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CLIMATE OF MINNESOTA

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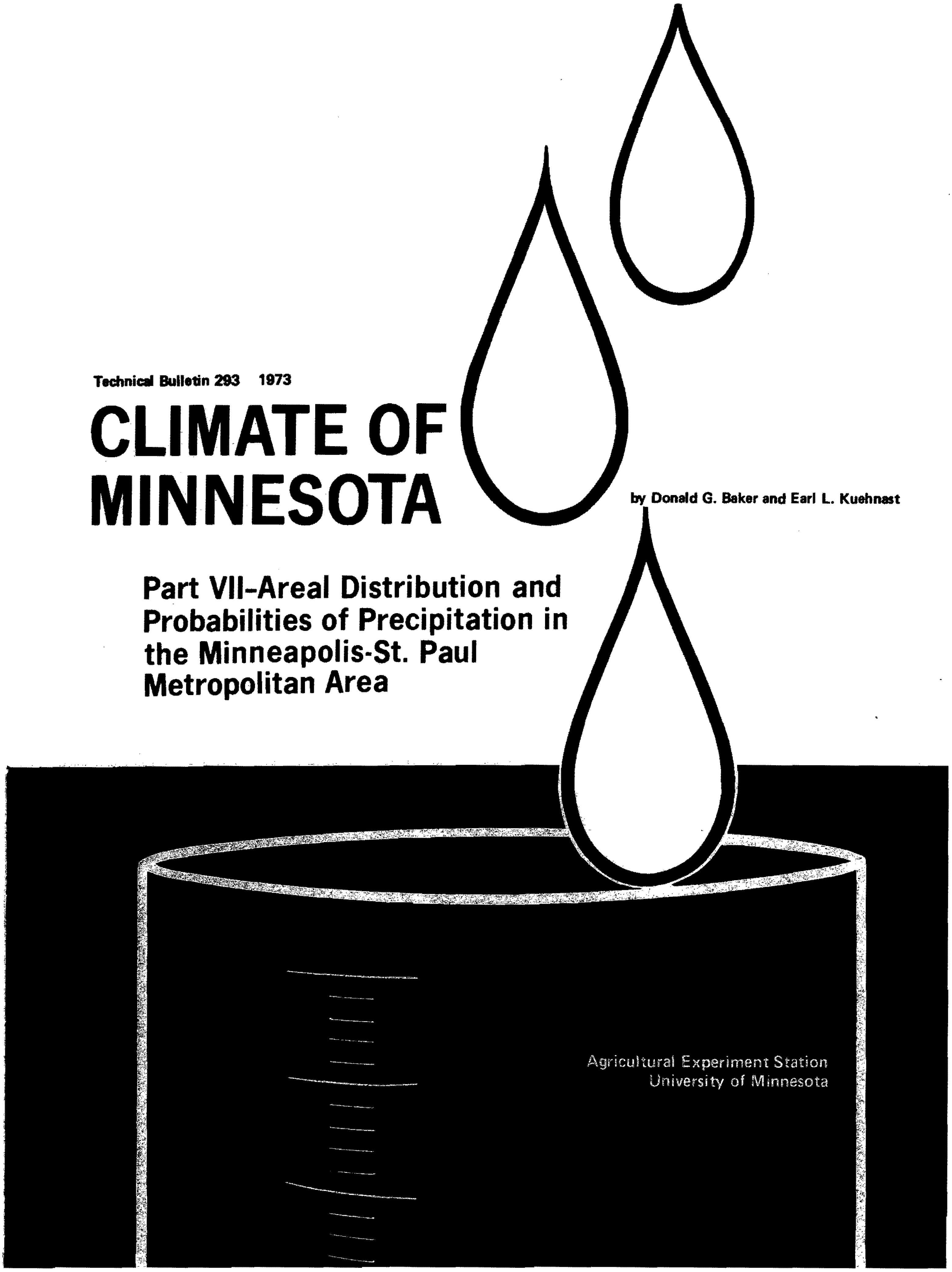
Part VII-Areal Distribution and Probabilities of Precipitation in the Minneapolis-St. Paul Metropolitan Area



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INTRODUCTION

Spatial precipitation variation can be great within limited areas of uniform topography, but is seldom measured because rain gage networks ordinarily are not extensive. This is accentuated in summer when localized convective showers are most common.

Several questions arise about the degree of variation possible in small areas: (a) how well can a single rain gage represent the area, (b) how many gages are required for adequate sampling, (c) what is the expected areal extent of given amounts of precipitation within the defined area, and (d) how great a precipitation variation may be expected within the defined area.

These are important when applied to urban areas. For example, precipitation in an urban area may be of immediate consequence since a large share is lost at once as runoff. As a result, urban drainage engineering designs require accurate precipitation data.

The primary objective of this bulletin is to answer these questions for the Minneapolis-St. Paul (Twin Cities) metropolitan area. The results of this study are based upon a dense precipitation network which has been in existence for several years. A secondary objective is to determine the occurrence probability of various amounts of precipitation in the metropolitan area and to compare these probabilities with those at the National Weather Service[1] airport station.

Results obtained in this study may be applicable to other parts of Minnesota as well, since precipitation characteristics probably do not differ greatly in the state.

The impetus for this study came from two sources—the realization that much more detailed precipitation information than that presently available is required for various engineering projects and basic resources studies; and a memorandum by Hughes (8) suggesting that an "Areal Coverage of Precipitation" project be initiated at each of the first order weather stations in the central region.

MATERIALS AND METHODS

The Twin Cities metropolitan area was defined as a 30-mile radius extending outward from the Minneapolis-St. Paul International Airport where the National Weather Service forecasting station is located (figure 1). Twenty-four other precipitation recording stations within the area were selected. This area equals about 3000 square miles[2]. This network with a concentration of about 0.88 stations per 100 square miles is much superior to the state average of about 0.22 stations per 100 square miles (1). However, it is exceeded by certain other networks (6).

Stations chosen had the same observing time and complete daily records (with a few exceptions) of rainfall from May-September for the 5-year period 1964-1968. A standard observation time was necessary to have a uniform "precipitation day." The standard observation time selected was 7 a.m. to give the most stations for the analysis.

Nine of the stations selected were part of the National Weather Service cooperative network. The remainder cooperated in the weather observation network established by the Metropolitan Mosquito Commission. The 25 station locations are shown in figure 1 with additional details for each station listed in table 1. Station elevations range from a minimum of 695 feet along the Mississippi River at Hastings to an estimated 1110 feet above mean sea level at New Market.

It was assumed that precipitation probability was equal throughout the Twin Cities. This is also assumed by a meteorologist when making a forecast for the area. However, the frequency of rain days in the Twin Cities was found to range from 25.6 percent at New Prague to a maximum of 39.6 percent at St. Louis Park for amounts of 0.01 inch or greater. For amounts of 0.10 inch or greater, the frequency varied from 20.1 percent to 25.8 percent (figure 1). An investigation beyond the scope of this study would be required to determine if these variations were physically significant, a factor of the short record period, or due to other undetermined factors. Spatial variations in the frequency of rain days were also found by Beebe for the Atlanta and Birmingham areas (2).

DISCUSSION

1. Number of Rain Gages Required for an Adequate Sample

The precipitation frequencies of certain amounts at the centrally located airport station were calculated and plotted. The frequencies were determined for the airport station plus four other stations. Each one of the four was selected to represent one quarter of the circular area surrounding the airport. This was repeated for nine stations, then 18 stations, and finally all 25 stations.

Results of these precipitation frequency calculations at a 1-, 5-, 9-, 18-, and 25-gage network for each month from May through September plus the full 5-month season are shown in figures 2-7. These figures demonstrate that a single gage anywhere within this area inadequately represents the rainfall frequency. Table 2 emphasizes the discrepancy between a 25-gage and single-gage network and lists the difference in precipitation frequencies between the two networks. A forecaster dependent only upon information from the single gage at the airport station would seriously underestimate the precipitation frequency even in his immediate forecast area.

Observers at the airport site are required to take four precipitation measurements per day while all other observers normally take only one measurement per day. There is, therefore, a greater likelihood that the airport site will record a greater number of small precipitation amounts. This is common at stations where precipitation is measured more frequently than once a day and thus less subject to evaporation losses (5). This would be apparent in table 2 were it not for the nonuniform increments of precipitation used.

The precipitation ranges used in this study are similar to those commonly used by the National Weather Service in various climatological studies (12) and were used for this reason. The nonuniformity of the ranges can be deceiving when frequencies are considered. With rainfall measured to the nearest 0.01 inch, the reader should keep in mind that there are only

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[1] The National Weather Service replaced the Weather Bureau as an entity by executive order on October 3, 1970.

[2] The exact area is 2826 square miles. However, the staions within the 30-mile radius are not ideally located. For this reason a rigorously defined area is deceiving.

