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Hydraulic Properties of the Ironton and Galesville Sandstones, Shakopee Mdewakanton Sioux Community, Southeastern Minnesota, 2004

Scientific Investigations Report 2005–5245

U.S. Department of the Interior
U.S. Geological Survey

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Gale A. Norton, Secretary

U.S. Geological Survey
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U.S. Geological Survey, Reston, Virginia: 2005

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Suggested citation:
Winterstein, T.A., 2005, Hydraulic properties of the Ironton and Galesville Sandstones, Shakopee Mdewakanton Sioux Community, southeastern Minnesota, 2004: U.S. Geological Survey Scientific Investigations Report 2005–5245, 30 p.

Prepared by U.S. Geological Survey in Mounds View, Minnesota (http://mn.water.usgs.gov)

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Conversion Factors, Abbreviations, and Datums

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
mile (mi)	1.609	kilometer (km)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
foot squared per day (ft^2/d)	0.9290	neter sqyared per day (m^2/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Mass	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)
	Pressure	
millimeter of mercury (mmHg)	0.0193	pound per square inch (lb/in^2)
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Hydraulic Properties of the Ironton and Galesville Sandstones, Shakopee Mdewakanton Sioux Community, Southeastern Minnesota, 2004

By Thomas A. Winterstein

Abstract

The U.S. Geological Survey, in cooperation with the Shakopee Mdewakanton Sioux Community, conducted an aquifer test December 6–22, 2004, to improve definition of the hydraulic properties of the Ironton and Galesville Sandstones beneath the Shakopee Community in southeastern Minnesota. Three wells were used in the aquifer test—a production well and two observation wells, located 3,247 feet northwest of the production well and 3,049 feet southeast of the production well. The production well, completed in the Ironton and Galesville Sandstones, was pumped at about 600 gallons per minute from 10:30 a.m. on December 6, 2004, to 3:26 p.m. on December 9, 2004. Drawdown and recovery water levels were measured in all three wells.

Four curve-fitting methods and two graphical methods were used to estimate the transmissivity and storage coefficient of the Ironton and Galesville Sandstones. The four curve-fitting methods were the Theis, Hantush, Hantush-Jacob, and Neumann-Witherspoon methods. These methods were applied to the drawdown and residual recovery curves of the observation wells. The two graphical methods were the Cooper-Jacob method and the Theis recovery method. The Cooper-Jacob method was applied to the drawdown curve of the production well and the drawdown curves of the two observation wells. The Theis recovery method was applied to the residual drawdown curves of the two observation wells.

The transmissivity estimated using the six methods ranged from 450 to 650 feet squared per day. The average transmissivity for the six methods was 540 feet squared per day. The storage coefficient estimated using the six methods ranged from 4.2 to 5.7 x 10^{-5}. The average storage coefficient for all six methods was 5.0 x 10^{-5}. The hydraulic conductivity was estimated by dividing the estimated transmissivity by 45 feet. The average hydraulic conductivity for the six methods was 12.1 feet per day.

Introduction

The Ironton and Galesville Sandstones are one of the sources of water for the Shakopee Mdewakanton Sioux Community (hereinafter termed Shakopee Community), Scott County, southeastern Minnesota (fig. 1). The U.S. Geological Survey, in cooperation with the Shakopee Community, conducted an aquifer test from December 6–22, 2004, to improve definition of the hydraulic properties of the Ironton and Galesville Sandstones beneath the Shakopee Community. Information from the test will be useful to tribal officials for water-management plans, to nontribal government officials for development of regional water-management plans, and to water-resource investigators for subsequent studies on the hydraulic properties of the sandstones.

The purpose of this report is to describe the aquifer-test design and analysis and to present the hydraulic properties of the Ironton and Galesville Sandstones beneath the Shakopee Community determined from the aquifer test. The test was conducted by pumping water from an existing production well (Franconia-Ironton-Galesville Well No. 2) for 76.9 hours and measuring the drawdown in the production well and two observation wells. The recovery was measured in the observation wells for 308.5 hours (12.9 days).

