WATER TEMPERATURES IN A WELL NEAR WILD ROSE, WISCONSIN*

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Temperature measurements made in a well near Wild Rose, Wis., show that ground-water temperatures, which are generally assumed to be almost constant, fluctuate seasonally, and vary with depth. The measurements, made by the U. S. Geological Survey in cooperation with the Wisconsin Geological and Natural History Survey, are discussed because an understanding of ground-water temperatures is becoming increasingly important in Wisconsin. Many industries in the State depend upon the relatively uniform temperature of water from wells, and the attraction of Wisconsin’s streams to thousands of sportsmen is the direct result of ground water discharging at temperatures favorable for cold-water game fish, especially trout. Moreover, the movement (Wenzel, 1942, p. 7) and the chemical character of ground water (Hem, 1959, p. 4) are related to its temperature. The knowledge gained by a study of ground-water temperatures in Wisconsin can aid in the development and conservation of the State’s ground-water resources.

The temperature of ground water is usually determined by measuring the temperature of the water as it is pumped from a well or as it flows from a well or spring. Sometimes the temperature is measured by lowering a thermometer or other device directly into a well and measuring the temperature of the water at various depths in the well. In Wisconsin experience indicates that temperatures obtained in these ways usually cannot be used to describe the manner in which temperatures are distributed within the aquifer, because, in practice, the observed temperatures are related to the geology and the hydrology of the aquifer plus such other factors as well construction, discharge rate, and housing that are unrelated to the distribution of temperature in the aquifer. For reasons which will be discussed in detail in the ensuing pages, the temperatures observed in the well near Wild Rose are assumed to approximate closely the temperature of the ground water at various depths in the aquifer, and, as such, they are used to interpret the movement of heat within the aquifer and to illustrate the role of ground-water movement in the thermal regimen of the area.

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Ground-water temperatures have been measured since 1869 when Lord Kelvin first began making systematic observations of the earth's temperature (Darton, 1920). Particular attention has been given to "thermal" areas, geothermal gradients, heat flow, hot springs, and geysers (Jakowsky, 1950, p. 966–986). The occurrence of ground water in areas of extreme cold or permafrost also has been studied (Cederstrom and others, 1953; and Hopkins and others, 1955). Temperatures of soil also have received considerable attention (Chang, 1958). By contrast, little attention has been given to the causes and variations of ground-water temperatures in "non-thermal" areas. However, the temperature of discharging ground water is nearly always measured as part of a ground-water study. For example, in Wisconsin, Foley and others (1953, p. 88) measured the temperature of ground water sampled for chemical analyses from the "dolomite" and "sandstone" aquifers of the Milwaukee-Waukesha area. Other investigators have considered: (1) The temperature of water pumped from wells (Harder, 1960, p. 24–25, Rasmussen and Andreasen, 1959, p. 54–56); (2) the areal distribution of temperature in an aquifer (Darton, 1898; and Suter and others, 1959, p. 74–75); (3) the temperature of ground water in the United States at depths of 30 to 60 feet (Collins, 1925, p. 97–98); (4) the effect of artificial recharge on ground-water temperature (Leggette and Brashears, 1938, p. 414–418; Brashears, 1941, and 1946, p. 504, 511, 513–515; and Jennings, 1950); and (5) the effect of infiltration of water from a nearby stream on ground-water temperature (Kazman, 1948, p. 840–844; Rorabough, 1951, p. 169, and 1956, p. 162–164; and Simpson, 1952, p. 68–72).

METHODS

All the temperatures presented in this paper were measured by the U. S. Geological Survey with a single underwater thermometer. The thermometer consists of a thermister or temperature sensitive element, a constant-resistance insulated cable, a power supply, a Wheatstone bridge, and a microammeter. The water temperatures were measured by lowering the thermister into the well, stationing it at progressively greater depths, and reading the meter, which is calibrated in degrees Fahrenheit. The temperatures were read to 0.1 degree.

