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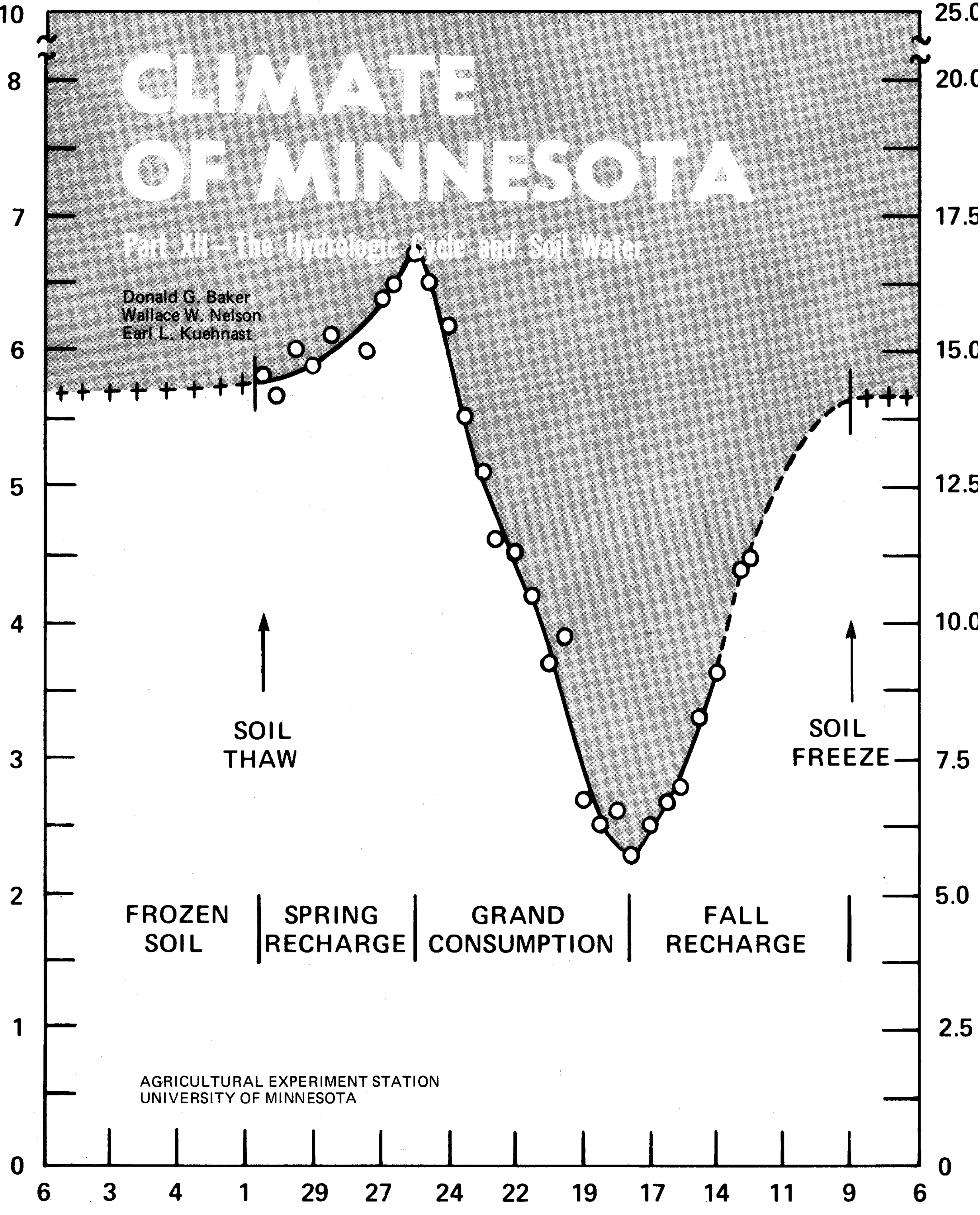
CLIMATE OF MINNESOTA

Part XII—The Hydrologic Cycle and Soil Water

Donald G. Baker
Wallace W. Nelson
Earl L. Kuehnast



AGRICULTURAL EXPERIMENT STATION
UNIVERSITY OF MINNESOTA

CLIMATE OF MINNESOTA — PART XII

The Hydrologic Cycle and Soil Water

Contents

Authors:

Donald G. Baker is a professor in the Department of Soil Science, University of Minnesota, St. Paul; Wallace W. Nelson is a professor and superintendent at the Southwest Agricultural Experiment Station, University of Minnesota, Lamberton; Earl L. Kuehnast is the state climatologist, Department of Natural Resources, St. Paul.

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1. Introduction

A unique series of soil water records from the Southwest Agricultural Experiment Station, Lamberton, Minnesota, deserve attention as they show how and with what efficiency precipitation is used. These records, now totaling 18 years (1960-1977), include years of climatic extremes, ranging from extended periods of surplus precipitation to the drought of 1976. Lamberton lies in the western part of the Corn Belt where soils are seldom completely recharged with water. This condition is common in more than half of the United States, but unusual in most of the Corn Belt. Associated meteorological and hydrological data are available that permit an investigation into the general climatology and hydrology of the area as well as a detailed study of soil water.

While the emphasis in this paper will be upon the Lamberton records, data from other locations within the state will be cited when appropriate.

2. Description of the Area and Measurements Made

The Southwest Agricultural Experiment Station at Lamberton, Minnesota, lies almost in the center of the Cottonwood River watershed in the southwestern part of the state (Figure 1). This watershed, which is instrumented for runoff providing data useful to this study, is approximately 1,280 square miles in area. Like much of southwestern Minnesota it is an area of gently rolling land without any large towns. About 85 percent of the land is under cultivation, and of the cultivated land approximately 44 percent is in corn and 38 percent is in soybeans. Trees are found only in planted windbreaks or along streams. The soils are derived from glacial till, are members of the Clarion-Nicollet-Webster and the Ves-Normania-Seaforth soil associations, and are mainly fine-textured. The most common soil texture is clay loam.

The climate is continental in character. At Lamberton, for example, the temperature ranges from an average of 11.8°F in January to 72.2°F in July (Table 1). On the basis of the Lamberton data for the years 1961-76, 13.1 percent (3.20 inches) of the mean annual precipitation of 24.44 inches falls in the December-March period. The mean annual runoff of the Cottonwood River watershed, as measured downstream at New Ulm, Minnesota, is equivalent to 3.32 inches (22).

Soil water was determined by gravimetric means, usually between May and October, on a monthly basis from 1960-69 and on a bi-weekly basis since 1970. The soil under continuous corn was sampled at the following depth increments: 0-6, 6-12, 12-18, 18-24, 24-36, 36-48, and 48-60 inches. Five borings were made at each sampling site each time.

The Webster silty clay loam (Typic Haplaquoll) at the Southwest Agricultural Experiment Station can hold 9.8 inches of plant available water in the first 60 inches of soil. The total water content at field capacity equals 21.0 inches and at wilting point equals 11.2 inches. The difference, 9.8 inches, is termed plant available water. Both field capacity and wilting point water constants were estimated as equivalent to one-third and 15 bars moisture suction, respectively.

The soil sampling area is about 500 feet from the agricultural weather station where air and soil temperatures, precipitation, pan evaporation, wind movement, and solar radiation are measured. These measurements plus those made by the U.S. Geological Survey (22) downstream at New Ulm, where the Cottonwood River joins the Minnesota River, supplement the soil water data.

3. The Source of Precipitation

Atmospheric moisture mainly flows into the North American continent from two major sources: the Gulf of Mexico and the Pacific Ocean. As a source of precipitation the Gulf of Mexico is by far the more important of the two in eastern North America. The fact that air masses from the Pacific Ocean are relatively insignifi-

Table 1. Average monthly temperature, precipitation, and pan evaporation at the Southwest Agricultural Experiment Station, Lamberton, and the average monthly runoff of the Cottonwood River at New Ulm.

Month	Temperature (1961-76)	Precipitation (1961-76)	Evaporation (1966-76)	Runoff (1960-76)[3]
	°F	Inches	Inches	Inches
Jan.	11.8	0.67	—	0.04
Feb.	17.8	0.65	—	0.07
March	29.8	1.12	—	0.43
Apr.	45.3	2.68	1.74[1]	1.09
May	58.1	3.11	7.67	0.42
June	68.6	3.36	8.91	0.32
July	72.2	3.89	9.10	0.29
Aug.	69.9	2.01	7.46	0.12
Sept.	59.9	2.98	5.52	0.09
Oct.	50.6	2.13	1.78[2]	0.24
Nov.	33.6	1.08	—	0.14
Dec.	17.8	0.76	—	0.07
Mean	44.6	—	—	—
Total	—	24.44	42.18	3.32

[1] For period April 21-30.

[2] For period October 1-10; 1968, 1969, and 1974 missing.

[3] For the hydrologic year, October-September (22). These values include tile flow, groundwater flow, and surface runoff.

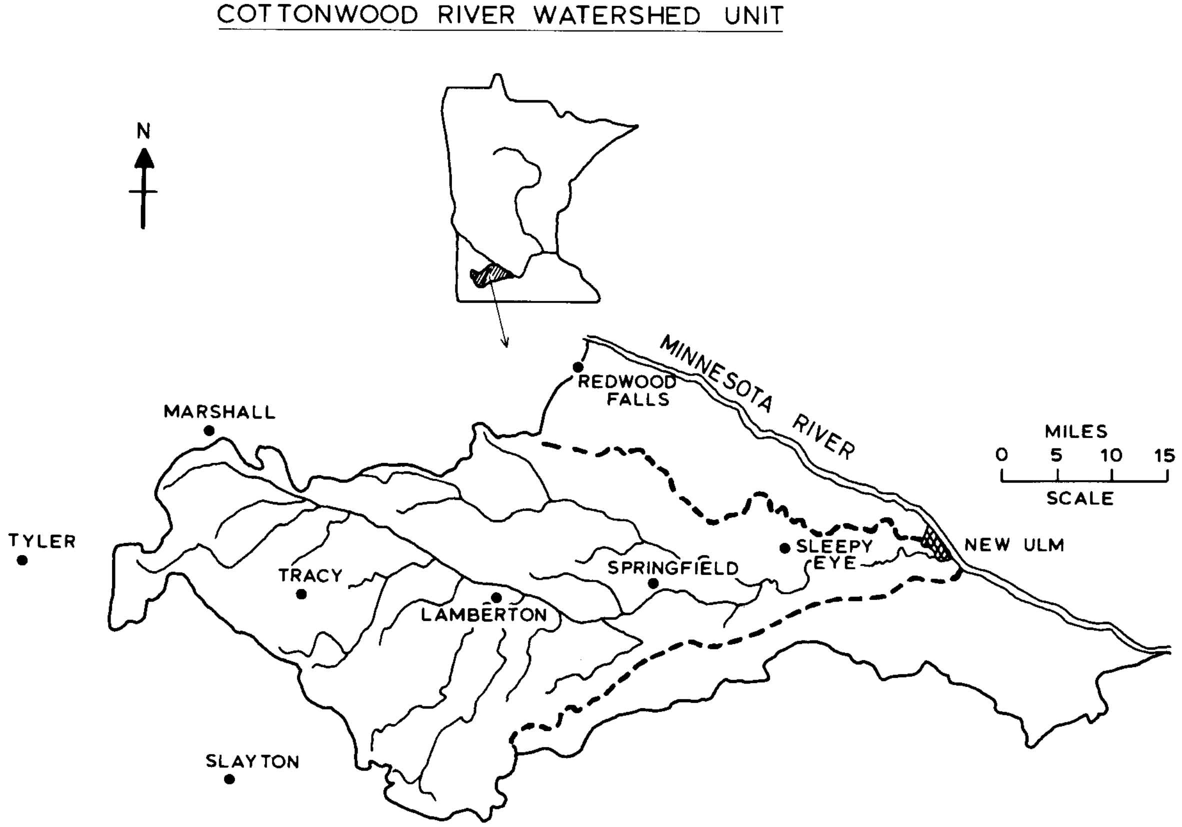

Figure 1. The Cottonwood River watershed and its location within Minnesota. The dashed lines indicate the northeastern and southeastern watershed boundaries. The streamflow is measured a few miles upstream of New Ulm before the Cottonwood enters the Minnesota River. Adapted from reference (13).

cant moisture sources in Minnesota is illustrated by the precipitation and vegetation patterns between Minnesota and the Rocky Mountains. Both indicate increasing aridity in the westward direction. Adding to the importance of the Gulf of Mexico are studies (4, 7, 17) which indicate that local moisture sources, such as evapotranspiration from fields and forests and evaporation from lakes and rivers, are of minor consequence as precipitation sources.

Therefore, the primary cause of midwestern seasonal and yearly differences in precipitation appears to be due to significant geographic displacement of the high level wind system over the central United States. Although high level winds do not carry appreciable moisture, they do influence the movement of low level systems carrying the moisture.

The mean flow path carries water vapor from the Gulf northward, with the main axis along the Texas-Louisiana border. The major track then curves in an anticyclonic sense (to the right) and moves off the east coast over the central Atlantic seaboard. The position of a station relative to this moist air current generally determines the amount of precipitation it receives. This factor is the major reason why Minnesota's average annual precipitation varies from about 19 inches in the northwest to 32 inches in the southeast. The southeastern counties are closer to and, therefore, more influenced by the moist, southerly air flow than are the northwestern counties.

The maximum mean intensity of moisture inflow is close to the land surface, normally at a height of about 2,500 feet mean sea level (m.s.l.). The amount of water vapor contained in the atmosphere decreases rapidly with increasing height. Thus, at 95°W in the southern United States along the axis of the water vapor stream, less than 25 percent of the inflow occurs above 10,000 feet m.s.l. Although this moist current is lifted while moving across the United States, the level of maximum intensity of the atmospheric vapor remains below 5,000 feet m.s.l.

Seasonal changes in the general circulation system explain several features of Minnesota's precipitation pattern. In the winter Minnesota is strongly under the influence of west and northwest winds. Warm, humid wind-flow off the Gulf is restricted to the southeastern United States.

