MOVEMENT OF WATER IN SEASONALLY FROZEN SOIL, SOUTHEASTERN NORTH DAKOTA, 1985-87

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U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 92-4110

Prepared in cooperation with the

NORTH DAKOTA STATE WATER COMMISSION

Bismarck, North Dakota

1992

U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS

Multiply	By	To obtain
centimeter (cm)	2.54	inch
kilometer (km)	0.6214	mile
meter (m)	3.281	foot
micrometer (μm)	0.00003937	inch
millimeter (mm)	0.03937	inch
square kilometer (km^2)	0.3861	square mile

To convert degrees Celsius (°C) to degrees Fahrenheit (°F), use the following formula: °F = (°Cx1.8)+32.

MOVEMENT OF WATER IN SEASONALLY FROZEN SOIL,

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ABSTRACT

A study of seasonally frozen soil was conducted from October 1985 through April 1986 and from October 1986 through April 1987. Three runoff plots were established. On October 30, 1985, 86 mm (millimeters) of water was applied to plot 1, and 43 mm of water was applied to plot 3. No water was applied to plot 2. The winter of 1985-86 had colder-than-normal air temperatures and greater-than-normal precipitation. Some freezing-induced redistribution was measured within the soil profile at some sites. No measurable upward movement of water from the water table to the freezing front was detected in any of the plots.

Snowmelt runoff occurred on March 21 and 22. Plot 1 had 14.2 mm of runoff, plot 2 had less than 0.1 mm of runoff, and plot 3 had 9.0 mm of runoff. Infiltration was determined as the difference between soil water content on March 3 and on March 24. Infiltration was 64.8 mm for plot 1, 43.0 mm for plot 2, and 34.8 mm for plot 3.

The ground-water level started to rise rapidly 2 days after the start of the major snowmelt. Recharge computed from the change in ground-water levels for March 24-27 was 13.2 mm. The mean change in soil water content for March 24-27 indicates a loss (recharge) of 5.1 mm for plot 1, a loss of 1.9 mm for plot 2, and a gain of 4.4 mm for plot 3. The difference between recharge computed from the change in ground-water levels and recharge computed from the change in soil water content indicates that some of the recharge is from a location other than the plots.

The winter of 1986-87 had warmer-than-normal air temperatures and less-than-normal precipitation. Because water was entering and leaving the soil profile during the mild winter, changes in soil water content caused by freezing-induced redistribution, infiltration, or evaporation could not be quantified. On February 26, rainfall runoff occurred from snow-free frozen soil on plots 2 and 3. Snowmelt runoff occurred on all three plots on March 4 and only on plot 3 on March 5. Between February 9 and March 5, infiltration was 50.1 mm for plot 1, 25.4 mm for plot 2, and 49.6 mm for plot 3.

The ground-water level rose very rapidly for a few days at the beginning of March. This rise corresponded to the snowmelt runoff on March 4 and 5. The ground-water level then stabilized until March 18 when it again started to rise rapidly. This rise continued throughout the month. Recharge computed from the change in ground-water levels for March 5-11 was 5.9 mm, recharge for March 11-26 was 50.4 mm, and recharge for March 26 through April 1 was 18.7 mm.

INTRODUCTION

The characteristics of seasonally frozen soil that underlies the snowpack must be considered when estimating ground-water recharge or predicting surface-water runoff. Progress was made during the 1960's and 1970's in understanding the processes of heat and water movement through seasonally frozen soils (Haupt, 1967; Harlan, 1973; Guymon and Luthin, 1974; Morel-Seytoux, 1978). Much of the knowledge of these processes was derived from laboratory experiments. More field-based knowledge, however, still is needed. One difficulty in applying the theory of simultaneous heat and water flux is in obtaining field measurements of the relevant properties during periods of freezing and thawing of the soil. Field measurements of properties such as liquid soil water content, frozen water content, pore water pressure, and soil temperature are needed to apply the theory to field situations. No reliable hydraulic-conductivity data for frozen soils are available (Guymon, 1979). Many field studies have been restricted to indirect inferences because of the lack of knowledge of the soil-water system, which includes accumulation and ablation of the snowpack, freezing and thawing of the soil, and ground-water recharge (Willis and others, 1964; Peck, 1974). More knowledge is needed on whether soil gains or loses moisture during the winter; on the significance, if any, of freezing-induced redistribution of soil moisture; on the effect of frozen soil on infiltration; and on whether snowmelt infiltration can be quantified. A general analysis of the soil-water system is very difficult to make and, even for site specific cases, many questions are left unanswered.

The U.S. Geological Survey, in cooperation with the North Dakota State Water Commission, conducted a study to evaluate heat and water transfer through seasonally frozen soils. The objectives of the study were to: (1) Collect site-specific hydrologic, meteorologic, and soil data in a study area; (2) evaluate the freezing and thawing processes; (3) develop a physically based model to simulate heat and water transfer in soils during freezing and thawing periods; and (4) couple the model to the U.S. Geological Survey's Precipitation-Runoff Modeling System. Emerson and others (1990) described the instrumentation used during the study and presented the data collected. Emerson (1991) documented the development of the model, the coupling of the model to the U.S. Geological Survey's Precipitation-Runoff Modeling System, and the evaluation of simulations conducted using data collected for this study. The purpose of this report is to present the results of the evaluation of freezing-induced redistribution of soil water, runoff, infiltration, and recharge in seasonally frozen soils in North Dakota in the winters of 1985-86 and 1986-87.

Description of Study Area

The study area is located 11.3 km southeast of Oakes, N. Dak., in the Drift Prairie district of the Central Lowland Province (fig. 1). The study area is in the northeast corner of an irrigated quarter section but is outside of the area covered by the center-pivot irrigation system. Several center-pivot irrigation systems in the vicinity are operated during the growing season. The study area is cropped periodically. During the summer of 1985, rye was planted as a cover crop. By the winter of 1985-86, the rye was 50 to 100 mm tall and provided a uniform soil cover. By the fall of 1986, the rye had fully grown and had reseeded itself. The old rye, which had bent over in clumps that produced an uneven soil cover, was removed from the study area. By the winter of 1986-87, the self-reseeded rye was 50 to 100 mm tall and provided a soil cover similar to that of the previous winter.

The topography of the study area is nearly flat. Relative elevations at pertinent locations in the study area are presented by Emerson and others (1990). No natural surface-drainage systems exist in the vicinity of the study area. The small quantity of runoff in the area occurs as overland flow to local depressions. Most of these depressions provide only temporary storage, however, and later are cultivated.

The Oakes aquifer, which is described by Armstrong (1980, p. 39-43), underlies the study area. The Oakes aquifer was deposited in two stages on an undulating surface. During the first stage, the aquifer material was deposited as valley fill. During the second stage, the valley was blocked and a glacial lake, Lake Dakota, was formed. Aquifer materials deposited during the second stage consist of deltaic and lake deposits, which now form most of the present land surface in the area. The valley-fill deposits consist of fine to coarse sand and gravel interbedded with silt and clay, the deltaic materials generally consist of fine to medium sand and silt, and the lake deposits generally consist of silt and silty clay.

The Oakes aquifer is as much as 13 km wide and 26 km long and underlies an area of about 240 km^2 (Armstrong, 1980, p. 39). Aquifer thickness averages 9 m but varies by as much as 21 m within a distance of 1 km. Aquifer thickness at the study area is about 12 m (Shaver and Schuh, 1990).

Descriptions and physical and chemical properties of the soils within the plots are given by Emerson and others (1990). The soil properties are within the range in characteristics of the Hecla soil series, which is classifed as sandy, mixed Aquic Haploboroll (U.S. Department of Agriculture, Soil Conservation Service, 1975). These soils were formed in sandy sediments in glacial Lake Dakota and have been reworked by wind. Texture throughout the soil profiles is very uniform. The majority of the particles are sand that ranges from 100 to 250 µm in diameter.

The climate of the area is semiarid to subhumid. The mean temperature at Oakes for November through March is -8.3°C (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data and Information Service, 1982). January, the coldest month, has a mean temperature of -14.8°C. The mean number of days at or below freezing is 190 per year (Jensen, no date). The mean total precipitation for November through March is 87 mm. The mean seasonal maximum snow depth is 305 mm, and the mean seasonal number of days with snow depth of 152 mm or more is 40.

Instrumentation and Data Collection

Three 7x7-m runoff plots were established in the study area. Each plot had three sites at which measurements were made (fig. 1). Each site consisted of: (1) A soil temperature profile probe composed of thermocouple wires, (2) a pair of thin-walled aluminum access tubes for measuring soil water

