Correlation of Ground-Water Levels and Air Temperatures in the Winter and Spring in Minnesota

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1539-D

Prepared in cooperation with the Division of Waters, Minnesota Department of Conservation, and the Minnesota Iron Range Resources and Rehabilitation Commission

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By ROBERT SCHNEIDER

CONTRIBUTIONS TO HYDROLOGY

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By Robert Schneider

ABSTRACT

In a study of natural ground-water recharge in Minnesota a close relationship was observed between air temperatures and ground-water levels in the winter and spring. Hydrographs of two wells, one in the south-central part of the State, the other in the northeast, indicate that the water table declines during the winter when the mean daily air temperature remains below 32°F. Within a few days after the air temperature has risen above freezing, ground-water recharge begins. If below-freezing temperatures return for some time, the water table again declines.

It has been shown in the laboratory that capillary water and water vapor move in the direction of the thermal gradient. The winter decline of the water table probably is caused in part by the upward movement of moisture below the frozen soil by capillarity, resulting in accretion to the frost layer from below. When the air temperature rises above freezing, the water table begins to rise as a result of downward percolation of melt water from the bottom of the frost layer.

The largest increment of ground-water recharge in Minnesota occurs in the spring. Because of the comparatively great depth of frost penetration and the relative impermeability of frost, the initial source of spring recharge is largely frostmelt. The frozen soil impedes or prevents the downward movement of snowmelt and rain. Once the frost layer is dissipated, recharge from infiltrating surface water begins. In addition, the reversal of the temperature gradient results in the downward movement of moisture from the warming soil zone to the water table.

INTRODUCTION

The largest increments to ground-water storage in Minnesota commonly occur in the spring. In a study of this recharge phenomenon, a close relationship was noted between air temperatures and water levels in the winter and spring. This paper describes the relationship and discusses its significance in the hydrologic cycle.

The study was made as part of a statewide ground-water investigation by the U.S. Geological Survey in cooperation with the Division of Waters, Minnesota Department of Conservation, and the

Minnesota Iron Range Resources and Rehabilitation Commission. This statewide investigation was supervised by the author, as district geologist for Minnesota.

The water-level data used herein have been published or are in the process of being published as water-supply papers of the Geological Survey. Air temperatures were obtained from records of the U.S. Weather Bureau.

GENERAL PATTERN OF WATER-LEVEL FLUCTUATIONS IN WATER-TABLE WELLS

The water table in Minnesota is usually at a relatively low level during the winter. In the spring it rises abruptly and generally reaches the highest level of the year. The spring peak is followed by a declining trend during the summer, caused by the large evapotranspirative draft of vegetation and the lateral movement of water toward lakes and streams. Summer and fall rains recharge the soil and ground-water reservoirs, occasionally reversing the downward trend of the water table.

The low water levels in winter have been attributed to the fact that the ground remains frozen, and precipitation, which is largely in the form of snow, cannot infiltrate to recharge the ground-water reservoirs. It is inferred that the decline results from continued natural ground-water discharge, which contributes to the base flow of streams. The spring recharge has been ascribed to the downward percolation of snowmelt and rain.

The present study of water levels and air temperatures suggests that the phenomena of spring recharge and declining winter water levels may involve factors other than those mentioned above.

WATER LEVELS AND AIR TEMPERATURES IN THE WINTER AND SPRING

The hydrograph of well 108.30.9add, SE¼SE¼NE¼ sec. 9, T. 108 N., R. 30 W., in south-central Minnesota, was the first used in the study. This water-table well, completed in glacial drift at a depth of 32 feet, has been measured about once a week since 1942, and daily maximum and minimum air temperatures have been recorded at the U.S. Weather Bureau station at New Ulm, Minn., about 10 miles north of the well. Several portions of the hydrograph, which best illustrate the subject of the paper, have been selected for the following discussion.