The Gulf winds just reach southeastern Minnesota in April. States to the south and west of Minnesota, particularly the western and southwestern Great Plains

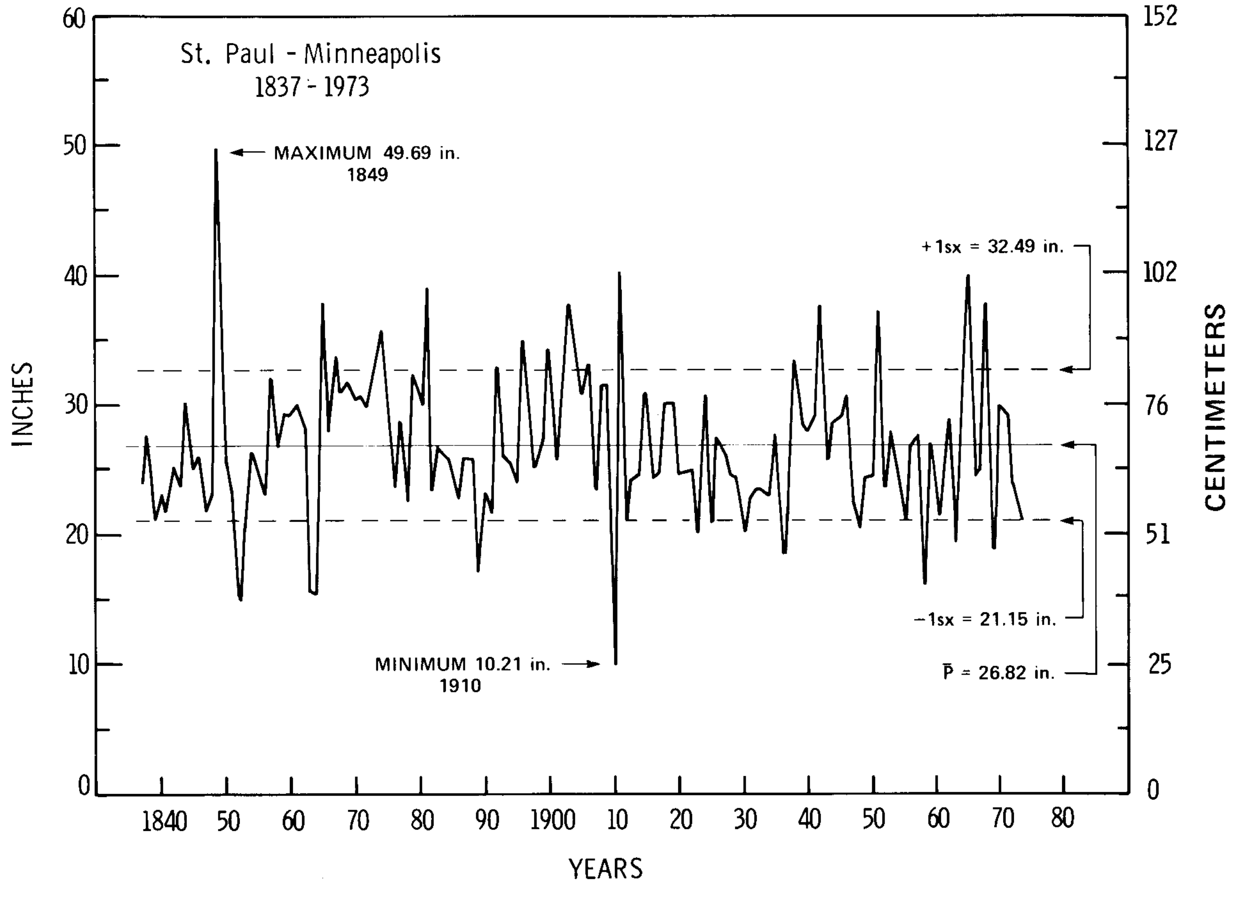

Figure 2. Total annual precipitation received at St. Paul-Minneapolis from 1837-1973. The data are from combined records of Fort Snelling, St. Paul, Minneapolis, and the Minneapolis-St. Paul International Airport. The mean for the 137 years is 26.82 inches, and the mean plus and minus one standard deviation equals 34.29 inches and 21.15 inches, respectively. Inspection of the original records indicate that serious observation errors probably occurred in parts of 1848 and 1849. Therefore, the 1849 maximum of 49.69 inches is questionable (3).

states, receive the major portion of their annual precipitation between April and July. At that time the Gulf winds sweep far inland over the southern Great Plains before turning northeastward and the northern limit of the moist air crosses the lower Great Lakes.

In late spring and summer the winds are more southerly and moisture-laden in the Mississippi Valley. One of the most favorable aspects of the Minnesota climate is that 65-75 percent of the annual precipitation falls within the May-September growing season. Only about 15 percent of the annual precipitation occurs within the December-March period of below freezing air temperatures and frozen soils.

Minnesota is effectively cut off from Gulf moisture by October and in most years remains under the dominance of westerly and northwesterly winds until the following May.

Air masses from the Gulf carrying the moisture, which eventually is released as precipitation in Minnesota, travel 1,200-1,500 miles to reach the state. Because of this long northward trek, a minor change in the wind system can mean that Minnesota and areas farther west

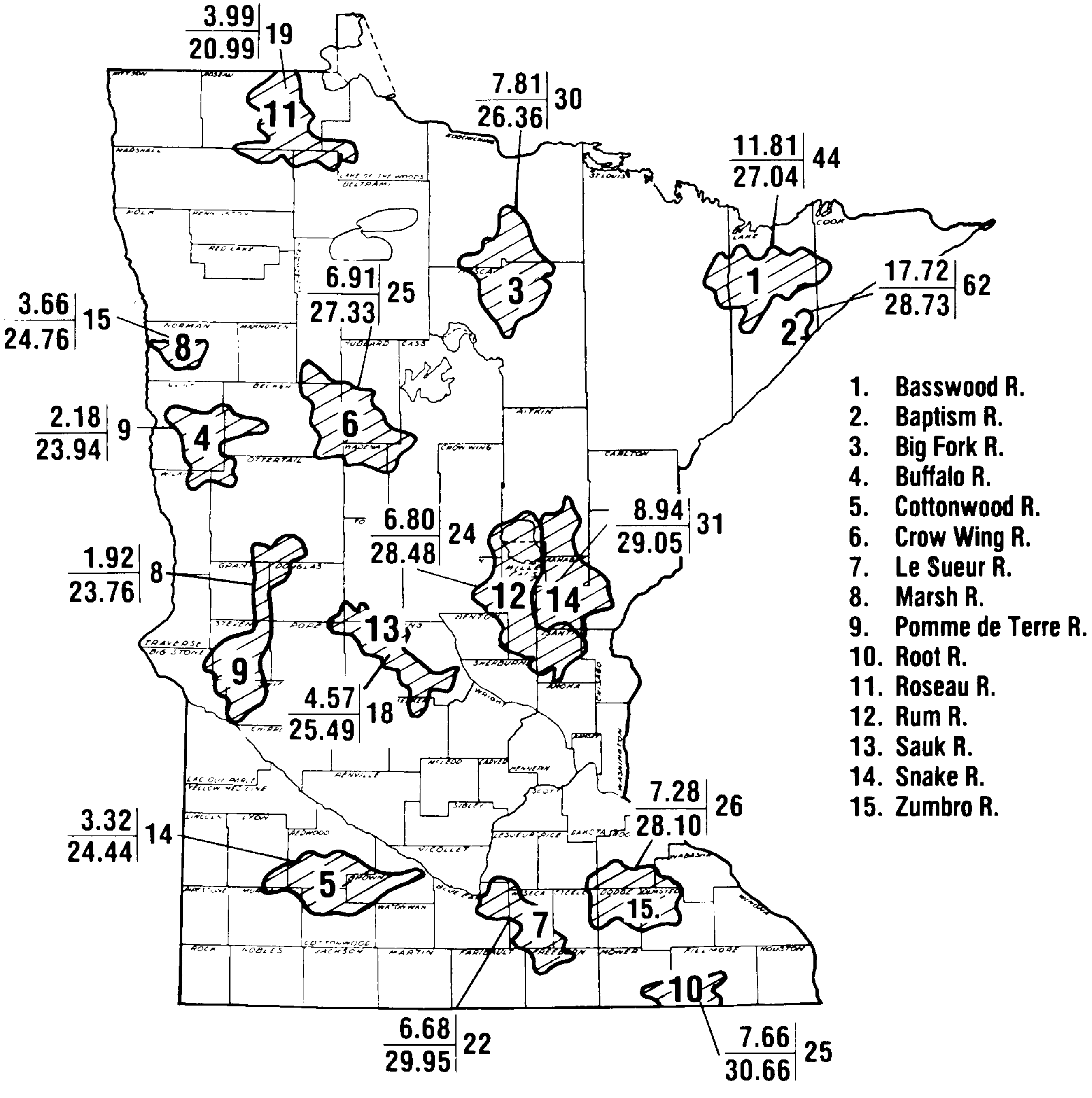

Figure 3. Average annual runoff in inches, October, 1960-September, 1976 (upper figure), annual normal precipitation in inches 1941-1970 (lower figure), and the ratio of the runoff to the precipitation expressed as a percent (figure to right) at 15 selected watersheds. For example, in watershed number 1, the Basswood River watershed, the annual average runoff and precipitation equal 11.81 and 27.04 inches, respectively, and the runoff is 44 percent of the precipitation. The precipitation data with one exception are based upon a single station within the watershed. Data source (21, 22).

can be either well above or well below their normal precipitation. It is no wonder that annual precipitation may vary appreciably from year to year. This variation is very evident in the total annual precipitation received in St. Paul-Minneapolis for the 1837-1973 period as shown in Figure 2.

4. The Fate of Precipitation

A. GROUNDWATER AND SURFACE STORAGE

Precipitation reaching land surfaces is partitioned as temporary storage in soils and runoff into lakes, bogs, and streams. The greater share of precipitation is returned to the atmosphere as vapor by the energy-consuming processes of evapotranspiration when plants are present and by evaporation, or sublimation in the winter, when plants are absent or not transpiring. The evaporation of 1 gram (1 cm^3 or 0.06 $inches^3$) of water requires about 580 calories.

Table 2 is an approximation of how precipitation is partitioned within the state. As mean values for the state the amounts are probably correct within ±10 percent. Additions to surface storage and groundwater supplies ordinarily occur at the expense of the runoff rather than evapotranspiration. The soil under most circumstances is the first to be replenished, and thus, evapotranspiration from the earth's surface continues to take place even when runoff is virtually nonexistent. This circumstance was evident in Minnesota in 1976 and during the first half of 1977. During and following the drought of 1976 there was almost no runoff in 1976 and virtually none in 1977 until the soil water had been replenished. In much of the state soils were not replenished until the above normal rains of August, 1977, had brought the soil water above average. Only then did runoff really begin.

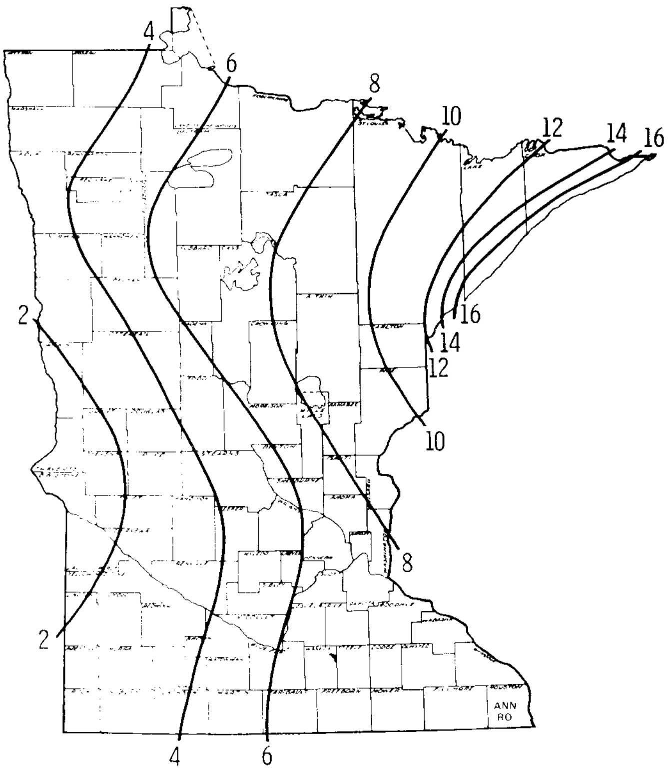

Figure 4. Average annual runoff in inches. The data are based upon average runoff values of 15 selected watersheds for the period October, 1960-September, 1976. Data source (21,22).

Table 2. Estimated average water budget of Minnesota.

Income	Inches	Percent
Precipitation	27.0	100.0
Outgo		
Runoff	6.5	24.1
(Groundwater)	(0.6)	(2.2)
(Surface runoff)	(5.9)	(21.9)
Evapotranspiration	20.5	75.9

The groundwater and surface runoff data of Table 2 are nominal values provided by the U.S. Geological Survey. For selected watersheds the groundwater flow may range from 2-35 percent of the runoff. Also, variations occur from one year to the next, with the groundwater flow making up a larger percentage of the total in dry years. A comparison of the runoff volumes between wet and dry years indicates much larger variations in surface runoff than in groundwater runoff (5).

B. RUNOFF

Because runoff is visible, while evaporation and evapotranspiration are not, and because so much attention is paid to river navigation, flooding, flood plains, and dams, it is not always appreciated that runoff in most regions accounts for only a small fraction of the precipitation. For example, in the Cottonwood River drainage basin the annual runoff is barely 14 percent of the annual precipitation.

The runoff from an area is a function of the climate and to a lesser degree the soils and vegetation of that area. This is demonstrated in both Figure 3 and Figure 4, which show an increase in the runoff eastward across the state. The climatic controls are both precipitation, which increases from west to east, and the evaporation potential, which decreases from west to east.

