An Application of Thermometry to the Study of Ground Water

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1544-B

Prepared in cooperation with the Division of Waters, Minnesota Department of Conservation

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By ROBERT SCHNEIDER

GENERAL GROUND-WATER TECHNIQUES

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By Robert Schneider

ABSTRACT

Except for studies of temperature data related to ground-water developments that induce infiltration from streams, little attention has been given to the possibility of using temperature fluctuations as a tool for studying the elements of the hydrologic cycle involving ground water.

The temperature of the water discharged from large installations that induce river infiltration through alluvial deposits depends primarily on the following factors: (a) the porosity of the aquifer, (b) the specific heat of the rocks or mineral grains making it up, (c) the temperature of the ground water in storage, (d) the temperature of the river water, and (e) the amount of mixing that occurs as a result of pumping. In six installations of this type, where the annual river-temperature fluctuations ranged from 44° to 52°F, the average range in ground-water temperature was 22°F. The cycles of ground-water temperature lagged behind the river-temperature cycles by 1 to 5½ months. Under the conditions that existed, the lag of the minima of the cycles was much greater than that of the maxima, largely because of variations in pumpage and of the effect of viscosity differences on the rate of flow.

An experimental study was made at Worthington in southwestern Minnesota to determine whether temperature fluctuations could be used to study rates and directions of ground-water movement or to evaluate recharge conditions. Three shallow glacial-outwash aquifers were studied by measuring temperatures at approximately monthly intervals in three municipal-supply wells whose average yields were about 60 to 150 gpm (gallons per minute). Temperatures were read with an accuracy of 0.01° to 0.02°C, and the data were analyzed graphically and correlated in detail with lake levels, lake temperatures, precipitation, and ground-water levels.

Thermographs for 2 wells, 1 completed in a semiconfined aquifer about 200 feet from Okabena Lake and the other in a water-table aquifer about 850 feet from the lake, indicate that pumping induces water to move from the lake into the aquifers. A larger percentage of cold lake water was mixed with ground water from January to March 1958 than from January to March 1959. On the assumption that the cold or warm lake water was a distinct mass, the average time required for water to move from the lake to the well 200 feet away, under the prevailing hydraulic gradient, was 2 to 4 months; and to the well 850 feet away, 5 to 7 months.

The thermograph for a well 1,800 feet from the lake, completed in an artesian aquifer that is confined by relatively impervious glacial till, indicates that the till acts as an insulating medium. However, despite the apparently low permeability of the till, the thermograph suggests that the lowering of artesian pressure, which results from pumping, induces warmer water to move downward through the till.

The infiltration of relatively warm spring and summer rainfall can be detected on the thermographs of all the wells.

The precise measurement of fluctuations in ground-water temperature, based on monthly readings in shallow glacial-outwash aquifers (up to about 70 feet deep), is useful in the study of ground-water movement and recharge. In addition to the study of natural phenomena in the hydrologic cycle, thermometry may be used as a tool in making detailed studies of (1) the effects of inducing the infiltration of surface water, (2) artificial recharge, (3) the effects of injecting petroleum products or radioactive or other wastes into the ground, and (4) ground-water movement in mines.

INTRODUCTION

Countless measurements of ground-water temperature have been made in the United States; however, most of these measurements were made to define the usability of the water for such purposes as cooling, or to determine vertical earth-temperature gradients. With the possible exception of studies of large ground-water developments that induce river infiltration, relatively little attention has been given to the use of temperature data as a tool for the study and interpretation of the elements of the hydrologic cycle involving ground water.

As part of an investigation of the geology and ground-water resources of Nobles County, in southwestern Minnesota, several apparently anomalous measurements of ground-water temperature were made at the city of Worthington, about 150 miles southwest of Minneapolis and St. Paul. For several reasons this area appeared to be typical of many other areas, particularly in the glaciated parts of the United States. First, only a small amount of information was available on the geologic and hydrologic characteristics of the aquifers in the area. Second, the aquifers were complex bodies of glacial outwash of limited extent; and third, the details of the glacial history were somewhat obscure. It was decided, therefore, to make an experimental study to determine if fluctuations in ground-water temperature could be used to study rates and directions of ground-water movement or to evaluate recharge conditions.

