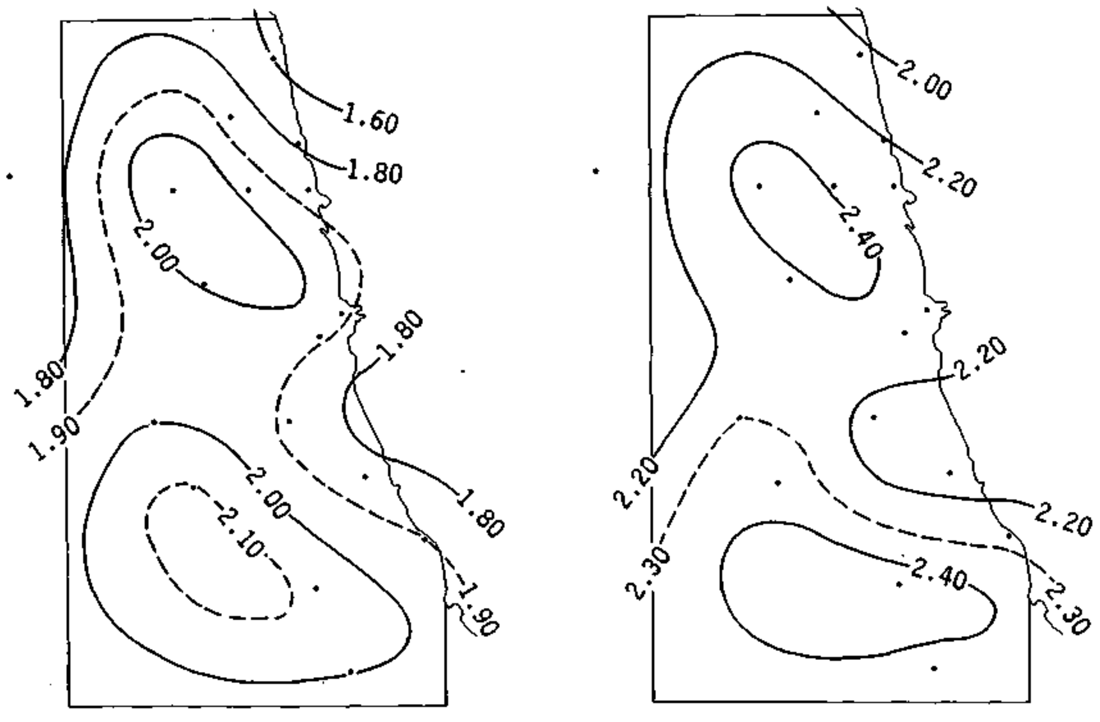
30-MINUTE, 2-YEAR RAINFALL

Figure 5. 2-year frequency of urban-area rainfall



1-HOUR, 2-YEAR RAINFALL

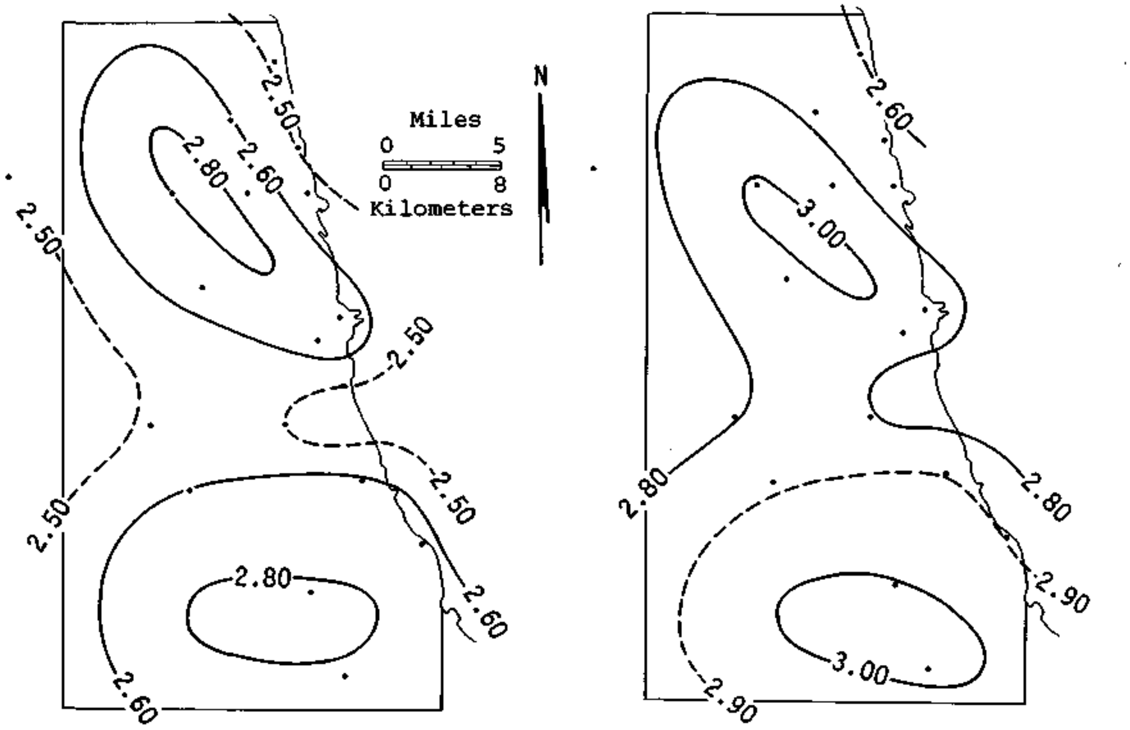
2-HOUR, 2-YEAR RAINFALL



3-HOUR, 2-YEAR RAINFALL

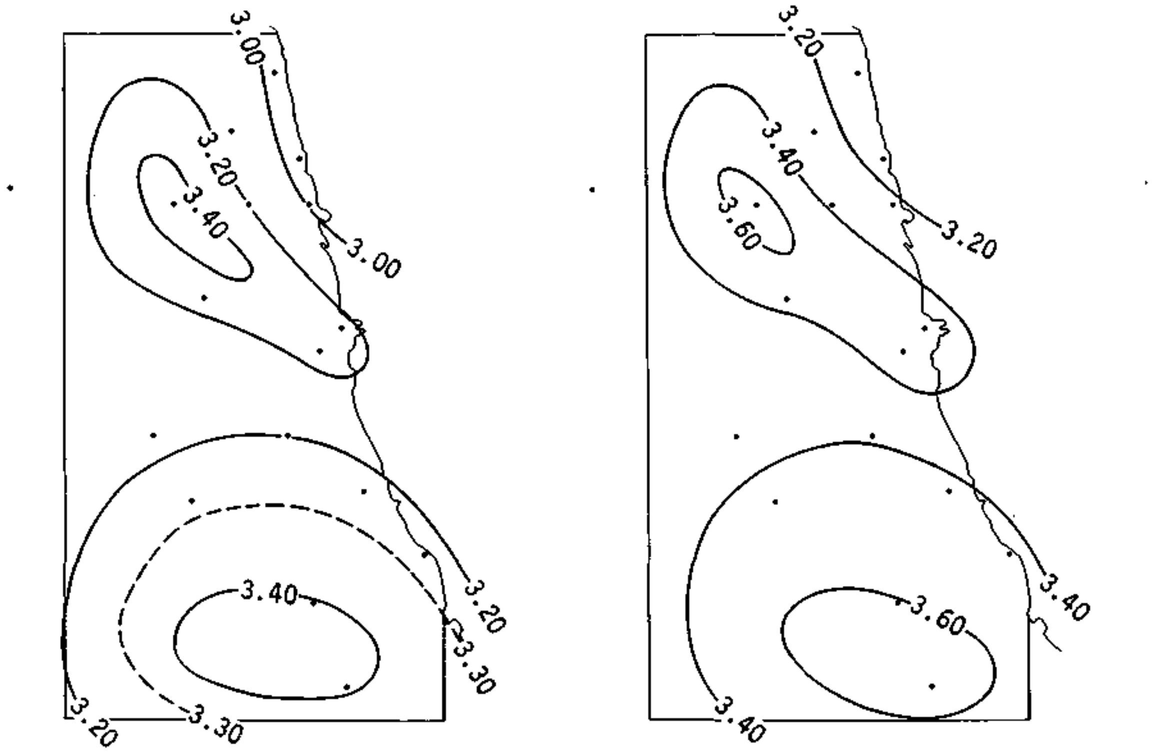
6-HOUR, 2-YEAR RAINFALL

Figure 5 (Continued)



12-HOUR, 2-YEAR RAINFALL

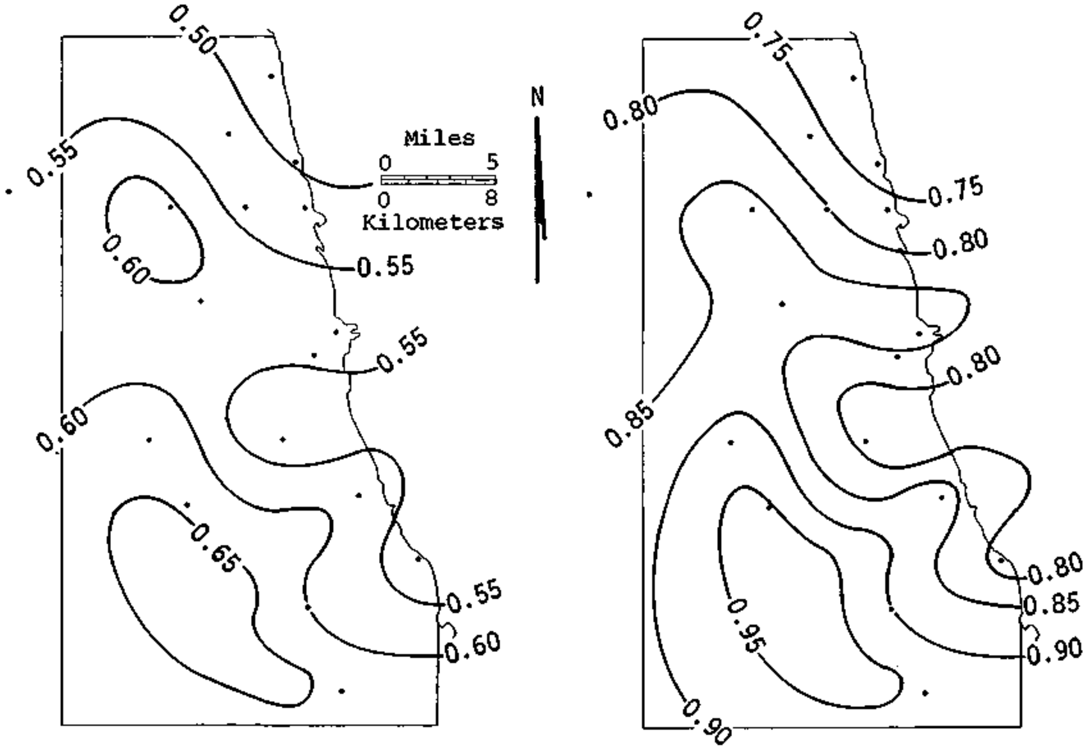
24-HOUR, 2-YEAR RAINFALL



48-HOUR, 2-YEAR RAINFALL

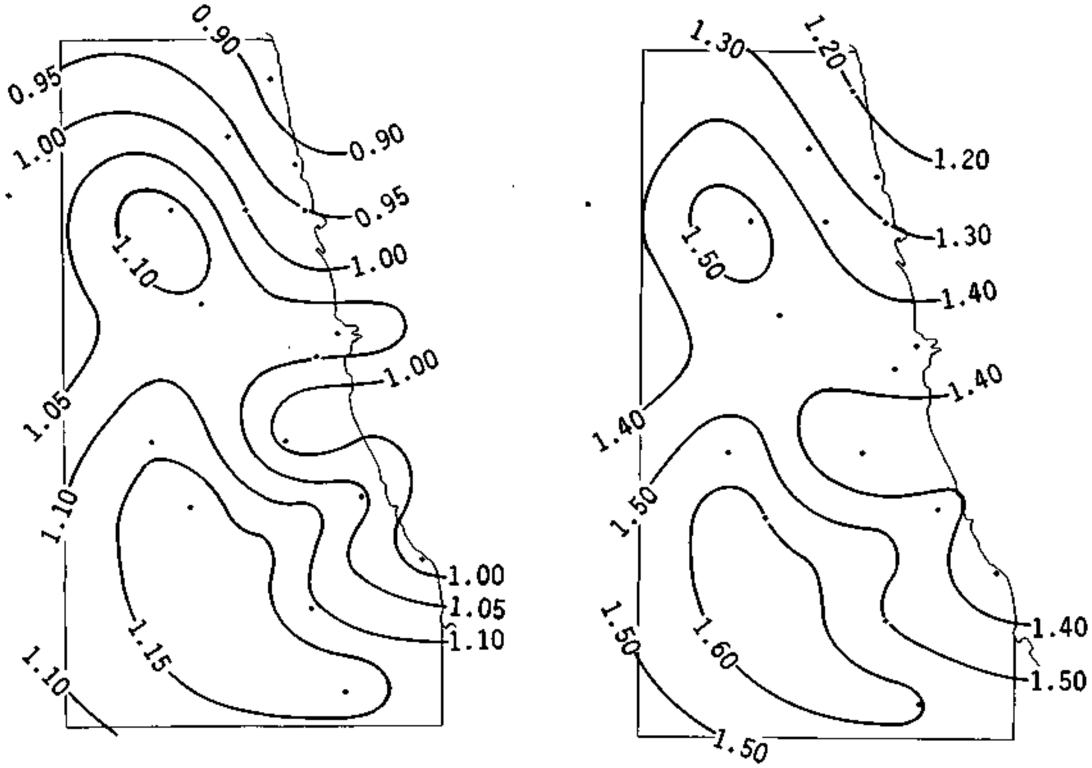
72-HOUR, 2-YEAR RAINFALL

Figure 5 (Concluded)



5-MINUTE, 5-YEAR RAINFALL

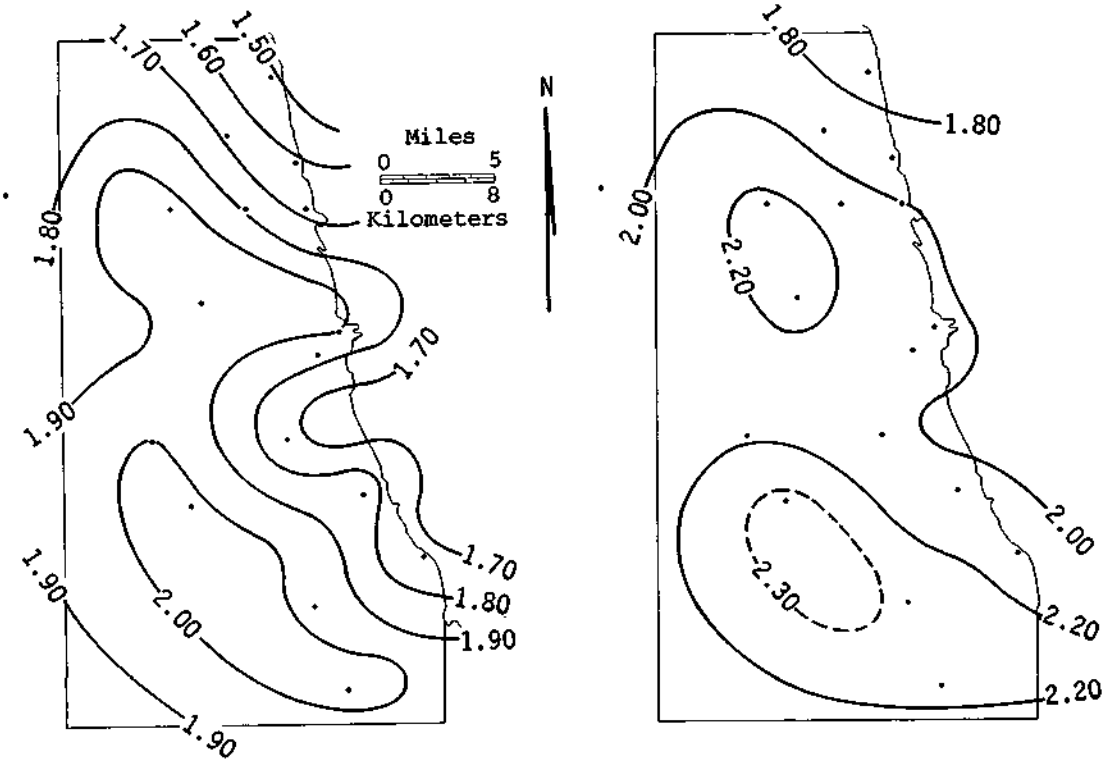
10-MINUTE, 5-YEAR RAINFALL



15-MINUTE, 5-YEAR RAINFALL

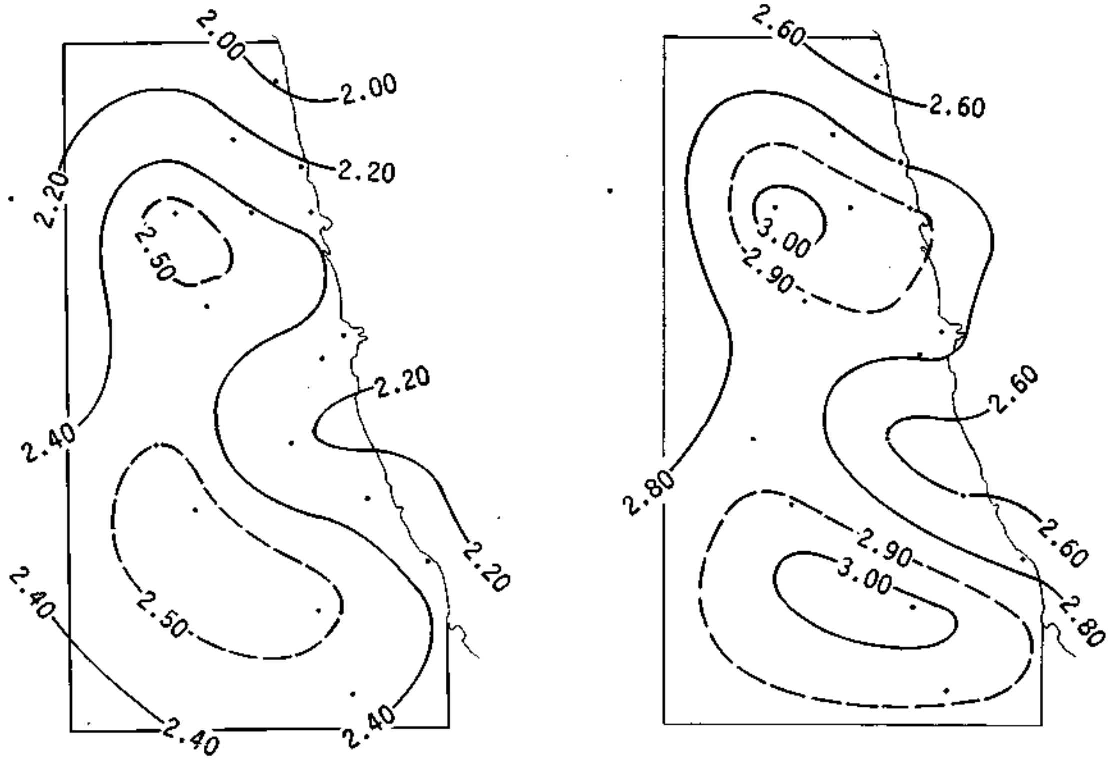
30-MINUTE, 5-YEAR RAINFALL

Figure 6. 5-year frequency of urban-area rainfall



1-HOUR, 5-YEAR RAINFALL

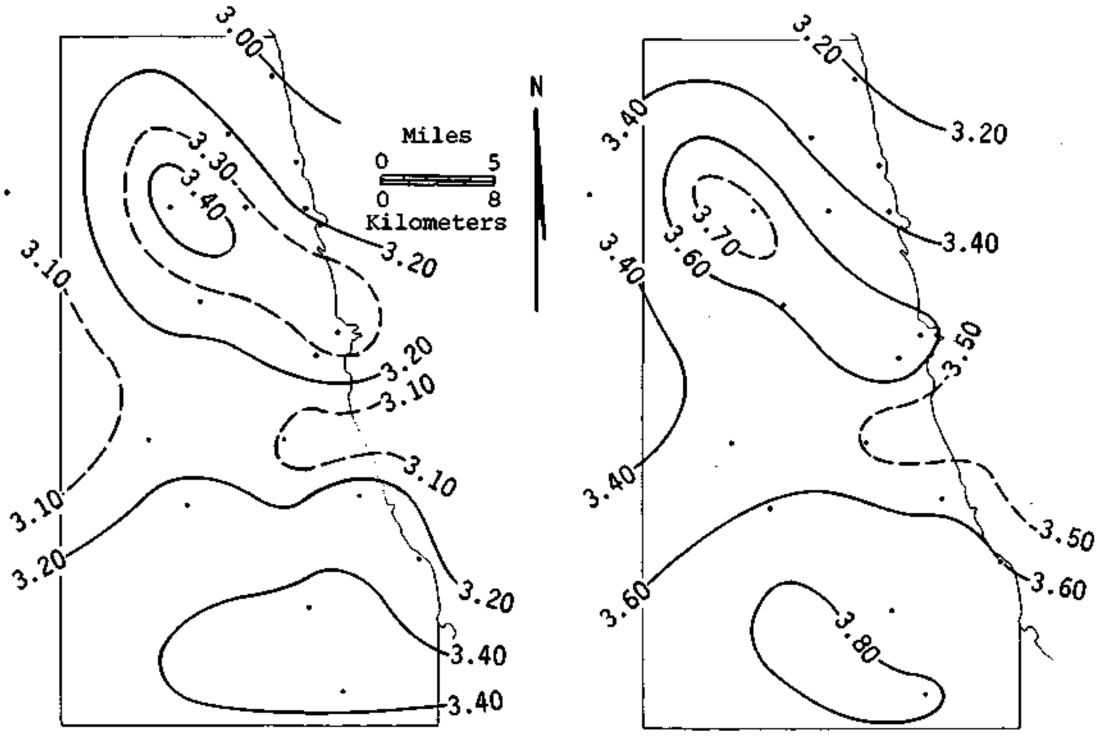
2-HOUR, 5-YEAR RAINFALL



3-HOUR, 5-YEAR RAINFALL

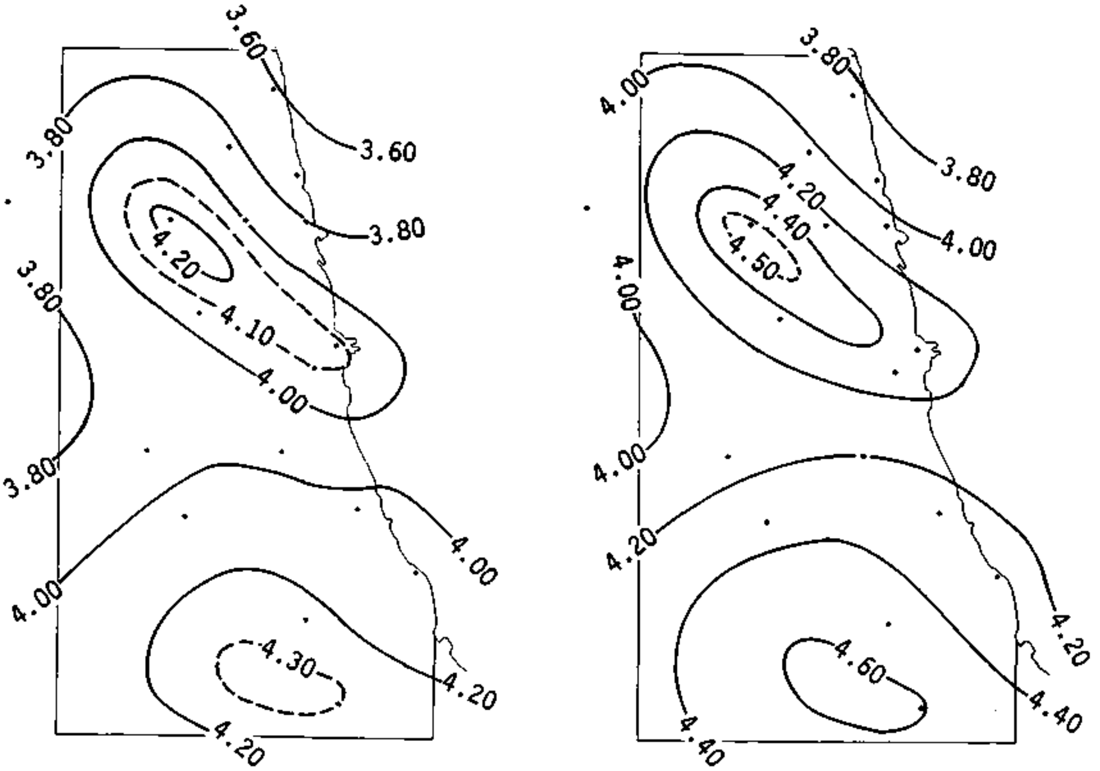
6-HOUR, 5-YEAR RAINFALL

Figure 6 (Continued)



12-HOUR, 5-YEAR RAINFALL

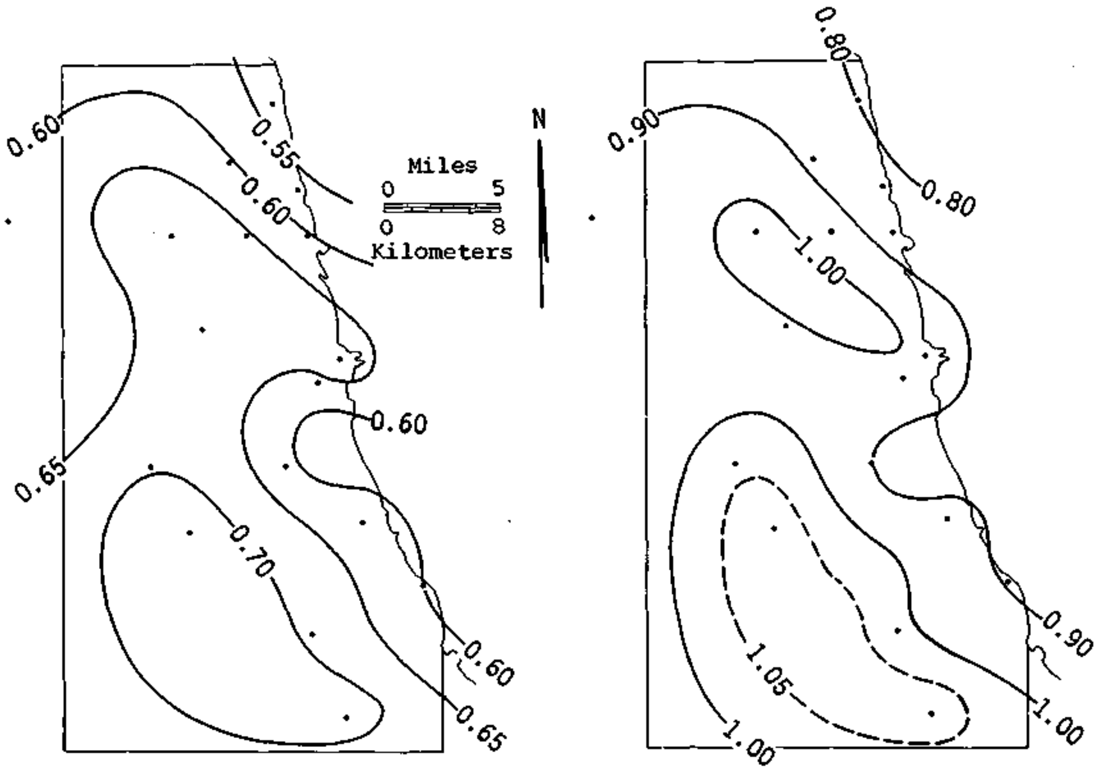
24-HOUR, 5-YEAR RAINFALL



48-HOUR, 5-YEAR RAINFALL

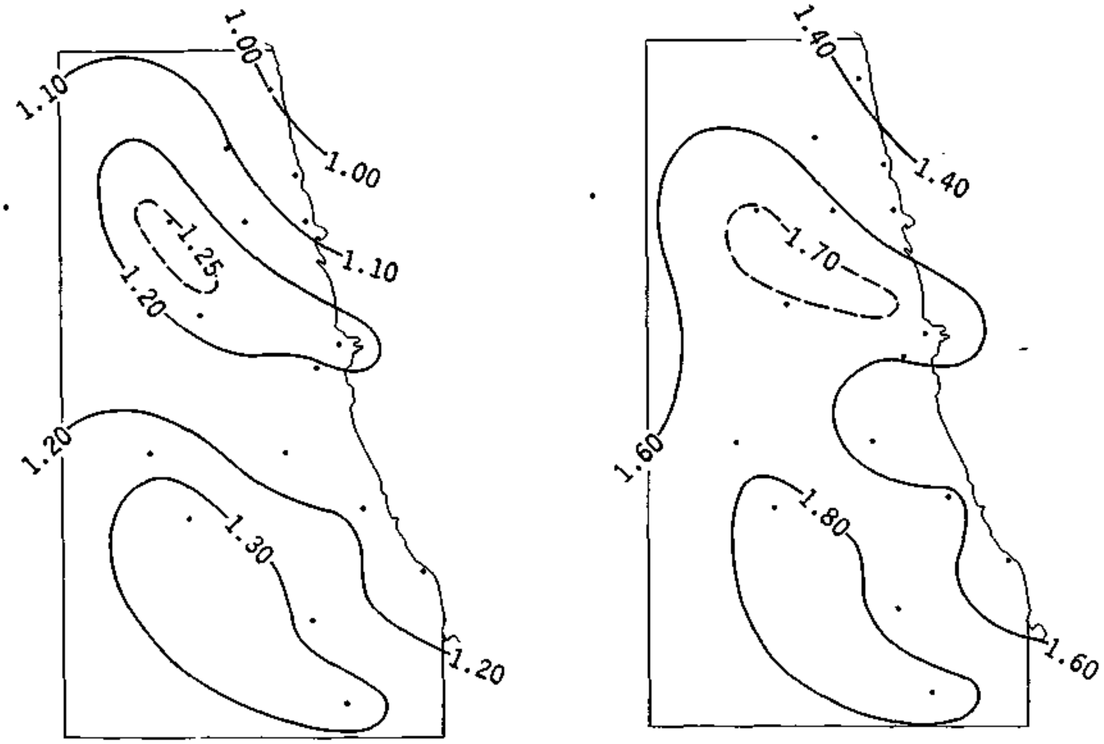
72-HOUR, 5-YEAR RAINFALL

Figure 6 (Concluded)