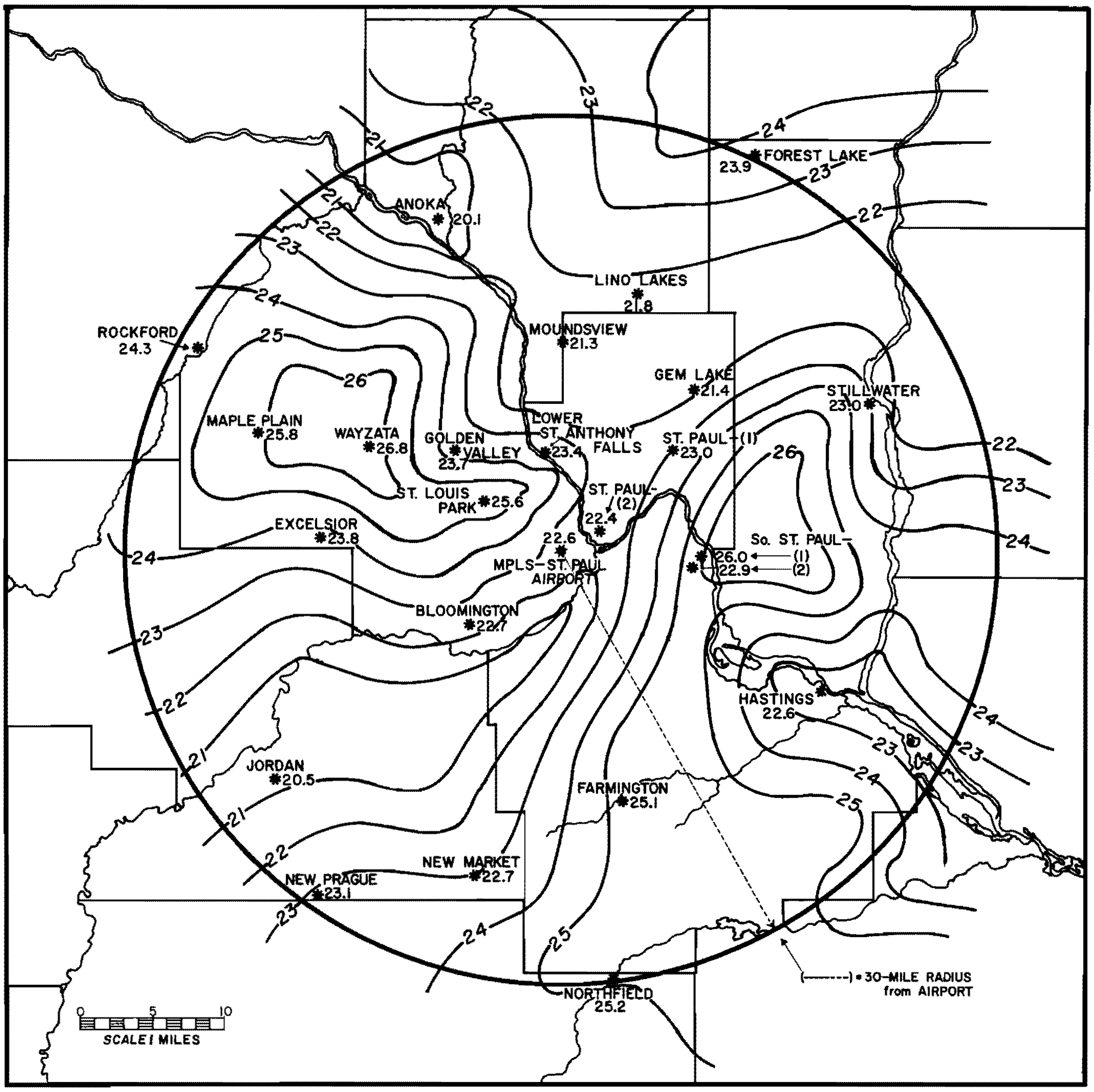

Figure 1. Location of the 25 precipitation observing stations in the metropolitan area. This figure also shows the percent frequency that days with 0.10 inch or greater precipitation were observed in the May-September period, 1964-1968.

Table 1. Addresses and names of observers at the 25 metropolitan area precipitation stations.

Station Name	Altitude[1]	Address	Name of Observer
1. Anoka	E870	11949 Crooked Lake Blvd.	M. Bodine
2. Bloomington	E870	10542 Vessey Rd.	J. Linton
3. Excelsior	940	Sewage Treatment Plant	E. M. Hafner C. Zieman
4. Farmington	E900	Spruce St.	R. E. Rademacher
5. Forest Lake	940	No. Shore Dr.	V. Loren
6. Gem Lake	E930	U.S. Highway 61-Co. Rd. E	C. D. Barnum
7. Golden Valley	915	7800 Golden Valley Rd.	J. Westlake
8. Hastings	695	U. S. Corps of Engineers Lock No. 2	J. L. Brewer Lockmaster
9. Jordan	E780	Hdqtrs., Scott County Mosquito Headquarters Control	
10. Lino Lakes	E900	441 Birch St.	J. Speiser
11. Lower St. Anthony Falls	755	U. S. Corps of Engineers Lock No. 1	M. G. Pratt
12. Maple Plain	970	Residence	D. McKown, R. Rhuby
13. Minneapolis - St. Paul Airport	834	FAA Bldg., 6301-34th Ave. S., Mpls.	National Weather Service
14. Mounds View	E900	1801 County Rd. H	C. D. Barnum
15. New Market	E1110	Webster St.	R. Simon
16. New Prague	E1000	405 Lincoln Ave.	E. P. Wermerskirchen
17. Northfield	890	Goodsell Observatory Carleton College	Prof. Matthews
18. Rockford	E940	Residence	H. M. Thompson
19. St. Louis Park	E900	4510 W. 36th St.	K. Shoberg
20. St. Paul (1)	920	707 Montana St.	J. Riddell
21. St. Paul (2)	E940	1709 Rome Ave.	A. W. Buzicky
22. So. St. Paul (1)	E820	649-6th Ave. So.	R. Neary
23. So. St. Paul (2)	750	Water Works Pumping Station No. 4	H. Weimer
24. Stillwater	710	Sewage Treatment Plant	J. Schelton
25. Wayzata	E990	Highway 101-12th Ave. N.	C. Martin

[1] Altitude in feet above mean sea level; E indicates that the altitude was estimated from U.S. Geological Survey topographic sheets.

Table 2. The difference in the average number of precipitation days per month and season for given amounts of precipitation between the 25-gage network and the single-gage at the Minneapolis-St. Paul International Airport, May-September, 1964-1968.[1]

	Months					
Amount (in)	May	June	July	August	September	Season (May-Sept.)
≥0.01	8.6	6.8	10.4	10.6	7.6	44.0
≥0.05	10.0	8.4	10.4	10.8	8.2	47.8
≥0.10	10.8	8.6	9.6	9.6	7.8	46.4
≥0.50	5.0	7.2	7.0	7.2	4.2	30.6
≥1.00	2.6	5.2	4.6	3.2	4.0	19.6
≥2.00	0.8	1.4	2.6	1.8	1.6	8.2

[1] All values are positive; that is, the rain days observed in the 25-gage network were greater in every case than observed at the single gage.

four rainfall amounts within the 0.01 - 0.04 inch range, but five in the 0.05 - 0.09 range, 40 in the 0.10 - 0.49 range, 50 in the 0.50 - 0.99 range, and 100 in the 1.00 - 1.99 range.

An interesting characteristic of the monthly rainfall is shown in table 3. Except for very large rainfalls of 2 inches, precipitation was most frequent in June and least frequent in September or May. The high frequency in June is to be expected, since it is normally the month of maximum precipitation.

While 50 gages may be the number required for a "true" sample of the season as a whole, the number varies from month to month (figures 2-6). The curves indicate that only about 45 gages would be needed in May and June, about 60 gages in July, and about 50 gages in August and September.

The required number of gages for a "true" sample indicated in figures 2-6 cannot be substantiated by any data presented so far; but the numbers indicated seem to follow the general view of the kind of storms typical of each of the 5 months. For example, convective activity ordinarily reaches its maximum in July when showers of relatively small areal extent would be most common and require the greatest number of gages. This is shown in tables 6-9 and figure 16.

Table 3. **Frequency in percent of days per month and per season that indicated daily amounts of rain were observed at one or more of the gages within the 25-gage network in the Twin Cities, May-September, 1964-1968.**

	Months					
Amount (in)	May	June	July	August	September	Season (May-Sept.)
≥ 0.01	67.1	69.3*	62.6	63.2	56.7+	63.8
≥ 0.05	61.9	65.4*	57.4	56.8	52.0+	58.7
≥ 0.10	57.4	59.4*	51.0	49.7	45.4+	52.5
≥ 0.50	21.9+	34.7*	31.0	31.0	22.7	28.2
≥ 1.00	10.3+	20.7*	19.4	15.5	16.0	16.3
≥ 2.00	2.6+	5.3	8.4*	6.5	6.7	5.8

* Maximum frequency

+Minimum frequency

Table 4 shows that the greater number of days recorded by the 25 stations fell within the 0.05 - 0.09 inch range rather than the 0.01 - 0.04 inch range with the exception of May. Part of this reflects the natural bias toward higher rainfall amounts recorded because observations were made only once per day at all except the airport site. Also, with precipitation increments of uniform size, the frequency would decrease as the amount of precipitation increases.

With a network of 40 rain gages for an area of 50 miles radius around both Atlanta, Georgia, and Birmingham, Alabama, the "true" sample would be obtained with about 70 rain gages according to our estimate of Beebe's data (2). This is equivalent to one gage per 112 square miles. For Peoria, Illinois, an area of 35-mile radius with 20 rain gages, the estimated "true" sample from data by Causey (3) would require 55 gages or 70 square miles per gage. These may be compared to the 50 rain gages or one gage per 57 square miles required in an area of 30-mile radius around the Twin Cities. This shows how sharply the number of gages required per unit area for adequate sampling decrease as the sample area is increased, a feature also noted by Huff (6). When sample areas are plotted on log paper against the rain gage density[3] values assumed for the "true" samples at Atlanta, Peoria, and the

Table 4. **Average number of days that given daily amounts of rainfall were recorded at one or more of the gages within the 25-gage network in the Twin Cities, May-September, 1964-1968.**

	Months					
Amount (in)	May	June	July	August	September	Season (May-Sept.)
0.01 - 0.04	1.6	1.3	1.6	2.0	1.4	7.9
0.05 - 0.09	1.4	1.8	2.0	2.2	2.0	9.4
0.10 - 0.49	11.0	7.4	6.2	5.8	6.8	37.2
0.50 - 0.99	3.6	4.2	3.6	4.8	2.0	18.2
1.00 - 1.99	2.4	4.6	3.4	2.8	2.8	16.0
≥ 2.00	0.8	1.6	2.6	2.0	2.0	9.0
	20.8	20.9	19.4	19.6	17.0	97.7

Figures 2-6 also show that a 25-gage network is obviously superior to a single gage but still insufficient to determine areal frequency. The assumed increase in efficiency in detecting precipitation with more than 25 gages is indicated by the dashed lines. If the curves continue as shown by the dashed lines in figure 8, a "true" sample of the Twin Cities for the season as a whole would be obtained with about 50 rain gages. This means that about one gage per 57 square miles or 36,480 acres is required for a "true" sample of the area. The number of gages required for a "true" sample may not be practical, and an adequate or acceptable sample might be about 30 gages or about one gage per 100 square miles.