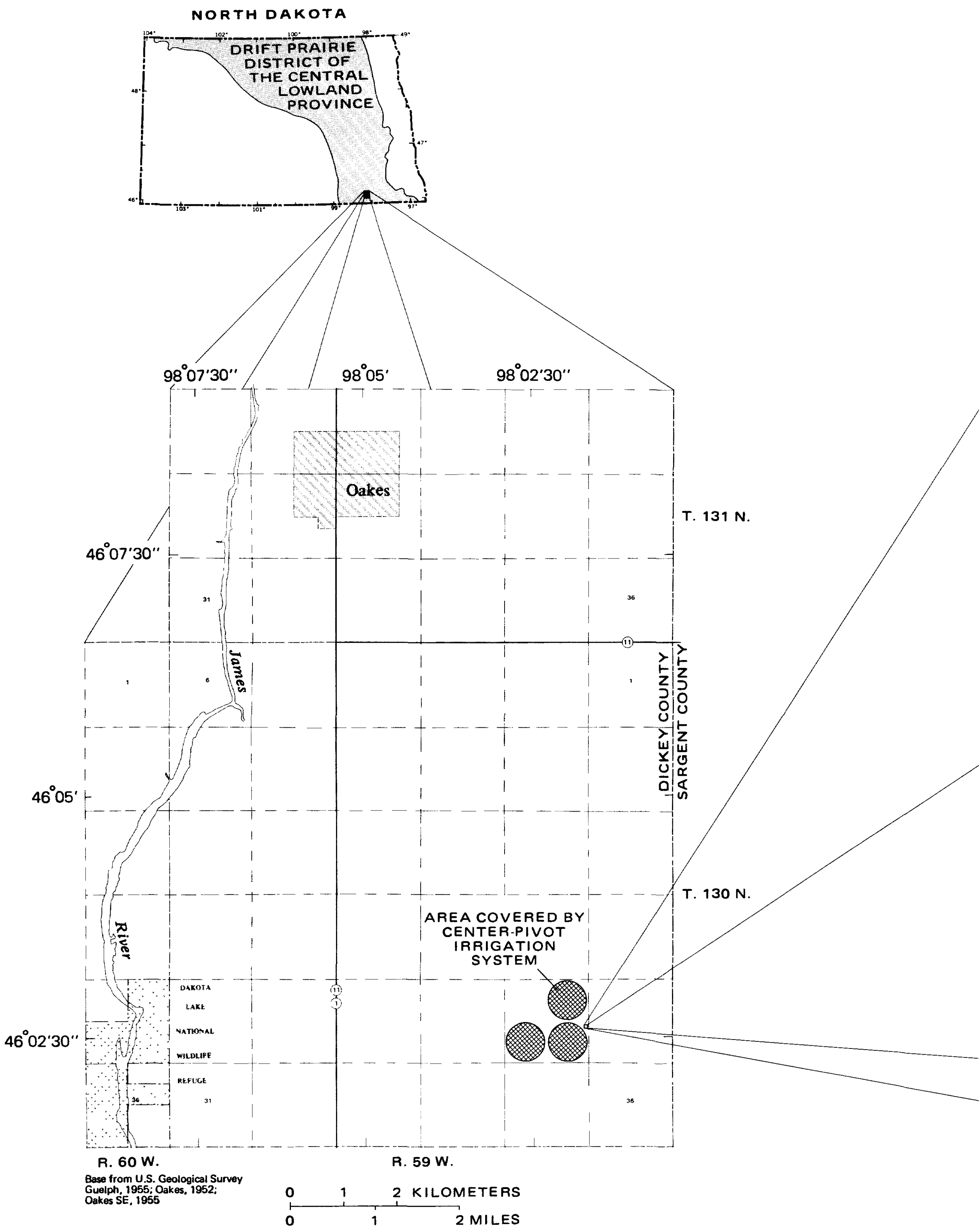
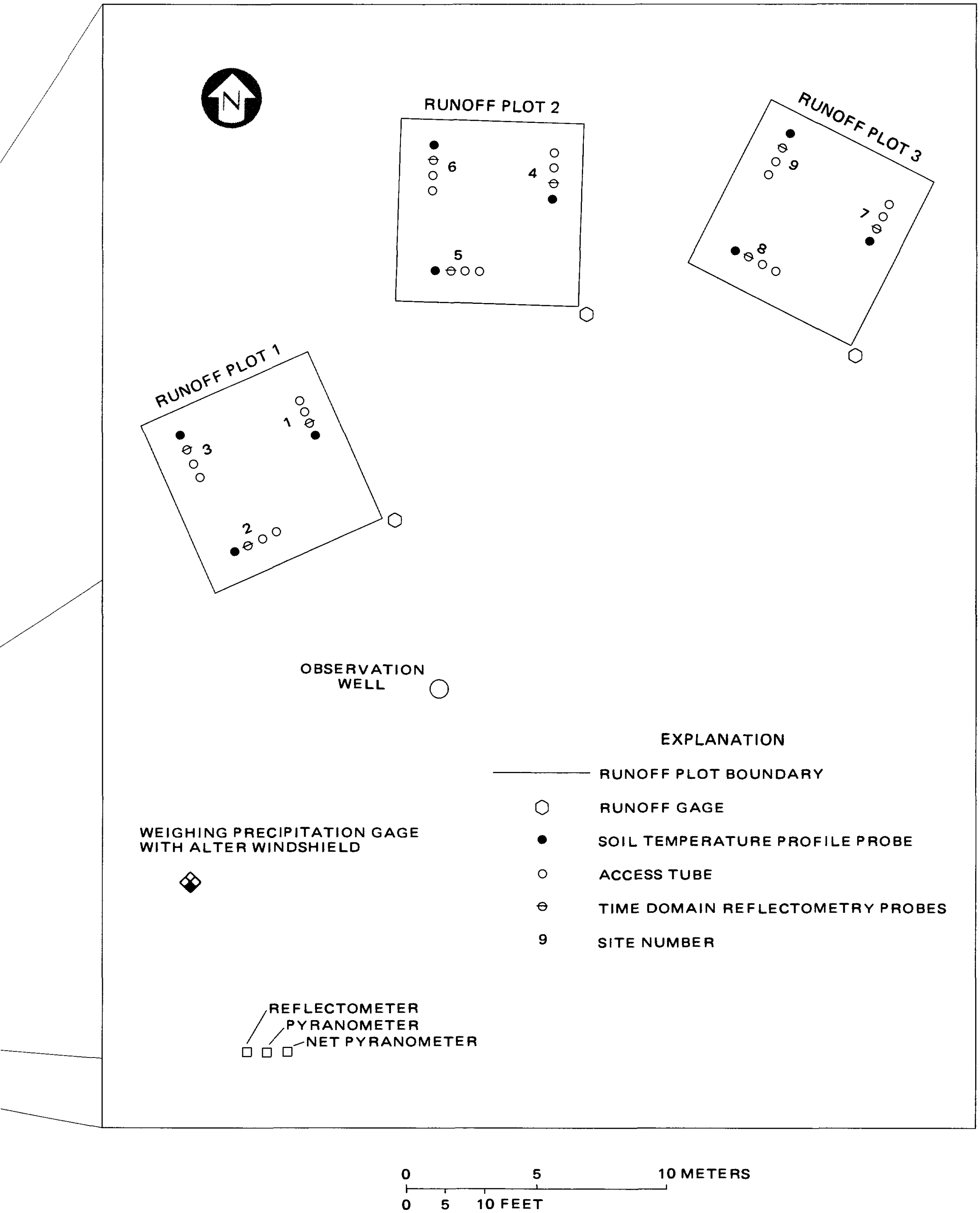


Figure 1.--Location of study area,



runoff plots, and instrumentation.

content (liquid and frozen) and soil density, and (3) a stack of time-domain reflectometry (TDR) probes for measuring liquid soil water content. Ground-water level, air temperature, global solar radiation, reflected solar radiation, net radiation, and precipitation also were measured at the study area. A detailed description of instruments used is given by Emerson and others (1990). Data collected from October 1985 through April 1986 and from October 1986 through April 1987 were used to evaluate seasonally frozen soils for freezing-induced redistribution of soil water, runoff, infiltration, and recharge.

MOVEMENT OF WATER IN SEASONALY FROZEN SOILS

Evaluation of 1985-86 Data

Data collected from October 1985 through April 1986 were used to evaluate seasonally frozen soil for freezing-induced redistribution of soil water, runoff, infiltration, and recharge. Water was applied to two of the three plots in order to measure the effects that different antecedent soil water contents had on freezing and thawing of soils. On October 30, 86 mm of water was applied to plot 1, and 43 mm was applied to plot 3. No water was applied to plot 2. The mean air temperature dropped below freezing on November 7. Because temperatures were cool, very little of the applied water was lost to evaporation, and the desired increase in soil water content was attained. The winter of 1985-86 had colder-than-normal air temperatures and greater-than-normal precipitation. A major snowmelt runoff occurred on March 21 and 22, 1986.

Freezing-Induced Redistribution

The freezing of moist soil induces movement of water from below the zone of freezing into the zone of freezing. As soil water freezes, the capability of the soil to transfer water declines. The process of water movement to the freezing front is called freezing-induced redistribution. A detailed description of this freezing phenomena in soil is given by Miller (1980).

Freezeup for the winter of 1985-86 began about November 7 (fig. 2). The assumption that no water entered or left the soil profile prior to spring breakup probably is valid because the plots had a continuous snow cover throughout the winter and air temperatures seldom were above 0°C (fig. 2). Soil water content data for November 18 through December 17 indicate that some freezing-induced redistribution occurred within the 0.10- to 0.50-m depth interval for sites 1, 2, 3, 8, and 9 (fig. 3). By December 17, the average frost depth was 0.75 m. The total change in soil water content for the 0.10- to 0.50-m depth interval ranged from -0.4 mm for site 7 to 9.8 mm for site 8 (table 1). Although small, these changes in soil water content imply that some freezing-induced redistribution of soil water occurred.

The mean change in soil water content for each plot for the 0.10- to 1.60-m depth interval is very small or negligible (table 1). The changes in soil water content are near or below the measurement accuracy of the neutron moisture meter. A measurement error in soil water content of 1 percent for a 0.20-m soil section would result in a change of 2.0 mm of soil water. If the

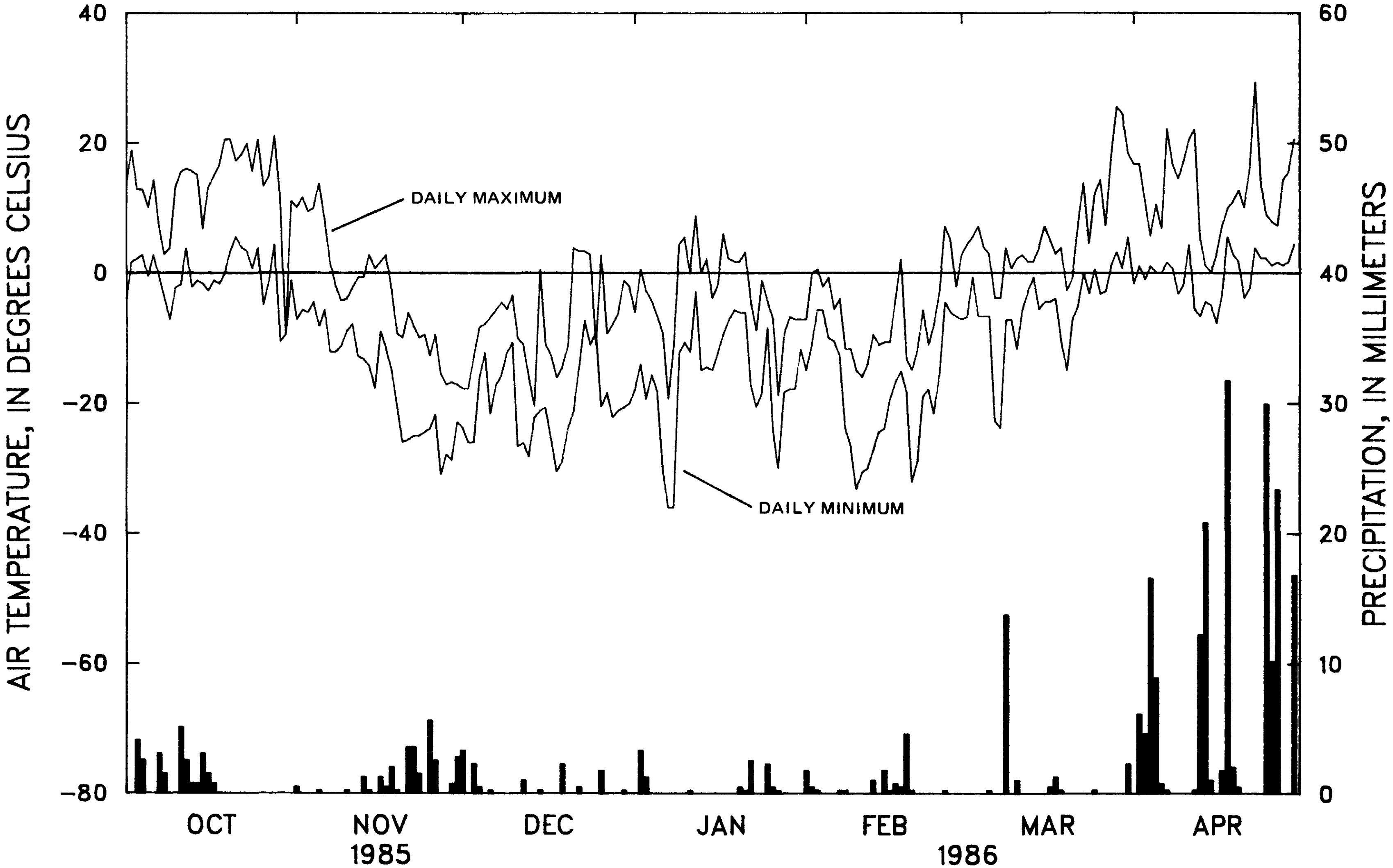


Figure 2.--Daily maximum and minimum air temperatures and daily precipitation for October 1985 through April 1986.