Although ground-water temperature at depths of 70 feet or more probably did not vary during this study, temperature measured at these depths at different times varied as much as 0.4°F. These differences are attributed to errors in calibration of the instrument. However, for a given set of measurements the deviation from the true temperature is constant.
Other sources of error have been recognized. These include: mixing of water from different depths by the cable; temperature changes due to heat exchange between the cable and the water in the well; and variations in the techniques of the different operators. In general, the quality of the measurements improved as the operators gained experience.

ACKNOWLEDGMENTS

The underwater thermometer is the property of the Division of Well Drilling, Wisconsin State Board of Health, and thanks are given for its use. The Wisconsin Conservation Department owns the well in which the measurements were made and the use of this well is gratefully acknowledged.

LOCATION OF THE WELL

The well in which the measurements were made is in central Wisconsin, in Waushara County, about 90 miles north of Madison. It is in the SE 1/4, sec. 24, T. 20 N., R. 10 E., about 0.5 mile north of the village of Wild Rose at the trout hatchery of the Wisconsin Conservation Department. Specifically, it is 300 feet west of Wisconsin State Highway 22, 50 feet north of the north raceway of the hatchery and 5 feet west of the rearing shed.

GEOLOGIC SETTING

Glacial deposits of Cary age (Thwaites, 1943), more than 200 feet thick, conceal an irregular bedrock surface in the Wild Rose area. The glacial drift consists of a mixture of sand and gravel, some silt, and very little clay (Whitson and others, 1913). At the well the deposits include poorly sorted silty sand, silty clay, and sandy gravel. A log of a well about 200 feet north of the well in which the temperatures were measured is given in table 1.

Less than 50 feet of sandstone of Cambrian age underlie the glacial drift at the well site. Both the glacial drift and sandstone are permeable, porous, and water-bearing. The total saturated thickness of the glacial drift and sandstone is estimated to be 250 feet. Granite of Precambrian age underlies the sandstone. The granite is, for practical purposes, impermeable.

HYDROLOGIC SETTING

The water table in the Wild Rose area slopes eastward about 30 feet per mile, except near streams where the slope is greater and toward the streams. The streams flow to the east. Recharge of the

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*The ground-water hydrology of Portage, Waupaca, and Waushara Counties was studied by the U. S. Geological Survey in cooperation with the Wisconsin Geological and Natural History Survey. Results of these studies are being prepared for publication.*
TABLE 1. LOG OF A WELL AT THE FISH HATCHERY, WILD ROSE, WIS. (PREPARED BY THE WISCONSIN GEOLOGICAL AND NATURAL HISTORY SURVEY FROM EXAMINATION OF SAMPLES)

<table>
<thead>
<tr>
<th>Description</th>
<th>Thickness (feet)</th>
<th>Depth (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No samples</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Sand, very fine, light-pink-gray, dolomitic, silty</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>Clay, light-pink, dolomitic, silty</td>
<td>20</td>
<td>45</td>
</tr>
<tr>
<td>Sand, very fine, light-pink-gray, silty</td>
<td>40</td>
<td>85</td>
</tr>
<tr>
<td>Sand, fine to very fine, light-yellow-gray</td>
<td>10</td>
<td>95</td>
</tr>
<tr>
<td>Sand, fine, light-gray, silty</td>
<td>25</td>
<td>120</td>
</tr>
<tr>
<td>Sand, fine to very fine, pink-gray, silty</td>
<td>10</td>
<td>130</td>
</tr>
<tr>
<td>Sand, very fine, pebbly, pink-gray, silty</td>
<td>5</td>
<td>135</td>
</tr>
<tr>
<td>Sand, very fine to medium, light-gray, silty</td>
<td>40</td>
<td>175</td>
</tr>
<tr>
<td>Sand, medium to coarse, light-gray</td>
<td>5</td>
<td>180</td>
</tr>
<tr>
<td>Gravel, sandy</td>
<td>3</td>
<td>183</td>
</tr>
</tbody>
</table>

ground-water reservoir results when precipitation in the area percolates to the water table, and discharge occurs when the water in the reservoir moves into a local stream, is used by vegetation, or is pumped from wells.

