COPY 2

Technical Bulletin 235 May 1960

Agricultural Drought and Moisture Excesses in Minnesota

G. R. Blake, E. R. Allred, C. H. M. van Bavel,
F. D. Whisler

University of Minnesota
Agricultural Experiment Station
in cooperation with
Soil and Water Conservation Research Division
ARS, USDA

Contents

★ ★ ★ ★ ★

Foreword

This bulletin follows a series of reports describing drought conditions in various southeastern states. The first report, "Agricultural Drought in North Carolina," was published as Technical Bulletin 122 of the North Carolina Agricultural Experiment Station in June 1956. Agricultural drought conditions in other southeastern states have been subsequently published.

In this bulletin the concept of drought conditions has been supplemented with a statistical treatment that describes moisture excesses under specified soil-moisture-holding capacities.

This report is a joint contribution of the Minnesota Agricultural Experiment Station and the Agricultural Research Service of the United States Department of Agriculture.

The authors acknowledge gratefully the cooperation of the National Weather Records Center of the United States Weather Bureau at Asheville, North Carolina, for punching the weather data on cards and making the computations on which information in this bulletin is based.

Submitted for publication December 14, 1959
Approved for publication January 25, 1960

3M—2-60

Agricultural Drought and Moisture Excesses in Minnesota

G. R. Blake, E. R. Allred, C. H. M. van Bavel, and F. D. Whisler[1]

The source of fresh water for all uses is precipitation. Though Minnesota's surface-water supplies—stored precipitation—consist of some 3 million acres of lakes and over 10 million acres of swamps and marshes, there are, nevertheless, shortages for crops at certain times and locations in almost every year. Likewise, for certain crops and soils, there are periods of moisture excess.

The purpose of this study is to predict drought probability, i.e., the number of days per month or season that rainfall is insufficient to supply the needs of growing plants after available soil moisture is depleted. The data are based on a statistical study of past amount and distribution of rainfall at 22 stations in Minnesota. Fundamental information is given on average monthly evapotranspiration at some stations. There is also a summary of the amount of precipitation in excess of plant needs and of the ability of soils to store it.

Information of this nature is basic to water planning for both agricultural and urban uses. In agriculture, for example, it can serve as a guide in problems of irrigation need and in the disposal of excess water.

Definition of Drought and Moisture Excess

Drought occurs whenever the supply of water to crops, either from rainfall or that stored in the soil, becomes inadequate. Each day there is inadequate moisture in the root zone is defined as a *drought-day* (Allred and Chen, 1953; van Bavel and Verlinden, 1956). The number of drought-days and the amount of the water deficiency can be predicted from evapotranspiration calculations and past precipitation data. Because of the uneven distribution of precipitation, droughts of varying length may occur periodically through a growing season.

Moisture excess is the amount of water in excess of that which the soil can store and hold for rainless periods. It can also be predicted by calculation and use of precipitation records.

Methods

The methods used to determine whether a drought existed consisted of computing a daily balance of available soil moisture for 25 consecutive years, beginning in 1932. This was done for each of a number of weather stations. Each day the supply of available moisture was exhausted was called a

[1] G. R. Blake is associate professor, Department of Soils; E. R. Allred is associate professor, Department of Agricultural Engineering; and C. H. M. van Bavel and F. D. Whisler are soil scientists, USDA.

drought-day. Three quantities are required for these calculations: daily precipitation; available water-holding capacity of the root zone; and the daily rate of water loss by evaporation and transpiration.

Runoff is not considered in the water-balance calculations. This loss varies widely, depending among other things on slope, cover, time of year, and intensity of rainfall. It is difficult to generalize these for the whole state or even a smaller geographic area. Runoff losses, however, should be given local consideration in applying the data.

A more detailed discussion of runoff and other possible errors in the methods used in this study is given by van Bavel and Verlinden (1956).

Precipitation Daily precipitation data were taken from official United States Weather Bureau records furnished by the National Weather Records Center in Asheville, North Carolina. The 25-year records (1932-56) of 22 stations in Minnesota (table 1) were used in this study. Six stations in eastern North and South Dakota were also used to more clearly define conditions along the western boundary of the state. These stations were Grand Forks and Lisbon in North Dakota and Brookings, Sioux Falls, Victor, and Watertown in South Dakota. The stations indicated were chosen because of their nearly uninterrupted length of record.

Available moisture-holding capacity of the root zone The capacity of the root zone to supply moisture for plants depends on the storage capacity of the soil and the depth of rooting of the crop.

The storage capacity of different soils depends primarily on their textures—that is, the relative proportion of clay, silt, and sand. Fine-textured soils have greater storage capacities than sandy soils.

When soils are thoroughly wetted, the excess water drains downward into the ground water. Drainage greatly decreases after 24 to 48 hours, and the soil holds an amount of water called its *field capacity.* This amount varies for different soils. If a crop is growing on the soil and it receives no additional water, the moisture supply is slowly depleted until finally the plant wilts and dies. The amount remaining in the soil at this stage is called the *permanent wilting percentage.* Obviously, the amount of *available water* that can be stored in the soil for use by the crop is limited to that between the field capacity and the permanent wilting percentage. Table 2 shows the effect of soil texture on available water-holding capacity (Allred, *et al*, 1958).

Available water-holding capacity of the root zone depends not only on the soil storage capacity per unit depth but also on the depth of exploitation by the crop. Data in table 3 give estimates of effective rooting depth for some common crops (Allred *et al.*, 1958).

For Minnesota crops and soils, water-holding capacity of the root zone may vary from 1 to more than 9 inches. Such a wide variation makes it impossible to generalize root-zone water-holding capacity when using it to define drought occurrence. To cover a wide soil-crop range, drought probability, moisture deficiency, and moisture excess were computed for root-zone water-holding capacities of 1, 3, 5, 7, and 9 inches.

Water loss by evaporation and transpiration Actual measurements of evaporation from the soil and crop by soil sampling are limited. Fortunately, it has been found that these losses can be estimated by calculations based on metereological data. In this study evapotranspiration was computed by a method developed by Penman, 1948.

Penman's method, described in the appendix, requires information on air temperature, wind velocity, relative humidity, and sunshine duration. These data are obtainable only from the records of first-order stations of the United States Weather Bureau. There are nine widely scattered first-order stations in or near Minnesota: Minneapolis and Duluth, Minnesota; Madison, Wisconsin; Sioux City, Iowa; Bismarck, Fargo, and

Devils Lake, North Dakota; Huron, South Dakota; and Winnipeg, Canada. By this method monthly evapotranspiration rate in inches was computed for each first-order station. Long-time averages were used in these calculations. Monthly evapotranspiration rates are given in table 4 and shown graphically in figures 1 and 2.

Monthly evapotranspiration values show some variation between stations, thus making it impossible to generalize this quantity over the entire state. However, by dividing the state into three areas, as shown in figure 3, these rates were found to be reasonably uniform within each area.

In the calculation of daily soil-moisture balances, daily (rather than monthly) evapotranspiration rates are required. However, use of daily values greatly increases the amount of calculation. To minimize this the daily value of estimated evapotranspiration was kept constant for each month as shown in table 5. This average eliminates a wide day-to-day variation shown by daily values. However, since the occurrence of drought-days depends on the accumulated evapotranspiration over many days, the effect of day-to-day variations from the long-time monthly average is minimized.

Computing the daily soil-moisture balance The computation for determining the daily soil-moisture balances was begun by assuming the root zone was at field capacity January 1, 1932. The daily balance was then calculated for each subsequent day of the 25-year period. Moisture excesses were determined for each month of the year, though drought-days were tabulated only for May through September, i.e., the growing season.

As indicated earlier, the computations were made using the maximum root-zone moisture-capacity of the soil as a parameter. The capacity values used were 1, 3, 5, 7, and 9 inches.

The amount of soil moisture available to the crop on the first day was equal to the root-zone capacity of the soil. An estimate for the next day was obtained by subtracting the estimated evapotranspiration and adding any precipitation that occurred during the day. The soil moisture present at the second day was then carried over to the third day, etc., and the computation repeated. This simple calculation was carried out for each successive day of the growing season with two limitations: at no time was the amount of available soil moisture allowed to exceed the maximum field capacity of the root zone; and the available soil moisture for any day could not be less than zero. Precipitation in excess of the field capacity was considered as excess. All days on which the computation showed no available soil moisture were considered drought-days.

The number of drought-days was then determined for a given month or for the entire growing season. The moisture-balance computation can be applied to any location and year for which a record of precipitation is available. Computations in this study were made for the 25-year period for the stations indicated in table 1, and also for the North and South Dakota stations referred to previously.

Calculation of the daily soil-moisture balance, together with the estimation of drought probability, is relatively simple. However, because of the large number of days of record, stations, and root-zone capacities, the total calculation became quite voluminous. For this reason the computations were done by the use of punch cards and machines.

To adapt the calculation to machine technique, the 25-year precipitation record of each station was punched one day to a card. The estimated evapotranspiration for each day was also punched on the card. With these data the daily moisture-balance for each of the five root-zone capacities (1, 3, 5, 7, and 9 inches) was computed. Thus, each card shows the moisture balance and whether or not a drought-day occurred. Tabulations were then made of the total number of drought-days occurring for each summer month and for a year for each station, at various probability levels. This tabulation was made for each root-zone capacity.

Results

Agricultural drought The occurrence and frequency distribution of drought-days for each station, year, and soil were determined from the moisture-balance tabulation. Such occurrences can be determined for any specific period or for the entire growing season. Table 6 shows the minimum number of drought-days one can expect for specific months, at different levels of probability, in the areas shown in figure 4. Monthly deficiencies in inches of water are shown in table 7.

Plotting drought-day frequency distribution for each station on probability paper (figures 5 through 15) shows the percent of years the number of drought-days will equal or exceed a given number. Each line shown on these graphs represents a different root-zone capacity. For example, figure 10 shows that for a soil in the Minneapolis area having a root-zone capacity of 5 inches, one can expect at least 40 drought-days per year, 20 percent of the time. The expected minimum number of drought-days per season is shown graphically in figures 16 through 20.

Moisture deficiency Drought intensity is sometimes more easily understood when expressed in terms of inches of water deficiency, rather than in drought-days. Figures 21 through 25 show inches of water deficiency at various probability levels and for the five root-zone capacities. For example, suppose one wishes to determine the moisture deficiency that will occur 3 years out of 10 on a farm in McLeod County. Assume the soil is a sandy loam, with a root-zone capacity of 5 inches. Under these conditions, figure 23 shows one can expect a total moisture deficiency of 4.5 inches, or more, 3 out of every 10 years.

Moisture excess While there may be deficiencies in all years, there can also be periods when the soil-moisture reservoir is full and excesses will occur. Annual excess precipitation is shown in figures 26 and 27, while average monthly excesses are shown in table 8.

A sizable portion of the moisture excesses occurs during spring and early summer. These excesses are removed from the root zone by surface runoff or underground drainage. When these losses occur, the probability of drought is greater than that shown in this bulletin.

Discussion and Summary

The normal rainfall pattern in Minnesota is such that soil moisture is near depletion almost every year in September. Fall and spring rains and snow melt restore the soil-moisture reservoir to a variable extent, depending on their amounts. In most parts of the state there is insufficient precipitation during July and August. In some parts there is a deficiency of precipitation over evapotranspiration even in the spring months (figure 1). During those times of unfavorable precipitation balance, water for crops comes from that stored in the soil. Stored water is not always enough either, so that drought occurs.

An important conclusion of this study is that the number of drought days occurring during the summer depends greatly on the storage capacity of the soil and the rooting depth of the crop.

The deeper the crop roots and the larger the soil-storage capacity the fewer drought days are experienced.

Shallow-rooted crops on sandy soils, exemplified by the 1- or 3-inch root-zone capacity (table 7, figure 16) would have a large number of drought-days per month. The sand plain, lying in the Anoka-Isanti-Sherburne-Benton County area, will average from 30 to 60 drought days (figures 16 and 17). In the driest year out of 10 with a 3-inch root-zone capacity this area will have at least 60 drought days. Table 6 shows how these might be distributed by months.

In south-central Minnesota many soils will have a root-zone moisture capacity of 9 inches and often more in the surface 4 feet. Figure 20 shows that in an average year (5 in 10 probability) the LeSueur-Sibley-Nicollet County area will have between 10 and 20 drought days. On the other hand the driest year in 10 at a 9-inch root-zone capacity (figure 20) shows this area will have at least 45 to 55 drought days per season.

If one is thinking of irrigation, data in this bulletin are valuable in determining how much water must be added to insure a continuous water supply to the crop. Three things must be taken into account, however: The odds one wishes to consider, the depth of rooting of the crop, and the storage capacity of the soil. Let us suppose one is irrigating a shallow-rooted vegetable on a sandy soil in Hennepin County. Figure 22 shows that with a 3-inch root-zone capacity one will have to add around 9 inches of water as irrigation in the driest year in 10. In a normal year (5 in 10 probability) figure 22 shows that about 5 inches will be needed during the whole season.

On the other hand, with a deeper rooted crop such as corn in Blue Earth County on Nicollet silt loam with a 9-inch storage capacity, one will need only 6 inches of water as irrigation, even in the driest year out of 10.

It should be noted that some crops suffer in yield more than others from a moisture deficiency. Corn is a more tolerant crop than most vegetables and will stand a few occasional drought days without serious setback. Furthermore, the time of season that drought occurs is tremendously important. Drought days just before and during silking and pollination will result in lower yields. This points up the fact that annual moisture deficiency is not always a reliable criterion of the benefits to be expected from supplemental irrigation.

While the data show that even in the wettest years there is a deficiency of moisture for optimum plant growth, one must balance the cost of application against possible crop returns. This must depend on the amount of the deficiency and on the response and economic value of the crop to which the water is added.