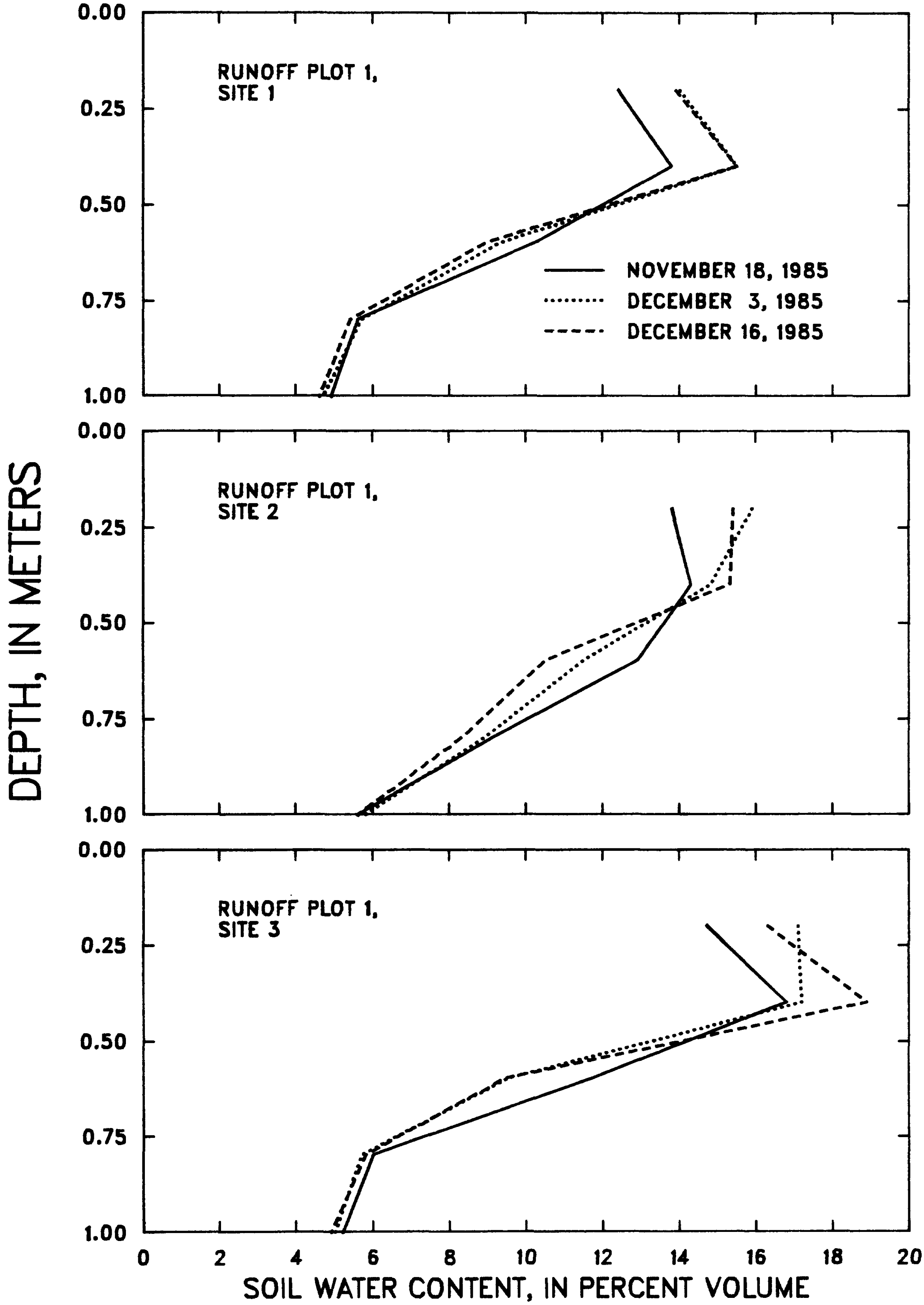


Figure 3.--Soil water profiles for sites in the study area.

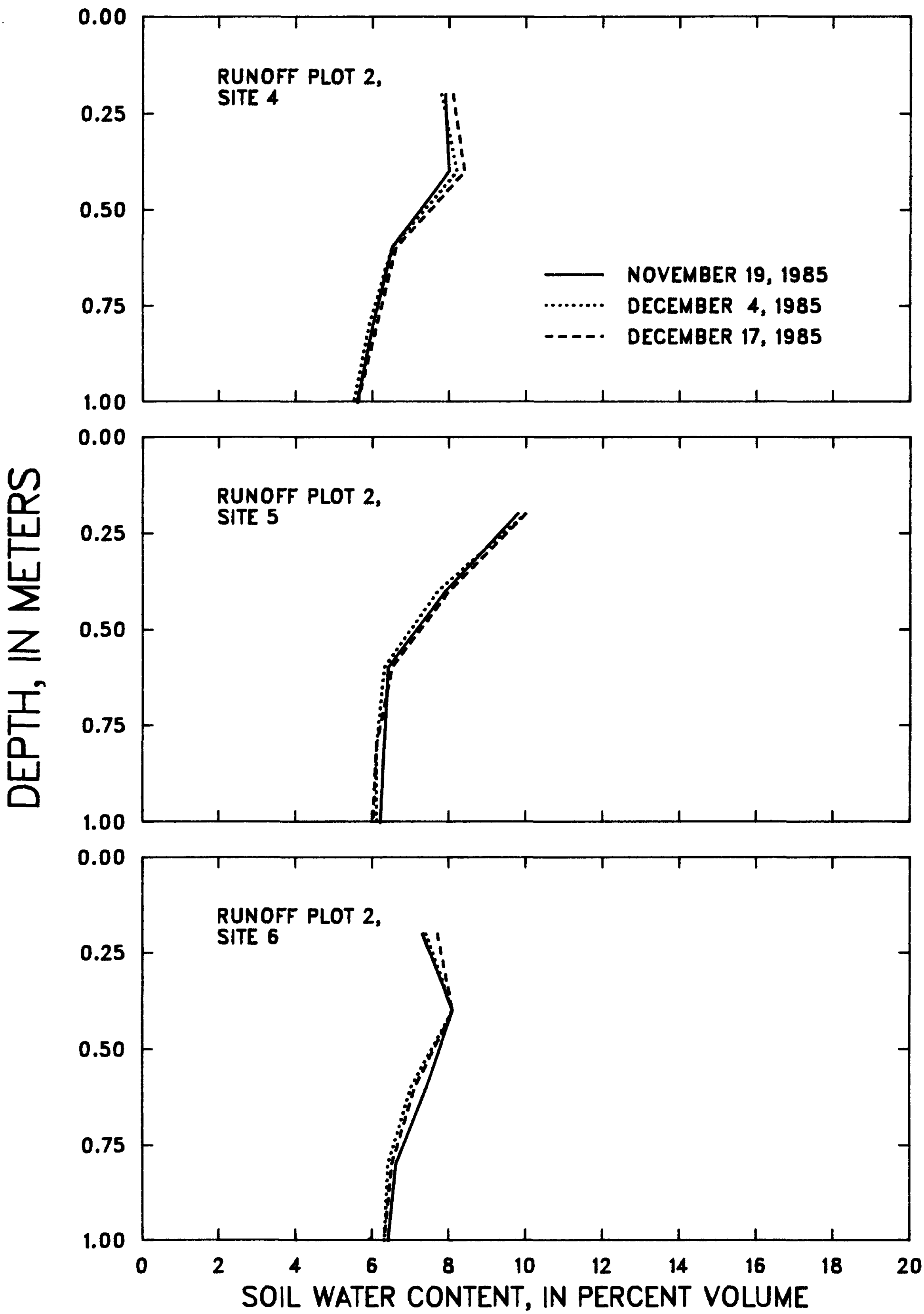


Figure 3.--Soil water profiles for sites in the study area--Continued.