At the well site, the ground water moves toward and discharges into the hatchery's raceways. The water flows from the raceways into the Pine River. Ground water also is discharged by springs and wells on the hatchery grounds and conducted into the raceways. The total discharge through the raceways was 2,200 gpm (gallons per minute) on September 1, 1956, and averaged about 2,200 gpm during 1957 (John Ockerman, Wisconsin Conservation Department, personal communication).

The water table in the shallower part of the aquifer at the well stays at an almost constant level about 3 feet below the land surface because the water level in the nearby raceway is artificially maintained. The well taps the deeper part of the aquifer, however, and water rises about 8 feet above the land surface, because permeability differences within the glacial drift create artesian conditions at depths below 10 feet.

The total depth of the well is 187 feet, but, during the period when the temperature measurements were made, it was filled with gravel to a depth of 141 feet. The 4-inch diameter steel casing extended from 0.4 foot above the land surface to the bottom of the well, so that all the water entered the well through an area of about 13 square inches at the bottom. Because the well was partly plugged, the flow during the period of the temperature measurements was about 4 gallons per hour. Differences in water levels and flow rates in the well were not measured.
THE OBSERVED TEMPERATURES

Temperatures were measured on six occasions during the period February 1957 to February 1958. The temperature measured in May, August, October, and November 1957 and February 1958 were plotted against depth (fig. 1). Although only a few measurements were made in February 1957, the data are sufficient to show that the temperatures were probably identical with the temperatures measured in February 1958. Figure 1 shows that from the land surface to a depth of about 60 feet the temperatures fluctuated with time, the magnitude of the fluctuation decreasing with depth.

The maximum observed range of water temperature at different depths, determined by subtracting the observed minimum from the observed maximum, was plotted against depth in figure 2. At a depth of 1 foot, the temperature range was 30.5°F, at 10 feet it was 9.9°F, and at 36 feet it was less than 1°F. For depths below 60 feet the temperature increased uniformly with depth (fig. 1) and did not fluctuate significantly with time (fig. 2).
Figure 2. Maximum observed range of water temperatures in a well near Wild Rose, Wis.

Relation of the Observed Temperatures to Aquifer Temperatures

The relation of the observed temperature of water in the well to the temperature of ground water in the aquifer may be derived from the following argument. First, consider the effect of water flowing through a well cased in unsaturated rock. Boldizsar (1958) has shown that for large flows of water, heat is exchanged between the water in the well and the rock penetrated by the well if a temperature difference exists, and usually the rock becomes warmer.
He points out that for small flows, from depths of less than 100 meters, the exchange of heat is negligible, and the temperature of the rock does not change. Therefore, at the well near Wild Rose, the temperature of the rock of the ground-water reservoir probably would not be measurably affected by the heat in the small volume of water flowing through the well.

Next, consider the effect of the heat in the water flowing through a well cased in a ground-water reservoir. For large flows, heat will be exchanged if a temperature difference exists between the aquifer and the water in the well. The warming or cooling of the aquifer will be less than if the rock were unsaturated, because more heat is required to warm saturated rock than is required to warm unsaturated rock, and some of the heat is carried away by the ground water moving past the well. Obviously, as the flow of water in the well approach zero, the exchange of heat between the well and the ground-water reservoir becomes more complete, and the difference in temperature between the water in the well and the ground-water reservoir approaches zero. Therefore, the temperature in the subject well and the temperature of the ground-water reservoir should be nearly identical, because the water in the well is flowing very slowly to the surface.

From the preceding discussion a condition of zero flow would appear to be ideal. This, however, is not always true, because other factors operate to disturb the temperature in a nonflowing well. These factors include convection within the well (Van der Merme, 1951), circulation from one part of the aquifer to another or from one aquifer to another through the well (Foley and others, 1953, p. 75), and external sources of heat.