Though there are moisture deficiencies for crops in nearly all years, there are other times of each year when the root zone is full and rain either runs off the soil surface, seeps into the tile lines or open ditches, or drains through the soil profile into the ground water. Thus the maximum expected drainage or underground stored water can be estimated. For example, figure 26 shows that with a root-zone capacity of 5 inches the usual excess precipitation (5 years out of 10) in Lincoln County is less than 2 inches annually. In the wettest year out of 10 there will be a little less than 6 inches excess. On fine-textured soils, however, exemplified by those with a 9-inch root-zone capacity, much of western Minnesota will have less than 2 inches annual excess precipitation except in the wettest year out of 10. Contrasted to this is the average excess of more than 4 inches in eastern Minnesota with as much as 10 inches in the wettest years. These facts, as shown in figures 26 and 27, are of tremendous importance if problems of water storage, either surface or underground, are being considered.

Literature Cited

ALLRED, E. R., and CHEN, R., 1953. Evaluating Irrigation Needs in Humid Areas. Agri. Engineering. **34**:611.

ALLRED, E. R., BLAKE, G. R., and LARSON, C. L., 1958. Planning for Irrigation in Minnesota. Minn. Agri. Ext. Bul. 288.

PENMAN, H. L., 1948. Natural Evaporation from Open Water, Bare Soil, and Grass. Proc. of the Royal Soc. **193**:120.

VAN BAVEL, C. H. M., 1953. A Drought Criterion and its Application in Evaluating Drought Incidence and Hazard. Agron. Jour. **45**:167.

VAN BAVEL, C. H. M., and VERLINDEN, F. J., 1956. Agricultural Drought in North Carolina. N. C. Agri. Exp. Sta. Tech. Bul. 122.

Penman's Formula

Penman's formula sums the radiant energy received, the advective heat received, and the energy lost by re-radiation from the soil and crop surface. The energy is then partitioned into that available for evaporation and that used in heating the soil or air. The whole is multiplied by a factor (0.7) to convert evaporation from a free water surface to that from a cropped surface. The complete statement of these facts is given by:

$$
\begin{aligned}
(1)\quad E_t = 0.7\ [&\Delta e/\Delta T_a\ (R_I - rR_I)\ (0.18 + 0.55\ n/N) \\
&- (\Delta e/\Delta T_a)\ \sigma T^4\ (0.56 - 0.092\ \sqrt{e_a})\ (0.10 + 0.9\ n/N) \\
&+ 0.27 \times 0.35\ (e_s - e_a)\ (1 + 0.0098\,u)\,] \div (\Delta e/\Delta T_a + 0.27)
\end{aligned}
$$

Where E_t = Evapotranspiration in mm/day. The values for the various quantities given below are for Minneapolis in July 1952.

$\Delta e/\Delta T_a$ = Vapor pressure, mm Hg/temperature in °F. = 0.695 mm Hg/°F.

R_I = Incoming radiation, 15.92 mm/day evaporation equivalent.

rR_I = Reflected heat loss, where r is the reflection coefficient = .05 × 15.92 = 0.796.

n/N = Ratio of sunlight to total possible sunlight, i.e. sunshine percentage of possible, = 76 percent.

σ = Boltzman constant = 2.01×10^{-9} mm/day.

T = Absolute temperature of air = 296° (73.2° F.)

$\sigma T^4 = 2.01 \times 10^{-9} \times 296^4 = 15.43$ mm/day evaporation equivalent.

e_a = Mean actual vapor pressure of air = 13.9 mm Hg. This value is based on a mean relative humidity of 66.5 percent at Minneapolis

e_s = Saturation vapor pressure of air at 73.2°F. = 20.9 mm Hg.

u = Wind velocity at 2 meters height = 116.1 miles/day. Observations at 73 feet were corrected to 2-meter height by the formula

$$u = u_{73} \times \frac{\log 6.6}{\log 73}$$

Substituting all values into equation 1 gives the following value for evapotranspiration at Minneapolis for July 1952.

$$\begin{aligned} E_t = 0.7\ [&0.695\ (15.92 - 0.80)\ (0.18 + 0.55 \times 0.76) \\ &- 0.695 \times 15.43\ (0.56 - 0.092\ \sqrt{13.9})\ (0.10 + 0.9 \times 0.76) \\ &+ 0.27 \times 0.35\ (20.9 - 13.9)\ (1 + 0.0098 \times 116.1)] \\ &\div (0.695 + 0.27) = 4.26 \text{ mm/day} \\ &\qquad 132.1 \text{ mm/month} \\ &\qquad 5.20 \text{ inches per month} \end{aligned}$$

The factor 0.7 for converting evaporation from a free water surface to that from a cropped surface is empiracally based on observations by Penman. Actually, based on his work in England, he suggested 0.6 for November to February, 0.8 for May to August, and 0.7 for the other four months. In this bulletin the factor 0.7 was used for all months.

The constants $\Delta e/\Delta T_a$, R_I, σ, e_s, and N are obtainable from standard tables. Values for n/N, mean relative humidity, and u are taken from United States Weather Bureau publications, Local Climatological Data.

Table 1. Minnesota rainfall stations used in this study

Station	County	Missing record
1. Baudette	Lake of the Woods	11/45
2. Cloquet	Carlton	....
3. Crookston	Polk	....
4. Detroit Lakes	Becker	2/34
5. Grand Marais	Cook	....
6. Grand Meadow	Mower	....
7. Grand Rapids	Itasca	....
8. Hallock	Kittson	2/48
9. Itasca	Clearwater	....
10. Little Falls	Morrison	....
11. Minneapolis	Hennepin	....
12. Mora	Kanabec	....
13. Morris	Stevens	....
14. Redwood Falls	Redwood	....
15. Virginia	St. Louis	....
16. Wadena	Wadena	3, 4, 6, 7, 10, 11/32 5, 6, 7, 8, 9, 10/33
17. Waseca	Waseca	....
18. Willmar	Kandiyohi	....
19. Winnebago	Faribault	....
20. Winona	Winona	7/34
21. Worthington	Nobles	....
22. Zumbrota	Goodhue	11, 12/37 1, 2, 3, 4/38

Table 2. Approximate available water-storage capacity of soils

Texture	Inches available water per foot of soil
Loamy sand	0.6 - 1.0
Sandy loam	1.0 - 1.3
Loam	1.7 - 2.3
Silt loam	2.0 - 2.8
Silty clay loam	2.5 - 3.5
Clay	2.0 - 3.5

Table 3. Effective rooting depths of various crops in well-drained soils

Very shallow (18 inches)	Shallow (24 inches)	Moderately deep (36-48 inches)	Deep (48-60 inches)	Very deep (greater than 60 inches)
onions	potatoes	soybeans	tomatoes	alfalfa
radishes	celery	spring grains	asparagus	some trees
lettuce	peas	sugar beets	corn	
spinach	red clover	bromegrass	sweetclover	
ladino clover	timothy	orchardgrass	birdsfoot trefoil	
white clover		cabbage	parsnips	
bluegrass		snap beans	lima beans	
		broccoli		
		peppers		

Table 4. Average monthly evapotranspiration*

	Duluth	Minneapolis	Madison	Sioux City	Bismarck	Devil's Lake	Fargo	Huron	Winnipeg
January	.12	.15	.34	.31	.03	.01	.06	.22	T
February	.42	.48	.73	.76	.42	.31	.42	.59	.20
March	1.02	1.18	1.39	1.49	1.02	.87	.93	1.21	.62
April	2.16	2.58	2.58	2.91	2.40	2.22	2.43	2.73	1.89
May	3.25	3.66	3.78	4.00	3.69	3.47	3.72	3.94	3.22
June	3.81	4.47	4.62	4.77	4.38	4.11	4.35	4.71	3.84
July	4.22	4.96	5.05	5.36	5.02	4.62	4.77	5.52	4.12
August	3.35	4.00	4.15	4.46	4.06	3.78	3.91	4.53	3.22
September	2.01	2.58	2.76	3.03	2.49	2.25	2.49	3.03	1.89
October	1.36	1.43	1.49	1.71	1.21	1.12	1.30	1.58	.90
November	.33	.48	.66	.69	.33	.27	.39	.57	.18
December	.06	.15	.25	.25	.03	.01	.06	.19	T
Annual	22.12	26.12	27.81	29.73	25.09	23.03	24.84	28.80	19.96

* Calculated by Penman formula.

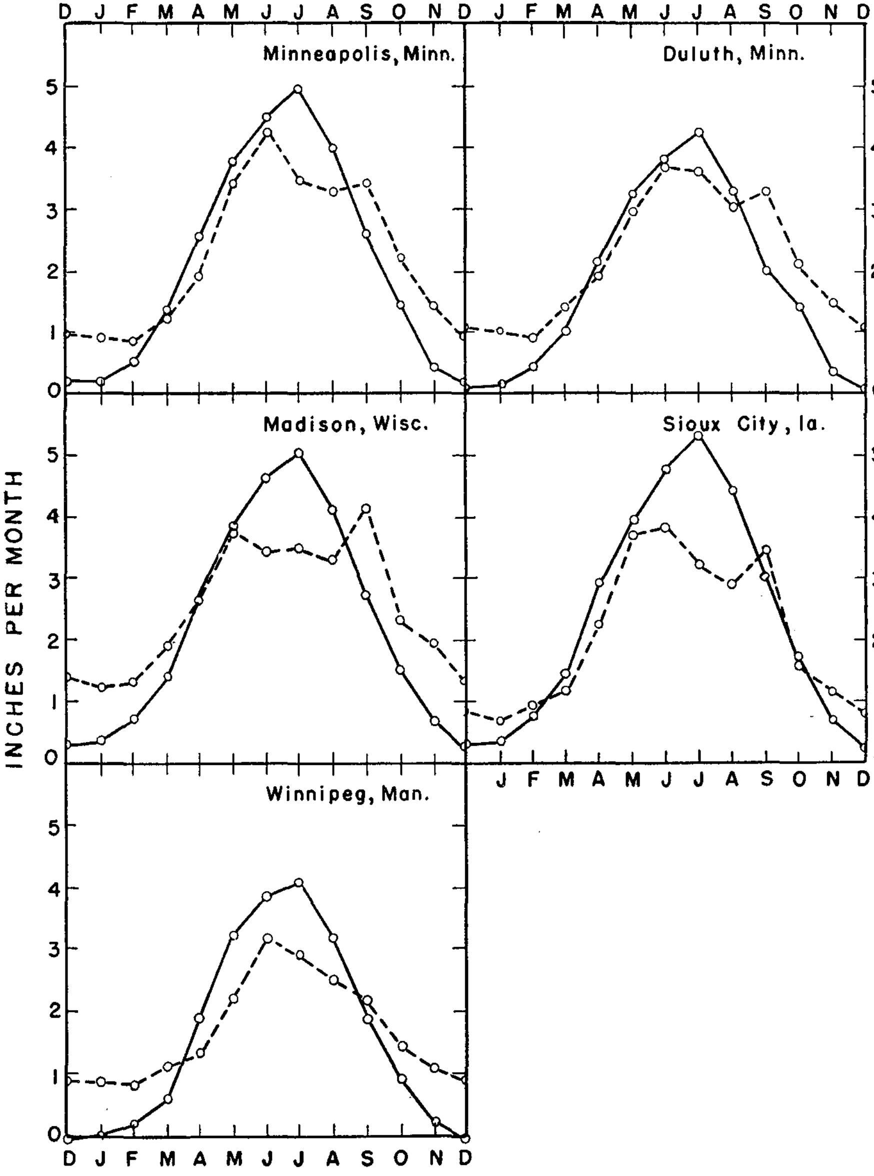


Fig. 1. Calculated monthly evapotranspiration rates and observed precipitation at various locations. (Solid line is evapotranspiration; dash line is precipitation.)

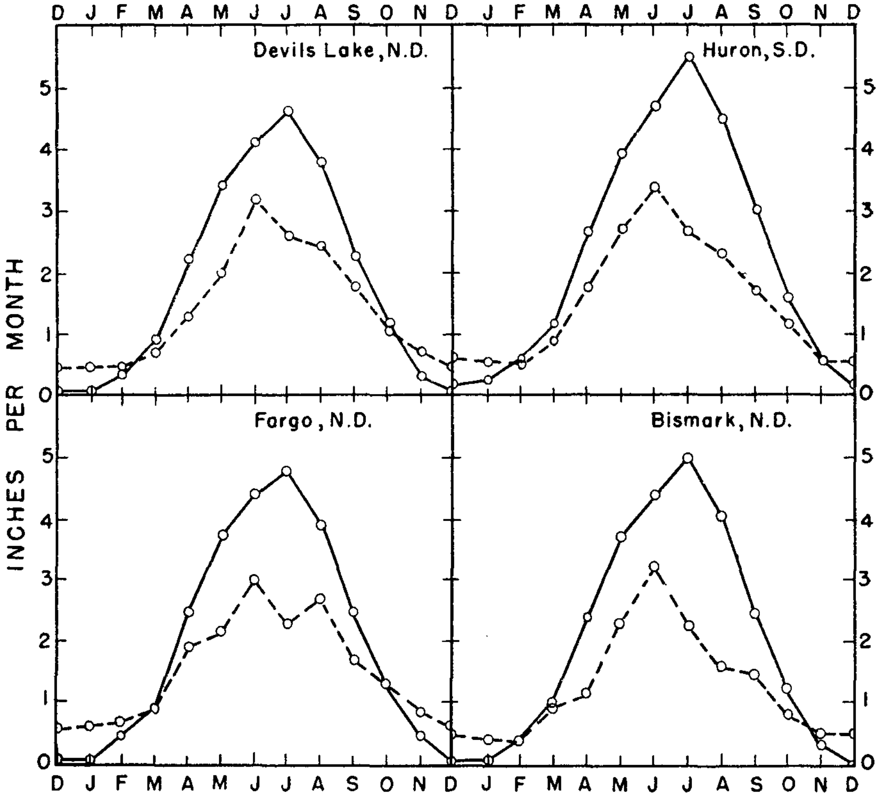


Fig. 2. Calculated monthly evapotranspiration rates and observed precipitation at various locations. (Solid line is evapotranspiration; dash line is precipitation.)