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[3] Huff has defined gage density as square miles per gage.

Twin Cities, a straight line is obtained which predicts that an area of 1000 square miles would require only one gage per 23 square miles. This may be compared to the one gage per 112 square miles in the 7850 square mile Atlanta sample area or the one gage per 57 square miles in the nearly 3000 square mile Twin Cities area. These results agree in general, but not in detail, with the summer (June-August) graph of Huff (6), which predicts a greater number of gages required per unit area to detect a trace of rain. It is possible that the difference between the two studies lies in the detection of different amounts of precipitation.

For the summer season of June, July, and August, rain equal to or exceeding 0.01 inch occurred on the average about 69 percent of the days somewhere within the Twin Cities. This is nearly the same as deduced from Causey's figures for Peoria (3), but about 15 percent lower than Beebe's data for Atlanta and Birmingham (2). Table 5 shows the estimated "true" frequency of rain-days for each of the 5 months in the Twin Cities area.

The U-shaped feature noted in figures 8-10 requires explanation. It indicates that rains of 0.10 inch or less occurred essentially in one of two modes: rains were either of an extremely limited areal extent, which most likely was associated with convection cells; or as rains of a very general nature which occur in the proximity of significant low pressure systems. Hughes (9) noted a similar feature in his study of the areal distribution of precipitation in the Chicago and vicinity area.

The U-shaped configuration of the frequency curve did not extend beyond rainfalls of 0.50 inch or more. According to figures 11-13 the larger rainfalls were almost always of a limited extent and became progressively more limited in area as the precipitation amount increased. Thus it appears that a rainfall of something less than 0.50 inch was the breaking point between rains of a very local extent and those of a relatively large areal extent. Rainfall of 0.50 inch or more during a 24-hour period was restricted to very localized rains probably of the showery or convective type.

Table 5. Estimated "true" frequency of rain-days per month in the Twin Cities, 1964-1968. (Data are based upon an extrapolation of the 0.01 inch curve in figures 2-7).

	Months					
	May	June	July	August	September	Season (May-Sept.)
Frequency (%)	70	71	72	65	61	67

2. Areal Distribution of Precipitation

Precipitation distribution and frequency over the metropolitan area were determined as follows. The frequency that rain-days of selected amounts occurred was determined when a rain-day was found at any one of the 25 gages, then at any two of the 25 gages, any three of the 25 gages, and so on through those days when rain was recorded at all 25 gages. In contrast to the previous section in which gages one through 25 always represented specific sites, that was not the case in this part of the study. Here precipitation frequency was based only upon the number of gages at which rain was recorded each day. The location of the gages in which rain was recorded was of no concern.

Figures 8-13 show the results of these tabulations. The base of each figure is labeled with both the number of gages and percent of the total area that the number of gages supposedly represented. Since there were 25 rain gages in the 30-mile radius area, each gage, therefore, represented 4 percent of the nearly 3000 square mile area. This was, of course, only an approximation because the gages were not ideally distributed across the area.

Figure 8 shows the likelihood of receiving 0.01 inches or more over 80 to 100 percent of the metropolitan area (21-25 gages) for the May-September period was nearly as great as receiving it over a limited portion, 4 to 20 percent of the area, as estimated by 1-4 gages. The probability occurrence for each of these averaged about 5 percent of the days. However, probabilities were only 1 to 2 percent that 0.01 inches or more of rain would cover 20 to 80 percent of the metropolitan area. This curious U-shaped feature of rainfall frequency versus areal coverage also occurred with the 0.05 and 0.10 inches or more rainfalls (figures 9-10).

Figures 14-18 show the monthly areal distribution of precipitation. July and August were different from the other 3 months. Fewer rainfalls of great areal extent seem to be characteristic of July and August. When rain occurs in July and August, it is generally associated with convective type showers. Rains of greater areal extent occur with higher frequency in May, June, and September due to the proximity of the polar front or low pressure systems. Perhaps even these months can be separated, with May and June showing more general convective shower activity than September.

The areal extent of individual rainfalls is of general interest and important for engineers particularly in the design of water control structures. Approximations rather than measurements are used for several reasons. First, accurate measurements rely upon a uniform distribution of the gages throughout the area, and secondly, upon a great number of gages. It has already been noted that neither requirment was met in this study. A third factor is that the rainfall measurements should be those of individual storms, rather than the 24-hour totals used in this study which may represent more than one storm. A fourth factor is the limited size of the study area itself.

The data obtained in this study permits at least a first approximation of the areal extent of individual storms. The mean area of rainfall of given daily amounts is shown in table 6. This table shows, for example, that on all days in May when precipitation equal to 0.05 inch or more was measured in the metropolitan area the mean extent was 410 square miles. In contrast, rainfalls of the same daily amount averaged 700 square miles in June. From what has been noted earlier it is not surprising that, in general, July rains occupied the least area, while in June the area of the rains was generally the greatest. As to be expected the area of the large amount rainfalls, such as 1 inch or more, was relatively small. Indeed the area of the large

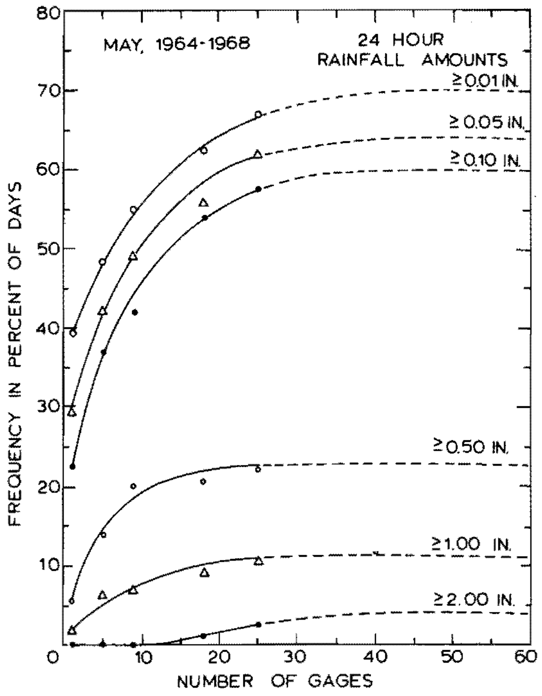

Figure 2. Frequency in percent of days that daily precipitation of indicated amounts was observed at the same network of 1, 5, 9, 18, and 25 stations during May, 1964-1968.

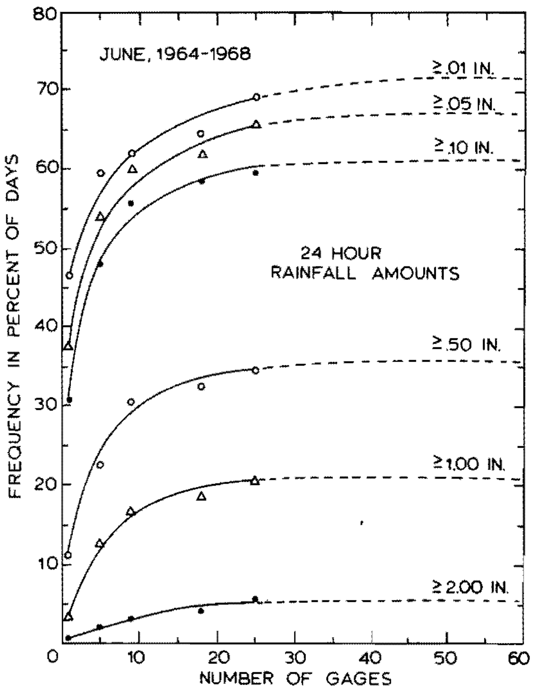

Figure 3. Frequency in percent of days that daily precipitation of indicated amounts was observed at the same network of 1, 5, 9, 18, and 25 stations during June, 1964-1968.

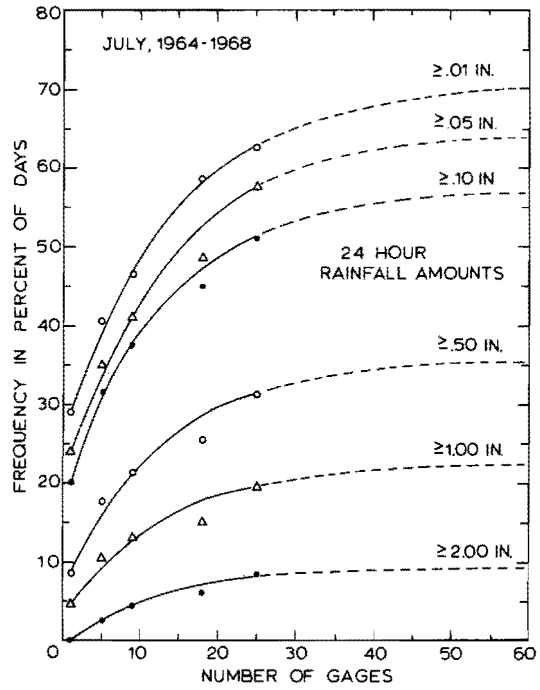

Figure 4. Frequency in percent of days that daily precipitation of indicated amounts was observed at the same network of 1, 5, 9, 18, and 25 stations during July, 1964-1968.