Hydrogeologic Setting

The geologic units beneath the study area that were examined in this study include thick glacial sediments and six bedrock units. The bedrock units are, in descending order, the Prairie du Chien Group, the Jordan Sandstone, the St. Lawrence Formation, the Franconia Formation, the Ironton and Galesville Sandstones, and the Eau Claire Formation of Early Ordovician and Late Cambrian age (about 500 million years ago). The lithology beneath the study area was determined from driller's logs of the production well and two observation wells and from an interpretation of a natural gamma borehole log of the production well (fig. 2 and table 1). The following description of the Franconia Formation, Ironton and Galesville

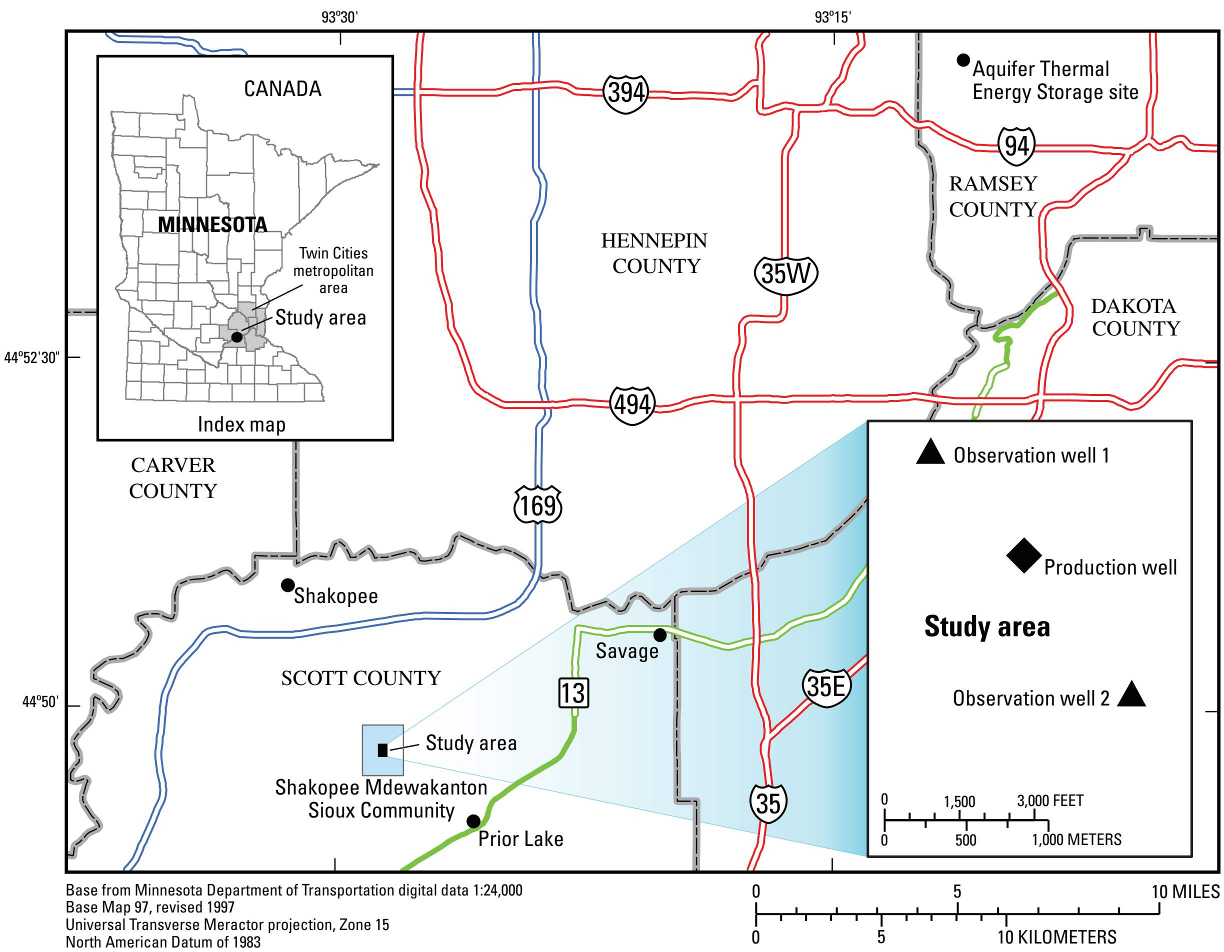

Figure 1. Location of study area, production well, and two observation wells, Shakopee Mdewakanton Sioux Community, southeastern Minnesota.