There is also an increase in runoff that extends from the central part of the state to the Arrowhead region of northeastern Minnesota (Figures 3 and 4). This is a reflection of a combination of several climatic factors. The important climatic controls include a more uniform distribution of precipitation during the year than elsewhere in the state. That is, there is a lower proportion of the total annual precipitation during the growing season and more during the winter, which produces more runoff; and due to the lower temperatures and greater cloud cover the atmospheric demand for evapotranspiration is greatly reduced. Another factor that assumes even greater importance in this part of the state than elsewhere is the soil. All soils act as reservoirs that both retard runoff by absorbing the precipitation and reduce runoff by providing water to the vegetation for evapotranspiration. In northeastern Minnesota, unlike the remainder of the state, the soil is so shallow over can be either well above or well below their normal precipitation. It is no wonder that annual precipitation may vary appreciably from year to year. This variation is very evident in the total annual precipitation received in St. Paul-Minneapolis for the 1837-1973 period as shown in Figure 2.

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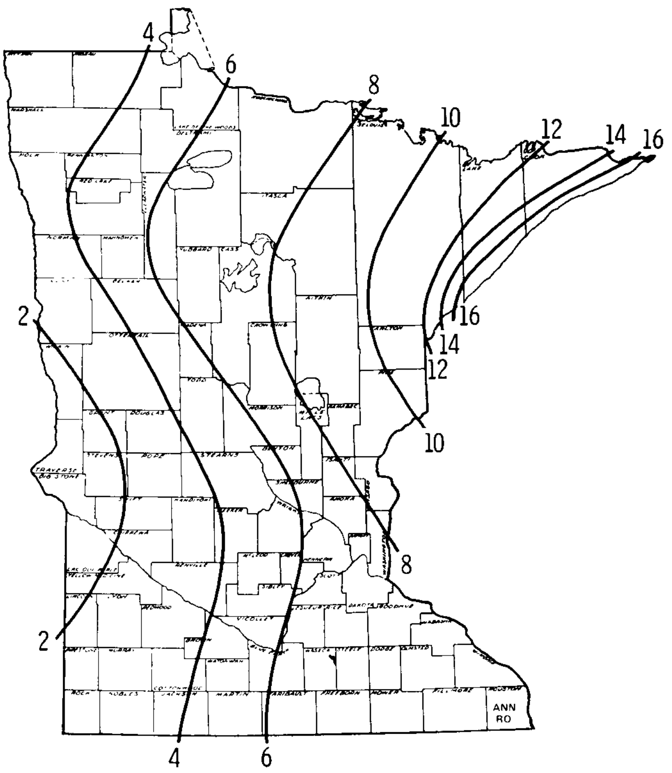

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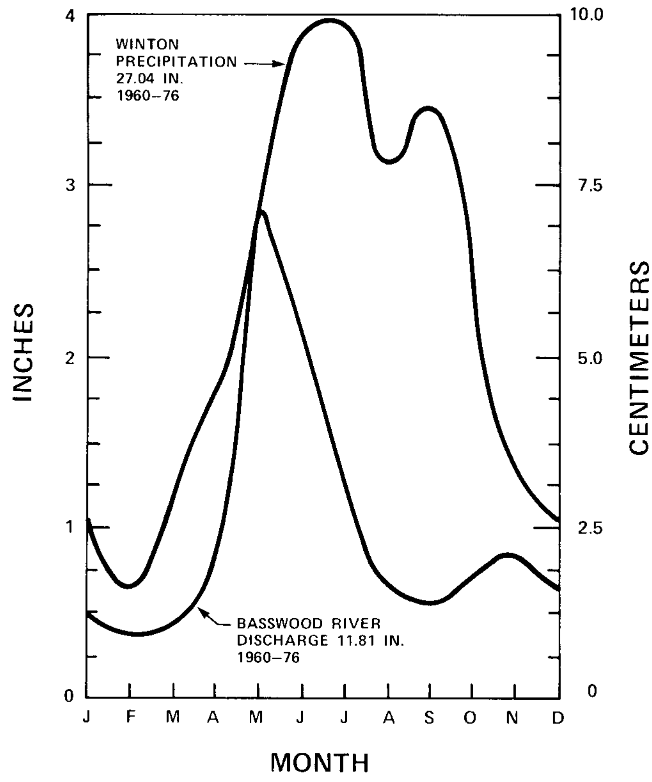

Figure 5. Average monthly total precipitation (upper curve) and runoff (lower curve) of the Basswood River watershed, area number 1 in Figure 3. The average annual runoff equals 44 percent of the precipitation. Data source (21, 22).

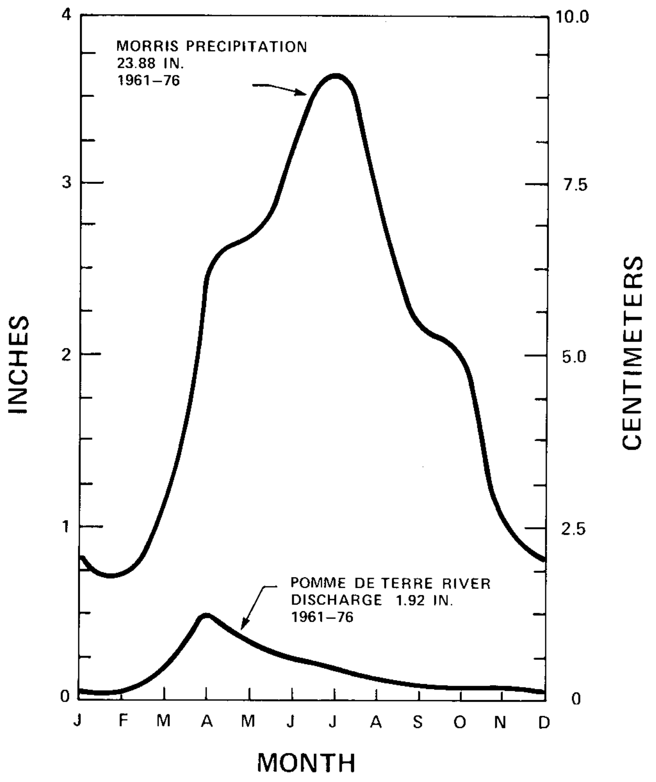

Figure 6. Average monthly total precipitation (upper curve) and runoff (lower curve) of the Pomme de Terre River watershed, area number 9 in Figure 3. The average annual runoff equals 8 percent of the precipitation. Data source (21, 22).

much of the area that its reservoir effect is severely reduced, and thus the runoff is both more immediate and greater in quantity.

Several things of interest are demonstrated in the data of the three watersheds shown in Figures 5, 6, and 7. One is the difference in the amount of runoff between two of these watersheds, Basswood and Pomme de Terre River watersheds, Figures 5 and 6, respectively, which nearly represent the extremes within the state. Another is the one month lag in time of maximum runoff between the northern and southern watersheds. For most of Minnesota the peak runoff occurs in April, while in the extreme northern part of the state, and particularly in the northeastern corner, it falls in May.

Also of interest is the nearly immediate response to spring snowmelt in all three watersheds, but an approximate one-two month lag between the secondary precipitation maximum in September and the corresponding minor runoff peak that is most evident in the Basswood River watershed. The latter point is further indication that runoff occurs only after the soil has been replenished—except in the case of high intensity storms, of course. The secondary runoff maximum in the Basswood River watershed in November (Figure 5), may indicate that on the average the shallow soils in the northeast are recharged by this time, although this is not the case at Lamberton as will be seen later. That the early spring peak runoff consists essentially of accumulated over-winter precipitation is also shown in Figure 5, where the May discharge almost equals the

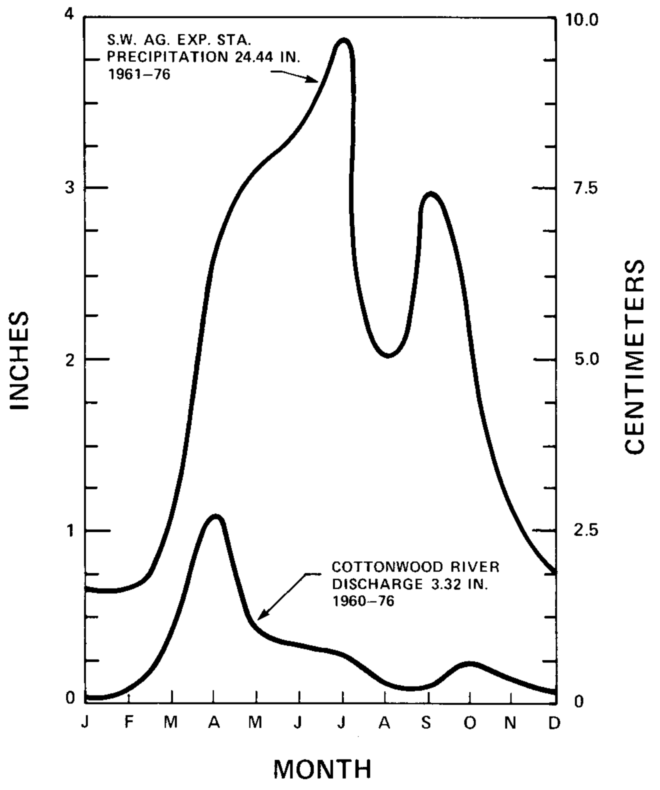

Figure 7. Average monthly total precipitation (upper curve) and runoff (lower curve) of the Cottonwood River watershed, area number 5 in Figure 3. The average annual runoff equals 14 percent of the precipitation. Data source (21, 22).

May precipitation. Only if the May evapotranspiration were insignificant could the source of this runoff be the May precipitation.

In regard to the seasonal variation in runoff, it has been suggested that a contributing factor to the secondary maximum in runoff, and unrelated to the late season secondary maximum in precipitation, is the cessation of the native vegetation growing season. That is, with the loss of leaves in October, water is released to stream flow that previously was consumed in transpiration. For example, a phenomenon observed in the more arid parts of the state is an increase in the October and November flow of streams paralleled by trees and shrubs. This coincides with the fall of leaves and even occurs following a dry August and September when there has been no apparent replenishment of water to the system.

C. EVAPORATION AND EVAPOTRANSPIRATION

By far the greatest share of the precipitation is returned to the atmosphere as invisible vapor through the process of evapotranspiration and evaporation and in the winter by sublimation. Although the amount can be estimated, it is difficult to obtain an accurate measure. For example, in the Cottonwood River watershed the mean evapotranspiration cannot exceed 21.12 inches, which is the difference between the annual average precipitation and runoff (Table 1). In an earlier study (2) it was estimated that the winter sublimation loss averaged 1.77 inches. If this figure is accepted, the mean evapotranspiration during the remainder of the year would average 19.35 inches, less whatever enters the groundwater supply.

The direct measurement of evapotranspiration is not an easy task, and there are few places in the United States, or the world, where such measurements are made. As a result, a number of schemes have been devised to estimate evapotranspiration. Some of the more popular ones make use of air temperature for two reasons: it is a commonly measured climatic element, and it is assumed to be directly related to evapotranspiration. It is true that as long as soil water content remains high there is a relatively high correlation between evapotranspiration and air temperature. However, on those occasions when soil water is low and evapotranspiration is necessarily limited, air temperature can be high. This occurs because the solar energy previously consumed in the evaporation process is available to heat the air when soil water supplies are low. Under such a circumstance the correlation between air temperature and evapotranspiration may even be negative.

The weighing lysimeter established in early 1978 on the experimental plot land at the University of Minnesota, St. Paul campus, is only one of two such instruments in the state which permits the direct measurement of evapotranspiration. Thus, evapotranspiration normally must be determined indirectly by measuring the precipitation and runoff and obtaining it by difference, or it can be estimated with various empirical calculation methods. Figure 8 shows the results of the difference method. The evapotranspiration values were obtained by simply finding the difference between precipitation and runoff. Additions to groundwater were assumed to be zero.

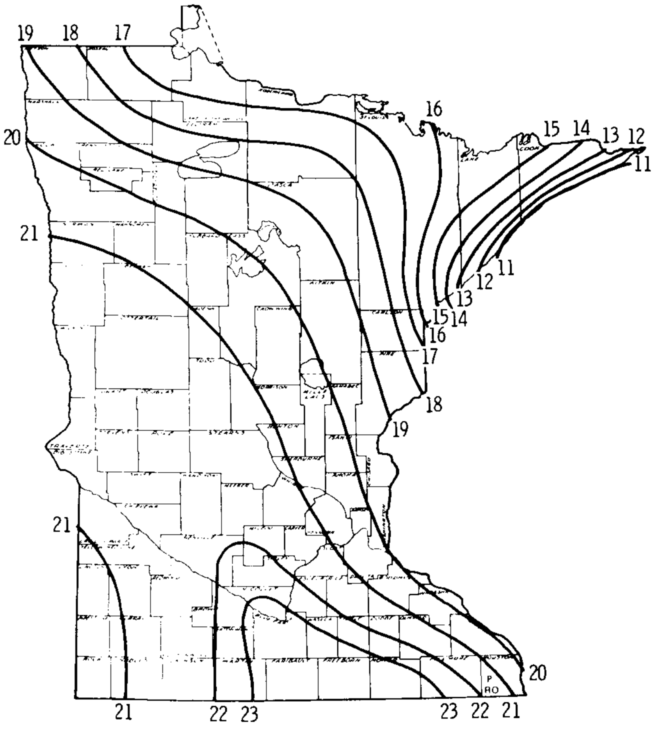

Figure 8. Mean evapotranspiration in inches based upon the difference between precipitation and runoff at the same 15 watersheds shown in Figure 3.

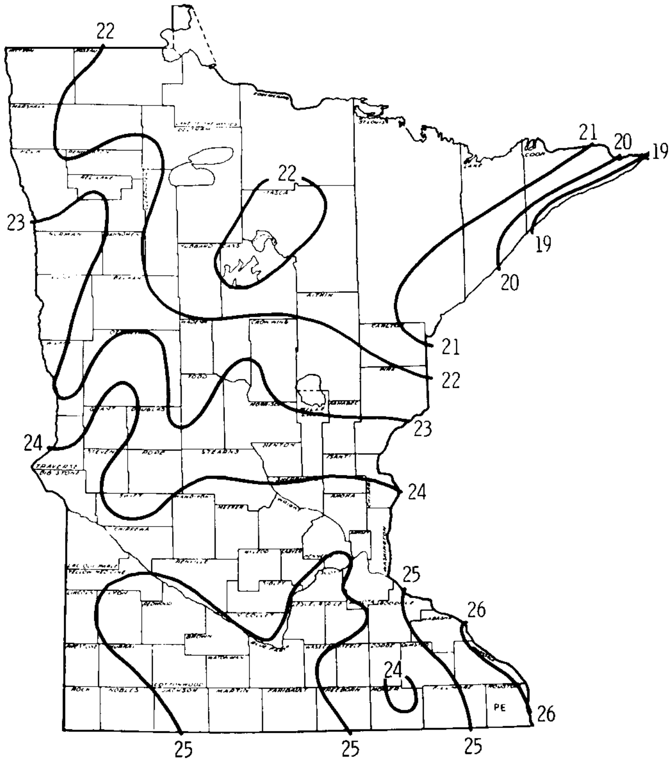

Figure 9. Mean potential evapotranspiration in inches calculated by the Thornthwaite method (20).