5-MINUTE, 10-YEAR RAINFALL

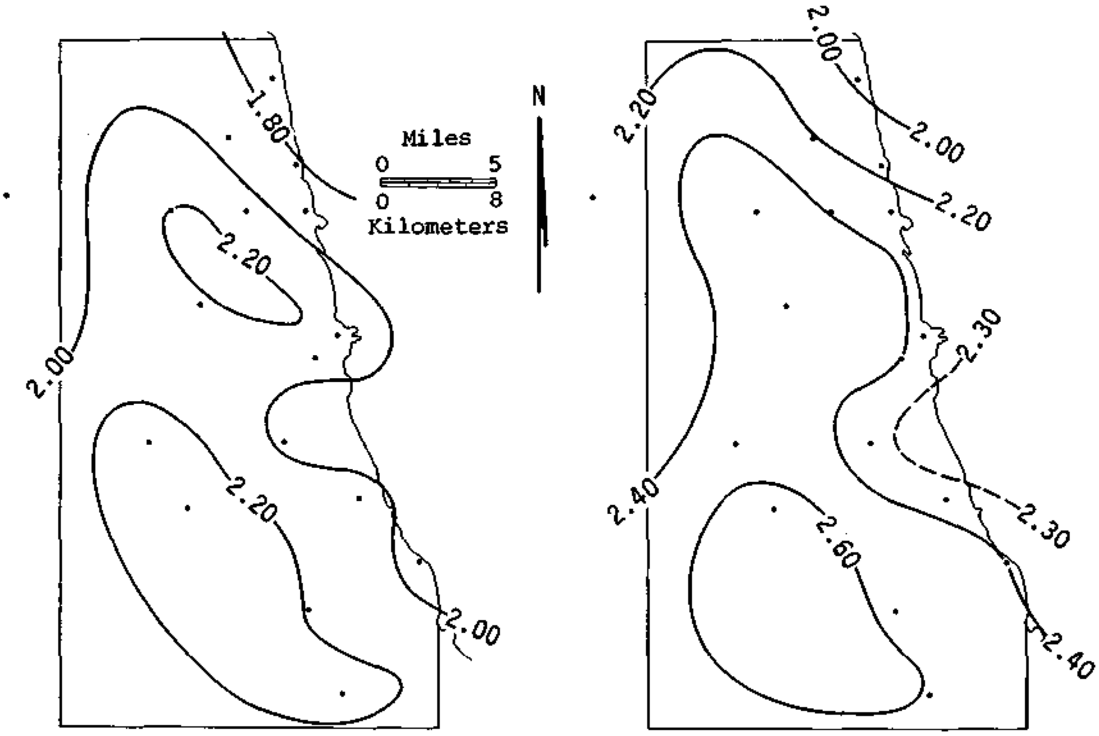
10-MINUTE, 10-YEAR RAINFALL



15-MINUTE, 10-YEAR RAINFALL

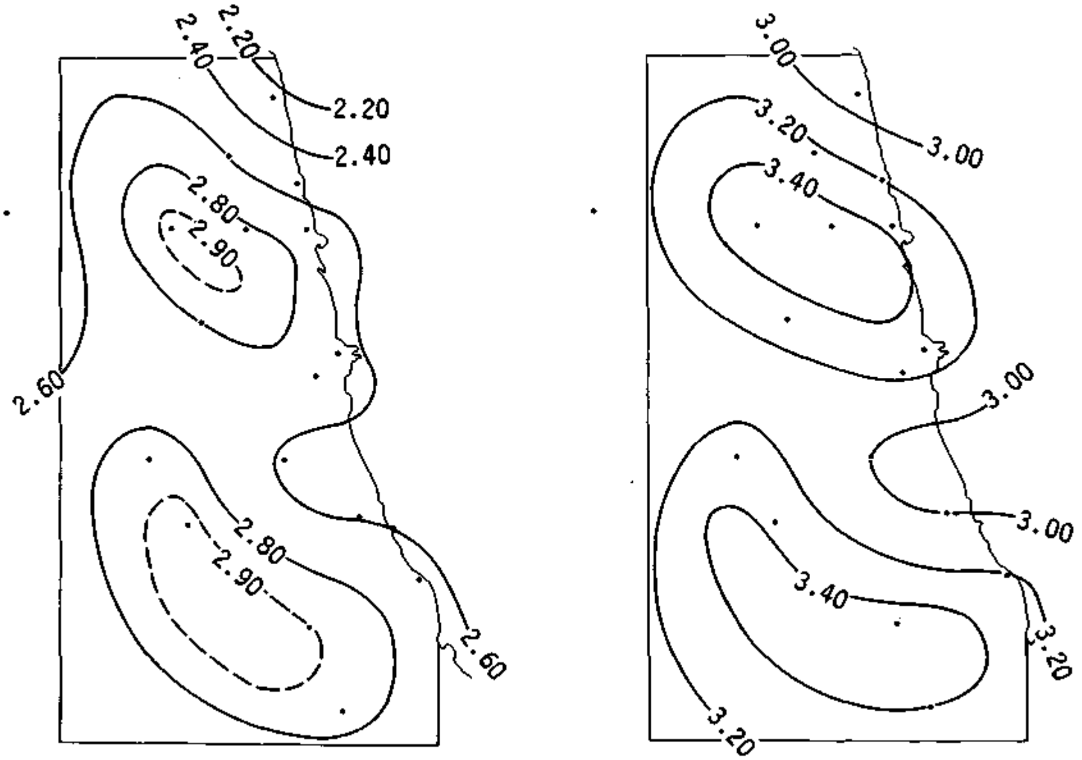
30-MINUTE, 10-YEAR RAINFALL

Figure 7. 10-year frequency of urban-area rainfall



1-HOUR, 10-YEAR RAINFALL

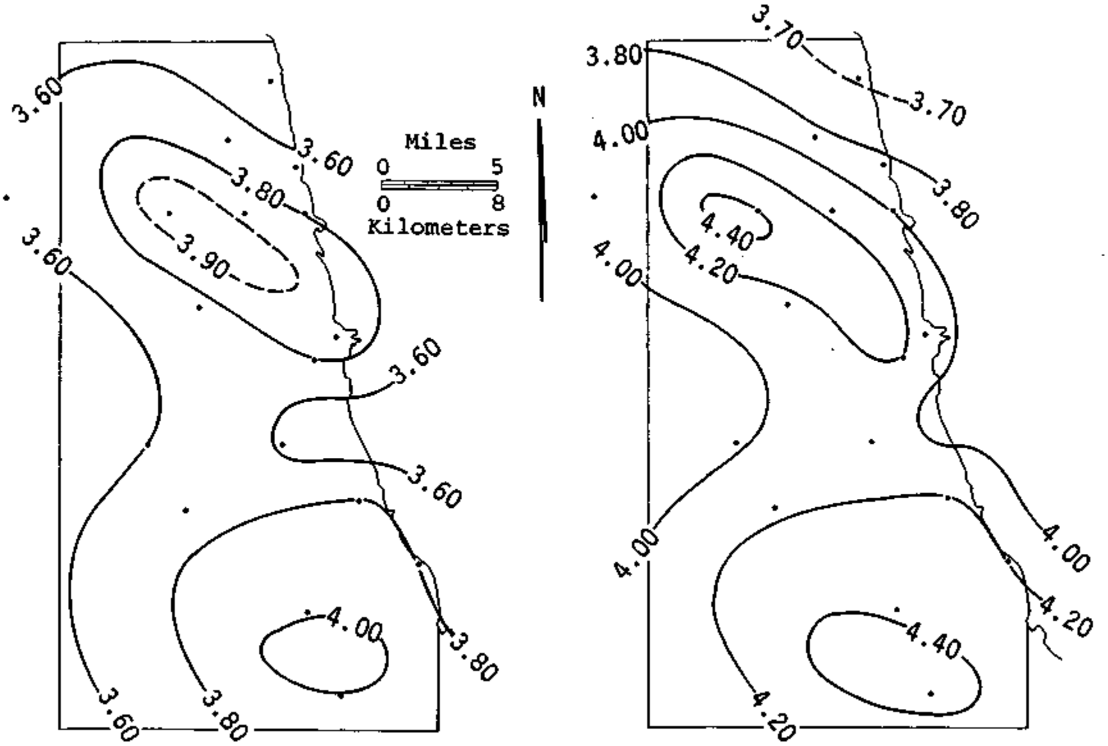
2-HOUR, 10-YEAR RAINFALL



3-HOUR, 10-YEAR RAINFALL

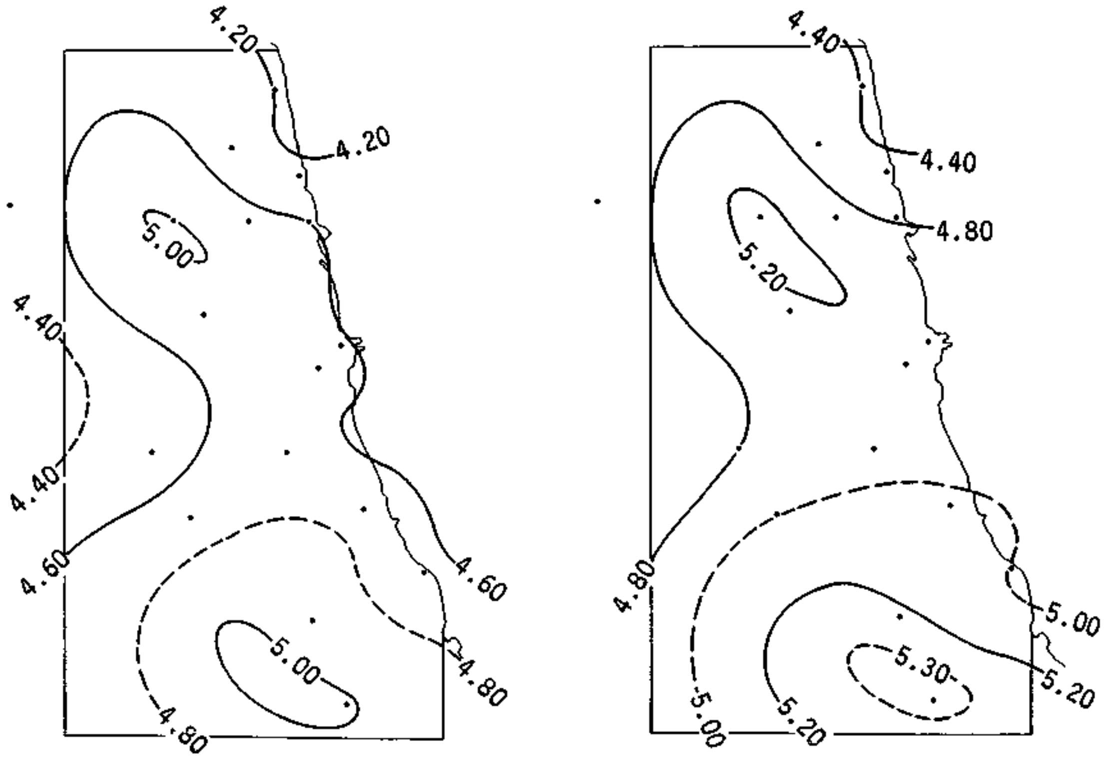
6-HOUR, 10-YEAR RAINFALL

Figure 7 (Continued)



12-HOUR, 10-YEAR RAINFALL

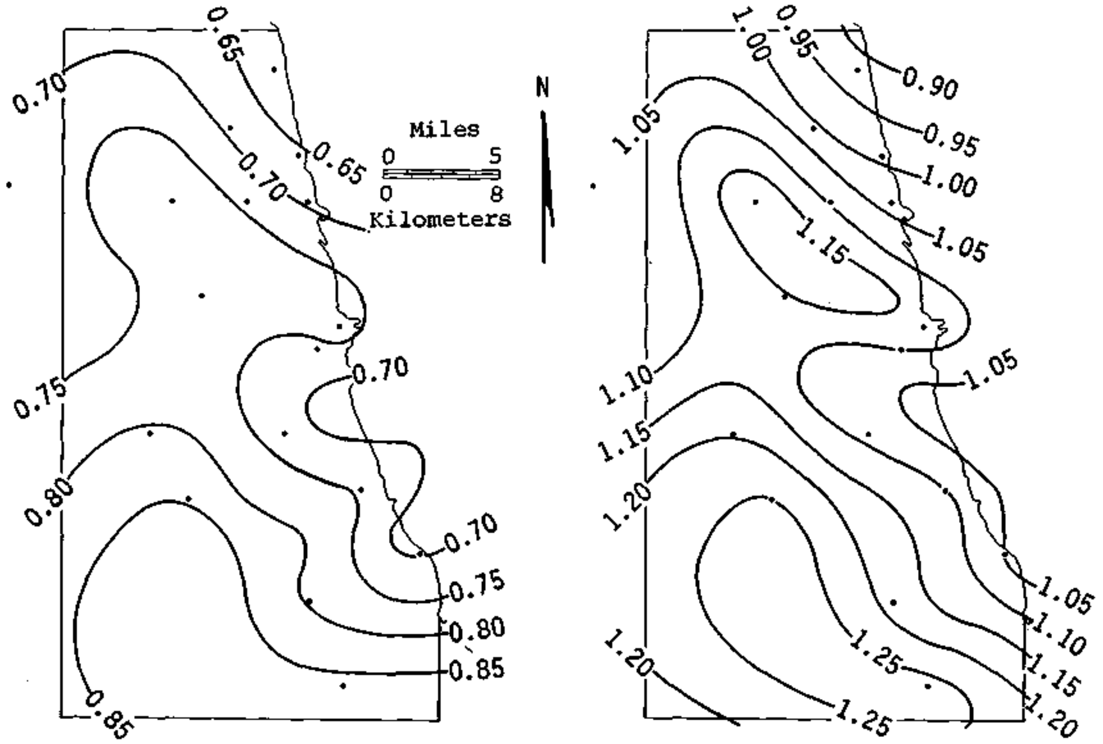
24-HOUR, 10-YEAR RAINFALL



48-HOUR, 10-YEAR RAINFALL

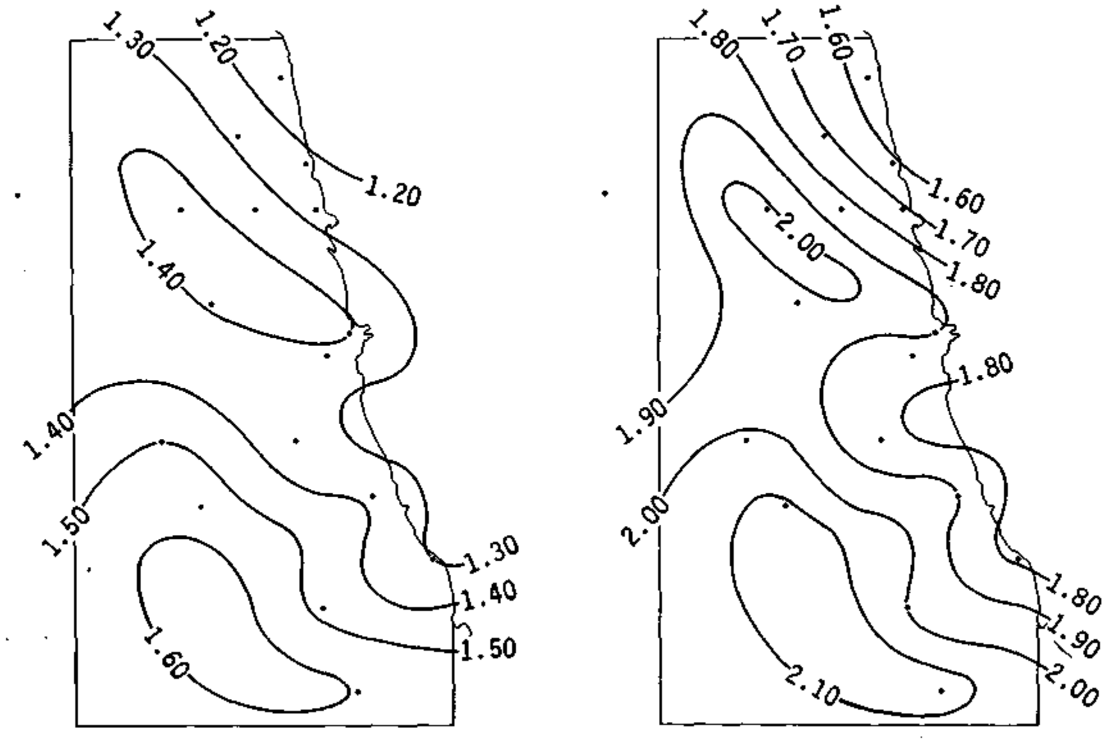
72-HOUR, 10-YEAR RAINFALL

Figure 7 (Concluded)



5-MINUTE, 25-YEAR RAINFALL

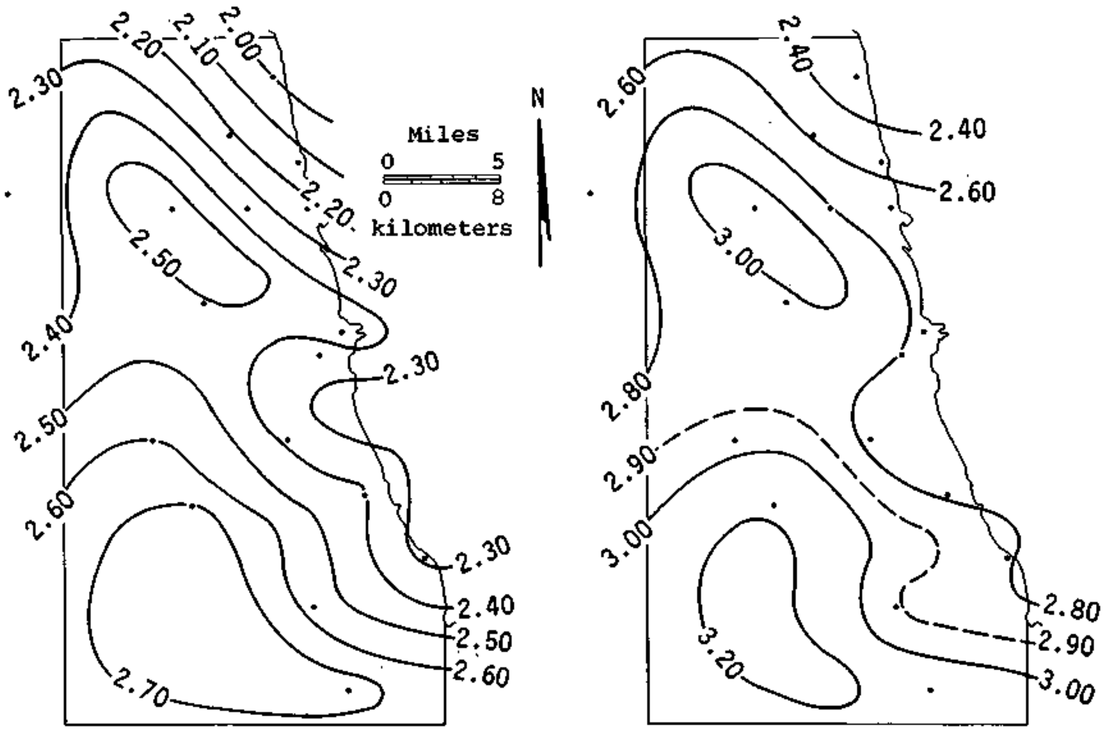
10-MINUTE, 25-YEAR RAINFALL



15-MINUTE, 25-YEAR RAINFALL

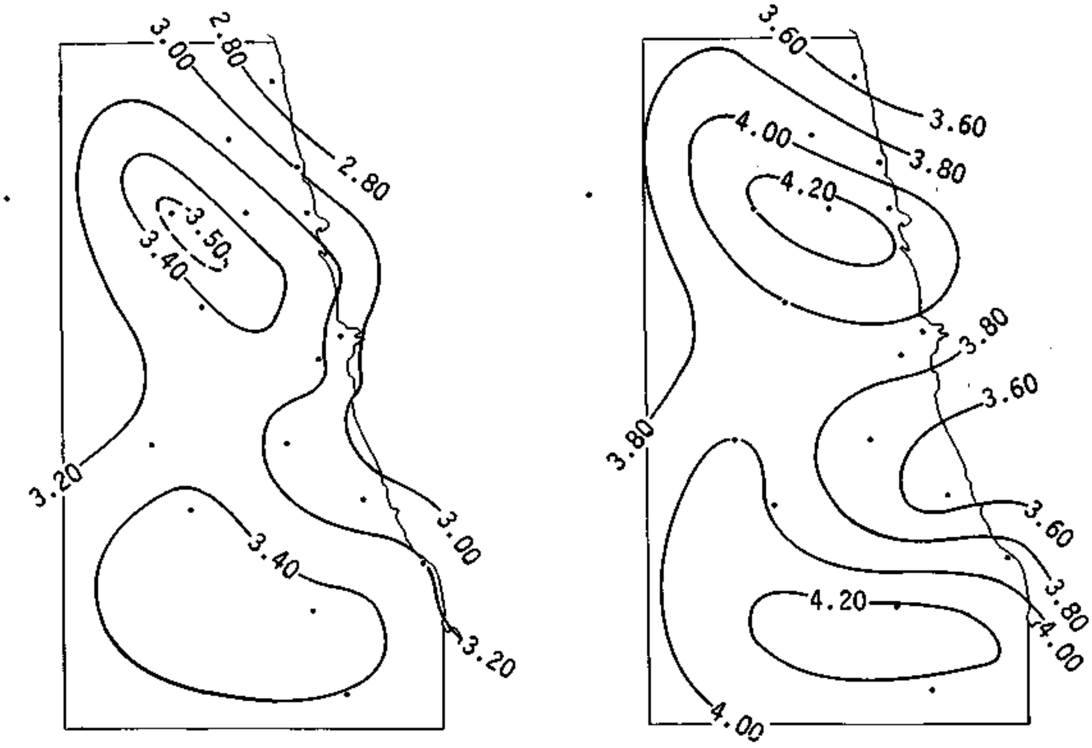
30-MINUTE, 25-YEAR RAINFALL

Figure 8. 25-year frequency of urban-area rainfall



1-HOUR, 25-YEAR RAINFALL

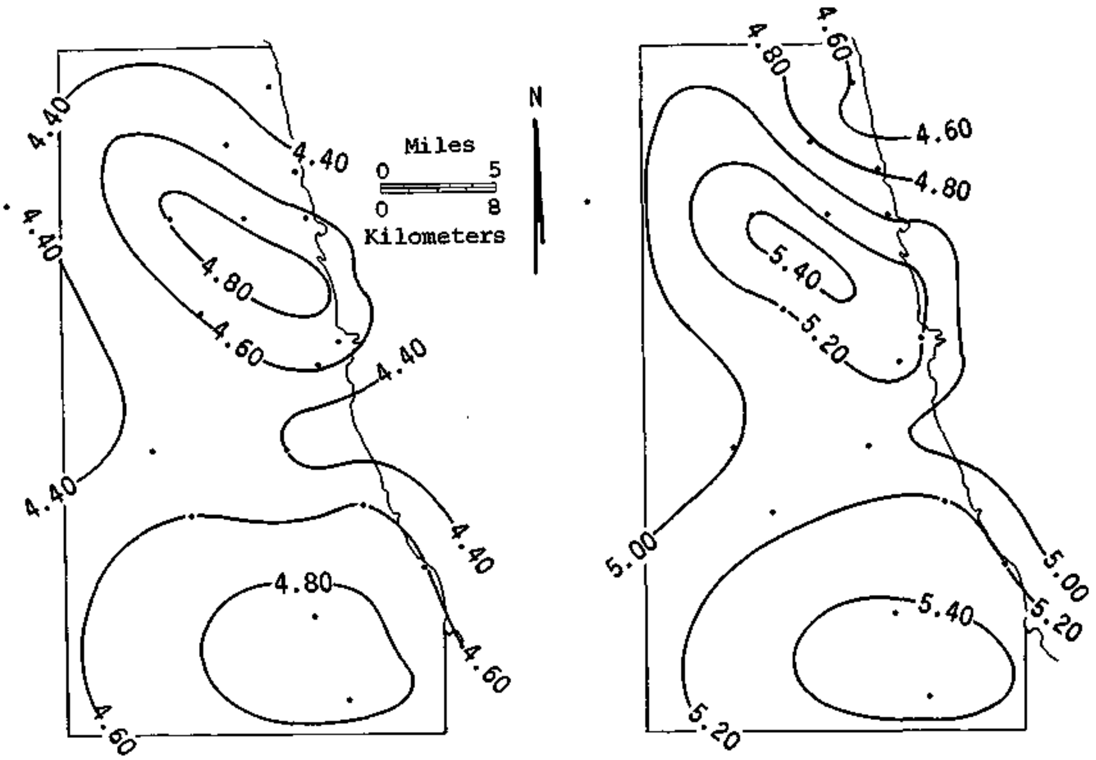
2-HOUR, 25-YEAR RAINFALL



3-HOUR, 25-YEAR RAINFALL

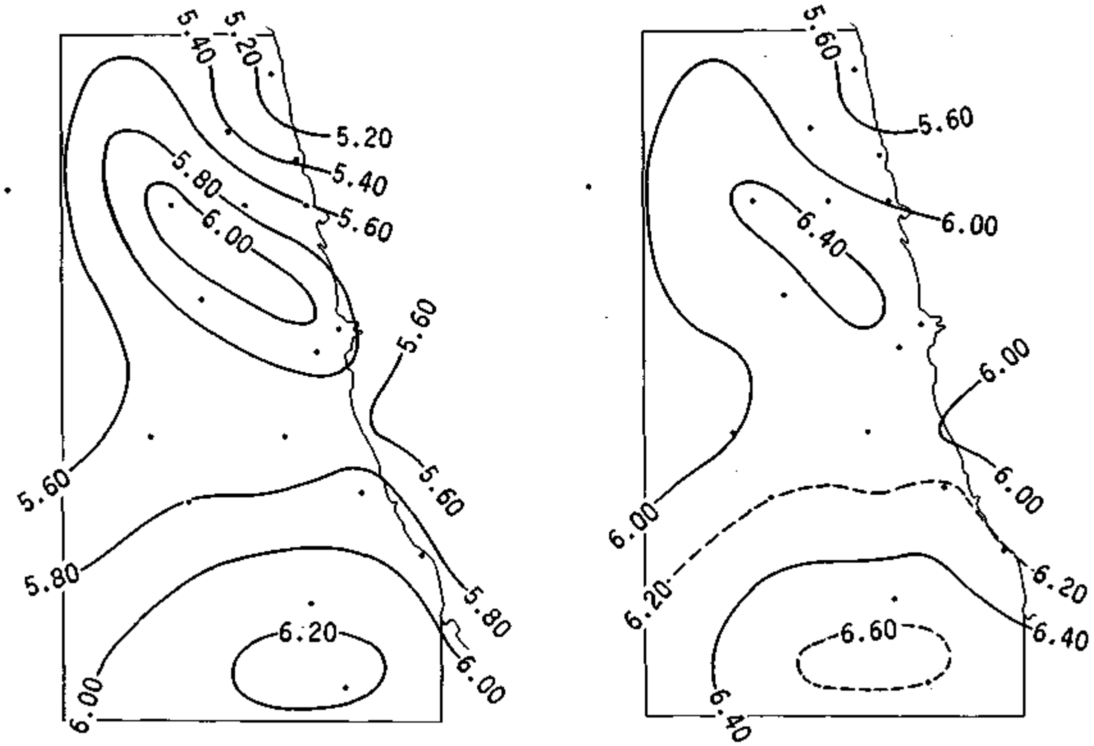
6-HOUR, 25-YEAR RAINFALL

Figure 8 (Continued)



12-HOUR, 25-YEAR RAINFALL

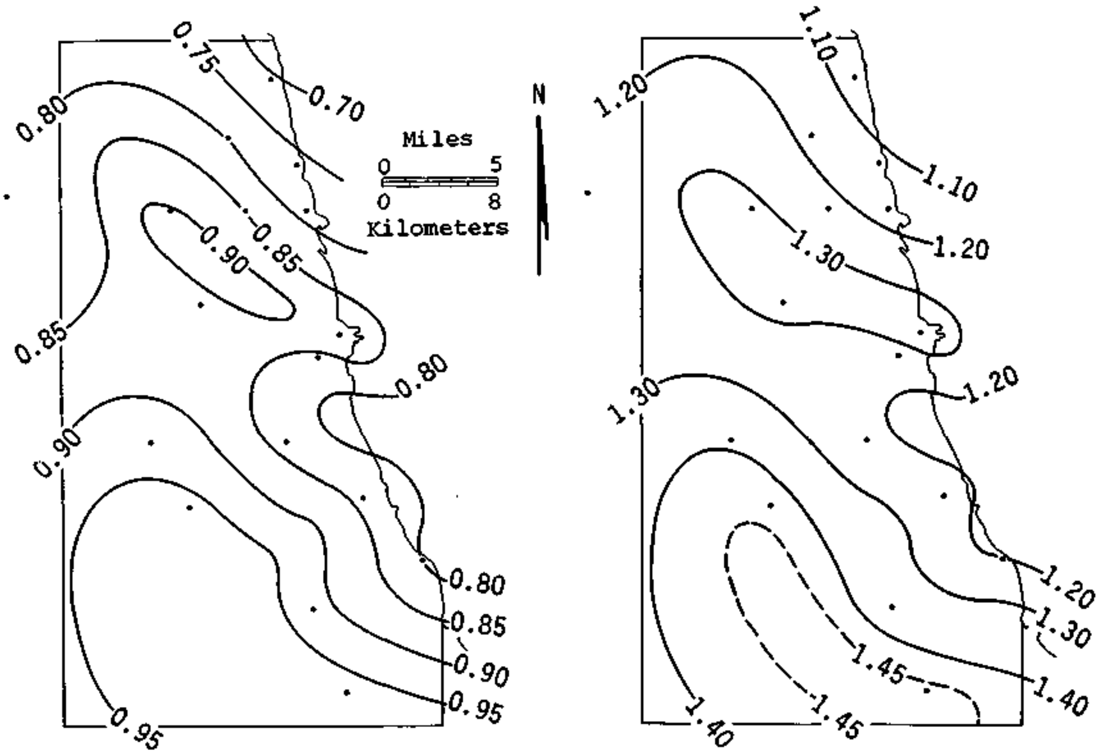
24-HOUR, 25-YEAR RAINFALL



48-HOUR, 25-YEAR RAINFALL

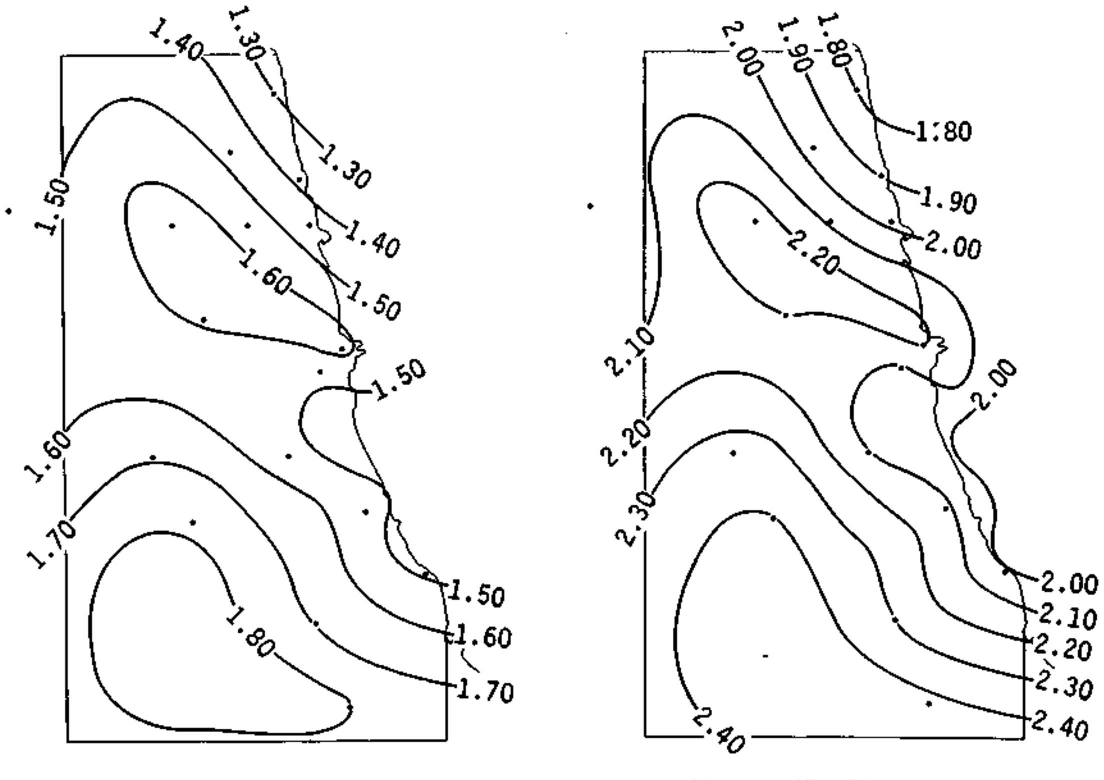
72-HOUR, 25-YEAR RAINFALL

Figure 8 (Concluded)