Sandstones, and the Eau Claire Formation was modified from Mossler and Tipping (2000, plate 1).

The Franconia Formation is of Late Cambrian age. In the study area, the upper part of the formation is greenish-gray, medium-bedded, very fine-grained to fine-grained, dolomite-cemented, glauconitic and feldspathic sandstone and is between 133 and 159 ft thick (table 1). The lower part of the formation consists of green-gray to light-green interbedded shale, siltstone, with lesser amounts of very fine-grained feldspathic sandstone as thick as 30 ft, which overlie dark-green, very fine-grained to fine-grained, medium to thick beds of highly glauconitic sandstone interlayered with thin beds of gray-orange to pink sandy glauconitic dolostone, also as thick as 30 ft. The contact with the underlying Ironton Sandstone is sharply defined but apparently conformable.

The Ironton and Galesville Sandstones are of Late Cambrian age. The sandstones consist of light-gray, very fine to fine-grained feldspathic sandstone and medium- to coarse-grained and very coarse-grained, commonly cross-laminated quartz sandstone interlayered with scattered thin beds of maroon or green shale. Although separated by a disconformity representing a hiatus of long temporal duration, the two formations cannot be distinguished with certainty where geologic control consists of water-well cuttings alone. The thickness of the Ironton and Galesville Sandstones beneath the study area is between 45 and 77 ft (table 1).

The Eau Claire Formation is of Late Cambrian age. The upper one-third to one-fourth of the formation consists of feldspathic sandstone that is light gray to yellow gray, very fine to fine grained, finely laminated to ripple cross-laminated, and slightly glauconitic; it is interlayered with scattered, thin partings of gray-green shale.

The lower part of the Franconia Formation is a confining unit, whereas the upper part is an aquifer in much of the Twin Cities metropolitan area (Runkel and others, 2003, p. 46). The Eau Claire Formation is a confining unit (Runkel and others, 2003, p. 38). The Franconia and Eau Claire Formations were considered to be confining units for the Ironton and Galesville Sandstones in the aquifer test described in this report.