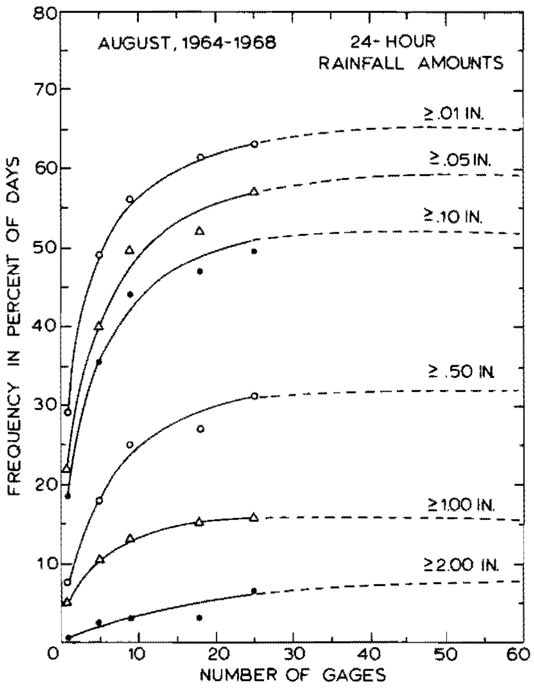

Figure 5. Frequency in percent of days that daily precipitation of indicated amounts was observed at the same network of 1, 5, 9, 18, and 25 stations during August, 1964-1968.

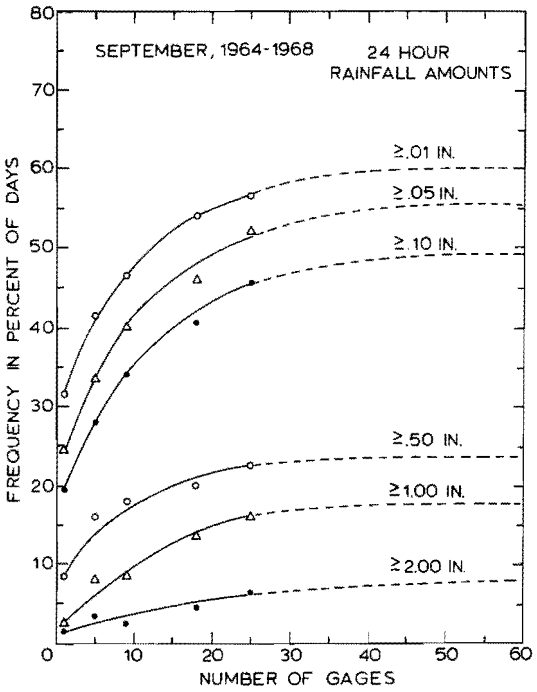

Figure 6. Frequency in percent of days that daily precipitation of indicated amounts was observed at the same network of 1, 5, 9, 18, and 25 stations during September, 1964-1968.

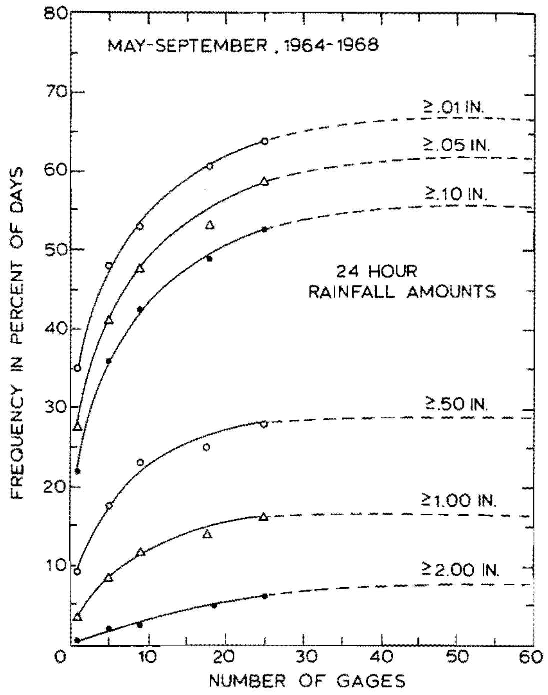

Figure 7. Frequency in percent of days that daily precipitation of indicated amounts was observed at the same network of 1, 5, 9, 18, and 25 stations during May-September, 1964-1968.

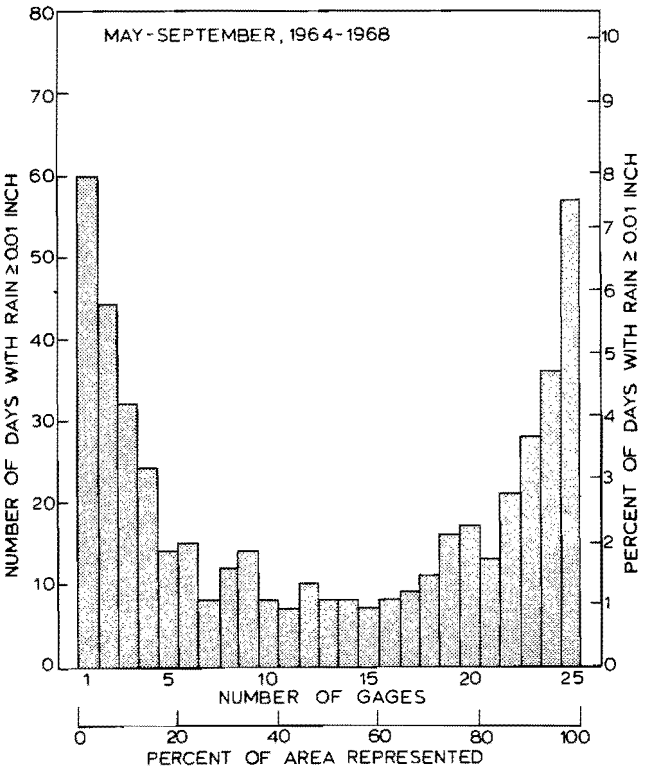

Figure 8. Frequency in number and percent of all days in May-September that daily precipitation of at least 0.01 inch was observed at from 1 to 25 observing stations.

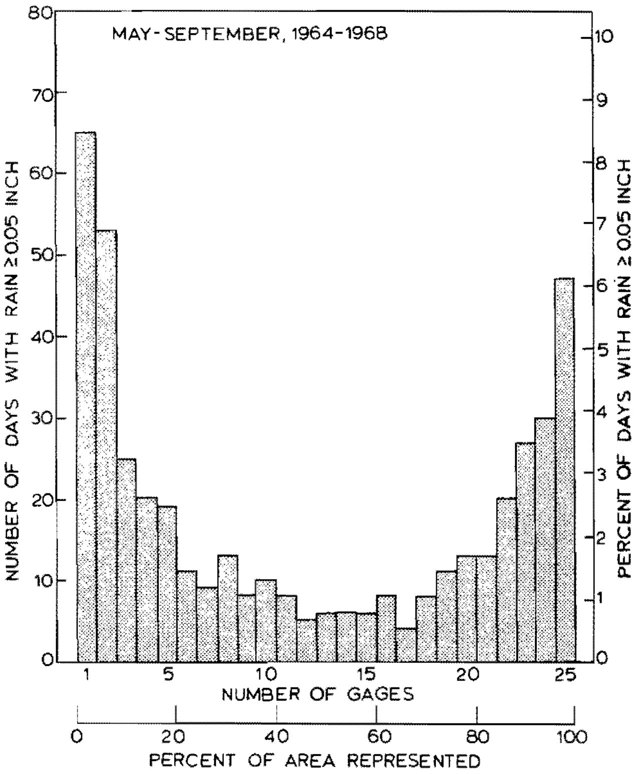

Figure 9. Frequency in number and percent of all days in May-September that daily precipitation of at least 0.05 inch was observed at from 1 to 25 observing stations.

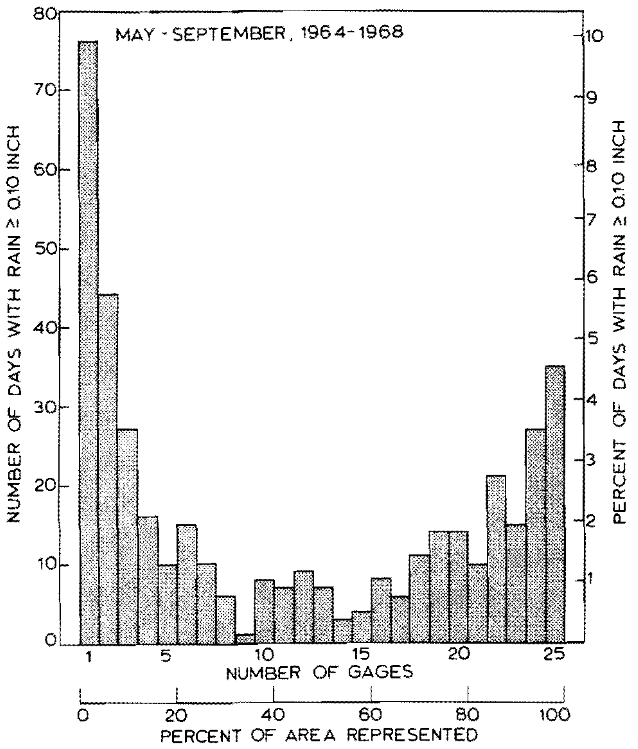

Figure 10. Frequency in number and percent of all days in May-September that daily precipitation of at least 0.10 inch was observed at from 1 to 25 observing stations.