External sources of heat are those that affect the water in the well but not those in the aquifer. In Wisconsin common external sources of heat are solar radiation and heated pump houses. Convection of air within the well causes warm or cold air to be brought in contact with the water, and as a result the temperature of the water standing in the well is not necessarily representative of the temperature of the water in the aquifer. During periods when the ground was frozen, the temperatures observed in the subject well were probably somewhat higher than those near the top of the aquifer.

The effect of the casing upon water temperature in a well may be significant also. For example, steel casing is an excellent conductor of heat so that the transfer of heat between the well and the atmosphere, or between the water in the well and the aquifer immediately outside the well, may be facilitated.
SIGNIFICANCE OF THE OBSERVED TEMPERATURES

If the observed temperatures (fig. 1) are representative of the aquifer, they are significant. They show the distribution of temperatures in the aquifer with depth and time, and the movement of heat in the aquifer can be inferred. In the following discussion, the observed temperatures are assumed to be representative of the aquifer at the site of the well, so that the fact that the temperatures were measured in a well becomes immaterial to the argument.

Seasonal fluctuations. The temperature of the ground water at shallow depths responded to seasonal changes in air temperature. Similar responses in earth or soil temperatures to depths of as much as 100 feet have been observed and reported by many investigators (Carslaw and Jaeger, 1947, p. 62). The effect of seasonal air temperature of the ground water is reflected in the data of figure 1. As the air temperature changed, the temperature of ground water to a depth of about 60 feet changed with a lag in time. The temperature fluctuations of ground-water decreased with depth (fig. 2), and the time required for the air temperature to affect the ground-water temperature increased with depth (fig. 3). Thus, the maxi-

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**Figure 3.** Average monthly air temperature at Hancock, Wis., and water temperatures at depths of 5, 10, and 30 feet in a well near Wild Rose, Wis.
mum temperature difference below 36 feet is less than 1°F, and the water temperature reaches a maximum after air temperature.

**Temperatures below 60 feet.** Below a depth of about 60 feet, the water temperature increased gradually with depth (fig. 1). From 60 to 140 feet, the average rate of increase is about 0.9°F per 100 feet. In addition to the observations in the subject well, temperatures were measured in four other wells in central Wisconsin. In these wells, which ranged in depth from 184 to 349 feet, the temperature increase with depth below 60 feet was less than 1°F per 100 feet.

**Movement of heat in the ground-water reservoir.** Heat moves through the ground-water reservoir by conduction and convection (R. W. Stallman, written communication, January 1960). The movement of heat by conduction is governed by the thermal conductivity of the media (k) and the temperature gradient (T/Z). The movement is along a path of diminishing temperature and is expressed quantitatively by the expression \( Q = KT/Z \), where \( Q \) is the heat flux through a unit area in unit time (Chang, 1958, p. 28). The movement of heat by convection is controlled by the properties of the water—specific heat, density, temperature, and velocity (R. W. Stallman, written communication, January 1960, p. 7). In general, the lateral movement of heat in an aquifer is by convection, whereas the vertical movement of heat is by conduction. The data shown on figure 1 are sufficient to determine a thermal gradient (T/Z) and, therefore, to show whether heat is being conducted upward or downward and to measure relative differences in the amount of heat moving through a vertical column of rock in the area. Two generalizations about the conduction of heat may be made immediately from inspection. First, heat is moving steadily through the aquifer from below; and, second, heat moves into and from the aquifer seasonally.\(^4\)

Heat moves laterally by convection, and, although measurements were made in only one well, the effect of convection also can be inferred from the observed temperature gradients. Earth temperatures usually increase steadily with depth below the zone of seasonal variation, because heat is flowing to the surface from the interior of the earth (Evans and others, 1942, p. 268–269). The average increase in temperature below a depth of 100 feet at eight sites in Michigan, Illinois, and Iowa is about 1.3°F per 100 feet (Spicer, 1942, p. 280–282). The temperature gradient in a well drilled more than 300 feet into crystalline rock of Precambrian age near Sextonville, Wis., about 80 miles southwest of Wild Rose,