The purpose of this report is twofold: to summarize the significant data on fluctuations in ground-water temperature associated with induced river infiltration, and to describe and present the results of the experimental study at Worthington, Minn.

The overall study in Nobles County is being made in cooperation with the Division of Waters, Minnesota Department of Conservation.

It is part of a statewide investigation which was under the direct supervision of the writer, and the fieldwork in Nobles County was under the direction of R. F. Norvitch.

Thanks are due Mr. G. S. Thompson, Worthington city clerk, for providing data on municipal wells; and to Mr. E. G. Smith, water superintendent, whose generous cooperation facilitated the fieldwork.

FLUCTUATIONS OF GROUND-WATER TEMPERATURE

In a report that summarizes the temperature of water available for industrial use in the United States, Collins (1925, p. 97–98) states that the temperature of ground water at a depth of a few tens of feet at any particular place is about the same as or a little higher than the mean annual air temperature. He cites C. E. Van Orstrand of the U.S. Geological Survey (written communication), who states that the ground-water temperature at a depth of 30 to 60 feet generally exceeds the mean annual air temperature by 2° or 3°F. In exceptional localities the excess may be 5° or 6°F. For practical purposes he observes that a ground-water supply obtained at any depth from 20 to 200 feet will have a temperature ranging from about 3° to 6°F above the mean annual air temperature.

Many ground-water installations along stream courses, by reversing the natural streamward hydraulic gradient, induce river water to infiltrate the ground-water reservoir. In most places where infiltration is either deliberately or unintentionally induced, the aquifers are permeable alluvial deposits that are hydraulically connected with the stream.

The temperature of the water discharged by a well that induces river infiltration is controlled by numerous factors. Of prime importance are the following: (a) the porosity of the aquifer, (b) the specific heat of the rocks or mineral grains that make it up, (c) the temperature of the ground water in storage, (d) the temperature of the river water, and (e) the amount of mixing that occurs as a result of pumping. The amount of mixing of river and ground water is dependent on (1) the distance to the well from the river, (2) the rate of discharge, which, in turn, is governed largely by the coefficient of transmissibility[1] of the subsurface deposits, and (3) the volume of ground water available from storage. Other factors that must be considered are heat exchange with the aquifer materials, upward and lateral flow of heat in the aquifer, and the rate of flow of ground water, which varies inversely with the viscosity (in the

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[1] The number of gallons per day that will flow under a unit hydraulic gradient at the prevailing water temperature through a vertical section of an aquifer, the section being 1 foot wide and equal in height to the saturated thickness of the aquifer.

normal temperature range of ground water in the United States, an increase of 1°F in the ground-water temperature lowers the viscosity sufficiently to increase the rate of flow by about 1½ percent).

Table 1 presents pertinent temperature data on six ground-water installations that induce river infiltration. The annual fluctuation in river temperature ranged from 44° to 52°F and averaged 48°F, whereas the annual fluctuation in ground-water temperature ranged from 14° to 32°F and averaged 22°F. Also, despite the large range in average pumping rate at the 6 installations, 3 to 80 mgd (million gallons per day), the lowest ground-water temperature at 5 of the 6 installations was 46° to 47°F. This very small range results largely from the small range in minimum river temperatures (33°–37°F) at these locations. The lower minimum temperature of the ground water at the sixth installation, at Schenectady, N.Y. (40°F), is due largely to the fact that the average temperature of the ground water in this area is the lowest of the six, and the average winter temperature of the Mohawk River is probably lower than that of the other rivers. It is noteworthy, moreover, that the geologic and hydrologic conditions at this location are very different from those at the other five installations. At Schenectady the source of recharge is a considerable distance from the well field (about 0.5 mile); the aquifer is in a buried channel of the Mohawk River, which is separated from the river by a relatively impermeable deposit; and most of the ground-water flow is along the axis of the channel, which is almost parallel to the Mohawk River (Simpson, 1952, p. 78). The other five installations studied are on the banks of the rivers, and most of the induced recharge moves into the aquifer directly from the bank and bed of the river.