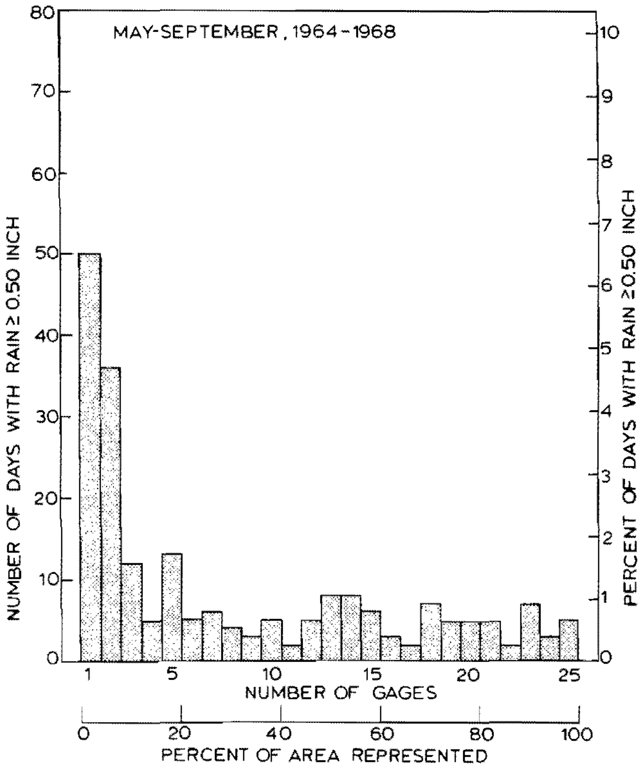

Figure 11. Frequency in number and percent of all days in May-September that daily precipitation of at least 0.50 inch was observed at from 1 to 25 observing stations.

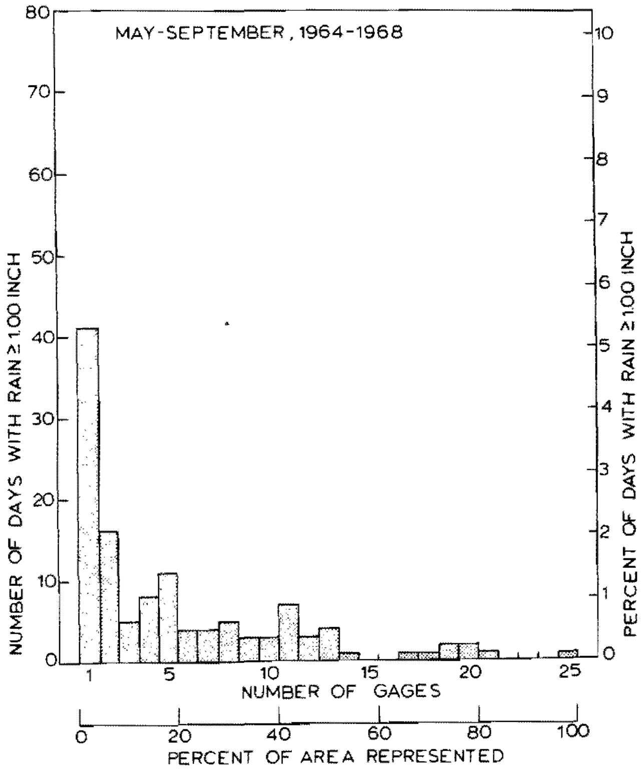

Figure 12. Frequency in number and percent of all days in May-September that daily precipitation of at least 1.00 inch was observed at from 1 to 25 observing stations.

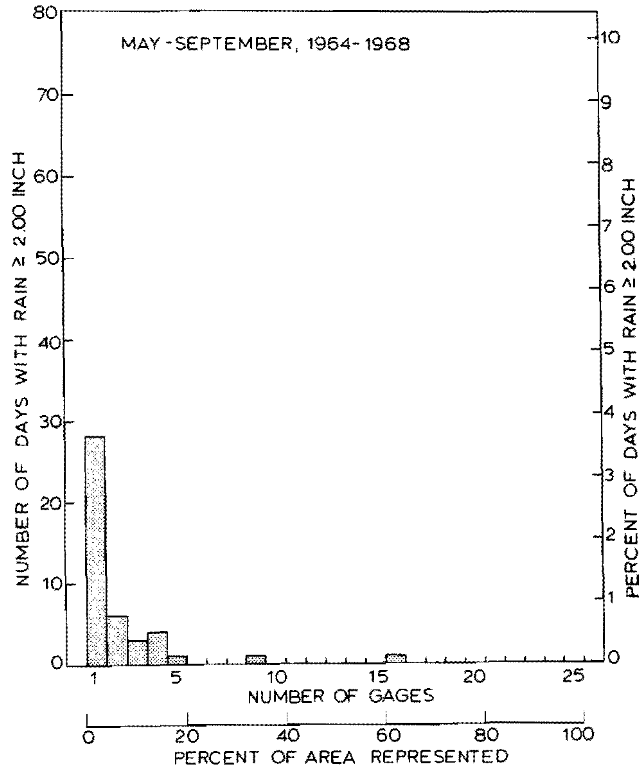

Figure 13. Frequency in number and percent of all days in May-September that daily precipitation of at least 2.00 inches was observed at from 1 to 25 observing stations.

Table 6. Mean areal extent (square miles) of rainfall of given daily amounts in the Twin Cities, May-September, 1964-1968.[1]

	Months				
Daily Amount (in.)	May	June	July	August	September
≥ 0.01	540	920*	340+	380	480
≥ 0.05	410	700*	300+	300	320
≥ 0.10	300	540*	280	340	250+
≥ 0.50	230	210	200+	220	390*
≥ 1.00	180	180	150+	190*	150+
≥ 2.00	120	120	120	120	120

[1] Assuming the metropolitan area equals 3000 square miles and areas rounded off to the nearest 5 square miles.

*Maximum area.

+Minimum area.

amount rainfalls is probably an indirect function of the number of gages. That is, if the percent network density had been greater, then the apparent area of the large amount rainfalls probably would have been smaller.

Tables 7,8, and 9 show another consideration of the areal extent of rains obtained from the approximate maximum areal extent of rains of selected amounts at three probability levels. The cumulative probabilities began with rainfalls of the smallest areal extent (those recorded at only one station) and worked upward to those days recorded at all 25 stations. An example from table 7 may aid in the use of these tables. For example, in July the maximum areal extent of rains equal to 0.05 inch or more was 2280 square miles. This means that on 75 percent of those days in July when a rain of at least 0.05 inch was measured, this amount was recorded at from one to 19 stations. These 19 stations represent 76 percent of the metropolitan area or about 2280 square miles.

As shown in all three tables, most rainfalls of 2 inches or more were limited in general to about 120* square miles. That is, they were recorded at only one of the 25 stations. Since clouds normally are not stationary, the rain area would be more or less rectangular in shape. If, for example, the rain area was 4 miles wide, a length of about 30 miles can be inferred.

The illusion that "it rained everywhere but here" is frequently heard and deserves comment. It is easy for this illusion to gain credence in relatively flat terrain where visibility is unrestricted and any rain shower that occurs within the immediate area can be observed. When it is realized that the tops of some convective type clouds have been measured by both aircraft and radar at 45-60,000 feet it is apparent why some storms may be observed from great distances. Thus with a storm cloud reaching such an altitude an observer at the heart of the metropolitan area could easily see any rainstorm within the 30-mile radius. As a matter of interest, a formula is presented by Scorer and Wexler (11) which shows that with an unrestricted horizon an observer at ground level can still see clouds, for example, that are at 25,000 feet above the horizon at a distance greater than 150 miles if visibility is good enough.

Figure 4 shows that, for a rainfall amounting to 0.50 inch or more, the occurrence frequency as noted at a single station in July was only about 9 percent (approximately 3 days). However, within the 25-gage network, rainfalls of this amount were observed about 31 percent of the time, or approximately 10 days. Thus the observer would note that it rained less than one-third as frequently as in the surrounding area and that seemingly over two-thirds of the storms bypassed his station. It is no wonder then that an observer gains the impression that his neighbors received rain, but he did not.

Another way to look at this is to consider the data in table 8. The data show that 50 percent of the July storms producing daily rainfalls totaling 0.50 inch or more were recorded over an area of no more than 240 square miles, that is, at two of the 25 stations. This equals only 8 percent of the defined Twin Cities. Thus, although the storm can be observed, the small areal coverage means, in fact, that 92 percent of the area did not receive this amount. Even one-half of the rainfalls of but 0.10 inch or more covered a maximum of only 720 square miles. This means that 24 percent of the area was covered by the rainfall but 76 percent of the area was not. The small areal coverage of these rainfalls can lead to the deception that it rained "everywhere but here." An article by McDonald (10) discusses this illusion in greater detail.

In general, according to these data, the rainfalls of greatest areal extent occurred in June with a midseason minimum occurring in July. This supports an earlier statement that rains of small areal extent were most common in July. A likely reason for this is that the July rains are more likely to be purely convective in origin.

In all cases except one, the maximum areal extent of a rainfall decreased as the amount of precipitation increased. The exception occurred with the September rains of 0.50 inch or more. Inspection of the original records indicate that this occurred as a result of an apparently unusual distribution of the September rains in 1964-1968. This would most probably disappear if either another period or a longer period was used.

3. Precipitation Variation

The mean monthly precipitation total at each of the metropolitan area stations is listed in table 10. Within the metropolitan area the average total May-September precipitation ranged from a high of 24.15 inches at Wayzata to a

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* The 120 square mile figure lends an air of preciseness which is misleading. Actually most rainfalls of 2 inches or more were limited to only one of the 25 stations, that is, 4 percent of the nearly 3000 square mile area or 120 square miles.

low of 17.59 inches at Anoka. This amounts to a difference of 6.56 inches within a distance of but 16 miles, and it equals or exceeds the mean difference between extreme southeastern and extreme northwestern Minnesota for the same 5 months over a 30-year period (1). This shows two things: precipitation is extremely variable over even short distances, and a dense rain gage network brings out details which previously were unrealized or could only be guessed.

