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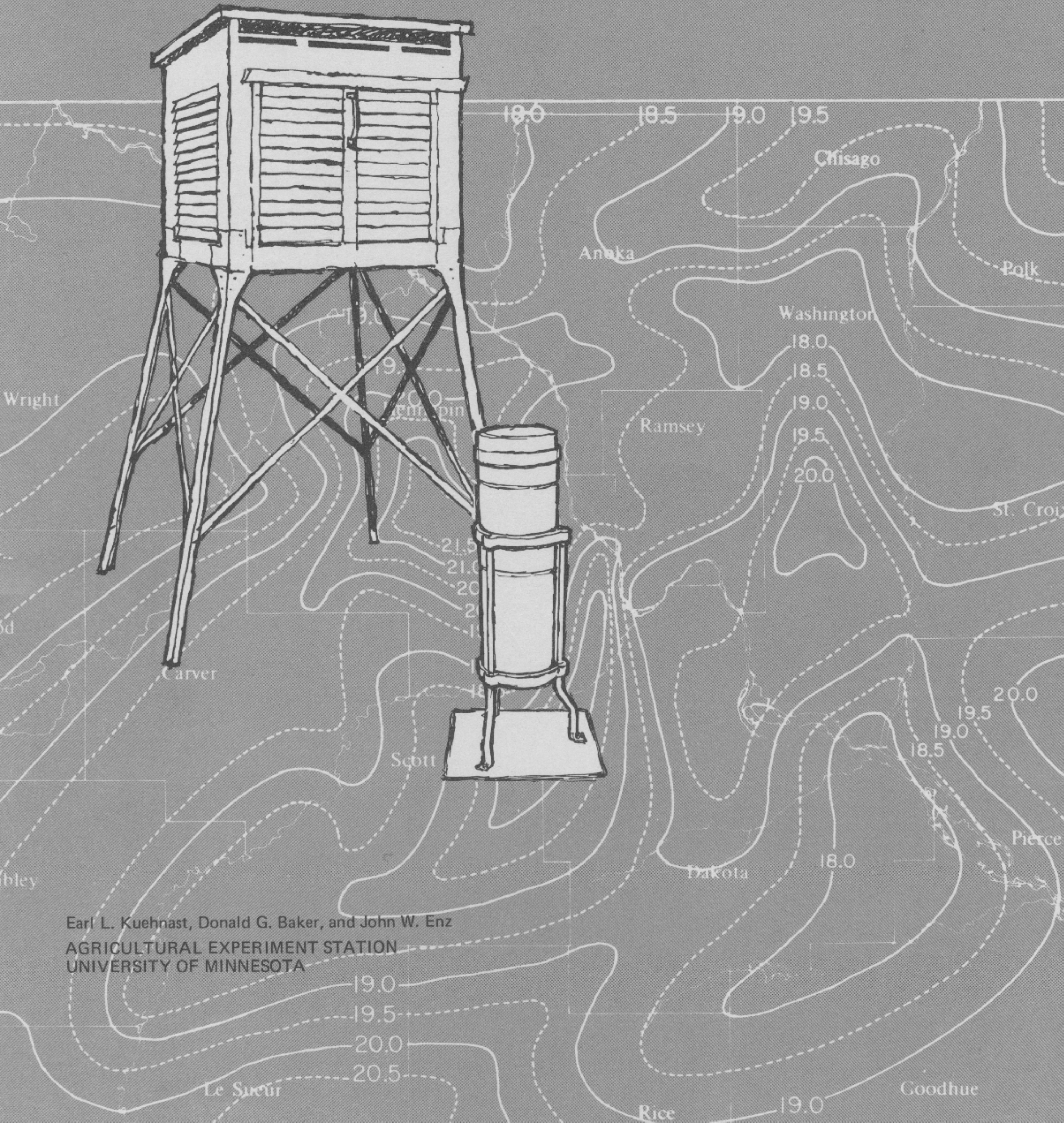
CLIMATE OF MINNESOTA

Part VIII -- Precipitation Patterns in the Minneapolis-St. Paul Metropolitan Area and Surrounding Counties



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CLIMATE OF MINNESOTA

Part VIII -- Precipitation Patterns in the Minneapolis-St. Paul Metropolitan Area and Surrounding Counties

As we move into the final quarter of the 20th century it is clear that the data relating to a number of resources are inadequate. The need to supply more and more detailed information increases, yet the adequacy of the data upon which the varied applications rest is often overlooked. Perhaps there is something about the resource itself, such as the apparent simplicity of measuring certain resources, that leads us into either neglecting the basic data or accepting inadequate information.

The subject of this bulletin is a case in point. It is often assumed that precipitation in Minnesota is adequately measured and its characteristics are well understood. The results of this study, however, indicate otherwise.

The distribution of precipitation over the state was first discussed in Part V (1) of the *Climate of Minnesota* series. This subject was later continued in Part VII (2), where it was restricted to precipitation distribution within the Minneapolis-St. Paul metropolitan area. The present study is a continuation of Part VII; it deals with a somewhat larger area than was considered in Part VII.

This bulletin has three main objectives. One is to provide relatively detailed water supply (precipitation) data for a limited but important part of the state for as brief a period of time as an adequate representation of the temporal variation in precipitation permitted. The urgent nature of some of the questions to be answered required that the data be made available as soon as an acceptable sample could be obtained. The importance of the study area rests upon the presence within it of the Twin Cities metropolitan area, in which nearly 2 million people live. The population, the associated commercial industry, and the agriculture in the area result in special considerations with respect to the planning, design, and supply of water. A second objective is to determine the validity of the regions of high and low precipitation that were first noted in a previous study (2). The third objective is to explain the presence of the high and low precipitation regions, presuming they are not due to chance.

MATERIALS AND METHODS

The previously mentioned need for detailed information about our resources includes the need for information on various elements of the hydrologic cycle. With that in mind, this study was based on a 14-year record of a May-September network of 75 stations and an October-April network of 52 stations in a 7,200 square mile area centered around the Twin Cities. A 14-year period was used because it appeared to be the best compromise between the number of station records available and an adequate time period for a relatively stable frequency distribution of the precipitation data.

The National Weather Service and the World Meteorological Organization have adopted a 30-year period as the time interval for which means are calculated. The 30-year period presently used is 1941-1970. With the 30-year mean, which is defined as a "normal," all stations with a record for that period are placed on a uniform time basis so acceptable comparisons can be made. The climates of two stations can thus be compared by examining their normals. In addition, the climate of any year, month, or day at a particular station can be compared to the normal by noting any departures from it.

The problems associated with a longer record should be recognized. For example, using a 30-year normal results in a long wait for a base or standard to be developed. Secondly, real climatic fluctuations that are short term in nature may be masked by a longer record. A 5-year record, for instance, may more nearly reflect the climate of the immediate future than a long term one. Although long term records are more valuable for assessing long range precipitation projections, shorter records are frequently more valuable for making projections over shorter time periods (for the coming decade, for example). It is also true that changes in the local environment and measurement site are more likely to occur and affect the record over the longer period. Enger (7), referring to temperature records, concluded that the optimum period of a monthly record is about 20 years.

Aside from the fact that a 14-year record might possibly be superior to a 30-year record with respect to short term climatic fluctuations, it seemed desirable to determine how well the 14 years used in this study (1959-1972) approximated the current normal period (1941-1970). To this end, the 1941-1970 normals, which were available

Table 1. Mean total of May-September precipitation observed at six stations for the 14-year (1959-1972) and the 30-year normal (1941-1970) periods

Station	Total precipitation, May-September		
	1959-1972	1941-1970	Difference
		inches	
Chaska	19.14	19.49	−0.35
Faribault	20.08	20.50	−0.42
Farmington 3NW	18.27	19.33	−1.06
Hastings	17.59	18.47	−0.88
Maple Plain	19.48	19.70	−0.22
MSPAP*	16.64	16.77	−0.13

* Minneapolis-St. Paul International Airport weather station.

for only six stations, were compared to the 1959-1972 means. Table 1 shows that the 1959-1972 May-September precipitation for each station was slightly lower than the 1941-1970 normal. A two-tailed t-test was applied to the differences shown in table 1 to determine whether they were significantly different from zero. Since the 1941-1970 normals and the 1959-1972 means are not independent, a pooled sample variance was calculated for the 32-year period. The resultant t values were all nonsignificant at the 30-percent level. This strongly supports the hypothesis of no difference between the 1941-1970 normals and the 1959-1972 means for all six stations.

To further verify this hypothesis, another comparison was made for those stations with 30-year means that were independent of the 1959-1972 means. Three stations had such records: Chaska, Farmington, and Maple Plain. A two-tailed t-test was used to test the differences between the 1929-1958 and the 1959-1972 May-September precipitation totals for each location. Results showed no difference between the means for the two periods at the 40-percent level.

The location of each station is shown in figure 1. The area covered measured 90 miles east to west and 80 miles north to south. Additional information on each station appears in table 2. The 75 stations include 11 that are just outside the mapped area. Data from these 11 stations were used as an aid to analyzing the precipitation maps. Twenty-three of the 75 stations are from the Metropolitan Mosquito Control District network; the remainder are part of the National Weather Service precipitation network. The altitude of the area ranges from 1,225 feet above mean sea level at Ellsworth, Wisconsin, in the southeastern part of the area, to a minimum of 677 feet mean sea level at the Red Wing Dam on the Mississippi River.

All of the 12-month stations were equipped with the National Weather Service standard 8-inch rain and snow gage except for Le Sueur and Northfield, Minnesota, and New Richmond, Wisconsin, which had the 8-inch automatic recording gage. All stations with 5-month (May-September) records had the plastic wedge-shaped "Tru-Chek" rain gage, except for the Horticultural Research Center at Excelsior, where the 8-inch National Weather Service rain and snow gage was used.

The area of concern centers around the Minneapolis-St. Paul International Airport Station (MSPAP), a major National Weather Service station, which is an important observing station as well as a state forecast center. The monthly data from this station plus 52 National Weather Service cooperative stations in Minnesota and Wisconsin and 23 Metropolitan Mosquito Control District stations were analyzed for the 14-year period 1959-1972. Observations at the National Weather Service stations were taken through the year, whereas those at the Metropolitan Mosquito Control District stations were taken only during the growing season months of May-September.

As noted earlier, data from 75 stations were used for the May-September analysis of the 7,200 square mile area, but data from 52 stations were used for the October-April period. The stations are not uniformly distributed around the area, as there is a concentration of stations

Table 2. Index of the precipitation station network (observations made January-December)

Station name, by county	Station address	Observer	Elevation, feet above sea level	County-township-range-section number
ANOKA COUNTY				
Cedar	Cedar Post Office	Mrs. D. Gallagher	907	02-033-24-26
St. Francis	19710 Rum River Blvd.	P. George	925	02 033-24-19
BROWN COUNTY				
New Ulm[P]	KNUJ transmitter site	G. Walston	826	08-110-30-34
CARVER COUNTY				
Chaska	American Crystal Sugar Co.	Plant personnel	726	10-115-23-04
Young America	Residence	D. Flewelling	1,020	10-115-26-11
DAKOTA COUNTY				
Farmington 1NW[1]	Residence	V. Kelly	915	19-114-19-31
Farmington 3NW	Residence	J. Akin	980	19-114-20-14
Hastings Dam	U.S. Corps of Engr., Lock No. 2	J. L. Brewer	695	19-115-17-21
Rosemount	U. of M. Ag. Exp. Stn.	A. Heine, C. Wilcox	950	19-115-19-33
South St. Paul	Pump House No. 4	City engineer	750	19-028-22-34
GOODHUE COUNTY				
Red Wing City	Waste treatment plant	Plant personnel	688	25-113-14-29
Red Wing Dam	U.S. Corps of Engr., Lock No. 3	W. Conley, E. Schulty	677	25-113-15-10
Zumbrota	15 Mill St.	H. Bailey, A. Lohman	985	25-110-16-25
HENNEPIN COUNTY				
Bloomington	9930 Logan Ave.	Police Dept., Barr Engr.	831	27-027-24-16
Excelsior	Sewage treatment plant	E. Hafner, C. Zieman	940	27-117-23-34

[1] Farmington 1W: 1½ years of data substituted from Farmington 3NW (2 miles NNW).
[P] Station located on or near the perimeter of the map.

Table 2 (continued). Index of the precipitation station network (observations made January-December)

Station name, by county	Station address	Observer	Elevation, feet above sea level	County-township-range-section number
HENNEPIN COUNTY (continued)				
Maple Plain	Residence	C. H. Meyers	970	27-118-24-25
Mpls. St. Paul Airport (MSPAP)	FAA Bldg., 6301 34th Ave. So.	National Weather Service	834	27-028-23-30
Robbinsdale[2]	3527 Grimes	R. C. Greene	900	27-029-24-07
St. Anthony Falls[3]	U.S. Corps of Engr., Lock No. 1	M. G. Pratt	755	27-029-24-23
U. of M., Minneapolis[4]	Dept. of Pub. Health, Mpls.	A. Hollenbeck	840	27-029-24-25
ISANTI COUNTY				
Cambridge[p]	Cambridge State Hospital	Hospital personnel	1,000	30-036-23-32
LE SUEUR COUNTY				
Le Center	Residence	F. Kampen, H. Schloesser	1,064; 1,090	40-111-24-29
Le Sueur	Green Giant Co.	Plant personnel	845	40-112-26-36
Montgomery	Green Giant Co.	Plant personnel	1,100	40-111-23-10
MC LEOD COUNTY				
Hutchinson[p]	KDUZ transmitter site	KDUZ personnel	1,095	43-117-29-30
Winsted	Residence	J. Baird	1,025	43-117-27-03
MEEKER COUNTY				
Litchfield[p]	Municipal power plant	L. Nelson	1,132	47-119-31-11
NICOLLET COUNTY				
St. Peter	Minnesota Security Hospital	Security personnel	825	52-110-26-29
RAMSEY COUNTY				
North St. Paul[5]	2194 E. Radatz Ave.	D. C. Wierstad	981	62-029-22-02
St. Paul	707 Montana Ave. E.	J. H. Riddell	920	62-029-22-20
U. of M., St. Paul[6]	Dept. of Soil Science, St. Paul	D. G. Baker and students	969	62-029-23-21
RICE COUNTY				
Faribault[p]	KDHL transmitter site	KDHL personnel	1,075	66-109-20-07
Northfield	Carleton College	R. Mathews	950	66-112-19-31
	Waste treatment plant	Plant personnel	890	66-112-19-30
SCOTT COUNTY				
Jordan	Residence	Mrs. G. Slavicek	930	70-114-23-29
SHERBURNE COUNTY				
Elk River	Municipal power plant	Plant personnel	910	71-033-26-33
SIBLEY COUNTY				
Gaylord	County engineer's office	G. Anderson	1,018	72-113-28-32
Stewart[p]	Residence	W. Schreiner	1,035	72-114-31-26
STEARNS COUNTY				
St. Cloud[p]	St. Cloud Airport	National Weather Service	1,034	73-124-28-02
		(since 1972)	1,028	71-035-30-03
WABASHA COUNTY				
Lake City[p]	318 S. Oak St.	B. J. Simons	680	70-111-12-04
WASECA COUNTY				
Waseca[p]	U. of M., Ag. Exp. Stn.	L. Alrichs, R. Frazier	1,153	81-107-22-18
WASHINGTON COUNTY				
Forest Lake	Residence	F. Cohoes	940	82-032-21-13
Stillwater	Waste treatment plant	Plant personnel	710	82-030-20-34
WRIGHT COUNTY				
Buffalo	809 5th Ave. S.	P. Schefchik	990[e]	86-120-25-19
Cokato	Green Giant Co.	Plant personnel	1,070	86-119-28-34
Delano[7]	130 3rd St.	C. A. Stein	944[e]	86-118-25-11
Rockford	Residence	H. N. Thompson	940[e]	86-119-24-29
WISCONSIN				
Amery[p]	Waste treatment plant	Plant personnel	1,070	90-033-16-33
Baldwin[p]	Residence	E. Rudesill	1,100	90-029-16-30
Ellsworth	Residence	G. Kay, C. Rice	1,225	90-026-17-19
New Richmond	Friday Canning, Waste treatment	Plant personnel	990, 980	90-031-18-36
River Falls	127 N. 4th St.	J. Mosher, Jr.	900	90-027-19-01
St. Croix Falls	Northern States Power	NSP personnel	770	90-034-18-19

[2] Robbinsdale: 5 years of data substituted; taken by S. C. Reckers, 2917 Sumter Ave. N., New Hope (2½ miles WSW).
[3] St. Anthony Falls: 1 year of data estimated from nearby stations.
[4] U. of M., Minneapolis: 1 year of data estimated from nearby stations.
[5] North St. Paul: 3 years of data substituted; taken by J. Riddell, 707 Montana Ave. E. (4 miles SW).
[6] U. of M., St. Paul: 2 years of data substituted; taken by D. Brostrom, 1957 Arona, Roseville (1 mile NE).
[7] Delano: 4 years of data substituted; taken by H. N. Thompson, Rockford (4 miles NE).
[e] Estimated.
[p] Station located on or near the perimeter of the map.

Table 2 (continued). Index of the precipitation station network (observations made May-September)

Station name, by county	Station address	Observer	Elevation, feet above sea level	County-township-range-section number
ANOKA COUNTY				
Anoka County Headquarters[8]	11949 Crooked Lane Blvd.	M. Bodine, P. Talbot	870e	02-032-25-36
Bethel	County Rd. 13	M. Bodine	915e	02-033-24-01
Lino Lakes[9]	441 Birch St.	J. Speiser	900e	02-031-22-29
South Columbus Township[10]	Mueller's Garage, U.S. Hwy. 8	J. Speiser, M. Bodine	909e	02-032-22-28
CARVER COUNTY				
Horticultural Research Center	U. of M., Excelsior	University personnel	1,016e	10-116-23-07
DAKOTA COUNTY				
Farmington	500 Elm St.	R. E. Rademacher	900e	19-114-19-31
South St. Paul	649 6th Ave. S.	R. Neary, A. Alex	820e	19-028-22-27
HENNEPIN COUNTY				
Bloomington[11]	10524 Vessey Rd.	J. Linton	870e	27-116-21-33
Brooklyn Center[12]	6330 Kyle Ave. N.	R. Lovberg	860e	27-119-21-34
Maple Plain	Residence	D. McKown, R. Rhuby	970	27-118-24-24
Plymouth Township	State Hwy. 101 & 12th Ave. N.	C. Martin	990e	27-118-22-32
St. Louis Park	4510 W. 36th St.	K. Shoberg	900e	27-028-24-06
RAMSEY COUNTY				
Gem Lake[13]	U.S. Hwy. No. 61 & County Rd. E	C. D. Barnum	930e	62-030-22-34
Moundsview	1801 County Rd. H	C. D. Barnum	900e	62-030-23-07
St. Paul	1709 Rome Ave.	A. W. Buzicky	940e	62-028-23-16
SCOTT COUNTY				
Belle Plaine[14]	Residence	M. Hartman, T. O'Laughlin	840e	70-113-24-06
Jordan (Scott County Headquarters)	Main St.	Mosquito Control personnel	780e	70-114-23-19
New Market	Webster St.	R. Simon	1,100e	70-113-21-28
New Prague	405 N. Lincoln Ave.	E. Wermerskirchen	1,000e	70-113-23-34
WASHINGTON COUNTY				
Forest Lake	22814 Haynard Ave. N.	V. Loren	920e	82-032-21-10
Grant Township Headquarters[15]	Northport Airport	V. Loren	1,000e	82-030-21-16
Oakdale Township[16]	4271 Friedrich, Lake Elmo	D. Delander	935e	82-029-21-15
Woodbury Township[17]	Section 11	D. Delander, D. Rabbas	925e	82-028-21-11

[8] Anoka County Headquarters: Headquarters moved in 1971 (2 miles SE).
[9] Lino Lakes: 6 years of data substituted; taken by W. J. Dufresne (5 miles NE).
[10] South Columbus Township: 6 years of data substituted; taken by W. J. Dufresne (2 miles SE).
[11] Bloomington: 3 years of data substituted; taken by Bloomington Police Dept. (3 miles NE).
[12] Brooklyn Center: 3 years of data observed by C. R. Klima, 5907 June Ave. (½ mile S); 2 years of data taken by B. McRae, 41st and Georgia (3 miles SSW).
[13] Gem Lake: 3 years of data substituted; taken by J. Brown (½ mile S).
[14] Belle Plaine: 4 years of data substituted from Scott County Headquarters, Jordan (6 miles ENE).
[15] Grant: 1 year of data taken at different location (2 miles SW).
[16] Oakdale: 2 years of data taken at 2829 Midvale Ave. (3 miles SW) and 3 years of data taken by J. Eder (2 miles W).
[17] Woodbury: 4 years of data taken at 2829 Midvale Ave. (4 miles NW).
e Estimated.

in and around the Twin Cities. Although the distribution is not uniform, the number of stations is vastly superior to most precipitation gage networks. For example, in Minnesota, there are only 91 regularly reported National Weather Service stations (10) with a 30-year normal for the 1941-1970 period. This is a density of only one station per 923 square miles. By comparison, the 75 stations for the May-September period in this study provide a density of one station per 96 square miles, and the 52 stations available for October-April, when storms tend to be more widespread, equal one per 138 square miles.