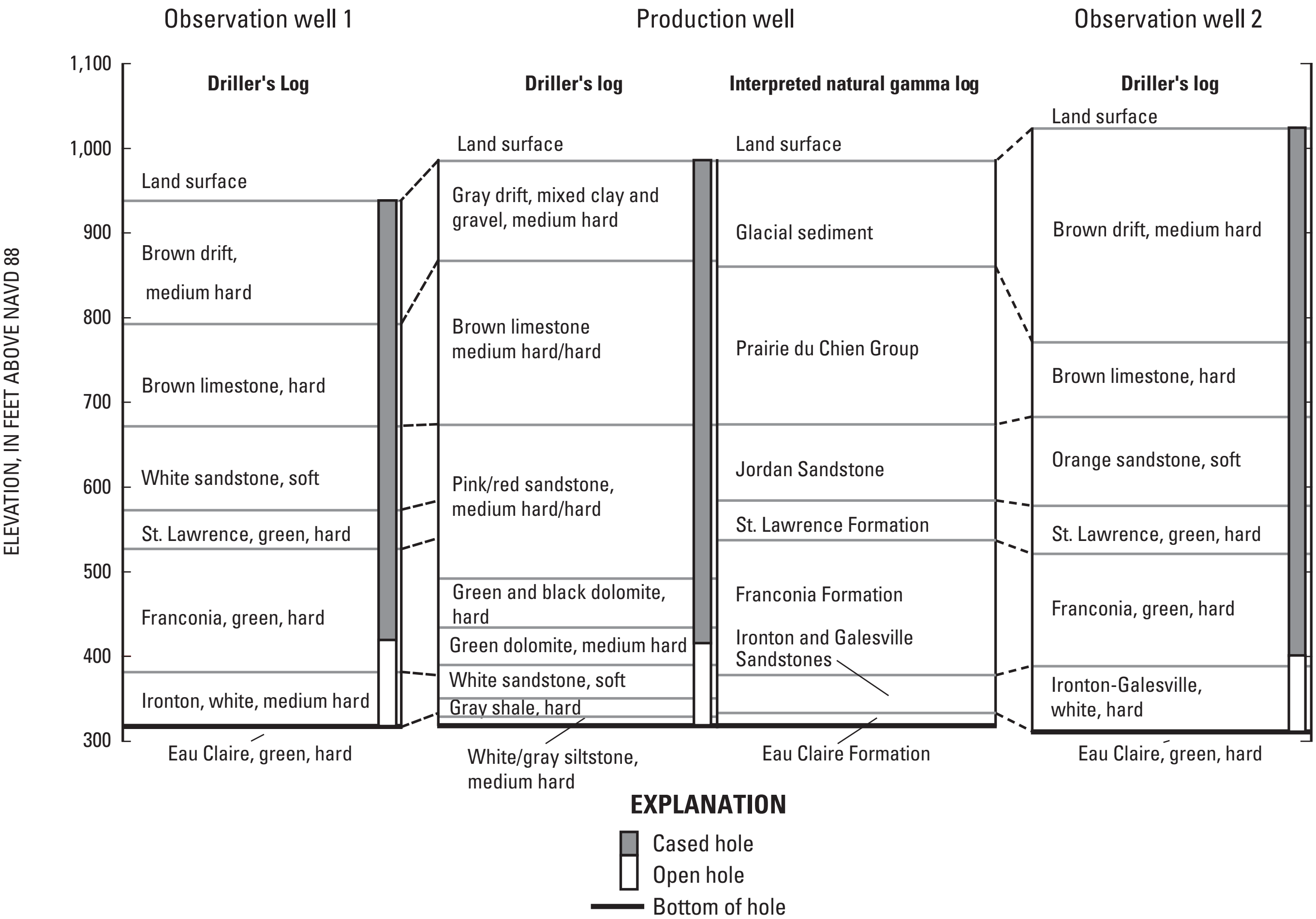

Figure 2. Lithology beneath production well and two observation wells. Natural gamma log made March 16, 1998, by Summit Envirosolutions, Inc., Minneapolis, Minnesota. Interpretation of natural gamma log by Summit Envirosolutions, Inc. Data provided by Scott Walz, Shakopee Mdewakanton Sioux Community, written commun., 2004.

Previous Hydraulic Investigations

Packer tests were used to determine the hydraulic properties of the Franconia Formation and the Ironton and Galesville Sandstones at the Aquifer Thermal Energy Storage (ATES) site in St. Paul, Minnesota, about 22 mi northeast of the study area (fig. 1). Analysis of results of the packer tests indicated two hydraulic zones within the Franconia Formation and two hydraulic zones in the Ironton and Galesville Sandstones, two of which act as a single aquifer (Runkel and others, 2003, p. 41). An aquifer test at the ATES site was used to determine that the transmissivity of the Ironton and Galesville Sandstones was approximately 690 ft^2/d, and the storage coefficient was approximately 2.4×10^{-5} (Miller and Delin, 1993, p. A8–A9). The vertical-to-horizontal hydraulic conductivity ratio for the Ironton and Galesville Sandstones was determined by Miller and Delin (1993) to be 0.1.

Barr Engineering (Edina, Minnesota) constructed a ground-water flow model for the vicinity of the study area in 2004 (Scott Walz, Shakopee Mdewakanton Sioux Community, written commun., 2004). Barr Engineering estimated the horizontal hydraulic conductivity for the layer representing the Franconia Formation and the Ironton and Galesville Sandstones using the results of a 7-day aquifer test conducted in 1999 on the city of Savage well in the Franconia-Ironton-Galesville aquifer. The horizontal hydraulic conductivity estimated for this layer was 6.6 ft/d, and the estimated storage coefficient was 0.4×10^{-6}.