Figure 9 is an example of the second method in which evapotranspiration has been calculated by the Thornthwaite method (20). A number of assumptions have to be made when using calculation methods such as this one. Perhaps the most important one is that soil water remains readily available throughout the season. Other factors include a green and actively transpiring crop of uniform height that completely covers the soil. The result is that the evapotranspiration calculated is a fictitious amount termed "potential" evapotranspiration. The more humid a region is, either naturally or through irrigation, the more closely the actual evapotranspiration will equal the potential amount, since the latter is determined solely by the meteorological factors.

As discussed in later paragraphs, the evaporation from pans (Figure 10) can be used to estimate evapotranspiration, but such estimates of evapotranspiration must be used with caution. For one thing, the free water surface of the pan is much different from the soil and plant surfaces. Secondly, as a small and isolated water surface the pan can be greatly affected by the air passing across it. As a result pan evaporation usually shows an evaporation amount that is even greater than the "potential" evapotranspiration obtained by the Thornthwaite or other calculation methods.

As crude as it is, the difference between precipitation and runoff as shown in Figure 8 probably provides the most accurate picture at this time as to the average evapotranspiration across the state.

When first conceived the evaporation pan was pictured as a simple means of arriving at the evaporation taking place at the surface of the earth (17). Certainly it shows a variation with time of year as shown in Figure 11, for the maximum is ordinarily reached in late June or early July indicating its close relationship to receipt of the sun's energy.

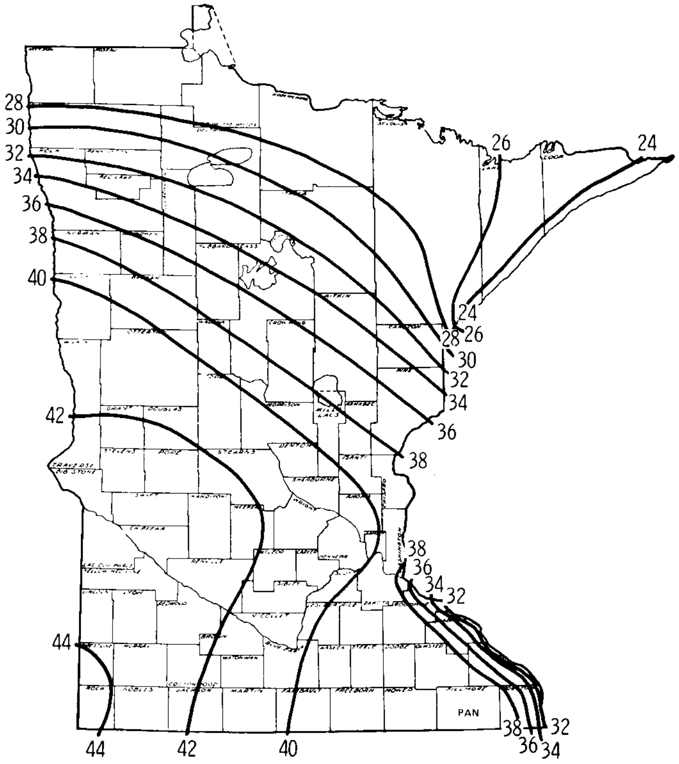

Figure 10. Mean annual pan evaporation in inches based upon records available in the period 1960-1977.

Table 3 shows that the pan evaporation also reflects a variation in geographic location or climate. For example, the cooler, more cloudy weather in northeastern Minnesota at Hoyt Lakes results in a mean April 21-

Table 3. Mean monthly and total pan evaporation in inches. The data are compiled from (19) and include all data within the period 1960-1977. None of the records are complete for this period.

	Month							
Station	April*	May	June	July	Aug	Sept	Oct*	Total
				Minnesota				
Farmington	1.46	7.20	8.44	8.30	7.34	4.89	1.51	39.14
Hoyt Lakes	1.25	4.94	5.62	6.30	5.03	2.92	0.65	26.71
Lamberton**	1.84	7.82	9.04	9.10	7.37	5.45	1.78	42.40
Morris	1.78	7.87	9.30	9.68	7.78	5.67	1.62	43.70
St. Paul	1.78	7.30	8.50	9.29	7.37	4.66	1.29	40.19
Waseca	1.84	7.65	8.38	8.56	6.68	4.78	1.42	39.31
				North Dakota				
Edgeley	1.56	6.39	6.90	7.73	7.55	4.91	1.29	36.33
Fargo	1.58	7.51	7.81	8.93	7.88	5.24	1.48	40.43
				South Dakota				
Brookings	1.74	7.78	8.77	9.55	8.54	5.79	1.63	43.80
Sioux Falls	1.85	7.98	9.11	10.18	8.96	5.73	1.80	45.61
				Wisconsin				
Trempleau Dam	1.76	5.54	6.14	6.69	5.47	3.78	0.99	30.37

* For the 10-day periods April 21-30 and October 1-10.

**These values differ from those shown in Table 1 and Figure 11 due to the slightly different time period used in determining the mean.

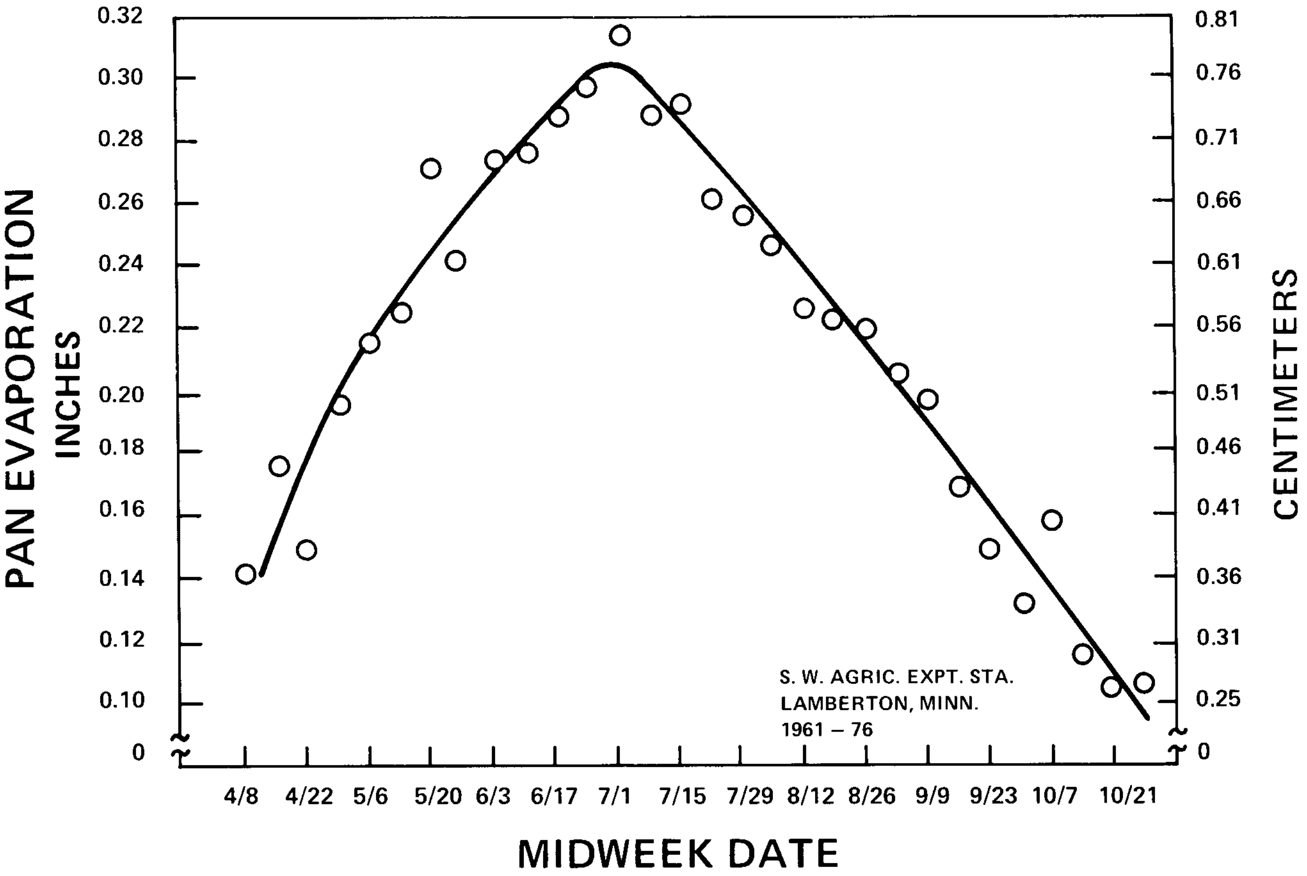

Figure 11. Average daily pan evaporation at the Southwest Agricultural Experiment Station, Lamberton, 1961-1976.

October 10 evaporation that is about 15 inches less than in southwestern Minnesota at Lamberton. As a result of the increase in evaporation from the northeast to the southwest, the isolines of pan evaporation are oriented approximately northwest to southeast across the state. This is shown in Figure 10.

Evaporation in the immediate area of Lake Superior may be much lower during May-September than indicated in Figure 10. For example, the normal summer temperature at Grand Marais, located on the north shore of Lake Superior, is more than 5°F lower than it is at Babbitt, located inland and near Hoyt Lakes (Table 3). Another possible error in Figure 10 is the relatively low values in the southeast along the Mississippi River that reflect measurements made at Trempleau Dam. These probably represent only a very local condition. First, the measurements were made in a protected river valley and the pan was, therefore, poorly exposed. A second reason the Trempleau Dam data are suspect is the affect that a nearby water body can have upon a pan measurement. This is discussed in succeeding paragraphs.

It was soon apparent to investigators that pan evaporation is not comparable to lake evaporation, which is markedly affected by the area and depth of the water body. An extreme example is the case of Lake Superior where the maximum evaporation occurs in December in contrast to a pan with the maximum ordinarily in early July in response to the radiation regime over a land surface.

In the early part of this century there apparently were a number of locations where pans were placed in lakes and even rivers. Such measurements were made in English Coulee (1906-1912), a small stream flowing through Grand Forks, North Dakota, and in Sandy Lake (1906-1911) near the federal dam. There were no pans located on land nearby so only an indirect comparison can be made between the "water site" and the "land site." The comparison we made was accomplished in the following manner. A ratio was established between calculated potential evapotranspiration using the Thornthwaite method (20) and the mean "land site" pan evaporation of five Minnesota stations. This ratio represents the expected ratio at a "land site." It was compared to the ratio of the calculated potential evapotranspiration and the pan evaporation of the two "water sites."

Results from this very indirect method indicate that the river pan at Grand Forks, lost only 70 percent of that from a "land site," while at Sandy Lake the pan loss was only 52 percent of that expected from a "land site." Although the results may not be acceptable quantitatively, they do give a qualitative picture as to the degree of reduction in evaporation that can occur due to the presence of a large water body.

In moving across a water surface of limited extent, such as a pan or small pond, the vapor gradient between the air and water is hardly changed between the upwind and downwind sides. However, as the size of the water

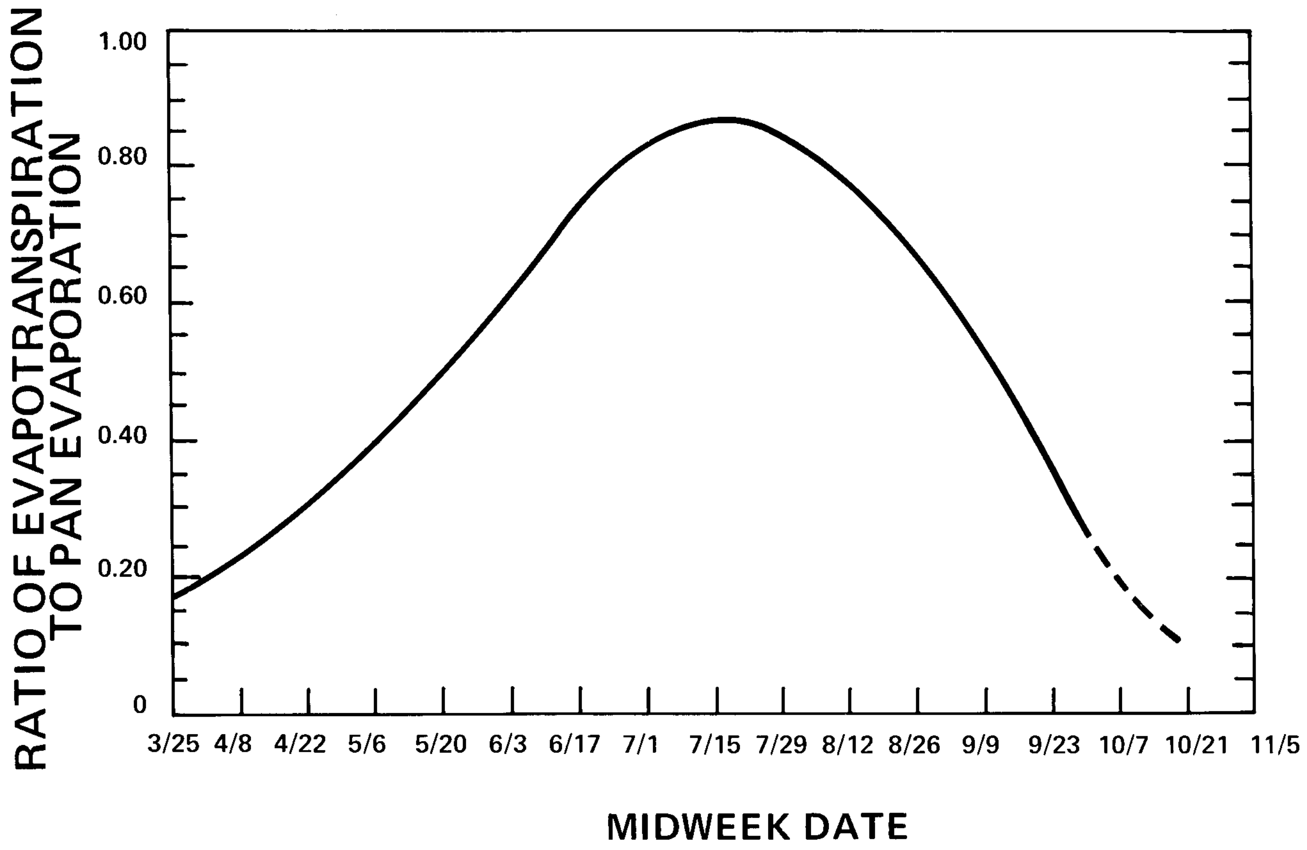

Figure 12. Ratio of evapotranspiration to pan evaporation when the soil water is at least 50 percent of the available soil water, Southwest Agricultural Experiment Station, Lamberton, 1961-76.

body increases, the air passing across it is increasingly modified. In addition to a temperature change the moisture content of the air is increased due to the evaporation that takes place. Thus, the vapor gradient between the water surface and the air above is decreased. This serves to reduce the evaporation rate as the air passes across any extended water body.