The water-level record for 1946 (fig. 1) indicates a gradual winter decline interrupted by one reversal early in February. This isolated

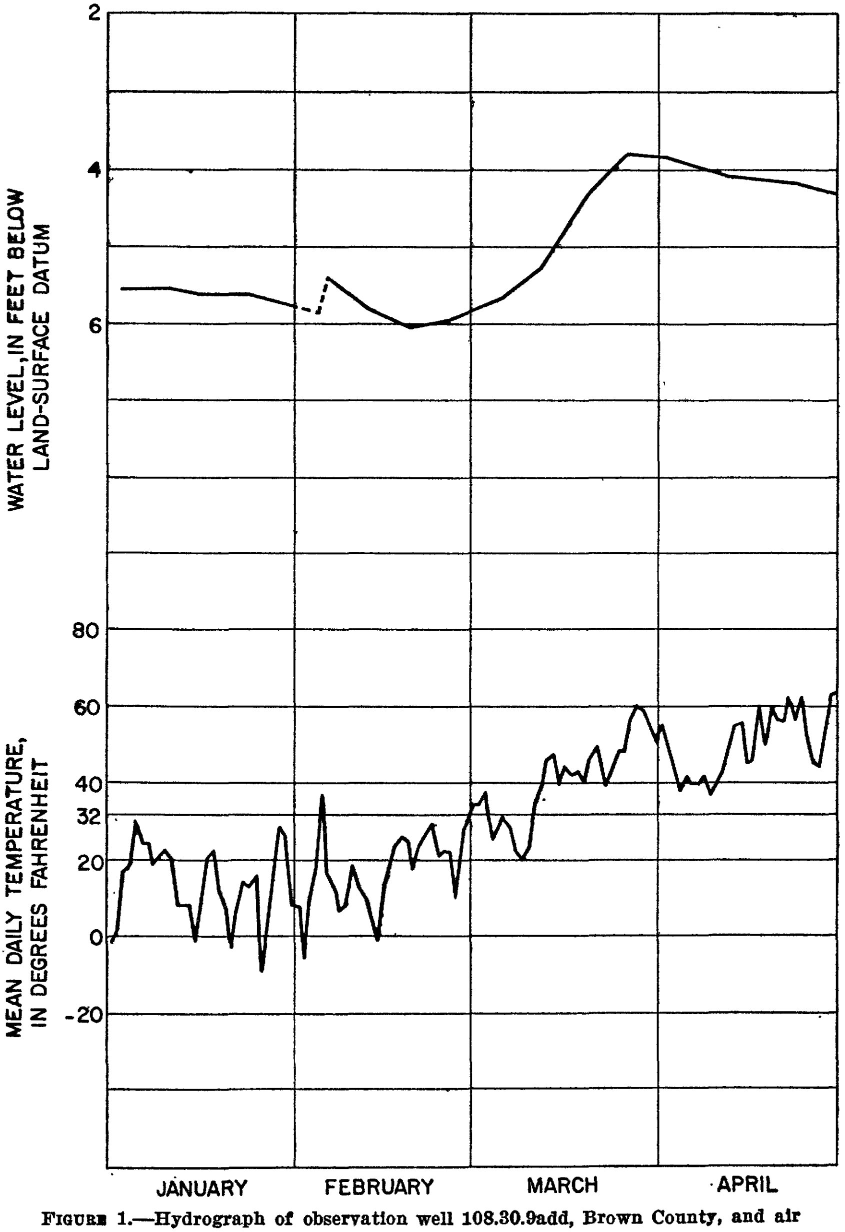

FIGURE 1.—Hydrograph of observation well 108.30.9add, Brown County, and air temperature at New Ulm, Minn., 1946.

winter reversal can be correlated with a rise of the mean daily air temperature at about the same time (February 5). Significantly, the mean daily temperature rose slightly above 32°F. Prior to this date, and for almost 2 weeks afterward, the mean temperatures were generally much lower. The spring rise of the water table began during the last half of February, and, although the mean daily temperature did not rise to 32°F. at New Ulm until the end of the month, it may have exceeded 32°F. at the well about mid-February.

In 1948 the hydrograph (fig. 2) indicates a downward trend of the water table through January and most of February, during which period the mean daily temperature was well below freezing. The first reversal in the trend of the water level in February can be correlated closely with the time when the mean daily temperature first exceeded 32°F. From the end of February until the middle of March, the mean daily temperature again dropped below 32°F, and this is reflected in the "plateau" in the hydrograph for most of the first half of March. During the rest of March and April, the water table and temperature continued to rise.