Table 5. Daily values of potential evapotranspiration, in inches, estimated from figures 1 and 2

	Area 1*	Area 2*	Area 3*
January	.00	.00	.01
February	.01	.02	.02
March	.03	.03	.04
April	.07	.08	.09
May	.11	.12	.12
June	.13	.15	.16
July	.14	.16	.17
August	.12	.13	.14
September	.07	.09	.10
October	.04	.04	.05
November	.01	.01	.02
December	.00	.00	.01

* Areas shown in figure 3.

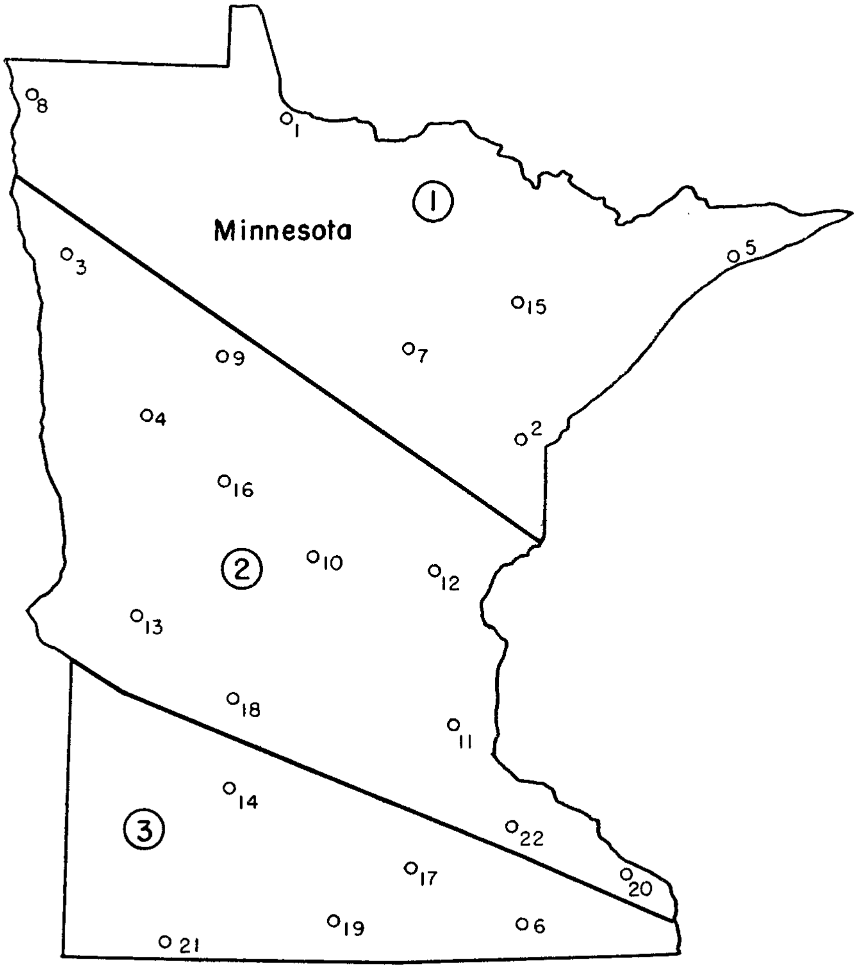


Fig. 3. Climatic areas for evapotranspiration calculations.

Table 6. Minimum number of drought days per month at various root-zone capacities and probability levels

Month	Probability level	Area 1* Root-zone capacity 1″	3″	5″	7″	9″	Area 2* Root-zone capacity 1″	3″	5″	7″	9″	Area 3* Root-zone capacity 1″	3″	5″	7″	9″
May	1/10	26	18	14	14	14	22	10	......	......	......	18	4	......	......	......
	2/10	22	12	6	6	6	18	6	......	......	......	16	1	......	......	......
	3/10	20	9	1	1	1	16	2	......	......	......	14	0	......	......	......
	5/10	16	3	0	0	0	12	0	......	......	......	10	0	......	......	......
June	1/10	22	20	15	15	15	19	15	10	4	0	18	12	......	......	......
	2/10	18	16	11	11	11	16	10	3	0	0	15	9	......	......	......
	3/10	16	13	8	8	8	14	7	0	0	0	12	6	......	......	......
	5/10	13	8	4	4	4	11	3	0	0	0	8	2	......	......	......
July	1/10	28	24	24	22	22	24	24	18	15	12	24	21	16	1	0
	2/10	24	20	18	16	15	21	19	12	8	5	21	16	7	0	0
	3/10	21	16	15	12	11	18	16	8	2	0	19	13	1	0	0
	5/10	16	11	9	5	3	14	10	2	0	0	15	8	0	0	0
August	1/10	25	24	23	22	22	23	22	20	16	15	24	22	16	10	......
	2/10	22	20	19	17	16	20	16	14	10	8	19	16	11	2	......
	3/10	20	18	16	14	12	17	13	10	6	2	16	12	7	0	......
	5/10	16	12	10	7	5	12	6	4	0	0	12	5	1	0	......
September	1/10	22	20	19	18	17	22	20	19	18	17	15	8	......	......	......
	2/10	18	15	14	12	11	18	15	14	12	11	11	3	......	......	......
	3/10	15	11	10	8	6	15	10	10	8	6	8	0	......	......	......
	5/10	10	4	3	1	0	10	4	3	1	0	3	0	......	......	......

* Areas shown in figure 4.

Table 6. Minimum number of drought days per month at various root-zone capacities and probability levels (continued)

Month	Probability level	Area 4* Root-zone capacity 1″	3″	5″	7″	9″	Area 5* Root-zone capacity 1″	3″	5″	7″	9″	Area 6* Root-zone capacity 1″	3″	5″	7″	9″
May	1/10	22	14	9	9	8	24	12	8	7	5	21	15	13	12	12
	2/10	18	10	2	2	1	20	6	2	1	0	17	9	5	4	3
	3/10	16	6	0	0	0	17	1	0	0	0	14	5	0	0	0
	5/10	12	2	0	0	0	12	0	0	0	0	10	0	0	0	0
June	1/10	21	16	14	12	11	21	14	8	6	3	20	15	11	10	9
	2/10	18	12	9	7	6	18	12	3	0	0	17	11	6	6	4
	3/10	16	9	6	4	2	15	10	0	0	0	15	8	2	2	1
	5/10	12	5	0	0	0	11	7	0	0	0	12	3	0	0	0
July	1/10	25	24	22	18	18	24	21	18	12	8	26	22	20	17	16
	2/10	22	19	14	10	8	22	17	13	7	2	23	18	14	12	12
	3/10	20	16	9	3	2	20	14	10	3	0	21	15	10	9	8
	5/10	16	10	0	0	0	16	9	4	0	0	18	10	4	4	2
August	1/10	23	21	20	17	16	24	22	20	18	14	24	22	20	18	18
	2/10	20	17	14	12	9	21	18	15	11	5	21	18	16	14	13
	3/10	18	14	10	8	4	18	14	12	6	0	19	15	14	12	10
	5/10	15	9	3	1	0	14	9	6	0	0	15	11	10	7	5
September	1/10	24	20	19	17	16	21	18	15	13	11	21	18	17	17	17
	2/10	20	16	14	11	10	17	14	10	8	6	18	15	12	12	11
	3/10	17	12	10	6	5	15	10	7	4	3	15	12	9	8	6
	5/10	12	9	3	0	0	11	4	1	0	0	12	9	4	2	0

* Areas shown in figure 4.

Table 6. Minimum number of drought days per month at various root-zone capacities and probability levels (continued)

Month	Probability level	Area 7* Root-zone capacity 1″	3″	5″	7″	9″
May	1/10	20	10	......	......	......
	2/10	16	6	......	......	......
	3/10	14	3	......	......	......
	5/10	9	0	......	......	......
June	1/10	20	13	4	......	......
	2/10	17	9	0	......	......
	3/10	14	6	0	......	......
	5/10	11	1	0	......	......
July	1/10	26	22	14	6	......
	2/10	23	17	11	1	......
	3/10	20	14	8	0	......
	5/10	16	8	4	0	......
August	1/10	22	21	17	14	9
	2/10	20	17	14	10	1
	3/10	17	13	11	6	0
	5/10	14	8	7	1	0
September	1/10	22	15	12	8	2
	2/10	18	11	8	3	0
	3/10	15	8	6	0	0
	5/10	10	3	1	0	0

* Areas shown in figure 4.

Table 7. Minimum moisture deficiency in inches per month at various root-zone capacities and probability levels

Month	Probability level	Area 1* Root-zone capacity 1″	3″	5″	7″	9″	Area 2* Root-zone capacity 1″	3″	5″	7″	9″
May	1/10	2.86	1.98	1.54	1.54	1.54	2.64	1.20	......	......	......
	2/10	2.42	1.32	.66	.66	.66	2.16	.72	......	......	......
	3/10	2.20	0.99	0.11	0.11	0.11	1.92	0.24	......	......	......
	5/10	1.76	0.33	0	0	0	1.44	0	......	......	......
June	1/10	2.86	2.60	1.95	1.95	1.95	2.85	2.25	1.50	0.60	0
	2/10	2.34	2.08	1.43	1.43	1.43	2.40	1.50	.45	0	0
	3/10	2.08	1.69	1.04	1.04	1.04	2.10	1.05	0	0	0
	5/10	1.69	1.04	0.52	0.52	0.52	1.65	0.45	0	0	0
July	1/10	3.92	3.36	3.36	3.08	3.08	3.84	3.84	2.88	2.40	1.92
	2/10	3.36	2.80	2.52	2.24	2.10	3.36	3.04	1.92	1.28	.80
	3/10	2.94	2.24	2.10	1.68	1.54	2.88	2.56	1.28	0.32	0
	5/10	2.24	1.54	1.26	0.70	0.42	2.24	1.60	0.32	0	0
August	1/10	3.00	2.88	2.76	2.64	2.64	2.99	2.86	2.60	2.08	1.95
	2/10	2.64	2.40	2.28	2.04	1.92	2.60	2.08	1.82	1.30	1.04
	3/10	2.40	2.16	1.92	1.68	1.44	2.21	1.69	1.30	0.78	0.26
	5/10	1.92	1.44	1.20	0.84	0.60	1.56	0.78	0.52	0	0
September	1/10	1.54	1.40	1.33	1.26	1.19	1.98	1.80	1.71	1.62	1.53
	2/10	1.26	1.05	.98	.84	.77	1.62	1.35	1.26	1.08	.99
	3/10	1.05	0.77	0.70	0.56	0.42	1.35	0.90	0.90	0.72	0.54
	5/10	0.70	.28	.21	.07	0	.90	.36	.27	.09	......

* Areas shown in figure 4.

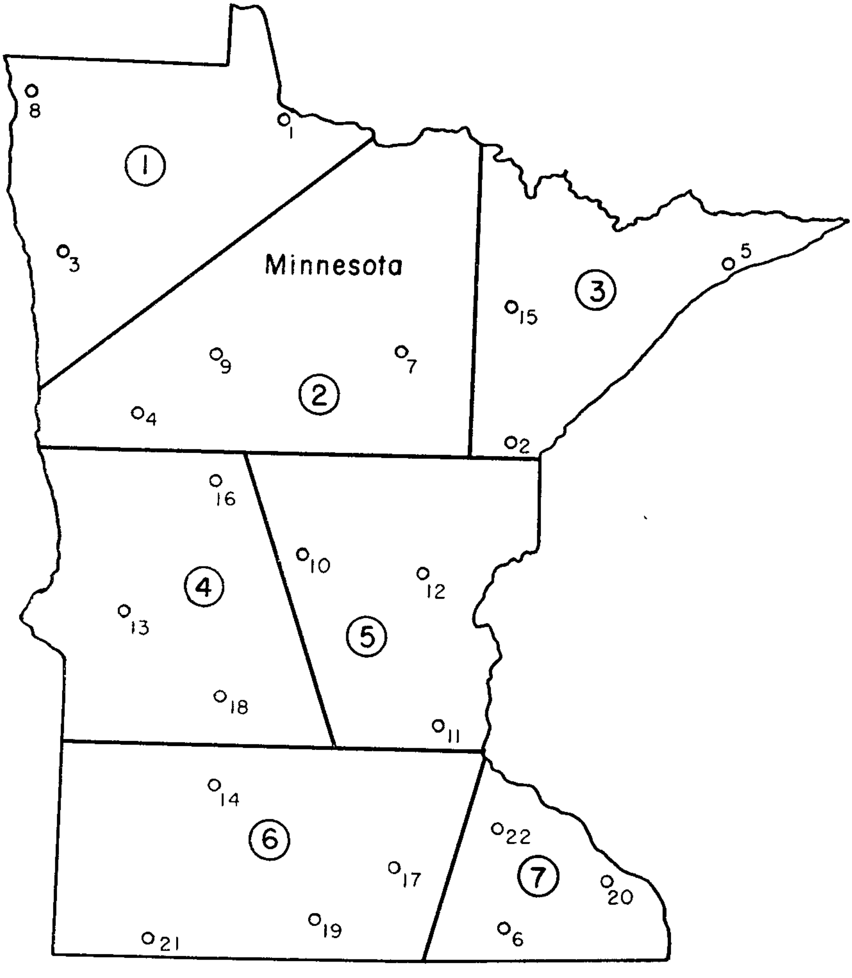


Fig. 4. Climatic areas for drought-frequency predictions.