The degree to which a water body can reduce evaporation as a result of the "vapor blanket" over the water surface was shown to be appreciable as in the two "land" and "water" site cases just noted.

Measurements of evaporation from a standard size pan are also used to estimate evapotranspiration losses. Since the same physical process is involved, a direct relationship between the two seems obvious. However, the pan differs from soil and the plants in several respects with the result that they do not absorb equal amounts of solar energy. One reason for this difference is that only the pan presents a free water surface, and even under optimum soil water conditions the soil and leaf surfaces are not comparable to free water. A second reason for a difference is in the plant itself. It is constantly changing, not only in orientation to the sun but also in color, (from green foliage of spring and summer to the browns and yellows of maturity or autumn), and in density as well as height (bare soil in early spring to complete vegetative cover 6-8 feet tall by mid-July in the case of a corn field). Another important reason is that except under irrigated conditions the soil water content fluctuates greatly during most growing seasons. There is hardly a year in which a dry period of some degree does not occur, resulting in a low soil water content and, therefore, decreased evapotranspiration. At such times the evaporation of the water from the pan greatly exceeds evapotranspiration. In this regard it is interesting to note that Dale and Scheeringa (6) found in Indiana that with each 10 percent decrease in plant available soil water (in the first 6 inches of soil), the pan evaporation increased nearly 0.01 inches per day.

For the reasons just cited evaporation pan data should be used with caution when applied as an estimator of evapotranspiration.

Limiting evapotranspiration to those times when the soil moisture content is at least 50 percent of the total plant available water, the ratio of evapotranspiration from a corn field to pan evaporation is shown in Figure 12. At the beginning of the season, when the soil is bare of vegetation, the ratio ranges from 0.2 to 0.4. It reaches a maximum of nearly 0.9 in mid-July and then declines quite rapidly to 0.3 by the end of September. The curve shown in Figure 12 is similar to that obtained in an Iowa study (8). However, the mid-season peak of about 0.85 found in that study persisted for nearly six weeks. This difference may be explained, in part at least, by the longer growing season in Iowa and the more humid surroundings of Ames.

In regard to the persistence or lack of persistence of the mid-season peak there is an important factor that cannot be overlooked. Evapotranspiration estimates based on gravimetric soil sampling, as in this study, suffer from possible errors due to an inability to accurately measure the movement of water into or out of the base of the soil profile. This can be a serious problem, particularly in the case of perched water tables. For example, Allmaras, et al (1), found on a Nicollet soil with a perched water table that early season evapotranspiration was overestimated by 20 percent. This error was the result of drainage out of the soil profile. In contrast, the upward movement of water into the root zone later in the season resulted in a 25 percent underestimation of evapotranspiration.

The similarity of the curve in Figure 12 to the one obtained in the Iowa study (8), except in the maintenance of the mid-season peak, supports the view that early season drainage out of the profile was not a factor of consequence at the Lamberton soil water sampling site. That the soils at this site are ordinarily not fully recharged in the spring is further evidence that downward drainage is not a common occurrence.

The upward movement of water in the soil during the latter part of the season does remain a possibility. If this is the case then evapotranspiration has been underestimated and the mid-season peak should persist through the end of July and into early August. In that case the graph shown in Figure 12 would more nearly equal that of the Iowa study. It should be noted, however, that one season's measurements from the weighing lysimeter at St. Paul lend credence to the briefer duration of the evapotranspiration-evaporation pan ratio peak in Minnesota as shown in Figure 12.

Because evaporation pan measurements can be easily made, their measurement in combination with the ratios shown in Figure 12 will permit a ready estimation of the water consumed by an annual crop that is relatively well watered. The fact that Figure 12 is based upon data from the Experiment Station at Lamberton does not negate its use at other sites.

An example will show how Figure 12 can be used to estimate evapotranspiration losses and thus the scheduling of irrigation applications at other locations. Assume an evaporation pan loss of 0.35 inches at Waseca during a day in the week of July 1(June 28-July 4). The ratio of evapotranspiration to pan evaporation on that date equals 0.84, according to Figure 12. Thus, the daily loss from a corn or bean field that is relatively well watered equals 0.29 inches; that is, $0.35 \times 0.84 = 0.29$. The summation of these calculated evapotranspiration values based on daily evaporation pan losses permits the ready determination of when irrigation should next be scheduled.

The evapotranspiration-evaporation pan ratio just discussed and illustrated in Figure 12 was developed from soil moisture measurements made with corn, an annual row crop. The ratio can be used in conjunction with other annual row crops, such as soybeans, though an adjustment may have to be made if the rate of crop growth does not coincide with that of corn, as indicated by plant cover in the spring and maturity later in the growing season.

A single-figure mean value of the evapotranspiration-evaporation pan ratio is 0.62 for the period from late April to late September for row crops when soil water is readily available, based upon the data in Figure 12. However, a frequently used correction factor of the evaporation pan data is 0.7. That is, it is assumed that evapotranspiration is about 70 percent of the evaporation losses from a pan. In a wet season, when plants are not short of water, this is probably an acceptable figure. But in light of the 19.35 inches or less estimate of the average evapotranspiration at Lamberton (see page 8), the 0.7 ratio is high, since 70 percent of the average season pan evaporation (42.18 inches) equals 29.53 inches. Based upon these figures it appears that 0.46 ($19.35 \div 42.18$) is a better estimate of the mean growing season ratio of evapotranspiration to pan evaporation. It should be understood that 0.46 is an estimate obtained under all conditions of soil water for a row crop (corn) and not just when the soil water is readily available. Nevertheless, for *general* conditions in Minnesota with a full-season row crop a figure of about 0.5 is apparently more realistic than the more frequently used 0.7.

For perennial crops such as alfalfa or grass sod which completely cover the soil and are actively transpiring throughout the season, the evapotranspiration-evaporation pan ratio shown in Figure 12 is not to be used. Rather a constant of about 0.7 throughout the season is probably a more correct value for a well-watered perennial such as alfalfa. Although there are no measurements in Minnesota that would substantiate this, the results of Penman (15) and Pruitt and Angus (16) among others indicate that 0.7 is an acceptable single-value ratio to be used during the growing season.

Evaporation from lakes can also be estimated from evaporation pan data. However, caution must be exercised for several reasons. One reason is the great variation that exists between lakes as to areal extent, shape, depth, and surrounding terrain. A second reason is the difference between a lake and a pan. As already indicated, the maximum pan evaporation and lake evaporation can lag one another by as much as five months as in the case of Lake Superior. A third reason is the exposure of the pan itself which can greatly influence results.

The ratio of lake to pan evaporation is usually termed the pan coefficient. A map of the average annual pan coefficient distribution across the United States is given by Kohler, Nordenson, and Baker (9). They show that the pan coefficient apparently varies from a minimum of about 0.6 to a maximum of about 0.8 across the United States. Since no two lakes are alike as to areal extent, depth and border characteristics, the so-called pan coefficient can serve only as a general guide at best. Sellers (17) noted that pan coefficients should not be used where accuracy better than 10 percent is required and should never be used to estimate monthly evaporation.

5. The Four Stages of Soil Water

The reconstruction of the fate of precipitation within a region representative of the northwestern part of the Corn Belt has served as the introduction to a detailed analysis of one particular element within the hydrologic cycle: the soil. It is an element all too often overlooked, even though it plays an important part in modifying the climate of a region. That is, the soil acts as a sink and a source of both heat and moisture. In this respect the soil serves to modify the climate just as does an ocean, though to a far lesser degree, of course. This has been discussed by Landsberg and Blanc (11).

The remainder of this paper will be restricted to the gross movement of water into and out of the soil in response to precipitation on one hand and crop needs on the other.

The smoothed 17-year (1960-76) mean of the soil water data (Figure 13), indicates four definite stages or periods of soil water in the course of a year. Although differing quantitatively, the stages shown in Figure 13 will be similar throughout the Midwest and in any part of the world having a similar climatic regime; that is, a continental climate with a frozen soil period and a major portion of the precipitation occurring during the growing season.

Although the same four soil stages will be found under a continental climatic regime, variations from that shown in Figure 13 are to be expected due to vegetation differences. For example, a perennial crop such as grass sod or alfalfa that has a much longer growing period than corn will modify the picture. A comparison between soils with different vegetative covers is not available at Lamberton, but is available at St. Paul and shown in Figure 14. The sod cover at St. Paul was mowed frequently and maintained at a height varying between 3-5 inches. The similarity between annual row crops, corn at Lamberton in Figure 13 and soybeans at St. Paul in Figure 14, is evident.

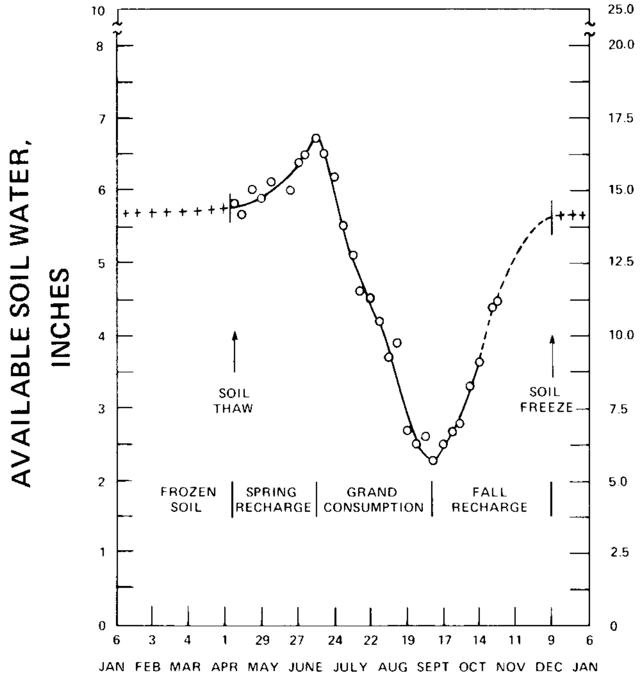

Figure 13. The average total plant available water to a depth of 5 feet under continuous corn during the course of a year at the Southwest Agricultural Experiment Station, Lamberton, 1960-76.

As shown in Figure 14, the occurrence of the maximum soil water content is delayed for the annual row crop (soybeans) relative to the perennial sod. Unlike an annual row crop, the bluegrass sod has a complete cover and is actively transpiring nearly as soon as the snow cover disappears. Why the maximum is not delayed on the soil bare of vegetation is not certain. It may occur because of puddling of the exposed Waukegan silt loam (Typic Hapludoll) soil surface.

The nearly equal drawdown of water by the sod and soybeans, as indicated by the difference between the maximum and minimum soil water values, is surprising. That is, unless the soil is kept continually moist, it is generally understood that the deeper rooted crop can exploit a greater volume of soil and thus has available to it a greater quantity of water than a shallow rooted crop. The explanation may rest with the more complete and longer transpiration period of the sod.

It should be noted, however, that the apparent equal amount of drawdown between a perennial and an annual row crop does not necessarily mean an equal amount of evapotranspiration has occurred. That would be true only if the runoff from the two vegetative covers was equal. Runoff measurements from the two covers have not been made, but during high intensity storms a greater runoff from the soybean plot has frequently been observed.

A. GRAND CONSUMPTION STAGE

One stage is the period of relatively rapid and steady drawdown of the soil water reservoir that takes place. Under corn this extends approximately from early June

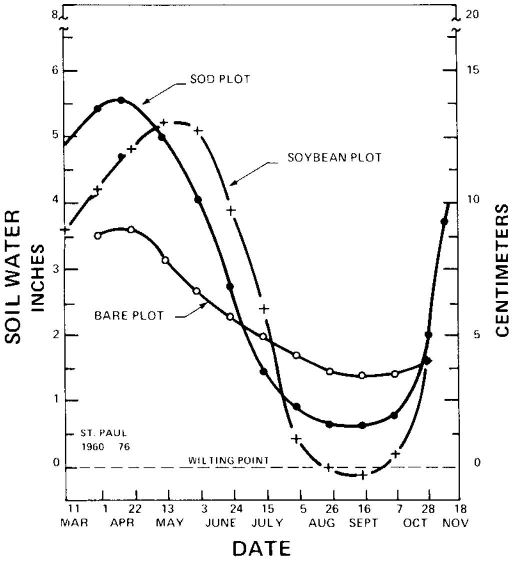

Figure 14. The average total plant available water to a depth of 5 feet under soybeans, bluegrass sod and no vegetation during the growing season at the Agricultural Experiment Station, St. Paul, 1970-76.

through August. Precipitation is ordinarily insufficient for crop requirements during this period. Thus, the soil reserves are drawn down to make up the deficit. An important point to note is that even in an average year, much less a drought year, the soil water reserves are heavily drawn upon during this stage. On the average the June-August drawdown equals more than 4 inches at Lamberton as shown in Figure 13 and Table 4.