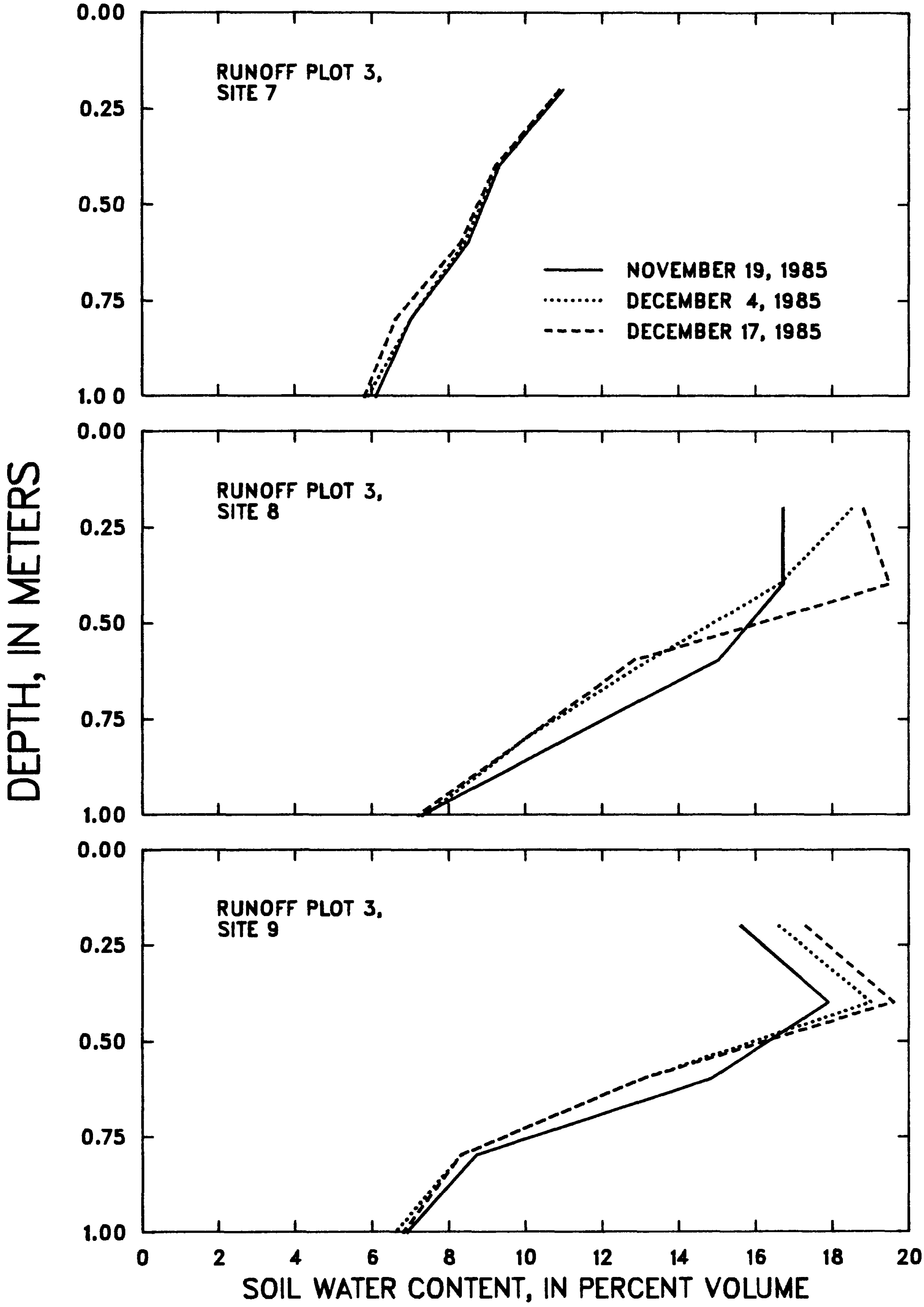


Figure 3.--Soil water profiles for sites in the study area--Continued.

Table 1.--Change in soil water content for November 18 through December 17, 1985

	Runoff plot 1			Runoff plot 2			Runoff plot 3		
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9
Change in soil water content for 0.10- to 0.50-meter depth interval, in millimeters	[1]6.4	[1]5.2	[1]7.4	[2]1.2	[2]0.6	[2]0.8	[2]-0.4	[2]9.8	[2]6.8
Change in soil water content for 0.10- to 1.60-meter depth interval, in millimeters	[1]1.8	[1]-2.4	[1]1.8	[2]1.0	[2]-0.8	[2]-1.4	[2]-3.5	[2]1.8	[2]1.0
Mean change in soil water content by plot for 0.10- to 1.60-meter depth interval, in millimeters		[1]0.4			[2]-0.4			[2]-0.2	

[1]November 18 through December 16, 1985.
[2]November 19 through December 17, 1985.

assumption that no water entered or left the soil profile through the soil surface is valid, then the soil water content, which is represented by the mean soil water content for the 0.10- to 1.60-m depth interval for each plot, indicates no measurable upward movement of water from the water table to the freezing front during freezing of the soil. That being the case, changes in soil water content for the 0.10- to 0.50-m depth interval were the result of freezing-induced redistribution that occurred within the 0.10- to 1.60-m depth interval.

Runoff and Infiltration

From November 10, 1985, through March 19, 1986, about 80 mm of precipitation (fig. 2) fell in the form of snow on the study area. Although the three plots are next to each other, have similar slopes, and have the same vegetation cover, snow surveys indicated the snow cover varied for each plot (Emerson and others, 1990). A snow survey conducted on February 4 indicated near-maximum snow depths for the winter; mean snow depths ranged from 18 to 28 cm for the three plots. By March 4, the snowpack had compacted, a hard crust had formed on the top of the snowpack, and an ice layer had formed on the bottom of the snowpack. Plot 1 still had complete snow cover, but plots 2 and 3 had some small areas of exposed ground. Because of the ice layer, snow density measurements were not obtained for the March 4 snow survey, and snow water equivalents were not computed. The snow water equivalent for each plot (table 2) was computed by adding the snow water equivalent obtained from the February 4 snow survey and the precipitation of 27.3 mm that fell between February 4 and March 21.

The temperature of the upper soil layers increased beginning on February 26 when the maximum air temperature began to rise above freezing (fig. 2). The soil temperatures at the 0.10-m depth (fig. 4) varied from site to site during the major snowmelt on March 21 and 22 but had similar trends. The soil temperature for site 2 at the 0.10-m depth was greater than 0°C for most of the time during March 21-23. However, the soil temperature for site 5 at the 0.10-m depth was greater than 0°C for only a few hours on March 22. Site 2 had the highest soil temperature at the 0.10-m depth and the greatest snow cover just before the major snowmelt. Site 8 had the second highest soil temperature and the second greatest snow cover. Site 5 had the lowest soil temperature and the least snow cover.

Soil water content consists of liquid and frozen water, which coexist in frozen soils. Liquid water has been detected in soil material at temperatures as low as -50°C (Anderson and Tice, 1971). Liquid soil water content during a melt period is influenced by soil temperature. Liquid soil water content increases as soil temperature increases and frozen water content decreases. Liquid soil water content also is affected by snowmelt infiltration and by soil water movement. Therefore, the change in liquid soil water content at the 0.10-m depth during the snowmelt (fig. 4) is only a partial response to the change in soil temperature. The total soil water content at the 0.10-m depth was not determined because of equipment failure (Emerson and others, 1990). Without total soil water content and soil water flux, a thorough analysis of liquid soil water content cannot be made.

During snowmelt periods, air temperature frequently drops below 0°C at night, and some refreezing of the soil water may occur. A manual data-collection procedure was used in this study to collect liquid water content data (Emerson and others, 1990). An automated data-collection procedure was developed after data were collected for this study. The automated procedure (William Herkelrath, U.S. Geological Survey, written commun., 1987) allows data loggers to periodically record liquid soil water content. Hourly measurements can be made during a snowmelt period to show the effects of both snowmelt infiltration and air temperature on liquid soil water content. However, for this study, no liquid soil water content data were collected during the night.

The major snowmelt began during the afternoon of March 21 and stopped by sunset. On March 21, plot 1 had 5.5 mm of runoff, plot 2 had no runoff, and plot 3 had 2.9 mm of runoff. At the end of the day, plot 1 had more than 75 percent snow cover, and plots 2 and 3 had about 25 percent snow cover.

The air temperature only dropped to 1°C during the night, and runoff started again shortly after sunrise on March 22. On March 22, plot 1 had

Table 2.--Snow water equivalent, runoff, infiltration, and evaporation for February 4 through March 24, 1986

	Water (millimeters)		
	Runoff plot 1	Runoff plot 2	Runoff plot 3
Snow water equivalent before major snowmelt on March 21, 1986 (snow water equivalent from February 4, 1986, snow survey plus precipitation to March 21, 1986)	94.5	70.5	80.1
Runoff	14.2	<0.1	9.0
Mean infiltration (difference between soil water content on March 3, 1986, and on March 24, 1986, for 0.10- to 1.60-meter depth interval)	64.8	43.0	34.8
Estimated evaporation	26.3	26.3	26.3
Unaccounted-for water (snow water equivalent minus runoff, infiltration, and estimated evaporation)	-10.8	1.2	10.0

8.7 mm of runoff, plot 2 had less than 0.1 mm of runoff, and plot 3 had 6.1 mm of runoff. At the end of the day, plot 1 had about 25 percent snow cover, and plots 2 and 3 had less than 10 percent snow cover. No runoff occurred after March 22, and all of the snow melted on or before March 24. Total runoff ranged from less than 0.1 mm for plot 2 to 14.2 mm for plot 1 (table 2).

The change in soil water content for the 0.10- to 1.60-m depth interval, obtained by using the neutron moisture meter, can be used as an estimate of snowmelt infiltration. The estimate is based on the assumption that no water left the soil profile and reached the ground water as recharge. The mean infiltration for March 3-24 ranged from 34.8 mm for plot 3 to 64.8 mm for plot 1 (table 2). The soil water content increased with the onset of the major snowmelt. The increase occurred mainly during March 21-23. The soil water content for the 0.10- to 1.60-m depth interval for sites 2, 5, and 8 is shown in figure 5. Measurements made on March 21 illustrate the dynamics of soil water movement during snowmelt infiltration. A measurement made at site 2 at the beginning of runoff on March 21 indicates an increase in soil water content of 7.3 mm between March 15 and 21. A measurement made at site 5