Table 7. Minimum moisture deficiency in inches per month at various root-zone capacities and probability levels (continued)

Month	Proba-bility level	Area 3* Root-zone capacity 1″	3″	5″	7″	9″	Area 4* Root-zone capacity 1″	3″	5″	7″	9″
May	1/10	1.98	0.44	....	....	....	2.64	1.68	1.08	1.08	.96
	2/10	1.76	.11	....	....	....	2.16	1.20	.24	.24	.12
	3/10	1.54	0	....	....	....	1.92	.72	0	0	0
	5/10	1.10	0	....	....	....	1.44	.24	0	0	0
June	1/10	2.34	1.56	....	....	....	3.15	2.40	2.10	1.80	1.65
	2/10	1.95	1.17	....	....	....	2.70	1.80	1.35	1.05	.90
	3/10	1.56	0.78	....	....	....	2.40	1.39	.90	.60	.30
	5/10	1.04	0.26	....	....	....	1.80	.75	0	0	0
July	1/10	3.36	2.94	2.24	0.14	0	4.00	3.84	3.52	2.88	2.88
	2/10	2.94	2.24	.98	0	0	3.52	3.04	2.24	1.60	1.28
	3/10	2.66	1.82	0.14	0	0	3.20	2.56	1.44	.48	.32
	5/10	2.10	1.12	0	0	0	2.56	1.60	0	0	0
August	1/10	2.88	2.64	1.92	1.20	....	2.99	2.73	2.60	2.21	2.08
	2/10	2.28	1.92	1.32	.24	....	2.60	2.21	1.82	1.56	1.17
	3/10	1.92	1.44	0.84	0	0	2.34	1.82	1.30	1.04	.52
	5/10	1.44	.60	.12	0	....	1.95	1.17	.39	.13	0
September	1/10	1.05	0.56	....	....	....	2.16	1.80	1.71	1.53	1.44
	2/10	.77	.21	....	....	....	1.80	1.44	1.26	.99	.90
	3/10	0.56	0	....	....	....	1.53	1.08	.90	.54	.45
	5/10	.21	0	....	....	....	1.08	.81	.27	0	0

* Areas shown in figure 4.

Table 7. Minimum moisture deficiency in inches per month at various root-zone capacities and probability levels (continued)

Month	Proba-bility level	Area 5* Root-zone capacity 1″	3″	5″	7″	9″	Area 6* Root-zone capacity 1″	3″	5″	7″	9″
May	1/10	2.88	1.44	.96	.84	.60	2.52	1.80	1.56	1.44	1.44
	2/10	2.40	.72	.24	.12	0	2.04	1.08	.60	.48	.36
	3/10	2.04	.12	0	0	0	1.68	.60	0	0	0
	5/10	1.44	0	0	0	0	1.20	0	0	0	0
June	1/10	3.15	2.10	1.20	.90	.45	3.20	2.40	1.76	1.60	1.44
	2/10	2.70	1.80	.45	0	0	2.72	1.76	.96	.96	.64
	3/10	2.25	1.50	0	0	0	2.40	1.28	.32	.32	.16
	5/10	1.65	1.05	0	0	0	1.92	.48	0	0	0
July	1/10	3.84	3.36	2.88	1.92	1.28	4.42	3.74	3.40	2.89	2.72
	2/10	3.52	2.72	2.08	1.12	.32	3.91	3.06	2.38	2.04	2.04
	3/10	3.20	2.24	1.60	.48	0	3.57	2.55	1.70	1.53	1.36
	5/10	2.56	1.44	.64	0	0	3.06	1.70	.68	.68	.34
August	1/10	3.12	2.86	2.60	2.34	1.84	3.36	3.08	2.80	2.52	2.52
	2/10	2.73	2.34	1.95	1.43	.65	2.94	2.52	2.24	1.96	1.82
	3/10	2.34	1.82	1.56	.78	0	2.66	2.10	1.96	1.68	1.40
	5/10	1.82	1.17	.78	0	0	2.10	1.54	1.40	.98	.70
September	1/10	1.89	1.62	1.35	1.17	.99	2.10	1.80	1.70	1.70	1.70
	2/10	1.53	1.26	.90	.72	.54	1.80	1.50	1.20	1.20	1.10
	3/10	1.35	.90	.72	.36	.27	1.50	1.20	.90	.80	.60
	5/10	.99	.36	.09	0	0	1.20	.90	.40	.20	0

* Areas shown in figure 4.

Table 7. Minimum moisture deficiency in inches per month at various root-zone capacities and probability levels (continued)

Month	Probability level	Area 7* Root-zone capacity 1"	3"	5"	7"	9"
May	1/10	2.40	1.20	....	....	....
	2/10	1.92	.72	....	....	....
	3/10	1.68	.36	....	....	....
	5/10	1.08	0	....	....	....
June	1/10	3.00	1.95	.60	....	....
	2/10	2.55	1.35	0	....	....
	3/10	2.10	.90	0	....	....
	5/10	1.65	.15	0	....	....
July	1/10	4.16	3.52	2.24	.96	....
	2/10	3.68	2.72	1.76	.16	....
	3/10	3.20	2.24	1.28	0	....
	5/10	2.56	1.28	.64	0	....
August	1/10	2.86	2.73	2.21	1.82	1.17
	2/10	2.60	2.21	1.82	1.30	.13
	3/10	2.21	1.69	1.43	.78	0
	5/10	1.82	1.04	.91	.13	0
September	1/10	1.98	1.35	1.08	.72	.18
	2/10	1.62	.99	.72	.27	0
	3/10	1.35	.72	.54	0	0
	5/10	.90	.27	.09	0	0

* Areas shown in figure 4.

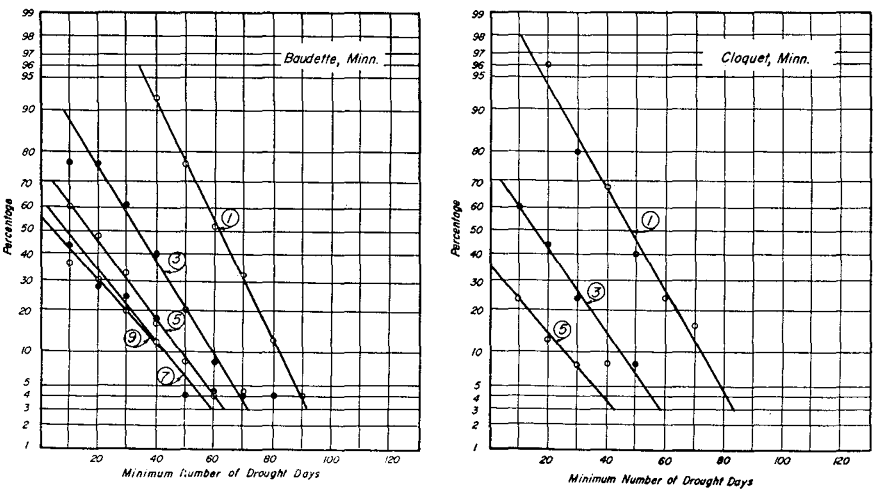
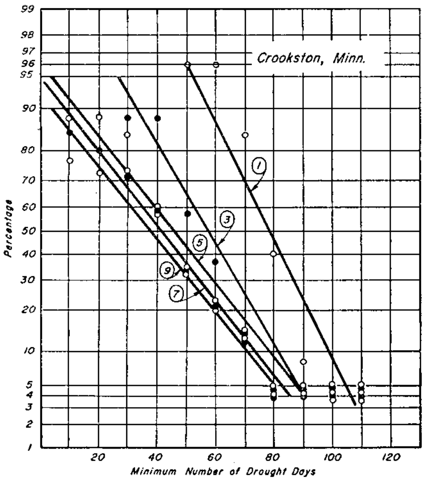


Fig. 5. Percent probability at various root-zone capacities of having at least the number of drought days per season shown.



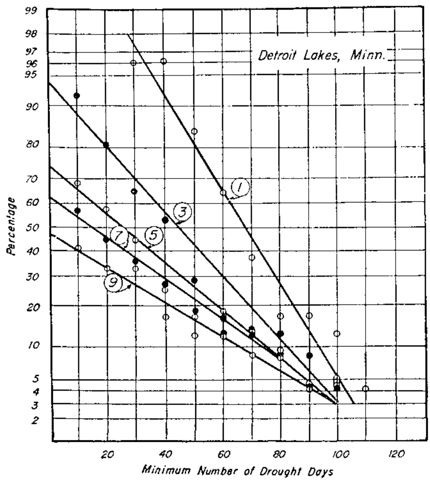
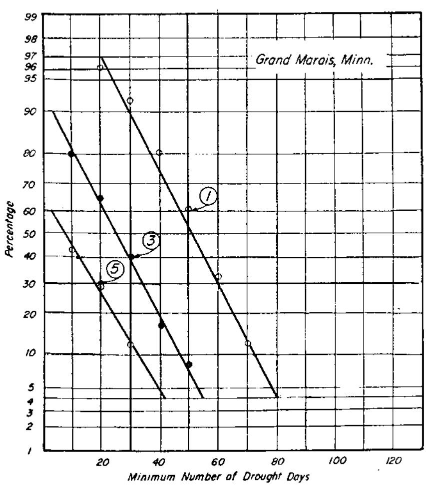


Fig. 6. Percent probability at various root-zone capacities of having at least the number of drought days per season shown.



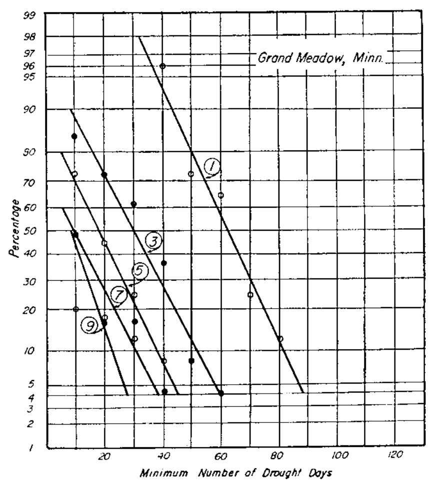


Fig. 7. Percent probability at various root-zone capacities of having at least the number of drought days per season shown.

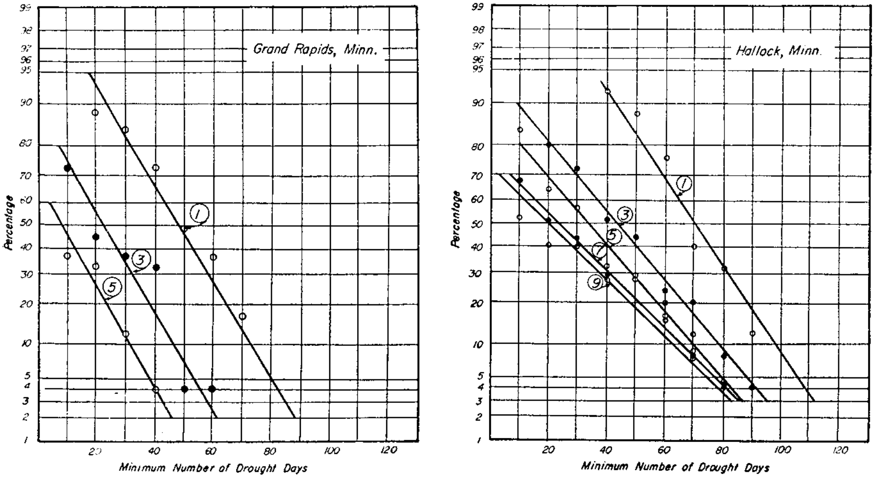


Fig. 8. Percent probability at various root-zone capacities of having at least the number of drought days per season shown.

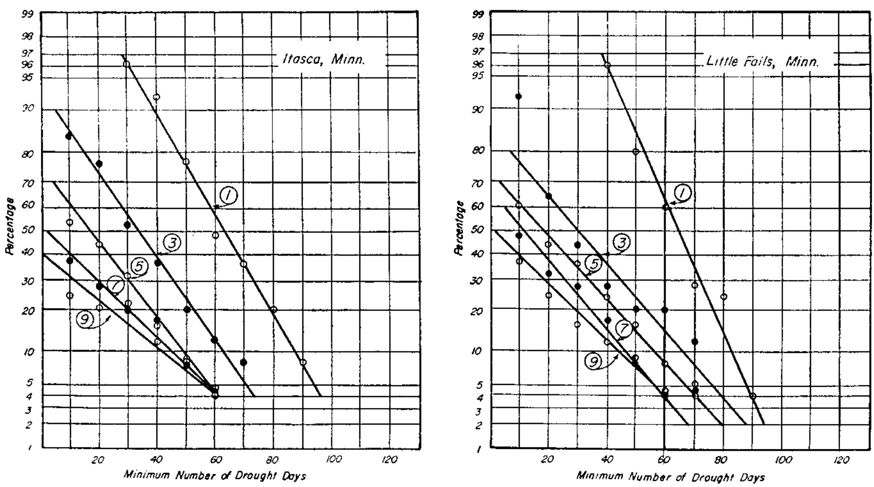


Fig. 9. Percent probability at various root-zone capacities of having at least the number of drought days per season shown.