The slight rise of the water table from the beginning of January to the early part of February 1951 (fig. 3) has no obvious relation to the temperature record. The decline during most of February is typical of the trend of the water table in the winter. A significant feature of the hydrograph is the abrupt rise that started in the latter part of February. A few days earlier the mean daily temperature exceeded 32°F for the first time that year. The pronounced flattening and slight decline of the hydrograph during March can be correlated with the period of mean daily subfreezing temperatures that started at the end of February.

A correlation between the water level in well 108.30.9add and the air temperature at New Ulm is apparent. Minor discrepancies probably can be attributed in part to the long distance between the observation well and the weather station or to the fact that water-level measurements were made at intervals of 1 week or longer.

In an attempt to study this phenomenon in greater detail in another area, a well in northeastern Minnesota was selected for observation. Well B58.20.16dbcl, SW¼NW¼SE¼ sec. 16, T. 58 N., R. 20 W., Chisholm, St. Louis County, is equipped with a recording gage, is 40 feet deep, and taps glacial sand and gravel. The water is under a small artesian pressure but the static water level is slightly lower than the water table. The water level is affected by the pumping of two nearby wells, although the pumping regimen is fairly regular. The nearest weather station is about 5 miles southwest, at the Mahoning Mine in Hibbing.

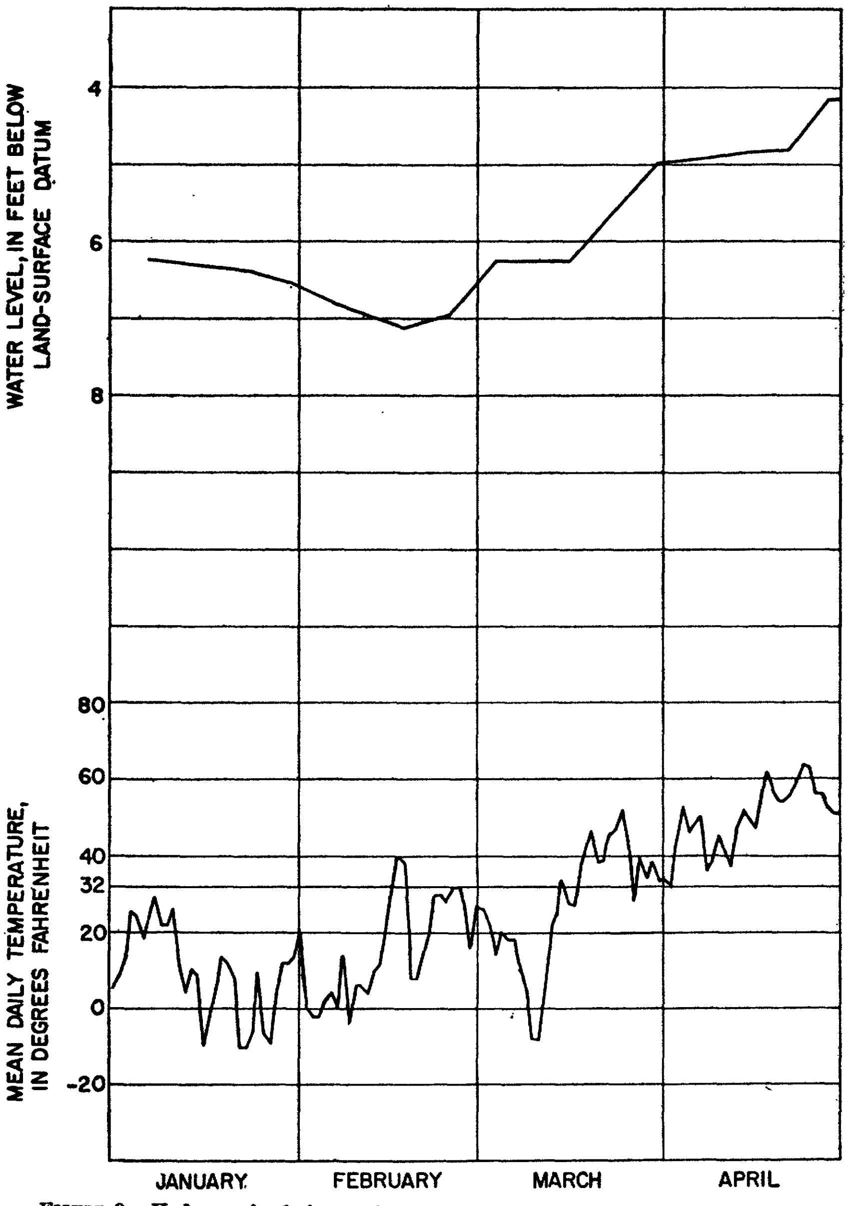

FIGURE 2.—Hydrograph of observation well 108.30.9add, Brown County, and air temperature at New Ulm, Minn., 1948.