5-MINUTE, 50-YEAR RAINFALL

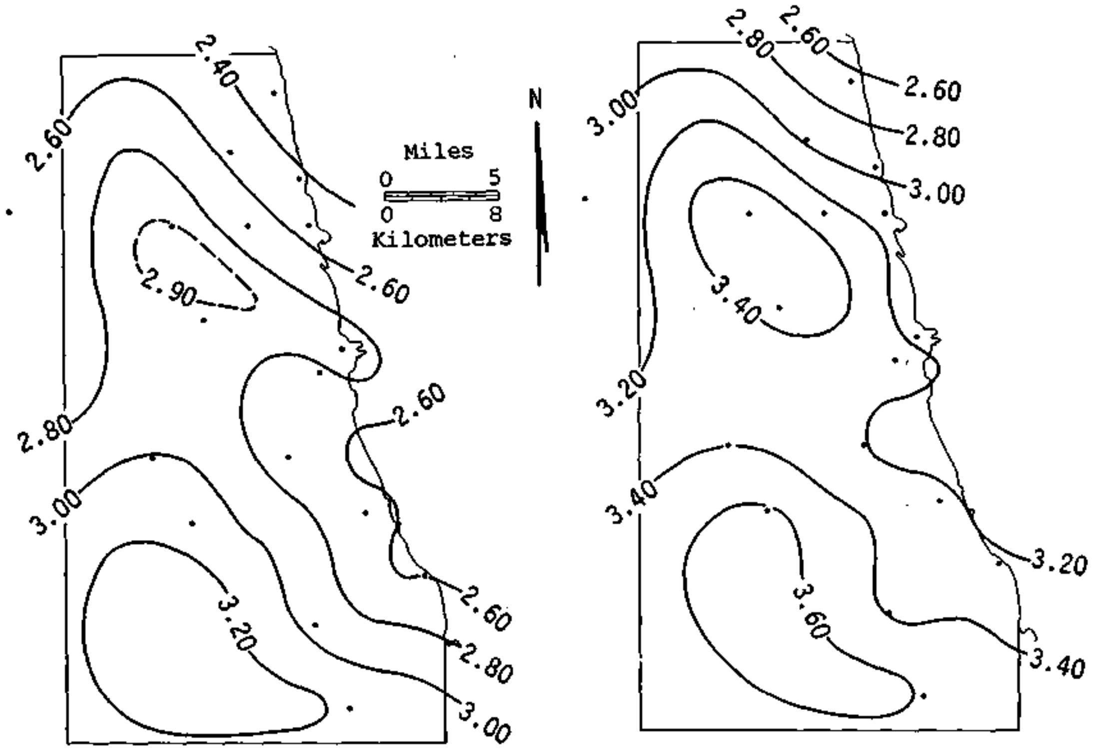
10-MINUTE, 50-YEAR RAINFALL



15-MINUTE, 50-YEAR RAINFALL

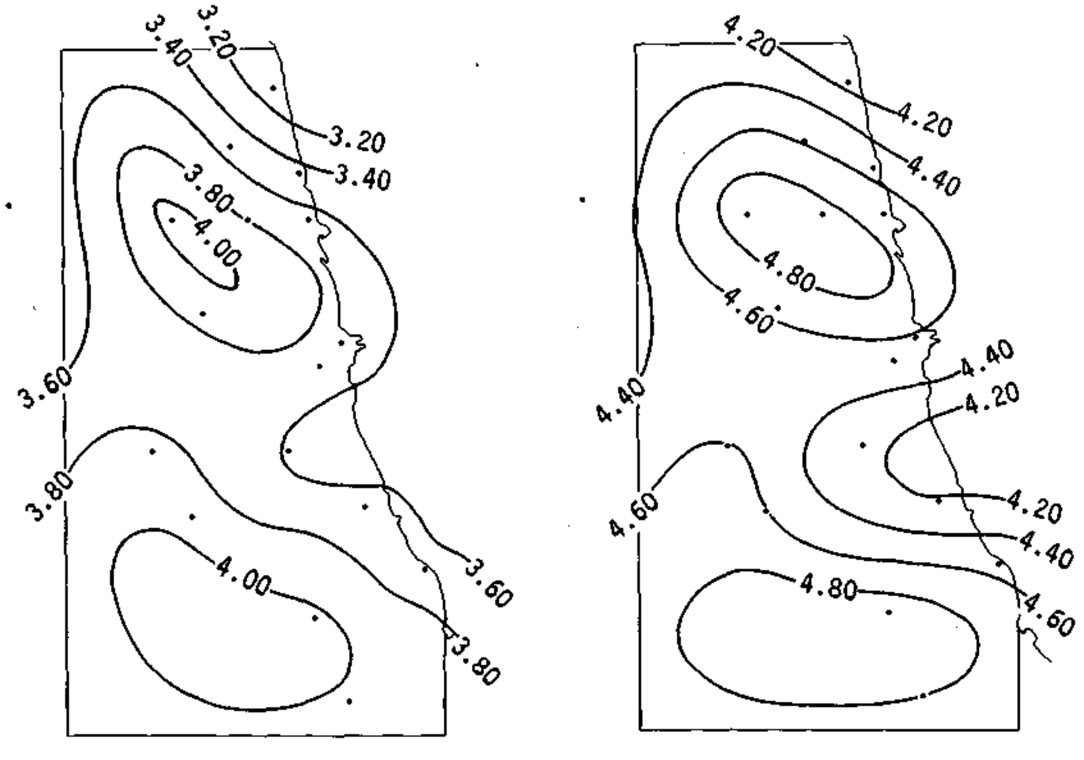
30-MINUTE, 50-YEAR RAINFALL

Figure 9. 50-year frequency of urban-area rainfall



1-HOUR, 50-YEAR RAINFALL

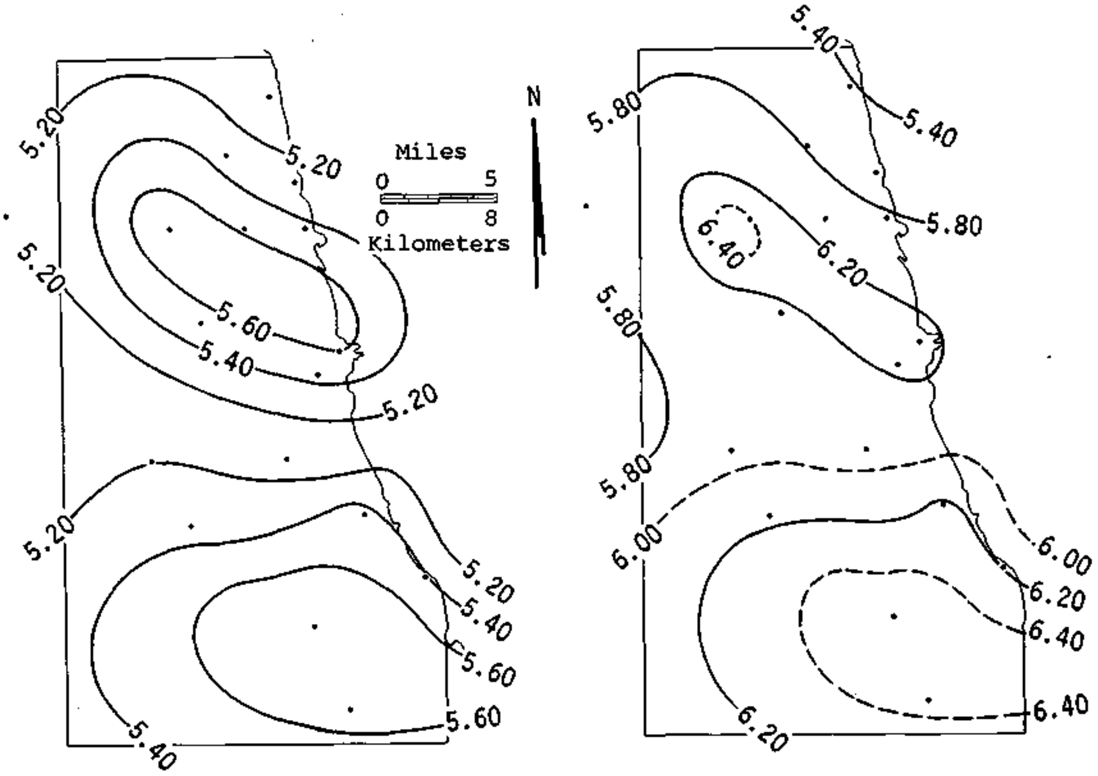
2-HOUR, 50-YEAR RAINFALL



3-HOUR, 50-YEAR RAINFALL

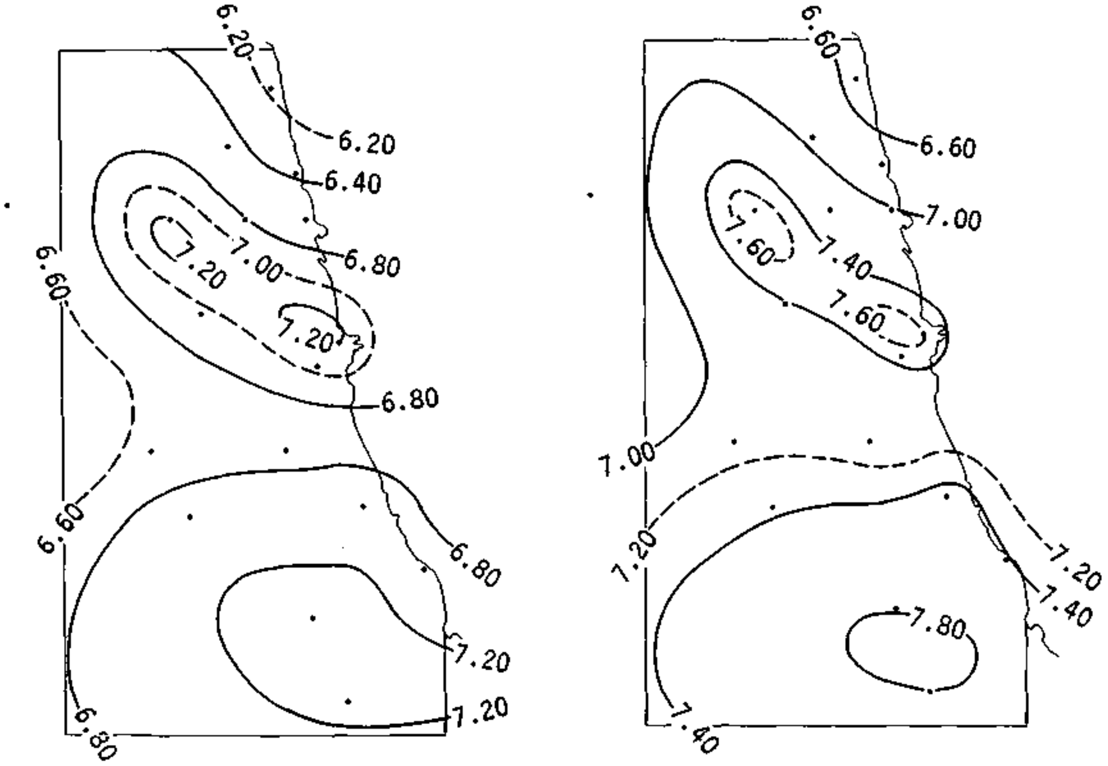
6-HOUR, 50-YEAR RAINFALL

Figure 9 (Continued)



12-HOUR, 50-YEAR RAINFALL

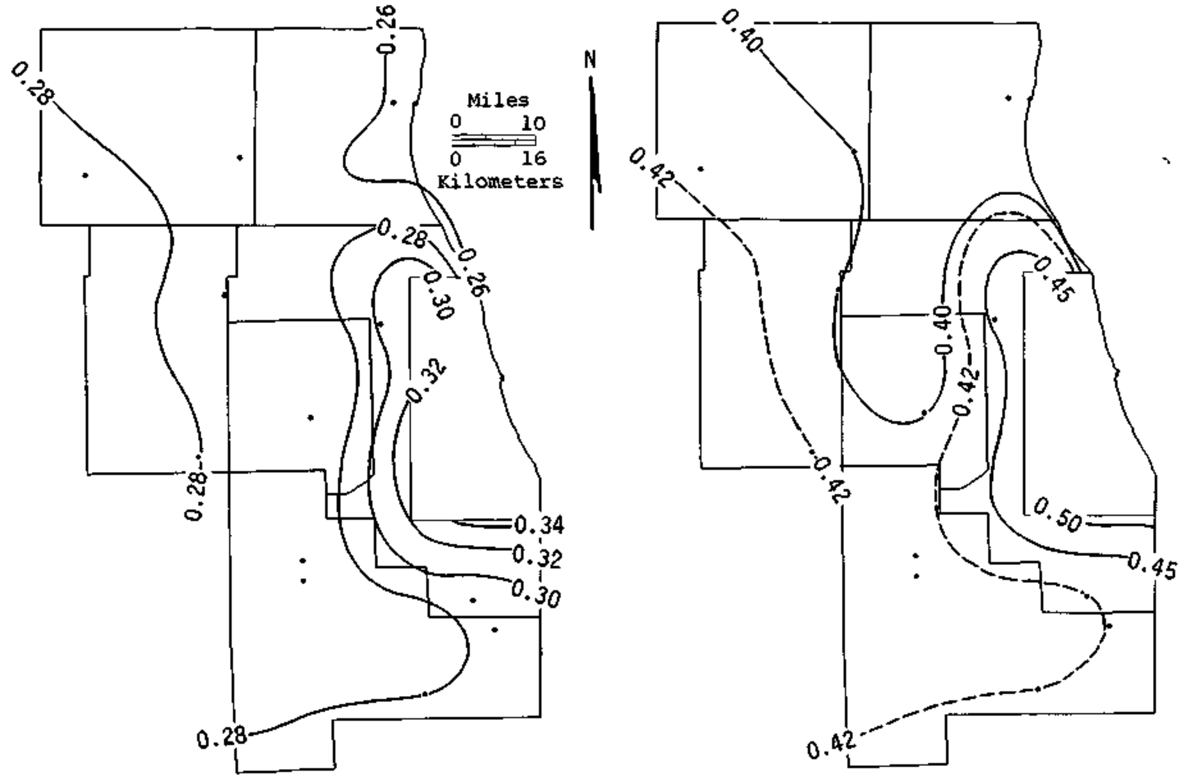
24-HOUR, 50-YEAR RAINFALL



48-HOUR, 50-YEAR RAINFALL

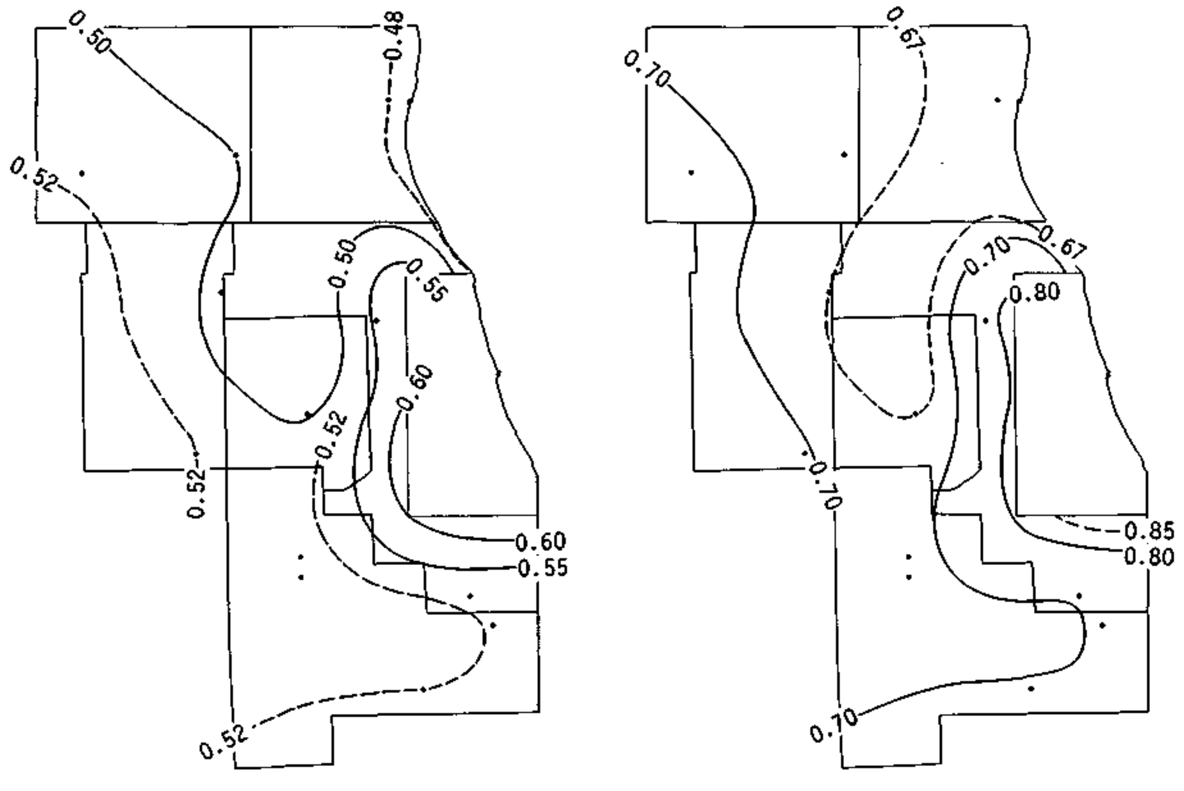
72-HOUR, 50-YEAR RAINFALL

Figure 9 (Concluded)



5-MINUTE, 6-MONTH RAINFALL

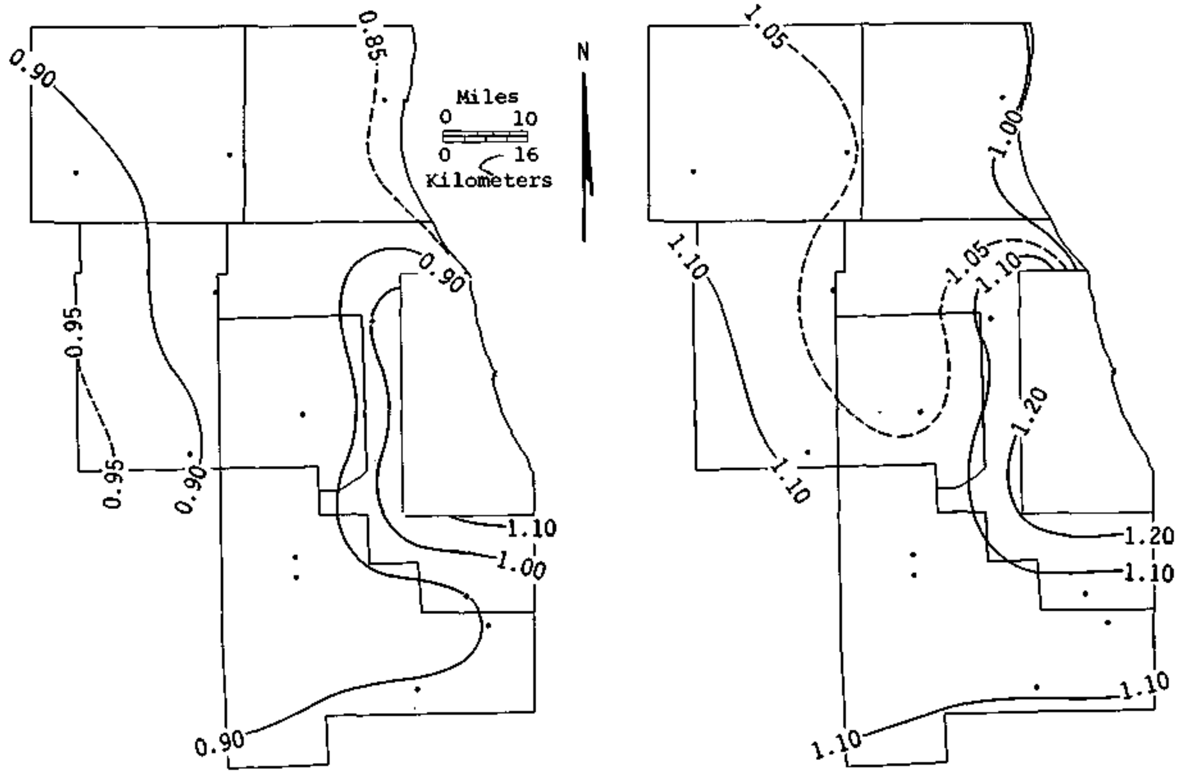
10-MINUTE, 6-MONTH RAINFALL



15-MINUTE, 6-MONTH RAINFALL

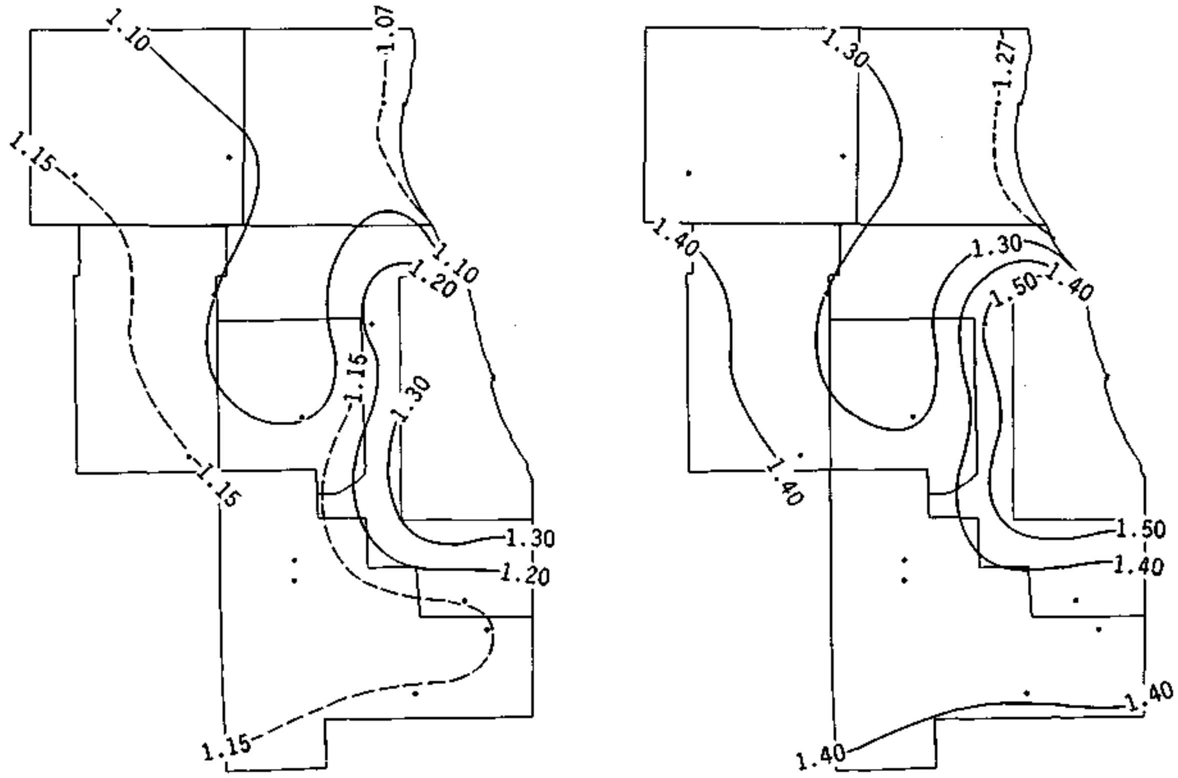
30-MINUTE, 6-MONTH RAINFALL

Figure 10. 0.5-year frequency of 6-county rainfall



1-HOUR, 6-MONTH RAINFALL

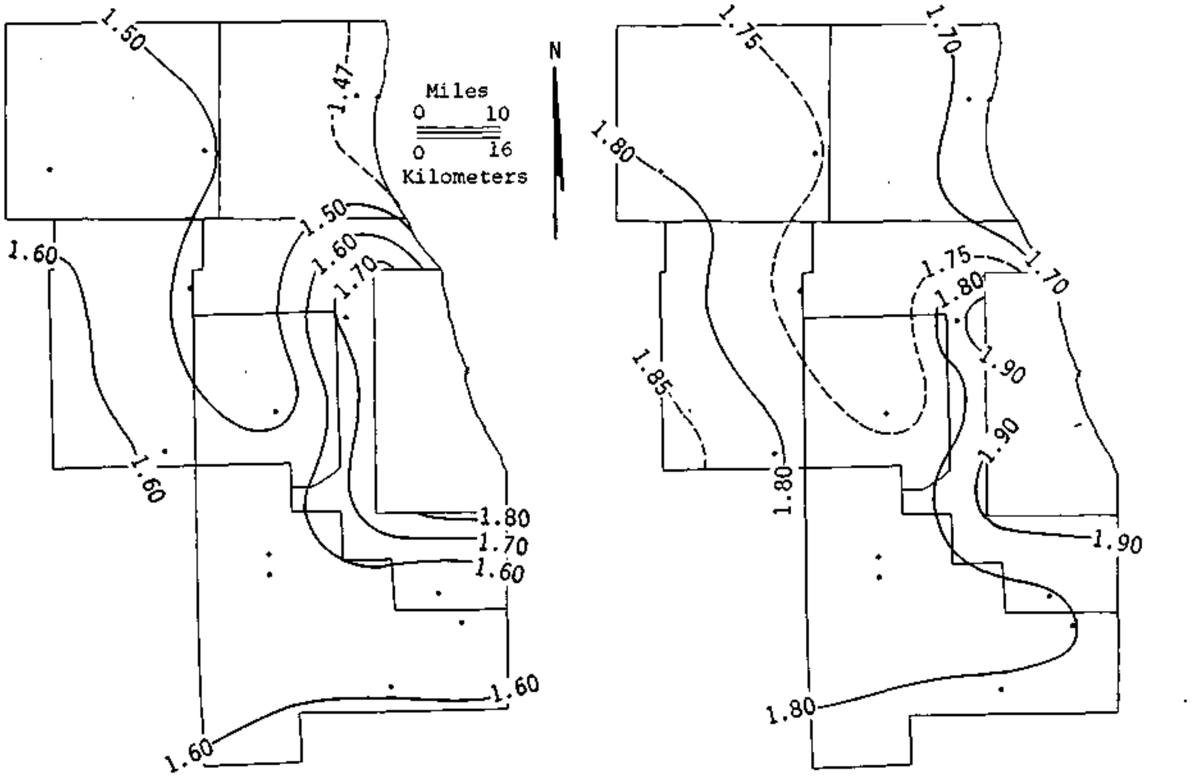
2-HOUR, 6-MONTH RAINFALL



3-HOUR, 6-MONTH RAINFALL

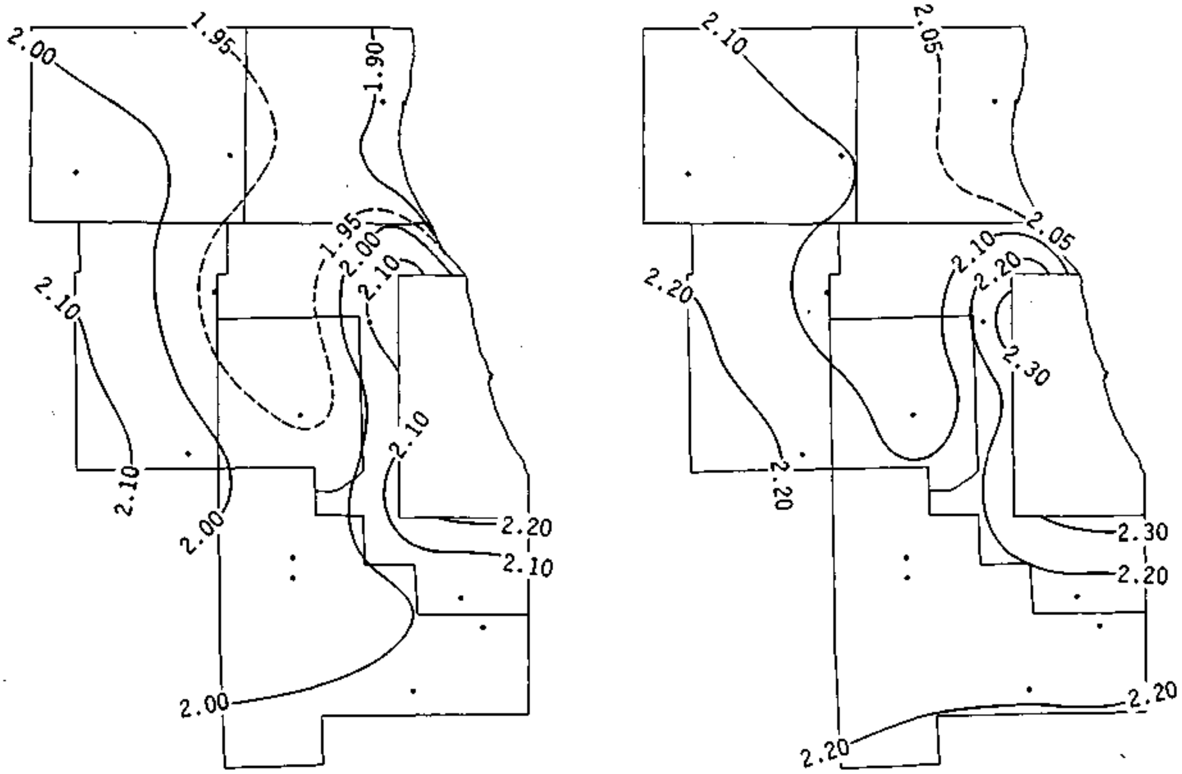
6-HOUR, 6-MONTH RAINFALL

Figure 10 (Continued)



12-HOUR, 6-MONTH RAINFALL

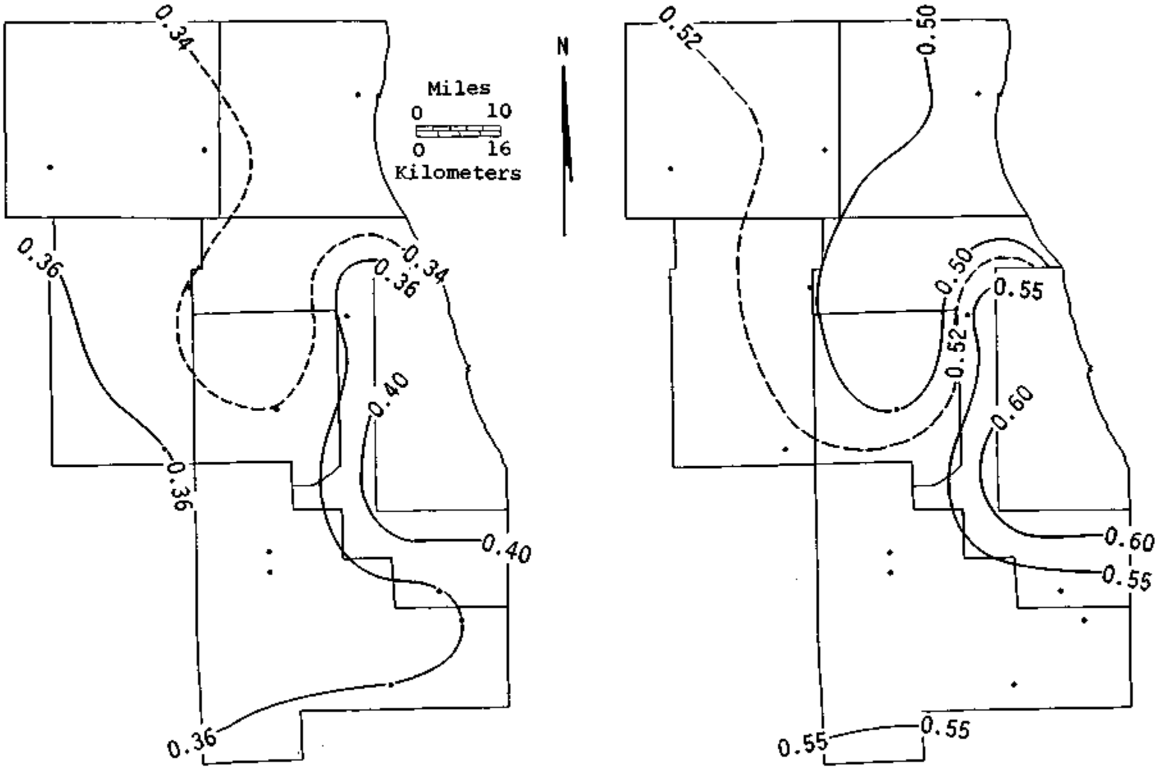
24-HOUR, 6-MONTH RAINFALL



48-HOUR, 6-MONTH RAINFALL

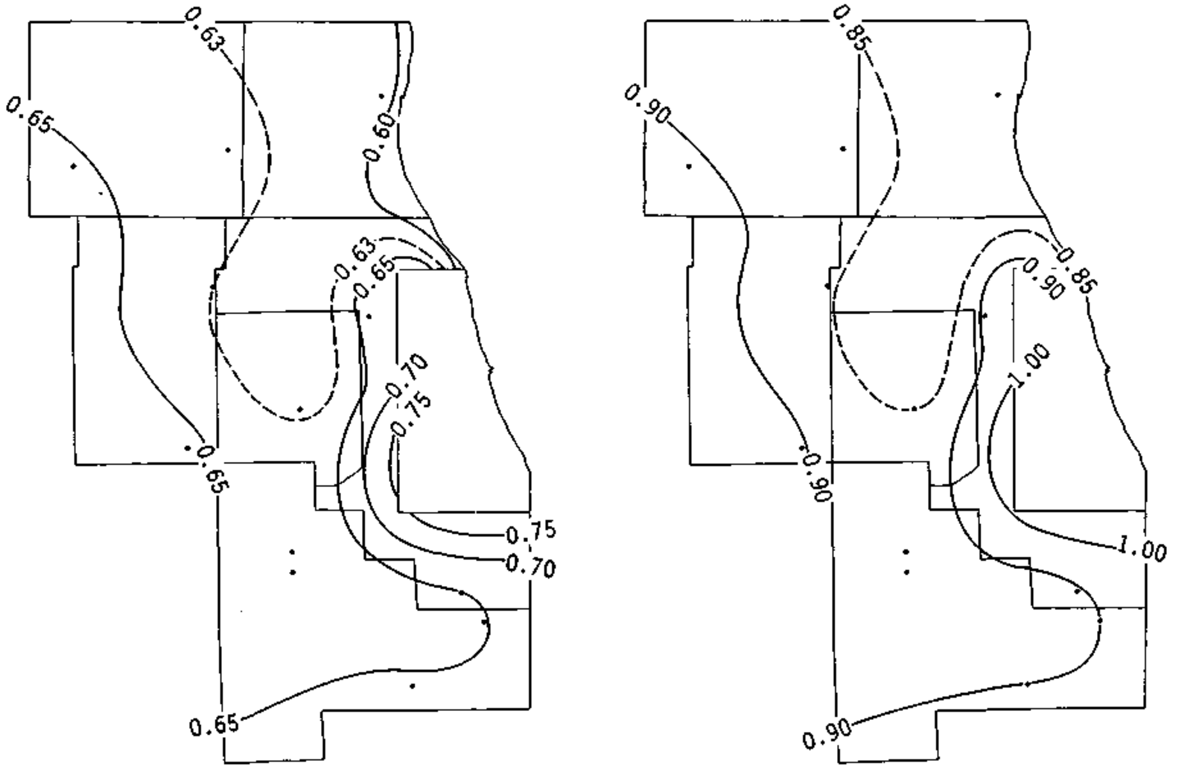
72-HOUR, 6-MONTH RAINFALL

Figure 10 (Concluded)