Huff (8) has shown the precipitation gage density in Illinois required to detect rainfall of various amounts for given probability levels. Care must be exercised in applying these results too broadly, for the largest area with a high density precipitation gage network available to Huff was only 550 square miles. Keeping this in mind, the extension of Huff's results to the much larger area of 7,200 square miles indicates that a density of about one precipitation gage per 250 square miles is sufficient to detect 99 percent of the summer storms of 0.01 inch or more. A lower station density is sufficient for winter precipitation of similar amounts because of the more widespread nature of winter storms. With a density of 96 square miles per gage, the 7,200 square mile Twin Cities area network is denser than required to detect 99 percent of the storms producing 0.01 inch or more, based on the extension of Huff's results. The adequacy of the network in this study to detect small area storms typical of summer convective showers is further substantiated by translation of data from studies of three precipitation networks of 7,850; 3,847; and 2,826 square miles investigated by Beebe (3), Causey (5), and Baker and Kuehnast (2), respectively, which indicate that an "ideal" network for a 7,200 square mile area requires about one gage per 100 square miles. An ideal network was defined (2) as the minimum number of rain gages required to determine the maximum frequency of rain-days. A rain-day is one in which at least 0.01 inch is measured. As mentioned before, the distribution of the stations is not uniform across the area, although the station density in this study is more than adequate to detect storms of a very small area.

Figure 1. Name and location of the stations used in this 14-year precipitation study, 1959-1972

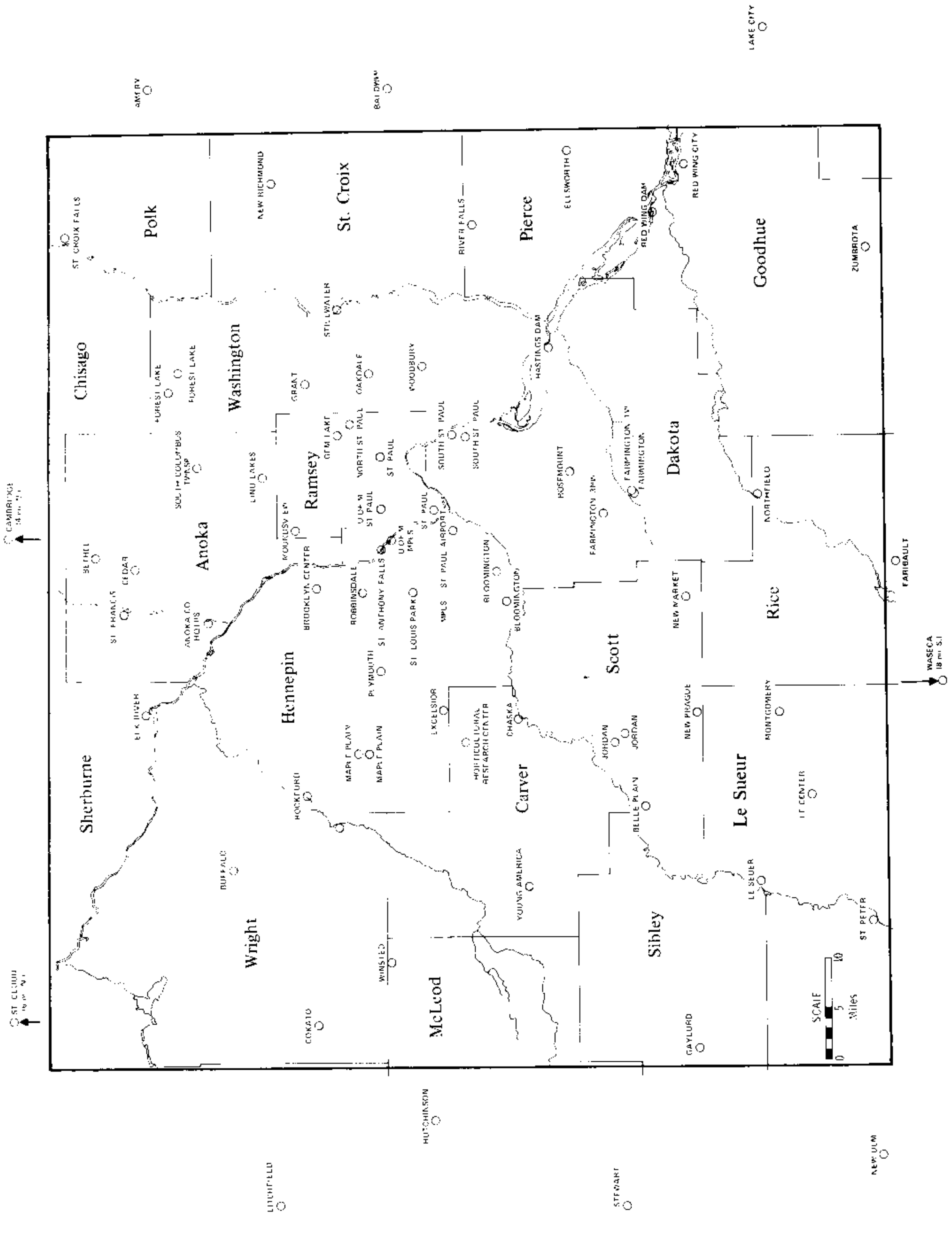

Table 3. Metropolitan Twin Cities 14-year precipitation averages, January-December, 1959-1972

Station	January	February	March	April	May	June	July	August	September	October	November	December	Annual
							inches						
ANOKA COUNTY													
Cedar	.99	1.07	1.44	2.42	4.26	3.68	3.91	3.80	3.22	2.72	1.27	1.27	30.05
St. Francis	.98	.87	1.42	1.98	3.85	3.39	3.73	3.58	3.16	2.55	1.30	1.24	28.05
BROWN COUNTY													
New Ulm	.76	1.03	1.40	2.59	3.97	3.66	4.54	3.22	3.18	2.55	1.06	1.06	29.02
CARVER COUNTY													
Chaska	.56	.55	1.31	2.29	4.52	4.29	4.18	2.93	3.22	2.50	1.22	.91	28.48
Young America	.73	.92	1.53	2.44	4.56	4.68	4.24	3.19	2.97	2.48	1.31	1.16	30.21
DAKOTA COUNTY													
Farmington 1NW	.84	.82	1.38	2.06	3.89	3.93	3.86	3.58	3.25	2.61	1.13	1.07	28.42
Farmington 3NW	.92	.99	1.65	2.25	3.93	3.96	3.83	3.27	3.28	2.71	1.25	1.24	29.28
Hastings Dam	.71	.57	1.42	1.98	3.53	3.94	3.90	2.78	3.44	2.58	1.22	.96	27.03
Rosemount	.94	.80	1.50	2.49	4.07	4.37	3.85	3.38	3.58	2.96	1.31	1.28	30.53
South St. Paul	1.01	.84	1.58	2.30	4.03	4.69	3.64	3.43	3.66	2.94	1.24	1.14	30.50
GOODHUE COUNTY													
Red Wing City	.82	.72	1.41	2.13	4.00	4.20	4.15	2.90	4.00	2.82	1.27	1.19	29.61
Red Wing Dam	.83	.65	1.49	2.50	3.87	3.59	4.16	2.92	3.84	2.61	1.14	1.07	28.67
Zumbrota	.86	.62	1.40	2.50	3.62	4.21	4.02	3.06	4.38	2.95	1.09	1.19	29.90
HENNEPIN COUNTY													
Bloomington	.62	.67	1.53	1.96	4.37	3.60	3.73	3.10	2.89	2.59	1.10	.90	27.06
Excelsior	.93	.89	1.46	2.58	4.40	4.28	4.25	3.17	3.35	2.77	1.44	1.28	30.80
Maple Plain	.83	.61	1.08	2.47	4.72	3.69	4.43	3.43	3.21	2.64	1.44	1.00	29.55
MSPAP	.92	.84	1.72	2.19	3.85	3.39	3.34	3.06	3.00	2.54	1.15	1.08	27.08
Robbinsdale	.87	.84	1.58	2.65	4.33	3.88	4.08	3.65	3.10	2.51	1.42	1.24	30.15
St. Anthony Falls	1.03	.78	1.43	2.42	4.16	3.65	3.74	3.34	3.42	2.55	1.34	1.24	29.10
U. of M., Mpls.	1.04	.89	1.73	2.52	4.19	3.45	3.76	3.45	3.20	2.77	1.36	1.33	29.69
ISANTI COUNTY													
Cambridge	.73	.63	1.27	2.10	3.56	3.94	3.91	3.37	3.50	2.67	1.29	1.20	28.17
LE SUEUR COUNTY													
Le Center	.76	.79	1.34	2.59	4.46	3.78	4.83	3.82	3.89	2.66	1.14	1.26	31.32
Le Sueur	.58	.57	1.19	2.43	3.76	3.45	4.55	3.37	3.08	2.33	.99	.94	27.24
Montgomery	.59	.69	1.47	2.68	4.56	3.51	4.49	3.48	3.92	2.51	1.15	1.04	30.09
MC LEOD COUNTY													
Hutchinson	.66	.65	1.14	2.19	3.90	3.94	3.44	3.26	2.45	2.12	1.23	1.00	25.98
Winsted	.79	.67	.98	2.59	3.96	3.00	4.20	3.15	2.98	2.27	1.73	.98	27.32
MEEKER COUNTY													
Litchield	.81	.67	1.19	2.49	3.66	3.85	3.73	3.38	2.87	2.15	1.23	.97	27.00
NICOLLET COUNTY													
St. Peter	.64	.78	1.16	2.54	4.18	4.00	4.80	3.86	3.45	2.33	1.06	1.04	29.84

Table 3 (continued). Metropolitan Twin Cities 14-year precipitation averages, January-December, 1959-1972

Station	January	February	March	April	May	June	July	August	September	October	November	December	Annual
							inches						
RAMSEY COUNTY													
North St. Paul	.80	.77	1.48	2.41	3.86	4.11	3.58	3.44	3.33	2.82	1.24	1.15	28.99
St. Paul	.87	.79	1.59	2.29	3.75	4.36	3.42	3.45	3.39	2.94	1.30	1.20	29.35
U. of M., St. Paul	.58	.56	1.36	2.35	3.88	3.82	3.92	3.46	3.65	2.84	1.26	1.01	28.69
RICE COUNTY													
Faribault	.90	.92	1.92	2.82	4.28	3.79	4.18	3.58	4.25	2.91	1.15	1.32	32.02
Northfield	.91	.83	1.69	2.54	3.59	3.82	3.85	3.19	3.73	2.51	1.16	1.27	29.09
SCOTT COUNTY													
Jordan	.71	.66	1.27	2.30	4.48	4.03	3.91	3.32	3.01	2.63	1.03	.97	28.32
SHERBURNE COUNTY													
Elk River	.77	.77	1.29	2.14	3.89	3.68	3.75	3.66	3.25	2.39	1.32	1.07	27.98
SIBLEY COUNTY													
Gaylord	.68	.78	1.47	2.79	4.26	4.11	4.47	3.47	3.11	2.57	1.12	1.00	29.83
Stewart	.74	.84	1.26	2.47	3.48	4.17	4.14	3.43	3.04	2.32	1.15	1.03	28.07
STEARNS COUNTY													
St. Cloud	.76	.63	1.08	2.29	3.90	3.72	3.17	3.92	2.54	2.12	.97	.95	26.05
WABASHA COUNTY													
Lake City	1.10	.73	1.61	2.62	3.86	4.37	4.18	2.94	3.79	2.85	1.36	1.35	30.76
WASECA COUNTY													
Waseca	.78	1.05	1.49	2.54	3.98	4.20	4.46	3.55	4.26	2.72	1.08	1.16	31.27
WASHINGTON COUNTY													
Forest Lake	.81	.54	1.20	1.92	3.79	4.01	3.39	3.66	2.79	2.52	1.17	1.16	26.96
Stillwater	.82	.72	1.46	2.33	3.45	3.97	3.52	3.38	3.59	2.87	1.16	1.09	28.36
WRIGHT COUNTY													
Buffalo	1.08	.81	1.40	2.56	4.03	3.29	4.23	3.70	3.06	2.35	1.42	1.27	29.20
Cokato	.95	.89	1.26	2.38	4.04	3.36	4.30	3.40	3.12	2.31	1.24	1.08	28.33
Delano	.75	.69	1.19	2.56	4.34	3.48	3.76	3.08	3.02	2.55	1.24	.93	27.59
Rockford	.82	.72	1.27	2.49	4.18	3.83	4.10	3.31	3.30	2.53	1.32	.98	28.85
WISCONSIN													
Amery	.95	.75	1.36	2.18	3.86	4.21	4.06	4.40	3.72	2.78	1.29	1.37	30.93
Baldwin	.85	.86	1.57	2.34	3.99	4.04	3.53	3.33	4.07	2.86	1.29	1.23	29.96
Ellsworth	1.01	.84	1.76	2.50	4.36	4.83	4.10	3.04	4.07	3.00	1.50	1.38	32.39
New Richmond	.93	.66	1.38	2.24	3.72	3.40	3.29	3.86	3.90	2.66	1.28	1.36	28.68
River Falls	.89	.68	1.53	2.40	4.09	4.33	3.79	3.42	3.96	2.85	1.40	1.21	30.55
St. Croix Falls	.99	.69	1.40	2.41	4.02	4.00	3.93	4.44	3.40	2.89	1.34	1.33	30.84

Table 3 (continued). Metropolitan Twin Cities 14-year precipitation averages, May-September, 1959-1972

Stations	May	June	July	August	September
	inches				
ANOKA COUNTY					
Anoka County Headquarters	3.76	3.41	3.76	4.14	3.32
Bethel	3.76	3.81	3.72	3.43	3.42
Lino Lakes	4.11	3.40	4.14	3.88	3.14
South Columbus Township	3.84	3.36	3.59	3.73	3.00
CARVER COUNTY					
Horticultural Research Center	4.32	4.08	3.71	3.20	3.14
DAKOTA COUNTY					
Farmington	4.00	3.97	4.03	3.58	3.65
South St. Paul	4.13	4.72	3.74	3.29	3.56
HENNEPIN COUNTY					
Bloomington	4.31	3.89	4.09	3.17	3.24
Brooklyn Center	4.04	3.97	4.29	3.20	3.37
Maple Plain	4.40	3.86	4.12	3.30	3.16
Plymouth	5.25	4.51	4.30	4.13	3.77
St. Louis Park	4.48	4.10	4.25	3.39	3.59
RAMSEY COUNTY					
Gem Lake	3.57	3.95	3.80	3.60	3.42
Moundsview	3.96	3.85	3.91	3.68	3.22
St. Paul	4.07	3.86	4.10	3.55	3.62
SCOTT COUNTY					
Belle Plaine	4.36	3.82	3.79	3.14	3.05
Jordan	4.25	3.88	4.05	3.24	3.06
New Market	3.82	3.80	3.86	3.40	3.48
New Prague	4.40	3.60	3.55	3.15	3.50
WASHINGTON COUNTY					
Forest Lake	3.94	4.37	3.69	3.89	3.12
Grant Township	3.76	4.27	4.04	3.78	3.52
Oakdale Township	3.90	4.69	4.15	3.65	3.98
Woodbury Township	3.89	4.45	3.85	3.53	3.93

DISCUSSION

Mean Monthly and Annual Total Precipitation

The mean monthly precipitation for the 52 stations that had 12-month records for the 14-year period of 1959-1972 is shown in table 3. This table also contains the mean monthly precipitation for the 23 stations that had records for the 5-month May-September period for the same years.

The calculated monthly and annual means for the 7,200 square mile area are shown in table 4. They are based on data from the same set of stations listed in table 3, with 52 stations used for the October-April period and 75 for the May-September period. The means in table 4 are correct if the stations are assumed to be uniformly spaced throughout the area. Under this assumption, the mean annual precipitation for the whole area equals 29.09 inches. The monthly averages range from a low of 0.76 inch in February to a maximum of 4.05 inches in May. Both the mean monthly totals and the standard deviation of the means shown in table 4 indicate that there are two different precipitation seasons. One is the "dry" season of November-February, with a monthly average of only 0.99 inch and a standard deviation that is limited to 0.13-0.14 inch. In contrast is the "wet" or growing season of May-September, with an average total monthly precipitation of 3.75 inches and a standard deviation ranging from 0.32-0.39 inch.

A seasonal or monsoon-like shift in the winds produces the wet and dry periods that occur during a typical year (1). These two seasons are separated by March-April and October. These three months are transition periods, as evidenced by the intermediate precipitation of 1.42-

Table 4. Mean monthly and annual precipitation totals for the 7,200 square mile area and the Minneapolis-St. Paul International Airport station (MSPAP), 1959-1972

Month	Number of stations in the area	Standard deviation of mean in the area	MSPAP mean	Area mean	Difference (MSPAP mean minus area mean)
		inches			
January	52	0.13	0.92	0.83	0.09
February	52	0.13	0.84	0.76	0.08
March	52	0.19	1.72	1.41	0.31
April	52	0.21	2.19	2.38	−0.19
May	75	0.32	3.85	4.05	−0.20
June	75	0.38	3.39	3.93	−0.54
July	75	0.34	3.34	3.96	−0.62
August	75	0.33	3.06	3.45	−0.39
September	75	0.39	3.00	3.40	−0.40
October	52	0.23	2.54	2.62	−0.08
November	52	0.14	1.15	1.24	−0.09
December	52	0.14	1.08	1.14	−0.06
May-September	75	0.95	16.64	18.79	−2.15
Annual	52	1.48	27.08	29.17	−2.09

2.62 inches and a standard deviation ranging from 0.19-0.23 inch.