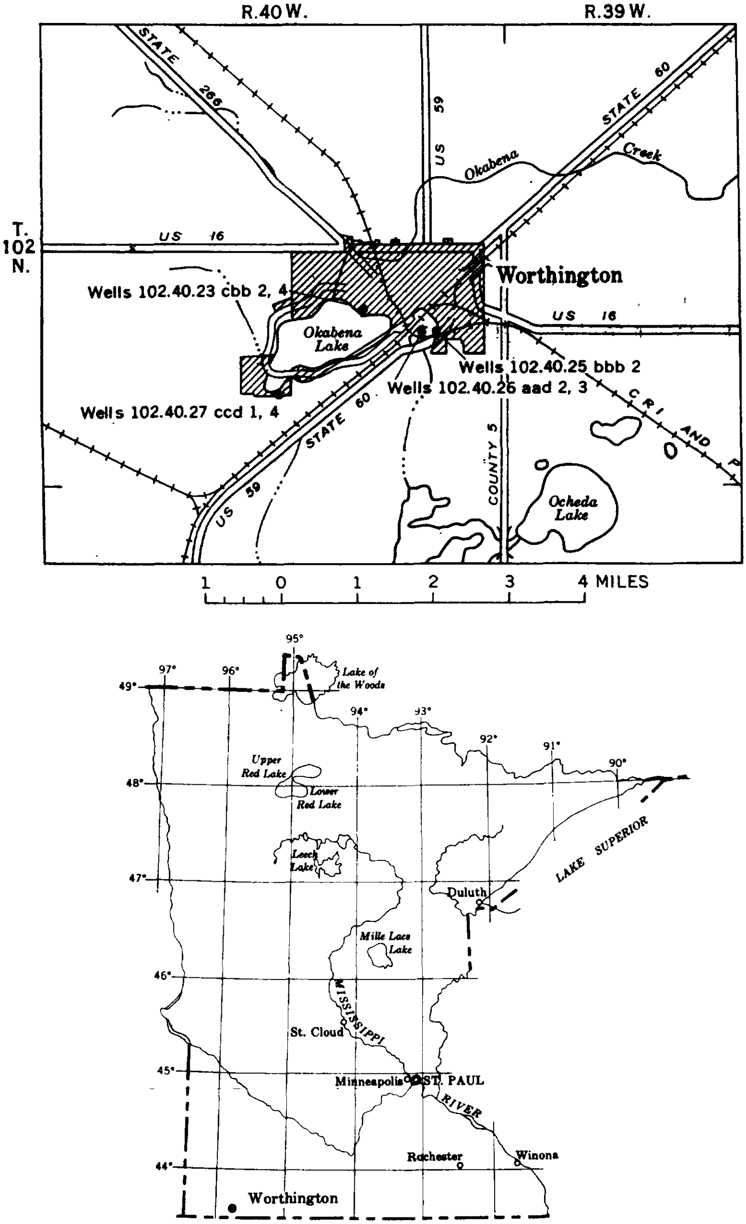
The data show that the temperature cycle of ground water from a development that induces river infiltration may lag behind the river-temperature cycle by 1 to 5½ months (table 1). Also, the lag of the minimum temperature of the cycle (2–5½ months) is much greater than that of the maximum temperature (1–3 months). This fact can be attributed largely to two factors: higher pumping rates in the summer induce infiltration of larger volumes of warm river water, and the inflow of warm river water lowers the viscosity of the water in the aquifer and increases the velocity of flow.

TEMPERATURE STUDY AT WORTHINGTON, MINNESOTA

Worthington is situated on a youthful glaciated plain composed largely of ground moraine. The few lakes in the area are believed to be iceblock basins formed late in Wisconsin time; numerous small sloughs probably represent original depressions in the drift surface.

TABLE 1.—*Temperature data for several ground-water developments that induce river infiltration*