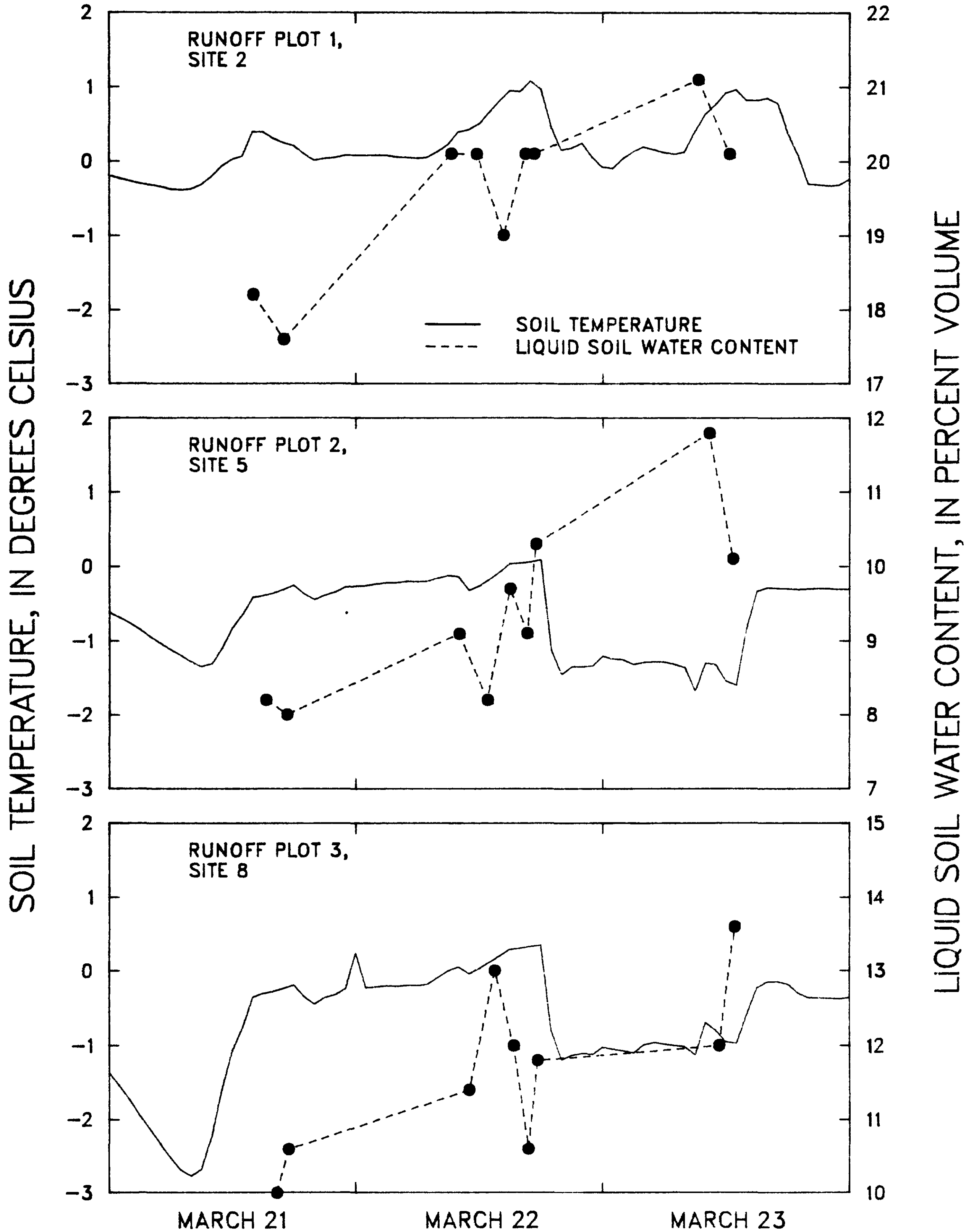


Figure 4.--Soil temperature and liquid soil water content for 0.10-meter depth for sites 2, 5, and 8.

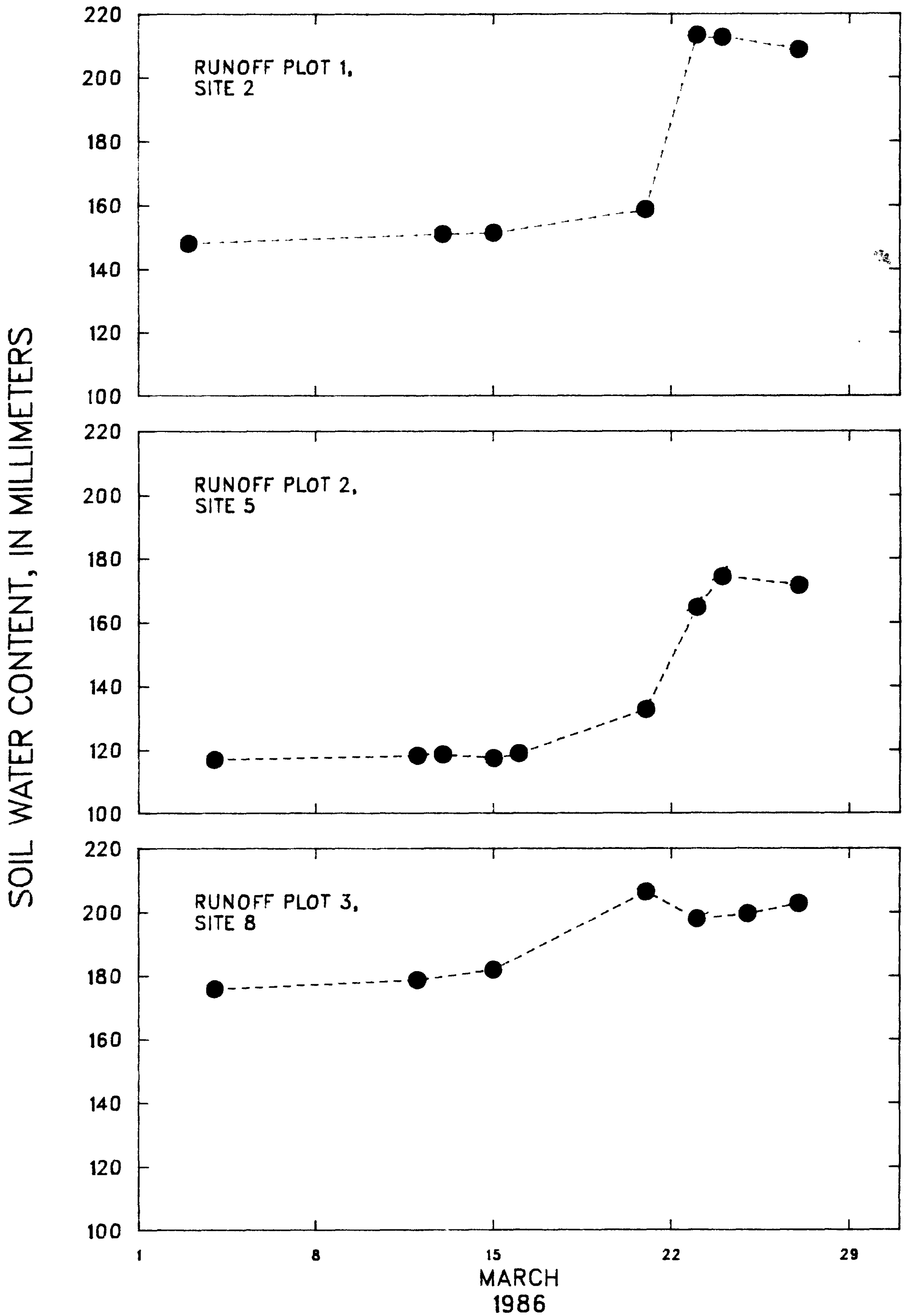


Figure 5.--Soil water content for 0.10- to 1.60-meter depth interval for sites 2, 5, and 8.

during the middle of runoff on March 21 indicates an increase of 15.3 mm. A measurement made at site 8 at the end of runoff on March 21 indicates an increase of 24.5 mm.

Infiltration for sites 2 and 5 was similar (fig. 5). Plot 1 had more snow cover and, therefore, more runoff. The soil water content for site 2 reached a maximum on March 22. Infiltration for site 5 stopped on March 22 when the snow cover was depleted. On the basis of maximum soil water content for sites 2 and 8, infiltration for site 5 could have been about 30 mm greater if more snowmelt water had been available. Site 8 had the least infiltration because the soil was much wetter before the snowmelt period, yet its maximum soil water content was similar to the maximum soil water content for site 2 (fig. 5). The small variation in soil temperature between the sites during snowmelt (fig. 4) seems to have a minor effect on runoff and infiltration, whereas the available snowmelt water and antecedent soil water content seem to have a major effect.

Few data for winter evaporation, which includes sublimation, are available in the northern part of the United States because of the difficulty in collecting the data. Computed annual free water surface evaporation at the study area is 990.6 mm (Farnsworth and others, 1982). The percentage of annual evaporation for February and March (U.S. Department of Agriculture, Soil Conservation Service, no date) was multiplied by the annual free water surface evaporation of 990.6 mm to obtain monthly evaporation estimates. The monthly evaporation estimates were used to calculate the daily evaporation rate for February (0.34 mm/day) and March (0.74 mm/day). The mean daily evaporation rates probably are less than these values. Male and Granger (1979) measured daily evaporation rates that ranged from 0.02 to 0.30 mm/day and had a mean of 0.10 mm/day. Total evaporation for February 4 through March 24 was estimated to be 26.3 mm (table 2). The actual evaporation for each plot would vary because of the varying snow depths and percentage of snow cover for each plot.

Most of the water for each plot is accounted for; however, there are measurement errors in all of the values given in table 2. Errors in snow surveys should be small. A polyvinyl-chloride pipe sampler has a correction factor of 1.00 (Farnes and others, 1983). The February 4 snow survey indicated a 129-percent redistribution of the snow on plot 1, an 84-percent redistribution on plot 2, and a 101-percent redistribution on plot 3. These redistributions include catchment error of the precipitation gage. If the redistributions are appropriate for the 27.3 mm of precipitation that fell from February 4 through March 21, then the snow water equivalent on plot 1 would be 102.4 mm, the snow water equivalent on plot 2 would be 66.1 mm, and the snow water equivalent on plot 3 would be 80.4 mm.

If a 10-percent error is assumed for runoff, then runoff for plot 1 would range from 12.8 to 15.6 mm. There would be no change in runoff for plot 2. Runoff for plot 3 would range from 8.1 to 9.9 mm.

Errors in the values for infiltration on each plot could be significant, whereas errors in measuring soil water content are very small. Instrument errors also are very small, and calibration errors are regarded to be less than those arising from field variability (Gardner, 1965, p. 112-113). Errors in the computed infiltration values also arise from the inability to measure the soil water content for the 0- to 0.10-m depth interval. No change in the soil water content for this depth interval was assumed in computing the infiltration. However, the 0- to 0.10-m depth interval easily could have stored an additional 8 to 16 mm of infiltrating water.

If an annual free water surface evaporation of 812.8 m (Kohler and others, 1959) was used rather than the 990.6 m from Farnsworth and others (1982), then the estimated evaporation for February 4 through March 24 would be 21.4 mm or 19 percent less.

For comparison, if all of the estimated errors associated with the values given in table 2 were such that they would cause the greatest total unaccounted-for water, then the total unaccounted-for water would be -28.2 mm for plot 1, -19.2 mm for plot 2, and 15.2 mm for plot 3. This comparison gives a general idea of what magnitude of error to expect. The magnitude of each component also gives a general idea of the importance of that component. If each component had an error of 10 percent, the snow water equivalent would have the greatest error.