The average monthly precipitation at the Minneapolis-St. Paul airport station for the 5-year period did not differ appreciably from the 30-year normal period of 1941-70, table 11.

In a previous section of this study it was noted that a single gage resulted in an underestimation of precipitation frequency in the Twin Cities. Table 12 shows that the central site was in fact one of lower than average precipitation for the area. A study based upon a greater record period would have to be made to determine if this is a persistent feature of the airport site. Therefore, until proven otherwise the initial assumption in this study that precipitation occurred randomly within the area still has to be accepted. It is true, however, that a forecaster at the airport site during the 1964-1968 period was operating under two handicaps: there was only a single gage available to him, whereas upwards of 30 would be required for an adequate sample, and 50 for a "true" sample; and the site which lies within the center of the area (the Minneapolis-St. Paul airport) received less than the average precipitation for the area it was intended to represent.

It is also of some interest to know the maximum precipitation recorded within the Twin Cities. In May and August the Wayzata Station had the highest mean monthly rainfall during the 5-year period, table 13. The South St. Paul Station

Table 7. The estimated maximum areal extent (square miles) of the smallest 75 percent of the daily rainfalls of given amounts, Twin Cities, May-September, 1964-1968.

	Months					
Amount (in)	May	June	July	August	September	Season (May-Sept.)
≥0.01	2880	2760	2400	2640	2760	2640
≥0.05	2760	2760	2280	2520	2760	2640
≥0.10	2640	2640	2160	2400	2760	2520
≥0.50	1800	1680	1560	1680	1920	1680
≥1.00	840	960	1080	960	840	960
≥2.00	120	480	240	120	120	240

Table 8. The estimated maximum areal extent (square miles) of the smallest 50 percent of the daily rainfalls of given amounts, Twin Cities, May-September, 1964-1968.

	Months					
Amount (in)	May	June	July	August	September	Season (May-Sept.)
≥0.01	1680	2160	960	1080	1440	1440
≥0.05	1080	1680	720	960	960	1080
≥0.10	1080	1440	720	960	600	960
≥0.50	600	480	240	600	1080	600
≥1.00	360	360	240	480	120	360
≥2.00	120	120	120	120	120	120

Table 9. The estimated maximum areal extent (square miles) of the smallest 25 percent of daily rainfalls of given amounts, Twin Cities, May-September, 1964-1968.

	Months					
Amount (in)	May	June	July	August	September	Season (May-Sept.)
≥0.01	360	720	240	360	360	360
≥0.05	240	600	240	240	240	240
≥0.10	240	360	240	240	240	240
≥0.50	240	120	120	120	240	240
≥1.00	120	120	120	120	120	120
≥2.00	120	120	120	120	120	120

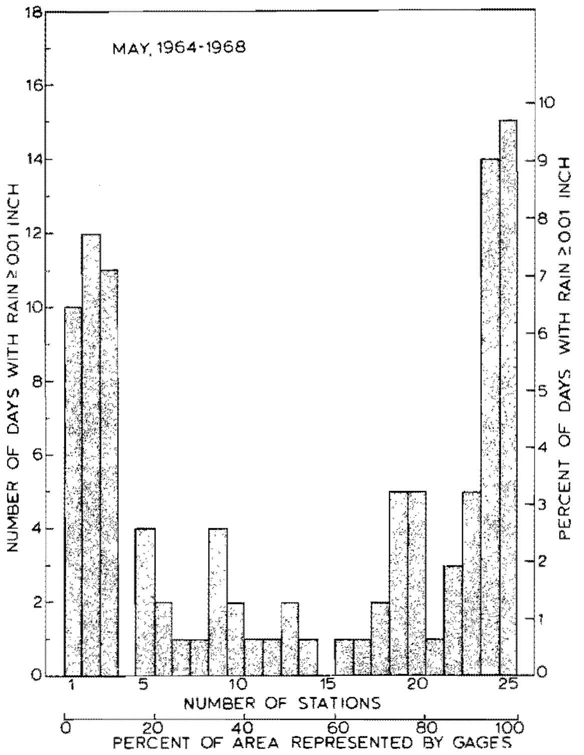

Figure 14. Frequency in number and percent of all days in May that daily precipitation of at least 0.01 inch was observed at from 1 to 25 observing stations.

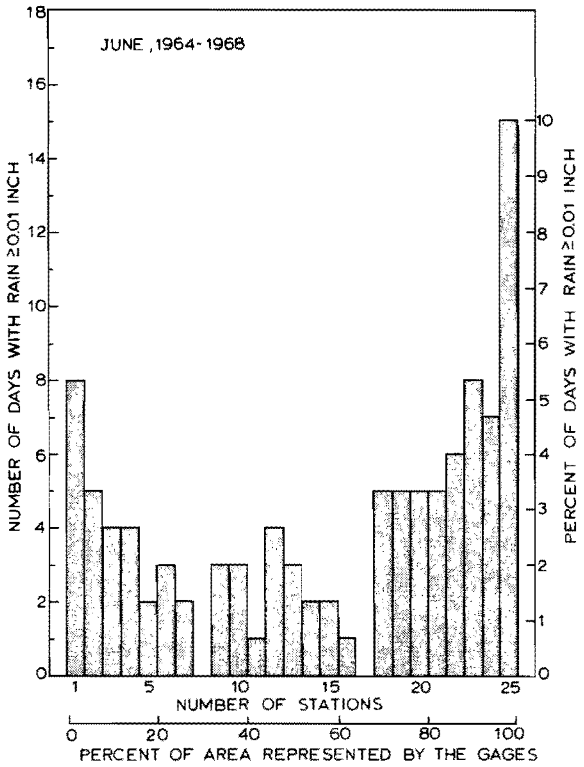

Figure 15. Frequency in number and percent of all days in June that daily precipitation of at least 0.01 inch was observed at from 1 to 25 observing stations.

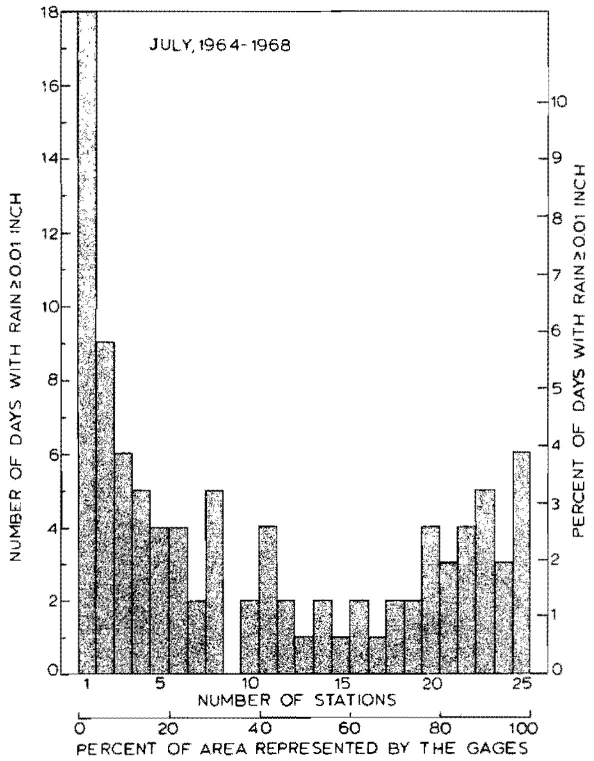

Figure 16. Frequency in number and percent of all days in July that daily precipitation at least 0.01 inch was observed at from 1 to 25 observing stations.

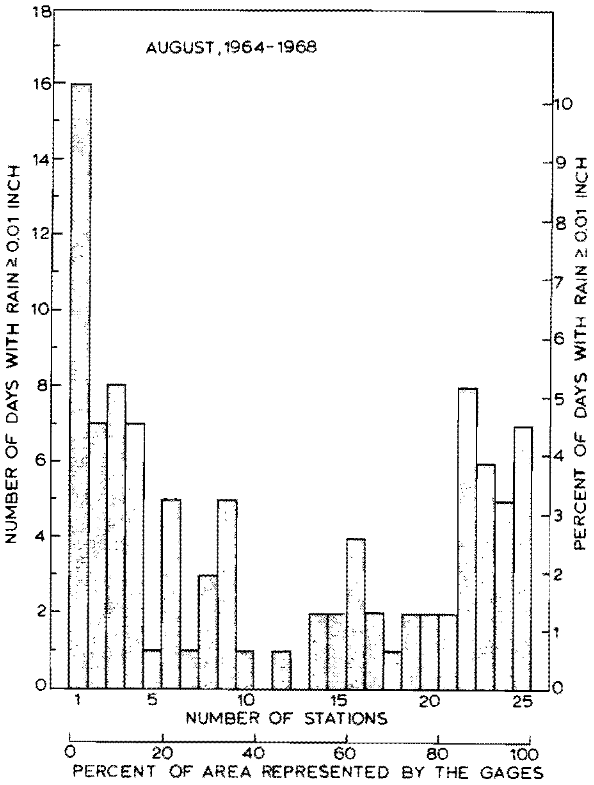

Figure 17. Frequency in number and percent of all days in August that daily precipitation at least 0.01 inch was observed at from 1 to 25 observing stations.