Location	River	Type of installation	Average pumpage (mgd)	Date	Temperature range of river water (°F)	Temperature range of discharge water (°F)	Approximate time lag, in months, of ground-water-temperature cycle behind river-temperature cycle		Remarks
							Maximum temperature	Minimum temperature	
Peoria, Ill., and vicinity	Illinois	Numerous vertical wells, 40–120 ft deep.	52	1941	33–77	46–72			Meinzer, Burdick, and Morris (1942, p. 1612–1613).
Wabash River Ordnance Works, Clinton, Ind.	Wabash	6 horizontal collectors	80	1942–45	37–82	47–61	1½	3	Klaer (1953, p. 623).
Des Moines, Iowa	Raccoon	Horizontal collecting gallery, about 3 miles long.	14	1941		47–70			Meinzer, Burdick, and Morris (1942, p. 1610–1613).
Indiana Ordnance Works, 12 miles north of Louisville, Ky.	Ohio	7 horizontal collectors	39.7	1941–45	34–86	46–78	2	4	Kazmann (1947, p. 839–844).
National Carbide Co., southwest of Louisville, Ky.	do	Horizontal collector	3	1945–48	33–85	47–63	1–2½	2–2½	Rorabaugh (1956, p. 163–164).
Schenectady, N.Y.	Mohawk	Several vertical wells	20	1948–49	32–79	40–64	1–3	3–5½	Source of recharge, about 0.5 mile upstream from well field. Simpson (1952, p. 50, 69, 72).



INDEX MAP OF MINNESOTA

FIGURE 1.—Map of Worthington area, Minnesota, showing locations of wells.

Okabena Lake is almost entirely within the city limits of Worthington (fig. 1). It occupies a shallow, elongate iceblock basin whose axis trends southwestward. The lake is about 2 miles long and, at the widest place, about three-fourths mile wide. The level of Okabena Lake is controlled by a dam at the east end and the overflow is conducted southward into Ocheda Lake through a ditch. Associated with the basin are shallow glacioaqueous deposits of clay, silt, sand, and gravel which are interbedded locally with till. An abandoned melt-water channel extends southward from the southwest end of the basin. It is about 400 to 500 feet wide, incised in till, and filled locally with about 35 feet of outwash.

HYDROGEOLOGIC CHARACTERISTICS OF AQUIFERS

For purposes of comparison attempts were made to measure fluctuations in ground-water temperature in wells completed in three different aquifers. One well (102.40.23cbb4) taps a shallow outwash aquifer near the shore of Okabena Lake; another somewhat deeper well (102.40.25bbb2) is a considerable distance east of the lake; and a third (102.40.27ccd4) taps outwash deposits in the surficial melt-water channel at an intermediate distance from the southwest end of the lake.

Tables 2 and 3 summarize pertinent data on the supply wells and observation wells used in the study; locations are shown on figure 1. The record for well 102.40.26aad3 is given because of its proximity to observation well 102.40.26aad2; also, because the samples were collected more carefully, the log of well 102.40.26aad3 is much more accurate than that of the observation well.

TABLE 2.—*Data on selected wells at Worthington, Minn.*

Well	Use	Depth (feet)	Diameter (inches)	Position of screen or casing perforations (feet below land-surface datum)	Date drilled	Approximate yield (gpm)	Remarks
102.40.23cbb2	Observation	32	6	24–32	1956	--------	Near the shore of Okabena Lake, 184 ft south of well 102.40.23cbb4.
102.40.23cbb4	Worthington supply well 4.	37	26	25(?)–37	1931	75±	About 200 ft north of shore of Okabena Lake.
102.40.25bbb2	Worthington supply well 22.	58.5	24 to 12	53–58.5	1957	150±	About 1,800 ft east of shore of Okabena Lake.
102.40.26aad2	Observation	72	8	53–72	1956	--------	About 10 ft north of well 102.40.26aad3.
102.40.26aad3	Worthington supply well 19.	63	12	58–63	1957	75±	About 1,250 ft east of shore of Okabena Lake.
102.40.27ccd1	Observation	36	6	20–36	1956	--------	17 ft north of well 102.40.27ccd4.
102.40.27ccd4	Worthington supply well 21.	30	12 to 8	14–30	1956	60±	About 850 ft south of shore of Okabena Lake.