5-MINUTE, 1-YEAR RAINFALL

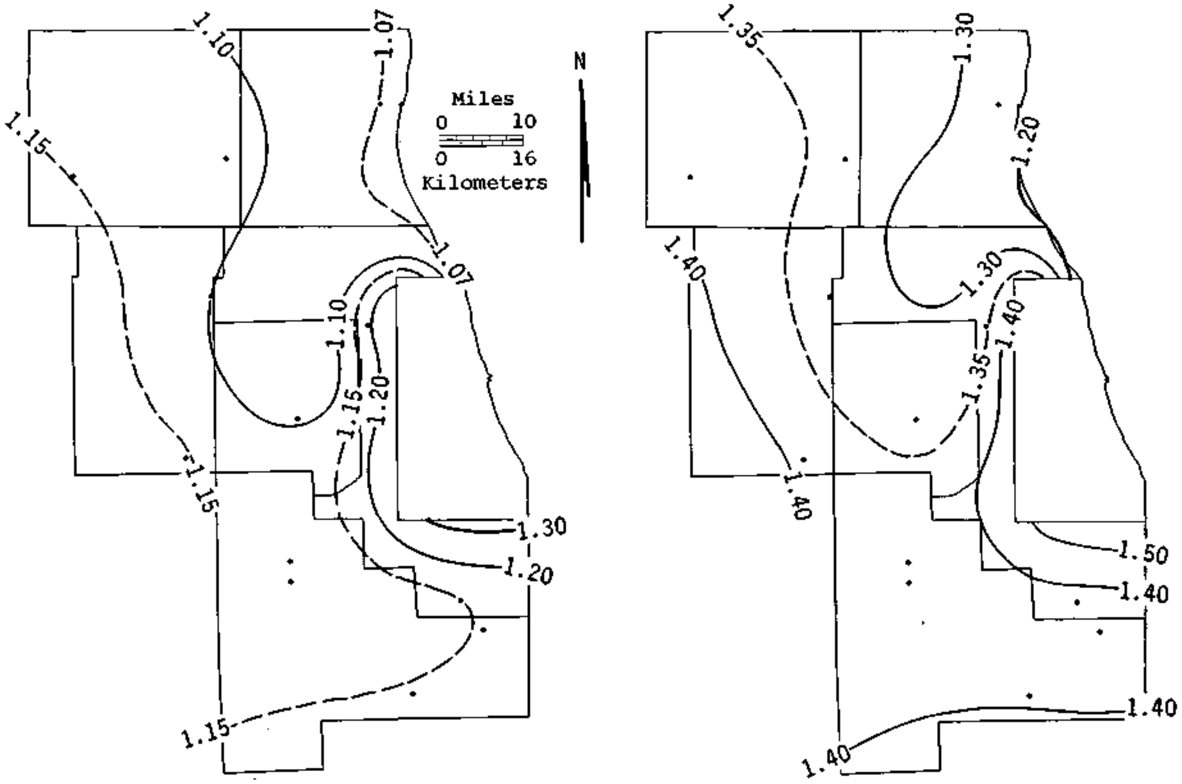
10-MINUTE, 1-YEAR RAINFALL



15-MINUTE, 1-YEAR RAINFALL

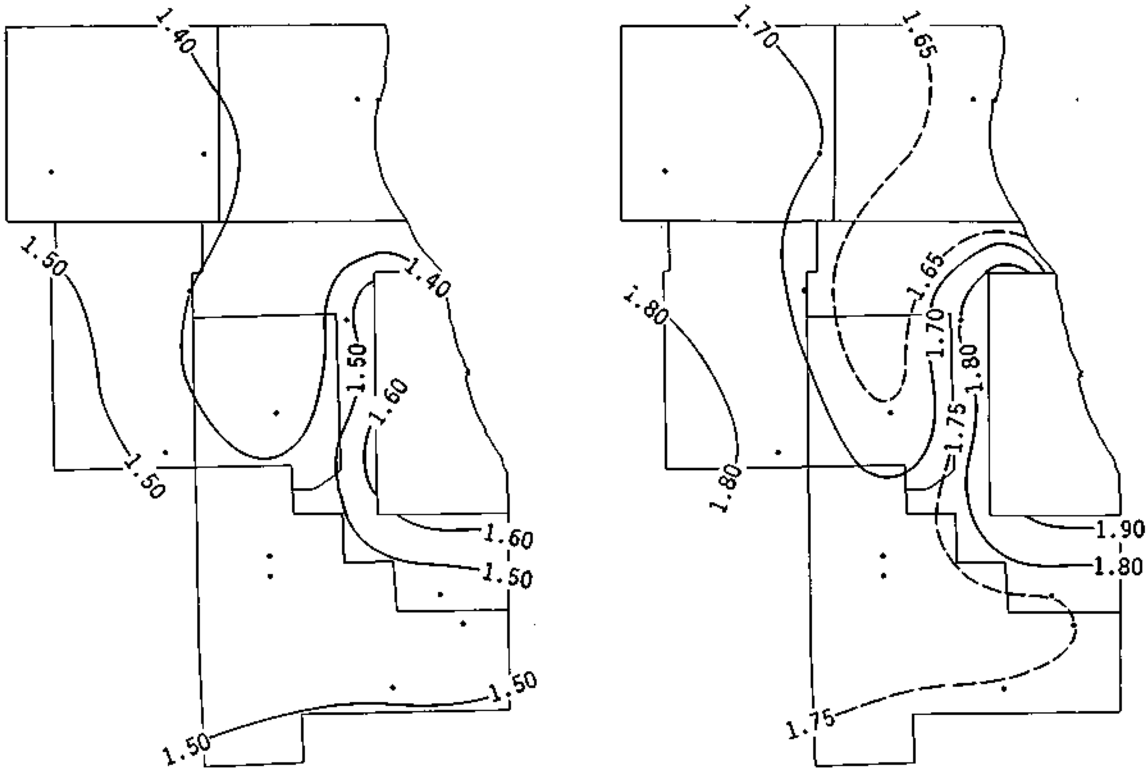
30-MINUTE, 1-YEAR RAINFALL

Figure 11. 1-year frequency of 6-county rainfall



1-HOUR, 1-YEAR RAINFALL

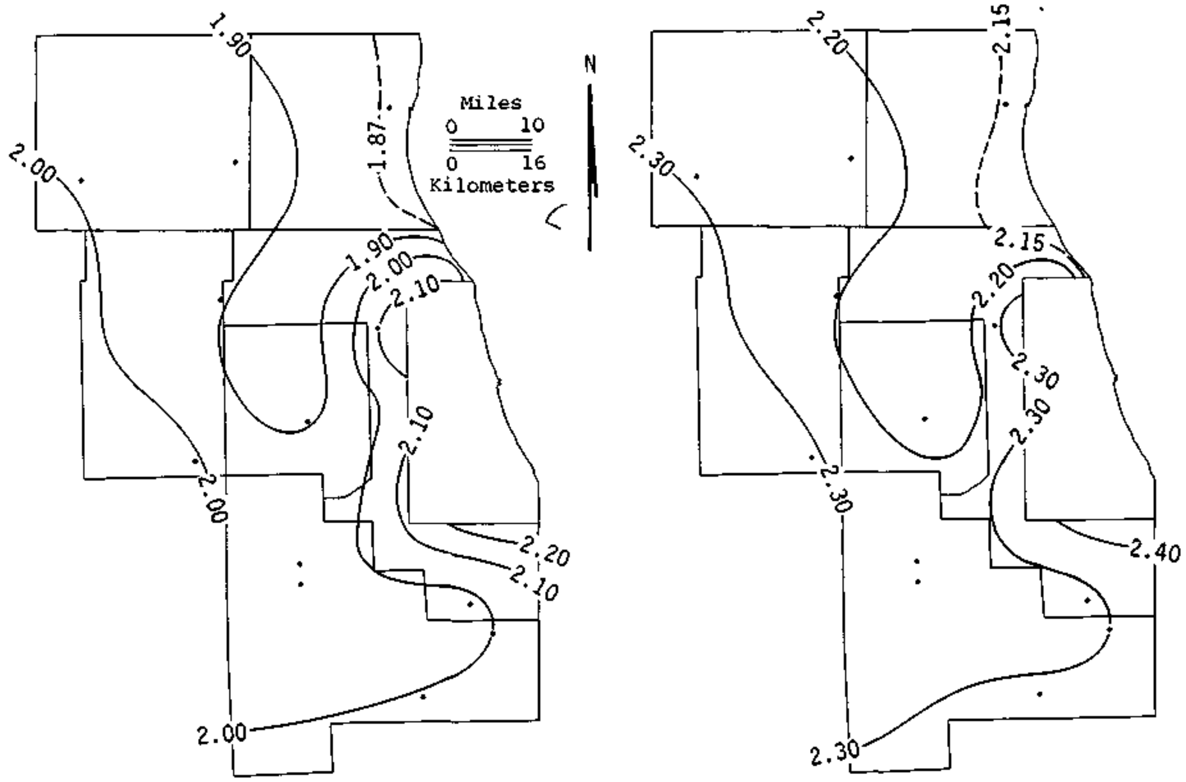
2-HOUR, 1-YEAR RAINFALL



3-HOUR, 1-YEAR RAINFALL

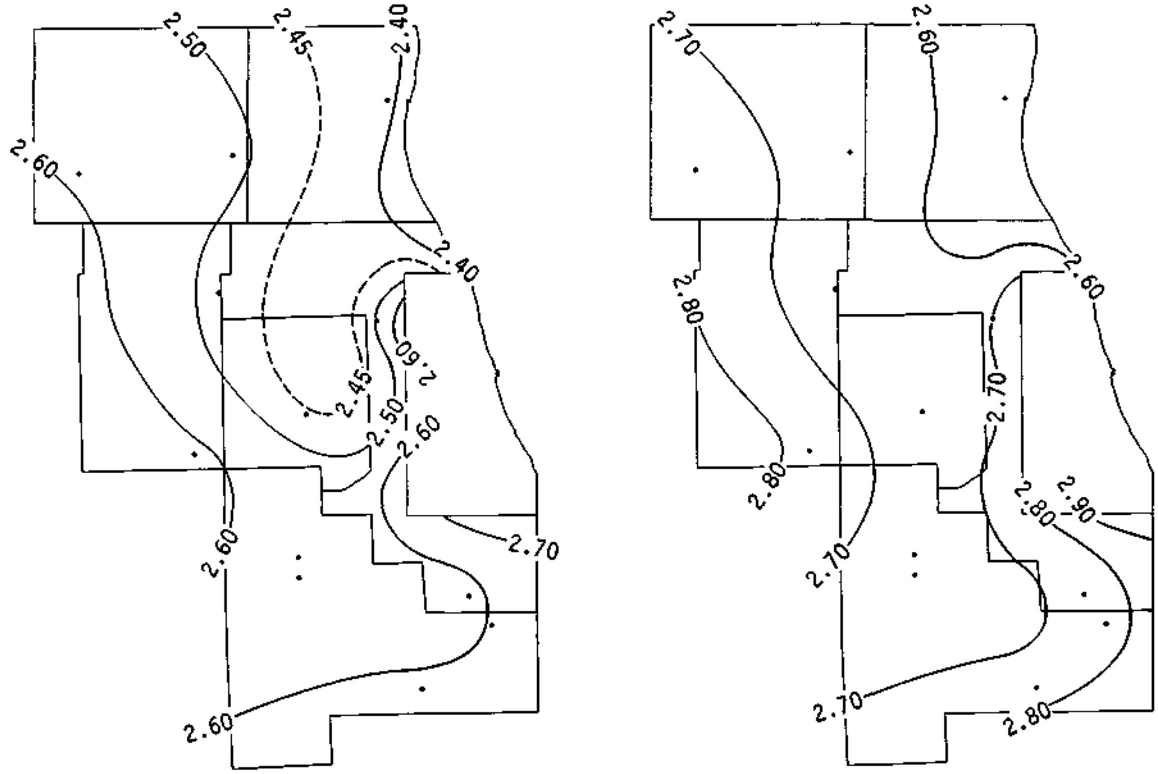
6-HOUR, 1-YEAR RAINFALL

Figure 11 (Continued)



12-HOUR, 1-YEAR RAINFALL

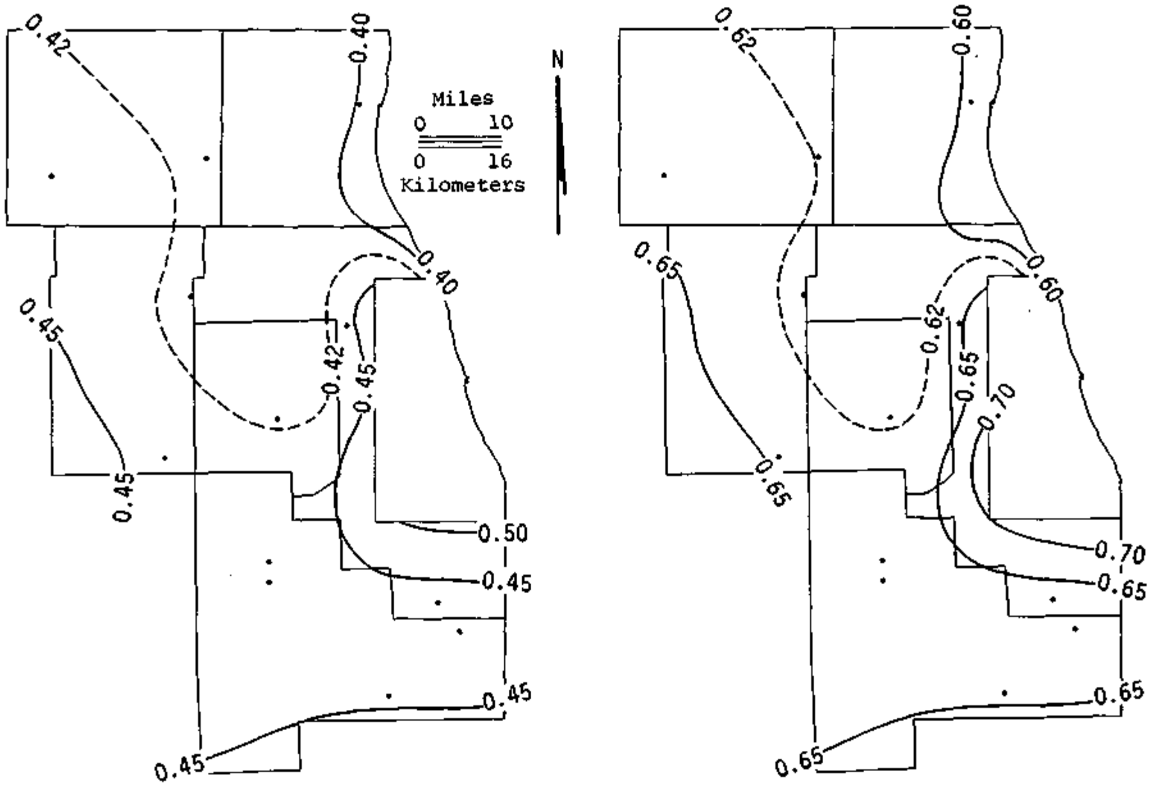
24-HOUR, 1-YEAR RAINFALL



48-HOUR, 1-YEAR RAINFALL

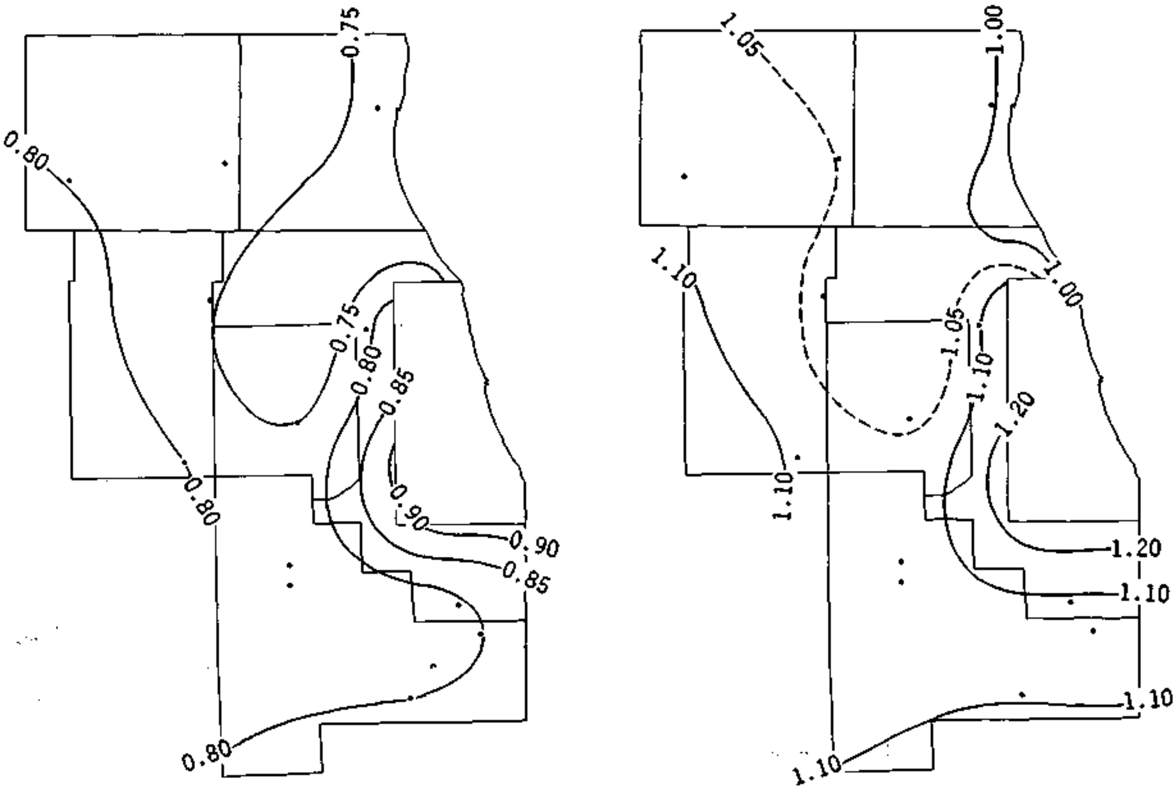
72-HOUR, 1-YEAR RAINFALL

Figure 11 (Concluded)



5-MINUTE, 2-YEAR RAINFALL

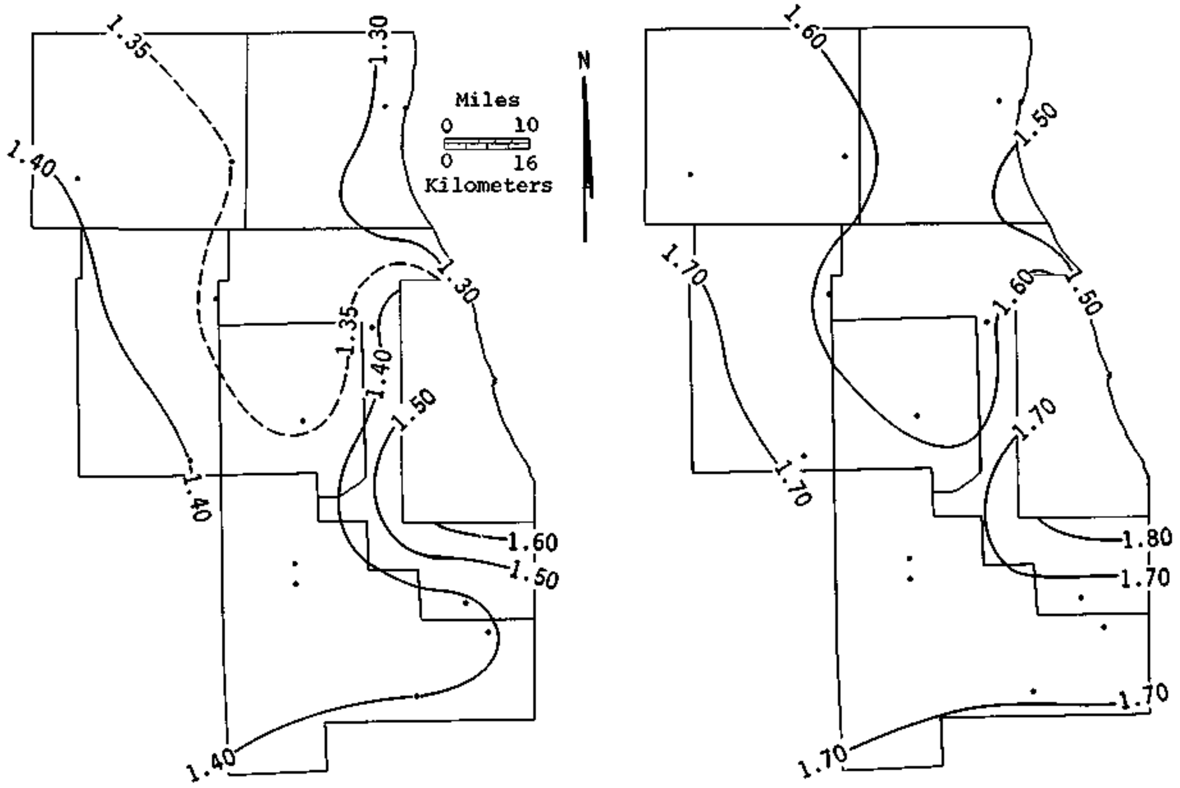
10-MINUTE, 2-YEAR RAINFALL



15-MINUTE, 2-YEAR RAINFALL

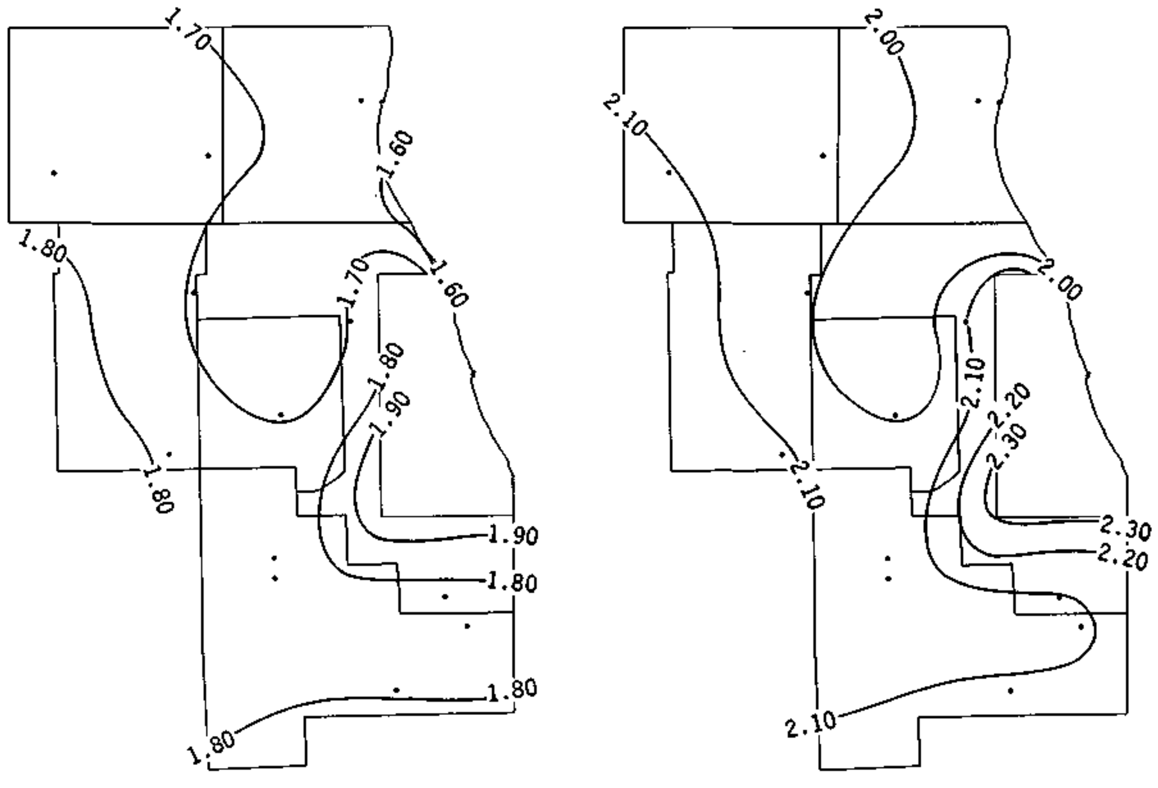
30-MINUTE, 2-YEAR RAINFALL

Figure 12. 2-year frequency of 6-county rainfall



1-HOUR, 2-YEAR RAINFALL

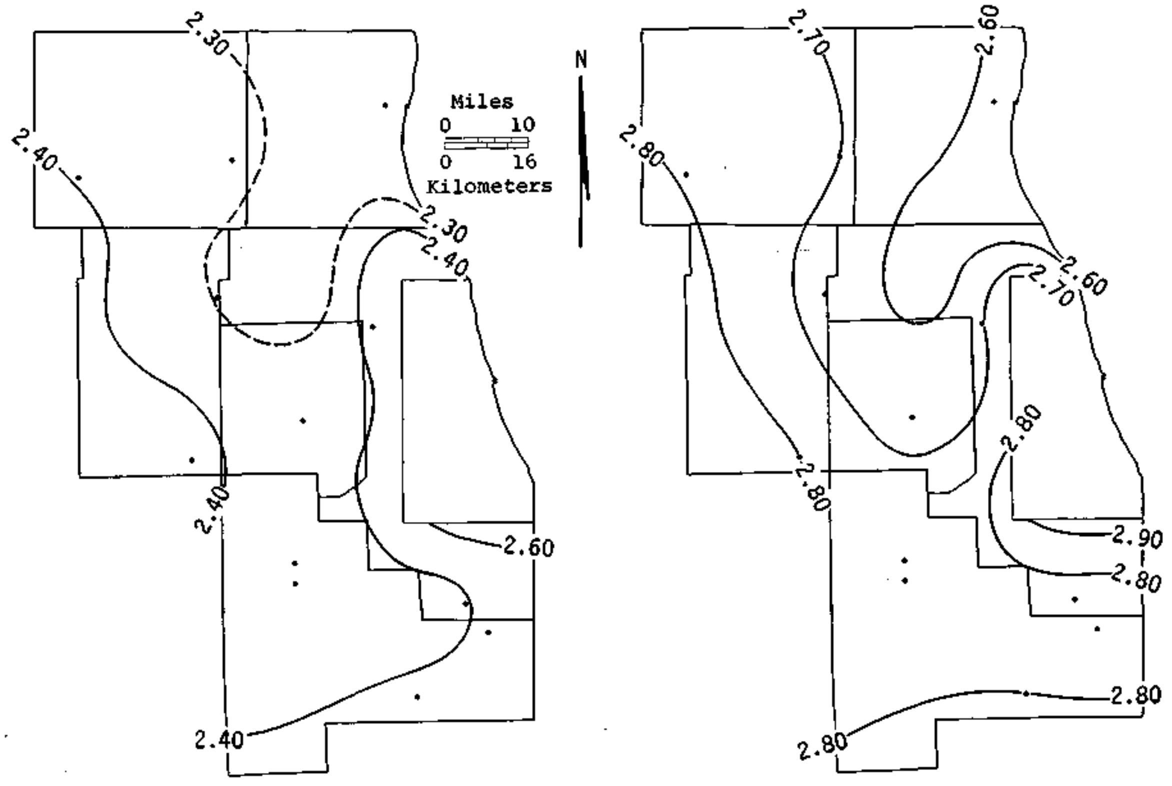
2-HOUR, 2-YEAR RAINFALL



3-HOUR, 2-YEAR RAINFALL

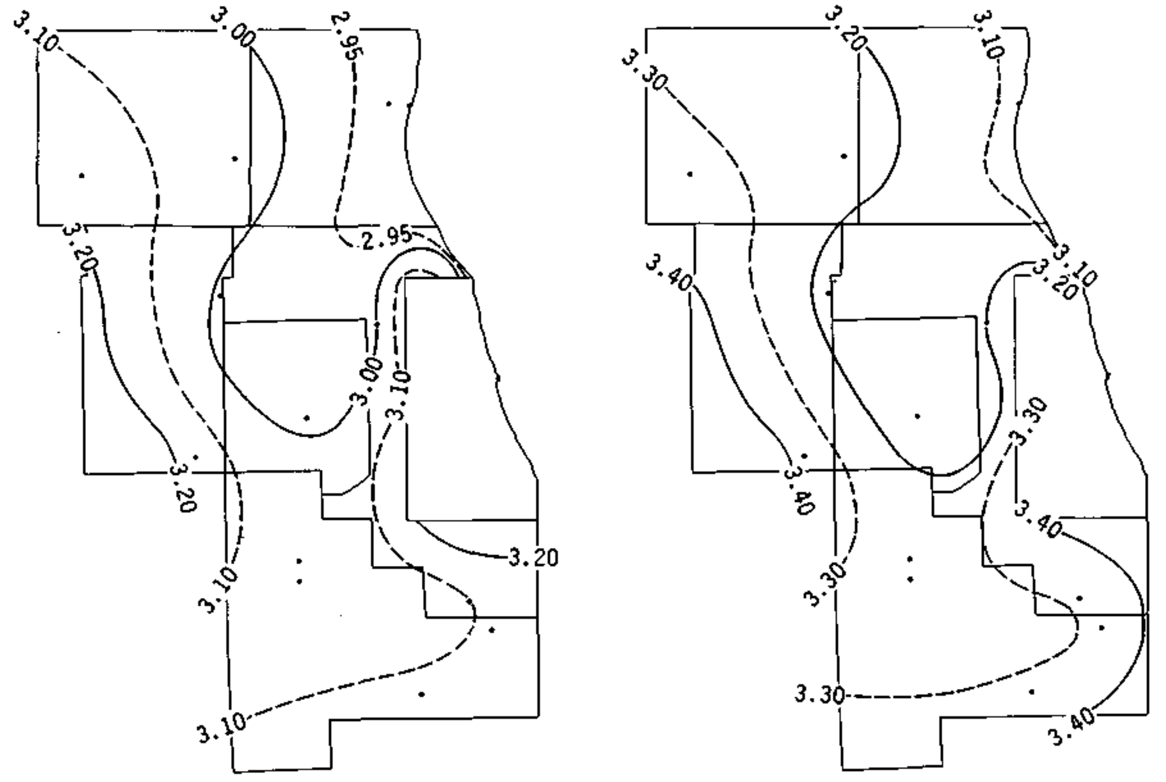
6-HOUR, 2-YEAR RAINFALL

Figure 12 (Continued)