Within the drawdown period of June-August occurs the extremely important reproductive period of the corn plant when water requirements are of extreme importance and at a maximum (10). For example, the silking and tasseling of corn take place during a relatively brief period that usually commences in mid- to late-July. With soybeans this period is more extended in time but the need for water remains just as important. Since the availability of water to plants decreases as the amount of soil water decreases, it is apparent that one advantage of early planting arises from having the critical reproductive period of the plant occur while soil water and precipitation probabilities are higher in early July than in the latter part of the month.

As Lamberton data show, the maximum soil water content under a row crop in Minnesota is ordinarily in the week of May 31-June 6, and the minimum amount occurs in about the week of August 23-29. The change that normally occurs within the soil water profile is shown in Figure 15. The difference in total water within the soil to the 60 inch depth averages 4.71 inches over this 12-week period.

It may be assumed that by the end of August the majority of the active corn roots are at 15-27 inches for the water has been withdrawn to below the wilting point at this depth. Since there is little or no change at the 60 inch depth, it can also be assumed that the corn roots do not normally exceed this depth.

B. FALL RECHARGE STAGE

The next soil water stage under corn commences at the end of the drawdown period which occurs in late August or early September. This stage ends when the soil freezes. Although temporary soil freezing may occur in November, the final freeze for the winter usually does not take place until early December in the southern one-quarter of the state. At Lamberton the mean date is December 7. Normally this autumn period is the major and most efficient of the soil water recharge periods, a fact already noted by Holt and Van-Doren (10) and by Timmons and Holt (19) for the same general area. A little more than half of the precipitation during this period remains in the soil for use in the following growing season (Table 4). The remainder of the precipitation is lost as runoff, or is consumed by evapotranspiration during the fall. A

Table 4. Precipitation, soil water change and storage efficiency during the four soil water stages, Southwest Agricultural Experiment Station, Lamberton, 1961-76[1].

Soil Water Stages	Precip-itation	Soil water change	Effic-iency[2]
	Inches	Inches	Percent
1. Grand consumption (June 1-Aug. 31)	9.19	−4.30	—
2. Fall recharge (Sept. 1-Dec. 6)			
a. End of grand consumption stage to last frequent fall sampling (Sept. 1-Oct. 12)	3.43	+1.30	37.9
b. Last frequent fall sampling to frozen soil (Oct. 13-Dec. 6)	2.81	+2.00	71.2
Total fall recharge	6.24	+3.30	51.3
3. Frozen soil (Dec. 7-Apr. 3)	3.74	+0.15	4.0
4. Spring recharge (Apr. 4-May 31)	5.77	+1.00	17.3
Total of the four stages	24.38[3]	0.00	

[1] While the soil water measurements began in 1960, the first complete year for soil temperature and precipitation observations was 1961.

[2] The ratio of the soil water change to the precipitation expressed as a percentage.

[3] Differs from the mean of 24.44 inches (Table 1) because several of the sample periods during the 16 years are omitted due to soil sampling problems.

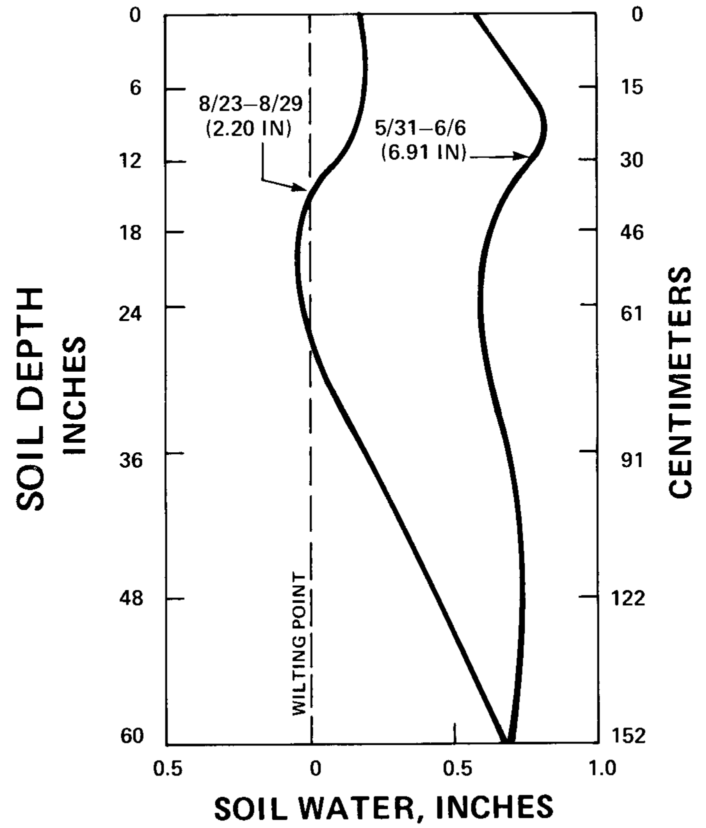

Figure 15. Average soil water profile under corn to a depth of 5 feet in the week of maximum soil water content, May 31-June 6, and in the week of minimum soil water content, August 23-29. Southwest Agricultural Experiment Station, Lamberton, 1960-76.

small and relatively insignificant amount of water may move out of the soil profile to become a part of the groundwater supply. Ordinarily, however, additions to the groundwater are limited to the spring recharge period since soil water is seldom in excess in the fall.

C. FROZEN STAGE (WINTER)

On the average the soil at Lamberton is frozen between December 7-April 4, a 118-day period (Table 5). It is estimated that with each 20 miles north or south of Lamberton there is on the average a one-day difference in the mean soil freeze and thaw dates noted in Table 5. Deviations from this estimate will occur due to variations in soil cover, moisture content, and slope. While the soil is frozen little water enters it as shown in Figure 13. In the average winter the addition is less than about 5 percent of the over-winter precipitation (Table 4). Since the December-March precipitation averages only 3.20 inches (Table 1), even the total amount of water involved is small. Most of the December-March precipitation is lost as runoff (2) in the early part of each spring and is the major source of the high March-May runoff which peaks in April and totals 1.94 inches (Table 1).

A major exception to the amount of over-winter precipitation entering the soil recently occurred and deserves special mention. Several unusual events transpired following the 1976 drought which resulted in virtually 100 percent of the over-winter precipitation entering the soil.

The most important feature was the extreme dryness of the soil across most of the state. Thus, even though the winter temperature of the soil was well below freezing, there was little ice present to block soil pores to the entrance of liquid precipitation or meltwater. In addition the low moisture content of the soils meant that little heat was required to bring the soil above the freezing point. With this background it can be understood why a general rain in late February, 1977 (another unusual event), a snowfall of high water content in early March followed shortly by another general rain succeeded in entering and thawing the soils. In some areas of the state the precipitation totaled more than 5 inches with no recorded runoff.

Thus, based on the February-March, 1977, experience it is apparent that under certain circumstances much over-winter precipitation can enter agricultural soils in Minnesota. However, the circumstances under which an appreciable amount can enter the soil is believed to be a relatively infrequent event as shown by the 1960-1976 Lamberton data.

An approximate 49 percent efficiency in the over-winter precipitation was obtained in a west-central Minnesota study by Timmons and Holt (19). The difference may rest with the definition of the winter period and when samples were taken. A higher apparent efficiency would be expected if rains had occurred between the last fall soil sample and soil freezing and between soil thawing and the first spring soil water sample. The more probable reason for the greater recharge efficiency (in percentage terms at least) obtained by Timmons and Holt is that the soils they worked with are normally drier than those farther south at Lamberton. As noted above relative to the February-March, 1977, situation following the 1976 drought, dry soils are more receptive to the snowmelt and early spring rains.

Table 5. Dates of soil freezing and thawing and duration of the frozen soil period, Southwest Agricultural Experiment Station, Lamberton, 1961-76.

Freeze date	Thaw date	Duration in days
Dec. 6, 1961	April 24, 1962	139
Dec. 7, 1962	March 20, 1963	112
Dec. 8, 1963	April 10, 1964	123
Nov. 20, 1964	April 21, 1965	152
Nov. 27, 1965	March 30, 1966	123
Dec. 1, 1966	April 1, 1967	121
Dec. 14, 1967	April 2, 1968	109
Dec. 6, 1968	April 14, 1969	129*
Nov. 28, 1969	March 17, 1970	109*
Dec. 7, 1970	March 30, 1971	113*
Dec. 26, 1971	April 11, 1972	106
Dec. 3, 1972	March 21, 1973	108
Dec. 10, 1973	April 10, 1974	121
Dec. 1, 1974	April 16, 1975	136
Dec. 16, 1975	March 25, 1976	99
Dec. 20, 1976	March 14, 1977	84
Mean Dec. 7	April 4	118

*Soil temperatures remained relatively high and freezing depth was shallow. Drainage may have occurred all winter.

The soil freeze and thaw dates shown in Table 5 are defined as follows. The freeze date is the first date on which the soil temperature at 2 inches (5 cm after 1971) remains equal to or lower than 32°F until the next spring. The thaw date is defined as the first day in the spring when the daily minimum at 12 inches, changed

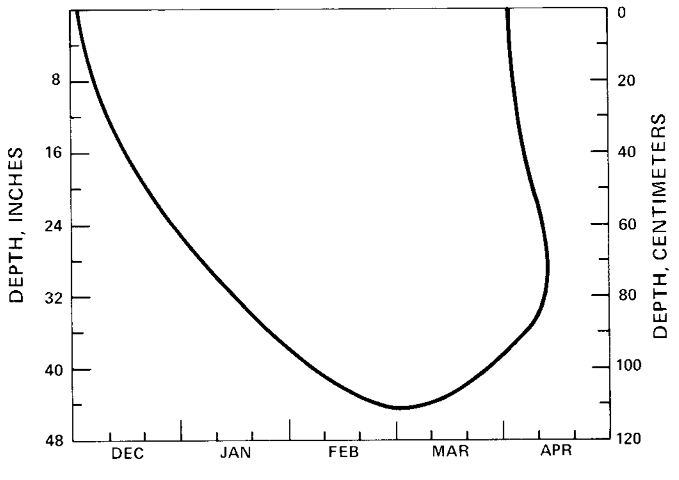

Figure 16. The average position of the 32°F isotherm within a well-drained soil that is bare of vegetation at St. Paul, November, 1960, through April, 1978.

to 8 inches after 1971, remains above 32°F for the rest of the season.

The dates shown in Table 5 are valid for an agricultural soil. They will, of course, vary if the soil or the vegetative cover differ from a cultivated soil as, for example, in the case of a meadow or a forested soil.

Figure 16 shows the mean frozen soil condition under a well-drained agricultural soil bare of vegetation at St. Paul. Although details may vary across the state, the general features will be similar to those shown. These features include three of note: the freezing rate is much slower than the rate of thawing; the maximum depth is reached in early March; and the soil thaws from both top and bottom resulting in a frozen layer within the soil that may persist for some time after the surface has thawed.

The difference between the freezing and thawing rates of the soil is highly dependent upon the effect of snow cover. From about mid-December onward the persistent snow cover acts as an insulator to decrease soil heat loss. As long as the snow remains it acts not only to insulate the soil from rapid heat loss, but also as a reflective agent which reduces the absorption of the sun's rays. Once the snow has disappeared in the spring, however, the soil can warm rapidly since the heat of the March and April sun can be strong; its strength is equal to that in September and August, respectively.

Besides snow cover, a factor of great importance in affecting the temperature regime of soils is their water content. While snow severely restricts the entrance and exit of energy through its reflective and insulating qualities, respectively, water plays an important part in the movement of heat already within the soil as well as the soil's total heat content. The extent to which water can control the soil thermal regime is shown in Figure 17. This figure shows the mean December 31, 1966-1976, temperature profile under a well-drained soil bare of vegetation at St. Paul. It is compared to the mean December 31 temperature profiles of the two wettest Octobers and Novembers (1970 and 1975; a mean total precipitation of 8.20 inches) and the two driest Octobers and Novembers (1967 and 1976; a mean total precipitation of 1.05 inches) in the 11-year period at St. Paul. Obviously under the natural conditions which the data in Figure 17 represent, the water content of the soil was not the only factor affecting soil temperature that varied. Nevertheless, water content was the major variable, for the meteorological records do not show a great variation between the four years in either snow cover or air temperature up to December 31.