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\(^4\)The exchange of heat between the well and the aquifer is negligible and is not considered here.
is 1.1°F per 100 feet. Therefore, the temperature gradient in the granite of the Wild Rose area also might be about 1.1°F per 100 feet. At the subject site, the average observed temperature gradient for the interval between 60 and 140 feet is about 0.9°F per 100 feet. Inasmuch as the thermal conductivity of granitic rocks is usually greater than the thermal conductivity of saturated sand and clay (Birch, 1942, p. 251–252 and 259; Ingersoll and others, 1948, p. 244; Chang, 1958, p. 30–32), and the temperature gradient in the granite is greater than that measured in the subject well, more heat is moving through the granite than is being conducted through the ground-water reservoir. Convection of heat can account for this difference. As the water moves through the aquifer, some of the heat received from the granite is convected by the moving ground water and is released from the aquifer, as the ground water is discharged.

In addition to the heat moving upward through the groundwater reservoir from below, heat is added from above to the groundwater reservoir in the summer and removed in the winter due to variations in solar radiation. Thus, on February 11, 1958, the temperature [of ground water in the subject well] increased with depth from the surface to 30 feet (fig. 1), indicating that in this zone heat was moving toward the surface. Between 30 and 50 feet the temperature decreased slightly, showing that heat was moving downward. Heat from a depth of 30 feet was either being conducted upward to be radiated at the surface or was being conducted downward to warm the water in the interval between 30 and 50 feet.

By a similar analysis, the data of May 6, 1957, show that although heat was flowing into the aquifer from the land surface and warming of the water had begun, not enough heat had moved into the aquifer to warm the water below a depth of 8 feet. Warming of the water continued as heat flowed downward from the surface, and by August 6, 1957, all the water to a depth of 60 feet had received some heat. By October 18, 1957, heat had ceased to flow into the aquifer from the surface, and the water in the top 10 feet had begun to cool. However, the water between 30 and 40 feet was still receiving heat. On November 29, 1957, heat was flowing toward the surface from a depth of about 18 feet, and the water in this interval was cooling. The water between 18 and 35 feet was still receiving heat.

On a smaller scale, heat is added to and taken from the soil as a result of diurnal and day-to-day air-temperature variations (Langbein, 1948, p. 543). Each of the curves of figure 1 have the effect of small short-term air-temperature variations “built in”. This effect is most obvious in the curves of August 6, and October 18, 1957. In the following discussion, the effect of these short-term variations have been disregarded.
CONCLUSIONS

Several generalizations have been drawn from the data obtained: (1) The temperature measured in the well closely approximates the actual temperature of the water at various depths in the aquifer; (2) in the Wild Rose area, Wisconsin, the temperature of water in the zone of saturation increases about 0.9°F per 100 feet below a depth of 60 feet, and, therefore, heat is flowing upward through the ground-water reservoir from a greater depth; (3) some of the heat that moves through the aquifer is released at the land surface as latent heat in discharging ground water; (4) water in the interval from a depth of 60 feet to the surface is subject to seasonal temperature fluctuations that are related to seasonal variation in air temperature.

If these generalizations are valid, then the temperature of ground water in the Wild Rose area is due primarily to two factors (1) the temperature of the water as it recharges the aquifer and (2) the change in temperature due to the gain or loss of heat as the water moves through the aquifer. The amount of heat gained or lost by the water (hence, the temperature of the ground water) is dependent upon the length of time the water is in the aquifer and the path the water takes as it passes through the zone of saturation from the point of recharge to the point of discharge.

Temperature relations similar to those described for the Wild Rose area probably occur in other areas where the hydrologic conditions are similar.

REFERENCES CITED