Ground-Water Recharge

The gradual rise of the ground-water level measured at the study site during the winter (fig. 6) probably is the result of recovery from irrigation pumpage. The ground-water level started to rise rapidly on March 23 and continued to rise throughout the remainder of the month (fig. 6). The start

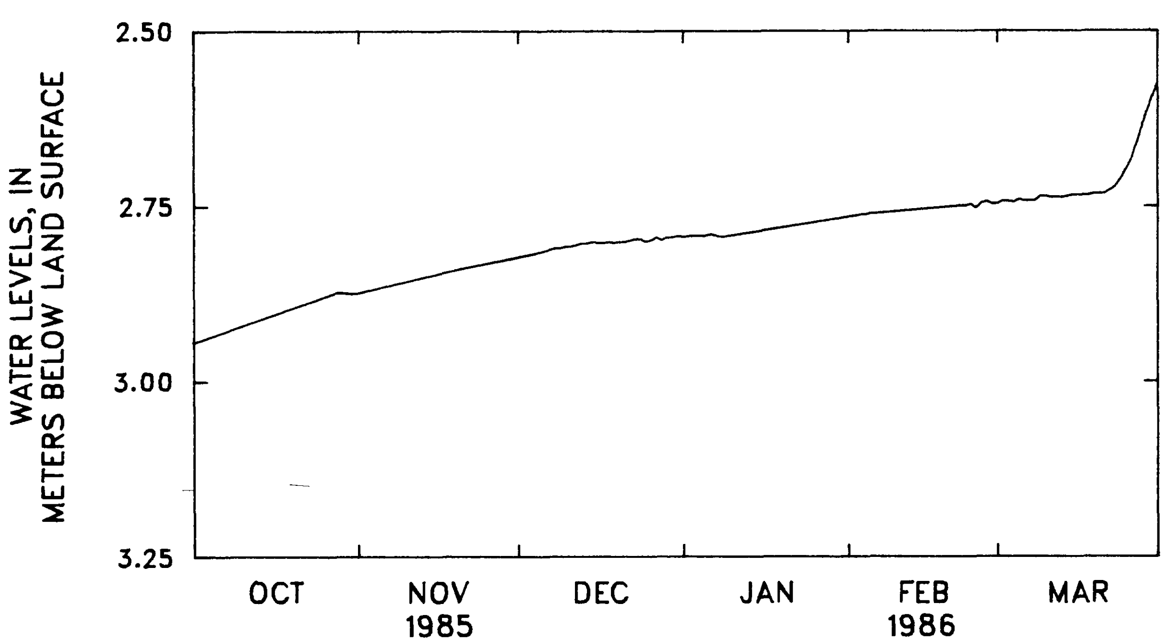


Figure 6.--Water level for study site observation well, October 1985 through March 1986.

of the rapid rise occurred 2 days after the start of the major snowmelt and 1 day after the end of runoff from the plots. During March 24-27, the ground-water level rose 60 mm. The rise continued through the end of the month at a rate of 20 mm per day. A ground-water recharge of 13.2 mm for March 24-27 was computed by multiplying the change in ground-water levels by a specific yield of 22 percent.

The change in soil water content for each site for the 0.10- to 1.60-m depth interval for March 24-27 is given in table 3. The soil water content loss during March 24-27 is assumed to be the source of the ground-water recharge that occurred during the same period. The changes in soil water content ranged from a loss (recharge) of 7.5 mm for site 3 to a gain of 12.8 mm for site 7. The mean change indicates a loss of 5.1 mm for plot 1, a loss of 1.9 mm for plot 2, and a gain of 4.4 mm for plot 3. The losses in plots 1 and 2 and the gain in plot 3 imply that, even on a microscale such as the 7x7-m plots, variation in ground-water recharge occurs and accounting for all of the water in a plot is difficult.

Measurements made at point locations in the plots represent a small sample size when compared to the size of the plots. Three sites were established in each plot with the intent that the mean of the measurements made at the three sites would be representative of the plot. Although the texture throughout the soil profile is uniform (Emerson and others, 1990), large variations in soil water transfer may occur. These variations may be caused by root holes, cracks, and small animal holes.

Ground-water recharge computed from the change in ground-water levels does not compare well with recharge computed from the change in soil water content for any of the plots. The ground-water levels were obtained several meters from the plots and some difference between the measured ground-water levels and the actual ground-water levels below the plot may occur; however, the differences should be small. The recharge computed from the change in ground-water levels was 13.2 mm. Plot 1, which had 86 mm of water applied to it in the fall and had the most snow water equivalent (94.5 mm), had the greatest recharge computed from the change in soil water content (5.1 mm) but still much less than the recharge computed from the change in ground-water levels. Plot 2, which did not have any water applied to it in the fall and had the least snow water equivalent (70.5 mm), had less recharge (1.9 mm) than plot 1. Plot 3, which had 43 mm of water applied to it in the fall and had the second greatest snow water equivalent (80.1 mm), had a gain in soil water content (4.4 mm) rather than a loss (recharge).

If plot 2, which did not have any water applied to it in the fall, represents the general upland area, then only 14 percent of the ground-water recharge from snowmelt, which was computed from the change in ground-water levels, is produced from upland areas. An upland area, unlike a depressional area, is defined as an area that has enough slope that water does not accumulate in puddles or depressions. A possible source for the remaining 11.3 mm of recharge computed from the change in ground-water levels is water from depressions. Water from snowmelt runoff had accumulated in a small depression located downslope of the runoff plots and a few meters from the well. The water in the depression infiltrated after a couple of days. This depressional water could account for some or all of the remaining 11.3 mm of

Table 3.--Change in soil water content for 0.10- to 1.60-meter depth interval for March 24-27, 1986

	Runoff plot 1			Runoff plot 2			Runoff plot 3		
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9
Change in soil water content, in millimeters	-3.8	-4.0	-7.5	-0.5	-2.8	-2.4	12.8	3.2	-2.9
Mean change in soil water content by plot, in millimeters		-5.1			-1.9			4.4	

recharge. Lissey (1971) outlined the concept of depression-focused recharge. He stated that because the major part of all water available for recharge is collected in local depressions of regional topographic uplands prior to infiltration, these depressions must act as focal points for ground-water recharge on the prairies.

Evaluation of 1986-87 Data

Data collected from October 1986 through April 1987 also were used to evaluate seasonally frozen soil. Although no water was applied to the three plots in the fall of 1986, soil water content of the plots was greater than in the fall of 1985 after water was applied. The greater soil water content in the fall of 1986 was caused by greater-than-normal precipitation during September and October. The winter of 1986-87 had warmer-than-normal air temperatures and less-than-normal precipitation. Rainfall runoff occurred on February 26, and a major snowmelt runoff occurred on March 4 and 5. Because ground-water levels were higher during 1986-87 than during 1985-86 and the capillary fringe was above the 1.60-m depth, the soil water content for the 0.10- to 1.12-m depth interval was used in the water-budget analysis rather than the soil water content for the 0.10- to 1.60-m depth interval.

Freezing-Induced Redistribution

Freezeup for the winter of 1986-87 began about November 8 (fig. 7). The assumption that no water entered or left the soil profile prior to spring breakup probably is not valid for this winter. The plots had no snow cover during most of the winter, and daily maximum air temperatures often were above 0°C. The lack of snow cover and the warm temperatures allowed the little precipitation that occurred to either evaporate or infiltrate and allowed the movement of soil water to the atmosphere; therefore, changes in

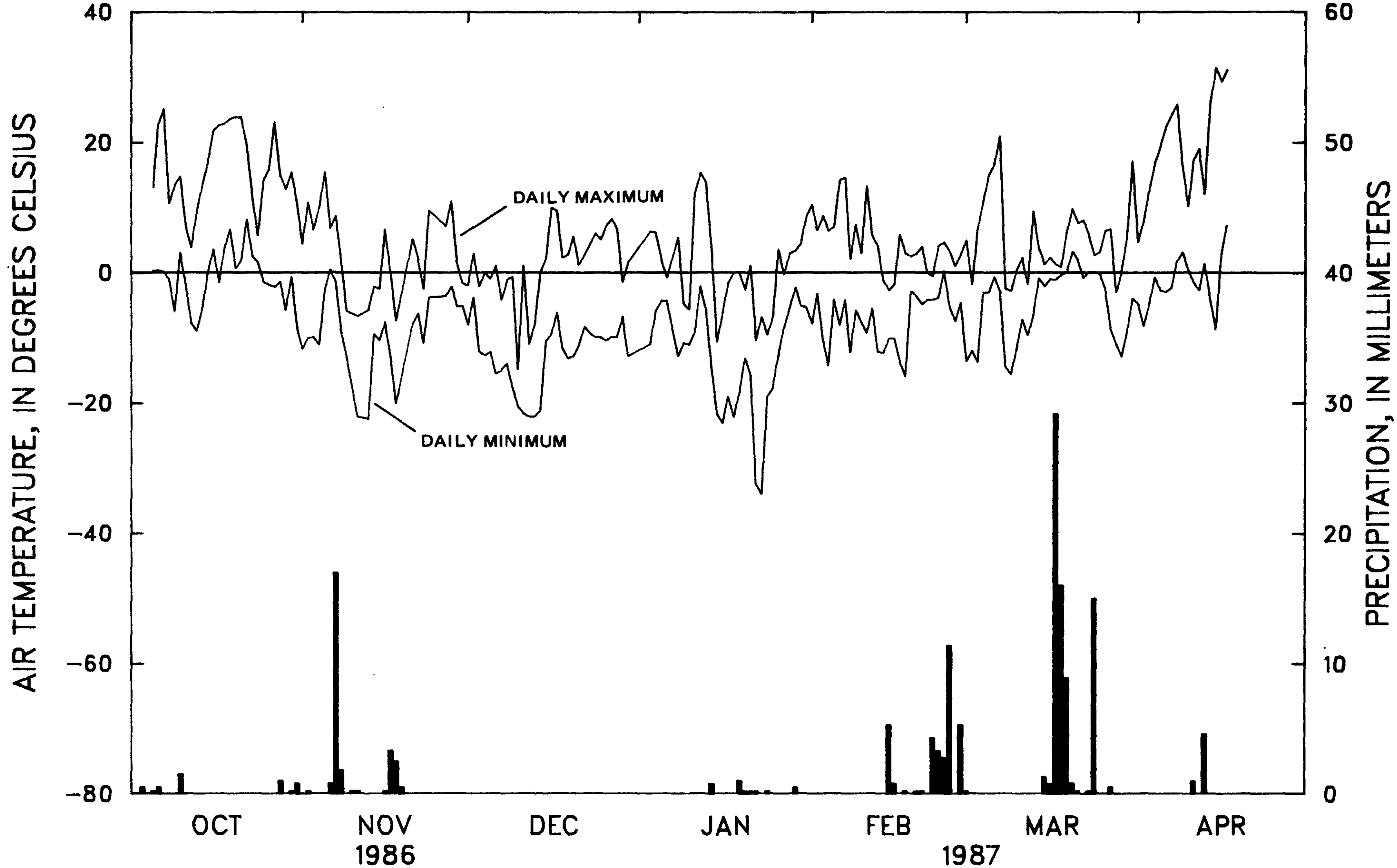


Figure 7.--Daily maximum and minimum air temperatures and daily precipitation for October 1986 through April 1987.

soil water content caused by freezing-induced redistribution, infiltration, or evaporation cannot be quantified. Changes in soil water content for the 0.10- to 0.50-m depth interval and for the 0.10- to 1.12-m depth interval for November 17, 1986, through January 6, 1987, are given in table 4.