12-HOUR, 2-YEAR RAINFALL

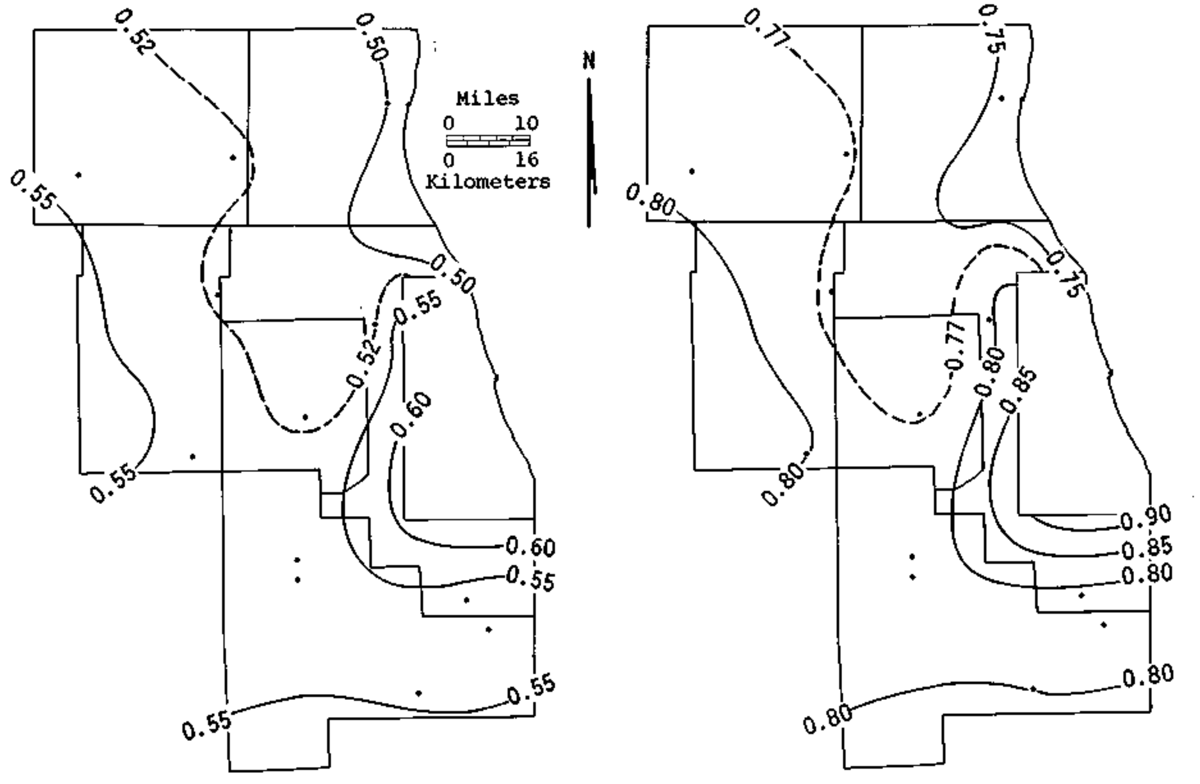
24-HOUR, 2-YEAR RAINFALL



48-HOUR, 2-YEAR RAINFALL

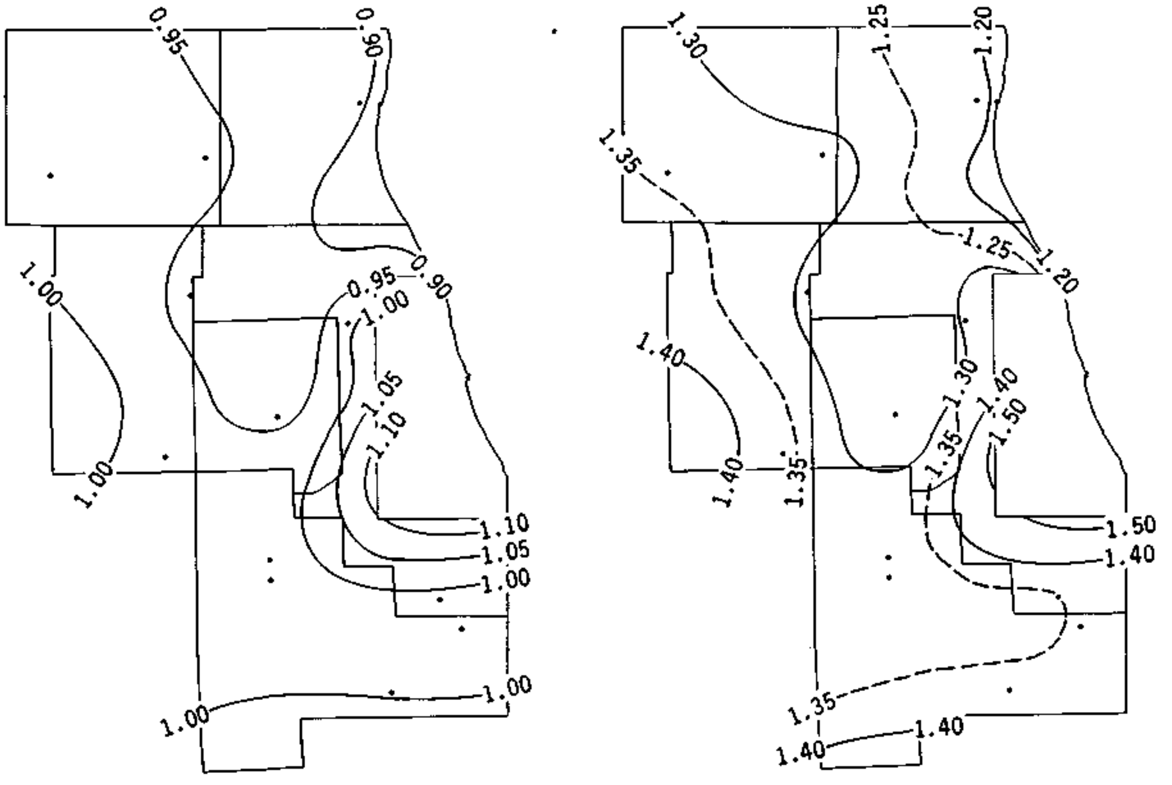
72-HOUR, 2-YEAR RAINFALL

Figure 12 (Concluded)



5-MINUTE, 5-YEAR RAINFALL

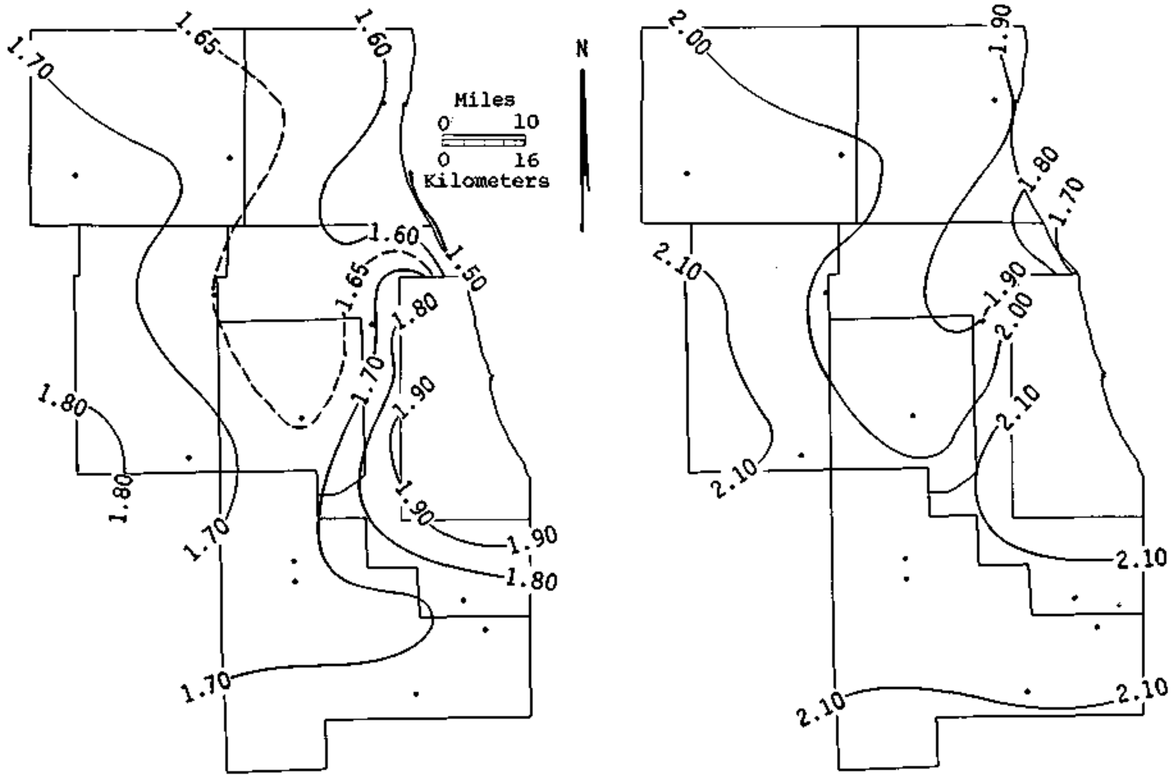
10-MINUTE, 5-YEAR RAINFALL



15-MINUTE, 5-YEAR RAINFALL

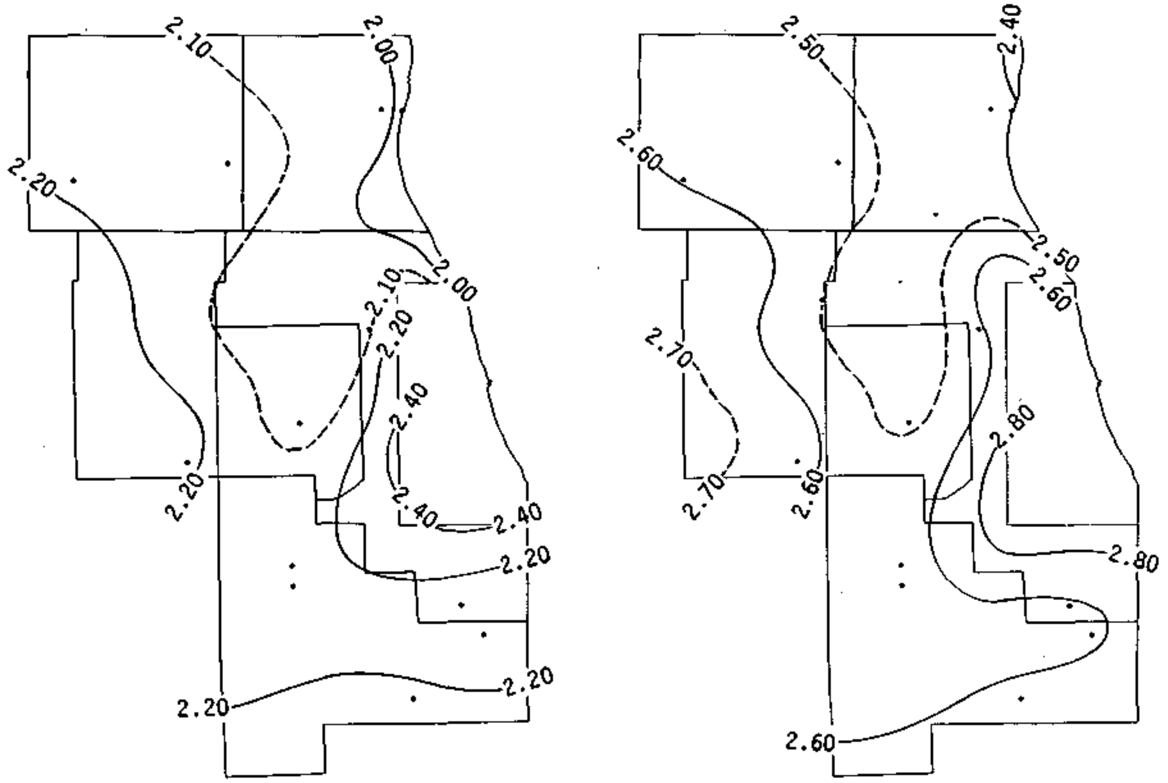
30-MINUTE, 5-YEAR RAINFALL

Figure 13. 5-year frequency of 6-county rainfall



1-HOUR, 5-YEAR RAINFALL

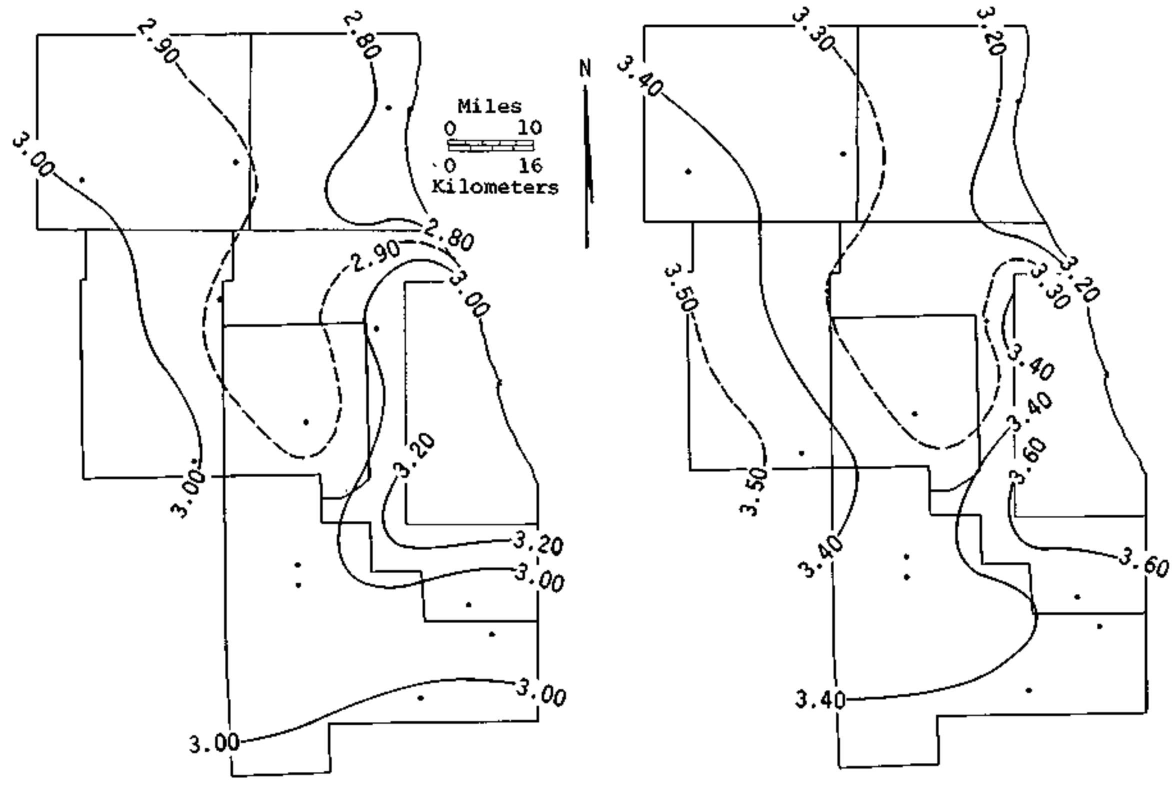
2-HOUR, 5-YEAR RAINFALL



3-HOUR, 5-YEAR RAINFALL

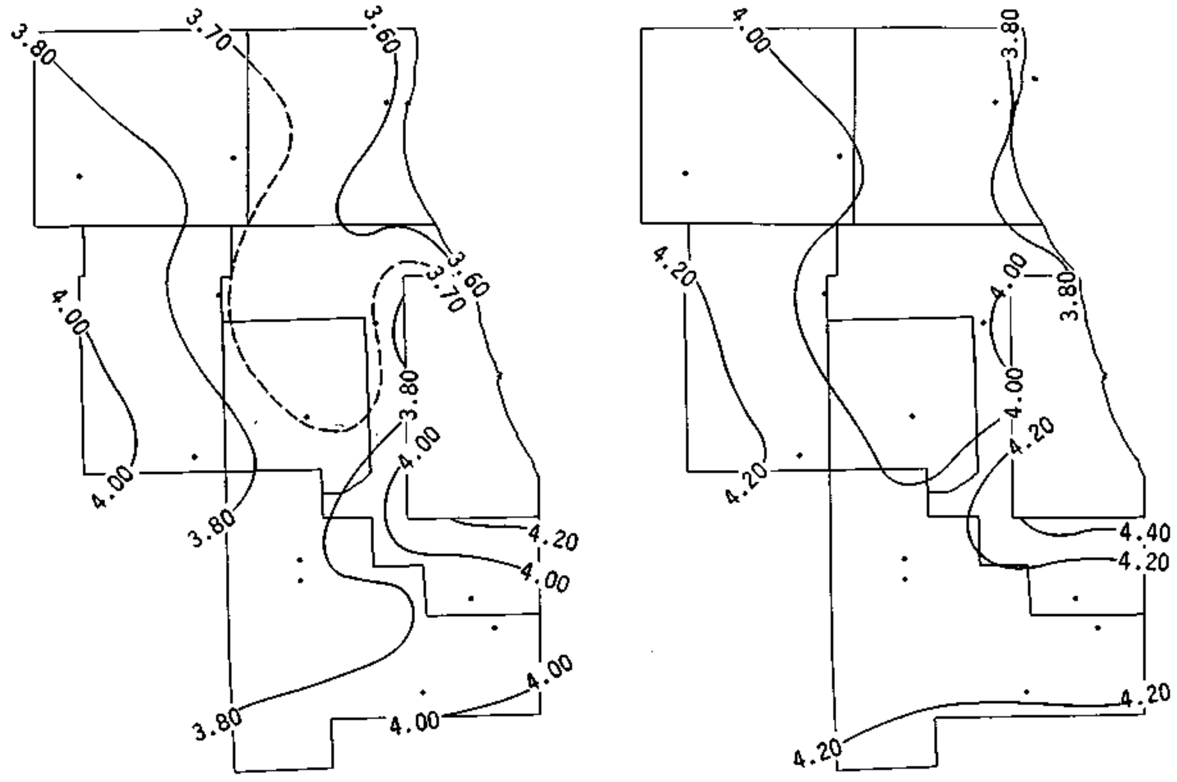
6-HOUR, 5-YEAR RAINFALL

Figure 13 (Continued)



12-HOUR, 5-YEAR RAINFALL

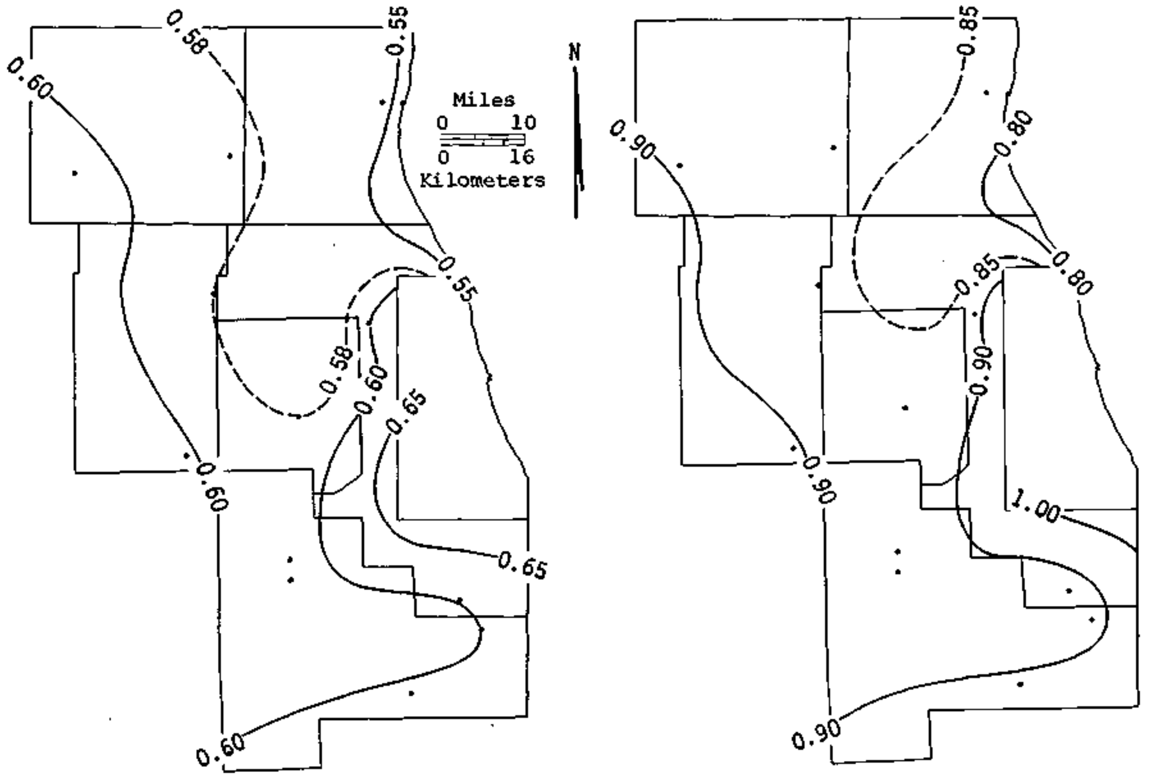
24-HOUR, 5-YEAR RAINFALL



48-HOUR, 5-YEAR RAINFALL

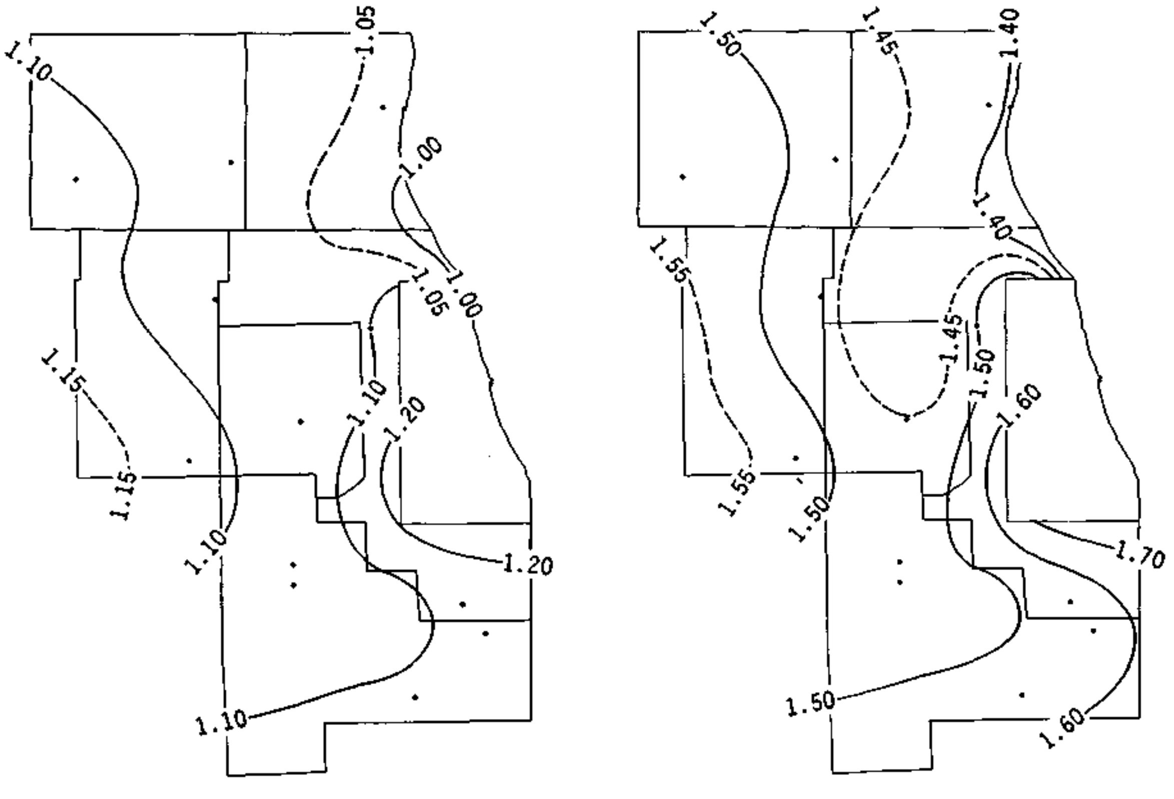
72-HOUR, 5-YEAR RAINFALL

Figure 13 (Concluded)



5-MINUTE, 10-YEAR RAINFALL

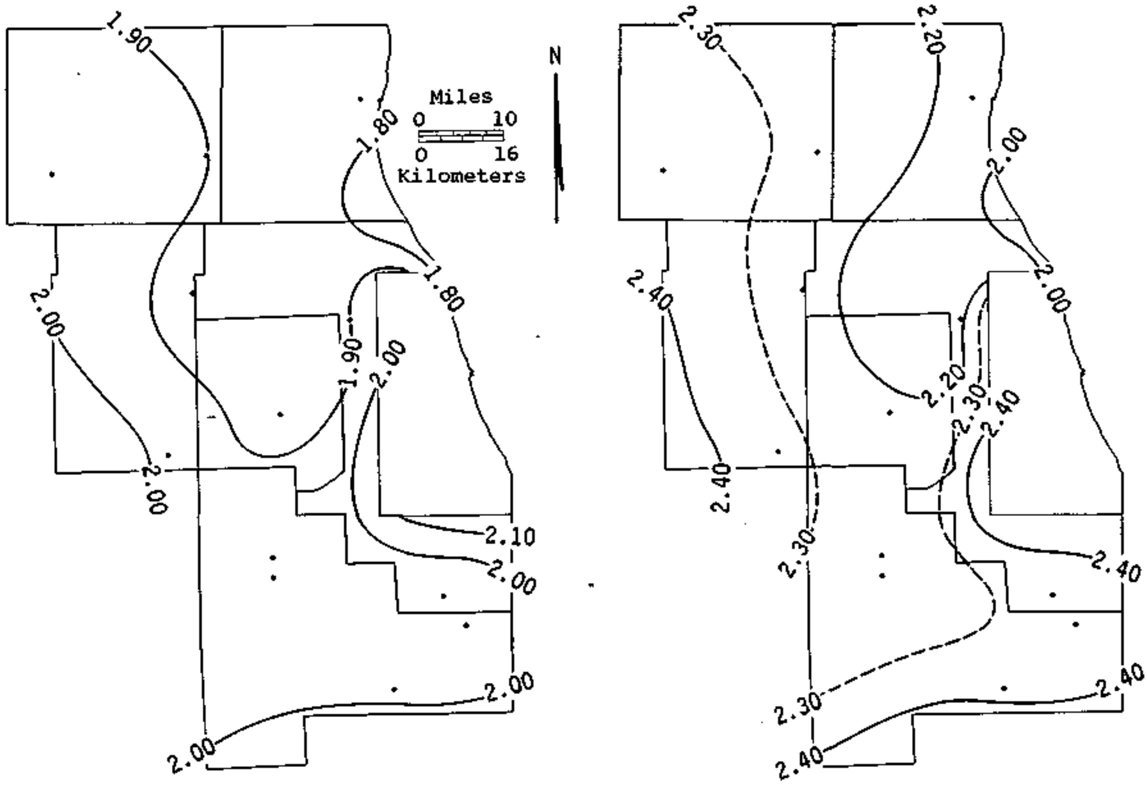
10-MINUTE, 10-YEAR RAINFALL



15-MINUTE, 10-YEAR RAINFALL

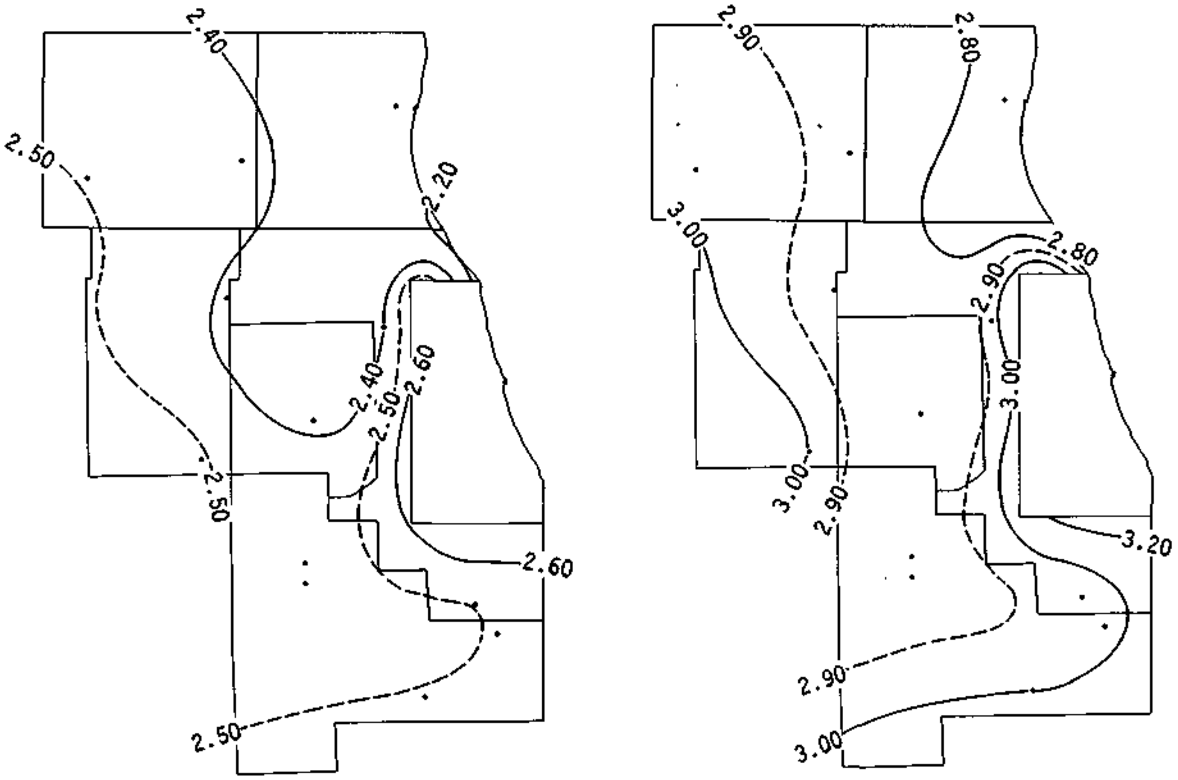
30-MINUTE, 10-YEAR RAINFALL

Figure 14. 10-year frequency of 6-county rainfall



1-HOUR, 10-YEAR RAINFALL

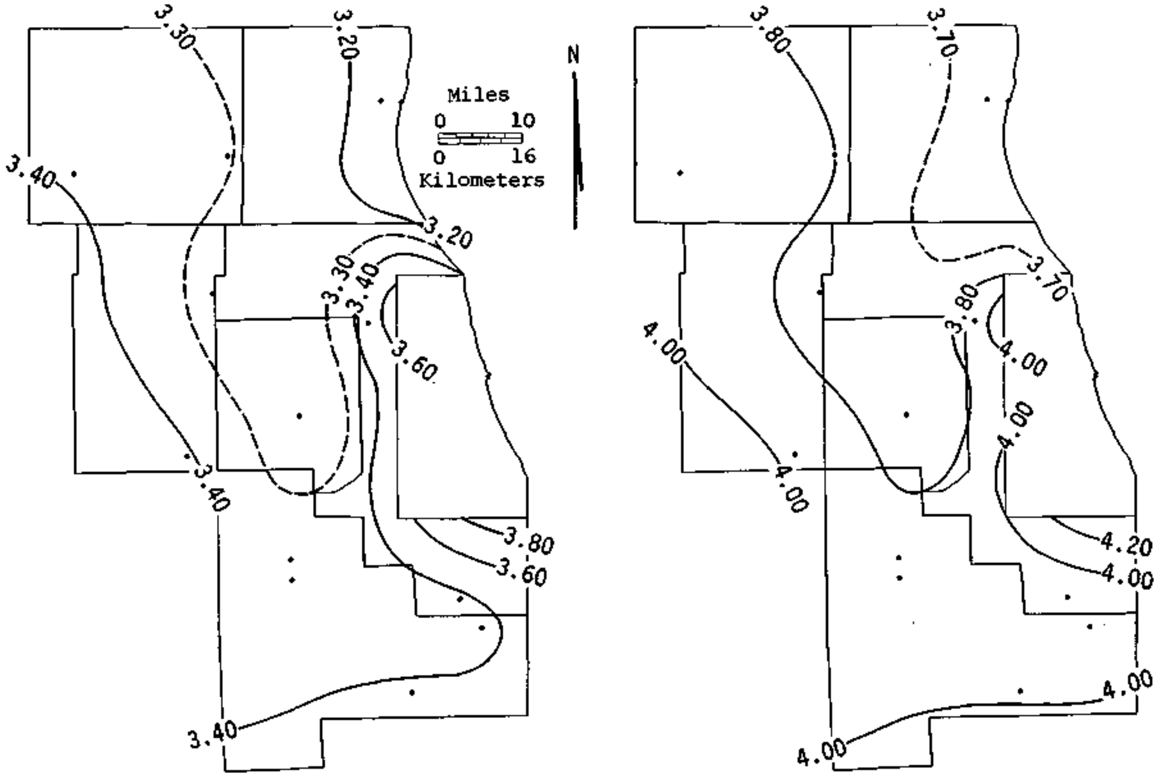
2-HOUR, 10-YEAR RAINFALL



3-HOUR, 10-YEAR RAINFALL

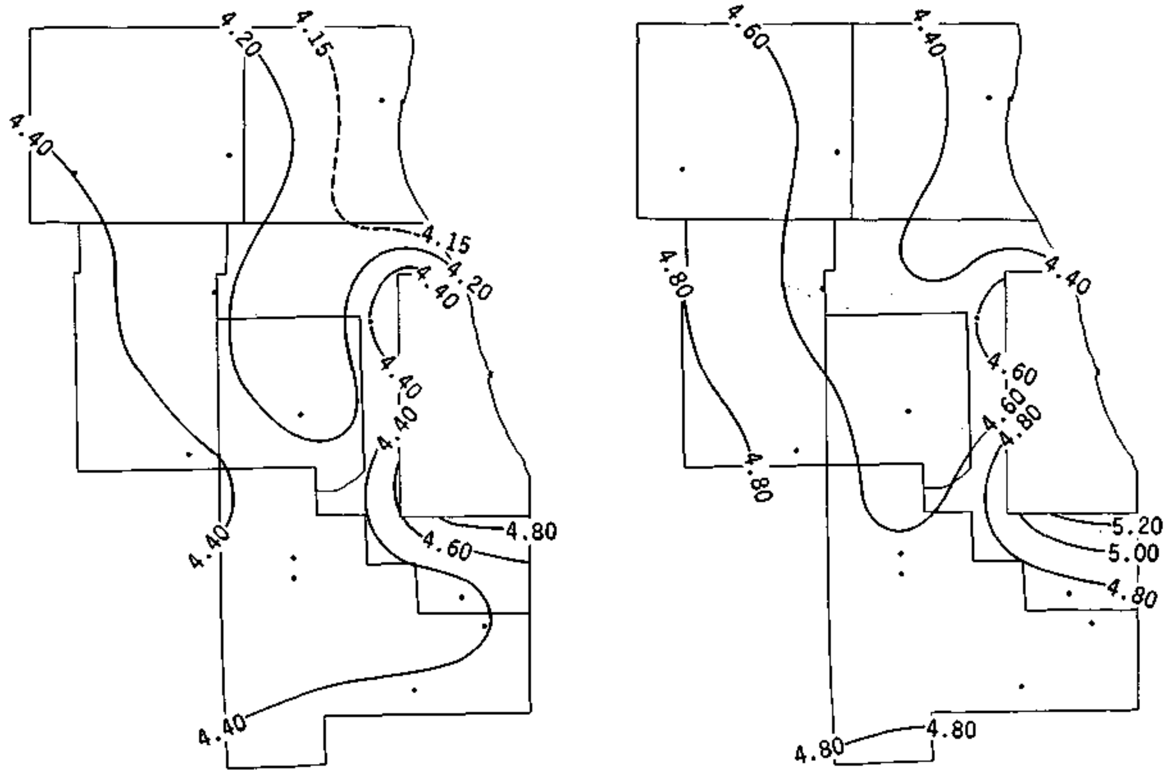
6-HOUR, 10-YEAR RAINFALL

Figure 14 (Continued)