TABLE 3.—*Logs of wells at Worthington, Minn.*

Material	Thickness (feet)	Depth (feet)
Well 102.40.23cbb2		
Boulders, gravel, and clay	9	9
Gravel, coarse; boulders	6	15
Gravel, medium to coarse; contains some boulders and medium sand	17	32
Clay, gray	2	34
Gravel, fine, and silt	11	45
Clay	(?)	(?)
Test hole 35 ft south of well 102.40.23cbb4		
Clay, brown	9	9
Boulders, gravel, and brown clay	21	30
Clay, gray	6	36
Gravel, medium to fine, and medium sand; contains minor amount of clay	7	43
Gravel, medium to fine, and medium sand; contains thin layers of clay	5	48
Gravel, medium to coarse, and medium sand	9	57
Clay, gray	4	61
Well 102.40.25bbb2		
Soil and silt	7	7
Clay, gray	6	13
Sand and gravel	2.5	15.5
Till, gray	15.5	31
Till, gray, sand, and gravel	13	44
Sand and gravel	14.5	58.5
Till, gray	2.5	61
Well 102.40.26aad3		
Till, buff, sandy, pebbly, compact; contains a few boulders	9	9
Till, gray, sandy, pebbly, plastic	37	46
Sand, very fine to very coarse, fine to very coarse gravel, and boulders	3	49
Till or dark-gray, pebbly, sandy clay	4.5	53.5
Sand, fine to very coarse, fine to very coarse gravel, and boulders	9.5	63
Till, gray, sandy, pebbly, plastic	5	68
Well 102.40.27ccd1		
Soil, sandy, black	2	2
Clay, silty, sandy, buff	3	5
Silt, clayey, gray	1	6
Sand, fine to very coarse; contains medium gravel and a little gray silt	28	34
Till, clayey, silty, sandy, pebbly; contains a few thin layers of silt	66	100

Well 102.40.23cbb4, about 200 feet north of Okabena Lake, taps a permeable outwash aquifer which is overlain, at least locally, by deposits of much lower permeability. These deposits probably act as a semiconfining layer, one whose permeability is appreciably lower than that of the underlying aquifer but high enough for the layer to yield a perceptible amount of water by gravity drainage when the artesian level is lowered sufficiently. The yield of the well has been reported to increase when the lake level rises; also, there is a pronounced induced hydraulic gradient from the lake to the well.

Well 102.40.25bbb2, about 1,800 feet east of the lake, taps an artesian aquifer—one that is confined by impervious strata and that contains water under sufficient hydrostatic pressure to make the water rise above the top of the aquifer when it is tapped by a well. The confining beds at the well are relatively impervious glacial till.

Well 102.40.27ccd4, about 850 feet south of the lake, taps outwash in the narrow surficial melt-water channel that extends southward from the southwest end of the lake. The outwash in this channel contains water under water-table (unconfined) conditions, and it is probable that when the level of Okabena Lake is high the channel conducts seepage from the lake basin.

INSTRUMENTATION AND METHODS

Measurements were made with a standard laboratory partial-immersion mercury thermometer, calibrated from −1° to 51°C in tenths of a degree. It is believed that the thermometer is accurate to within 0.1° to 0.3°C of the true temperature. However, owing to the fact that the objective was to measure temperature differences in a relatively small range, readings were estimated with a precision of 0.01° to 0.02°C, which could be done readily by means of a monocular magnifying attachment held normal to the thermometer stem by a spring. Even if the indicated absolute temperatures were in error, the measured differences are believed to be significant.

Several precautions were taken to minimize the effect of heat exchange between the water and the well, pump, discharge pipe, and atmosphere. The readings were made inside brick wellhouses where the air temperature ranged from about 54° to 88°F. In practically every instance the wells had been pumping for a long time before the measurements were made. If the well was not pumping when it was desired to take a reading, it was pumped for at least 20 to 30 minutes before the measurement was made.

Water was allowed to flow from a tap near the well into a well-insulated 1½-gallon picnic jug having a highly polished stainless-steel exterior. The thermometer was read while immersed in water in the 3-inch-diameter neck of the jug while the water overflowed. For each determination, readings were made at intervals of several minutes until at least 3 or 4 successive readings agreed to the nearest 0.01° or 0.02°C. Measurements were made at approximately monthly intervals when the observation wells were visited.

The observation wells were equipped with float-actuated recording gages, and the lake level was measured weekly with a steel tape or a staff gage.

TEMPERATURE FLUCTUATIONS OF OKABENA LAKE

Table 4 presents a few measurements of summer temperatures at several depths in Okabena Lake, made during lake surveys by the Division of Game and Fish, Minnesota Department of Conservation. It was not possible to measure the temperature of the lake during the ground-water study.