The soil water content for the 0.10- to 0.50-m depth interval increased for all of the sites except site 8 (table 4). However, the soil water content for the 0.10- to 1.12-m depth interval decreased for six of the nine sites (table 4).

Runoff and Infiltration

From November 1, 1986, through February 9, 1987, only 29.8 mm of precipitation fell on the study area (fig. 7). The plots were free of snow except for a few days during this period. Precipitation occurred on 11 of the 15 days between February 11 and 26, but there was no appreciable snow accumulation. Precipitation on February 26 started as rain and then changed to snow. By March 4, some snow had accumulated on the plots. Precipitation on the plots for February 9 through March 5 was 34.0 mm (table 5).

On February 15, the soil was frozen from the surface to a depth ranging from 0.671 to 0.770 m. On February 26, the soil was frozen from the surface to a depth ranging from 0.602 to 0.692 m. On March 5, the soil was frozen from the surface to a depth ranging from 0.497 to 0.685 m.

Rainfall runoff from snow-free frozen soil is a rare event in North Dakota. For February 9-26, 20.3 mm of precipitation was recorded. The precipitation was infiltrating into frozen soil until rainfall runoff occurred on February 26. Plot 1 had no runoff, plot 2 had 1.2 mm of runoff, and plot 3 had 0.7 mm of runoff. Later in the day when the air temperature dropped below 0°C and rain turned to snow, runoff stopped and snow started to accumulate on the plots. On March 4, snowmelt runoff occurred on all three plots. On March 5, snowmelt runoff occurred only on plot 3, and all of the snow had disappeared before the end of the day. Total runoff ranged from 3.0 mm for plot 2 to 6.5 mm for plot 3 (table 5).

The change in soil water content for the 0.10- to 1.12-m depth interval can be used as an estimate of infiltration. The estimate is based on the assumption that no water left the soil profile and reached the ground water as recharge. A site visit after the February 26 runoff was delayed because poor weather prevented travel. The next visit was made on March 4. The mean infiltration for February 9 through March 5 ranged from 25.4 mm for plot 2 to 50.1 mm for plot 1 (table 5). Total evaporation for February 9 through March 5 was estimated to be 10.6 mm (table 5). The same procedure used to calculate evaporation for 1985-86 was used to calculate evaporation for 1986-87.

No precipitation fell during March 6-14. For March 15-26, 72.4 mm of precipitation occurred as a mixture of rain and snow; however, very little snow had accumulated on the plots by March 26. On March 26, the soil was frozen to an average depth of 0.395 m, and plots 1 and 2 had some thawing at the surface. No runoff occurred during this period. The change in soil water content for the 0.10- to 1.12-m depth interval was calculated for March 11-26

Table 4.--Change in soil water content for November 17, 1986, through January 6, 1987

	Runoff plot 1			Runoff plot 2			Runoff plot 3		
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9
Change in soil water content for 0.10- to 0.50-meter depth interval, in millimeters	5.1	3.6	3.4	1.6	0.2	2.8	2.4	-0.2	4.0
Change in soil water content for 0.10- to 1.12-meter depth interval, in millimeters	2.7	1.9	-1.0	-2.5	-3.8	-2.3	-1.5	-5.0	2.0
Mean change in soil water content by plot for 0.10- to 1.12-meter depth interval, in millimeters		1.2			-2.9			-1.5	

and was used to estimate infiltration. Again, the estimate is based on the assumption that no water left the soil profile and reached the ground water as recharge. The mean infiltration ranged from 8.4 mm for plot 3 to 23.4 mm for plot 2 (table 6). Total evaporation for March 11-26 was 12.2 mm (table 6).

Ground-Water Recharge

The ground-water level gradually rose during October, stabilized during November, slowly declined during December and January, and stabilized again during February (fig. 8). The ground-water level rose very rapidly from March 4-7 and then stabilized until March 18. On March 18, the ground-water level again started to rise very rapidly. The rise continued throughout the month (fig. 8). The March 4-7 rise started during the snowmelt. The rise that started on March 18 began during a period of precipitation that occurred on 9 of the 10 days between March 15 and 24 and during a period of no runoff. For March 17-26, the ground-water level rose 260 mm. From March 27 until the end of the month, the ground-water level rose another 50 mm.

The change in soil water content for each site for the 0.10- to 1.12-m depth interval for March 5-11 is given in table 7. The changes ranged from a

Table 5.--Precipitation, runoff, infiltration, and evaporation for February 9 through March 5, 1987

	Water (millimeters)		
	Runoff plot 1	Runoff plot 2	Runoff plot 3
Precipitation	34.0	34.0	34.0
Runoff	5.8	3.0	6.5
Mean infiltration (difference between soil water content on February 9, 1987, and on March 5, 1987, for 0.10- to 1.12-meter depth interval)	50.1	25.4	49.6
Estimated evaporation	10.6	10.6	10.6
Unaccounted-for water (precipitation minus runoff, infiltration, and estimated evaporation)	-32.5	-5.0	-32.7

loss (recharge) of 0.9 mm for site 2 to a gain of 19.2 mm for site 3. The mean change indicates gains of 8.7 mm for plot 1, 10.7 mm for plot 2, and 4.0 mm for plot 3. These gains probably are caused by the movement of soil water from the 0- to 0.10-m depth interval to lower soil depths. The soil water in the 0- to 0.10-m depth interval was not accounted for, but the soil was at or near saturation on March 5. If the soil water content at site 1 for the 0- to 0.10-m depth interval was 32.3 percent volume, which was the measured soil water content at the 0.20-m depth on March 5, and if the soil water content was 24.5 percent volume on March 11, then the change in soil water content would account for the gain for site 1 (table 7).

Ground-water recharge computed from the change in ground-water levels for March 5-11 was 5.9 mm. Recharge computed from the change in ground-water levels does not compare well with recharge computed from the change in soil water content for each plot. In fact, the plots all had gains in soil water content rather than losses (recharge). The recharge of 5.9 mm is equivalent to a change in soil water content in the 0- to 0.10-m depth interval of 5.9 percent volume for recharge plus an additional 4.0 to 10.7 percent volume to compensate for the gains in the 0.10- to 1.12-m depth interval. These changes in soil water content could have occurred and the water could have moved to the water table, but the 0- to 0.10-m depth interval would have had to be supersaturated.

Table 6.--Precipitation, runoff, infiltration, and evaporation for March 11-26, 1987

	Water (millimeters)		
	Runoff plot 1	Runoff plot 2	Runoff plot 3
Precipitation	72.4	72.4	72.4
Runoff	0	0	0
Mean infiltration (difference between soil water content on March 11, 1987, and on March 26, 1987, for 0.10- to 1.12-meter depth interval)	10.9	23.4	8.4
Estimated evaporation	12.2	12.2	12.2
Unaccounted-for water (precipitation minus runoff, infiltration, and estimated evaporation)	49.3	36.8	51.8

The unaccounted-for water for March 11-26 (table 6) indicates that recharge from plot 1 was 49.3 mm, recharge from plot 2 was 36.8 mm, and recharge from plot 3 was 51.8 mm. The 50.4 mm of ground-water recharge computed from the change in ground-water levels for this period compares very well with the recharge based on the unaccounted-for water for plots 1 and 3 but poorly with that for plot 2.

The change in soil water content for each site for the 0.10- to 1.12-m depth interval for March 26 through April 1 is given in table 8. The changes ranged from a loss (recharge) of 33.6 mm for site 9 to a loss of 20.3 mm for site 7. The mean change indicates a loss of 28.3 mm for plot 1, a loss of 25.7 mm for plot 2, and a loss of 25.0 mm for plot 3. These losses imply that water from all three plots contributed to recharge. The 18.7 mm of ground-water recharge computed from the change in ground-water levels from March 26 through April 1 is much less than the recharge computed from the change in soil water content for each plot.

COMPARISON OF RESULTS WITH OTHER STUDIES

Freezing-induced redistribution of water was so small it was considered negligible during the winter of 1985-86 (table 1) and could not be quantified

Table 7.--Change in soil water content for 0.10- to 1.12-meter depth interval for March 5-11, 1987

	Runoff plot 1			Runoff plot 2			Runoff plot 3		
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9
Change in soil water content, in millimeters	7.8	-0.9	19.2	12.0	5.1	15.0	8.1	2.0	2.0
Mean change in soil water content by plot, in millimeters		8.7			10.7			4.0	

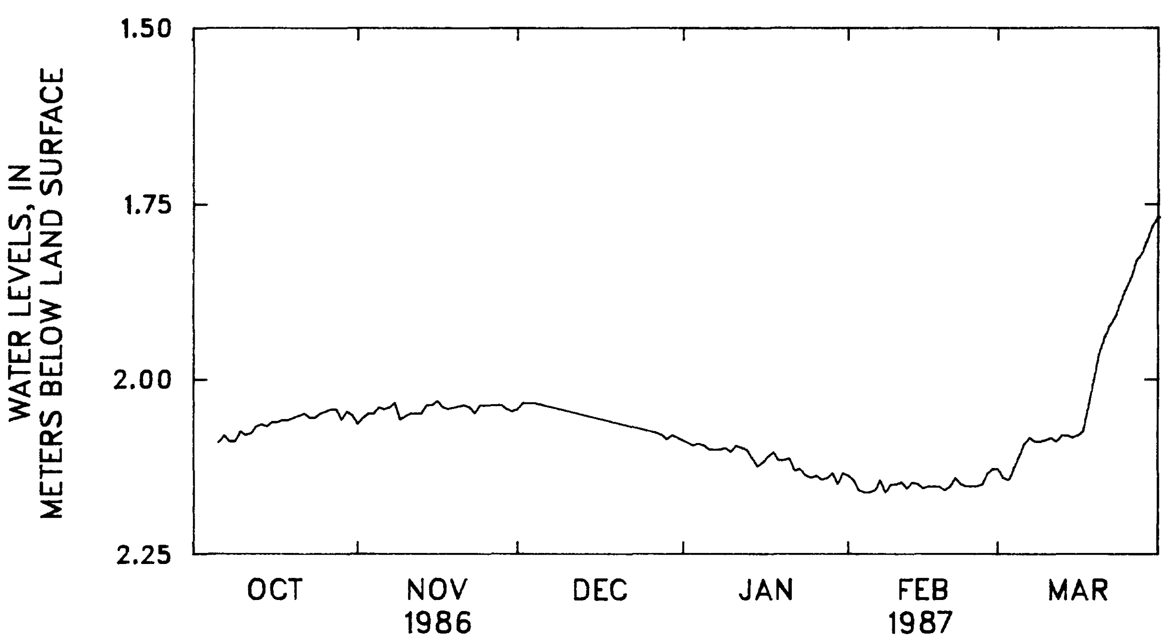


Figure 8.--Water level for study site observation well, October 1986 through March 1987.