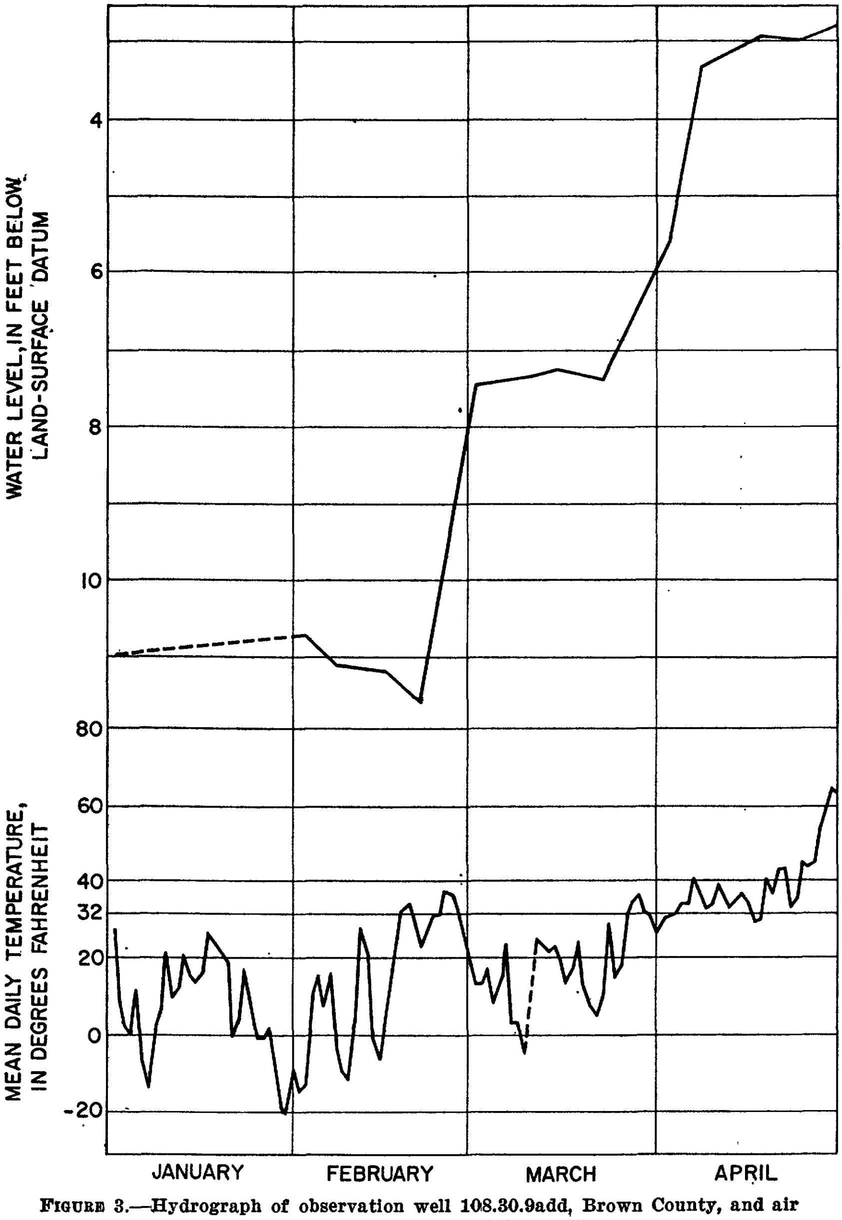

FIGURE 3.—Hydrograph of observation well 108.30.9add, Brown County, and air temperature at New Ulm, Minn., 1951.