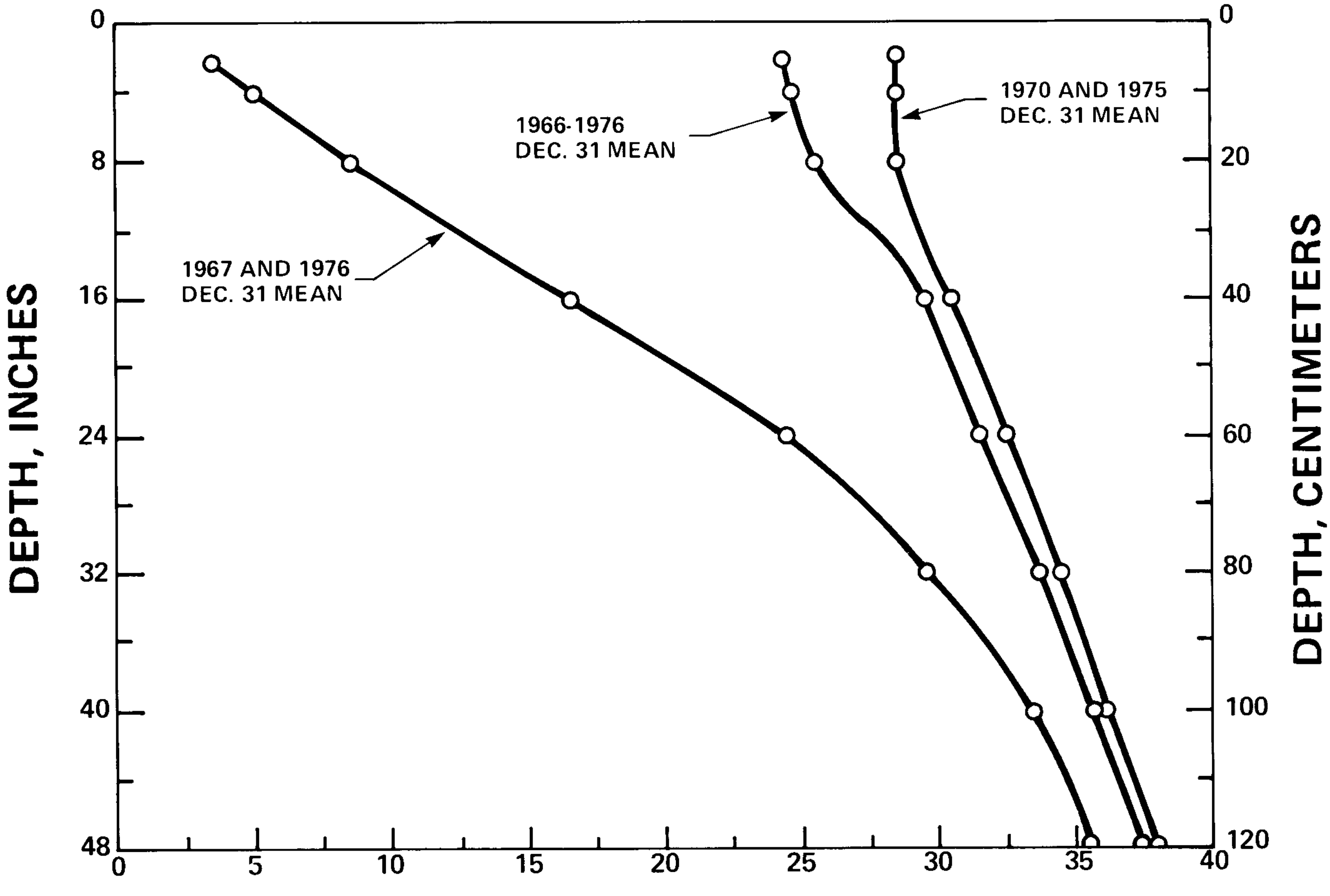

Figure 17. The mean December 31 soil temperature profile under a well-drained soil bare of vegetation at St. Paul, 1966-1976, compared to the mean December 31 profile with very dry soils, 1967 and 1976, and very wet soils, 1970 and 1975.

D. SPRING RECHARGE STAGE

The fourth soil water stage is the interval from the spring thaw until late May or early June. This is the third period in which precipitation ordinarily exceeds the water lost to the atmosphere as vapor through evapotranspiration, evaporation, or sublimation. It is apparent from Figure 13 that in the average spring only a relatively small amount of precipitation remains within the soil for the following June-August grand water consumption period. In fact the data show that less than 20 percent of the spring rain serves to recharge the soil (Table 4). Although almost always small in quantity, major additions to the groundwater supply occur during this stage.

The approximate 17 percent spring recharge efficiency is supported by the 29 percent efficiency obtained by Timmons and Holt (19) in west-central Minnesota. Although this is about a 10 percent greater efficiency than obtained at Lamberton, the difference is small in absolute terms.

There are several reasons why spring recharge efficiency is lower than it is in the fall. First, there is a greater evaporation rate in spring as shown in Figure 11. The mean pan evaporation during the spring period, April 4-May 31, equals about 0.21 inches per day compared to a mean of about 0.12 inches per day for the 40-day longer fall period. Thus, while the total pan evaporation for the two periods is nearly equal with 11.96 inches and 11.59 inches for the spring and fall periods, respectively, the fall precipitation is greater by 0.47 inches. Because agricultural soils do not present a free-water surface, a more appropriate comparison is the evapotranspiration for the two periods. Using Figure 11 in conjunction with Figure 12 the spring evapotranspiration is calculated to be about 4.64 inches. The estimated fall evapotranspiration, limited to September and October, is considerably less; about 3.00 inches for the two months.

A second reason for the greater recharge efficiency in the fall is the usually higher content of soil water in the spring, as shown in Figure 15. Not only is the total water content higher, but more importantly, it is found mostly in the upper part of the soil (Figures 18A-H), thus restricting the entrance of additional water into the soil.

A third reason rests with the occurrence of intense rains. The frequency of intense precipitation is associated with the warmer and higher precipitation months, and it reaches a peak in June or July in Minnesota. For example, the frequency of 24-hour rainfalls of 0.50 inches or more is greater in May than in any fall month, and in April the frequency is about equal to that in September, and it is much greater than in either October or November in Minnesota (12). Thus, as a result of the greater frequency of intense rains in the spring on soils already higher in water content than in the fall, the infiltration rate of the soils will be exceeded more often giving greater runoff.

A forest and forest floor cover, which both insulate the soil and retard water movement, can change conditions from that described for a cultivated soil. For example, the soil ordinarily does not freeze as deeply nor is it subjected to as low temperatures as an agricultural (cultivated) soil. Other things being equal, water is slower to leave a forest, and the soil is also more open to the infiltration of water. Evidence that the spring and fall may be more nearly equal in terms of soil water recharge in a forest is indicated in measurements obtained in north-central Minnesota (23). The nearly equal recharge in the spring and fall is probably due to the entrance into the soil of a greater share of the spring snowmelt and precipitation, which in turn is due to the different freezing characteristics of the forest soil.

In the Introduction to this study it was stated that Lamberton lies in the western Corn Belt where soils are seldom completely recharged with water. This is equally true for the state with the possible exception of the northeastern corner. There, due to the more generally humid conditions and shallower soils, field capacity may be reached nearly every spring. The state as a whole, however, lies in the transition zone between the arid West, where soils seldom reach field capacity in the spring, and the more humid East, where soils are normally fully recharged each spring. Evidence of the transition character of the soils is shown in Table 6.

The 120 percent of capacity found in Blowers fine sandy loam in Todd County may indicate that there are some areas in Minnesota, in addition to the already noted possible exception in the northeastern corner, where soils do reach field capacity. The soil in Todd County was at or above field capacity in 6 of the 10 years sampled. There remains the possibility that this may be due to a perched water table or a peculiarity of the years sampled. The available water holding capacity in this fine sandy loam is 8.3 inches, not much less than that of a medium-to fine-textured soil.

Table 6. Average amount of water occupying the total plant available water space in a 5-foot column of soil at the spring and fall samplings.

County	Soil Type	Spring (~May 1)		Fall (~Nov. 1)	
		Years[3]	Percent	Years[3]	Percent
Dodge[1]	Kasson silt loam	19	67	21	50
Itasca[2]	Eight sites[2]	10	92	10	66
Mille Lacs[1]	Freon silt loam	19	93	18	87
Redwood	Webster silty clay loam	18	61	18	45
Sibley[1]	Nicollet clay loam	19	80	18	62
Todd[1]	Blowers loamy fine sand	10	120	9	83
Wabasha[1]	Fayette silt loam	20	68	19	62
Watonwan[1]	Nicollet clay loam	17	64	16	46

[1] Data obtained by a cooperative project with the Area Conservationists, Soil Conservation Service, U.S.D.A., of the respective counties.

[2] Data courtesy of Dr. E. S. Verry, North Central Forest Experiment Station, Forest Service, U.S.D.A., Grand Rapids. The mean of eight sites to 7.5 feet (rather than 5 feet) that include the Menahga and Warba and Nashwauk series with textures ranging from sand to sandy loam and deep textures ranging from sand to clay loam.

[3] For the years 1957-1977 inclusive, with some spring and fall sampling missing.

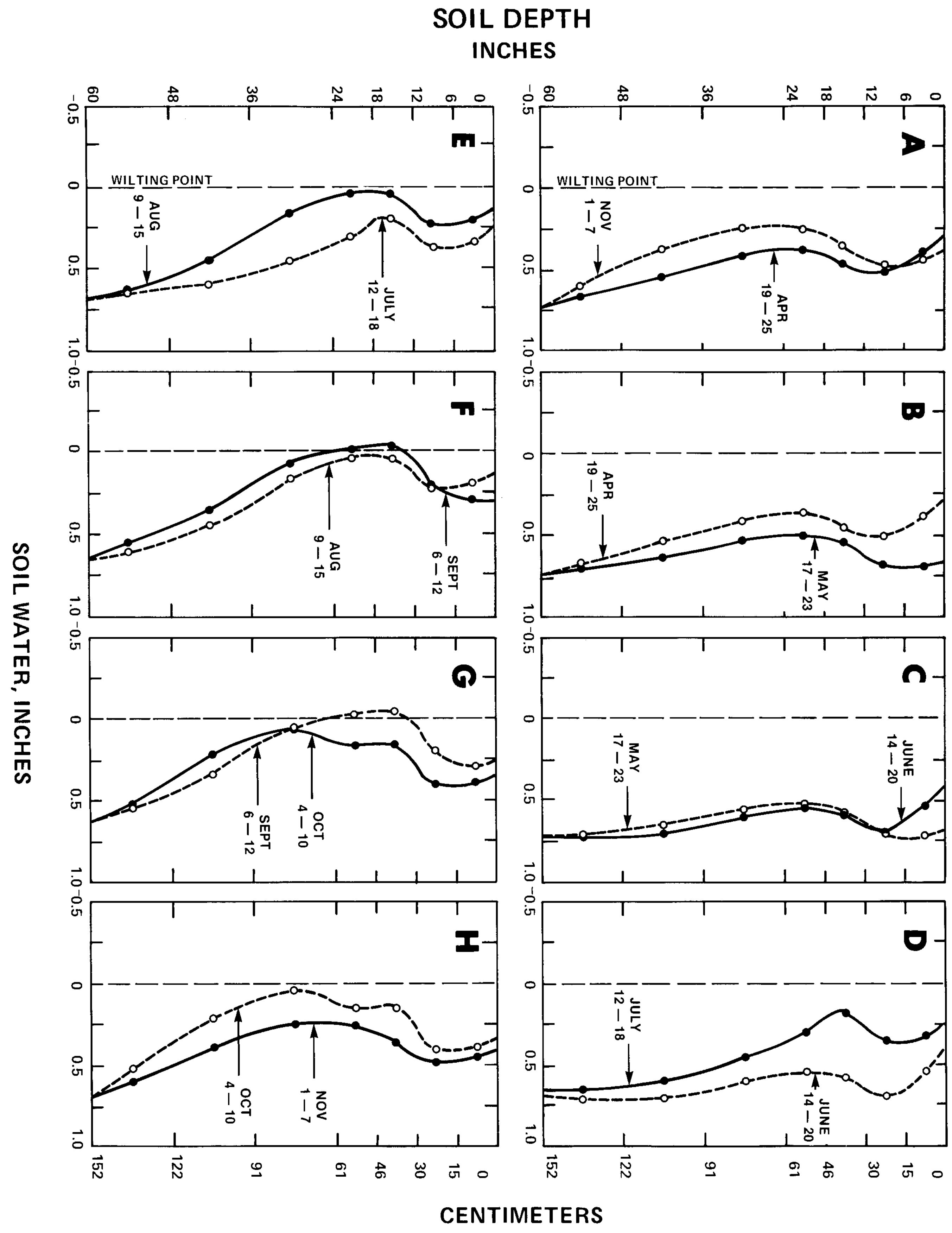

Figure 18. A-H Comparison of average soil water profiles under corn to a depth of 5 feet at four-week intervals from mid-April to early November, Southwest Agricultural Experiment Station, Lamberton, 1960-76.

6. Profile Changes with Time

The eight profiles in Figures 18A-H depict at four-week intervals, extending from mid-April to early November, the mean soil water changes within the average year. Between November and April, (Figure 18A), the major change is the apparent downward movement of water in the profile. Increases in the soil water content occur at all levels during the spring (Figure 18B), until mid-June. From late June the losses in the first 6 inches (Figure 18C), indicate the increasing concentration of roots at this depth. The next three profiles (Figures 18D-F), clearly indicate the deeper penetration of the roots and the increasing demand for water. By early September (Figure 18F), it is evident in the first 6 inches, that the precipitation exceeds the water demand and from then on the fall recharge moves deeper and deeper into the soil (Figure 18G-H), respectively.

7. Soil Water Profiles, 1960-1977

The soil water profile for each of the 18 years of measurement is shown in Figure 19. Only once in the 18 years on record has the total possible plant available water been exceeded. This happened in the spring of 1962. (The fall of 1968 and early spring of 1969 were too wet to sample. Therefore, it is possible that the soil water content exceeded field capacity not once, but two times in the 18-year period). The occurrence in spring, 1962, was due to the wetter than usual fall and spring recharge periods. The final sample taken on October 2, 1961, showed a total of only 3.65 inches of plant available water. However, between October 2 and the soil freeze date the precipitation totaled 3.85 inches and 5.72 inches of rain was measured between the soil thaw date and May 31. By the end of May, 1962, there was 11.10 inches of water in the soil.

A soil water profile can serve as a qualitative measure of the crop yield. The circumstances surrounding the crop years of 1972-76 are very interesting and will be used as examples of just how strong the correlation between yield and soil water can be upon occasion. In looking over these five years it is apparent that very nearly the optimum year with respect to both soil water and precipitation occurred in 1972. Figure 19 shows how the soil water in 1972 varied from the 17-year mean profile. It is to be noted that in 1972 the water content was above the mean throughout the growing season and particularly during the critical tasseling and silking period of mid- to late-July. The combination of adequate precipitation and soil water was reflected in corn yields which averaged 108 bushels per acre in the two counties, Redwood and Cottonwood, which surround the Southwest Agricultural Experiment Station at Lamberton (14).

The next four years (1973, 1974, 1975, and 1976) represent a sequence of years in which there was an increasing depression of the soil water reserves from June or July to the end of August. As the soil water reserves departed farther and farther from the mean the yield decreased similarly. In 1973 the soil water was above average until the end of July and then dropped below the average (Figure 19). Since the water-sensitive silking and tasseling period was relatively well supplied with water the mean Cottonwood and Redwood county yield only dropped to 90 bushels per acre (14). In 1974 and 1975 the July and August departures of the soil water from the mean were not only greater than in 1973, but they also occurred earlier. As a result the average corn yield dropped to 64 bushels in 1974 and 69 bushels in 1975. The 1976 drought, the effects of which are very evident in Figure 19, reduced the two county yield average to 51 bushels. Soil water in 1977 was brought up to the average amount as a result of unusual late winter snowfalls and rains which were followed by rains at critical times during the growing season. The 1977 yield average was increased to 104 bushels per acre.