The last column in table 4 shows the difference between MSPAP and the area as a whole. In the May-September period, MSPAP averaged 2.15 inches less than the areal mean. Only in January-March did MSPAP exceed the areal mean. The amount and sign of the differences point to preferred locations of convective activity as the main cause of the variation. That the annual total precipitation at MSPAP averaged 2.09 inches less than the area indicates that the airport site represents the area very poorly during the growing season.

Nearly two-thirds of the state's annual precipitation falls in the growing season of May-September, a fortunate circumstance for Minnesota agriculture. Table 4 shows that less than 20 percent of the annual precipitation falls during the 4¼ month period from about December 8 to April 14, when agricultural soils in the area ordinarily are frozen. Much of this precipitation is lost as runoff during spring snow melt and therefore is ineffective in adding to soil moisture reserves.

The mean precipitation of the 7,200 square mile area for various combinations of months is listed in table 5. These data will be of value in certain types of planning studies. It should be noted that Ellsworth, Wisconsin, appears in five of the various "highest mean" categories.

Worthy of note is the 5.32-inch difference between Plymouth and MSPAP for the May-September period. This is nearly equal to the maximum difference found between the northwestern and southeastern corners of the state, which normally represent the driest and wettest areas, respectively. For example, the 1941-1970 normal May-September precipitation at Spring Grove in Houston County was 20.51 inches, whereas at Angus in Polk County, the total was only 14.19 inches, a difference of 6.32 inches. The importance of the regional precipitation differences that exist across the state are recognized in such matters as agricultural production. That differences of similar magnitude can and do exist within a few miles of each other, however, is seldom considered.

Precipitation Gradient Across the Cities

The distribution of the mean monthly and seasonal precipitation for the area is illustrated in figures 2-13 and 14-20, respectively. Perhaps the most obvious feature in these maps of the areal distribution is the weak gradient that exists in the winter months and the comparatively strong gradient that exists in the summer months. The difference in the gradients appears to coincide with the same seasons noted earlier in reference to the mean monthly precipitation: a winter or dry season of November-February with a very low gradient across the region and a growing or wet season of May-September with a monthly precipitation gradient that is more than three times greater than that for the dry season. The last column in table 6 gives a measure of the differences that occur for the two precipitation seasons and the transition periods between them. The wettest location was Ellsworth, Wisconsin, with 32.39 inches; the driest was Forest Lake, with 26.96 inches for the annual total 14-year average.

Table 5. Mean precipitation totals and associated information for various combinations of months for the 7,200 square mile area, 1959-1972

Months	Number of stations	Mean total	Standard deviation	Percentage of annual	Highest mean	Lowest means	Difference
		inches			inches		
December-February	52	2.73	0.34	09.3	3.33 Cedar	2.02 Chaska	1.31
December-March	52	4.15	0.48	14.3	5.06 Faribault	3.28 Le Sueur	1.78
November-March	52	5.40	0.51	18.6	6.49 Ellsworth	4.27 Le Sueur	2.20
March-May	52	7.82	0.50	26.8	9.02 Faribault	6.91 Forest Lake	3.11
April-June	52	10.36	0.61	35.6	11.69 Ellsworth	9.22 St. Francis	2.47
April-July	52	14.29	0.85	49.1	15.92 Young America	12.65 New Richmond	3.27
April-August	52	17.74	0.85	61.0	19.48 Le Center	15.83 MSPAP	3.62
April-September	52	21.13	1.05	72.6	23.37 Le Center	18.83 MSPAP	4.54
April-November	52	24.98	1.18	85.9	27.40 Ellsworth	22.52 MSPAP	4.88
May-July	75	11.98	0.72	41.2	14.06 Plymouth	10.41 New Richmond	3.65
May-August	75	15.37	0.77	52.8	18.19 Plymouth	13.64 MSPAP	5.55
May-September	75	18.78	0.75	64.6	21.96 Plymouth	16.64 MSPAP	5.32
June-August	75	11.33	0.59	39.0	12.94 Plymouth	9.79 MSPAP	3.15
September-November	52	7.26	0.65	25.0	8.57 Ellsworth	5.63 St. Cloud	2.94
Annual	52	29.09	1.48	100.0	32.39 Ellsworth	26.96 Forest Lake	5.43