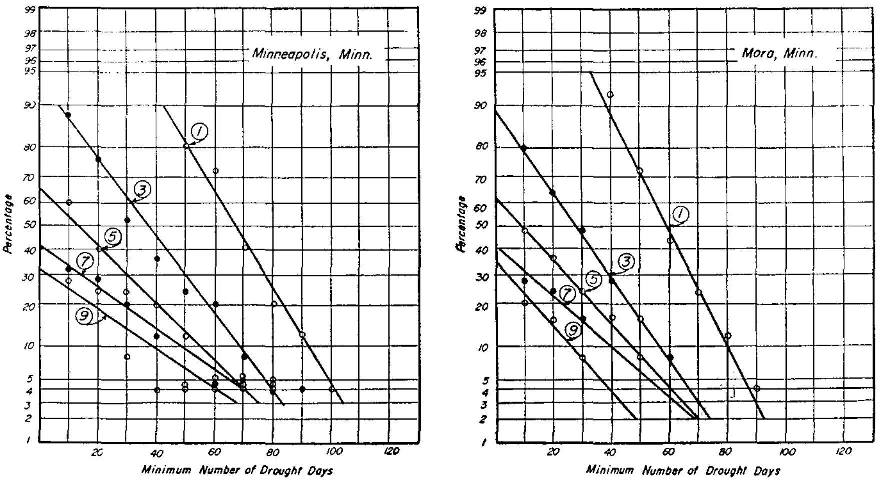


Fig. 10. Percent probability at various root-zone capacities of having at least the number of drought days per season shown.

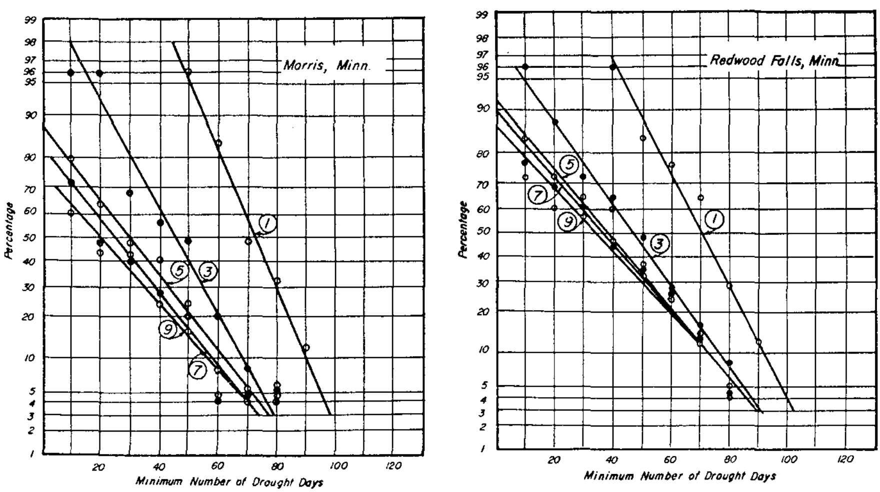


Fig. 11. Percent probability at various root-zone capacities of having at least the number of drought days per season shown.

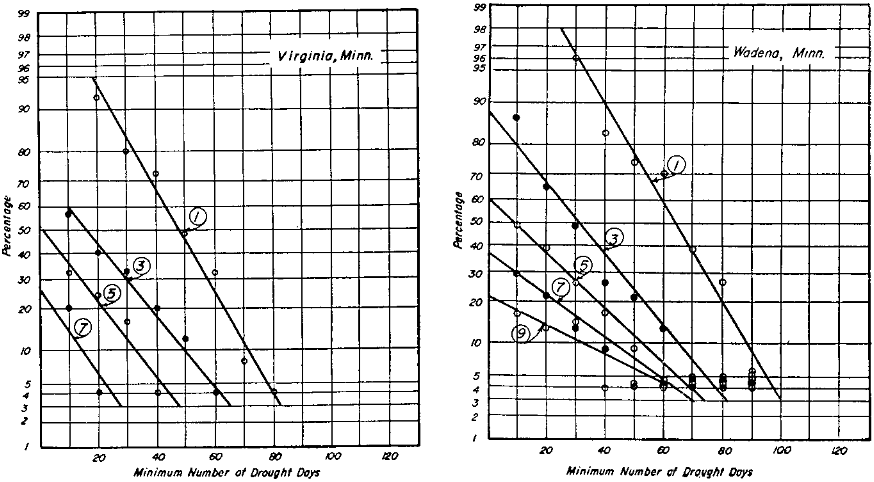


Fig. 12. Percent probability at various root-zone capacities of having at least the number of drought days per season shown.

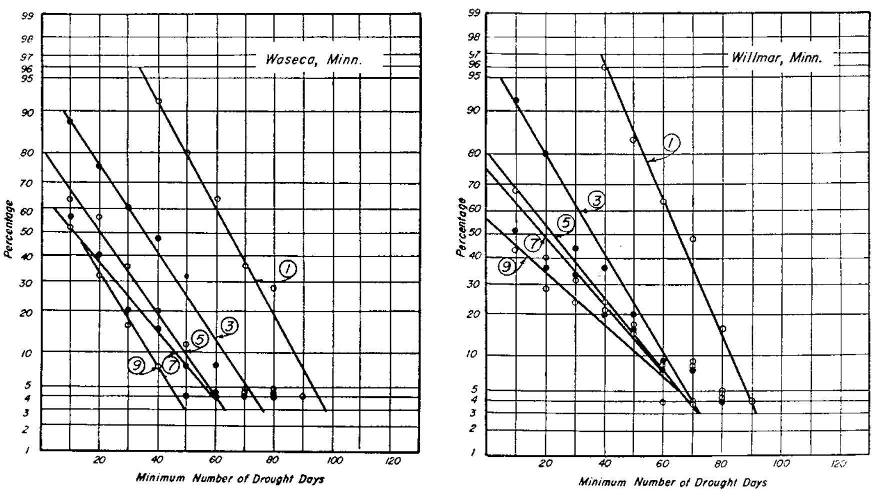


Fig. 13. Percent probability at various root-zone capacities of having at least the number of drought days per season shown.

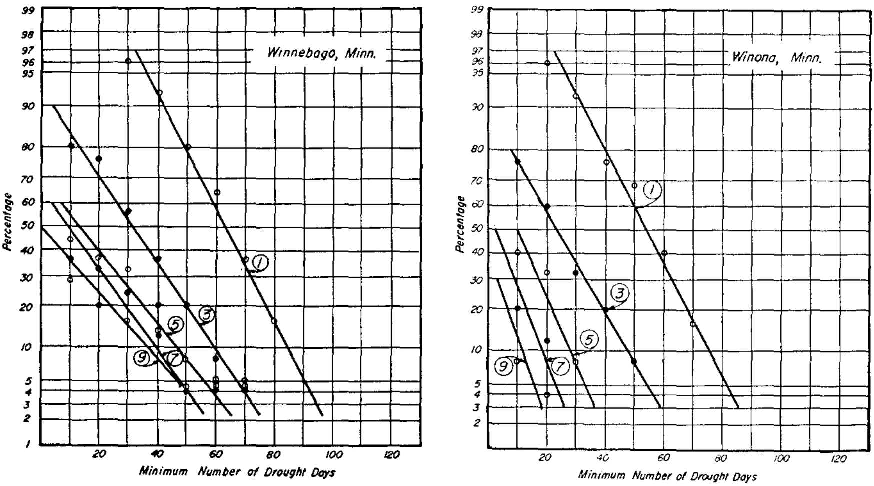


Fig. 14. Percent probability at various root-zone capacities of having at least the number of drought days per season shown.

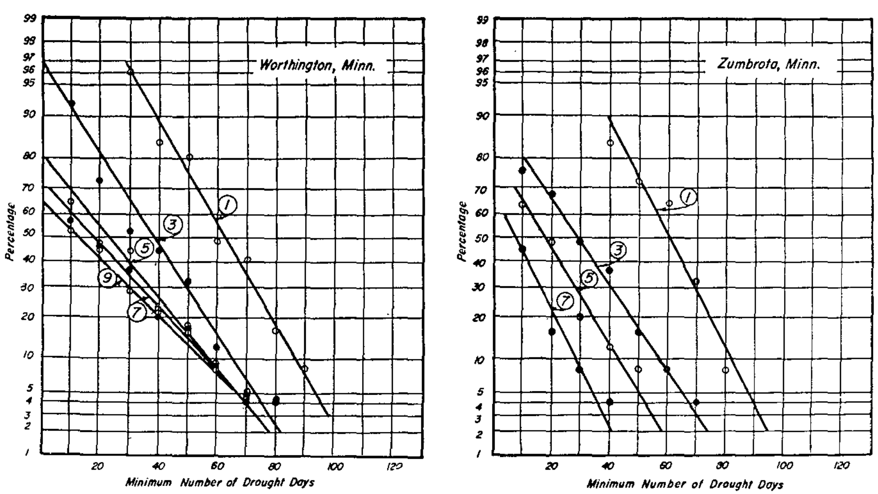


Fig. 15. Percent probability at various root-zone capacities of having at least the number of drought days per season shown.

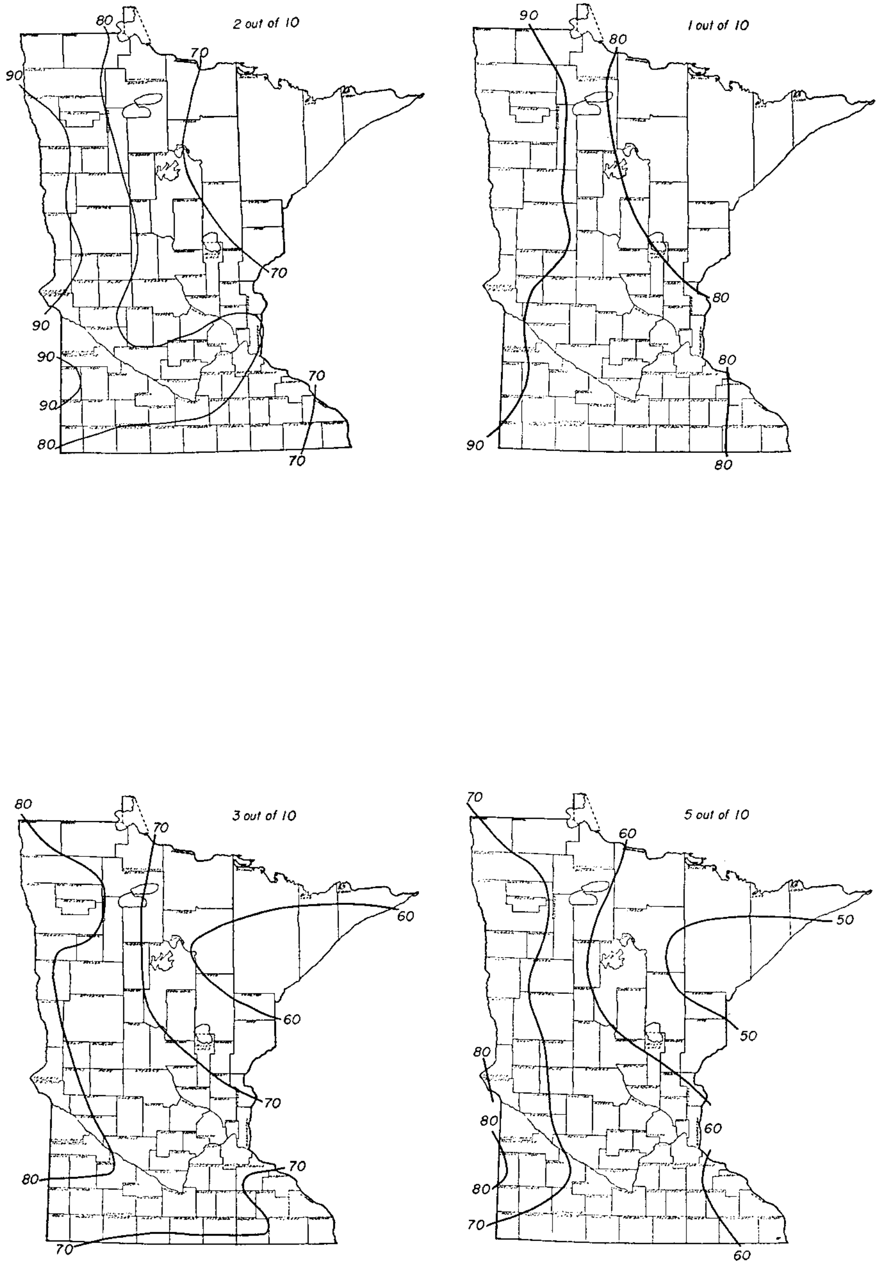


Fig. 16. Expected minimum number of drought days from May through September at various probability levels (assuming soil can store 1 inch of water).