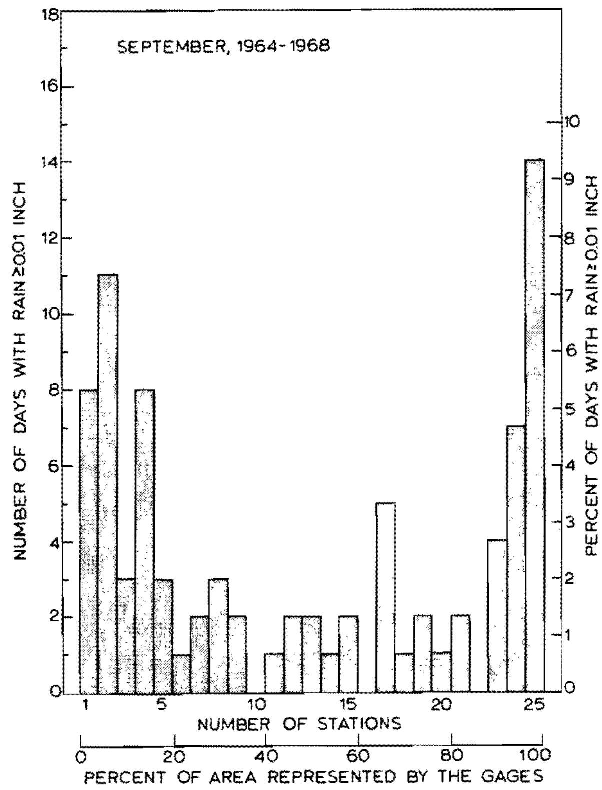

Figure 18. Frequency in number and percent of all days in September that daily precipitation at least 0.01 inch was observed at from 1 to 25 observing stations.

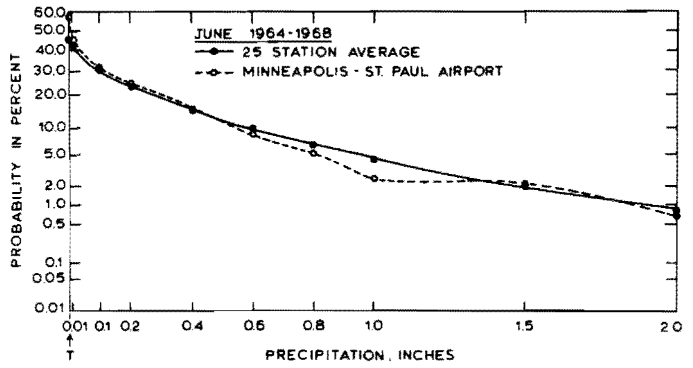

Figure 20. Average probability in percent that daily precipitation totals equalled at least the amount indicated in June, 1964-1968.

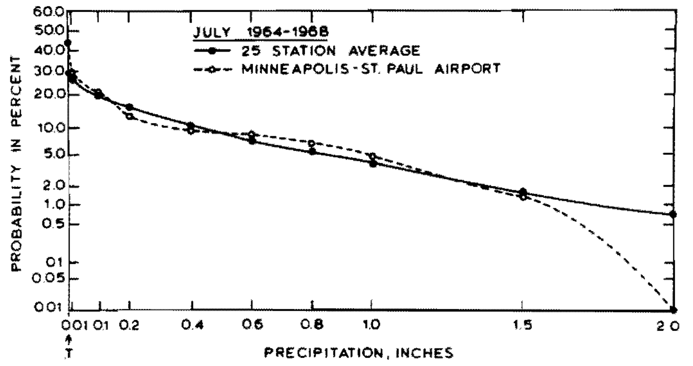

Figure 21. Average probability in percent that daily precipitation totals equalled at least the amount indicated in July, 1964-1968.

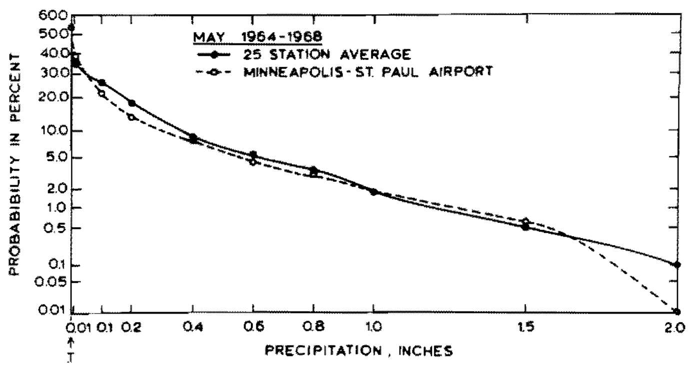

Figure 19. Average probability in percent that daily precipitation totals equalled at least the amount indicated in May, 1964-1968.

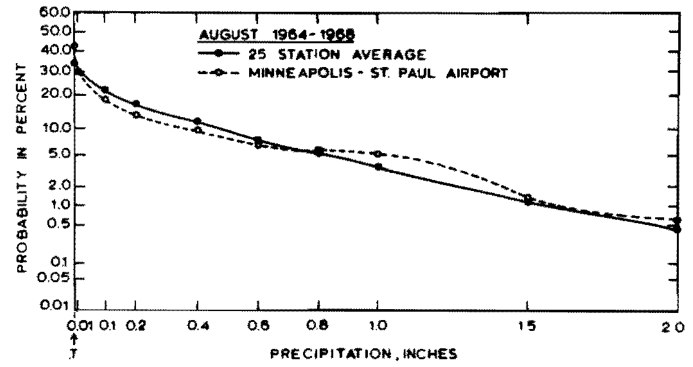

Figure 22. Average probability in percent that daily precipitation totals equalled at least the amount indicated in August, 1964-1968.

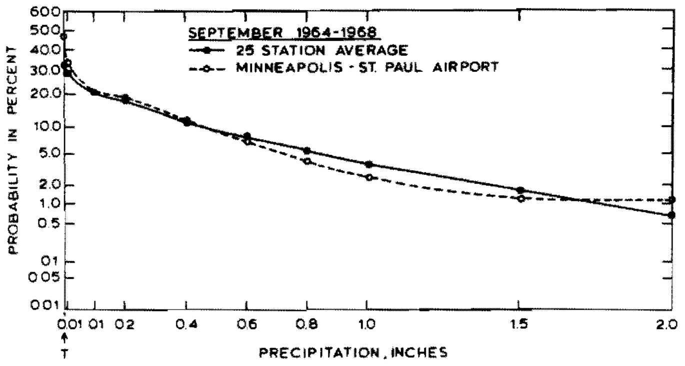

Figure 23. Average probability in percent that daily precipitation totals equalled at least the amount indicated in September, 1964-1968.

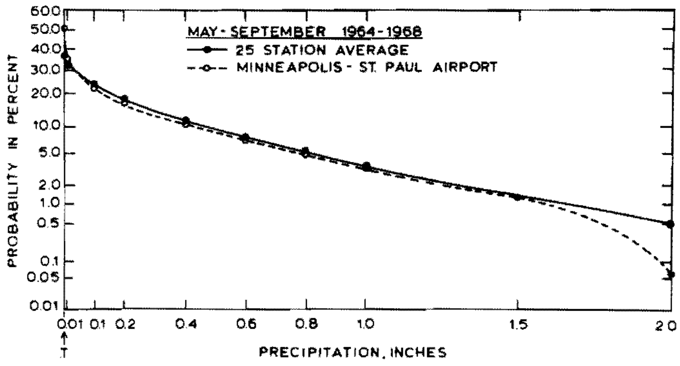

Figure 24. Average probability in percent that daily precipitation totals equalled at least the amount indicated in May-September, 1964-1968.

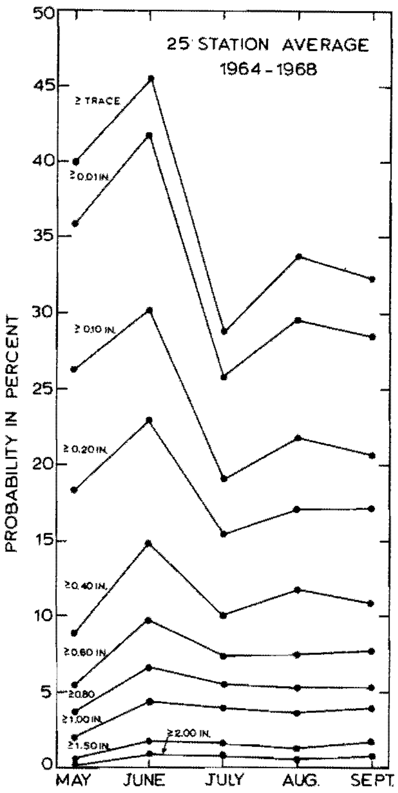

Figure 25. Average probability in percent that the daily total precipitation of given amounts was observed at the 25 stations in the metropolitan area during each month, May-September, 1964-1968.

Table 10. Average monthly rainfall in inches at each of the metropolitan area stations for the years 1964-1968.

	Month					Season
Station	May	June	July	August	September	May-September
1. Anoka	3.22	4.04	3.28	3.77	3.28	17.59**
2. Bloomington	3.53	5.62	3.79	4.03	3.82	20.79
3. Excelsior	3.80	5.36	4.19	3.98	4.12	21.45
4. Farmington	3.59	5.19	3.86	3.30	4.65*	20.58
5. Forest Lake	3.99	6.20	3.12	3.30	3.17**	19.78
6. Gem Lake	3.22	4.81	3.37	3.51	4.12	19.03
7. Golden Valley	3.31	4.98	4.40	3.88	3.45	20.03
8. Hastings	2.95	5.63	4.34	2.71**	4.04	19.73
9. Jordan	3.31	5.45	3.88	3.72	3.98	20.34
10. Lino Lakes	3.89	4.23	3.97	4.11	3.48	19.66
11. Lower St. Anthony Falls	2.94	5.47	3.80	4.34	3.83	20.38
12. Maple Plain	4.06	5.40	3.55	4.09	3.79	20.89
13. Minneapolis-St. Paul Airport	3.19	4.97	3.66	3.47	3.73	19.02
14. Mounds View	3.44	5.13	3.08**	3.97	3.72	19.34
15. New Market	3.12	4.50	4.01	3.30	4.10	19.03
16. New Prague	3.47	4.61	3.89	2.89	4.49	19.35
17. Northfield	3.30	3.84**	4.29	3.76	4.32	19.51
18. Rockford	3.54	4.36	3.98	4.23	3.44	19.55
19. St. Louis Park	3.48	5.68	4.40*	4.21	4.32	22.09
20. St. Paul (1)	2.97	6.14	3.36	3.77	3.91	20.15
21. St. Paul (2)	3.03	5.76	4.08	3.86	4.04	20.77
22. So. St. Paul (1)	3.54	6.57	3.45	3.56	4.03	21.15
23. So. St. Paul (2)	3.39	6.72*	3.43	3.14	4.29	20.95
24. Stillwater	2.71**	5.59	3.32	3.21	3.79	18.62
25. Wayzata	4.23*	6.12	4.13	5.13*	4.54	24.15*
Average	3.41	5.30	3.79	3.73	3.87	20.16

* Maximum monthly or seasonal value

** Minimum monthly or seasonal value

Table 11. Mean monthly total precipitation in inches at the Minneapolis-St. Paul airport station for the periods 1964-1968 and 1941-1970.