Figure 2. Mean monthly precipitation in inches, January, 1959-1972

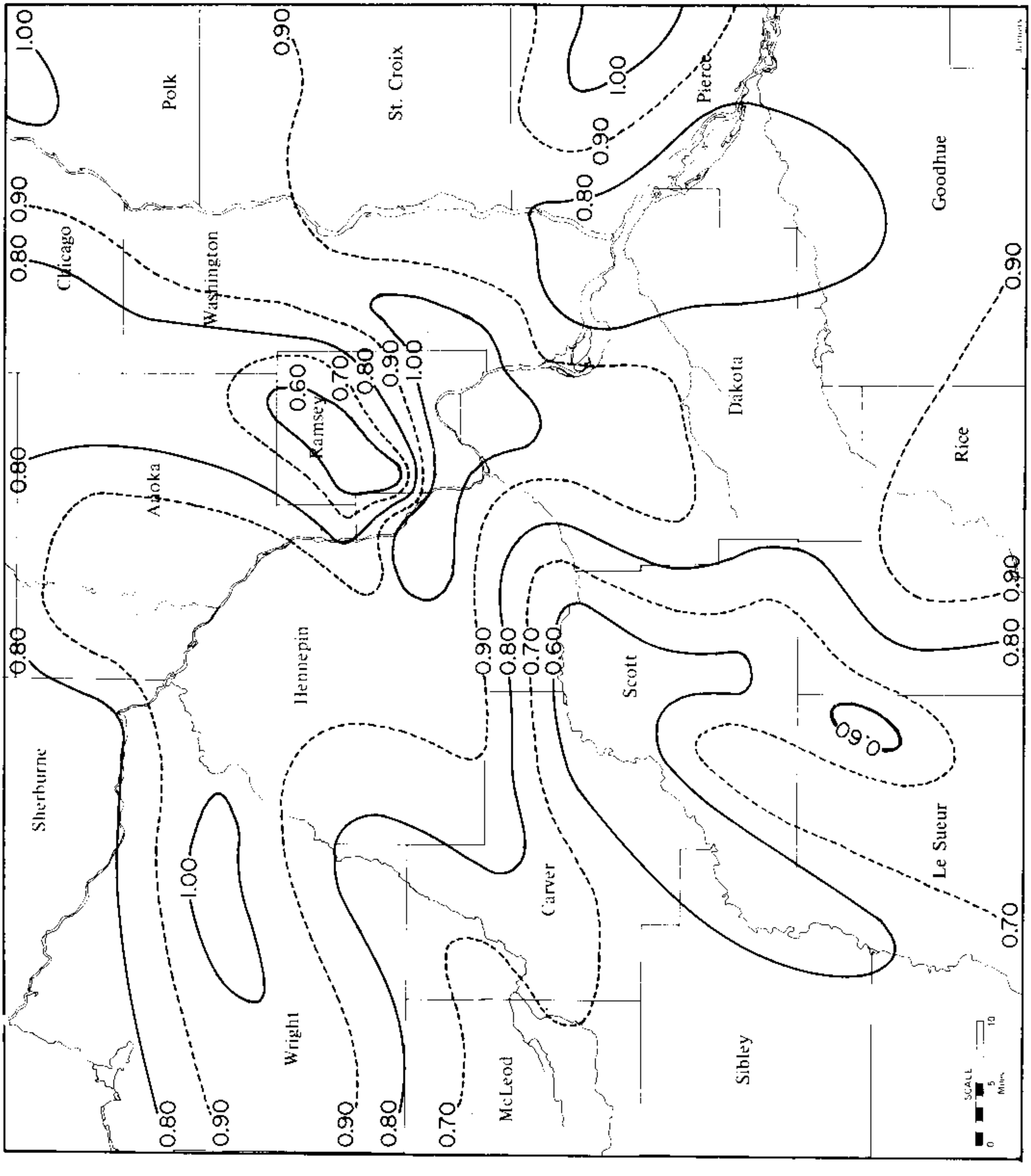

Figure 3. Mean monthly precipitation in inches, February, 1959-1972

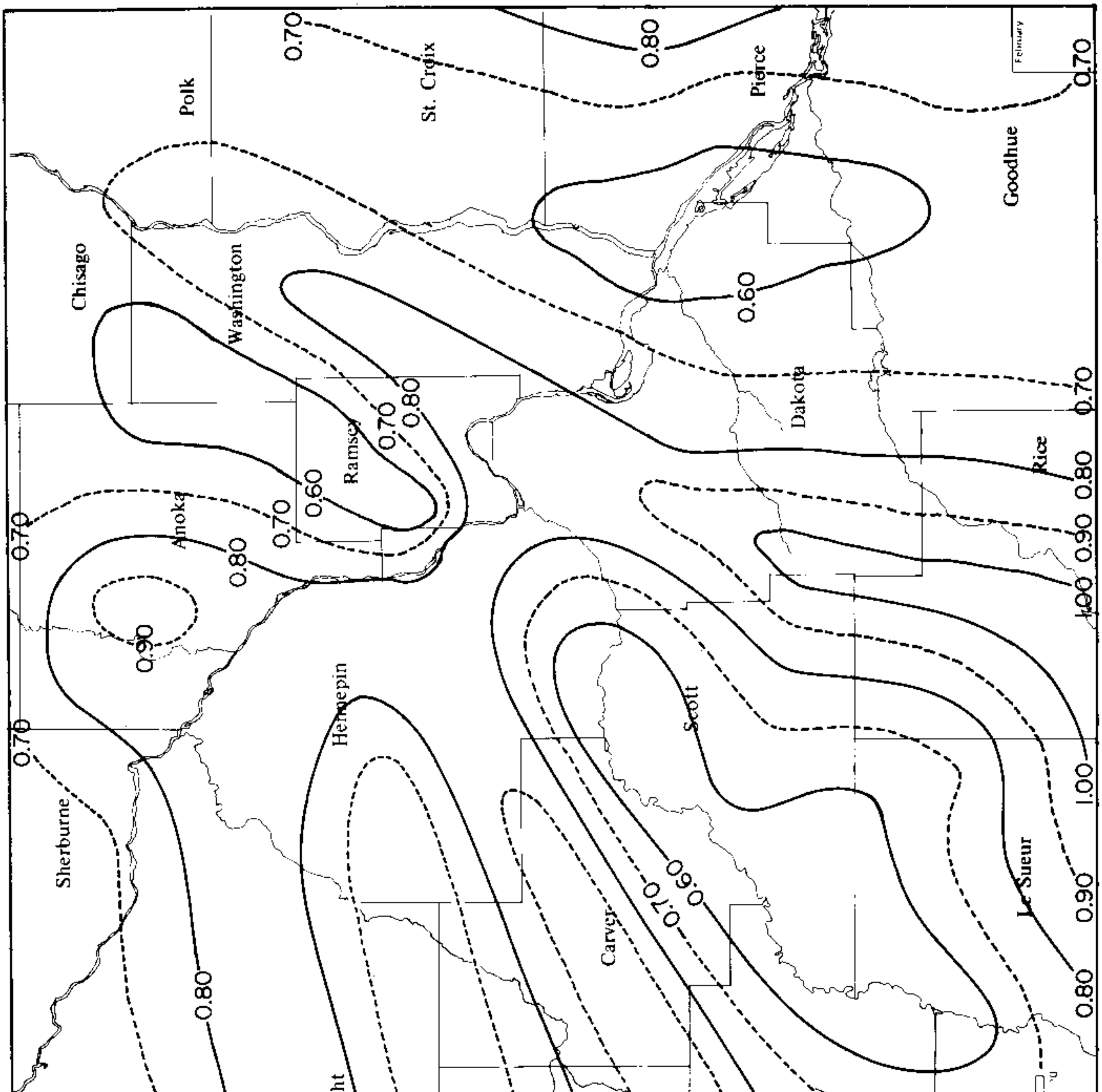

Figure 4. Mean monthly precipitation in inches, March, 1959-1972

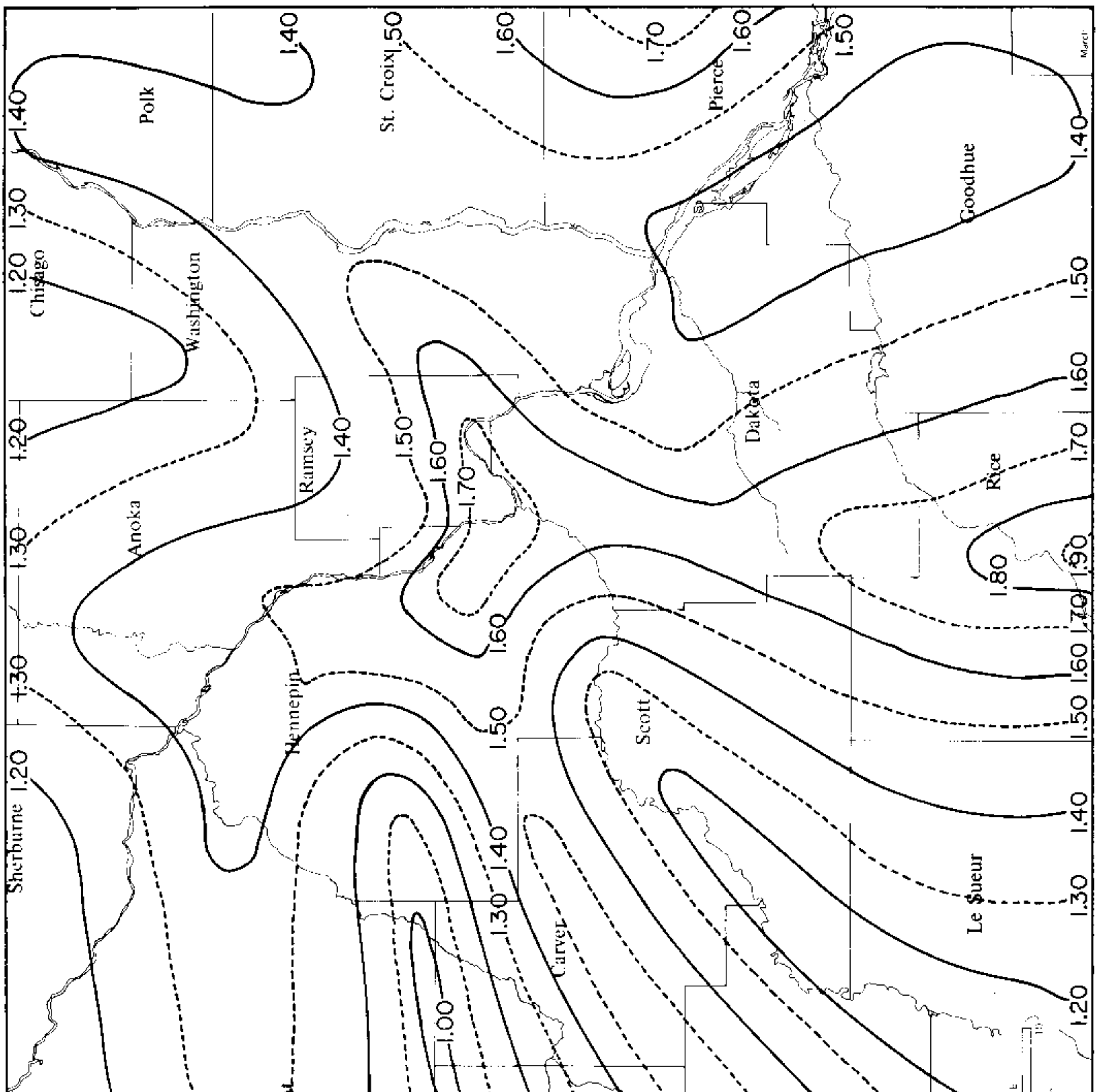

Figure 5. Mean monthly precipitation in inches, April, 1959-1972

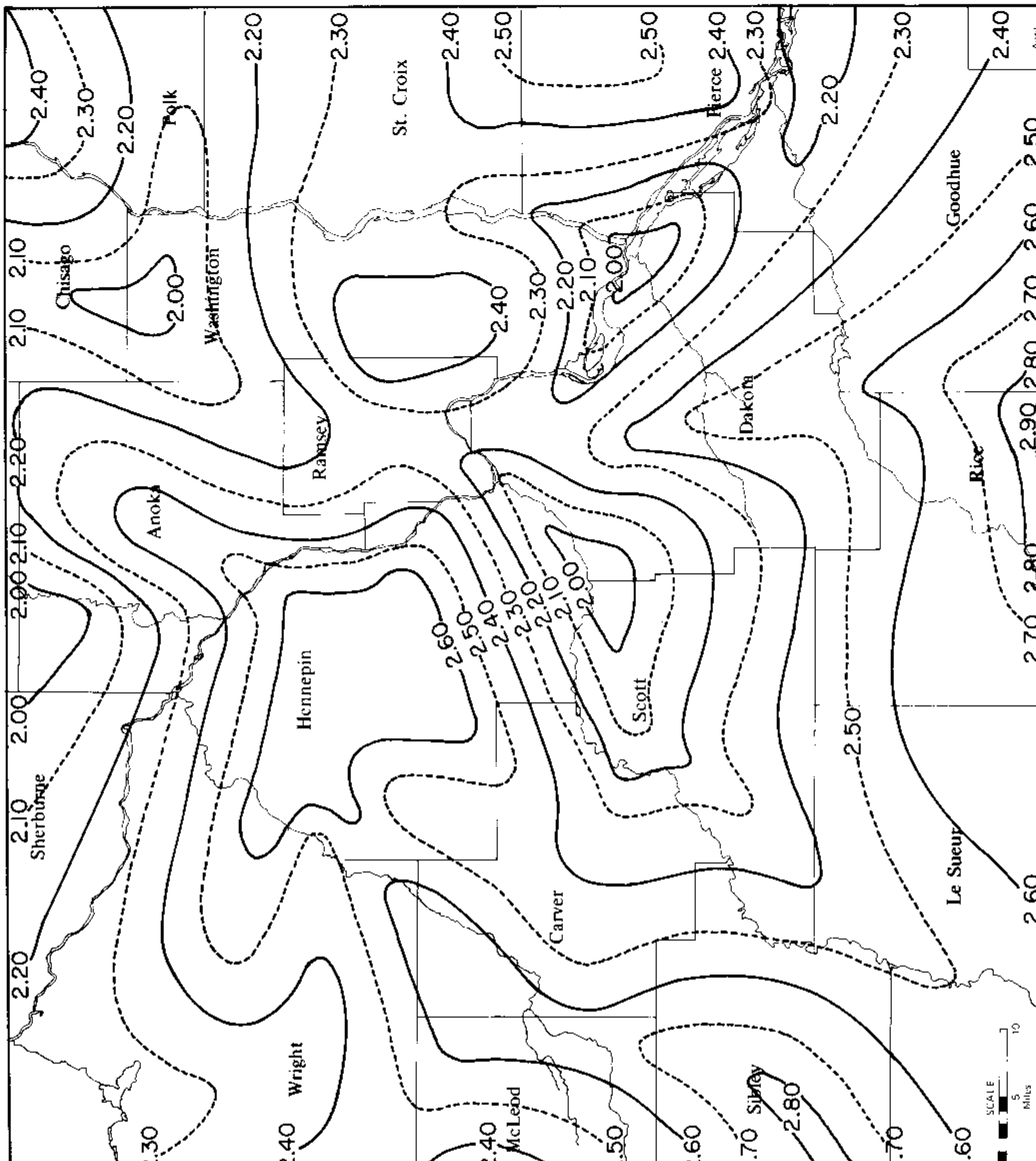

Figure 6. Mean monthly precipitation in inches, May, 1959-1972

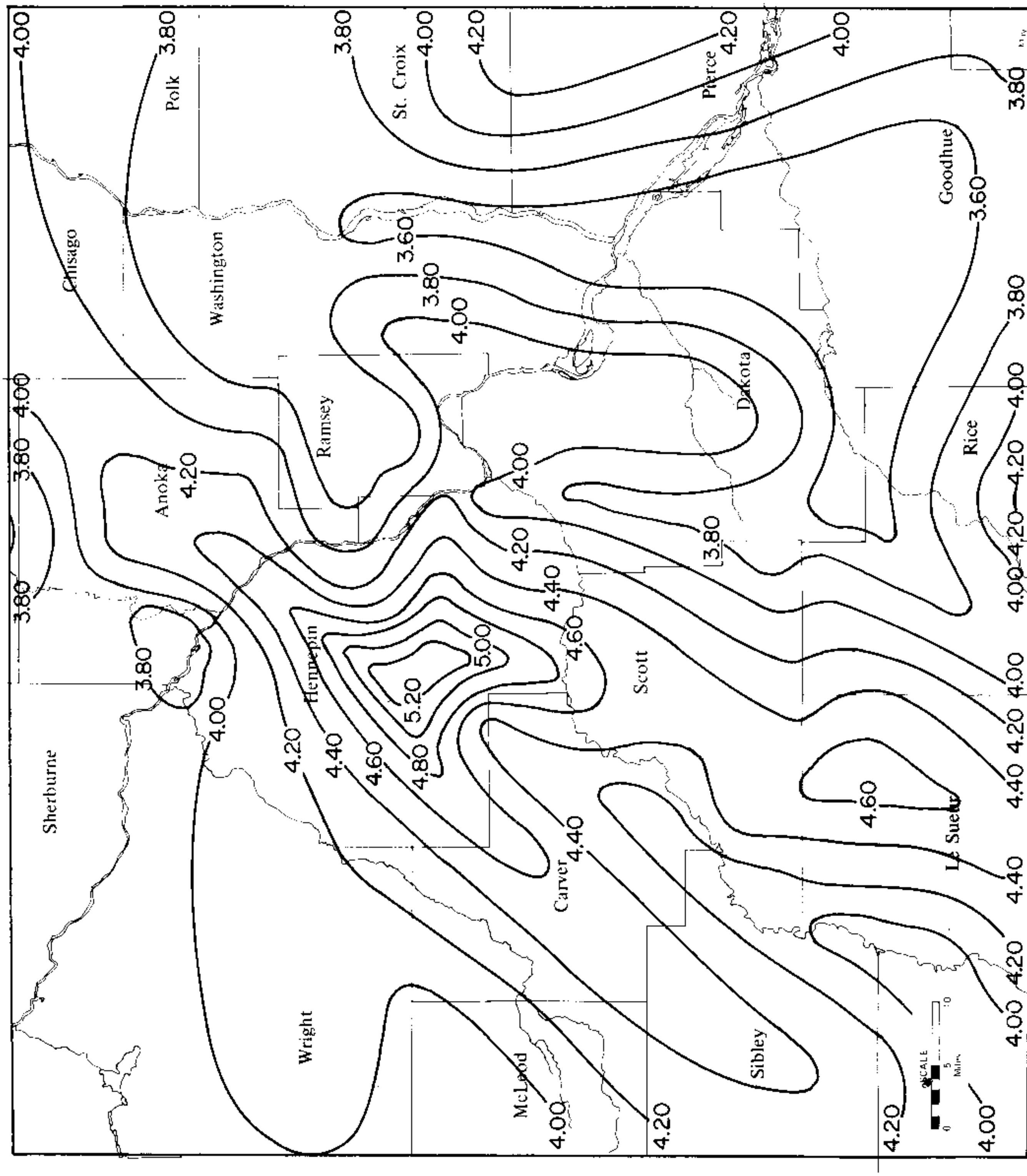

Figure 7. Mean monthly precipitation in inches, June, 1959-1972

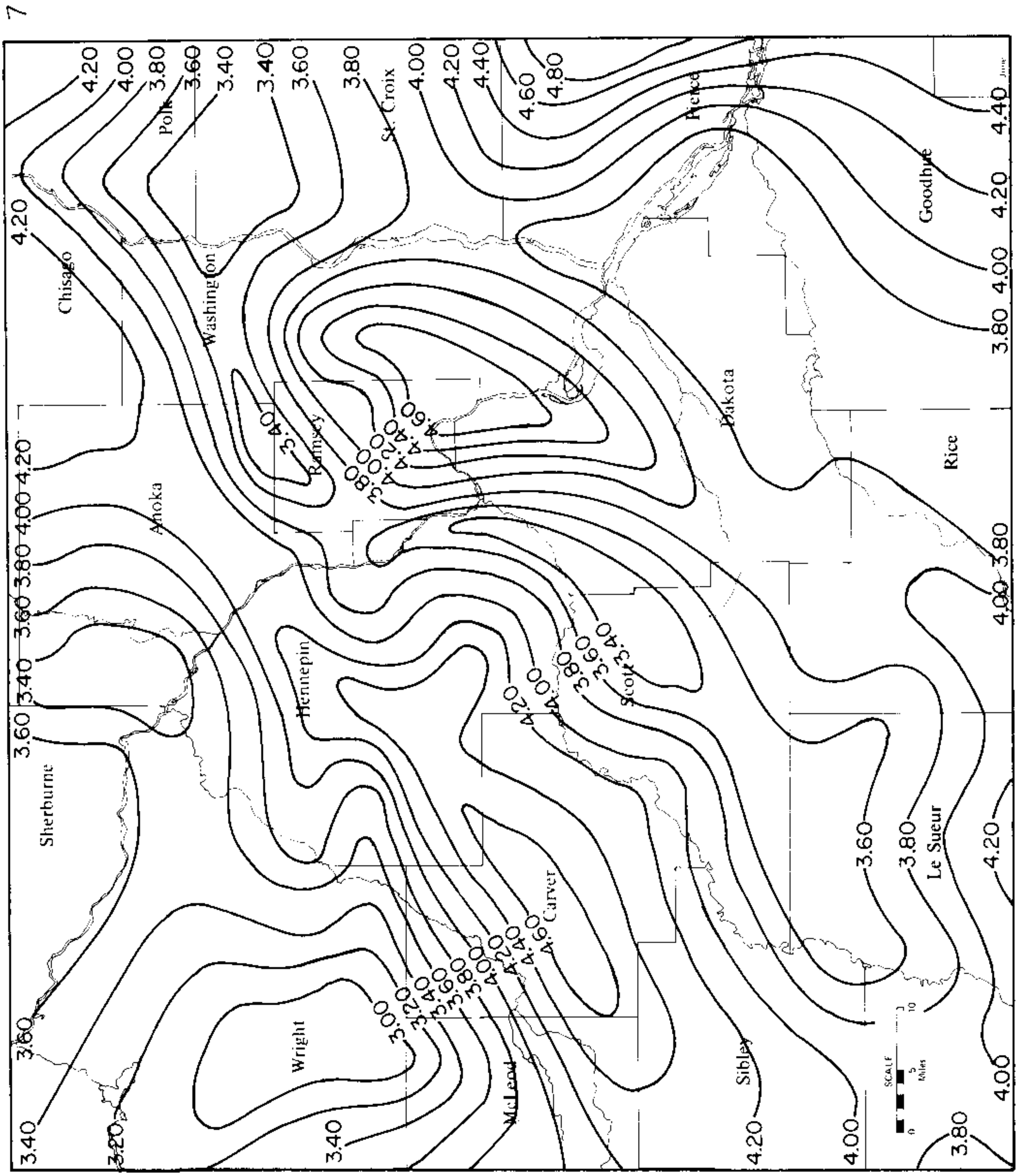

Figure 8. Mean monthly precipitation in inches, July, 1959-1972

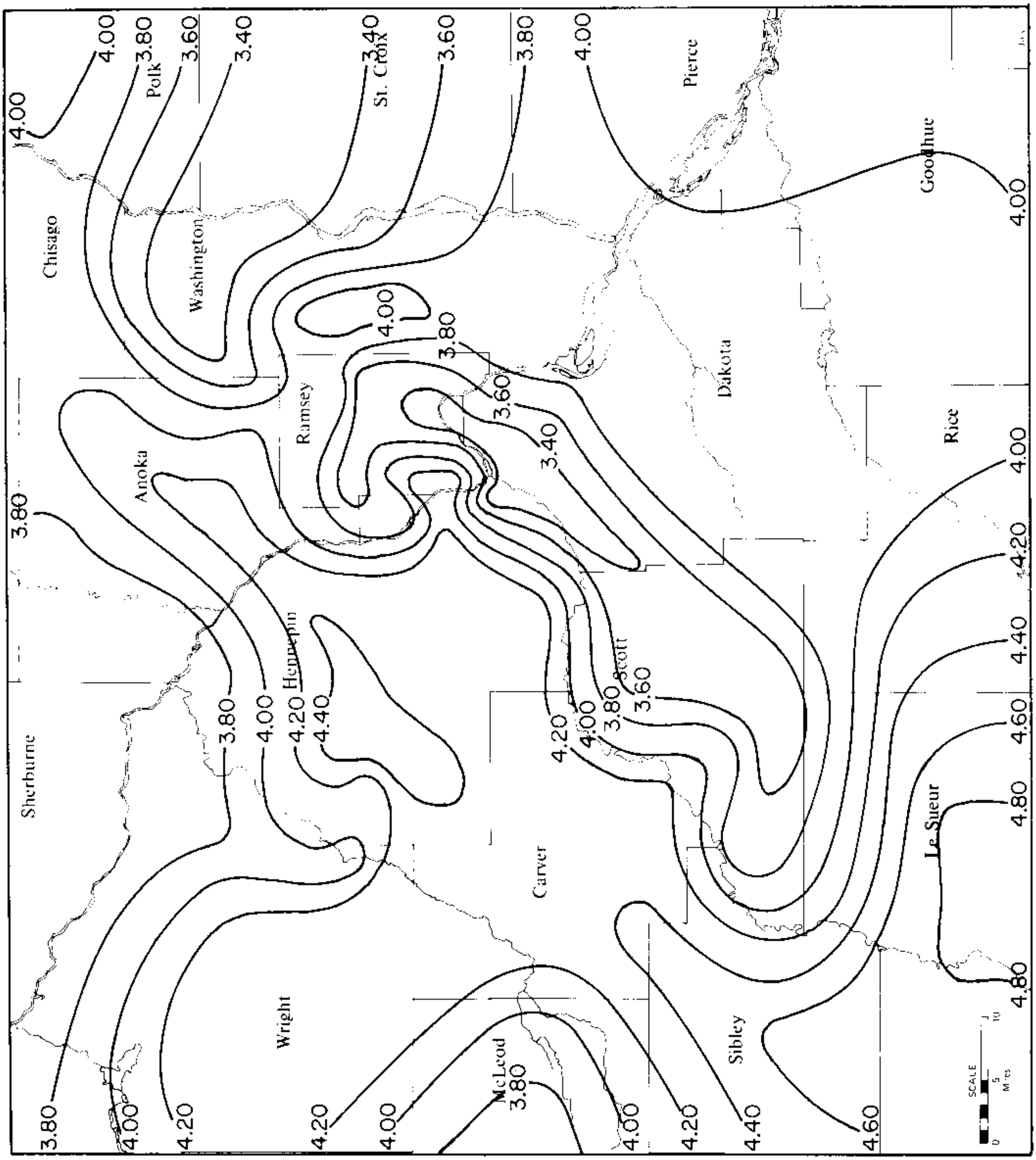