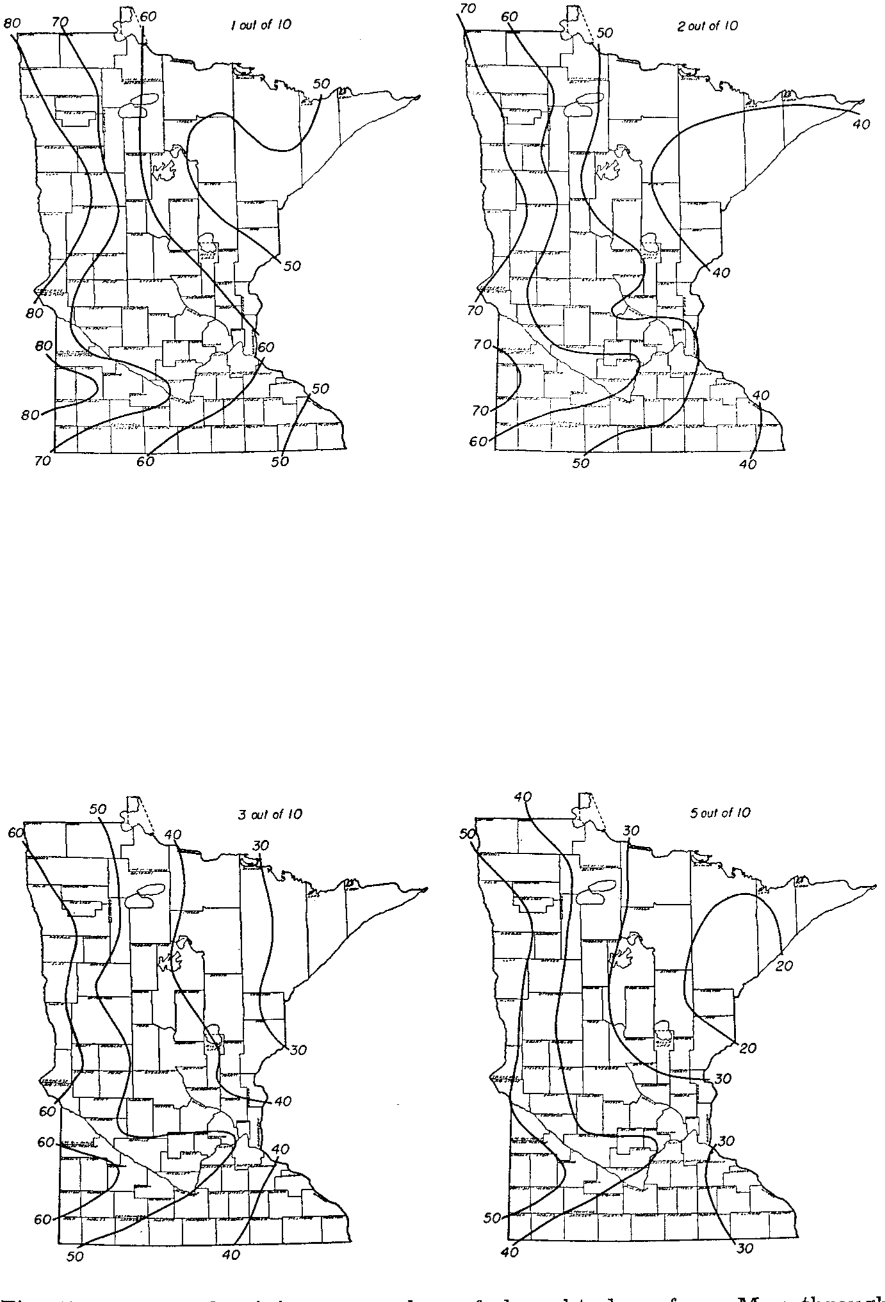


Fig. 17. Expected minimum number of drought days from May through September at various probability levels (assuming soil can store 3 inches of water).

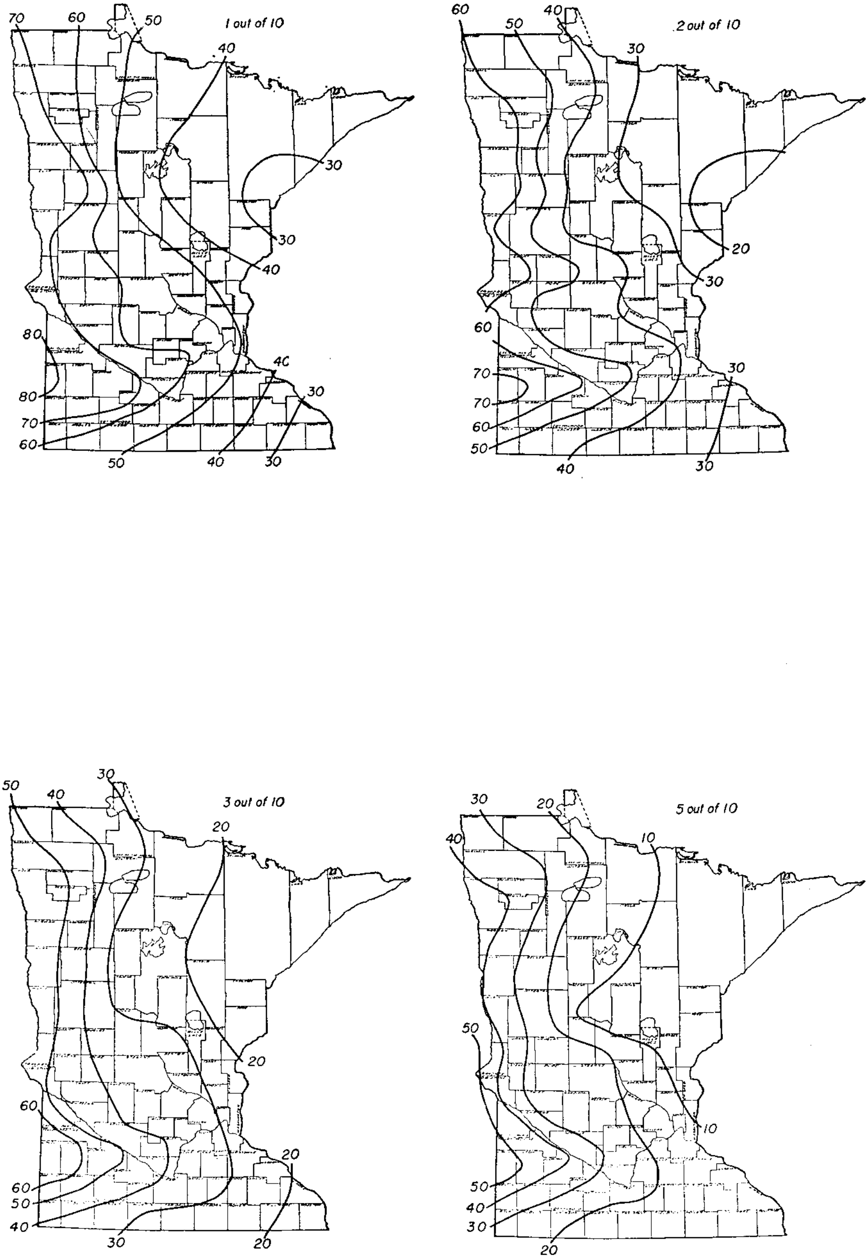


Fig. 18. Expected minimum number of drought days from May through September at various probability levels (assuming soil can store 5 inches of water).

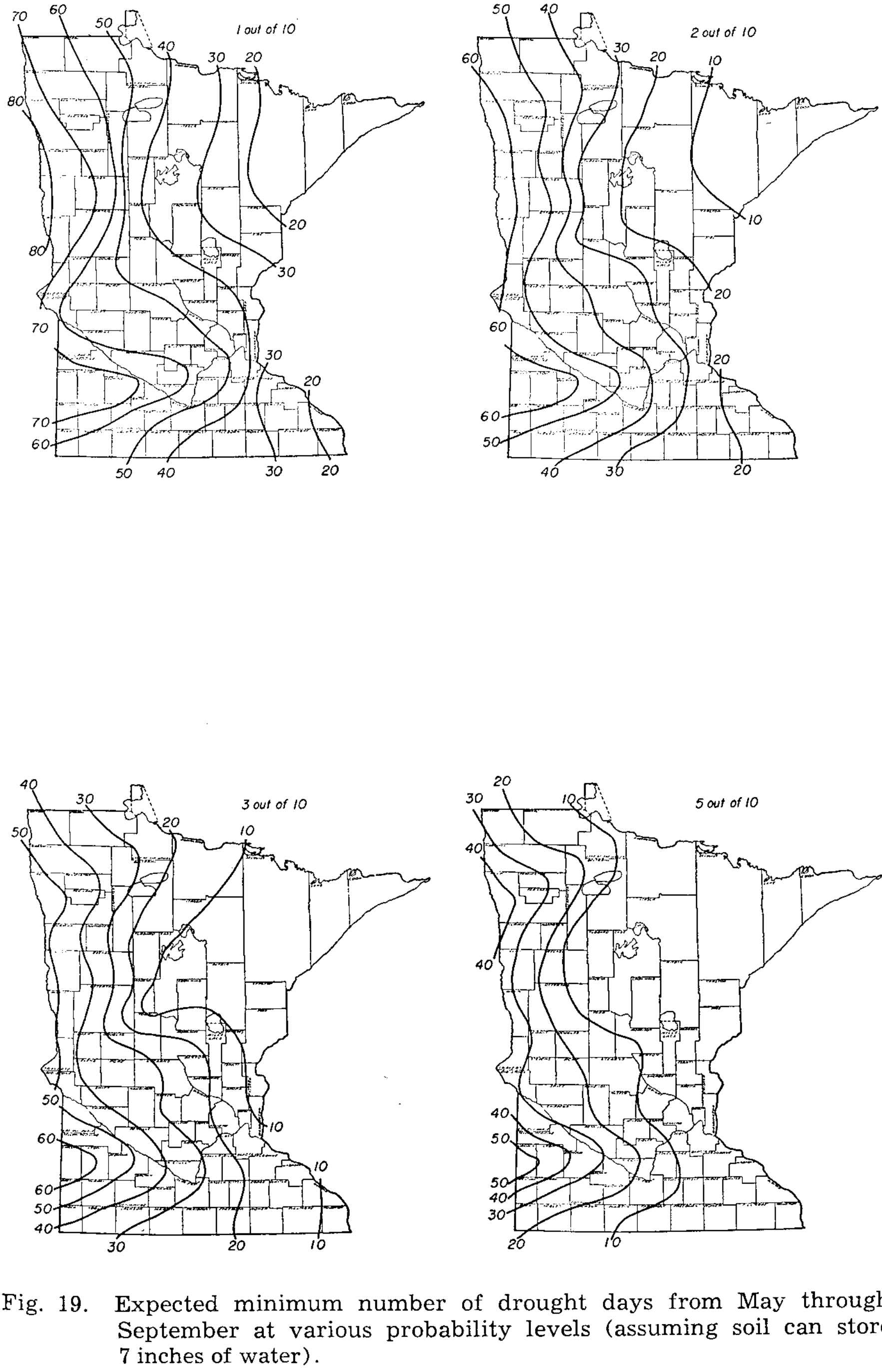


Fig. 19. Expected minimum number of drought days from May through September at various probability levels (assuming soil can store 7 inches of water).

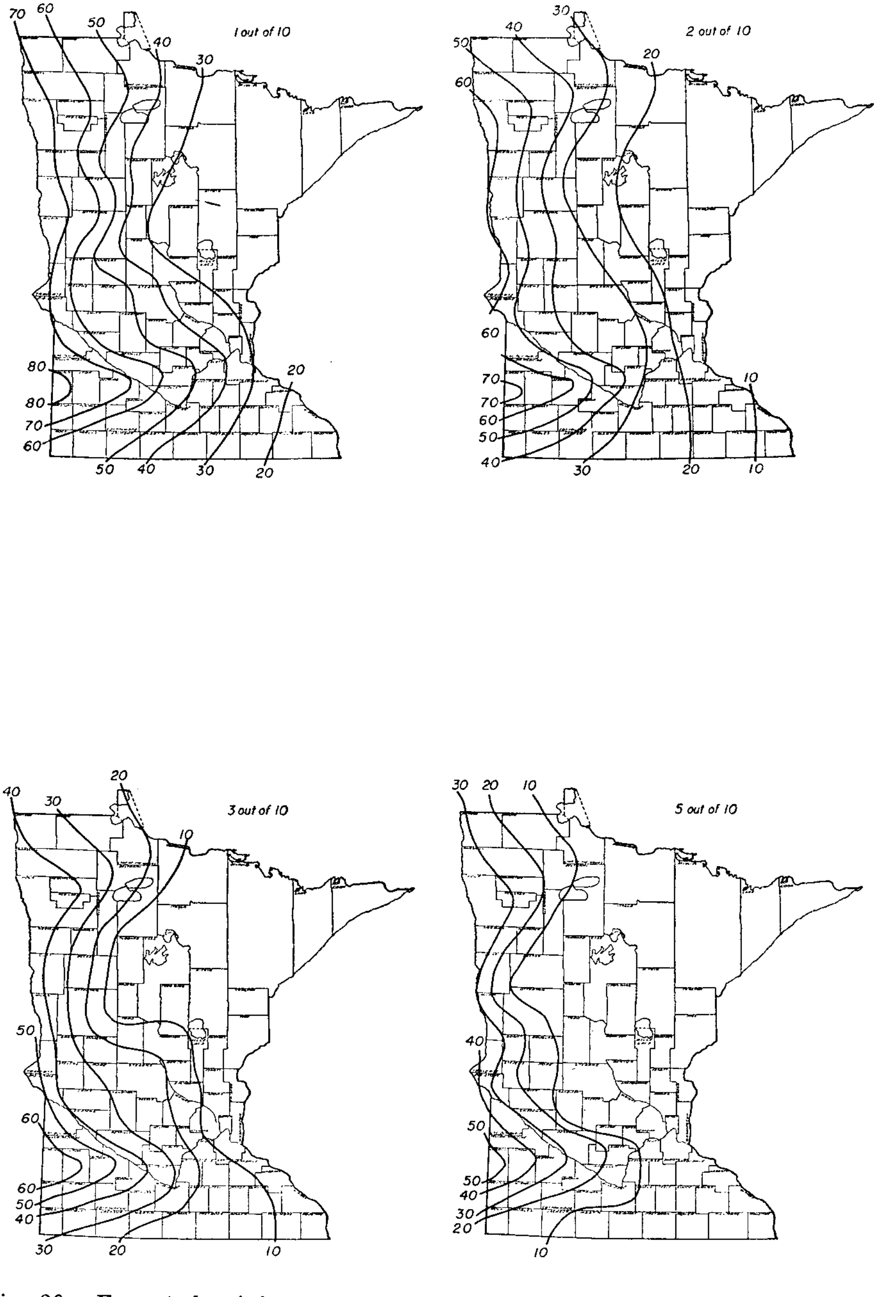


Fig. 20. Expected minimum number of drought days from May through September at various probability levels (assuming soil can store 9 inches of water).