8. Summary

This study emphasizes the part played by the soil within the hydrologic cycle, particularly as it pertains to the climatic conditions of Minnesota. The major data source is the 1960-1977 soil water measurements from the Southwest Agricultural Experiment Station at Lamberton. Important points of this study include the following:

1. The average annual runoff across the state ranges from a high of more than 60 percent of the annual total precipitation within a watershed to a low of less than 10 percent. Of the 15 watersheds considered, the maximum runoff was found in the northeast and the least runoff in west-central Minnesota. The runoff to precipitation ratio is a function of both the regional climate and the local soils.

2. A simple means of estimating local evapotranspiration loss for replacement by irrigation is shown. The only measurement required is pan evaporation. The potential error in evapotranspiration calculations with the use of a single-value pan factor is noted, and the point is made that the commonly used pan factor of 0.7 for annual row crops over a full season in Minnesota can greatly overestimate evapotranspiration losses. At Lamberton, for example, over the 17 years of measurements with a great variety of soil water conditions a seasonal value of 0.46 was obtained, while under optimum soil water conditions the mean seasonal pan factor was raised to only 0.62. For perennial crops the commonly used pan factor of 0.7 may be acceptable for a full growing season.

3. The soil water data indicate there are four distinct stages or periods during a typical year: (a) the spring recharge stage, (b) the grand consumption stage, (c) the fall recharge stage, and (d) the winter (frozen) stage. Fall is the period of maximum and most efficient recharge, while little or none of the over-winter precipitation is of value in recharging the soil. Although very little recharge occurs during the normal winter (frozen) stage, a very dry soil at the beginning of this stage is conducive to a greater than the usual amount of over-winter recharge. Whether or not the recharge actually occurs depends, of course, upon succeeding conditions.

In contrast to agricultural soils, the recharge of for-

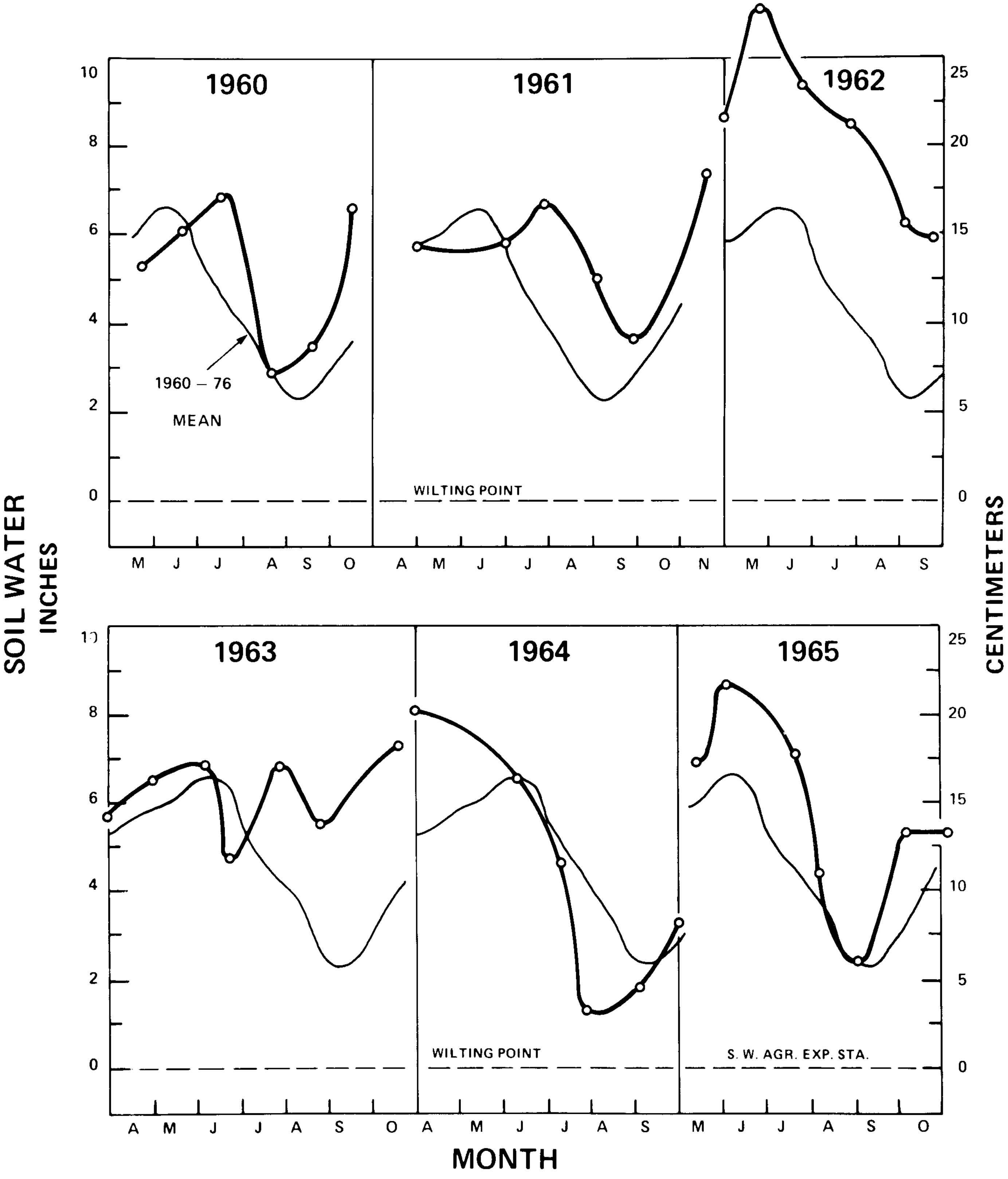

Figure 19. The total plant available soil water under corn to a depth of 5 feet for each year during 1960-77, Southwest Agricultural Experiment Station, Lamberton. The mean profile for 1960-76 is shown as the light line.

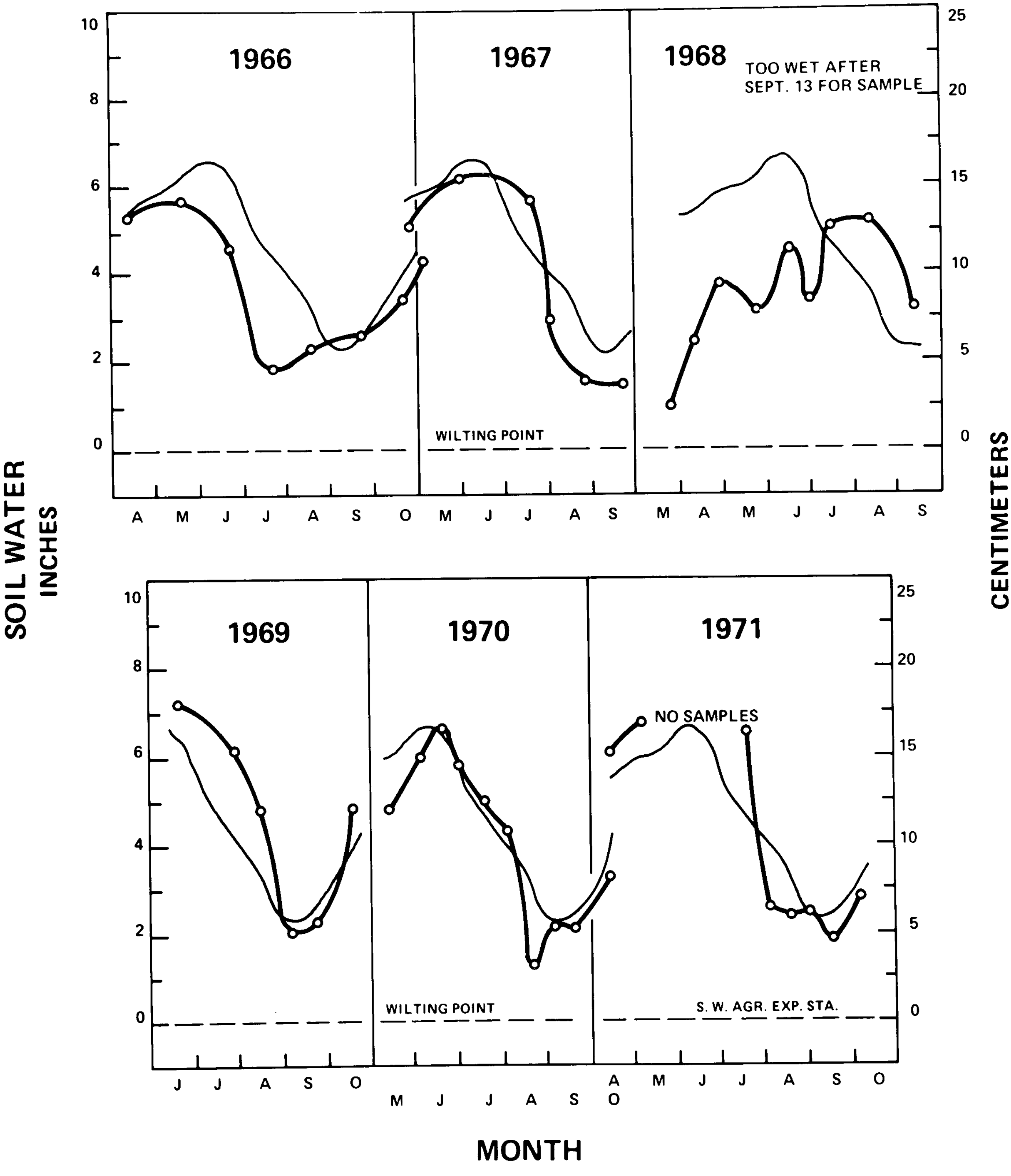

Figure 19. The total plant available soil water under corn to a depth of 5 feet for each year during 1960-77, Southwest Agricultural Experiment Station, Lamberton. The mean profile for 1960-76 is shown as the light line.

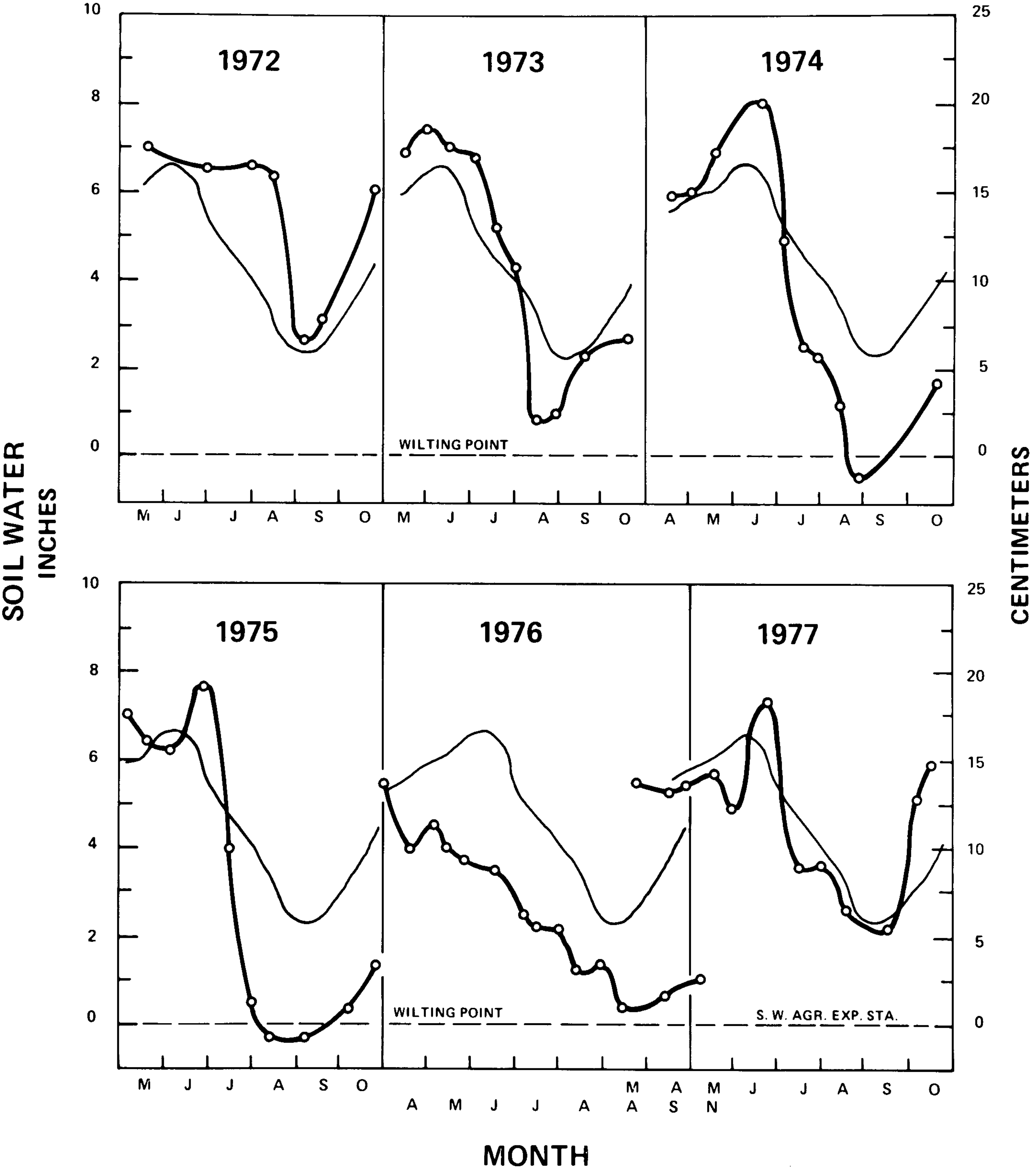

Figure 19. The total plant available soil water under corn to a depth of 5 feet for each year during 1960-77, Southwest Agricultural Experiment Station, Lamberton. The mean profile for 1960-76 is shown as the light line.

est soils during the spring stage may equal or exceed the recharge of the fall stage.

4. Under an annual row crop the soil normally reaches its maximum water content in late May or early June, and its minimum water content occurs in late August or early September. On the average most Minnesota soils are not fully recharged to their field capacity.

5. Soil water is vital to the growth of crops, and it should not be overlooked as a tool in the prediction of crop yield.

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