Figure 9. Mean monthly precipitation in inches, August 1959-1972

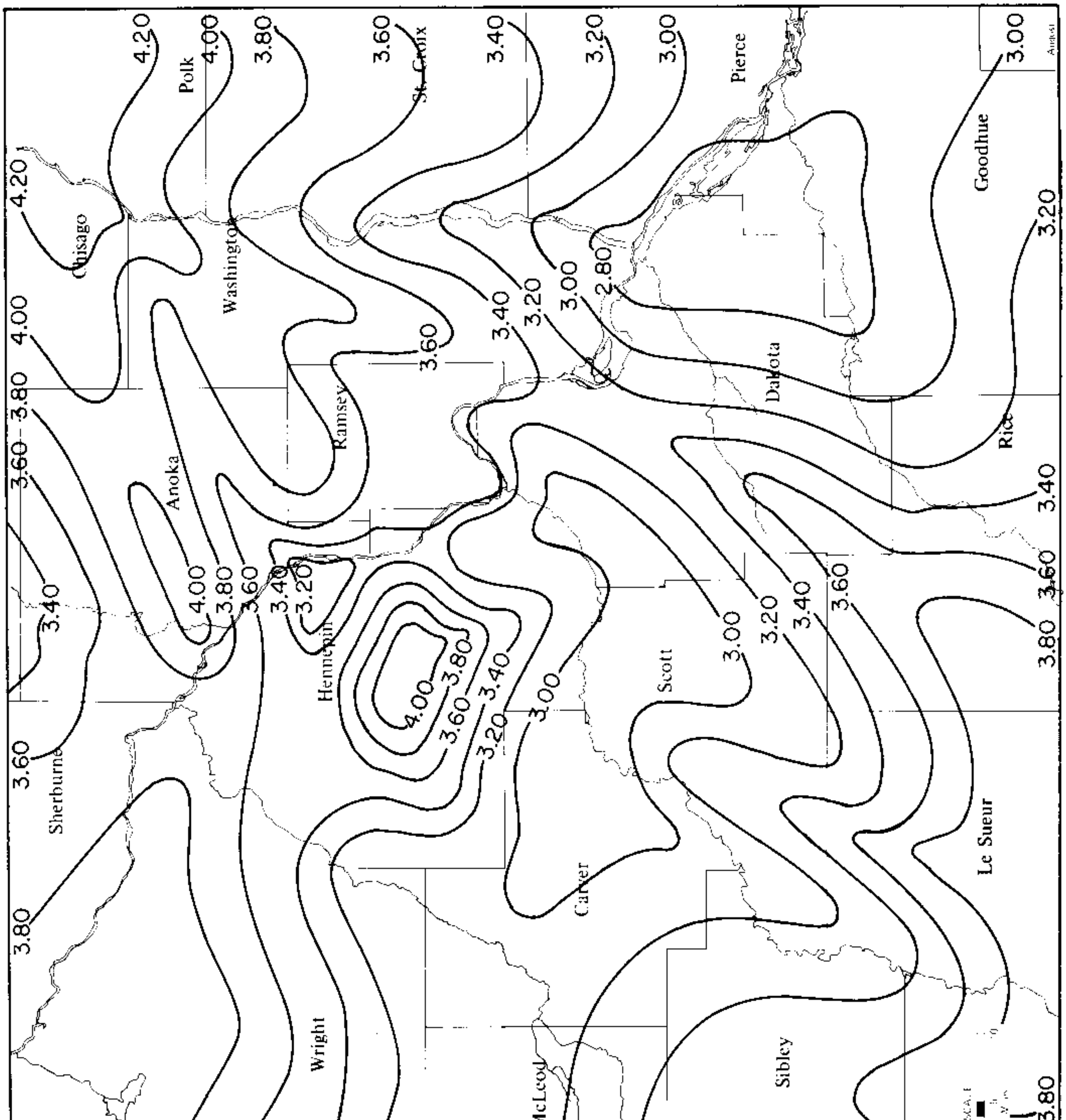

Figure 10. Mean monthly precipitation in inches, September, 1959-1972

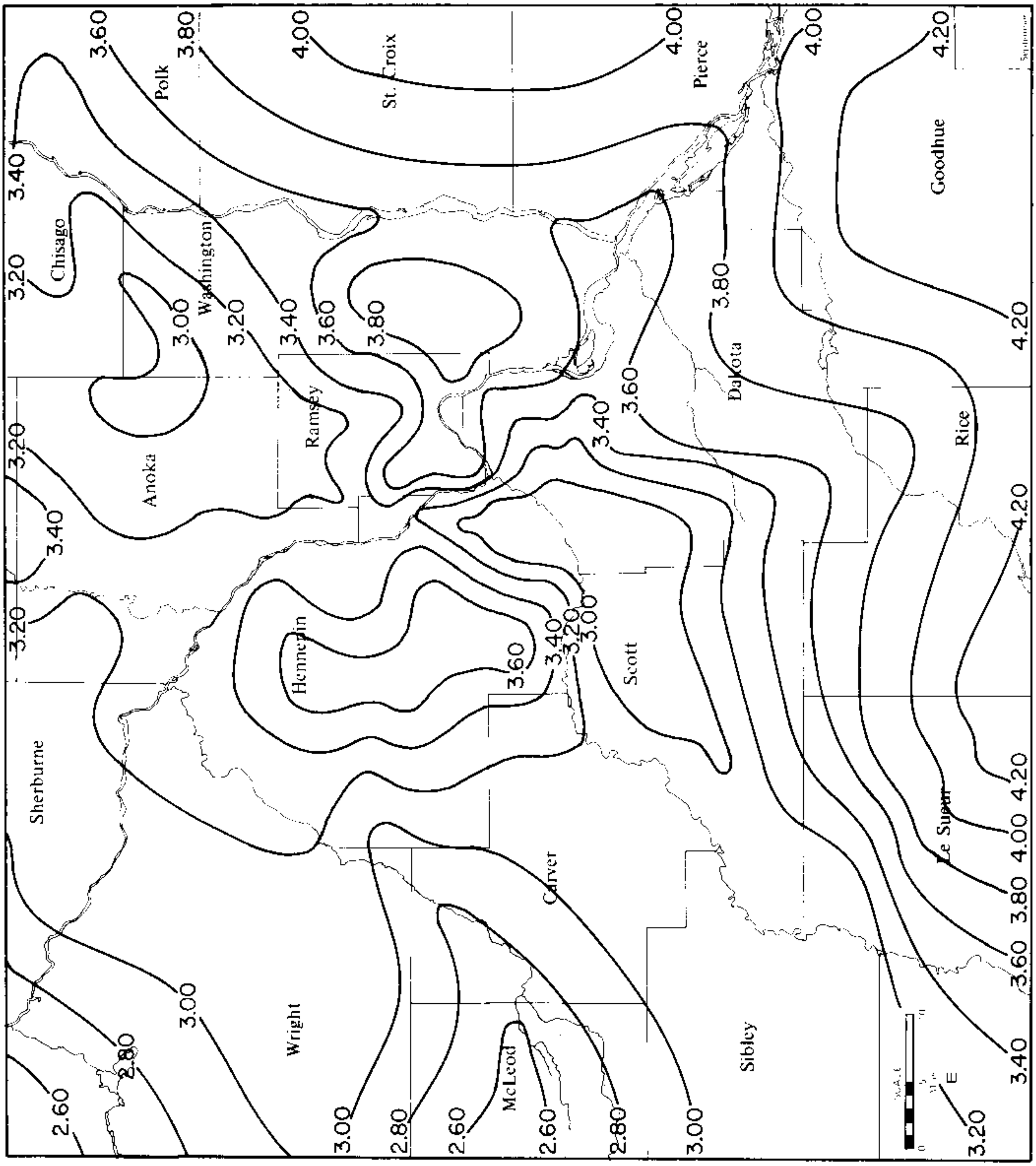

Figure 11. Mean monthly precipitation in inches, October, 1959-1972

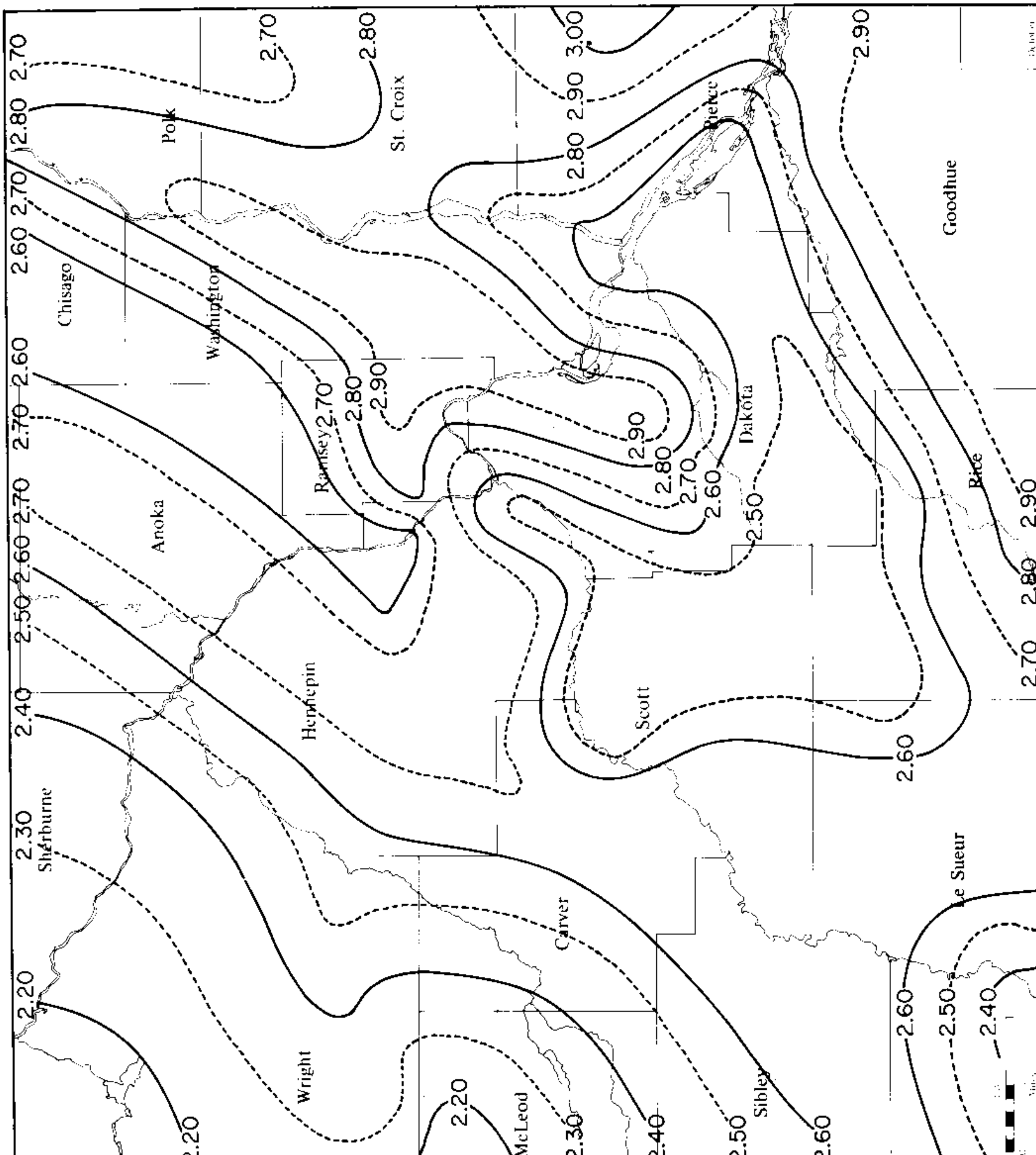

Figure 12. Mean monthly precipitation in inches, November, 1959-1972

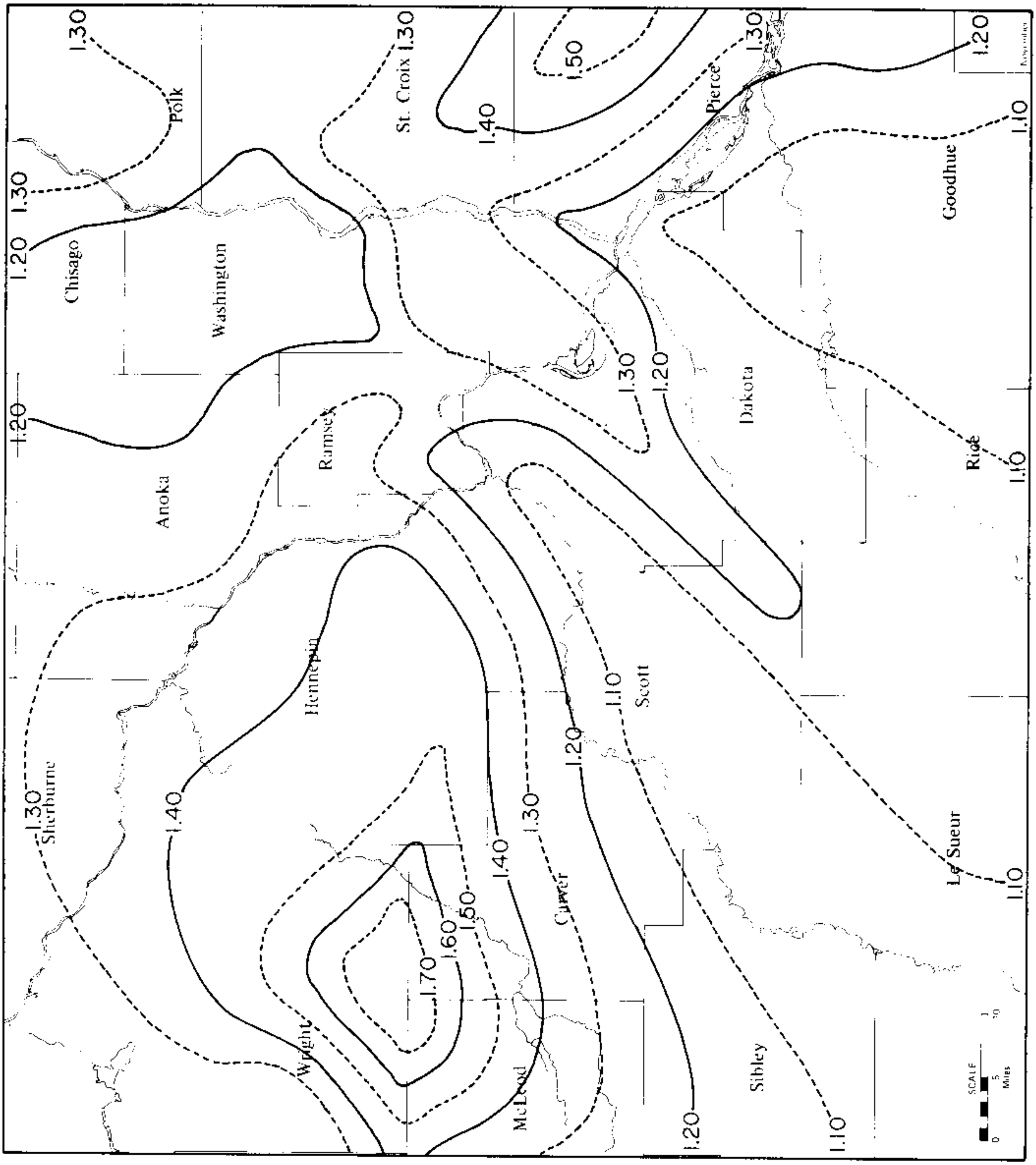

Figure 13. Mean monthly precipitation in inches, December, 1959-1972

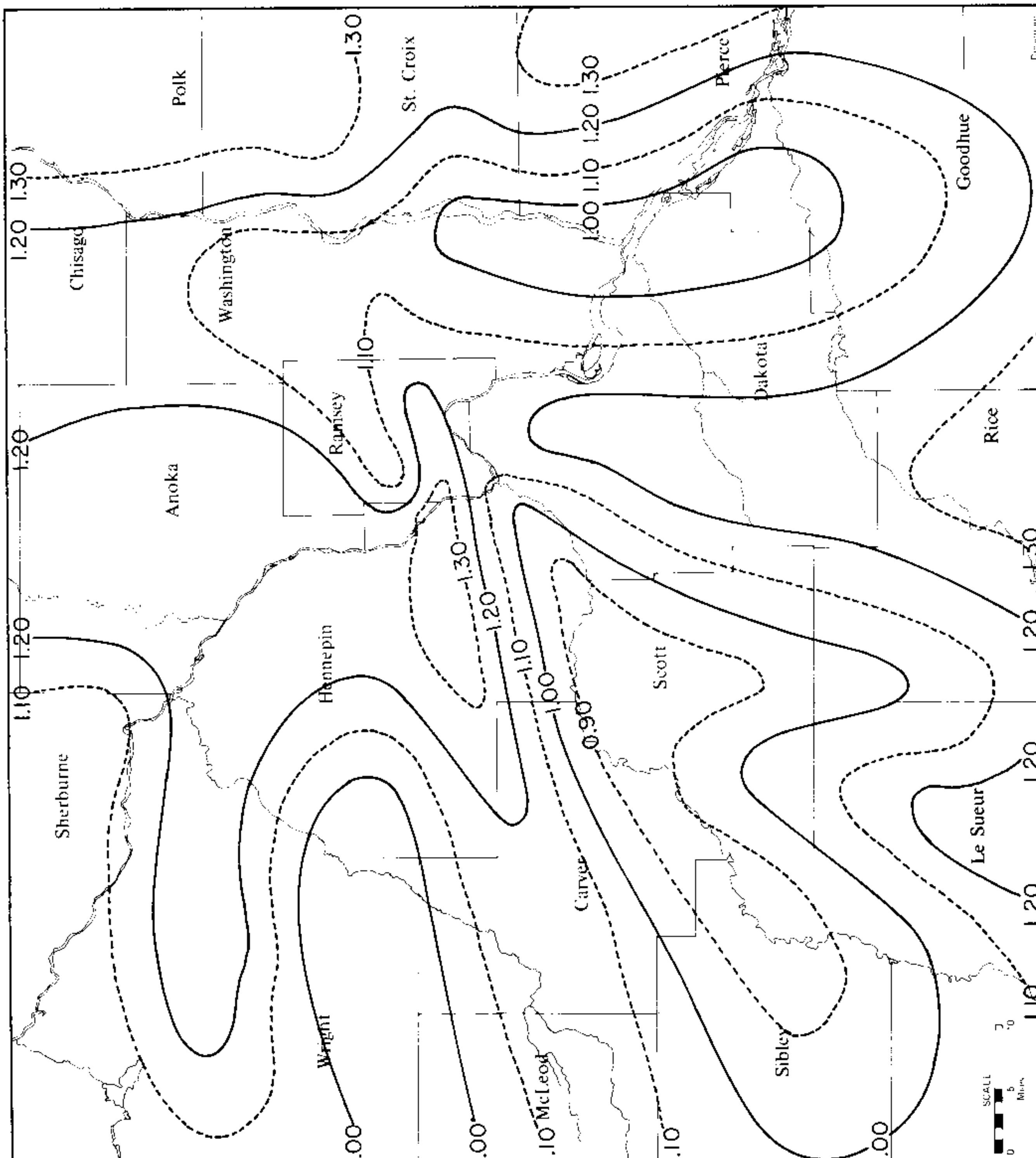

Figure 14. Mean spring (March-May) precipitation in inches, 1959-1972

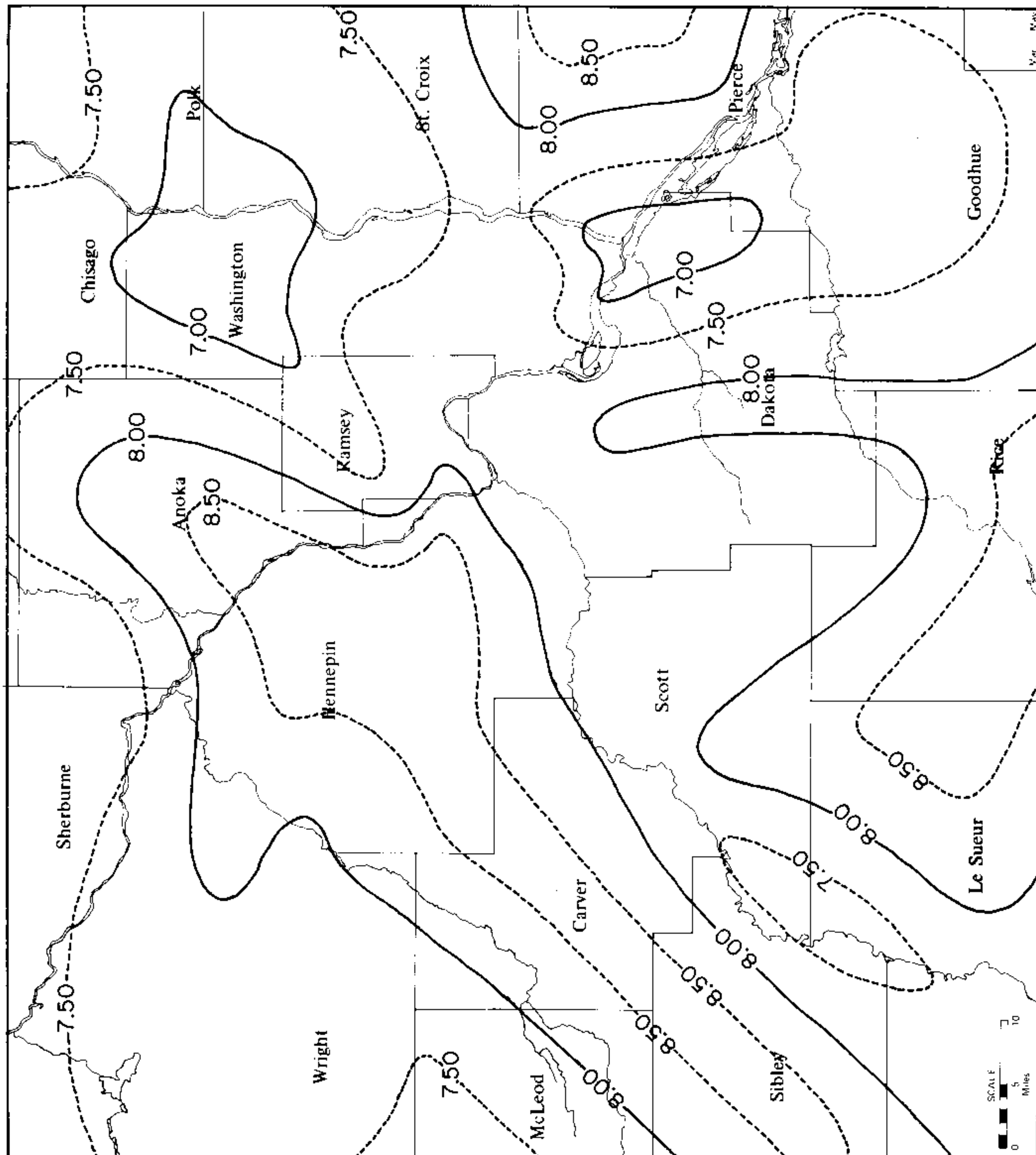

Figure 15. Mean summer (June-August) precipitation in inches, 1959-1972