	Month					Season
	May	June	July	August	September	May-September
1964-1968	3.19	4.97	3.66	3.47	3.73	19.02
1941-1970	3.42	4.31	3.97	3.21	3.19	18.10
Difference	-0.23	+0.66	-0.31	+0.26	+0.54	+0.92

Table 12. Comparison of monthly mean precipitation in the Twin Cities (data based upon the 25 stations) and the Minneapolis-St. Paul airport, 1964-1968.

	Months					Season
	May	June	July	August	September	May-September
Twin Cities Area	3.40	5.29	3.74	3.73	3.95	20.11
Minneapolis-St. Paul Airport	3.19	4.97	3.66	3.47	3.73	19.02
Difference	+0.21	+0.32	+0.08	+0.26	+0.22	+1.09

Table 13. Location and amount in inches of the highest average monthly rainfall and the absolute maximum monthly total rainfall in the Twin Cities, 1964-1968.

	Months				
	May	June	July	August	September
Highest Monthly Average	4.12	6.72	4.40	5.13	4.65
Station	Wayzata	So. St. Paul (21)	St. Louis Park	Wayzata	Farmington
Absolute Monthly Maximum	10.50	11.85	8.02	8.53	9.03
Year of Occurrence	1965	1965	1965	1964	1964
Station	Lino Lakes	So. St. Paul (21)	Jordan	Wayzata	Northfield

total of 6.72 inches had the highest June average. St. Louis Park and Farmington had the highest means in July and September, respectively.

Table 14 shows also the highest monthly totals recorded in the area during 1964-1968. For the brief period of 5 years it is surprising to find that none of the monthly extremes was less than 8 inches and that a maximum of 11.85 inches was measured at the South St. Paul Station.

The greatest 24-hour rainfalls recorded within the 7 a.m. to 7 a.m. observation period for each station are listed in table 14. The absolute maximum occurred at Stillwater on May 31, 1965 when a severe thunderstorm moved across the area with the most intense rainfall occurring in and near Stillwater. It should be noted that this rainfall shows up in the June record because it was recorded at the 7 a.m. observation on June 1, 1965.

4. Precipitation Probabilities

The probability that precipitation of various amounts may occur is important in certain structure designs as well as to the forecaster. The opportunity to compare a central station, such as the airport, with a number of nearby stations is not often found. For that reason the probability of precipitation occurrence at each of the 25 stations was determined. The results for the airport site are compared to the 25 station average in figures 19-24. Each of the figures show the greater frequency of small amounts of precipitation at the airport station. This has been noted previously and is due to the difference in observation procedures between the airport station, where observations are taken four times per day, and the cooperative stations, where only one observation is made per day. In general, (figure 24) the frequency of precipitation at the airport station was somewhat lower than the average for the area with respect to amounts of 0.05 inch to 0.70 inch. The greatest difference between the airport and the 25 station average occurred in May and August (figures 19 and 22).

A common feature in all 5 months is the rapid decrease in the probability of precipitation occurrence that is found between a trace (T) and 0.10 inch. Close comparison of figures 19-23 shows a marked difference between months. These differences are more obvious in figure 25 which shows that June was the month of highest probability for all amounts of precipitation. For amounts less than 0.40 inch, May was the next highest, but for amounts equal to or greater than 0.40 inch, it had the least likelihood of precipitation. In contrast to May, July was the period of the least chance of precipitation for amounts less than 0.40 inch.

SUMMARY

A study was made of the daily precipitation at 25 stations within a 30-mile radius of the Twin Cities airport from May-September for the 5-year period 1964-1968. There were four objectives of this study.

The first objective was to determine the adequacy of a single rain gage to represent the area. One gage was inadequate because it greatly underestimated what actually occurred in this area of only 30-mile radius. For example, the frequency of daily rains of 0.01 inch or more indicated by a single gage was about 35 percent while in reality the frequency was closer to 65 percent.

The second objective was to find how many gages were required for an adequate sampling of the area. Results indicated that about 50 gages were required for a "true" sample. The number of gages required varies from about 45 in May and June to 60 in July.

Determination of areal extent of precipitation of given amounts was the third objective. While only approximations could be obtained, it appeared that the area of a rain was generally least in July and greatest in June. For example, the mean area of a daily rainfall of 0.05 inch or more was about 300 square miles in July and 695 square miles in June. In contrast, it was found that the maximum areal extent of the smallest 50 percent of the rains of 0.05 inch or more were 720 and 1680 square miles in July and June, respectively.

Table 14. Maximum daily (24-hour) rainfall in inches recorded at 25 Twin Cities stations, 1964-1968.

	Months					
Station	May	June	July	August	September	Maximum
1. Anoka	2.00	2.00	2.76	2.10	1.98	2.76
2. Bloomington	1.60	3.35	2.35	1.95	1.55	3.35
3. Excelsior	2.26	2.47	2.10	1.97	2.98	2.98
4. Farmington	1.90	1.95	2.02	1.40	3.35	3.35
5. Forest Lake	2.40	5.45	1.75	1.90	1.30	5.45
6. Gem Lake	1.65	5.25	2.75	1.95	2.80	5.25
7. Golden Valley	1.31	1.98	1.70	1.58	1.82	1.98
8. Hastings	1.62	5.83	2.69	1.49	2.50	5.83
9. Jordan	1.85	2.50	2.50	2.30	1.80	2.50
10. Lino Lakes	1.05	5.00	1.80	2.00	1.78	5.00
11. Lower St. Anthony Falls	1.20	2.46	1.56	2.15	2.18	2.46
12. Maple Plain	1.80	2.75	4.00	2.48	1.65	4.00
13. Minneapolis-St. Paul Airport	2.39	1.39	1.89	2.05	2.16	2.39
14. Mounds View	1.42	5.20	2.15	2.25	1.48	5.20
15. New Market	1.60	1.90	2.05	1.75	2.75	2.75
16. New Prague	2.05	2.25	3.25	1.75	2.30	3.25
17. Northfield	1.44	1.52	2.49	1.43	3.34	3.34
18. Rockford	1.06	1.84	1.95	2.66	2.60	2.66
19. St. Louis Park	1.15	2.50	3.00	1.55	2.85	3.00
20. St. Paul (1)	1.66	4.97	1.50	1.67	2.34	4.97
21. St. Paul (2)	1.25	4.75	1.65	2.20	2.45	4.75
22. So. St. Paul (1)	1.10	4.20	1.90	1.76	1.74	4.20
23. So. St. Paul (2)	1.31	7.44	2.01	1.32	2.82	7.44
24. Stillwater	0.92	7.98	1.40	1.23	2.19	7.98
25. Wayzata	1.50	2.75	2.32	2.25	2.75	2.75
Absolute Maximum	2.40	7.98	4.00	2.66	3.35	7.98

Daily rains of 0.10 inch or less fell in one of two ways: they were either local or very generalized in the area. For larger rainfalls the area of rain decreased as the amount of rain increased.

The fourth objective was to determine the variation in precipitation amounts experienced within the Twin Cities. In the brief 5-year study period, it was found that the maximum daily rainfall recorded equalled 7.98 inches, and the greatest total monthly rainfall was 11.85 inches. With respect to the density of a rain gage network, of even greater importance was the 6.56 inch different in the average May-September total precipitation between two stations that are only 16 miles apart. That this kind of difference can exist in an area of relatively level topography emphasizes the necessity of as dense a rain gage network as possible. Added emphasis to the need for a denser network is the fact that precipitation was lower at the airport site, the major station in the area, than the 5-year average of all of the stations for the May-September period.

The fact that greater precipitation occurs elsewhere in the metropolitan area may be due to the short period of record used. There is also a possibility, however, that the areas of greater precipitation within the metropolitan area may be tied to the influence of the urban - industrial complex. Recent evidence has shown (4, 7) that a large urban - industrial area may influence the local precipitation particularly in the summer. This is an extremely interesting and important consideration that, important as it is, cannot be undertaken at this time. It is hoped that this can be the subject of a study in the near future.

ACKNOWLEDGEMENT

We wish to acknowledge the foresight of Joseph H. Strub, Jr., supervisory meteorologist at the National Weather Service, Minneapolis-St. Paul International Airport station, for helping establish a number of the stations used in this study and the system of maintaining records. A.W. Buzicky, director of the Metropolitan Mosquito Control District, also deserves acknowledgement for being instrumental in establishing the Mosquito Control District weather observation network and in maintaining continuity of those stations. We, and the public in general, are also greatly indebted to the many weather observers in the National Weather Service cooperative network who regularly and voluntarily contribute their time and energy to provide the data upon which studies such as this are based.

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