Although no record was obtained of the precise date of the initial spring rise of the water table in 1954 (fig. 4), the start of the rising trend appears to correlate with the date when the mean daily temperature rose to 32°F for the first time that year. Part of the water-level rise in March resulted from the gradual reduction in discharge from one of the nearby pumped wells. The drop in temperature to 1°F early in March can be correlated with the relatively flat portion of the hydrograph for about the same period. On April 2 the mean temperature was 6°F, which is the bottom of a "trough" in the thermograph coinciding with a decrease in slope of the rising hydrograph for about the same time interval. The almost vertical portion of the graph, starting early in April, coincides with the time when the mean daily temperature rose well above 32°F and remained above this temperature. During part of February and March, when the water level was rising at a lesser rate, the mean temperature fluctuated considerably but was close to 32°F most of the time.

In 1955 the water level dropped steadily from January through March (fig. 5), while the mean daily temperature remained well below freezing most of the time. The brief above-freezing period, March 9–10, coincides with a flat portion of the hydrograph. At the end of March, the mean daily temperature exceeded and remained above 32°F, and the period of spring recharge started a few days later. The distinct increase in the slope of the rising curve early in the second week of April should be noted. This break in slope is similar to the one that occurred early in April 1954 (fig. 4).

Despite the long distance between the observation well and the weather station, the relationship between water levels and air temperatures appears to be well exhibited by the hydrograph of well B58.20.16dbc1 and the temperature data at the Mahoning Mine at Hibbing.

RELATION BETWEEN GROUND-WATER LEVELS AND AIR TEMPERATURE

As a prelude to an explanation of the relationship discussed above, it is necessary to describe the physical characteristics of frozen soil. The form of the frost layer is influenced by several factors, among which are the type of soil or rock and the availability and state of the moisture.

Storey (1955) describes four types of frozen soil: concrete, granular, honeycomb, and stalactite. Concrete frost structure consists of thin ice lenses and crystals; it is dense and usually associated with freezing to great depths. Granular frost is a loose, porous arrange-