Table 8.--Change in soil water content for 0.10- to 1.12-meter depth interval for March 26 through April 1, 1987

	Runoff plot 1			Runoff plot 2			Runoff plot 3		
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9
Change in soil water content, in millimeters	-32.8	-27.2	-24.8	-27.0	-24.1	-26.0	-20.3	-21.2	-33.6
Mean change in soil water content by plot, in millimeters		-28.3			-25.7			-25.0	

for the winter of 1986-87. Results of previous field studies on the effects of freezing-induced redistribution have varied from no change in soil water content to increases to saturation in soil water content at the freezing front (Ferguson and others, 1964; Benz and others, 1968; Sheppard and others, 1981). The most important factors affecting freezing-induced redistribution of water are soil type, freezing rate, and water supply. These factors have not been quantified in any studies nor have their interactions been determined.

Laboratory studies (Dirksen and Miller, 1966) and field studies (Benz and others, 1968) that showed significant freezing-induced redistribution commonly were conducted on frost-susceptible soils that had a fairly high freezing rate and a readily available water supply. Benz and others (1968) described increases in soil water content that ranged from 49 to 73 mm for a 0- to 2.7-m depth interval. The water-table depth at the beginning of freezeup was about 1.8 m below land surface. Their experiments were conducted on silt to silty clay loam soils. Frozen silt and clay soils have greater hydraulic conductivities than frozen sandy soils (Burt and Williams, 1976).

Chamberlain (1981) reviewed more than 100 methods for determining the frost susceptibility of soils. The numerous methods for determining the frost susceptibility of soils indicate the lack of success in developing a comprehensive method. Highly frost-susceptible soils are comprised of particles in the size range of silts and coarse (noncolloidal) clays (Miller, 1980, p. 288). The sandy soils in the study area near Oakes, N. Dak., would be classified as slightly frost susceptible, whereas the soils studied by Benz and others (1968) would be classified as highly frost susceptible. Hydraulic conductivities for frozen sands are small when compared to hydraulic conductivities for unfrozen sands or for frozen silts and clays (Burt and Williams, 1976). Burt and Williams (1976) concluded that frost-susceptible soils have significant hydraulic conductivities when soil temperatures are well below freezing. Very little freezing-induced redistribution is likely to occur for the sandy soils in the study area near Oakes, N. Dak., because they are slightly frost susceptible and have very small hydraulic conductivities when frozen.

The freezing rate of the soil was not given for laboratory studies conducted by Dirksen and Miller (1966) nor for a field study conducted by Benz and others (1968). During this study, the average freezing rates for November 18 through December 17, 1985, were 6 mm per day for site 2 in plot 1, 18 mm per day for site 5 in plot 2, and 15 mm per day for site 8 in plot 3. Plot 1 had the greatest snow cover and plot 2 had the least snow cover. Snow acts as an insulator and, as expected, the snow cover is inversely proportional to the freezing rate. Soil water content also affects the freezing rates and is inversely proportional to the freezing rates. On December 17, 1985, site 8 in plot 3 had the greatest soil water content, site 2 in plot 1 had the next greatest, and site 5 in plot 2 had the least (Emerson and others, 1990).

On November 18, 1985, the water table in the study area was 2.8 m below land surface and the depth of the freezing front averaged 0.3 m below land surface. The relation between the depth to the water table and the volume of water moving towards the freezing front is not known. The maximum distance between the freezing front and the water table at which water stops moving towards the freezing front also is not known. However, given the conditions that existed during this study, a depth to the water table of 2.8 m apparently is too great to have a significant volume of water move from the water table to the freezing front.

Infiltration into frozen soils was measured for the 1986-87 period. Under certain conditions, such as those for February 15 through March 5, 1987, soil can become saturated or supersaturated. A thorough review of the literature on infiltration into frozen soils has not been done, but Dingman (1975) presented a brief chronological review. "Until the 1940's, it was apparently generally held by American hydrologists that frozen ground is completely impermeable" (Dingman, 1975, p. 28). More recently, researchers have reported various results depending on the hydrogeologic conditions. Mosienko (1958) concluded that soil without ice-free pores is impermeable and soil with more than 50 percent ice-free pores can have infiltration regardless of soil temperatures. Similar conclusions were reached by Megahan and Satterlund (1962).

Recharge during snowmelt rarely has been measured or analyzed. In many studies, when the ground-water level declined as the frost depth increased, the decline was attributed to the migration of water to the freezing front. When the ground-water level increased as the frost depth decreased, part of the increase was attributed to the release of water melting at the bottom of the frozen soil layer and subsequently returning to the water table. In this study, no significant movement of water from the water table to the freezing front was measured in the plots.

SUMMARY

Seasonally frozen soils were evaluated for freezing-induced redistribution of soil water, runoff, infiltration, and recharge. Three 7x7-meter runoff plots were established in a study area southeast of Oakes, N. Dak. Data were collected from October 1985 through April 1986 and from October 1986 through April 1987. Data that were collected include soil temperature, soil water content, ground-water level, air temperature, global solar radiation, reflected solar radiation, net radiation, and precipitation.

The winter of 1985-86 had colder-than-normal air temperatures and greater-than-normal precipitation. On October 30, 1985, 86 millimeters of water was applied to plot 1, and 43 millimeters of water was applied to plot 3. No water was applied to plot 2. The mean change in soil water content for the 0.10- to 1.60-meter depth interval for November 18 through December 17 was 0.4 millimeter for plot 1, -0.4 millimeter for plot 2, and -0.2 millimeter for plot 3. These small changes indicate negligible freezing-induced redistribution from the water table to the freezing front.

The snow water equivalent for each plot was computed by adding the snow water equivalent obtained from the February 4, 1986, snow survey and the precipitation that fell between February 4 and March 21. Plot 1 had a snow water equivalent of 94.5 millimeters, plot 2 had a snow water equivalent of 70.5 millimeters, and plot 3 had a snow water equivalent of 80.1 millimeters. Snowmelt runoff occurred on March 21 and 22. Plot 1 had 14.2 millimeters of runoff, plot 2 had less than 0.1 millimeter of runoff, and plot 3 had 9.0 millimeters of runoff. Infiltration was determined as the difference between the soil water content on March 3 and on March 24 for the 0.10- to 1.60-meter depth interval. Infiltration for plot 1 was 64.8 millimeters, infiltration for plot 2 was 43.0 millimeters, and infiltration for plot 3 was 34.8 millimeters. The soil temperature for site 2 in plot 1 at the 0.10-meter depth was greater than 0°C for most of the time during March 21-23. However, the soil temperature for site 5 in plot 2 was greater than 0°C for only a few hours on March 22.

The ground-water level gradually rose during the winter of 1985-86. On March 23, the ground-water level started to rise rapidly. By the end of the month, the level had risen 140 millimeters. Ground-water recharge computed from the change in ground-water levels for March 24-27 was 13.2 millimeters. The mean change in soil water content for March 24-27 indicates a loss (recharge) of 5.1 millimeters for plot 1, a loss of 1.9 millimeters for plot 2, and a gain of 4.4 millimeters for plot 3.

The winter of 1986-87 had warmer-than-normal air temperatures and less-than-normal precipitation. Soil water content at the beginning of freezeup in 1986 was greater than soil water content at the beginning of freezeup in 1985 even though water was added to two of the three plots in 1985. The greater soil water content was caused by greater-than-normal precipitation during September and October 1986. Because water was entering and leaving the soil profile during the mild winter, the changes in soil water content caused by freezing-induced redistribution, infiltration, or evaporation could not be quantified. Rainfall runoff from snow-free frozen soil occurred on plots 2 and 3 on February 26. The soil was frozen from the surface to a depth ranging

from 0.602 to 0.692 meter. Snowmelt runoff occurred on March 4 and 5. Plot 1 had 5.8 millimeters of runoff, plot 2 had 3.0 millimeters of runoff, and plot 3 had 6.5 millimeters of runoff. Infiltration was determined as the difference between soil water content on February 9 and on March 5 for the 0.10- to 1.12-meter depth interval. Infiltration for plot 1 was 50.1 millimeters, infiltration for plot 2 was 25.4 millimeters, and infiltration for plot 3 was 49.6 millimeters.

During the winter of 1986-87, the ground-water level gradually rose during October, stabilized during November, slowly declined during December and January, and stabilized again during February. The ground-water level rose very rapidly for a few days at the beginning of March. This rise corresponded to the snowmelt runoff. The ground-water level then stabilized until March 18 when it again started to rise rapidly. This rise continued throughout the month. Ground-water recharge computed from the change in ground-water levels for March 5-11 was 5.9 millimeters, recharge for March 11-26 was 50.4 millimeters, and recharge for March 26 through April 1 was 18.7 millimeters.

Ground-water recharge for each plot also was computed from the change in soil water content or the unaccounted-for water for the 0.10- to 1.12-meter depth interval. For plot 1, a gain of 8.7 millimeters was computed for March 5-11, a loss (recharge) of 49.3 millimeters was computed for March 11-26, and a loss of 28.3 millimeters was computed for March 26 through April 1. For plot 2, a gain of 10.7 millimeters was computed for March 5-11, a loss of 36.8 millimeters was computed for March 11-26, and a loss of 25.7 millimeters was computed for March 26 through April 1. For plot 3, a gain of 4.0 millimeters was computed for March 5-11, a loss of 51.8 millimeters was computed for March 11-26, and a loss of 25.0 millimeters was computed for March 26 through April 1.

Little is known about the effects of freezing-induced redistribution on soil water content. Results of previous field studies varied from no changes in soil water content to increases to saturation due to freezing-induced redistribution. The main factors that affect freezing-induced redistribution of soil water are soil type, freezing rate, and water supply. The negligible freezing-induced redistribution of soil water for the study area near Oakes, N. Dak., during the winter of 1985-86 may be attributed to the fact that the sandy soils in the area are classified as slightly frost susceptible and have small hydraulic conductivities when frozen.

Frozen ground was once believed to be completely impermeable. However, in recent studies various results have been reported depending on the hydrogeologic conditions. Infiltration into frozen soils was measured during the study near Oakes, N. Dak.

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