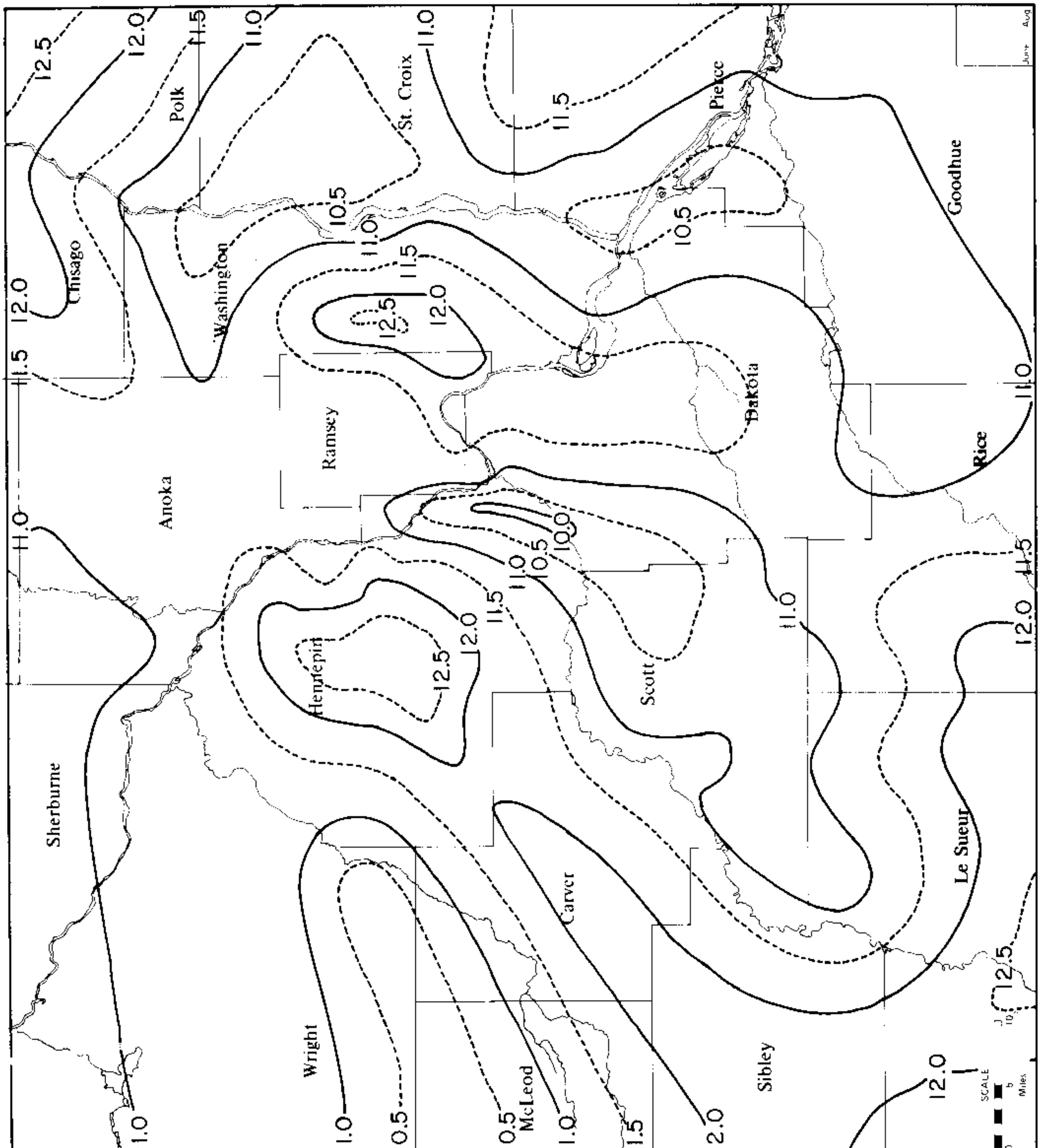

Figure 16. Mean fall (September-November) precipitation in inches, 1959-1972

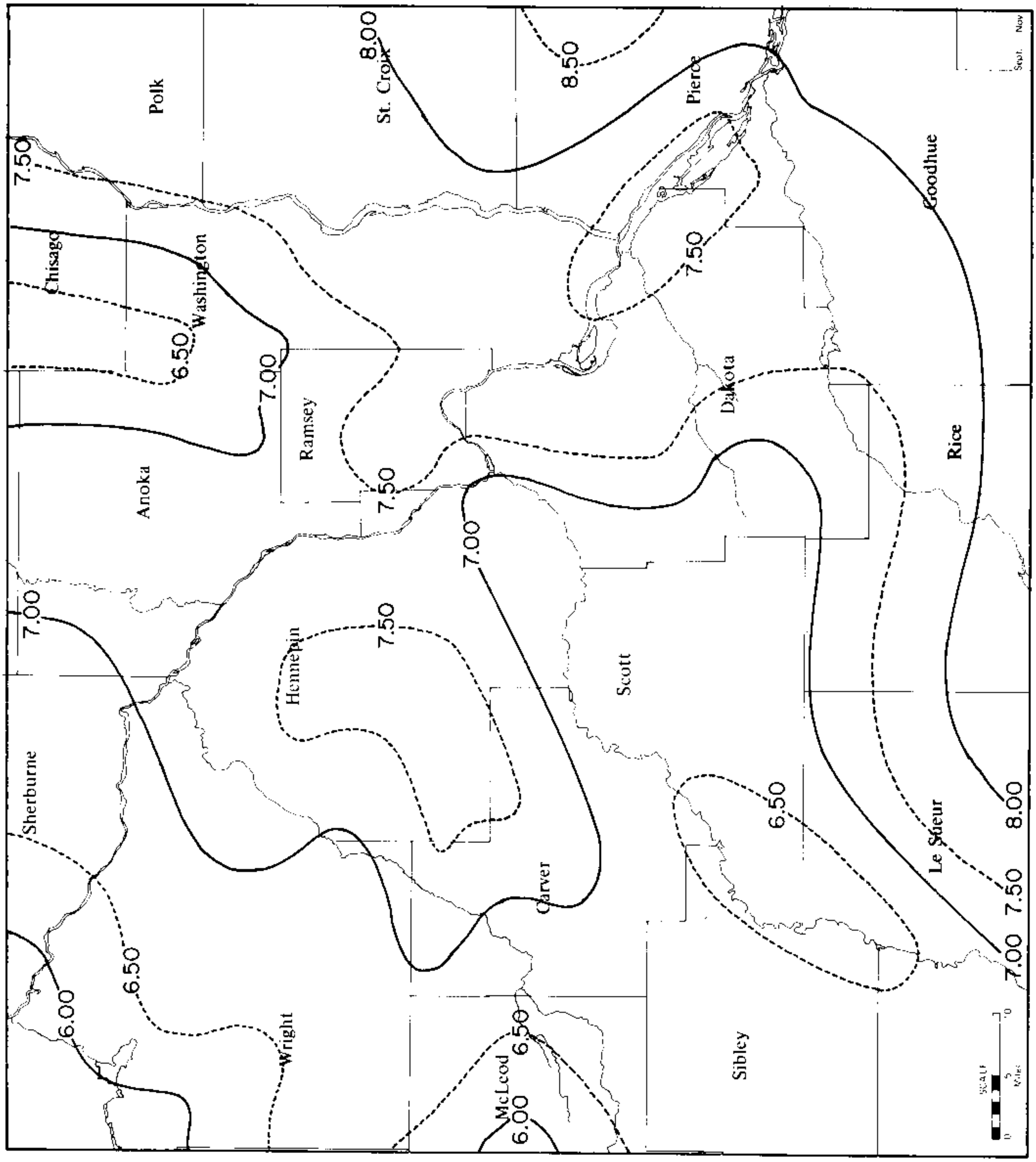

Figure 17. Mean winter (December-February) precipitation in inches, 1959-1972

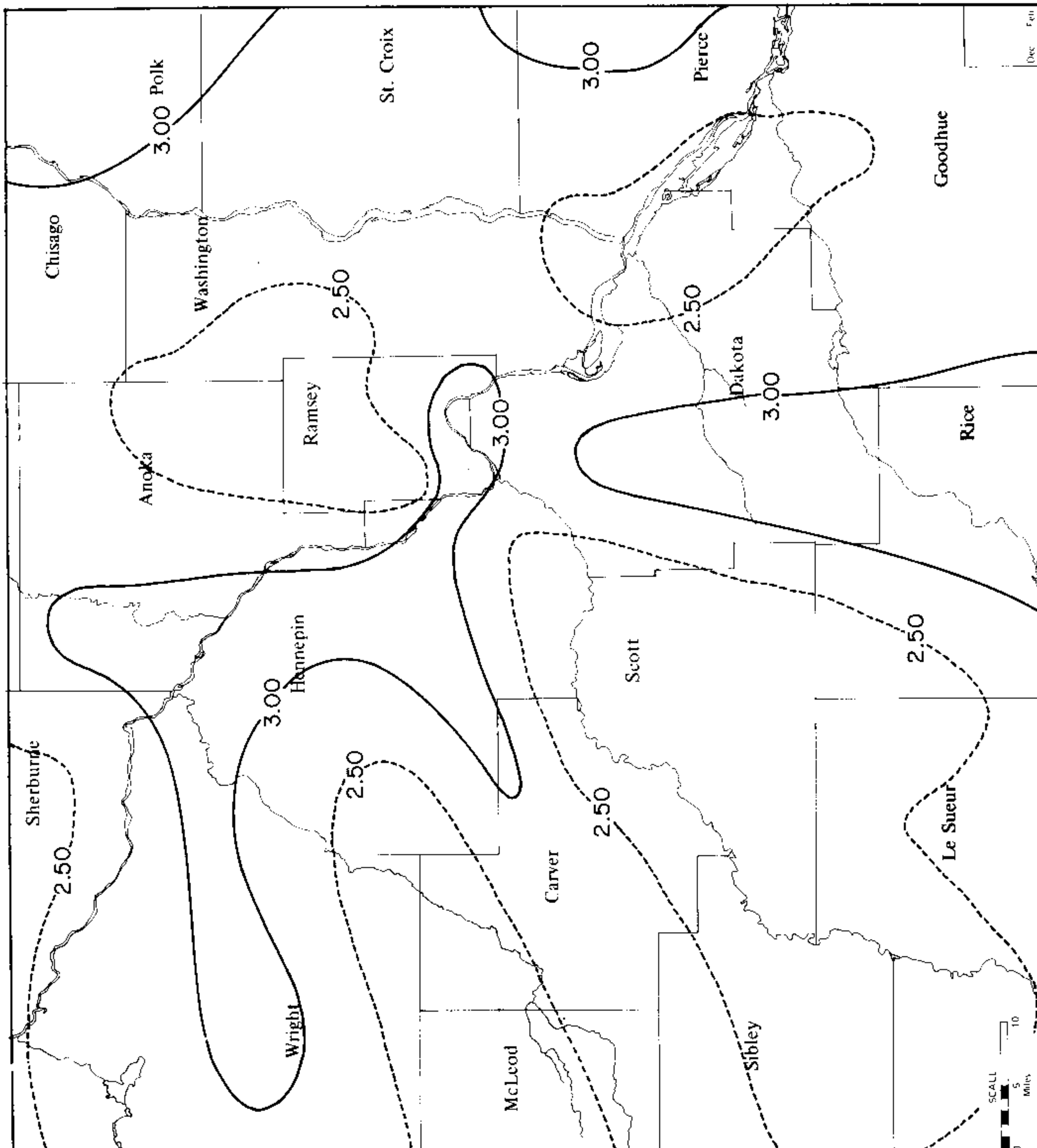

Figure 18. Mean growing season (May-September) precipitation in inches, 1959-1972

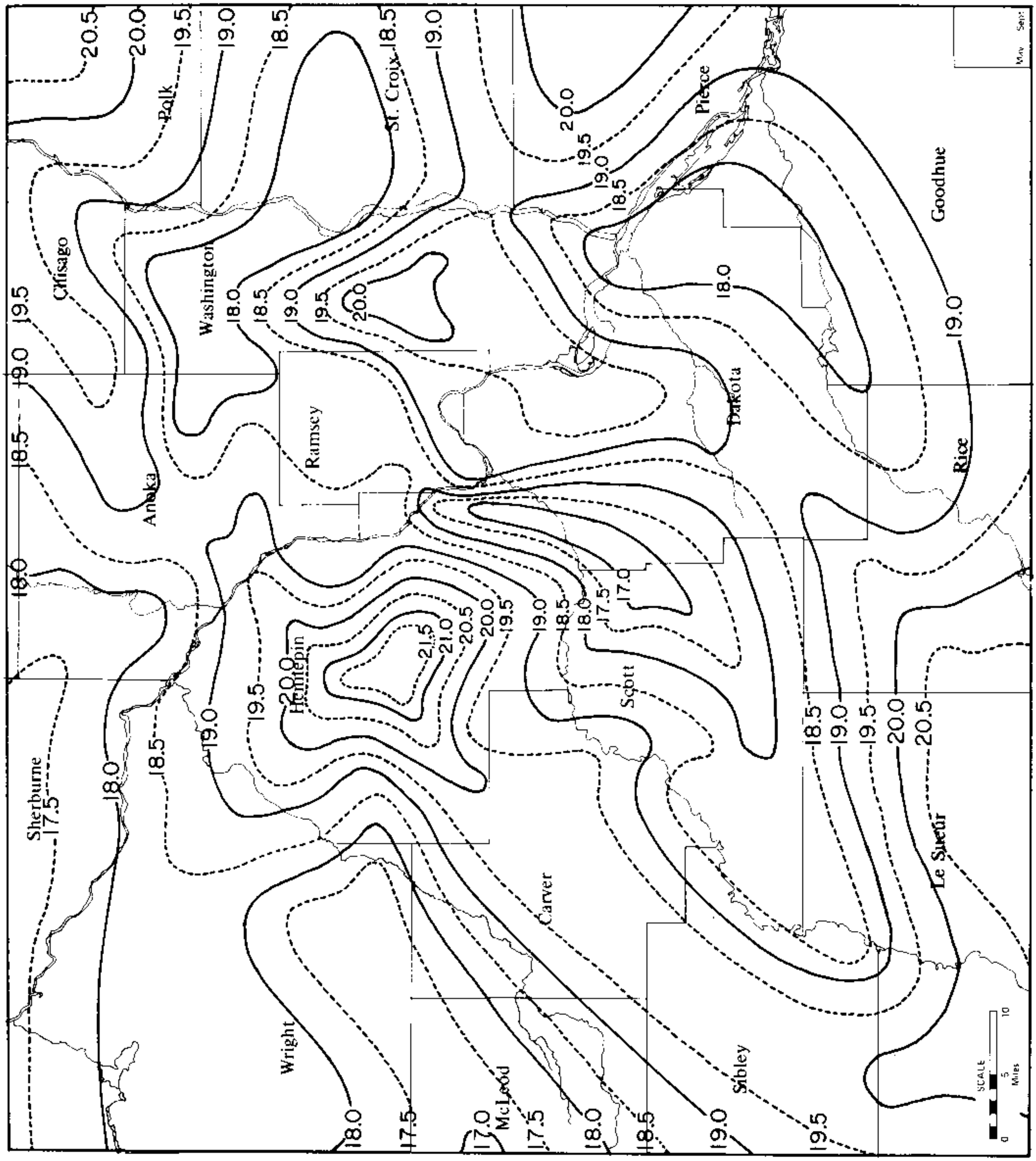

Figure 19. Mean cold season (November-March) precipitation in inches, 1959-1972

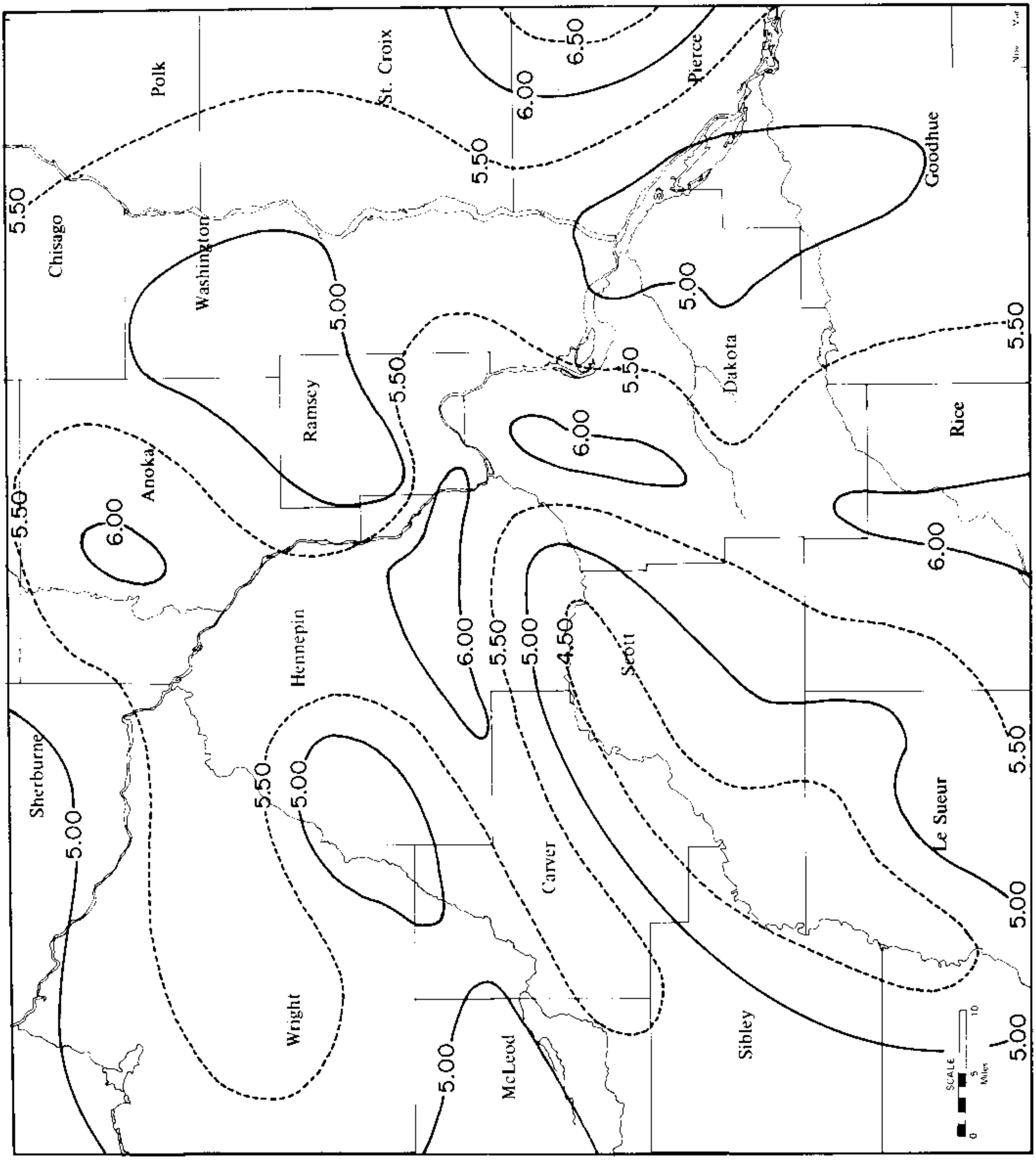

Figure 20. Mean annual precipitation in inches, 1959-1972

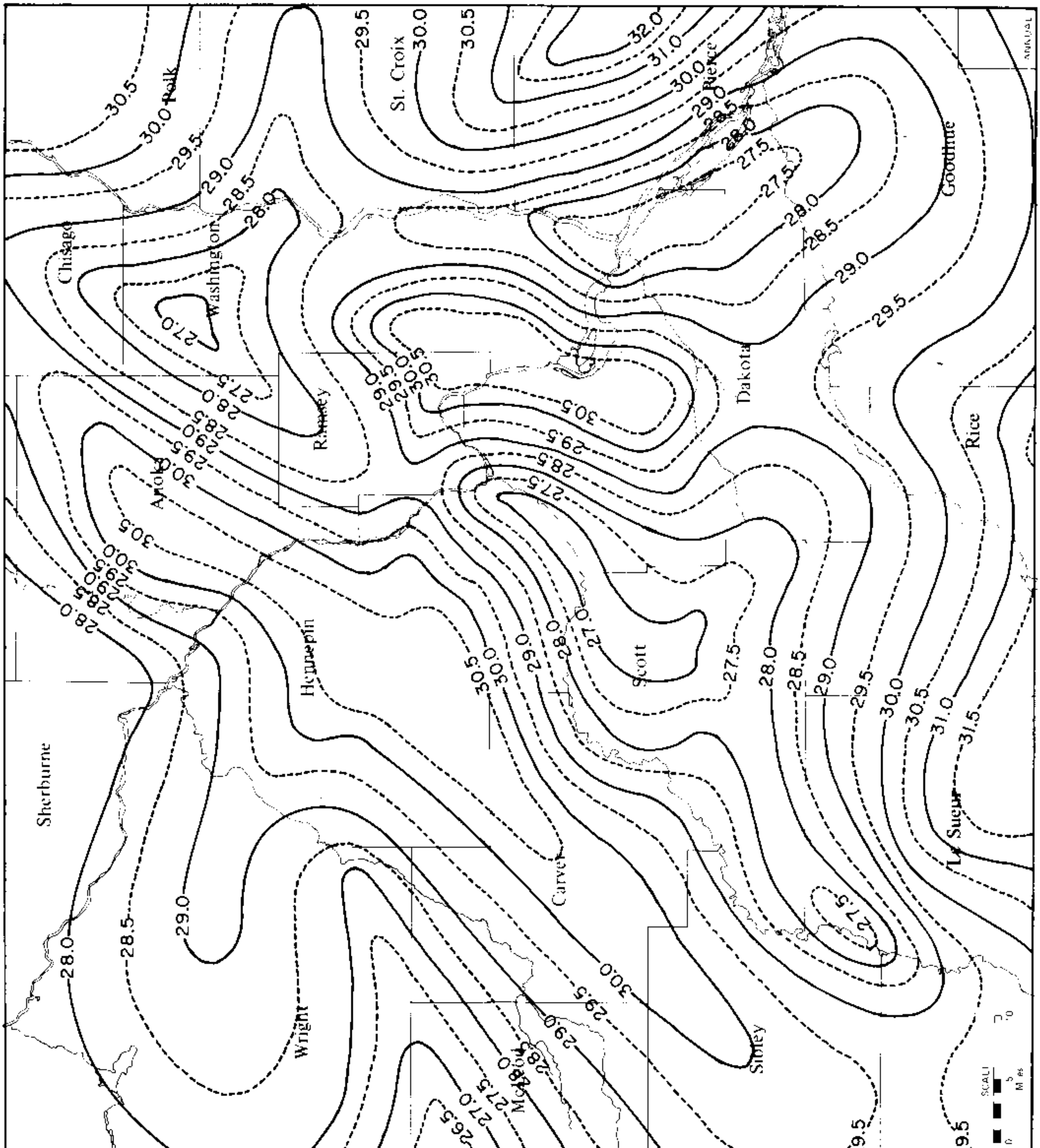

Table 6. Highest and lowest mean monthly precipitation totals found within the area, 1959-1972