Aquifer Test

A production (pumped) well and two observation wells were used in the aquifer test described in this report (fig. 1). The production well is cased with a 20-in. diameter steel casing to a depth of 179 ft and a 16-in. diameter steel casing from 170 to 570 ft. The casing ends about 25 ft above the bottom of the Franconia Formation. The production well is an open hole from a depth of 570 to 667 ft (table 1; fig. 2). The open hole

Table 1. Driller's log and interpreted natural gamma borehole log of production well and driller's logs of two observation wells, Shakopee Mdewakanton Sioux Community, southeastern Minnesota.

[Natural gamma log made March 16, 1998, by Summit Envirosolutions, Inc. (Minneapolis, Minnesota). Interpretation of natural gamma log by Summit Envirosolutions, Inc. Data provided by Scott Walz, written commun., Shakopee Mdewakanton Sioux Community, 2004. NAVD 88, North American Vertical Datum of 1988]

Thickness (feet)	Depth interval (feet)	Range in elevation above NAVD 88 (feet)	Formation
		Driller's log of production well	
168	0–168	982–814	Gray drift, mixed clay and gravel, medium hard
144	168–312	814–670	Brown limestone, medium hard/hard
181	312–493	670–489	Pink/red sandstone, medium hard/hard
58	493–551	489–431	Green and black dolomite, hard
44	551–595	431–387	Green dolomite, medium hard
40	595–635	387–347	White sandstone, soft
21	635–656	347–326	Gray shale, hard
11	656–667	326–315	White/gray siltstone, medium hard.
			Bottom of hole is 667 feet below land surface
		Interpreted natural gamma log of production well	
125	0–125	982–857	Glacial sediments
186	125–311	857–671	Prairie du Chien Group
90	311–401	671–581	Jordan Sandstone
47	401–448	581–534	St. Lawrence Formation
159	448–607	53–375	Franconia Formation
45	607–652	375–330	Ironton and Galesville Sandstones
15	652–667	330–315	Eau Claire Formation
			Bottom of hole is 667 feet below land surface
		Driller's log of observation well 1	
145	0–145	937–792	Brown drift, medium hard
120	145–265	792–672	Brown limestone, hard
100	265–365	672–572	White sandstone, soft
45	365–410	572–527	St. Lawrence, green, hard
145	410–555	527–382	Franconia, green, hard
65	555–620	382–317	Ironton, white, medium hard
	620	317	Eau Claire, green, hard
			Bottom of hole is 620 feet below land surface
		Driller's log of observation well 2	
252	0–252	1,023–771	Brown drift, medium hard
88	252–340	771–683	Brown limestone, hard
105	340–445	683–578	Orange sandstone, soft
57	445–502	578–521	St. Lawrence, green, hard
133	502–635	521–388	Franconia, green, hard
77	635–712	388–311	Ironton-Galesville, white, hard
	712	311	Eau Claire, green, hard
			Bottom of hole is 712 feet below land surface

was enlarged by blasting and removing sand and sandstone to form a chamber at least 20 ft across (Stan Ellison, Shakopee Mdewakanton Sioux Community, oral commun., 2004). The pump is set inside the casing. The bottom of the pump is at a depth of 465 ft. The production well was not pumped between September 17 and December 6, 2004, which was the beginning date for the aquifer test.

Observation well 1 is 3,247 ft northwest of the production well. The well is cased with an 8-in. diameter steel casing from 0 to 145 ft and 4-in. diameter casing from 145 to 520 ft. The well is a 4-in. diameter open hole from 520 to 620 ft. Observation well 2 is 3,049 ft southeast of the production well. The well is cased with 8-in. diameter steel casing from 0 to 252 ft and with a 4-in. diameter steel casing from 252 to 623 ft. The well is a 4-in. diameter open hole from 623 to 712 ft. Both observation wells were cased to about the same elevation as the production well (fig. 2) so that they were all open to the same formations.