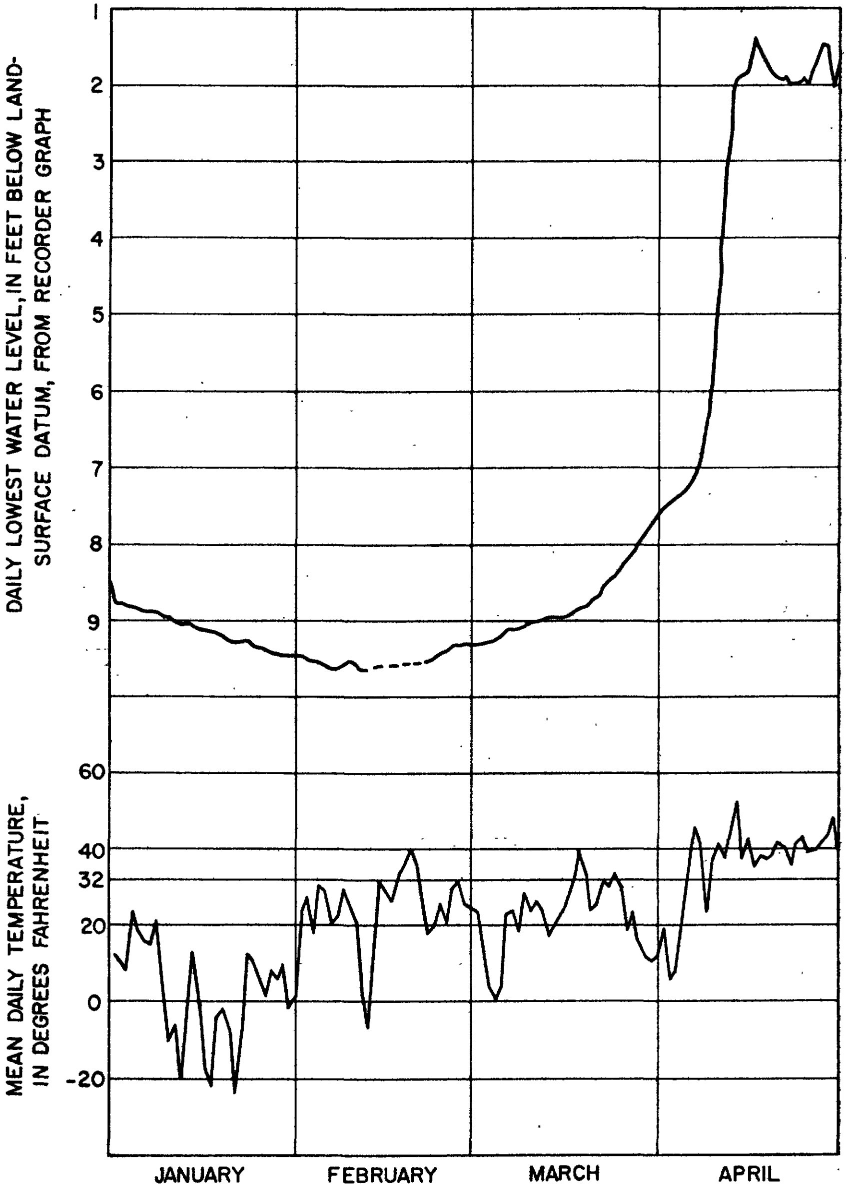

FIGURE 4.—Hydrograph of observation well B58.20.16dbcl, Chisholm, and air temperature at Mahoning Mine, Hibbing, Minn., 1954.

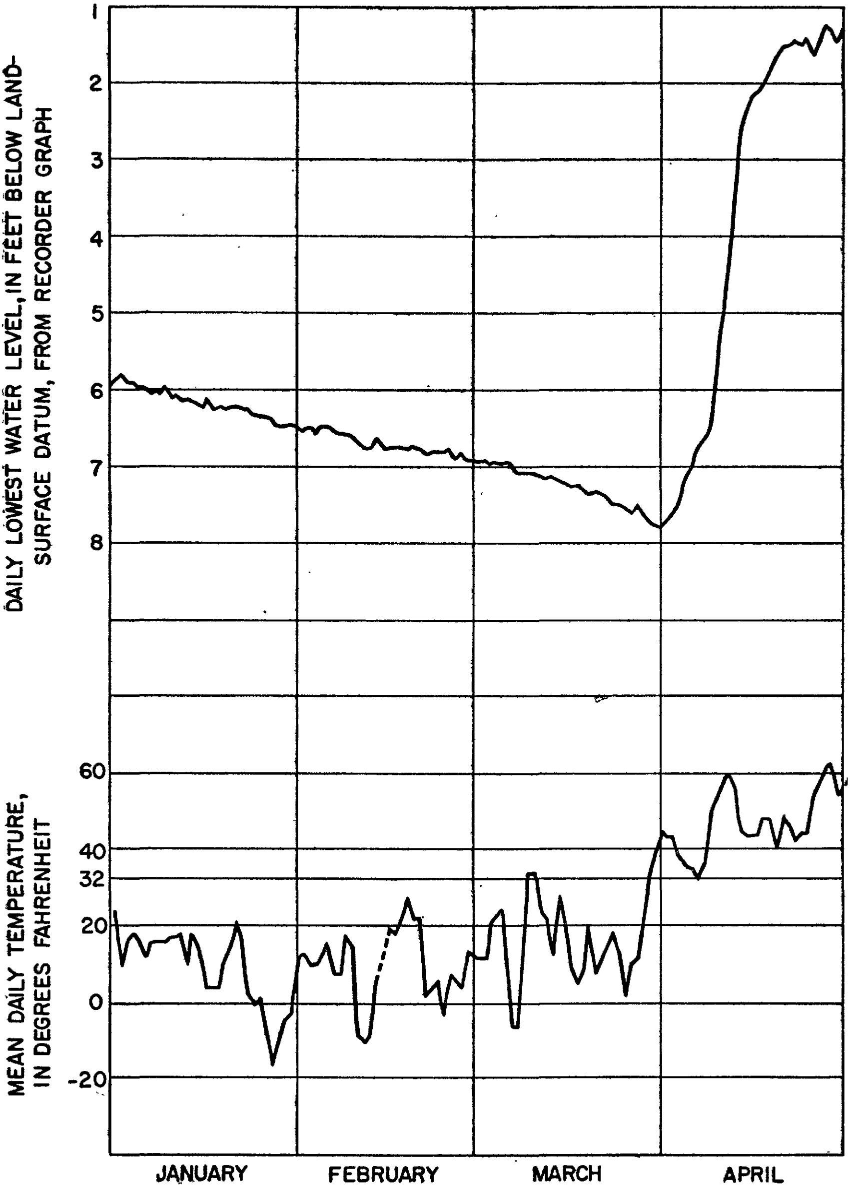

FIGURE 5.—Hydrograph of observation well B58.20.16dbcl, Chisholm, and air temperature at Mahoning Mine, Hibbing, Minn., 1955.

ment of small grains or crystals of ice scattered through the soil; it occurs as a result of shallow freezing. Honeycomb frost is loose and porous; it also is associated with shallow freezing. Stalactite frost consists of many small icicles partly fused into sheets or loosely bound blocks; it is formed during a refreeze of partly thawed honeycomb frost.