The temperature records suggest that summer temperatures near the surface of the lake and at the bottom are within a few degrees of the mean daily air temperature. In view of the fact that the 13-foot depth at which the August 9, 1954 measurement (73°F) was made is near the maximum depth, it is presumed that the water circulates more or less vigorously during the summer and that little or no thermal stratification occurs (Welch, 1952, p. 50, 132).

Collins (1925, p. 99–100) states that during above-freezing weather the mean monthly temperature of the air at Minneapolis, Minn., is within about 2° to 6°F of that of Mississippi River water. Likewise, the upper 25 feet of water in a lake follows the air temperature in much the same manner as river water.

It is believed that, during the period of above-freezing temperatures, the graph of mean daily air temperatures (pl. 1) gives a reasonable approximation of lake-water temperature.

TABLE 4.—*Temperature of air and Okabena Lake water, Worthington, Minn.*

[From data furnished by H. R. Kittel, aquatic biologist, Division of Game and Fish, Minnesota Dept. Conserv.]

Date	Water temperature (°F)	Depth below lake surface (feet)	Air temperature (°F)	
			Maximum	Minimum
June 30, 1947	68	1		
August 9, 1954	75	0	83	60
Do	73	[1] 13	83	60
July 22–26, 1957 (exact date uncertain)	81	0	[2] 81	[2] 61
Do	80	4	81	61

[1] Bottom.
[2] Average for period.

During the winter Okabena Lake is covered continuously by ice and the temperature of the water ranges from about 32° to 39°F. Accordingly, the temperature range of the lake water during this study (1958–59) was from about 32° to 80°F.

TEMPERATURE FLUCTUATIONS OF GROUND WATER

Thermographs of wells 102.40.23cbb4, 102.40.25bbb2, and 102.40.27-ccd4 are presented in plate 1, together with a graph of mean daily air temperature at Worthington.

WELL 102.40.23cbb4

One of the most significant characteristics of the thermograph of well 102.40.23cbb4 is the wide range of temperature; the low is about 45.4°F and the high is about 63.1°F, a difference of 17.7°. Also, the maximum temperatures shown by the graph on September 30, 1958, and October 27, 1959, lag behind the maxima of the air-temperature curve by about 2 to 2½ months. The minimum points follow those of the air-temperature curve by about 4 months. The low temperature in May 1958 (45.4°F) is 2.6° lower than the low in May 1959 (48.0°F). Also of significance is the relatively steep slope of the ascending segment from May to September 1958 as compared with the descending segment from October 1958 to May 1959.

The wide range of temperature in this well corroborates the fact that pumping induces infiltration of lake water into the aquifer.

The lower minimum temperature in 1958 indicates that more cold lake water was mixed with ground water in 1958 than in 1959. This might possibly be attributed to a change in pumping rate. However, the average difference between the lake level and the water level in well 102.40.23cbb2 (pl. 2) from January to March of 1958 and 1959 was about the same. (If one selects the average altitude of the ground-water level in Jan.–Mar. 1958 as about 1,566 ft above mean sea level and that in Jan.–Mar. 1959 as about 1,564 ft, the head difference between the lake and the water level in both periods was about 9 ft.) Consequently the average rate of pumping in these periods probably was about the same. It should be noted, however, that during these periods the lake level was about 2 feet higher in 1958 than in 1959. Because of the shallowness of the lake basin, it is believed that the higher stage in 1958 increased the opportunity for inducing the infiltration of more cold lake water.

It is apparent from the lag in time between the peaks and lows of the thermograph of the well and those of the air-temperature curve (2 to 4 months) that, if one were to visualize the warm or cold lake water as a distinct mass or slug, the lags would represent the approximate time required for the water to travel from the lake to the well under the prevailing hydraulic gradient.

The relatively steep slope of the ascending curve from May to September 1958 as compared with the slope of the descending curve from October 1958 to May 1959 is believed to have been due to a higher rate of flow, caused largely by greater pumping during the summer of 1958 and probably also by the lower viscosity of the warmer water, which facilitated the flow.

In view of the relatively few points controlling the May to October 1959 section of the graph, the somewhat greater slope of the May to June segment might have gone unnoticed. However, it seems to correlate with the period of heavy precipitation in May and the rise of the lake level (pl. 2). It will also be seen below that the same factors can be correlated similarly with the thermograph of well 102.40.27ccd4.