12-HOUR, 10-YEAR RAINFALL

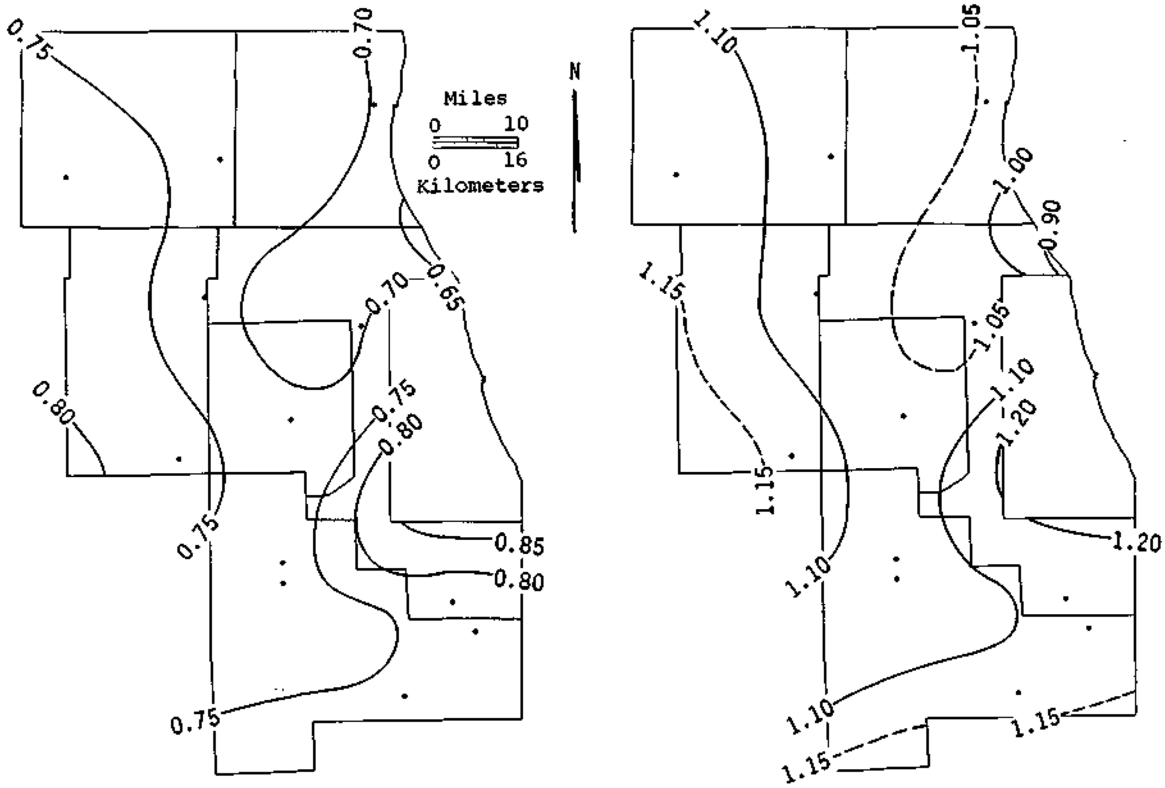
24-HOUR, 10-YEAR RAINFALL



48-HOUR, 10-YEAR RAINFALL

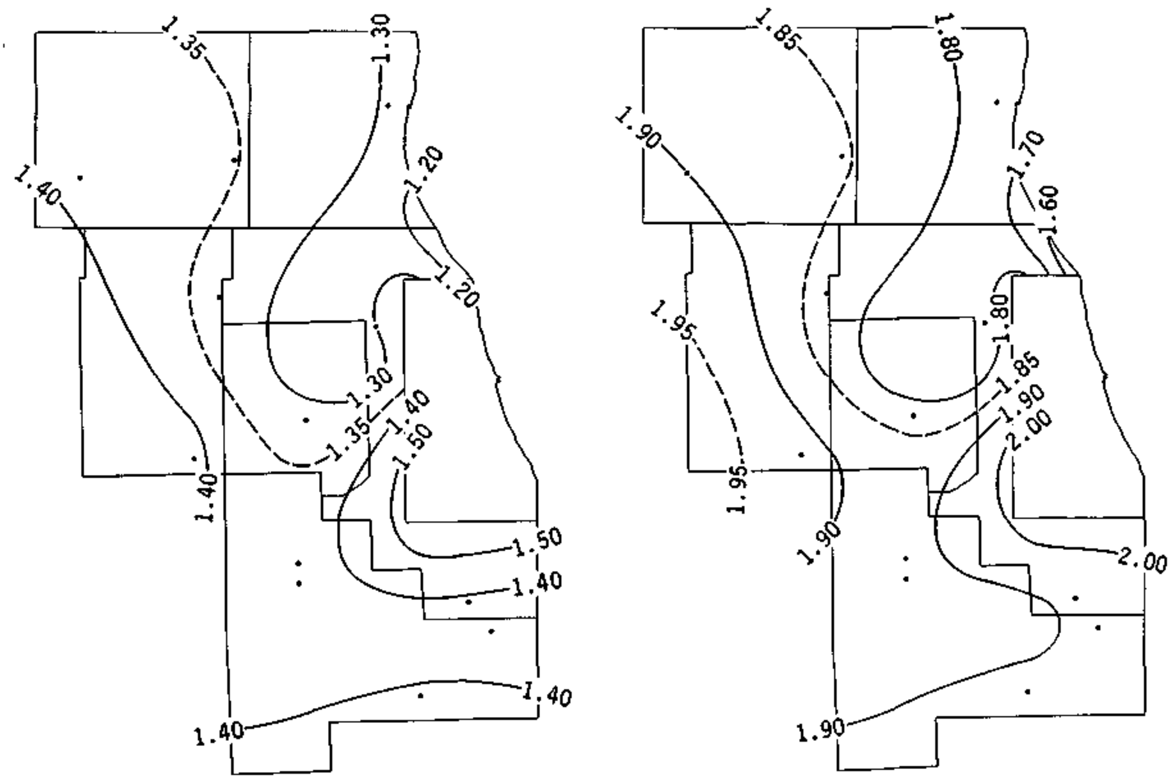
72-HOUR, 10-YEAR RAINFALL

Figure 14 (Concluded)



5-MINUTE, 25-YEAR RAINFALL

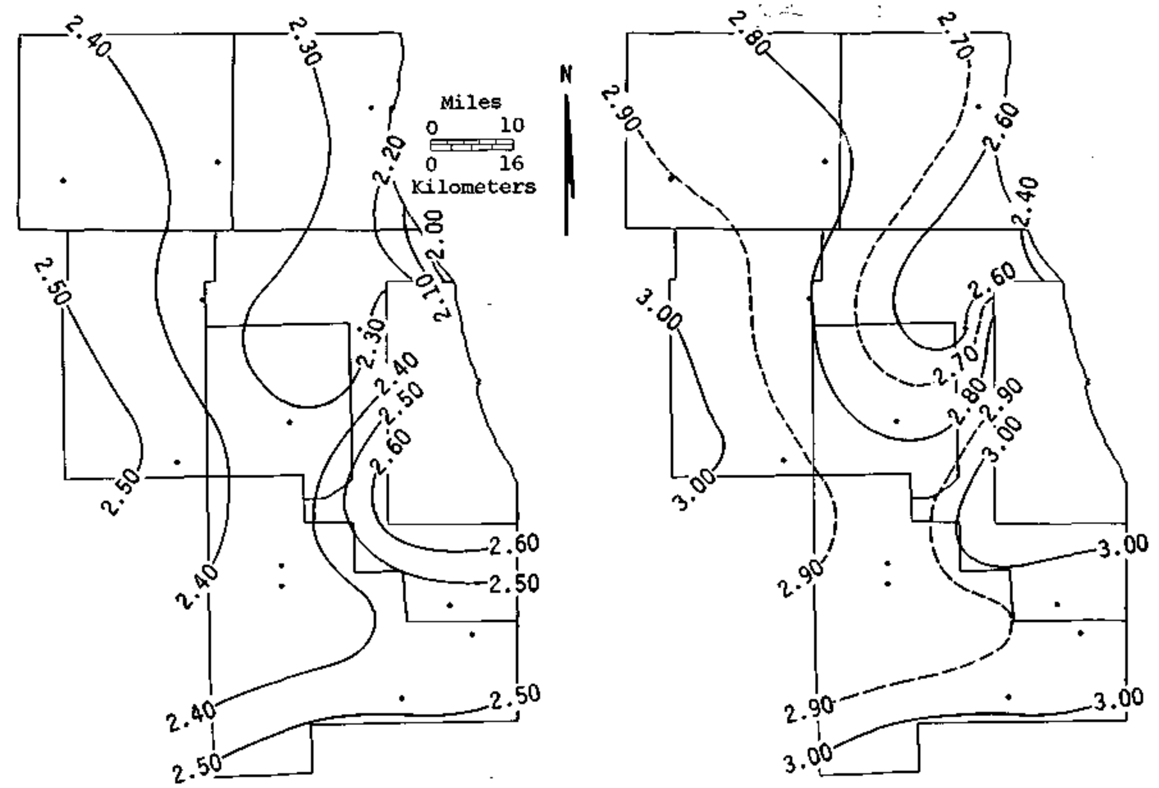
10-MINUTE, 25-YEAR RAINFALL



15-MINUTE, 25-YEAR RAINFALL

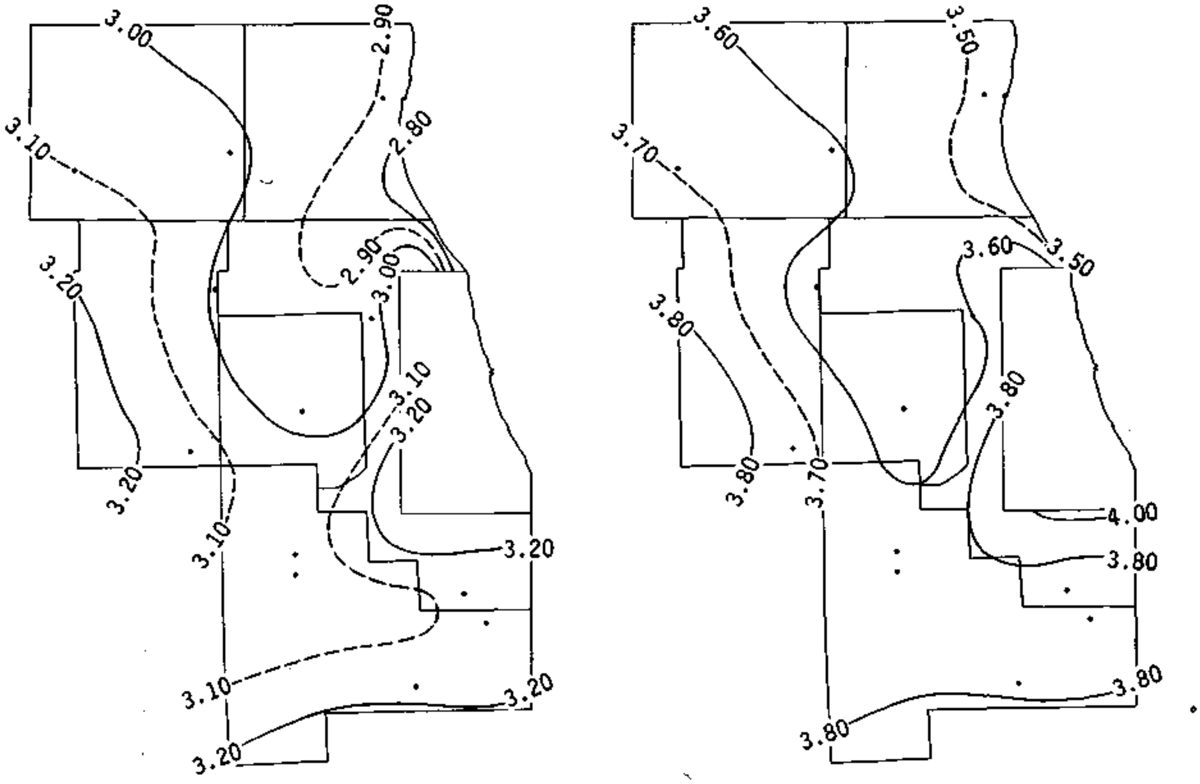
30-MINUTE, 25-YEAR RAINFALL

Figure 15. 25-year frequency of 6-county rainfall



1-HOUR, 25-YEAR RAINFALL

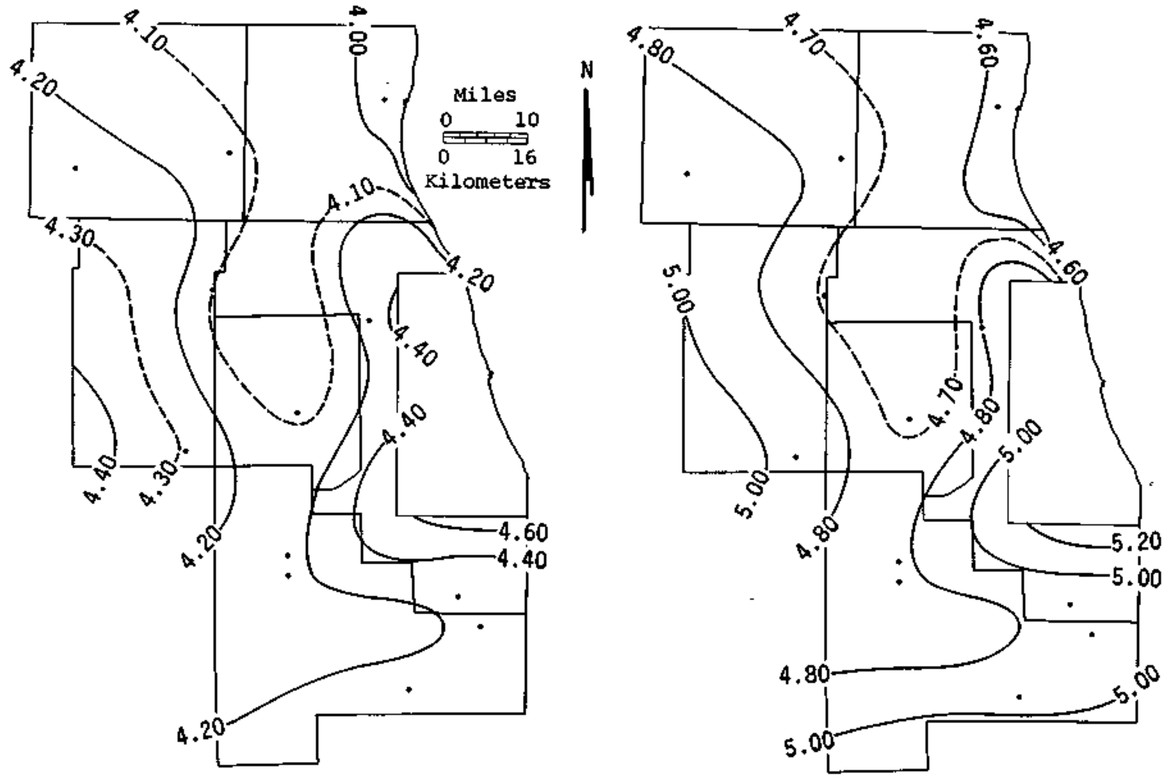
2-HOUR, 25-YEAR RAINFALL



3-HOUR, 25-YEAR RAINFALL

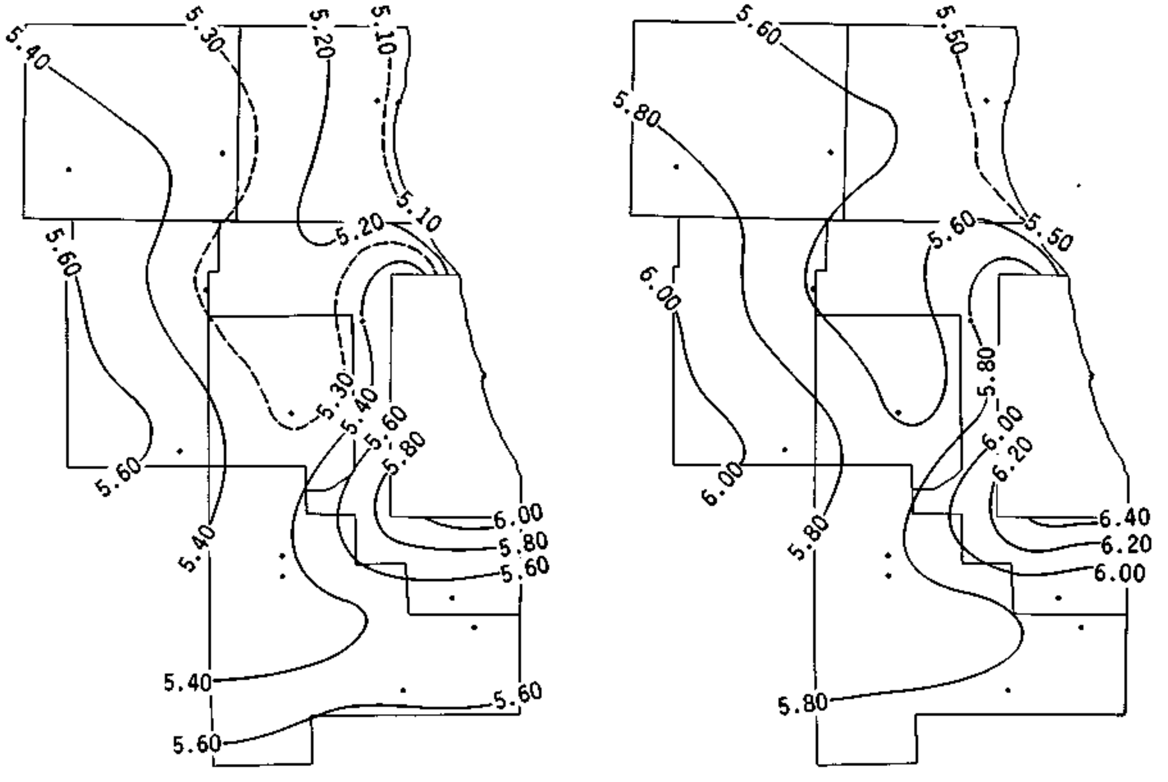
6-HOUR, 25-YEAR RAINFALL

Figure 15 (Continued)



12-HOUR, 25-YEAR RAINFALL

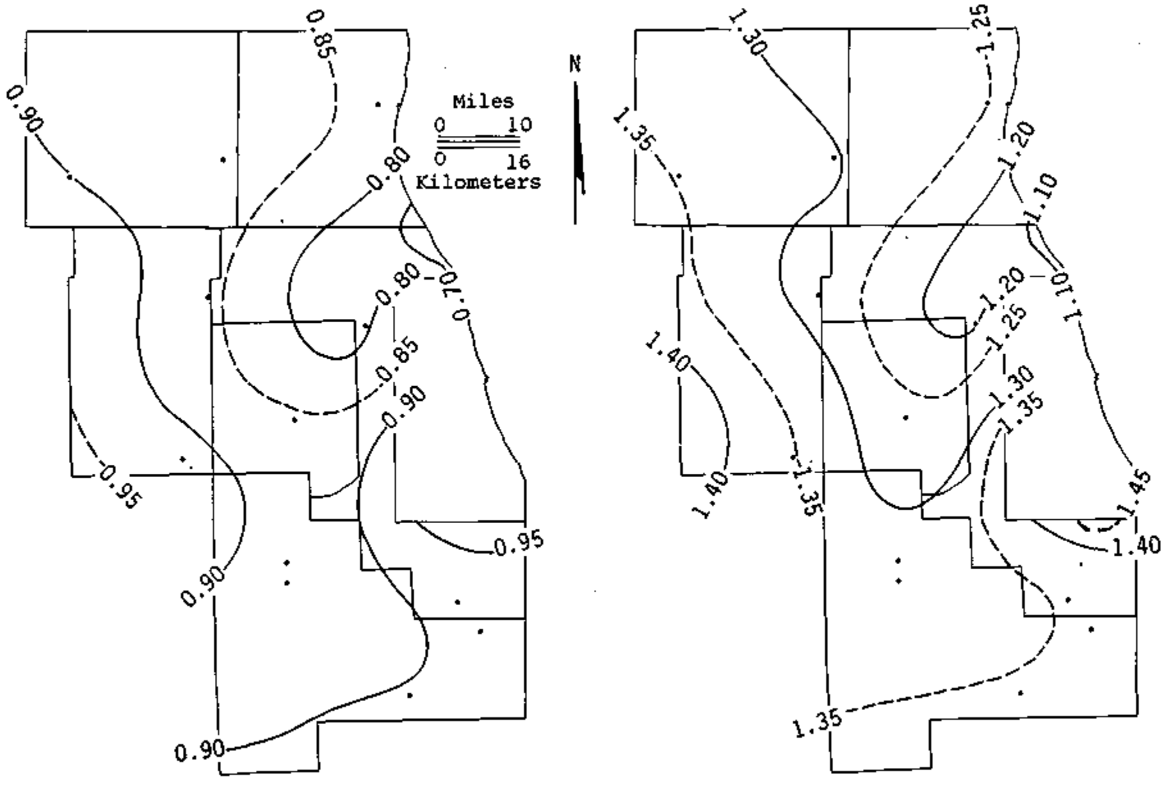
24-HOUR, 25-YEAR RAINALL



48-HOUR, 25-YEAR RAINFALL

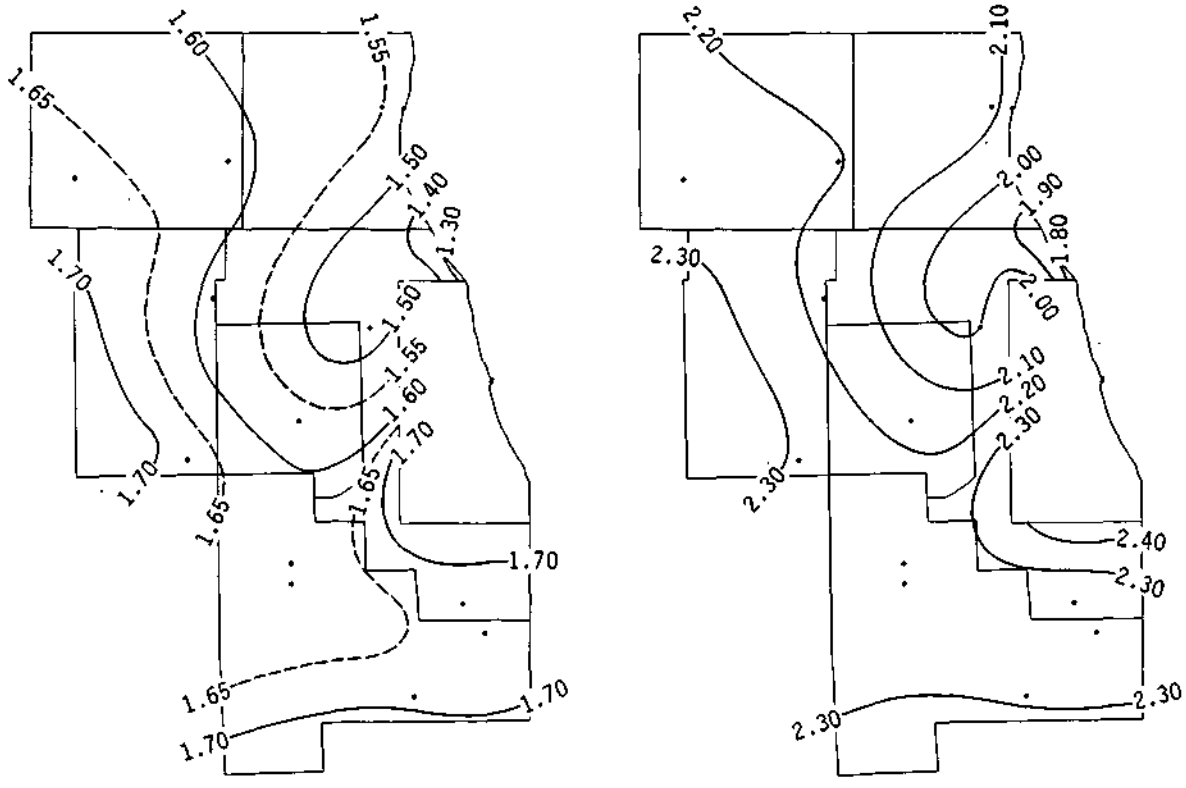
72-HOUR, 25-YEAR RAINFALL

Figure 15 (Concluded)



5-MINUTE, 50-YEAR RAINFALL

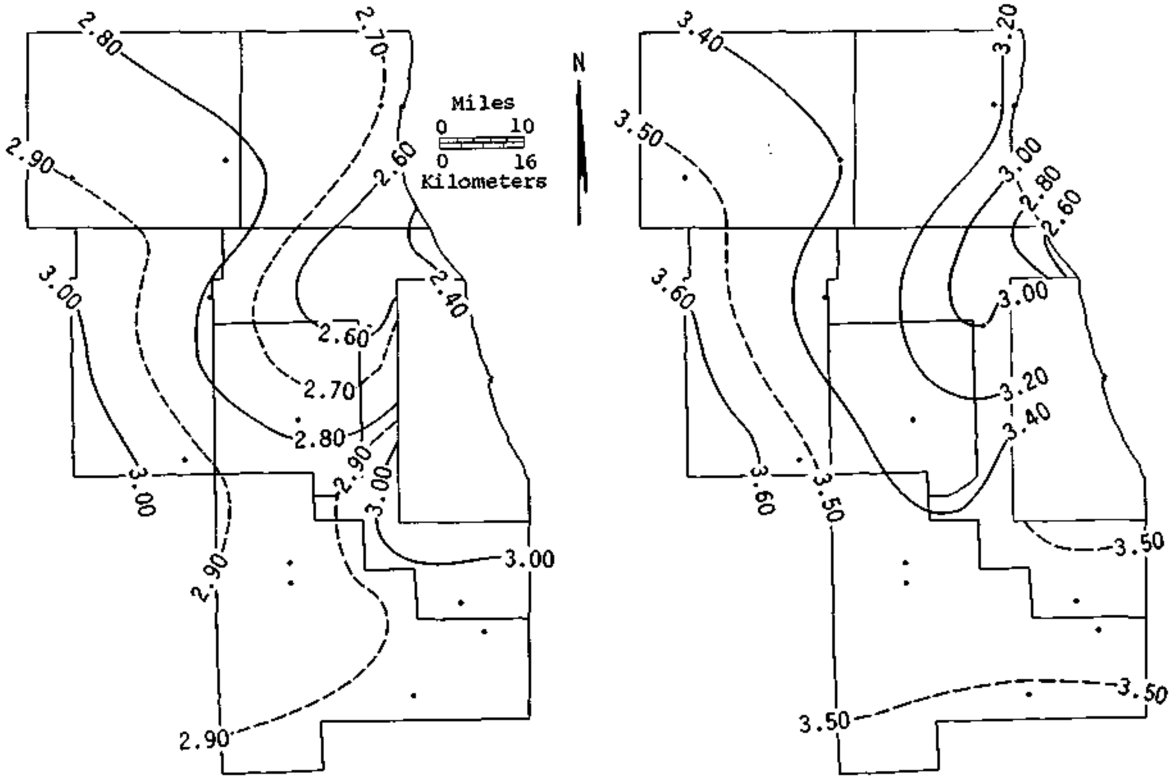
10-MINUTE, 50-YEAR RAINFALL



15-MINUTE, 50-YEAR RAINFALL

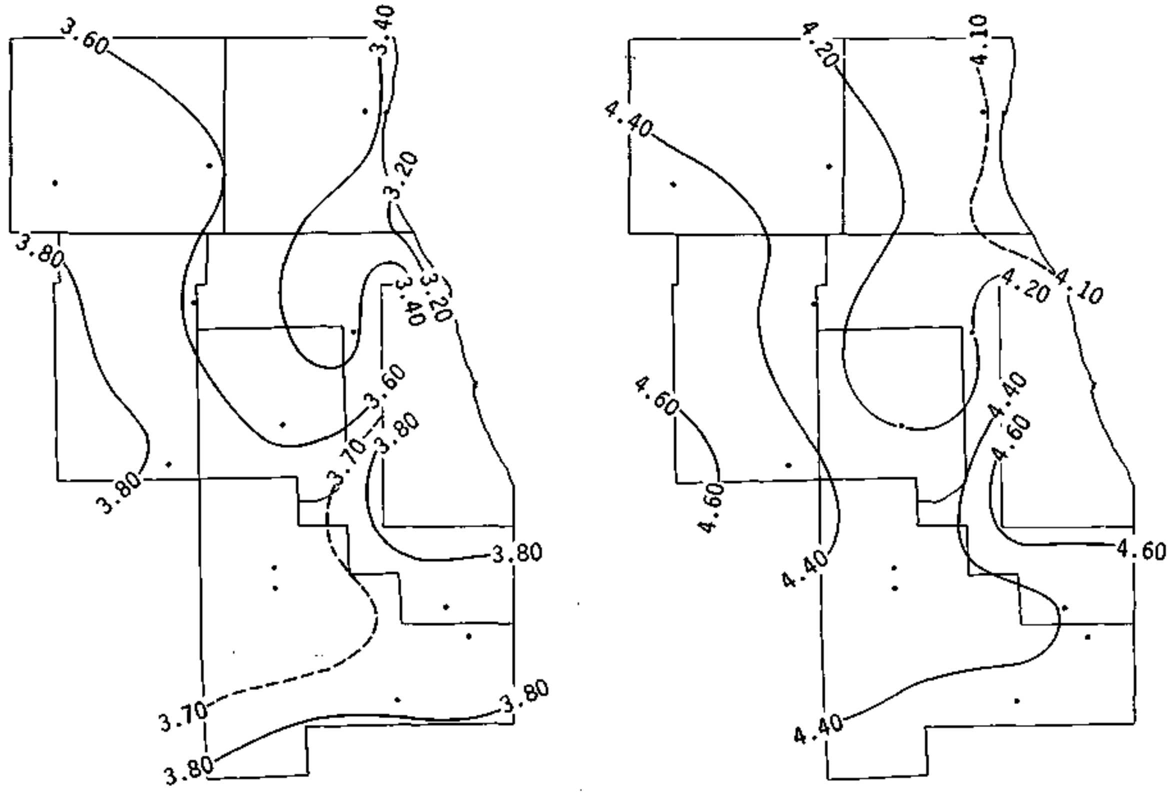
30-MINUTE, 50-YEAR RAINFALL

Figure 16. 50-year frequency of 6-county rainfall



1-HOUR, 50-YEAR RAINFALL

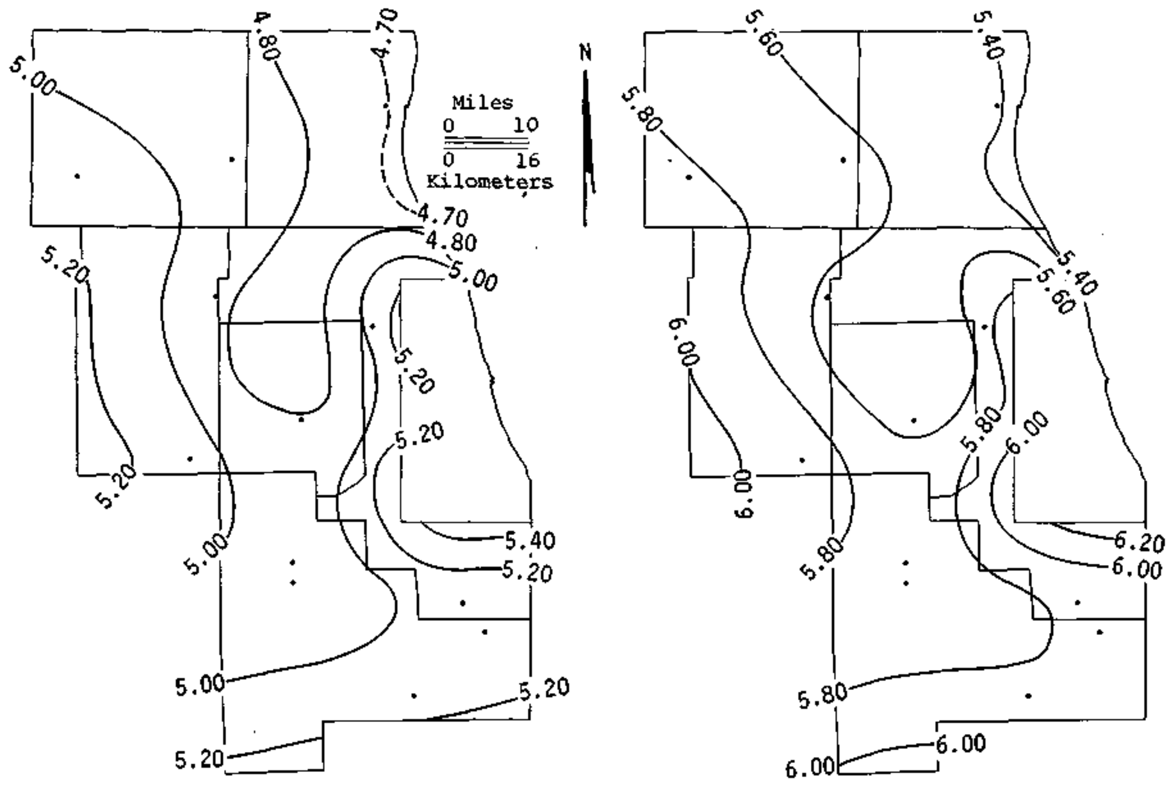
2-HOUR, 50-YEAR RAINFALL



3-HOUR, 50-YEAR RAINFALL

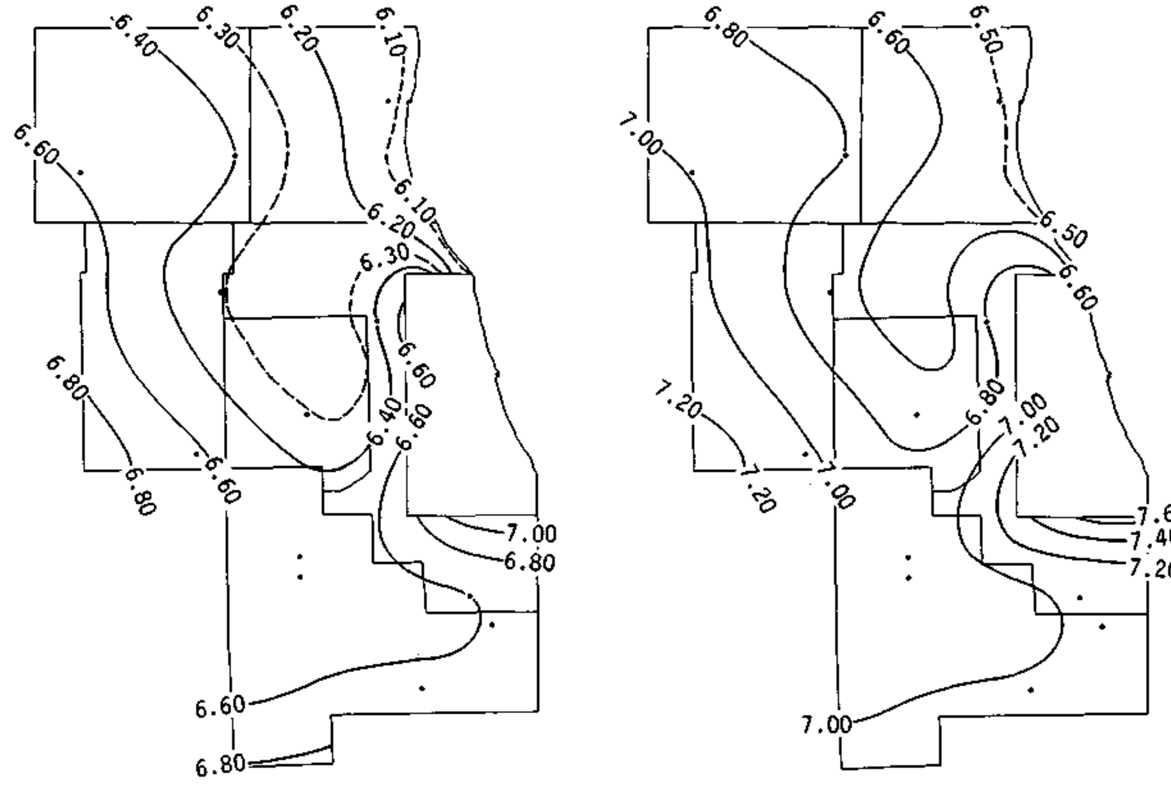
6-HOUR, 50-YEAR RAINFALL

Figure 16 (Continued)