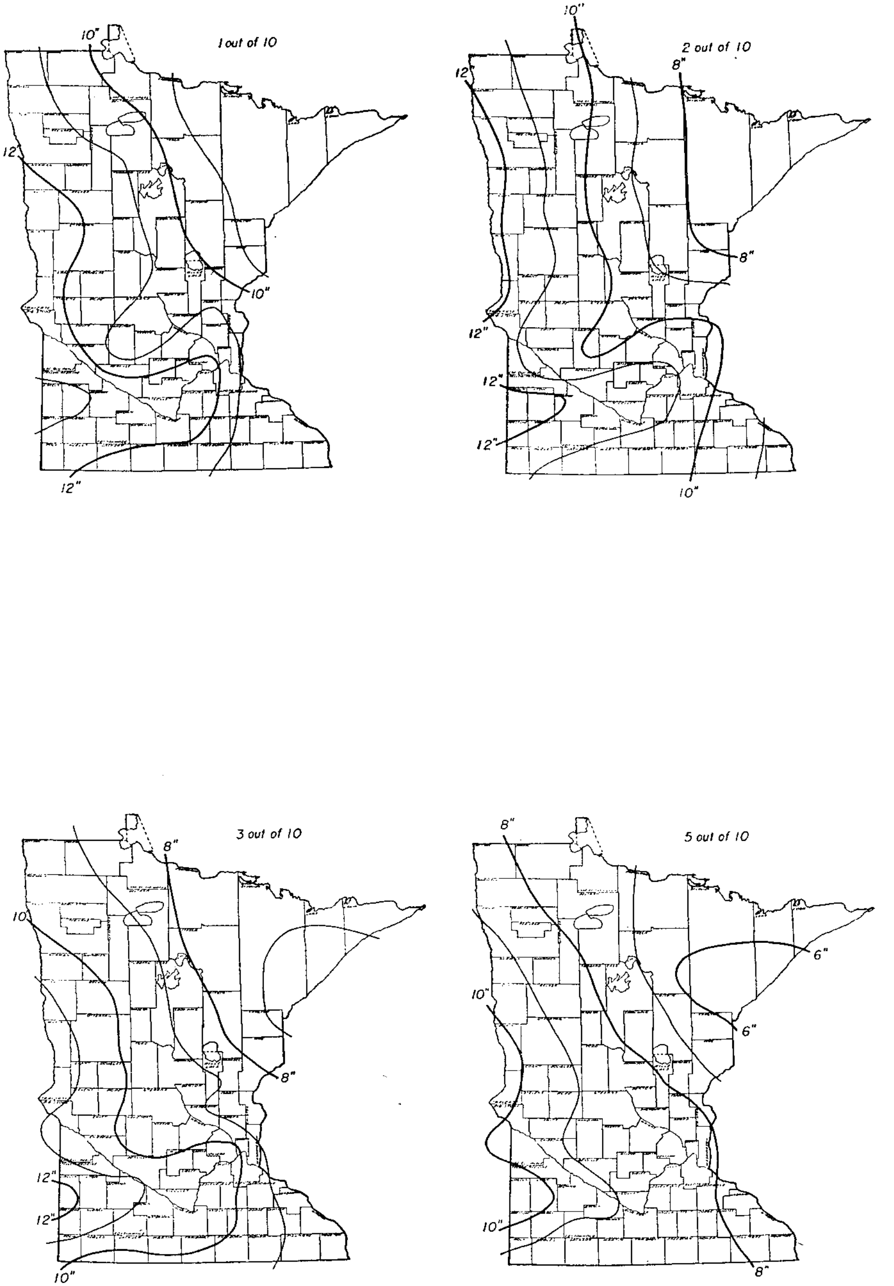


Fig. 21. Expected minimum water deficiency in inches per season at various probability levels (assuming soil can store 1 inch of water).

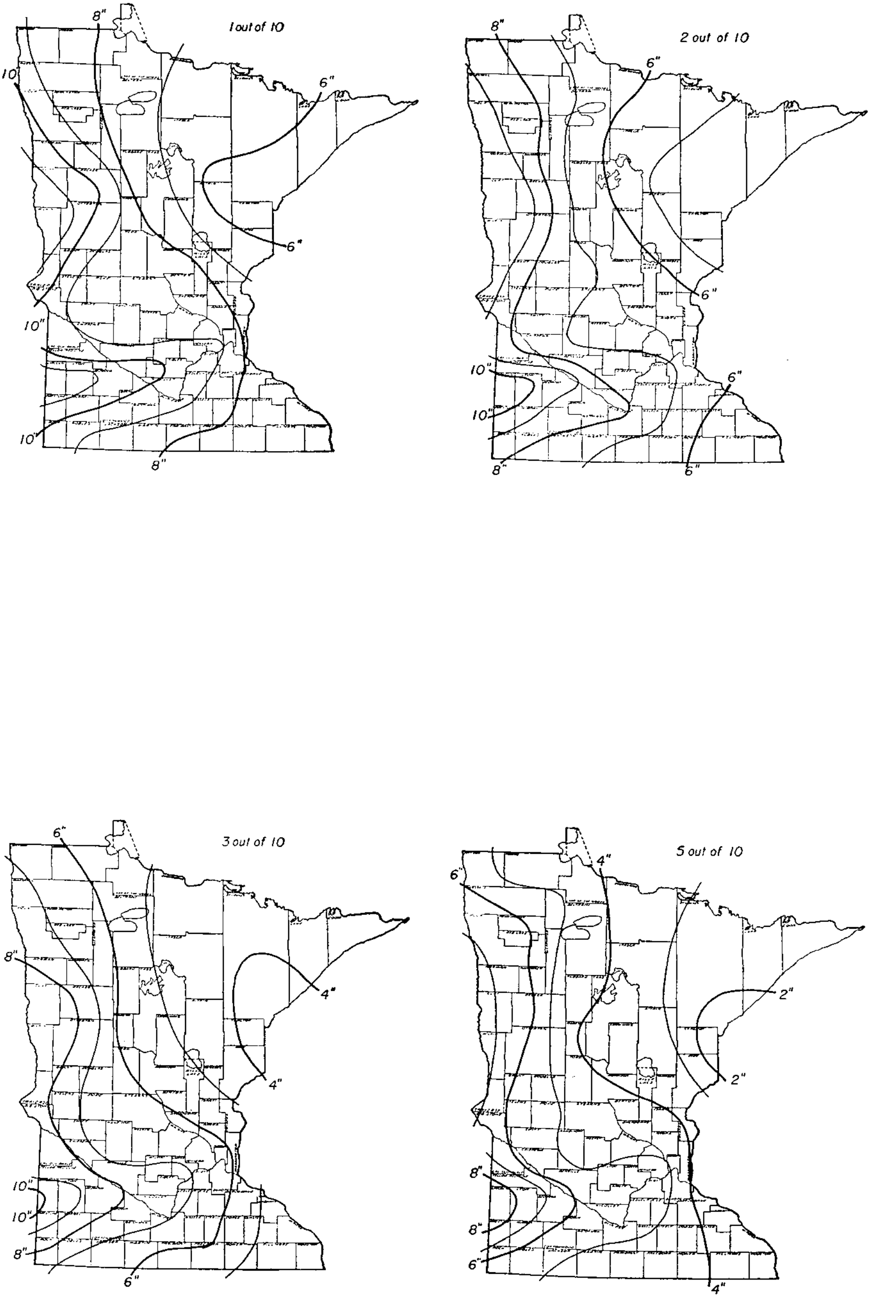


Fig. 22. Expected minimum water deficiency in inches per season at various probability levels (assuming soil can store 3 inches of water).

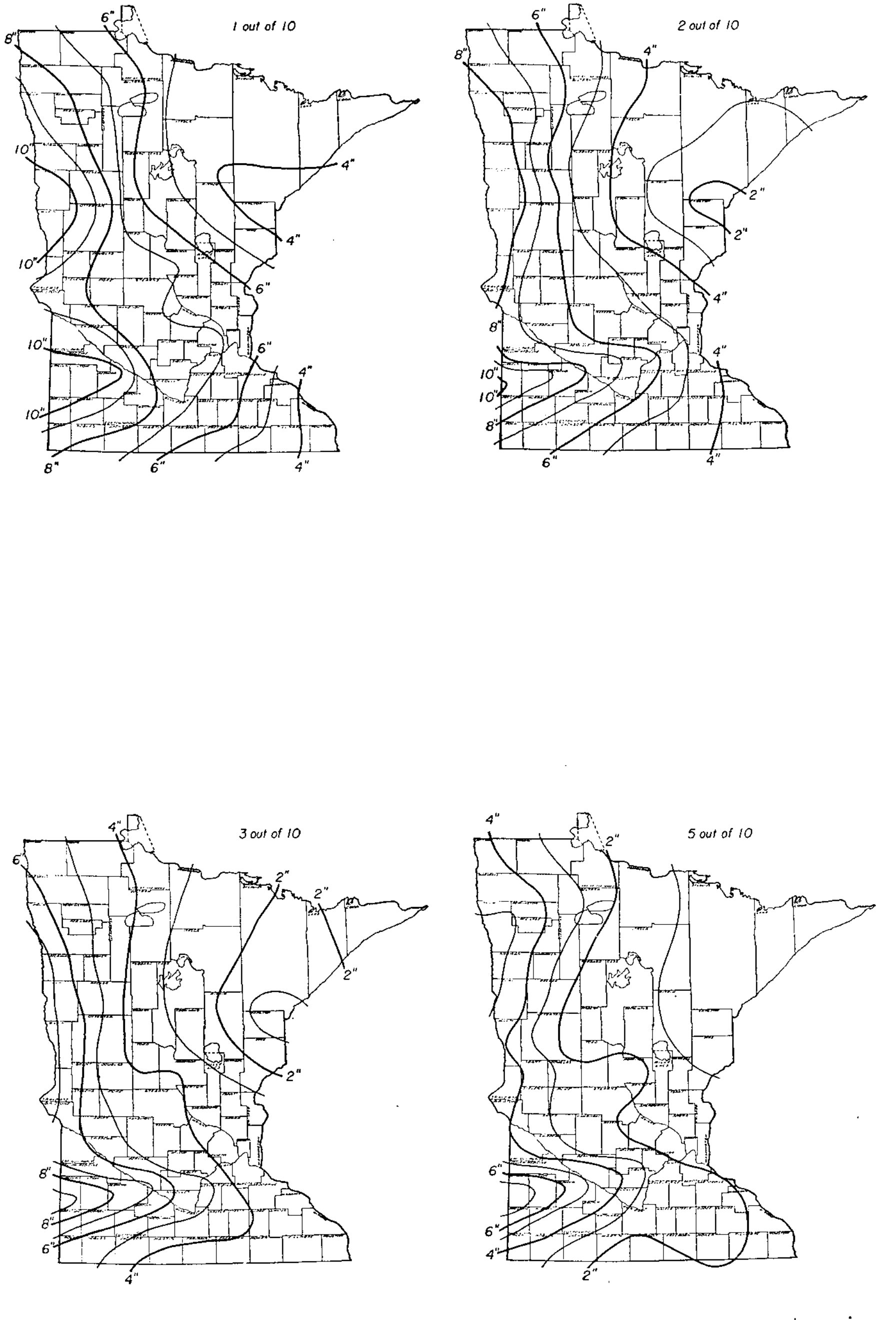


Fig. 23. Expected minimum water deficiency in inches per season at various probability levels (assuming soil can store 5 inches of water).

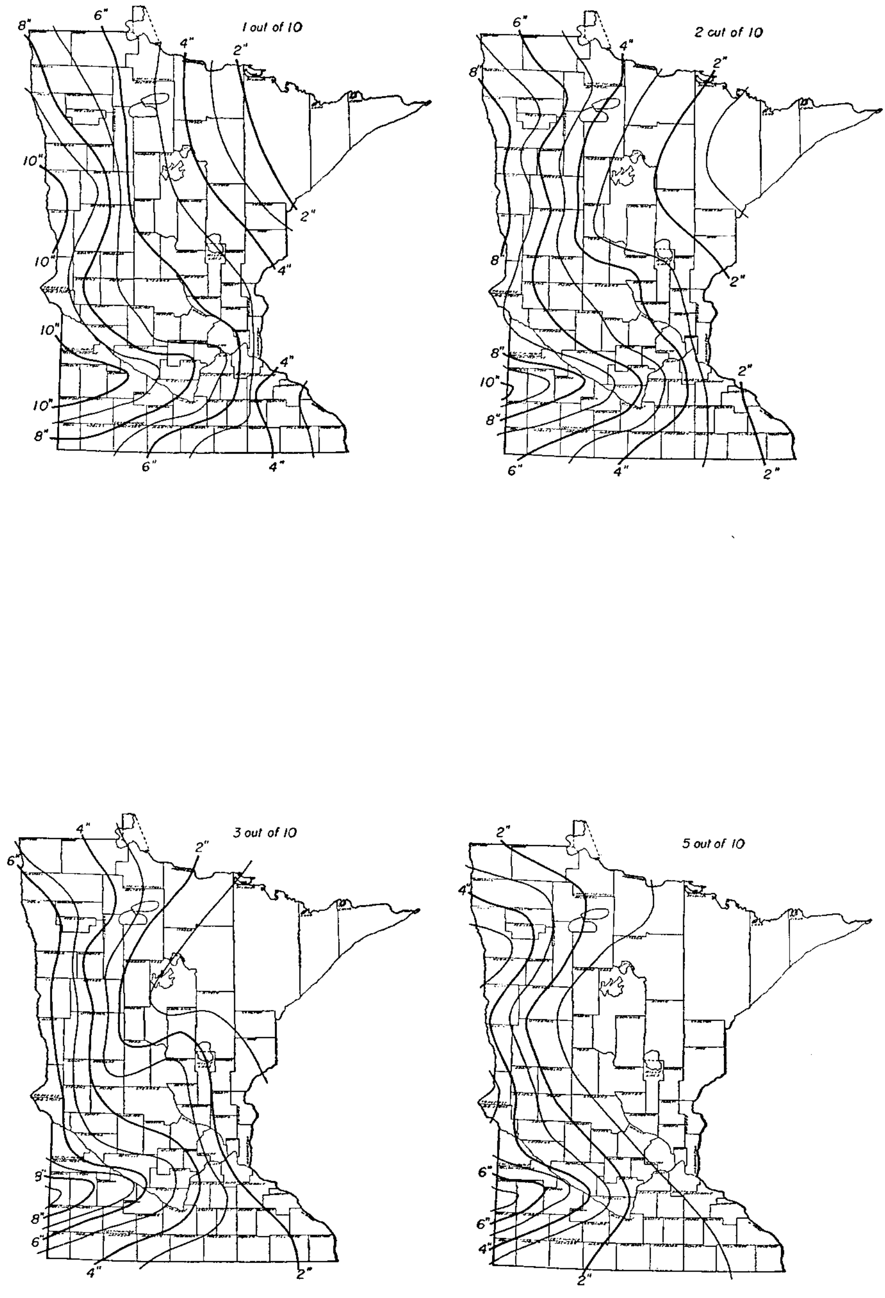


Fig. 24. Expected minimum water deficiency in inches per season at various probability levels (assuming soil can store 7 inches of water).