WELL 102.40.25bbb2

The thermograph of well 102.40.25bbb2 indicates a range of only 0.4°F, from 48.9°F from March to May 1958 to 49.3°F in September and October 1959. From February through July 1958 the temperature seemed to remain practically constant. A slight but perceptible rise started in August and a peak was reached in November. This peak was followed by a gradual decline through March 1959 and a small rise from August to September 1959. Except for the fluctuations mentioned above, the net trend of the graph seems to be a gentle rise.

The small range of temperature probably results from the fact that the relatively impervious till that encloses the aquifer acts as an insulating medium. Probably the average temperature in this well is close to that for shallow ground water in the entire area. It should be noted that the average, about 49°F, is about 4° higher than the mean annual air temperature (45.1°F). Also, this difference agrees in general with the observations made by Collins (1925). (See section on "Fluctuations of ground-water temperatures," page B–3.)

Observation well 102.40.26aad2 taps the same water-bearing zone as well 102.40.25bbb2. The hydrograph (pl. 2) shows numerous pronounced short-term fluctuations in artesian pressure which are produced by nearby pumping. Disregarding these fluctuations, a comparison of the general trend of the hydrograph with records of precipitation and lake levels indicates that variations in artesian pressure can be correlated directly with changes of lake levels but only indirectly with precipitation. The correlation with changes in lake level is best exemplified by the rises in early April and early June 1958, the pronounced decline from June to October 1958, and the abrupt rise in May and June 1959. The apparent lack of direct correlation of the water level with precipitation is demonstrated by the heavy rains of early May 1959. The large magnitude of the water-level fluctuations as compared with the correlative lake-level fluctuations, and the rapidity with which lake-level fluctuations produce changes in the water level, strongly suggest that the artesian pressure fluctuates largely in response to changes in loading produced by variations in the amount of water stored in the lake basin.

Despite the low permeability of the till overlying the aquifer, and the apparent lack of direct correlation of the water level with precipitation, the thermograph of well 102.40.25bbb2 suggests that the lowering of artesian pressure has produced a sufficiently large head differential to induce downward movement of warmer precipitation-derived water through the till. An example is believed to be the small but distinct rise in temperature that started in August 1958, after the temperature had been practically constant for about 5 months. It is possible also that the rise in temperature in August and September 1959 resulted from the infiltration of warm water derived from the large amount of precipitation in August. The possibility of recharge from precipitation is evident also from the hydrograph of well 102.40.26aad2. From January to June 1958, when the average position of the water level was about 1,534 feet above mean sea level, the pumping regimen produced numerous sharp fluctuations of artesian pressure. During the last part of 1958 and in 1959, when the water level had descended below about 1,527 feet, the short-term fluctuations were much smaller. In view of the fact that the altitude of the top of the aquifer is about 1,530 feet, it is apparent that, at least locally, pumping has lowered the artesian water level below the top of the aquifer, thus making it possible for a significant amount of shallower ground water to infiltrate. It is believed that the change in pattern of the short-term fluctuations on the hydrograph resulted from the fact that conditions in the aquifer changed locally from artesian (confined) to water-table (unconfined). In the following discussion it will be pointed out that the thermograph of well 102.40.27ccd4 also indicates that recharge from precipitation results in the infiltration of warm water.

WELL 102.40.27ccd4

The apparent temperature range on the thermograph of well 102.40.27ccd4 is 4.63°F, from a low of 46.45°F to a high of 51.08° F. The peak of the graph in January 1959 lags behind the peak in the air-temperature curve by about 5 to 5½ months, and the lows follow the air-temperature lows by about 6 to 7 months. The low in 1958 (46.45°F) occurred about mid-June and the low in 1959 (47.03°F), in addition to being about 0.6° higher than the 1958 low, occurred about 1½ months later. Of significance is the fact that the declining segments of the curves in 1958 and 1959 have average slopes of about 0.8°F per month, whereas the rising segments have average slopes of about 1.1°F to 1.2°F per month.