12-HOUR, 50-YEAR RAINFALL

24-HOUR, 50-YEAR RAINFALL



48-HOUR, 50-YEAR RAINFALL

72-HOUR, 50-YEAR RAINFALL

Figure 16 (Concluded)

Table 1. Relation between Areal Mean and Point Rainfall Frequency Distributions

Storm period (hours)	*Ratio of areal to point rainfall for given area (mi^2)*					
	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

Table 2. Probability of Equaling or Exceeding a Given Return-Period Value

Return period (years)	*Probability (%) of equaling or exceeding the indicated return-period event (years)*						
	2	*4*	*5*	*10*	*20*	*25*	*50*
1	39	22	18	10	5	4	2
2	63	39	33	18	10	8	4
3		53	45	26	14	11	6
4		63	55	33	18	15	8
5			63	39	22	18	10
6				45	26	21	11
7				50	30	24	13
8				55	33	27	15
9				59	36	30	17
10				63	39	33	18
11					42	36	20
12					45	38	21
13					48	41	23
14					50	43	24
15					53	45	26
16					55	47	27
17					57	49	29
18					59	51	30
19					61	53	32
20					63	55	33
21						57	34
22						59	36
23						60	37
24						62	38
25						63	39

1 was constructed to show the average ratio 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 distribution of areal mean rainfall for small areas. The ratios of table 1 are considered to be applicable throughout Illinois and most of the Midwest.

The values in table 1 differ only slightly from those published earlier by the U.S. Weather Bureau for application throughout the United States (U.S. Weather Bureau, 1955). The small differences may be due to several factors, such as climatic differences in the data samples, length of mean rainfall records, and accuracy of areal mean rainfall measurements.

Use of table 1 is illustrated as follows. Assume a hydrologist is designing a storm sewer system in a subarea of 100 mi^2 in the Roseland area (figure 1), and that part of his design criteria involves computation of the 3-hour rainfall to be expected on an average of once in 5 years. From figure 6, this is approximately 2.5 inches. • Then, multiplying 2.5 by each of the 3-hour areal ratios in table 1, values of 2.40, 2.33, 2.25, and 2.18 inches, respectively, are obtained for 10, 25, 50, and 100 mi^2. A more precise computation would involve construction of maps for each subarea (10 to 100 mi^2), based on table 1 and figure 6, and then computing areal mean rainfall for the area of interest from the maps.

Risk of Exceeding Return-Period Values

A frequent question concerns the probability of exceeding the average return-period value in a given period of time. For example, what is the probability that a 5-year rain event will be exceeded in the next 5 years? Several investigators, including Court (1952) and Thorn (1959), have shown how an estimate of this probability can be obtained from theoretical considerations.

Table 2 has been computed from an equation presented by Thorn (1959), and serves as a useful guide in hydrologic design problems. This table shows the probability in percent of experiencing a rain event that is equal to or greater in severity than the mean return-period value.

Interpretation of table 2 is illustrated as follows. Assume a storm sewer design based on rain events having an average frequency of occurrence (return period) of once in 5 years. Moving horizontally from the return period of 5 years, one finds that the probability of equaling or exceeding the 5-year rainfall event in any given 5-year period is 63% or nearly 2 chances out of 3. Proceeding farther, there is a probability of 39% that a 10-year or greater event will occur in the next 5 years, and a 10% probability (1 chance in 10) that a 50-year event will be experienced. Thus, if the designer wished to be 90% certain that his design value would not be exceeded in the next 5 years, he would have to design for the 50-year event which has only a 10% probability of being exceeded.

TIME DISTRIBUTIONS

Time between Successive Heavy Storms

The frequency with which one heavy storm may follow another is a matter of concern in hydrologic design and operations. Data for five stations in the Chicago urban area were analyzed for the 20 years, 1949-1968, to obtain some information on this subject. Stations used were Mayfair, WB/City, Sanitary Dispatch Plant, Midway, and Roseland (see locations in figure 1). These were selected to sample various parts of the urban area for small-scale variances. In the analyses, all 3-hour and 24-hour rainfalls that equaled or exceeded an average 2-year storm event were tabulated by date and the shortest times between successive occurrences were ranked to study their distribution.

Analyses of individual station data indicated no significant differences in the time between storms across the city. Therefore, values for the 5 stations were combined to obtain a measure of average urban conditions. Results are summarized in table 3 where the median time between storms for equivalent rank values has been presented for the five shortest intervals between 2-year storm events. Thus, the median of the shortest time between 3-hour storms was 0.4 month (12 days). The range among the five stations (not shown) was 0.1 to 10.6 months.

Similarly, the second shortest interval for 3-hour storm periods was 0.9 month and the fourth shortest was 11.1 months. Thus, there were four times in the 20-year period when 3-hour excessive rainfalls occurred within less than one year over approximately 50% of the urban area, as indicated by the median time intervals between storms at the five stations. Table 3 shows that there were five occasions in the 20 years when 24-hour amounts equaling or exceeding 2-year frequency values occurred within less than one year of each other.

Table 3. Minimum Times between Successive Storms having Rainfall Greater than or Equal to 2-Year Return-Period Value in Urban Area

Rank of intervals (shortest to longest)	*5-station median interval (months) for given rain period*	
	3 Hours	*24 Hours*
1	0.4	1.0
2	0.9	2.6
3	10.2	6.7
4	11.1	9.7
5	12.6	10.6

Rainfall Distribution within Storms

Knowledge of the time distribution of rainfall in heavy storms is essential to optimize application of rainfall data in urban hydrologic problems, such as the design of storm sewer systems. Utilization of time distribution characteristics has become increasingly important in hydrologic models used in storm drainage design. For example, the Water Survey's ILLUDAS model provides an objective method for the hydrologic design of storm drainage systems in urban areas and for the evaluation of an existing system (Terstriep and Stall, 1974). This technique is now being utilized widely both within and outside of Illinois, and employs a time distribution model devised by Huff (1967) in its computations.

As part of this study, time distribution characteristics were analyzed for the Chicago urban area to ascertain if they were different from those developed in an earlier study that employed data from dense raingage networks in central Illinois (Huff, 1967; Huff et al., 1969). Data for six urban network stations were used in the Chicago study. Storms were used in which 5-minute and/or 15-minute amounts had been tabulated in earlier rainfall studies by personnel of the Metropolitan Sanitary District (MSD). All storms were used in which total rainfall exceeded 0.5 inch. This provided a total of 417 storms from the MSD tabulations during the period 1932-1966. The six stations were selected to provide data for different sections of the city and included Calumet, Midway, University, WB/City, Springfield, and Mayfair (see figure 1 for locations).

The method derived by Huff (1967) was used in the data analyses. First, storms were divided into four groups depending on whether the heaviest rainfall occurred in the first, second, third, or fourth quarter of the storm. Within each group, the data were further stratified according to storm duration and total storm rainfall. The time distributions were expressed as cumulative percentages of storm rainfall and storm duration to enable valid comparisons between storms and to simplify analyses and presentation of the data.

Data for the six stations were combined, since analyses showed little variation in the time distribution relations across the urban area. Other analyses showed storm duration and total storm rainfall explaining only a small portion of the variance between storms having durations of 24 hours or less, when the time distributions were classified by quartile and expressed as percentages of total storm duration and rainfall. This corresponds to findings in the 1967 and 1969 studies referenced above. Consequently, time distributions were classified by quartile only.

Median time distribution curves for point rainfall derived from the Chicago data are shown in figure 17. This curve compares closely with the point rainfall curve obtained with data from central Illinois in the earlier study (Huff, 1967). First-quartile storms were the most common among

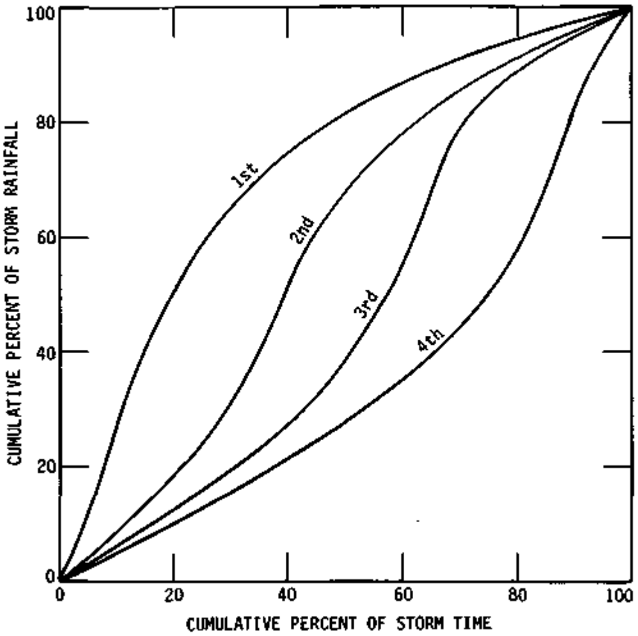


Figure 17. Time distribution of point rainfall

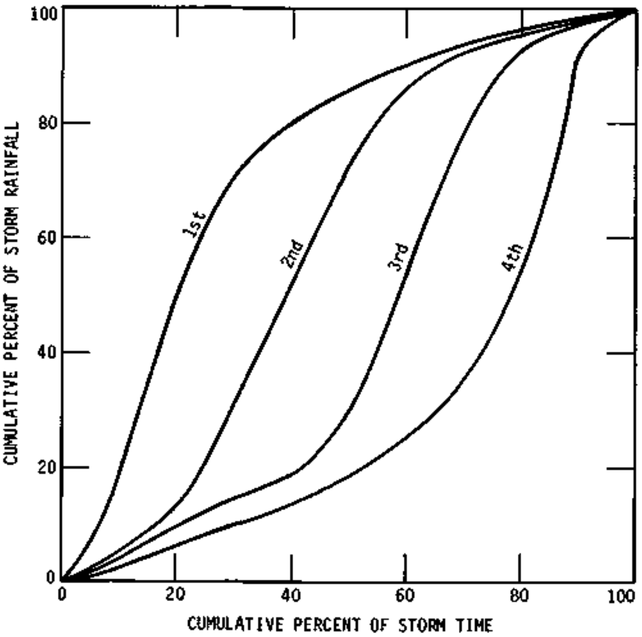


Figure 18. Time distribution of areal mean rainfall

the Chicago storms, and accounted for 40% of the total of 417 storms. Nearly equal frequencies (18 to 21%) occurred among the other three storm types.

Storm durations of 6 to 12 hours occurred most frequently, but were followed closely in numbers by storms having durations of 3 to 6 and 12 to 24 hours. Storms of less than 3-hour duration accounted for only 12% of the cases.

Analyses of the time distributions of areal mean rainfall were not made in the Chicago study, because the gage density was only about 1 gage per 27 mi^2. Furthermore, considering expected sampling variations, the point curves compared satisfactorily with those obtained with a 12-year sample from the central Illinois network of 49 gages in 400 mi^2. Consequently, it was concluded that the areal curves derived in the earlier study by Huff (1967) were applicable to northeast Illinois also. Median curves derived for areas of 50 to 400 mi^2 in the 1967 study are presented in figure 18. It was found that the above range of areas could be combined with only small losses in accuracy, since no pronounced trend was found with increasing area from 50 to 400 mi^2. For more details on the time distribution derivations, the reader is referred to Huff's 1967 paper. That paper also provides a family of curves for each quartile showing the more extreme percentage changes that may occur within a storm, along with a probability estimate for each curve in the family. The data from the Phase II network of 300 recording raingages will provide additional information on the time distribution of areal mean rainfall.

Interpretation of the curves in figures 17 and 18 is illustrated by the following example. Assume a design based on a 2.0-inch rainstorm of 2-hour duration is being made at a given point, and the most critical distribution is a first-quartile storm. Then, from figure 17, one can determine that, on the average, 26% (0.52 inch) of the rain would be expected to occur in the first 10% (12 minutes) of the storm. Similarly, 59% (1.18 inches) would be expected in the first 25% (30 minutes) of the storm, and 82% (1.64 inches) in the first 50% (60 minutes) of the rain period.

SPATIAL DISTRIBUTIONS

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 mi^2 (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 mi^2.

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.

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 curve is shown in figure 19 for areas of 10 to 1000 mi^2 . For those interested, the curve can be continued to 10,000 mi^2, since storms up to this size were included in the historical storm study.

Area-Depth Relations

Area-depth curves, frequently used in hydrological analyses, provide a simple mathematical expression for defining the spatial distribution characteristics of storm rainfall. The curve provides a measure of the mean and maximum rainfall, rainfall gradient, and skewness of the distribution. It is constructed by planimetering the storm isohyetal map and summing the areal mean rainfall from the storm center outward (high to low values). The y-intercept of the curve then represents the maximum point rainfall and the last point on the curve is the areal mean rainfall. The slope of the curve provides a measure of the rainfall gradient in the storm. Huff and Stout (1952) found that the area-depth curve for small areas in Illinois thunderstorms is well represented by a data transformation in which area is plotted against the square root of the area. In our study, area-depth curves were constructed for outstanding storms on 1) the entire 6-county area of 3714 mi^2, and 2) the urban area of 430 mi^2.

6-County Analyses

In the 6-county study, analyses were made of all storms which produced a mean rainfall of 1.50 inches or more on

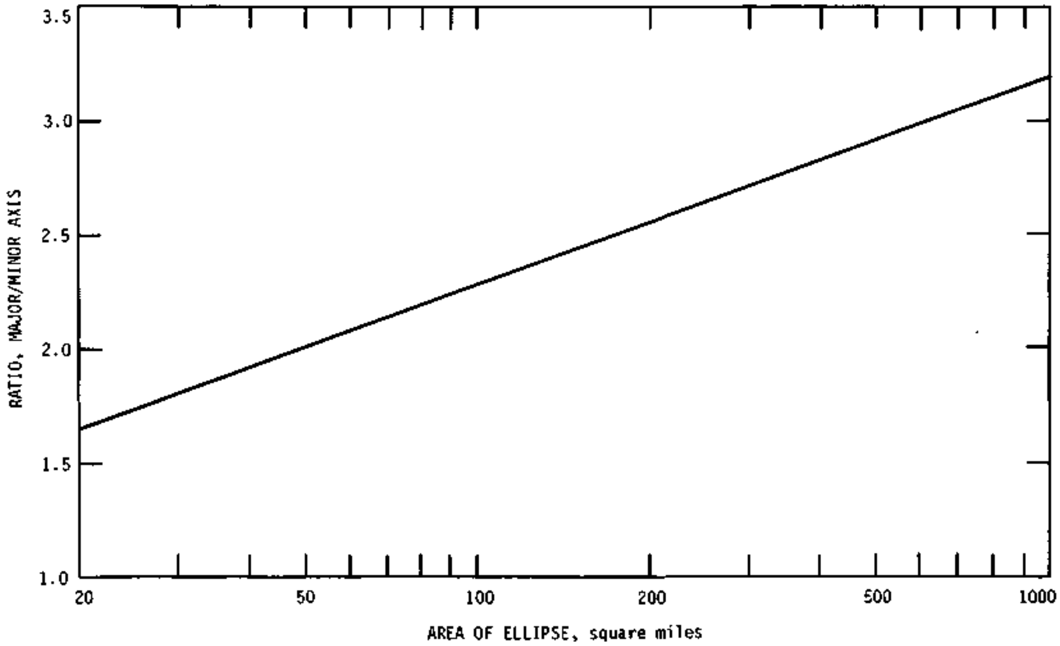


Figure 19. Mean shape factor for heavy storms

Table 4. Area-Depth Relations in Outstanding Storms in 6-County Area

Date	Storm duration (hours)	Mean rainfall (inches) for given area (mi^2)											Storm centers
		25	50	100	200	500	1000	1500	2000	2500	3000	3714	
July 12-13, 1957	14	9.5	9.4	9.2	8.9	8.3	7.7	7.0	6.5	6.0	5.5	4.8	Peotone
October 9-10, 1954	24	10.7	10.5	10.2	9.8	8.8	7.6	6.8	6.1	5.6	5.1	4.5	Aurora
August 16-17, 1968	10	6.4	6.3	6.0	5.7	5.2	4.6	4.2	3.9	3.6	3.4	3.1	Park Forest
June 2, 1950	6	5.0	4.9	4.8	4.7	4.4	3.9	3.6	3.4	3.2	3.0	2.8	Aurora
July 8-9, 1951	24	4.3	4.2	4.1	4.0	3.7	3.5	3.3	3.1	3.0	2.9	2.7	Marengo
August 25-26, 1972	10	9.2	8.9	8.4	7.7	6.2	4.9	4.2	3.7	3.3	3.0	2.7	Aurora
January 11-12, 1960	24	4.3	4.2	4.1	4.0	3.7	3.4	3.1	2.9	2.8	2.6	2.5	Wheaton
June 14, 1949	15	4.7	4.6	4.4	4.1	3.9	3.7	3.4	3.2	3.0	2.7	2.4	Mayfair
July 6-7, 1954	19	3.9	3.8	3.8	3.7	3.4	3.2	2.9	2.7	2.6	2.5	2.3	Sycamore
September 13-14, 1961	8	3.6	3.5	3.5	3.4	3.2	3.1	2.9	2.8	2.7	2.5	2.3	McHenry
June 1-2, 1970	24	4.8	4.7	4.6	4.4	4.0	3.6	3.3	3.0	2.8	2.5	2.2	McHenry
June 10-11, 1967	11	6.5	6.2	5.8	5.3	4.5	3.8	3.3	2.9	2.6	2.4	2.1	WB/City
July 26-27, 1966	19	5.6	5.5	5.3	5.0	4.4	3.7	3.2	2.9	2.6	2.3	2.0	Midway
July 17-18, 1972	16	3.8	3.7	3.6	3.4	3.0	2.7	2.5	2.3	2.1	2.0	1.9	Multiple
April 24-25, 1954	15	3.1	3.0	3.0	2.9	2.8	2.6	2.5	2.3	2.1	1.9	1.7	Mayfair
June 16-17, 1973	14	3.0	2.9	2.9	2.8	2.6	2.4	2.2	2.0	1.9	1.8	1.7	Peotone
June 12-13, 1958	12	3.0	3.0	2.9	2.9	2.7	2.5	2.2	2.1	1.9	1.8	1.6	Wheaton
July 2, 1962	11	3.7	3.6	3.4	3.2	2.8	2.5	2.2	2.0	1.9	1.7	1.6	Springfield
September 28-29, 1972	11	3.7	3.7	3.6	3.4	3.1	2.7	2.4	2.2	2.0	1.8	1.6	Midway
July 16-17, 1950	19	5.0	4.8	4.5	4.2	3.7	3.1	2.8	2.5	2.2	1.9	1.5	Sanitary District Office
May 10-11, 1951	20	4.2	4.1	4.0	3.8	3.5	3.2	2.8	2.4	2.1	1.8	1.5	Aurora
March 25, 1954	6	4.9	4.6	4.3	3.6	3.4	3.0	2.7	2.4	2.1	1.9	1.5	NE-Du Page County
June 3-4, 1954	11	3.0	2.9	2.9	2.9	2.8	2.6	2.4	2.2	2.0	1.8	1.5	Waukegan
October 3, 1954	8	5.1	4.9	4.7	4.4	3.8	3.2	2.7	2.4	2.1	1.8	1.5	Roseland
June 23-24, 1968	18	3.0	2.9	2.8	2.8	2.6	2.4	2.2	2.0	1.8	1.7	1.5	WB/City

3714 mi^2 within 24 hours or less during 1949-1974. Area-depth relations for 25 of these storms are shown in table 4. Duration of each storm and the station (or area) where the heaviest rainfall occurred are also given. Mean rainfall is not shown for areas of less than 25 mi^2 because of gage density limitations.

The area-depth relations in table 4 provide guidance with respect to spatial distribution properties of heavy storms in the six counties. An approximate measure of the rainfall gradient in these storms can be obtained by comparing the mean rainfall for 25 mi^2 with that for the total area of 3714 mi^2. From this comparison, it is apparent that the rainfall gradient has a wide range among individual storms. For example, the ratio of mean rainfall for these two areas ranges from 1.52 in the 8-hour storm of September 13-14, 1961, to 3.41 in the 10-hour storm of August 25-26, 1972, and the 25-storm mean is 2.23.

Table 5. Average Area-Depth Ratios
for 6-County Area

Area (mi^2)	Average ratio	Area (mi^2)	Average ratio
Point maximum	2.33	1000	1.64
25	2.23	1500	1.48
50	2.21	2000	1.35
100	2.11	2500	1.24
200	2.03	3000	1.13
500	1.84	3714	1.00

Table 5 shows mean ratios for various partial-area means to the areal mean. These average ratios fit the Huff-Stout area-depth relation and provide a measure of the areal variability (rainfall gradient) under average storm conditions. The ratios (or the curve derived from them) can be used to provide first estimates of the space distribution of areal mean rainfall in heavy storms in the 6-county area.

For example, assume one wishes to estimate the distribution for an areal mean of 2.0 inches on the 3714 mi^2. Then proceeding inward from the storm perimeter, one would expect, on the average, to find a subarea of 2000 mi^2 with a mean of 2.70 inches (1.35 x 2.0). Proceeding further, a mean of 3.28 inches would be expected on the 1000 mi^2 with heaviest rainfall, and 4.22 inches on the 100 mi^2 of maximum rainfall.

Urban Analyses

The urban network of recording raingages was used to derive area-depth relations for heavy rainfall periods of 3, 6, 12, and 24 hours in the 430-mi^2 urban area. For each rainfall period, all storms were selected in which 1) at least one raingage had recorded a point rainfall that was equal to

Table 6. Area-Depth Relations in Outstanding 3-Hour Storm Periods in Urban Area

Date	*Mean rainfall (inches) for given area (mi^2)* 10	*25*	*50*	*100*	*200*	*300*	*430*	*Storm center*
July 12, 1957	4.18	4.09	3.95	3.77	3.53	3.35	3.15	Sanitary District Office
August 16, 1968	3.40	3.30	3.17	3.02	2.82	2.63	2.30	Springfield
June 25, 1959	4.65	4.50	4.15	3.63	3.03	2.60	2.20	Midway
October 3, 1954	4.35	4.23	4.07	3.72	3.03	2.54	2.12	Calumet
June 10, 1967	5.42	5.27	5.05	4.55	3.43	2.69	2.06	WB/City
September 13, 1961	2.34	2.32	2.28	2.24	2.18	2.13	2.03	Springfield
October 10, 1954	2.72	2.67	2.62	2.51	2.30	2.12	1.95	South Filter
August 18, 1954	2.84	2.75	2.65	2.50	2.30	2.14	1.95	Springfield
July 16, 1950	3.55	3.32	3.17	2.88	2.49	2.18	1.78	Sanitary District Office
June 13, 1958	2.46	2.38	2.28	2.15	1.97	1.83	1.67	Stickney
June 14, 1949	2.74	2.69	2.63	2.51	2.26	1.97	1.64	Springfield
July 2, 1960	2.13	2.10	2.06	1.97	1.84	1.74	1.64	Midway
June 2, 1950	2.59	2.53	2.43	2.25	2.01	1.83	1.63	Springfield
August 9, 1957	2.14	2.11	2.08	2.02	1.95	1.87	1.62	Sanitary District Office
July 2, 1962	2.91	2.80	2.64	2.41	2.10	1.86	1.60	Mayfair

or greater than the 2-year frequency value, and 2) all raingages had amounts in excess of a selected base amount. This base amount was 0.50, 0.60, 0.80, and 1.20 inches, respectively, for the 3-, 6-, 12-, and 24-hour rain periods. These periods included both partial and total storm rainfall; if partial, they include the maximum storm amount for the particular duration (3, 6, 12, 24 hours) during the total storm period. The foregoing procedure isolated the heaviest storms of record in the 1949-1974 period, and those considered to be of major interest to hydrologists.

The selection procedure provided 32, 3-hour rainfalls for analysis. Table 6 shows area-depth relations for the 15 heaviest storms, based on the urban areal means. Table 7 is based on the 32 storms and provides area-depth ratios for storms having steep, moderate, and flat rainfall gradients. These represent storms with gradients (area-depth slope) that were equaled or exceeded in 10%, 50%, and 90% of the 3-hour rainfalls analyzed.

Curves may be constructed from table 7 and have a straight-line fit when logarithms of the ratios are plotted against square root of the partial areas. This reflects rainfall gradients that are steeper than those normally found in convective rainstorms. This results largely from two causes. Rainfall gradients tend to be steeper in short-duration rainfalls. More importantly, rainfall gradients tend to be relatively steep in the Chicago urban area, because its major axis is close to a N-S orientation, whereas storms most frequently move from WSW, W, or WNW. Rainfall gradients are usually much steeper in directions perpendicular to the storm movement than parallel to the movement. The Chicago storms frequently move nearly perpendicular to the urban major axis.

The three types of rainfall gradients shown in table 7 reflect the relatively large differences that may occur in rainfall patterns between storms. Huff (1968) has pointed out that the wide range of storm rainfall gradients is related to synoptic storm types and precipitation types. Steep gradients are likely to occur in thunderstorms of small areal extent, such as summer air mass storms. Flat gradients are most likely to be associated with large-scale storm systems from mid-fall to early spring, when steady types of precipitation are most prevalent. Moderate gradients are typical of warm-season frontal or squall-line storms. The relative variability, as measured by the area-depth ratios, will be less, on the average, in the heaviest rain producers. These are usually of longer rain duration and greater areal extent than the lighter storms, and the time-averaging of many raincells crossing the area of interest tends to decrease the spatial variability. Rainfall gradients also tend to be greater in storms which pass near the boundary of a given area; these produce a strong 1-directional gradient from the storm center across the sampling area.

Table 8 shows area-depth relations for 6-hour periods in the 15 heaviest storms. Table 9 shows area-depth ratios derived from the 33 qualifying storms in the 6-hour category, and has the same interpretation as table 7. The area-depth ratios for 6 hours are slightly greater than those for 3 hours; but the differences are not really significant and well within the limits of random sampling variation. An average

Table 7. Area-Depth Ratios for Urban Area in Heavy 3-Hour Rainfalls

Area (mi^2)	*Steep gradient*	*Moderate gradient*	*Flat gradient*
Point maximum	3.30	2.18	1.45
10	2.75	1.93	1.37
25	2.47	1.81	1.33
50	2.20	1.67	1.28
100	1.85	1.50	1.22
200	1.47	1.29	1.13
300	1.23	1.14	1.07
430	1.00	1.00	1.00

Table 8. Area-Depth Relations in Outstanding 6-Hour Storms in Urban Area

	Mean rainfall (inches) for given area (mi^2)							
Storm date	*10*	*25*	*50*	*100*	*200*	*300*	*430*	*Storm center*
July 12, 1957	6.70	6.50	6.28	5.98	5.60	5.30	5.00	Mayfair
August 18, 1968	3.71	3.68	3.65	3.59	3.40	3.23	2.92	Springfield
September 13, 1961	3.46	3.39	3.30	3.18	3.02	2.89	2.74	Mayfair
October 3, 1954	5.45	5.30	5.08	4.57	3.75	3.20	2.70	Calumet
June 25, 1959	5.00	4.67	4.32	3.85	3.30	2.93	2.55	Midway
October 9, 1954	4.27	4.09	3.90	3.60	3.20	2.88	2.52	Calumet
June 10, 1967	6.22	6.04	5.77	5.14	3.90	3.15	2.45	WB/City
July 2, 1962	3.83	3.77	3.70	3.57	3.24	2.78	2.23	Mayfair
July 28, 1954	3.02	2.92	2.82	2.67	2.46	2.30	2.11	Springfield
June 14, 1949	3.32	3.26	3.18	3.03	2.70	2.40	2.06	North Branch
August 29, 1955	3.31	3.24	3.14	2.96	2.62	2.35	2.05	South Filter
July 16, 1950	4.70	4.30	3.90	3.40	2.82	2.43	2.03	Sanitary District Office
April 27, 1959	2.65	2.61	2.55	2.48	2.37	2.23	2.01	Roseland
July 27, 1966	3.77	3.56	3.33	3.00	2.68	2.18	1.79	Stickney
August 3, 1957	3.15	3.01	2.85	2.62	2.31	2.06	1.78	South Filter

Table 9. Area-Depth Ratios for Urban Area in Heavy 6-Hour Rainfalls

Area (mi^2)	*Steep gradient*	*Moderate gradient*	*Flat gradient*
Point maximum	3.42	2.25	1.48
10	2.83	1.98	1.39
25	2.55	1.85	1.35
50	2.26	1.71	1.30
100	1.90	1.52	1.23
200	1.50	1.30	1.14
300	1.24	1.15	1.08
430	1.00	1.00	1.00

of the two sets of ratios can be applied to storm periods of 3 to 6 hours for guidance in hydrologic design problems.

Area-depth relations for 12-hour periods in the heaviest storms of the 1949-1974 period are presented in table 10. Typical area-depth ratios are shown in table 11, based upon a 30-storm sample of the outstanding storms. With the longer period of rainfall integration, the rainfall gradients show a substantial decrease from those for 3 hours and 6 hours. A trend for more uniform rainfall distribution is associated with increasing time-averaging of storm rainfall.

Figure 20a shows the 12-hour isohyetal pattern in one of the most intense storms ever experienced in the Chicago region (Huff et al., 1958). Most of the maximum 12-hour amounts recorded in the urban network during 1949-1974 came from this storm. Figure 20b illustrates the variability of the storm rainfall in terms of the recurrence interval of point rainfall. Recurrence intervals ranging from 15 to over 100 years were recorded, based upon the point frequency relations developed in this study. On the basis of U.S. Weather Bureau values (Technical Paper No. 40), all except the NE and SE tips of the city had 100-year recurrence values ($\geq$ 5.0 inches) for 12 hours.