Month	Highest mean precipitation Amount	Highest mean precipitation Station	Lowest mean precipitation Amount	Lowest mean precipitation Station	Range in extremes of precipitation
	inches		inches		inches
January	1.08	Buffalo	0.56	Chaska	0.52
February	1.07	Cedar	0.54	Forest Lake	0.53
March	1.76	Ellsworth	0.98	Winsted	0.78
April	2.79	Gaylord	1.92	Forest Lake	0.87
May	5.25	Plymouth	3.45	Stillwater	1.80
June	4.83	Ellsworth	3.00	Winsted	1.83
July	4.83	Le Center	3.29	New Richmond	1.54
August	4.44	St. Croix Falls	2.78	Hastings Dam	1.66
September	4.38	Zumbrota	2.79	Forest Lake	1.59
October	3.00	Ellsworth	2.27	Winsted	0.73
November	1.73	Winsted	0.99	Le Sueur	0.74
December	1.38	Ellsworth	0.90	Bloomington	0.48
Annual	32.39	Ellsworth	26.96	Forest Lake	5.43

Table 7. Difference and gradient in mean monthly precipitation between downtown Minneapolis (MPS) and the airport site (MSPAP), between downtown St. Paul (STP) and MSPAP, and between MPS and STP[1]

Month	Minneapolis MPS-MSPAP	Minneapolis Gradient[2]	St. Paul STP-MSPAP	St. Paul Gradient[2]	Minneapolis and St. Paul MPS-STP	Minneapolis and St. Paul Gradient[2]
	inches	inches/mile	inches	inches/mile	inches	inches/mile
January	0.11	0.02	0.08	0.01	0.03	0.00
February	—0.04	—0.01	0.01	0.00	—0.05	—0.01
March	—0.02	0.00	—0.04	—0.01	0.02	0.00
April	0.31	0.06	0.10	0.01	0.21	0.02
May	0.40	0.08	0.10	0.01	0.30	0.03
June	0.31	0.06	1.11	0.14	—0.80	—0.08
July	0.66	0.13	0.04	0.01	0.62	0.06
August	0.38	0.08	0.37	0.05	0.01	0.00
September	0.35	0.07	0.63	0.08	—0.28	0.03
October	0.10	0.02	0.31	0.04	—0.21	0.02
November	0.21	0.04	0.09	0.01	0.12	0.01
December	0.24	0.05	0.14	0.02	0.10	0.01
Annual	3.01	0.60	2.94	0.37	0.07	0.01

[1] Downtown Minneapolis and St. Paul are located at T26N, R24W, section 27, and T29N, R22W, section 32, respectively.
[2] The distances between MPS and MSPAP, between STP and MSPAP, and between the two downtown districts are 5, 8, and 10 miles, respectively.

The gradients of monthly mean total precipitation between downtown Minneapolis and MSPAP, between downtown St. Paul and MSPAP, and between the two downtown districts are shown in table 7. Because of the consistently lower precipitation at MSPAP, the gradient is one of increase from MSPAP to the two downtown districts, except in February and March for downtown Minneapolis and in March for downtown St. Paul. There is very little difference between the amount of precipitation that fell in the two downtown districts. The maximum difference, 1.11 inches, was in June between downtown St. Paul and MSPAP and equals a gradient of 0.14 inch per mile. A gradient that is nearly as great occurred in July between downtown Minneapolis and MSPAP, although the absolute difference was only 0.66 inch.

Precipitation Patterns

The most persistent features in the monthly maps (figures 2-13) are the regions of relatively high and low precipitation, with strong precipitation gradients in the summer and weak gradients in the winter.

The low precipitation region is generally located in the south-central part of the Twin Cities, extending southwestward across Scott County. Less well defined is another low precipitation region that lies in the north-central part of the Twin Cities, extending northeast towards Forest Lake, and then southeast into Wisconsin. These two features are prominent in the months of April, June, and July (figures 5, 7, and 8, respectively).

The other persistent feature is the region of relatively high precipitation located west of Minneapolis with an extension oriented southwest and sometimes to the northeast into Anoka County. This feature first develops in April (figure 5) and is apparent in all succeeding months until October (figure 11), when it becomes very diffuse.

Less well defined is another relatively high precipitation region east of St. Paul that often occurs with an extension to the southwest. The feature is first apparent in April and is visible on the monthly maps through October (figures 5-11), although it is diffuse in August (figure 9).

Other regions of relatively high precipitation exist, but they cannot be described adequately because they are located on the periphery of the map. One is the region around Ellsworth, Wisconsin, which is about 30 miles southeast of St. Paul; another occurs around St. Croix Falls, Wisconsin, which is about 35 miles northeast of St. Paul.

The seasonal and annual precipitation patterns are shown in figures 14-20. The regions of high and low precipitation found in the summer season map, June-August, the growing season map, May-September, and the annual map, (figures 15, 18, and 20, respectively) are even more evident than they were in the monthly maps.

Maps of the winter season, December-February, (figure 17), and the cold season, November-March, (figure 19), contrast greatly with the summer and growing season maps (figures 15 and 18, respectively). In the latter maps, there is a more concentrated pattern and a greatly increased precipitation gradient.

Severe Storm Patterns

Very intense precipitation is usually associated with severe weather such as thunderstorms and tornadoes. Thus, if the precipitation occurrence shows consistent patterns, severe storms can be expected to show similar patterns. The tornado touchdown points and paths for all tornadoes that occurred during 1959-1972 are plotted in figure 21. Twenty-three of the 27 tornadoes that occurred in the 14 years, or over 85 percent of them, are found in two general swaths or alleys; both are oriented southwest to northeast across the area.

The predominant tornado alley crosses the northwestern part of the metropolitan area and the secondary one crosses the southeastern part. This pattern has left the center or business areas of the Twin Cities devoid of tornadoes during these 14 years. As expected, the tornado alleys follow the heavier summer precipitation patterns for the area. The predominant alley, as well as the heavier summer precipitation pattern, starts in central Sibley County and extends northeast through Carver, Hennepin, Anoka, and into southern Chisago Counties. Within this alley there were 16 tornado touchdowns.

The secondary alley is much less pronounced. It begins in eastern Le Sueur County and extends through northwestern Rice County to the northeast through Dakota and into Washington County. Seven tornadoes occurred within this alley; they coincided approximately with areas of heavier summer precipitation, as previously noted. This alley, however, is not as well defined as the primary one that crosses the northwestern part of the metropolitan area. The regions with low summer precipitation were devoid of tornado touchdowns with the exception of the one that occurred south of Hastings. The major dry region, which extends south and west from MSPAP through Scott County, had no tornadoes during the 14-year period.

The number of tornadoes that can occur in a short time period and within a relatively small area cannot be over emphasized. For example, on May 6, 1965, six tornadoes touched down in just over 2 hours in the western and northwestern suburbs of the Twin Cities. Figure 22 shows the relative location of each tornado at 2-minute intervals during the May 6th storm. All the tornadoes that occurred that day were located in the tornado alley. During this outbreak, there were three tornadoes on the ground during the same time. Later, two tornadoes passed over the junction of Interstate 694 and University Avenue in Fridley within 80 minutes of each other (figure 22).

Validity of the Wet and Dry Areas

The greatest precipitation difference in the May-September period between the regions of maximum and minimum precipitation totals amounted to about 5 inches. The centers of these regions are only about 15 miles apart. Since relationships between local convergence and topography are imperfectly understood, the validity of these data may be questionable. In an attempt to establish validity, records were searched to determine whether the differences were the result of a few high intensity storms. It was found that this was not so. Next the precipitation differences between various combinations of the stations within the regions of high and low 5-month precipitation totals for each of the 14 years were tested statistically. Each of the seven series of differences shown in table 8 was found to be significantly different

Table 8. Differences between total May-September precipitation for various combinations of stations that received the maximum and minimum totals in the 7,200 square mile area

Year	Differences in inches						
	1*	2*	3*	4*	5*	6*	7*
1959	5.31	1.94	−1.99	−3.44	6.08	−1.22	3.90
1960	13.00	4.74	3.63	3.63	7.18	−2.19	7.18
1961	4.97	2.18	4.39	5.68	2.38	1.80	3.30
1962	6.57	2.93	6.45	4.73	7.21	7.09	5.09
1963	5.07	3.40	4.96	3.09	3.53	3.42	4.34
1964	7.33	1.55	3.65	5.03	4.03	0.35	0.68
1965	8.02	−1.54	5.38	4.35	5.70	3.06	4.43
1966	2.49	0.52	3.24	2.26	2.44	3.19	2.38
1967	6.16	4.80	1.77	2.37	7.26	2.87	5.53
1968	2.66	−1.05	1.34	0.15	4.19	2.87	3.82
1969	0.39	5.00	1.70	1.90	−0.34	0.97	−0.68
1970	3.24	4.96	3.58	2.17	2.06	2.40	−0.06
1971	3.39	3.22	7.88	6.54	2.13	6.62	2.57
1972	6.14	7.17	5.97	3.48	6.17	6.00	3.49
Average	5.33	2.84	3.71	3.00	4.31	2.66	3.28
Probability	≤0.001	≤0.001	≤0.001	≤0.001	≤0.001	≤0.001	≤0.005

*1 = Plymouth Township—MSPAP.
2 = Maple Plain—MSPAP.
3 = Oakdale Township—MSPAP.
4 = Woodbury Township—MSPAP.
5 = Plymouth Township—Bloomington (27-027-24-16).
6 = Oakdale Township—Bloomington (27-027-24-16).
7 = Plymouth Township—Bloomington (27-116-21-31).

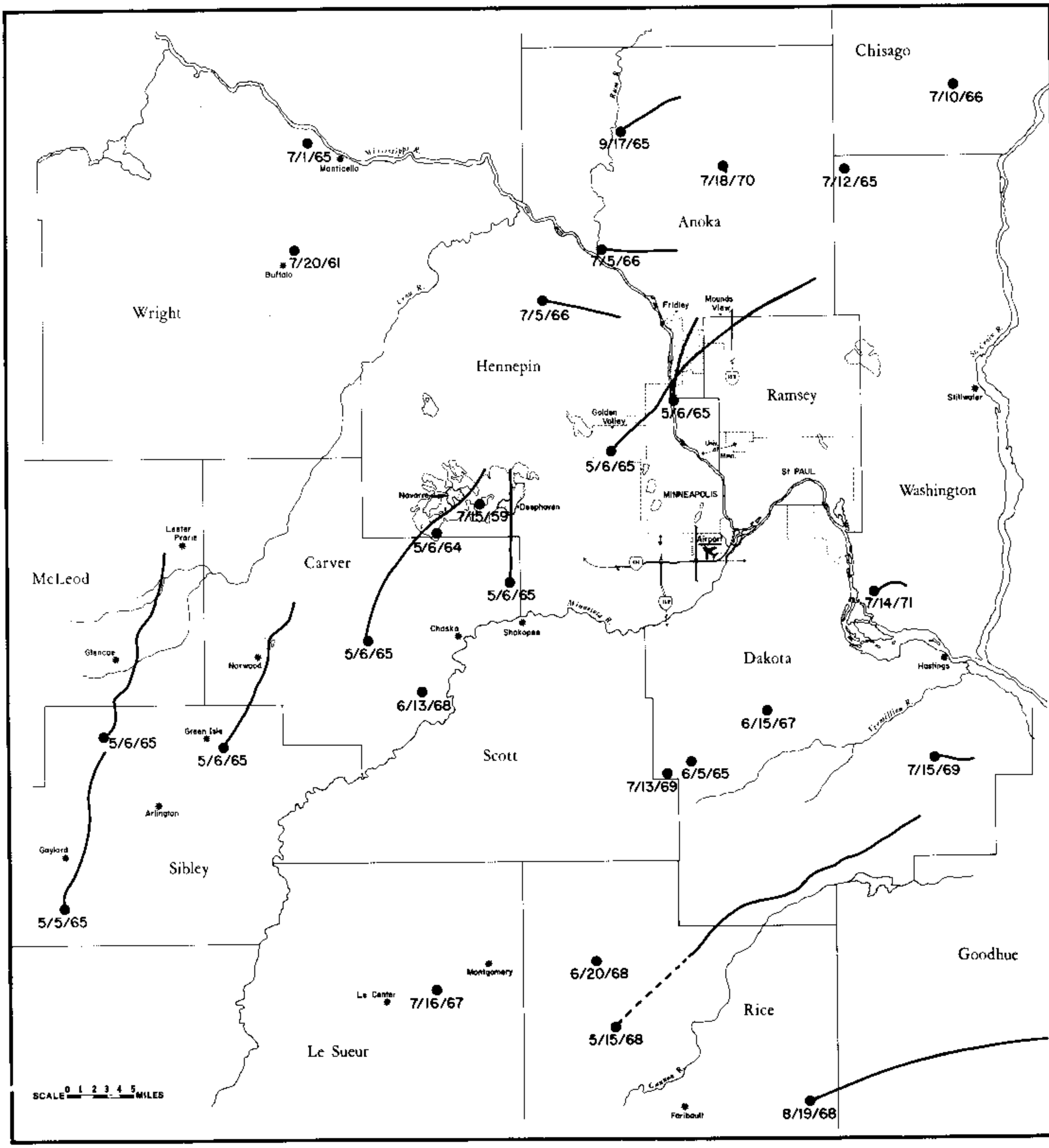

Figure 21. Point of touchdown and ground path of all tornadoes in the area, 1959-1972

Figure 22. Location of ground path of the May 6, 1965, tornadoes at 2-minute intervals

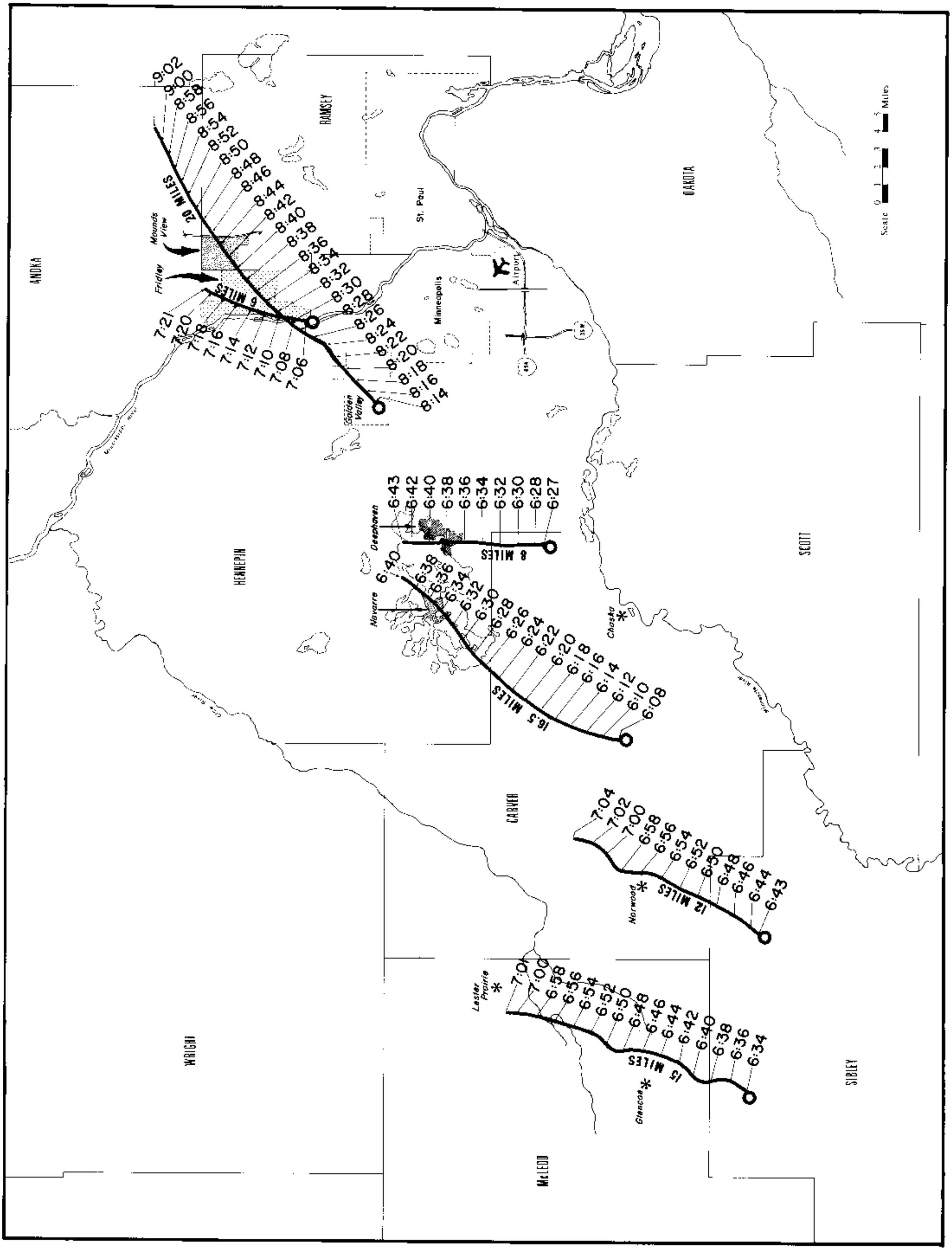

Table 9. Differences in number of rain-days for indicated precipitation amounts between stations within the eastern (Oakdale-Woodbury) high precipitation region and MSPAP and between the western (Maple Plain-Wayzata) high precipitation region and MSPAP for the period May-September, 1964-1968[1]

Stations	Precipitation amounts in inches									
	≧T	≧0.01	≧.10	≧0.20	≧0.40	≧0.60	≧0.80	≧1.00	≧1.50	≧2.00
Oakdale—MSPAP	−69	18	16	16	9	4	4	6	−1	−1
Woodbury—MSPAP	−84	10	15	23	11	8	3	7	−3	−2
Maple Plain—MSPAP	−108	−4	28	19	10	6	1	1	5	1
Wayzata—MSPAP	−95	5	34	34	32	18	17	14	5	1

[1] All data are from the 0700 hour observation, including data from MSPAP (11).

Table 10. Percentage frequency of occurrence of wind direction by quadrants during precipitation periods at MSPAP, 1961-1964 (11)

Direction by quadrants	Months											
	January	February	March	April	May	June	July	August	September	October	November	December
N-ENE	25.7	31.3	39.9	19.9	33.0	22.9	18.5	22.6	18.0	32.6	18.2	15.9
E-SSE	20.4	27.1	25.4	28.7	40.8	40.1	43.3	35.7	33.4	34.8	32.5	24.5
S-WSW	18.6	11.7	14.6	13.0	14.8	19.3	24.8	21.5	21.4	16.3	15.7	23.9
W-NNW	35.3	29.9	20.1	38.4	11.3	17.7	13.3	20.3	27.2	16.3	33.6	35.8

from zero by the single sample t-test. This result supports the validity of the hypothesis that there are growing season (May-September) differences between the stations and that the two regions of high and low precipitation are not due to chance.