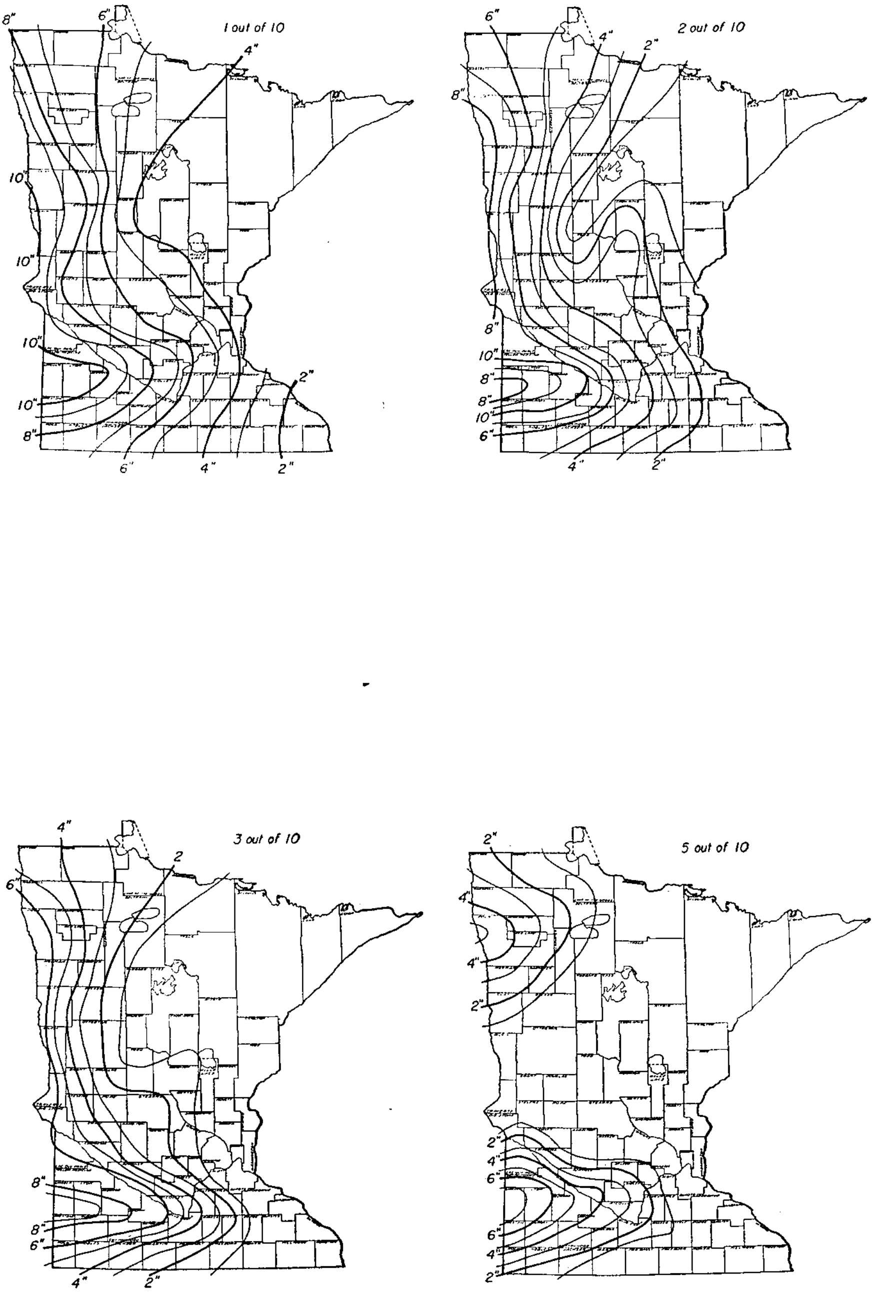


Fig. 25. Expected minimum water deficiency in inches per season at various probability levels (assuming soil can store 9 inches of water).

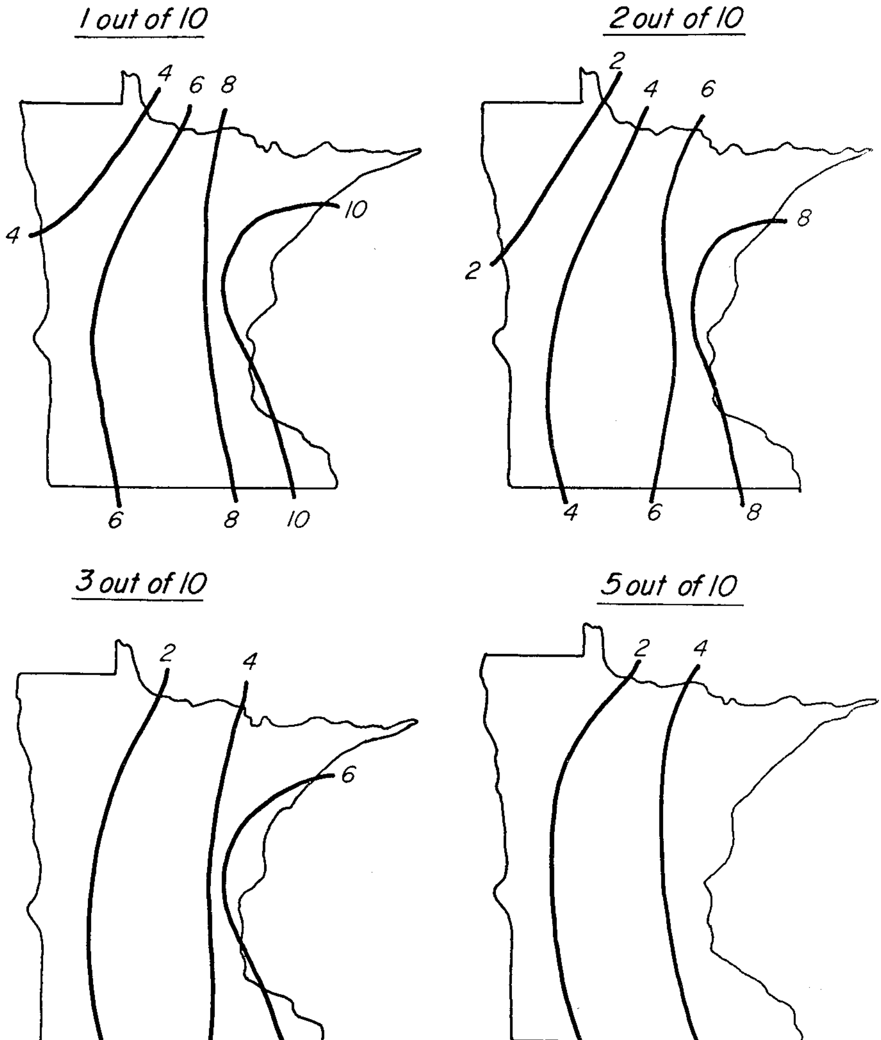


Fig 26. Annual excess precipitation (5-inch root-zone capacity).

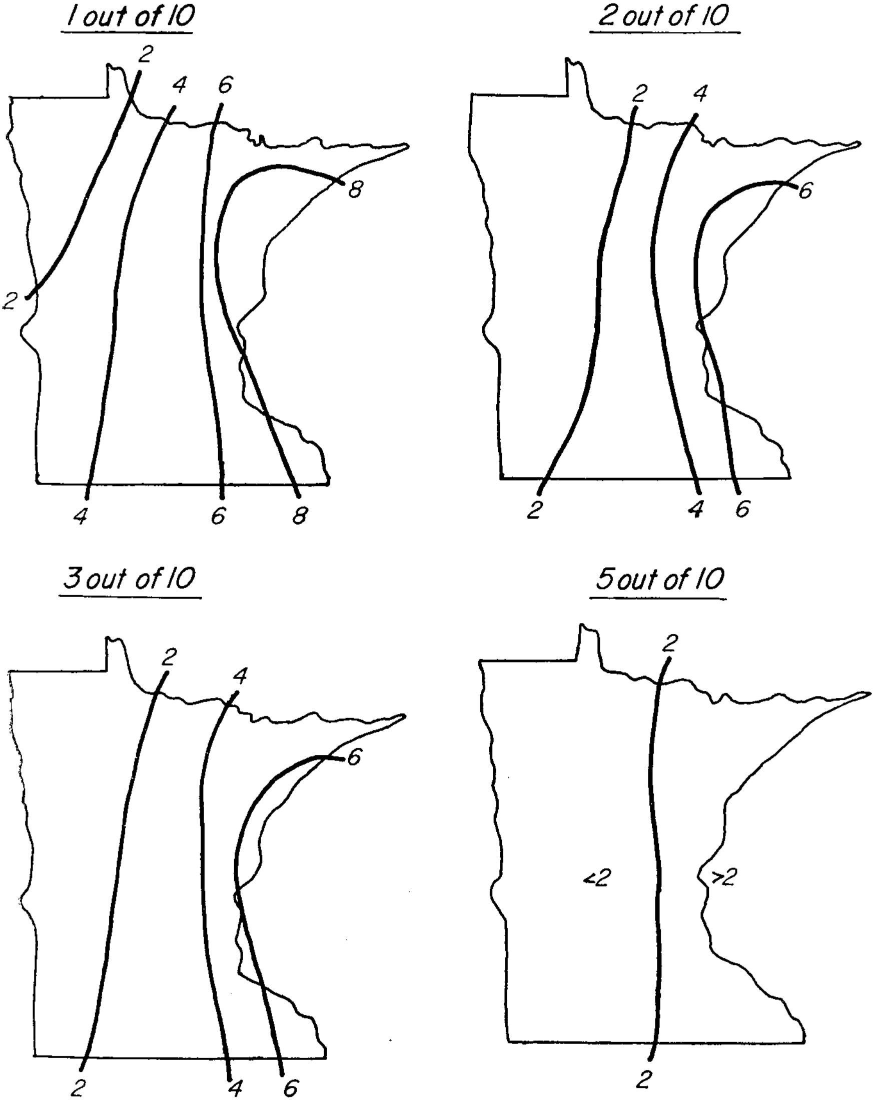


Fig. 27. Annual excess precipitation (9-inch root-zone capacity).

Table 8. Average monthly excess precipitation

	Area 1* Root-zone capacity		Area 2* Root-zone capacity		Area 3* Root-zone capacity		Area 4* Root-zone capacity		Area 5* Root-zone capacity		Area 6* Root-zone capacity		Area 7* Root-zone capacity	
	5″	9″	5″	9″	5″	9″	5″	9″	5″	9″	5″	9″	5″	9″
January	.11	.04	.25	.14	.76	.60	.08	.06	.22	.13	.07	.04	.43	.25
February	.04	.01	.12	.09	.38	.32	.06	.02	.15	.06	.05	.03	.18	.15
March	.10	.06	.22	.14	.56	.52	.15	.06	.31	.18	.16	.06	.44	.31
April	.05	.00	.17	.13	.44	.42	.33	.09	.24	.15	.06	.03	.34	.20
May	.05	.02	.33	.20	.41	.40	.27	.12	.61	.39	.29	.14	.57	.45
June	.12	.05	.22	.14	.41	.41	.27	.23	.47	.40	.38	.28	.41	.39
July	.11	.05	.37	.22	.22	.19	.14	.09	.22	.18	.09	.08	.23	.15
August	.03	.03	.27	.17	.17	.14	.05	.03	.20	.13	.10	.04	.14	.09
September	.14	.03	.09	.07	.35	.35	.08	.07	.11	.08	.14	.13	.23	.16
October	.03	.01	.05	.05	.25	.22	.04	.02	.08	.05	.02	.01	.25	.17
November	.04	.01	.06	.06	.38	.27	.03	.01	.13	.04	.06	.03	.41	.26
December	.02	.01	.13	.11	.48	.32	.07	.05	.19	.12	.04	.01	.28	.16

* Areas shown in figure 4.