Except for magnitude the thermograph of this well is similar in several respects to that of well 102.40.23cbb4. If one assumes that the warm or cold lake water is a distinct mass, the lag in time between the peaks and lows of the air-temperature curve and those of the well thermograph indicates that the average time required for water to move from the lake to the well, under the prevailing hydraulic gradient, is 5 to 7 months. As with well 102.40.23cbb4, it is believed that the higher lake level from January to March 1958 increased the opportunity for inducing the infiltration of more cold lake water in 1958 than in 1959. Also, the possibility of attributing this condition to a change in pumping rate is minimized by the fact that the average head difference between the lake and the water level in observation well 102.40.27ccd1 in the periods January to March 1958 and 1959 was about the same (pl. 2). (If one selects the average altitude of the ground-water level in Jan.–Mar. 1958 as about 1,569.5 ft above mean sea level and that in Jan.–Mar. 1959 as about 1,567.8 ft, the head difference between the lake and the water level in both periods was about 5.5 ft.) Further evidence for the infiltration of a larger percentage of cold lake water in 1958 than in 1959 is that the low temperature in 1958 occurred about 1½ months earlier than it did in 1959.

The thermograph of well 102.40.27ccd4 indicates also that recharge from spring and summer rainfall results in the infiltration of relatively warm water. One of the best examples of this infiltration is the correlation of the heavy rains in May 1959 with the flattening of the cooling trend between the mid-April and mid-May measurements. It is believed that a similar correlation can be made for the period of precipitation in early April 1958, although the magnitude of the flattening is small. The steepness of the earliest segment of the warming trend in August 1959 can be correlated with the heavy rainfall in August (pls. 1 and 2).

CONCLUSIONS

The temperature of the water discharged from large ground-water installations that induce river infiltration depends primarily on the porosity and specific heat of the aquifer, the temperature of the ground water in storage, the temperature of the river water, and the mixing of ground water and river water. In six installations in alluvial deposits hydraulically connected with rivers at or near Peoria, Ill., Clinton, Ind., Des Moines, Iowa, Louisville, Ky., and Schenectady, N. Y., the annual river-temperature fluctuations ranged from 44° to 52°F and averaged 48°F, and the ground-water-temperature fluctuations ranged from 14° to 32°F and averaged 22°F. These values indicate the order of magnitude of the relation between river-temperature and ground-water-temperature fluctuations in developments of this type. The ground-water-temperature cycle may lag behind the river-temperature cycle by as much as 6 months. Also, the time lag of the minimum temperature of the cycle is much greater than that of the maximum temperature.

Monthly fluctuations of ground-water temperatures in shallow glacial-outwash aquifers (up to about 70 ft. in depth), estimated to the nearest 0.01° or 0.02°C, are useful in studying ground-water movement and recharge. Together with data on other hydrogeologic and climatologic factors, ground-water and surface-water thermographs may be used to determine whether a development is inducing infiltration from a body of surface water and to estimate the order of magnitude of travel time from the source of recharge. Direct infiltration of rainfall may be detected from the ground-water thermograph even where an aquifer is overlain by strata of low vertical permeability.

POSSIBLE ADDITIONAL APPLICATIONS OF THERMOMETRY

Despite the facts that the instrumentation used in the experimental study at Worthington, Minn., was simple, and that the measurements were made at relatively infrequent intervals, the thermographs reflect relatively minor changes in the hydrologic environment. This fact would suggest that precise thermometry may be a most useful tool for studying the movement of subsurface water—in particular, the interrelation of ground water and surface water. It would appear to be useful also in studying the movement of ground water in limestone and basalt terranes because of the high permeability of some of the water-bearing zones in these rocks.

The writer (1958) has described the movement of moisture from the water table to the frost layer in response to a thermal gradient, and the return of frost melt to the water table in the spring. It is possible that this phenomenon could be studied in more detail by the use of precise thermometry.

In addition to the possibility of studying natural phenomena in the hydrologic cycle, it is probable that the effects of artificial changes in the ground-water environment, in addition to pumping or inducing the infiltration of surface water, also can be studied effectively through thermometry. For example, the general effect of returning warm air-conditioning water to the ground through recharge wells on Long Island, N.Y. has been described by Leggette and Brashears (1938) and by Brashears (1941). Precise thermometry undoubtedly could be used to study in considerable detail the effects of recharging aquifers artificially. Other applications might include studies of the effects of the underground storage or injection of petroleum products and radioactive or other waste materials, and as an aid in studying the movement of ground water in mines.

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