Storey states that concrete frost is relatively impermeable. Although the other frost structures described probably have little significance so far as percolation of water is concerned, as little as 1 inch of concrete frost prevents infiltration of rain or melting snow. The freezing of heavy-textured soils prevents percolation of precipitation more effectively than frost in light-textured soils.

MELTING OF THE FROST LAYER FROM THE BOTTOM

The rise of the water table in the spring generally has been attributed to the downward percolation of snowmelt and rain. In Minnesota the available data indicate that spring recharge starts within a few days after the mean daily air temperature rises to 32°F. If downward-percolating snowmelt from the land surface were responsible for the initial rise of the water table in the spring, it would be necessary for the relatively impermeable frozen soil to thaw within a few days after the air temperature rose to 32°F. Unfortunately, no quantitative data are available on the depth of the frozen soil in the areas under consideration. However, according to a study made at Madison, Wis., by Bay, Wunnecke, and Hays (1952), frost penetration reached depths of 30 to 35 inches under various field conditions in the winter of 1949–50. They indicate also that it took at least 2 to 3 weeks from the time thawing started for the frozen layer to dissipate. The climate at Madison is similar to that in the vicinity of well 108.30.9add in south-central Minnesota. Winter temperatures are considerably lower in northeastern Minnesota, where well B58.-20.16dbcl is located, and the general depth of penetration of frost in the soil probably is greater than it is at Madison.

Because of the denseness of the soil at both well sites it is probable that impermeable (concrete) frost is present. Consequently a source other than snowmelt must be responsible for the start of spring recharge within a few days after the air temperature rises above freezing. The author believes that, under these conditions, melt water from the bottom of the layer of frozen soil produces the initial rise of the water table in the spring. Also, when the mean daily air temperature rises above freezing periodically during the winter, when the general water-level trend is downward, some melt water from the bottom of the frozen soil percolates to the water table. In a study by the Portland, Me., Water District (Public Works, 1940), it was observed that thawing of the frozen soil, which was 45 inches thick, began at the bottom; a few days later, thawing started at the top. The frost layer disappeared at a depth of 15 inches below the surface, after having melted both upward and downward to this depth. In the investigation by Bay, Wunnecke, and Hays (1952) of four sites at Madison, Wis., the frozen layer (30 to 35 inches thick) started to thaw from the bottom first. At each site the frozen layer disappeared at a depth equal to about one-half to one-third the original thickness of the layer.

CAPILLARY MOVEMENT OF WATER TO THE FROST ZONE

Bouyoucos (1915) showed by laboratory experiments that soil moisture moves from a warm to a cold column of soil. He attributed the movement to the increase in cohesion between water particles and in adhesion between water and soil particles that occurs with a decrease in temperature.

Smith (1943) stated that capillary water and water vapor move in the direction of the thermal gradient, and that condensation of vapor, by the forming of capillary bodies, triggers the capillary movement.

According to Jumikis (1956), Ruckli derived an equation for the depth of frost penetration and stated as one of his assumptions that, under the proper thermal gradient, there is upward movement of capillary moisture derived from ground water toward the growing and downward-advancing ice lenses or crystals (frozen soil).

The sketch in figure 6 illustrates hypothetical thermal conditions, the trend of the water table, and the occurrence of frost in the winter and spring. In the winter, heat moves upward from the zone of saturation to the atmosphere. The thermal gradient induces the upward movement of moisture, which freezes to form the frost layer as heat is continually removed. When the air temperature rises above 32°F in the spring, heat continues to move upward from the zone of saturation; however, instead of moving through the frozen layer, it starts thawing the bottom of the layer because an opposing thermal gradient now causes heat to move downward from the atmosphere to the frozen soil.