Comparing the May-September growing season total precipitation from the wettest point to the driest, it was found that in each of the 14 years Plymouth Township, located just west of Minneapolis in Hennepin County, was wetter than MSPAP. Further, it was found that on the average, Plymouth Township received 5.33 inches more precipitation each May-September period than was received 15 miles away at MSPAP.

A similar comparison was made between MSPAP, the driest station, and a secondary region of maximum precipitation, Oakdale Township, located 16 miles east-northeast of MSPAP in Washington County. The comparison showed that in 13 out of 14 years more rain was received in Oakdale Township during each May-September period. The average difference was 3.71 inches.

Daily data provide further evidence of real precipitation differences between MSPAP and these same two regions of maximum precipitation. The data in table 9 show that there were more total rain days at MSPAP than at the stations in the high precipitation regions. This difference is of little significance, however, because the greater number of rain days at MSPAP was restricted almost without exception to the very light precipitation days; that is, to days with less than 0.01 inch.

The greater number of rain-days at MSPAP can be explained by the frequency with which precipitation observations are taken. They are taken four times per day at MSPAP but only once per day at the other stations. This results in the frequently observed phenomenon of more rain-days with respect to very small precipitation amounts at National Weather Service stations than at their cooperative stations due to more frequent observations (6). This occurs because the once per day observation frequently fails to detect the occurrence of very small precipitation amounts or because there is a loss of water due to evaporation between observation periods.

When slightly larger precipitation amounts (0.01 inch or more) were considered, the difference in rain-days reversed, as shown in table 9. With few exceptions the greatest number of rain-days occurred at the four stations within the two high precipitation regions, Maple Plain-Wayzata and Oakdale-Woodbury in the western and eastern regions, respectively.

Cause of the Areal Variation in Precipitation

In the search for causes of the observed precipitation distribution, interest centered on the influence of the cities themselves. This seemed a logical choice because topography, which normally would be the first choice, appeared to be of insufficient magnitude to explain the observed precipitation differences. But, because of the location of the two centers of high precipitation, one to the west and the other to the east of the two cities, the influence of the cities was eliminated as a possible cause.

Topography was thus turned to as a major cause of the areal distribution observed. It apparently was effective only under certain conditions, however, since the presence of the high precipitation region was restricted largely to the growing season. Two meteorological features that are seasonal in character are considered very important in this regard. One is wind direction, which shows a distinct seasonal shift. The other is convective activity, a phenomenon associated primarily with the warm months of the year.

The frequency with which low level winds blow from the four quadrants at MSPAP during precipitation periods is shown in table 10. Especially important with respect to the cause of the high precipitation regions is the frequency of the low level winds from the southeast quadrant. Winds from this quadrant occur more frequently than from any other during May-October; a frequency that exceeds 40 percent is reached in May, June, and July.

Assuming that the three factors (local low level winds, topography, and convective activity) acting together under special circumstances constitute the mechanism that causes the observed precipitation maximums, the following explanation shows how they are believed to operate.

During precipitation periods, some of the low level moisture bearing winds flow within river valleys where the air flow is channeled by valley walls that may be 200-

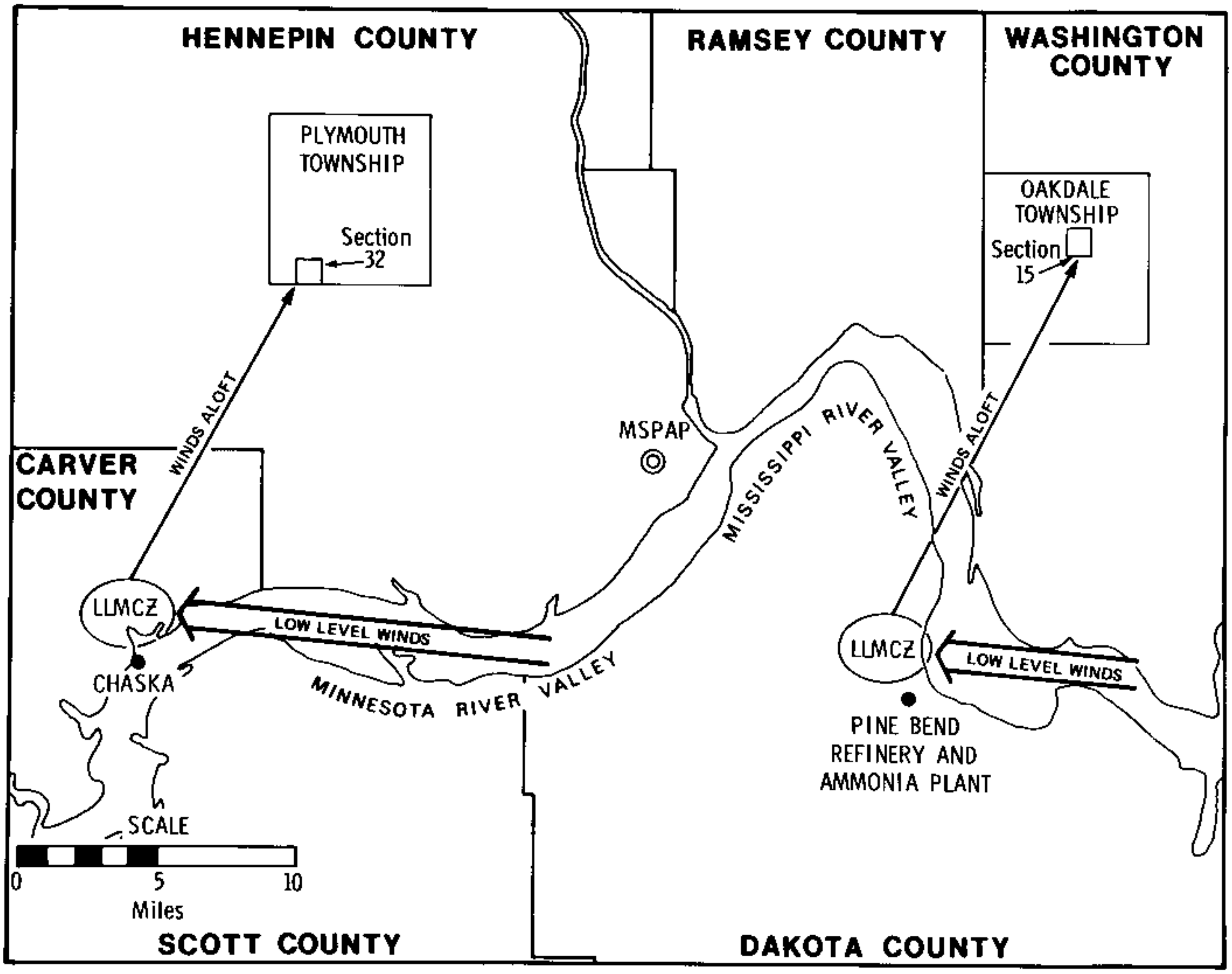

Figure 23. Commonly occurring surface wind flow in the Minnesota and Mississippi River Valleys at the time of precipitation and location of the Chaska and Pine Bend low level moisture convergence zones and the associated upper level winds at about 18,000 feet

400 feet above the valley floor. Where the valley bends rather sharply, some of the air will be forced to rise abruptly. Jones et al. (9) noted that constant level balloons did not follow the river valley configuration when bends occurred. Rather, they were forced up and out of the valley just as is suggested here. At the point where the winds rise out of the valley, a low level moisture convergence zone (LLMCZ) is created. The forced ascent of the air and the attendant expansion and cooling may be sufficient to trigger some precipitation.

More important, however, is the influence that the LLMCZ may have upon a rain or thundershower that is overhead or approaching. The rising, moist air will provide an added influx of moisture into the overhead or approaching convective storm cell. In other words, the precipitation characteristics of the storm cell will be enhanced with the introduction into its base of the air rising abruptly out of the river valley. The result of the additional moisture being fed into all storm cells passing a given location should be an area of relatively high precipitation. This, of course, depends on the surface winds having the proper direction and magnitude so that local topography does have an influence. It also depends on the presence of convective activity, which is essentially a warm season phenomenon.

Two distinct precipitations maximums were found in this study. One is located to the west of Minneapolis in Plymouth Township, Hennepin County; the other is east of St. Paul in Oakdale Township, Washington County. They are shown in figure 18.

The LLMCZ believed to cause the Plymouth Township precipitation maximum is located near Chaska. The east-southeasterly surface winds common during summertime precipitation periods are viewed as flowing up the relatively wide Minnesota River Valley for a distance of about 12 miles to near Chaska, where the river bends south-southwest (figure 23). At this point the valley air is forced to rise abruptly about 250 feet out of the river valley, producing a LLMCZ (figure 24). Meanwhile, the winds aloft at 15,000-20,000 feet are guiding any convective cells that pass over the LLMCZ. According to the Ekman spiral, in which winds increase in speed and turn clockwise with increasing altitude (4), the winds at 15,000-20,000 feet are approximately south-southwesterly when the surface winds are from the east-southeast (figure 23). Thus a storm cell fed by the LLMCZ near Chaska is directed by the south-southwest winds aloft in a north-northeasterly direction toward Plymouth Township. The south-southwest flow at 15,000-20,000 feet is also supported by the normal 500 millibars (about 18,000 feet

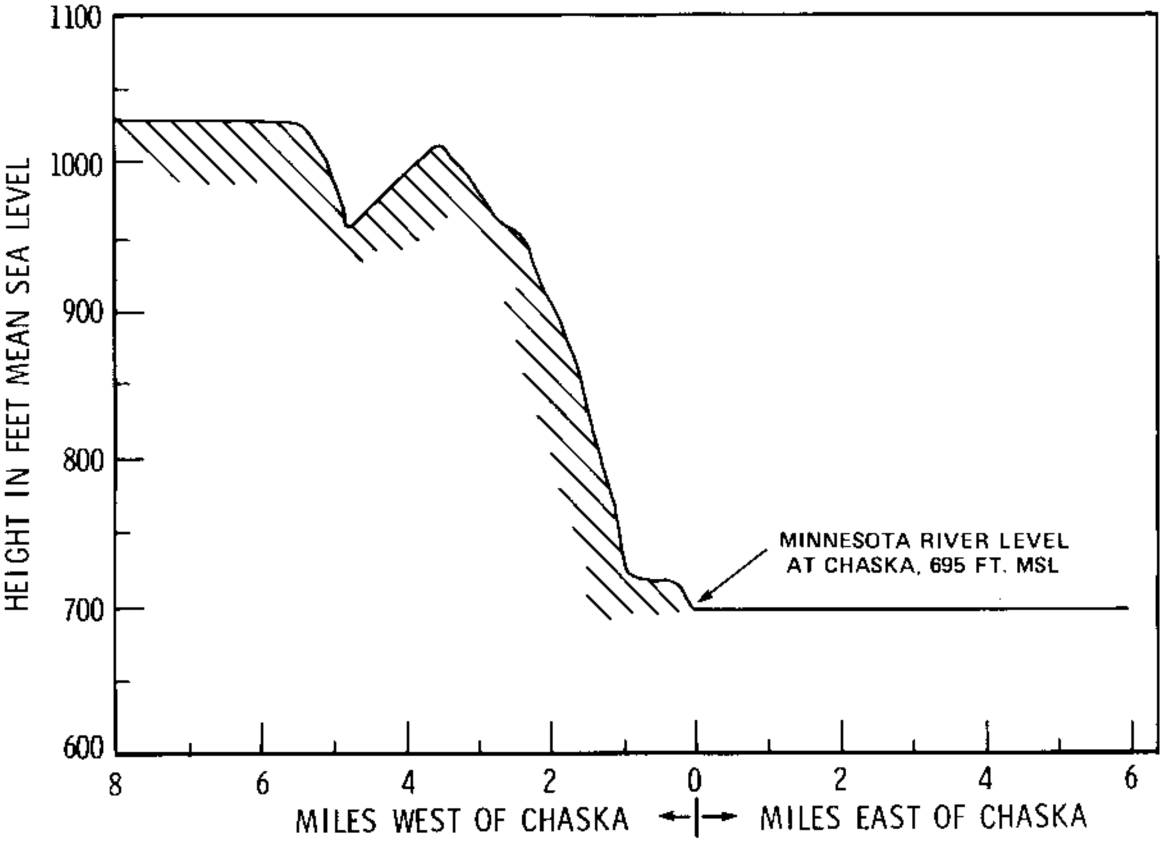

Figure 24. Vertical cross-section of the terrain immediatey west of the Minnesota River Valley at Chaska

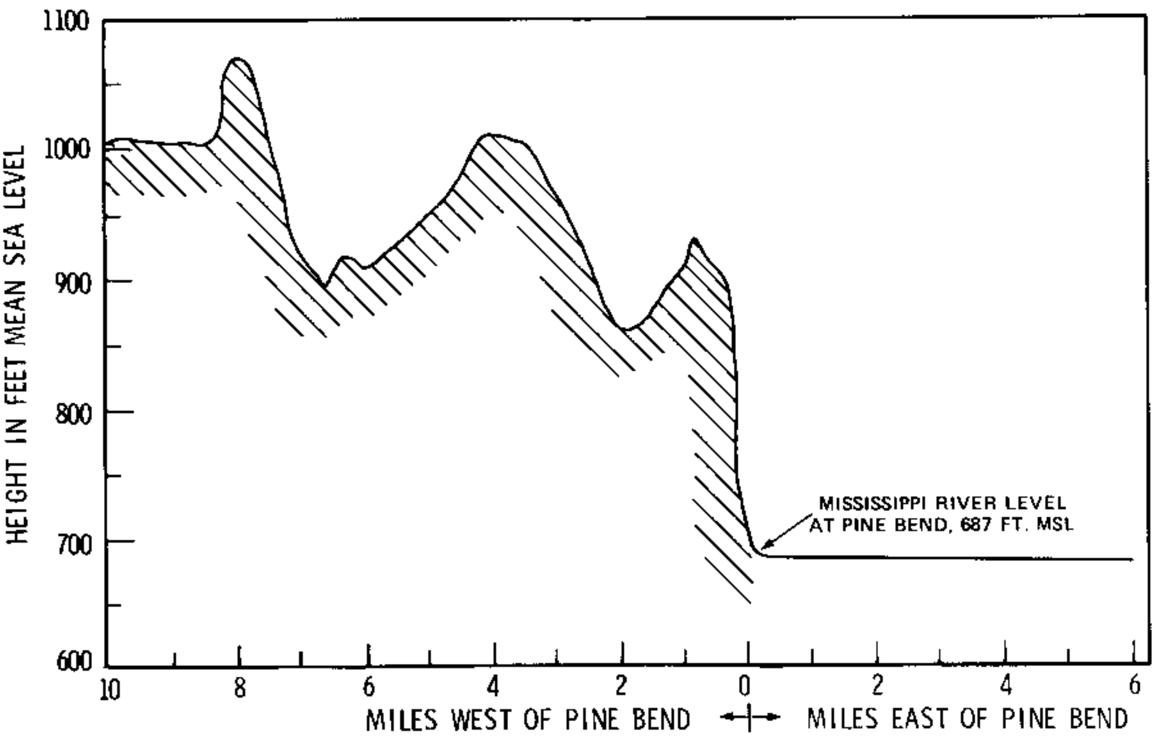

Figure 25. Vertical cross-section of the terrain immediately west of the Mississippi River Valley at Pine Bend

mean sea level) wind pattern, which approximates the storm cell movement in this area when surface winds are from the east-southeast. The movement of severe storms shown in figures 21 and 22 is a further example of the south-southwest flow aloft, which directs the storm movement while surface winds are from the southeast quadrant.

The LLMCZ believed to cause the Oakdale Township precipitation maximum is located just north of Pind Bend (figure 23). Again, east-southeasterly surface winds are pictured as blowing up the wide Mississippi Valley for about 10 miles, at which point the valley bends to the north with the wind forced abruptly up and out of the valley (figure 25). The south-southwest winds aloft carry the convective cell, fed by the LLMCZ, to the north-northeast and over Oakdale Township.

Thus, based on those occurrences of easterly to southeasterly surface winds during certain summertime precipitation periods, the position of a LLMCZ relative to the region of precipitation maximum should be located upwind and about 90 degrees from the location of the maximum. Two LLMCZ's can be identified to the south-southwest of the precipitation maximums; each is about 15 miles from the respective maximums.

To further confirm this analysis, an examination was made of other places along the Mississippi River Valley where similar configurations occur and for which precipitation data were available. One such spot is near Red Wing, where the broad Mississippi Valley is oriented approximately east-west. A few miles northwest of Red Wing the Cannon River enters the Mississippi River. Just northwest of their confluence, the Cannon turns to the northwest. On the west bank are bluffs that would force the air to rise. About 12 miles north-northeast of this LLMCZ is an area of higher precipitation centered near Ellsworth, Wisconsin.

North of LaCrosse, Wisconsin, the valley is level and very wide with abruptly rising bluffs near Centerville. This situation is believed to result in another LLMCZ. An area of higher precipitation occurs some 15 miles north-northeast at Blair, Wisconsin, during the growing season.

Much farther downstream, near Cape Girardeau, Missouri, another LLMCZ can be found. (Lack of readily available precipitation data prevented a search for likely places between LaCrosse and Cape Girardeau). North-northeast of Cape Girardeau the Mississippi River bends to the northwest. At this point, air moving up the valley is pictured as being forced out of the valley. North-northeast of this point about 15 miles, a precipitation maximum exists near Makanda, Illinois, during the summer months (9).

SUMMARY AND CONCLUSIONS

This study concentrated on the monthly, seasonal, and annual precipitation that falls within the 7,200 square mile area centered around the Twin Cities of Minneapolis and St. Paul. Records from 75 stations were available for the 14-year period 1959-1972. Fifty-two of the stations had records for January-December and all 75 had May-September records. Statistical tests of the different station records showed no significant difference between this 14-year period and a 30-year period preceding 1959 and between the 14-year period and the current 30-year normal period (1941-1970).

It was determined that the May-September station density of one per 96 square miles is sufficient to detect more than 99 percent of the summer storms of 0.01 inch or more. The distribution of the stations used, however, was not uniform across the 7,200 square mile area.

For the area as a whole, the total annual precipitation averaged 29.17 inches, varying from 26.96 inches at Forest Lake to 32.39 inches at Ellsworth, Wisconsin. The major forecasting and observing station within the area, MSPAP (Minneapolis-St. Paul International Airport station), averaged only 27.08 inches, or 2.09 inches below the areal mean.

Areas of persistently high and low precipitation were found. The low area centered around MSPAP, with two centers of high precipitation located to the north-northwest and northeast of MSPAP in Hennepin and Washington Counties, respectively. The higher precipitation amounts in these two areas was limited to the May-September period. The differences in precipitation amounts between stations in the high and low regions were found to be statistically valid. Of equal or greater importance is the fact that the presence of the high precipitation areas can be explained on a sound physical basis. The explanation rests upon the occurrence of low level moisture convergence zones that result from a combination of local topography, summertime convective activity, and the surface winds at the time of precipitation.

Tornado paths within the area were shown to apparently prefer paths or alleys that more or less coincide with the orientation and location of the high precipitation areas.

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