Figure 20c shows the percentage area-depth curve for the 12-hour period. The city averaged 5.96 inches and over 50% of the urban area had an average of 6.50 inches. This is a tremendous amount of rain to fall in 12 hours. Apparently

Table 10. Area-Depth Relations in Outstanding 12-Hour Storms in Urban Area

	Mean rainfall (inches) for given area (mi^2)							
Storm date	*10*	*25*	*50*	*100*	*200*	*300*	*430*	*Storm center*
July 12, 1957	7.86	7.60	7.28	6.90	6.55	6.36	5.96	Mayfair
October 9, 1954	5.90	5.62	5.33	4.94	4.45	4.10	3.75	Calumet
August 18, 1968	4.19	4.10	3.98	3.84	3.63	3.42	2.98	Springfield
September 13, 1961	3.59	3.51	3.43	3.31	3.15	3.03	2.88	Mayfair
July 27, 1966	5.40	5.13	4.84	4.39	3.78	3.29	2.76	Midway
June 10, 1967	6.65	6.40	6.05	5.45	4.38	3.52	2.75	WB/City
October 3, 1954	5.65	5.37	5.00	4.50	3.82	3.27	2.68	Calumet
June 25, 1959	5.00	4.67	4.32	3.85	3.30	2.93	2.55	Midway
August 29, 1955	3.76	3.63	3.48	3.27	2.97	2.74	2.49	South Filter
May 11, 1966	2.96	2.90	2.83	2.73	2.61	2.51	2.40	Roseland
June 14, 1949	3.75	3.62	3.48	3.28	2.97	2.75	2.40	North Branch
July 2, 1962	4.02	3.93	3.84	3.67	3.28	2.80	2.28	Mayfair
March 24, 1954	4.40	4.18	3.93	3.56	3.06	2.66	2.24	Mayfair
May 10, 1951	3.03	2.95	2.85	2.71	2.52	2.38	2.20	Sanitary District Dispatch
April 27, 1959	2.97	2.91	2.83	2.73	2.55	2.42	2.18	Roseland

Table 11. Area-Depth Ratios for Urban Area in Heavy 12-Hour Rainfalls

Area (mi^2)	*Steep gradient*	*Moderate gradient*	*Flat gradient*
Point maximum	3.04	2.10	1.32
10	2.56	1.88	1.27
25	2.33	1.77	1.23
50	2.09	1.63	1.20
100	1.78	1.48	1.16
200	1.43	1.28	1.09
300	1.22	1.14	1.05
430	1.00	1.00	1.00

through coincidence, the 12-hour storm pattern is very similar to the patterns for the frequency distribution of point rainfall that were derived from analyses of all major storms in the 1949-1974 period (see figures 3-16).

Tables 12 and 13 provide area-depth relations for 24-hour rainfall periods in the urban area. The area-depth ratios in table 13 fit the square-root formula (R vs $A^{0.5}$) described earlier. As is apparent from tables 7, 9, 11, and 13, the areal relative variability, as reflected in the area-depth ratios, decreases substantially as the storm rain time increases. For example, 50-mi^2 ratios for steep, moderate, and flat gradients decrease from 2.20, 1.67, and 1.28 for 3-hour periods to 1.75, 1.39, and 1.18 for 24-hour rainfalls.

Table 13. Area-Depth Ratios for Urban Area in Heavy 24-Hour Rainfalls

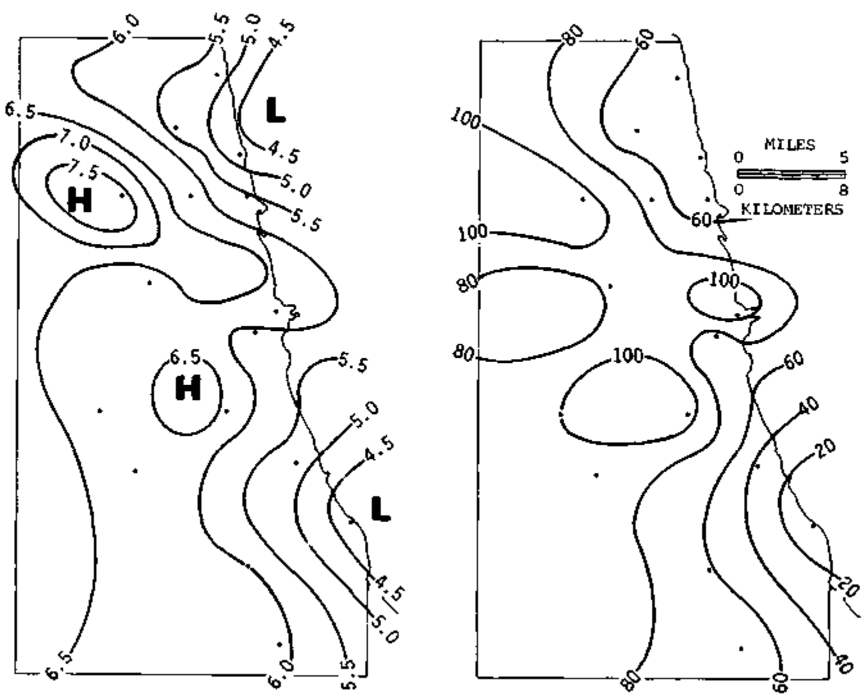
Area (mi^2)	*Steep gradient*	*Moderate gradient*	*Flat gradient*
Point maximum	2.24	1.59	1.27
10	1.96	1.50	1.23
25	1.86	1.45	1.21
50	1.75	1.39	1.18
100	1.59	1.31	1.14
200	1.37	1.19	1.09
300	1.20	1.10	1.05
430	1.00	1.00	1.00

Figure 21a shows the isohyetal pattern for the maximum 24-hour rainfall in the very severe rainstorm of October 9-10, ,.1954. This was one of the most widespread, heavy rainstorms in the history of Chicago and northeastern Illinois (Huff et al., 1955). The southern and northeastern parts of the city experienced their heaviest 24-hour rainfall during the 1949-1974 sampling period in this storm.

Similar to the July 1957 storm discussed earlier, there was a wide range of storm severity as shown in figure 21b. Point rainfall amounts in the urban network exhibited recurrence-interval values varying from less than 20 years to over 100 years for a 24-hour rain period. The area-depth curve of figure 21c shows an urban area mean of 6.08 inches in this storm, and localized areas having over 7 inches.

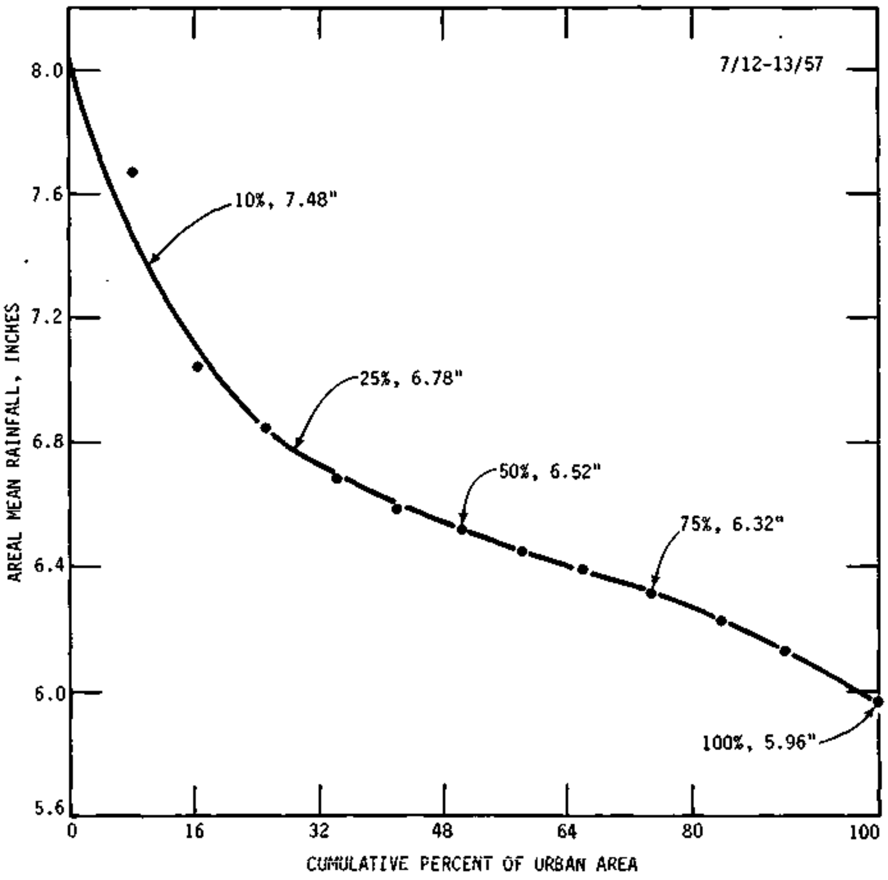
Table 12. Area-Depth Relations in Outstanding 24-Hour Storms in Urban Area

	Mean rainfall (inches) for given area (mi^2)							
Storm date	*10*	*25*	*50*	*100*	*200*	*300*	*430*	*Storm centers*
October 9, 1954	7.43	7.32	7.16	6.92	6.66	6.45	6.08	Calumet
July 12, 1957	7.92	7.67	7.36	6.98	6.64	6.45	6.05	Mayfair
June 2, 1950	4.98	4.92	4.82	4.52	4.03	3.69	3.42	Springfield
June 14, 1949	4.72	4.67	4.61	4.44	4.07	3.66	3.18	Mayfair
May 10, 1951	4.17	4.07	3.94	3.77	3.53	3.35	3.14	Sanitary District Dispatch
May 11, 1966	3.82	3.77	3.73	3.65	3.49	3.33	3.14	Calumet
July 16, 1950	5.30	5.03	4.71	4.30	3.80	3.45	3.09	Sanitary District Office
August 16, 1968	4.21	4.14	4.06	3.94	3.74	3.50	3.05	Springfield
July 27, 1966	5.72	5.43	5.12	4.65	4.04	3.55	3.00	Midway
September 13, 1961	3.59	3.51	3.43	3.31	3.15	3.03	2.88	Mayfair
June 10, 1967	6.67	6.46	6.15	5.52	4.50	3.70	2.80	WB/City
January 12, 1960	3.35	3.32	3.27	3.18	3.03	2.91	2.77	WB/City
October 5, 1955	3.43	3.40	3.35	3.25	3.05	2.89	2.70	South Filter
March 25, 1954	5.10	4.87	4.55	4.00	3.35	2.97	2.68	Mayfair
July 8, 1951	3.02	2.97	2.92	2.83	2.73	2.64	2.54	Skokie



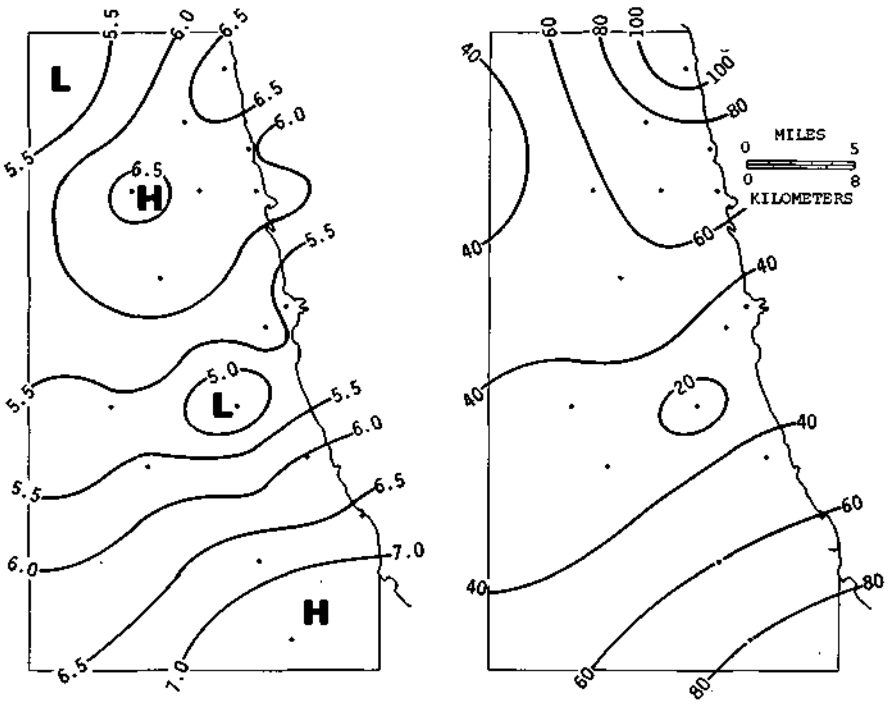
a. ISOHYETAL PATTERN

b. RECURRENCE INTERVAL (YEARS) OF 12-HOUR AMOUNTS



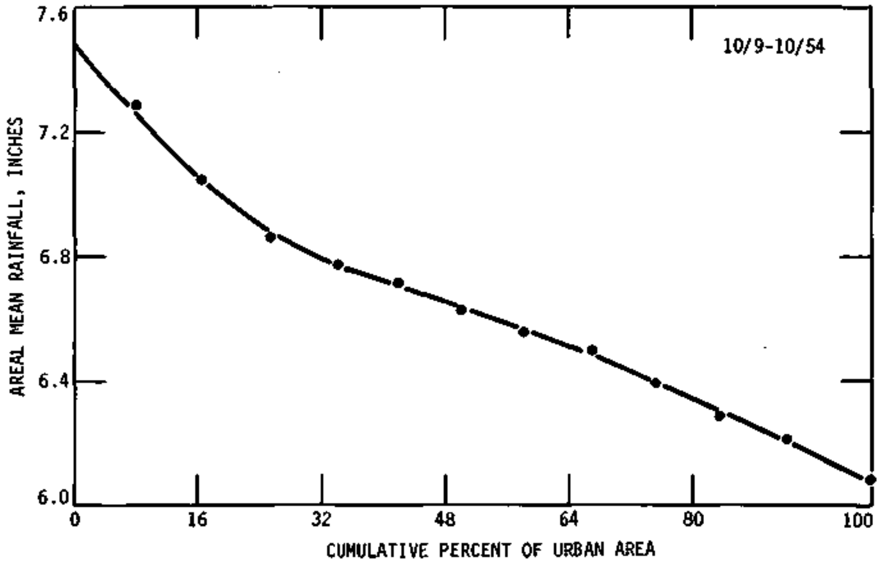
c. AREA-DEPTH RELATIONS

Figure 20. 12-hour storm of July 12-13,1957



a. ISOHYETAL PATTERN

b. RECURRENCE INTERVAL (YEARS) OF 24-HOUR AMOUNTS



c. AREA-DEPTH RELATIONS

Figure 21. 24-hour storm of October 9-10,1954

STORM CHARACTERISTICS

The characteristics of heavy rainfall over northeast Illinois were studied through the use of heavy 1-day storms occurring from 1949 to 1974. All storms were included in which one or more raingages in the 6-county area recorded 2.5 inches or more. This corresponds to a 24-hour point frequency of 1.0 to 1.5 years. The sample included 87 qualifying storms. These are the type which frequently produce local flooding.

One-day storms were chosen for this analysis because many rain reporting stations of the National Weather Service do not report more frequently than once a day. However, Huff et al. (1969), using data from a dense raingage network, showed that an average of 10% of the convective rainfall at a point occurs in less than 2% of the rain time, 50% of the total rain occurs during 11% of the time it is raining, and 90% of all the rain at a point occurs in 37% of the rain period. For the most part, storms in the sample are those characterized by short bursts of intense rain with the major portion of the heavy rain falling in 6 hours or less of the 24-hour period. The 87 storms were analyzed to determine 1) the frequency distribution of storm centers in the 6-county area, 2) associated weather conditions, 3) seasonal and diurnal distribution of storms, and 4) orientation and movement of storms.

Distribution of Storm Centers

All primary and secondary centers of precipitation equal to or in excess of 2.5 inches were plotted for the 87 heavy storms. Figure 22 shows the location of the 111 centers. A total of 83 centers occurred within the boundaries of the six counties and 28 storm centers were located in adjacent counties.

A large number of the heavy storm centers were concentrated over the southern and eastern sections. A total of 59 centers or 75% of the centers within the six counties were located in Cook and Will counties, even though the two counties make up only 48% of the total area. Only 13 centers were located in the northern counties of McHenry and Lake. Of the 28 centers located beyond the 6-county boundary, 18 were either due west of Kane County or due south of Will County.

Within the urban study region (outlined on figure 22), a tendency was noted for centers to congregate in three distinct arrays. There was a concentration on a NW-SE line from the northwest part of the metropolitan area to the vicinity of the Loop (WB/City in figure 1). A second group was located along a SW-NE line from the west side of the urban region to the Loop, and a third group occurred over the southeast corner of the metropolitan area.

However, there is a chance for bias over Chicago, since the raingage density (mi^2/gage) over the urban region was greater than in the rest of the 6-county area. To evaluate potential bias, the gage density in each county and the remainder of Cook County was calculated. This gage density was then divided by the gage density in Chicago to provide a normalizing ratio. The number of centers within each county was multiplied by this ratio, and the density of the adjusted number of centers within each county was found. This normalization procedure assumed that each gage in northeastern Illinois had an equal chance of being near the center of a heavy 1-day storm.

After normalizing, the urban region still had more centers per square mile than any other part of the 6-county study area. In fact, the density of centers in Chicago was 3 to 4 times the density in the western counties of McHenry and Kane, and 1.6 to 2.2 times greater than in the remaining 6-county region. The locations of the centers agree well with the frequency distributions of point rainfall discussed earlier which show heavier intensities over the urban area for a given recurrence interval. The relatively large number of centers in adjacent counties is consistent with other findings (Hershfield, 1961) which indicate an increase in heavy rainfall occurrences west and south of the 6-county area. Huff and Changnon (1972, 1973) also found a high frequency of heavy rainfall centers in the Chicago urban area and determined that this high frequency extended into northwest Indiana with a still higher peak in the La Porte area. The precipitation distribution in this 2-state region is affected by both urban and lake factors, and only an intensive hydrometeorological field measurement and analysis program can properly evaluate these two effects. As mentioned earlier, such a program is now being initiated by the Illinois State Water Survey with financial support from the National Science Foundation.

Over 67% of the heavy precipitation centers occurred during summer, and the summer pattern was similar to the all-season pattern in figure 22. After normalization, more centers per square mile again occurred over Chicago. Except for Lake County, the difference between the urban region and the surrounding counties was even greater for summer than for all seasons combined. Heavy precipitation centers were recorded in Lake County only during the summer. Asa result, the density of centers between Lake County and Chicago was not as great. However, the urban region still had 1.3 times more centers per unit area. The maximization of heavy precipitation over the urban region during the warm season has also been noted by Huff and Changnon (1972,1973).

Summarizing, analyses of the location of heavy storm centers showed a distinct trend for a greater frequency in the Chicago urban region than in the remainder of the 6-

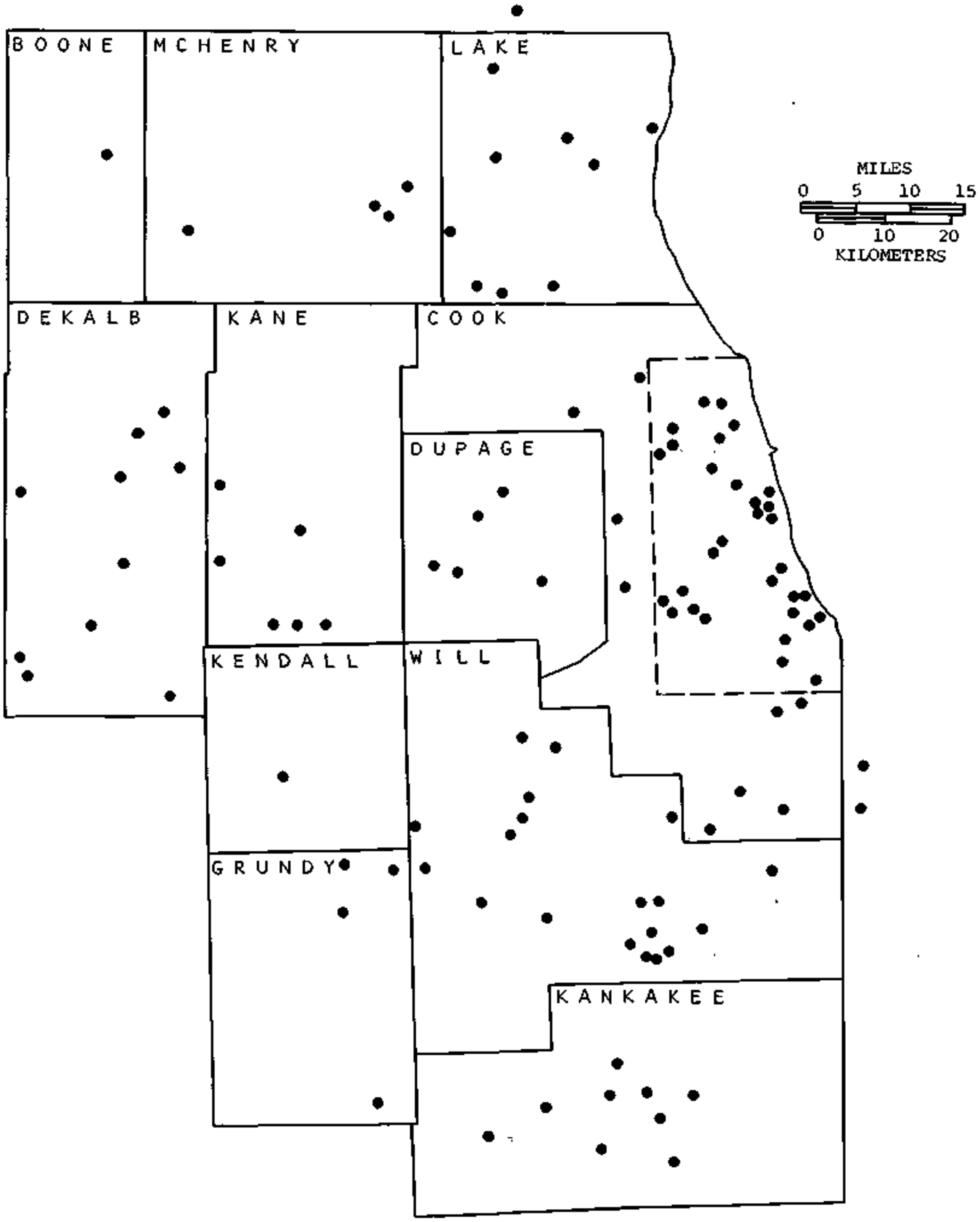


Figure 22. Location of centers in heavy 1-day rainstorms

county area. As expected, the greatest frequency of storm centers was in summer when the difference in frequency between the urban and rural regions tended to be greater than in the other seasons. This is in general agreement with findings by Huff and Changnon (1973) for 8 major cities in the United States, where urban-induced enhancement of precipitation was identified in 6 cities and this enhancement maximized in summer. Hydrologically, the results here and elsewhere in this report indicate a need to incorporate the urban factor in the design of hydraulic structures.

Diurnal, Monthly, and Seasonal Distributions

In defining the heavy storm characteristics in northeast Illinois, analyses were made of the diurnal frequency of storm initiations, and the monthly and seasonal distributions of storms. Well-defined peaks in all three time distributions are usually found, but the location of these peaks in the time distributions may vary substantially between regions depending upon climatic conditions and local weather anomalies.

The diurnal distribution of storm initiations was studied

Table 14. Diurnal Frequency of Storm Initiations

Start of 3-hour period	*Percent of total occurrences*	*Start of 3-hour period*	*Percent of total occurrences*
0100	13	1300	26
0200	13	1400	25
0300	7	1500	20
0400	6	1600	14
0500	3	1700	13
0600	5	1800	11
0700	3	1900	13
0800	5	2000	11
0900	15	2100	8
1000	20	2200	6
1100	23	2300	6
1200	23	2400	11

through use of the 87 heavy 1-day storms. Table 14 shows the percent of total initiations for each 3-hour period. In view of sample size, the 3-hour totals are considered the best indicator of diurnal trends. These totals show a primary maximum in early to mid-afternoon (1300-1600) when solar heating is most intense and when atmospheric conditions are also most favorable, on the average, for urban enhancement of storms (Huff and Schlessman, 1974). A secondary maximum occurs shortly after midnight and is apparently related to nocturnal thunderstorms which are prevalent in the northern part of Illinois (Huff, 1971). The 6-hour maximum (48%) occurs from 1100-1700, and the 6-hour minimum (9%) during early forenoon (0400-1000). The foregoing discussion relates only to initiation of heavy storms and does not imply that the heaviest rainfall intensities have this diurnal distribution.

The monthly and 3-monthly distributions of heavy storms are presented in table 15. A peak frequency was found in July when 30% of the storms occurred. The 3-month totals show that summer (June-August) has the most heavy rainstorms with 67% of the total occurrences. In an earlier study, Huff and Neill (1959) found that 2-day to 10-day periods of heavy rainfall also occur most frequently in summer throughout Illinois. As expected, heavy rainstorms are quite unusual during winter in northeast Illinois where snowfall is the most frequent cause of severe winter storms.

Summarizing, heavy rainstorms tend to initiate most frequently during the early afternoon and to occur with the greatest frequency in summer when 67% of the heavy 1-day storms were recorded. The greatest monthly frequency (30%) occurs in July. Thus, storms of major hydrologic significance, defined as those having an average return period of 2 years or longer, occur most frequently during the time of the year and the time of day when the atmosphere tends to be unstable and the moisture supply (precipitable water) is greatest (Huff, 1963).

Table 15. Frequency of Initiations of Heavy 1-Day Storms by Month and 3-Month Periods

Month	*Number*	*3-Month periods*	*Number*
January	1	Jan-Mar	3
February	0	Feb-Apr	6
March	2	Mar-May	11
April	4	Apr-Jun	27
May	5	May-Jul	49
June	18	Jun-Aug	58
July	26	Jul-Sep	47
August	14	Aug-Oct	27
September	7	Sep-Nov	14
October	6	Oct-Dec	10
November	1	Nov-Jan	5
December	3	Dec-Feb	4

Storm Orientation and Movement

An important consideration in any region is the orientation of the major axis of heavy rainstorms. For example, if the axis of heavy rainstorms tends 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, the azimuth angle ascribed to each storm ranged from 180 to 360 . Thus, if a storm had an orientation of 230 , the orientation of the storm was along a line from 230 to 050 (SW-NE). Our network studies show it is then very likely that the major rain-producing cells within the storm moved from the southwest to the northeast.

Table 16 shows the orientation of heavy 1-day storms in northeast Illinois sorted by 10-degree intervals. Over a third of all storms had orientations between 236 and 255 , and over 80% had their major axis oriented between the west-southwest and northwest (236 to 315°). This is in excellent

Table 16. Orientation of Major Axis of Heavy Storms

Azimuth range (degrees)	*Percent of total storms*	*Azimuth range (degrees)*	*Percent of total storms*
180-205	2	276-285	7
206-215	1	286-295	5
216-225	5	296-305	7
226-235	5	306-315	4
236-245	18	316-325	1
246-255	18	326-335	1
256-265	15	336-345	0
266-275	10	346-360	1

agreement with a study by Huff and Semonin (1960) which showed the most frequent orientation of major flood-producing storms in Illinois was along lines from WSW-ENE, W-E, and WNW-ESE. It is quite fortunate that the orientation of most of the major drainage basins in northeast Illinois are closer to a north-south than a west-east orientation.

Data for northeast Illinois were not adequate for determining the motion of individual storm elements (raincells) in heavy storms. However, such information was available from 1971-1974 operations of the 225-gage, 2000-mi^2 METROMEX network centered in St. Louis (Huff, 1975). Consideration of meteorological conditions associated with heavy storms and experience gained from analyses of data from several dense raingage networks in central and southern Illinois indicate that the METROMEX raincell data should be quite representative of midwestern conditions, in general.

Raincells are defined as closed isohyetal entities within the enveloping isohyet of the parent storm system. These intensity centers were determined from 5-minute rainfall amounts in the METROMEX network, and are the basic storm entity from which heavy short-duration rates develop in thunderstorm-dominated climates (Huff, 1975). They are responsible for the burst characteristics of the typical rainfall trace obtained with recording raingages exposed to convective rainstorms. Since raincell movements appear to be important to complete evaluation of urban hydrologic design problems (such as storm sewer design), METROMEX analyses of heavy raincell movements for 1971-1974 have been summarized in table 17. These results were based upon raincells producing a mean rainfall of 0.25 inch or more within the area exposed to the cell during its lifetime. This included 365 raincells and constituted only 9% of the sample of over 4000 cells. The heavy raincells had an average duration of 35 minutes and an average area of 45 mi^2 exposed to the cell rainfall.

Table 17 shows that approximately 29% of the heavy cells remained quasi-stationary after development. Moving cells came from the WSW most frequently (20%). In general, raincells moved most frequently from directions ranging from WSW through W to WNW and NW. These movements are similar to the most frequent orientation of total storm rainfall, discussed above, and verify the earlier statement that storm orientation provides a good index of storm movement. Raincell characteristics will be studied in the Chicago region under Phase II of the research program.

Synoptic Weather

The weather conditions associated with each of the heavy 1-day storms were classified according to six general synoptic weather types. Such classifications are useful in understanding the meteorological processes associated with heavy storms, and in identifying approaching storm systems as to their potential for producing flash floods. Three types of frontal storms (cold, warm, and stationary) were used in the classification. With cold and warm fronts, the rainfall is associated with the approach and/or passage of the front. Stationary fronts are those in which the rainfall is associated with the overrunning of warm, moist air over cold air, or with minor waves traveling along a relatively stationary boundary between warm and cold air. Squall lines, the fourth class, are those storm systems which produce a narrow band of thunderstorms or rainshowers (convective rainfall), and these are frequently the precursors of cold fronts and indicative of a very unstable atmosphere. Precipitation associated with the passage of a major cyclone was classified as a low pressure center. Air mass storms include those which occur in a relatively homogeneous body of air without the presence of fronts. The Daily Weather Map Series of the National Weather Service was used to obtain these classifications. Because only one or two surface maps a day were available, it was not possible to obtain a more detailed weather typing. The seasonal and annual synoptic weather classifications are shown in table 18.

Table 17. Movement of Heavy Raincells

Direction (degrees)	*Percent of cells*	*Direction (degrees)*	*Percent of cells*
Quasi-stationary	29.4	181-210	2.2
001-030	2.4	211-240	7.3
031-060	1.9	241-270	20.2
061-090	2.4	271-300	12.8
091-120	0.5	301-330	12.2
121-150	0.8	331-360	6.3
151-180	1.6		

During summer, all types of weather systems occurred with heavy rains. However, stationary fronts, squall lines, and cold fronts dominated the weather. Air mass storms were associated with eight heavy events during summer, and these accounted for all but one air mass storm. Hiser (1956) also found that storms associated with air mass situations gave more rain and occurred most often during the summer months at Midway. Thus, the occurrence of heavy rain events with air mass weather situations appears to be highly seasonal.

Air mass storms were associated with 3 of the 25 heaviest

Table 18. Seasonal and Annual Synoptic Weather Classifications for Heavy 1-Day Storms

	Number of storms for given period				
	Winter	*Spring*	*Summer*	*Fall*	*Annual*
Cold Front	0	1	12	5	18
Warm Front	0	3	5	2	10
Stationary Front	0	2	14	1	17
Squall Line	0	2	13	3	18
Low Center	4	2	6	3	15
Air Mass	0	1	8	0	9
Total	4	11	58	14	87

storms listed in table 4. However, none of the 15 heaviest storms for each of the four storm durations in tables 6, 8, 10, and 12 occurred with air mass situations. Although very heavy rainfall intensities occur at times in air mass storms, these are usually shorter in duration and smaller in areal extent than frontal or squall-line storms. Among the heaviest urban-area storms, 65% were associated with cold fronts or pre-frontal squall lines.

During spring and fall there was no dominating weather system associated with heavy precipitation events. However, all four heavy storms in winter were associated with the passage of major cyclones. These cyclones passed 50 to 150 miles south of the area. With such a trajectory, the low-level winds often come from the north or east and Lake Michigan enhances the precipitation, usually snow, by adding moisture and heat to the low levels of the atmosphere (Changnon, 1969).

In a more detailed study of heavy precipitation events, Stout and Huff (1962) showed that severe rainstorms over Illinois are often accompanied by greater than average low-level moisture and upper-level winds which veer from WSW at low levels to W at mid levels of the troposphere. These rainstorms had extreme values of point rainfall, but the basic weather characteristics should be similar for all heavy precipitation events in northeast Illinois.

Huff and Changnon (1972) determined the synoptic weather types for 461 storms which moved across Chicago from 1959-1968. They found a storm distribution similar to table 17, and during summer the urban environment appeared to enhance the precipitation in the more intense storms. Similarly, using a more detailed classification scheme, Vogel (1974) showed that the more active and intense the synoptic situation during summer, the greater the chances for urban-industrial enhancement of precipitation. Since most of the heavy rainstorms over northeast Illinois occur during the summer, the heavier rainfall intensities found over Chicago (figures 3 through 9) may be primarily due to inadvertent enhancement from the urban-industrial complex.

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