It is concluded, on the basis of the preceding paragraphs, that part of the water-level decline during periods when the air temperatures are below freezing results from upward movement of moisture from the water table with the thermal gradient. In Minnesota,

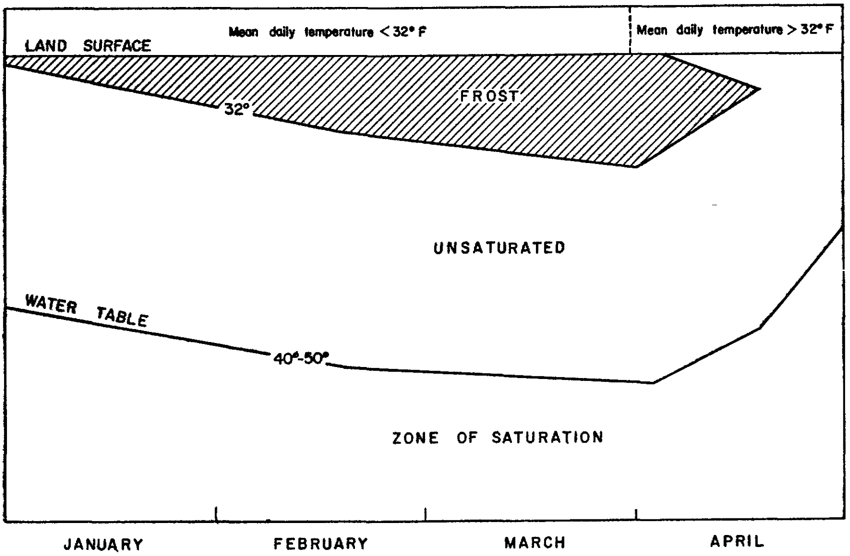

FIGURE 6.—Sketch illustrating thermal conditions, the trend of the water table, and the occurrence of frost in the winter and spring.

where the depth of frost penetration is greater than it is in most of the rest of the United States, such upward movement probably accounts for a significant part of the winter decline of ground-water levels and accumulation of frost.

EFFECT OF THE FROST LAYER ON RECHARGE AND RUNOFF

Recharge occurs when the mean daily air temperature rises above 32°F for some time and the bottom of the frost layer starts to melt. Where concrete frost is present, the frozen layer is relatively impermeable and impedes or prevents recharge from snowmelt and rain. The steepening of the hydrographs of well B58.20.16dbcl early in April 1954 and April 1955 (figs. 4 and 5) probably represents the final disappearing of the frost layer, when more rapid recharge by snowmelt and rain, as well as by the frostmelt that had been accumulating above the last of the remaining frost, became possible.

Drescher (1955, p. 12) presents the hydrograph of a shallow well near Hancock, Wis., which was completed in sand and gravel of a glacial-outwash plain. The rise of the water level was greatest and most rapid at the end of March and the beginning of April 1952, before all the snow melted. In a written communication (1957), Drescher states that it is doubtful that the frost was completely gone, but much of the melting snow probably percolated to the water table through the frost zone. This interpretation apparently corroborates Storey's statement (1955) that frost in light-textured (sandy) soils is relatively ineffective in preventing percolation of precipitation. The areas under consideration in the present study are underlain largely by dense silty or clayey soils, in which concrete frost is likely to form.

The frost layer affects surface runoff to a considerable degree. In view of the fact that much of the winter streamflow represents discharge from ground-water storage, thickening of the frost layer as described above, as well as a declining water table, is a factor contributing to the progressive diminution of streamflow during the winter. Also, because the frost layer retards or prevents infiltration, it affects surface runoff in another way—it leads to flooding when heavy winter rains are unable to infiltrate the soil.

CONCLUSIONS

A significant part of the winter water-table decline in Minnesota probably results from the upward movement of capillary moisture to the frost layer, which is thickened by accretion from below. The movement is in response to the thermal gradient, and it begins when the mean daily air temperature declines in the late fall or early winter. Within a few days after the air temperature has risen above 32°F, the water table begins to rise as a result of downward percolation of frostmelt from the bottom of the frost layer.

In the spring, the initial source of recharge to aquifers in areas of dense soil and concrete-type frost is frostmelt because the frost impedes or prevents the downward movement of snowmelt and rain. After the frost layer disappears, the main source of recharge is infiltrating surface water. Because of the reversal of the temperature relations, downward movement of moisture will be accelerated by a downward temperature gradient.

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