Water levels in the production well were recorded every 10 seconds during the aquifer test with a transducer that is part of the Shakopee Community's monitoring system. The depth of the transducer below land surface was not known, and drawdown and recovery water levels in the well were measured from an arbitrary datum. The transducer appeared to have moved about the time recovery began; the recorded water levels at the end of recovery were about 8 ft higher than at the beginning of the aquifer test (fig. 3*A*, table A1 in appendix). Water levels in the production well also were measured manually with an electric tape for 1 hour at 1- to 5-minute intervals after the pump was shut off (fig. 3*B*, table A2 in appendix). The depth to water was measured from the measuring point at the top of the well, which is 985.02 ft above NAVD 88. A comparison of the water levels measured with an electric tape and those recorded by the transducer is shown in figure 3*C*.

Pressure transducers also were used to record changes in water levels in the observation wells (fig. 4, table A3). The pressure of the water above the transducer was measured and recorded every 90 seconds or when the pressure changed by 0.004 lb/in^2 (an approximate 0.01-ft change in water level). Manual measurements of the water depth below the top of the well casing were made using an electric tape during the aquifer test and during recovery. These measurements were used to convert the measured pressures to water-level elevations in the wells.

Background water levels were measured before the beginning of the aquifer test in both observation wells (fig. 5). These measurements show that the potentiometric surface in the aquifer increased by about 1 ft in the week prior to the beginning of the test.

Barometric pressure was measured at a weather station maintained by the Shakopee Community adjacent to observation well 1. The recorded barometric pressure is shown in figures 5 and 6. The barometric efficiency of both observation wells was computed from the water levels measured before the beginning of the aquifer test. The barometric efficiency (*B*) of a well is defined as:

$$B = \frac{\gamma \Delta h}{\Delta p_a}, \qquad (1)$$

where γ is the specific weight of water (62.409 lb/ft^3 at 50 °F, the approximate temperature of the water in the Ironton and Galesville Sandstones); Δh is the change in water level in the well; and Δp_a is the change in atmospheric pressure (Todd, 1980, p. 236). The barometric efficiencies of observation wells 1 and 2 were estimated to be -0.52 and -0.34, respectively. The expected water-level changes caused by barometric pressure changes are shown in figure 6. The largest expected change in water level was about 1 ft for both wells. Consequently, the measured water levels in the observation wells during the test were not adjusted for changes in atmospheric pressure because the measured changes were greater than 33 ft, which is much greater than the 1-ft change in water level caused by changing atmospheric pressure.

The discharge from the production well pump was measured by a discharge meter that recorded the number of gallons pumped. The pumping rate in gallons per minute (gal/min) was determined by dividing the gallons pumped over 6 minutes by 6. Pumping rates measured by this method are listed in table 2. The discharge from the pump was not regulated; the pump operated at its greatest output. Therefore, when the water level in the production well declined, the output of the pump decreased. Average discharge during the aquifer test was 610 gal/min. The water pumped from the well was discharged to a wetland about 430 ft from the well. The discharged water did not infiltrate to the pumped aquifer because of the intervening confining units (fig. 2) and was assumed not to affect the measured water levels during the test.

The aquifer test began at 10:30 a.m. on December 6, 2004. The pump was shut off December 9 at 3:26 p.m. The pump was turned on briefly December 13 as indicated by the drawdown spike in figure 3. The recorded and measured water levels for the production well are presented in tables A1 and A2 in the appendix and are shown in figure 3. Drawdowns for the pumped well and observation wells were used in the analyses of aquifer properties. However, the measured recovery for the production well was not used in the analyses of aquifer properties because the transducer seemed to have moved when the pump was turned off on December 9 and when it was turned on briefly on December 13. Drawdown and recovery were recorded in both observation wells from December 6–22, 2004. The recorded drawdown and recovery for both observation wells are given in table A3 of the appendix and are shown in figure 4.

The cities of Prior Lake, Savage, and Shakopee, Minnesota (fig. 1), also withdraw water from wells screened in the Ironton and Galesville Sandstones. Pumpage in these wells may affect the water levels in the two observation wells used for this aquifer study (Jay Frischman, Minnesota Department of Natural Resources, written commun., 2005). However, the

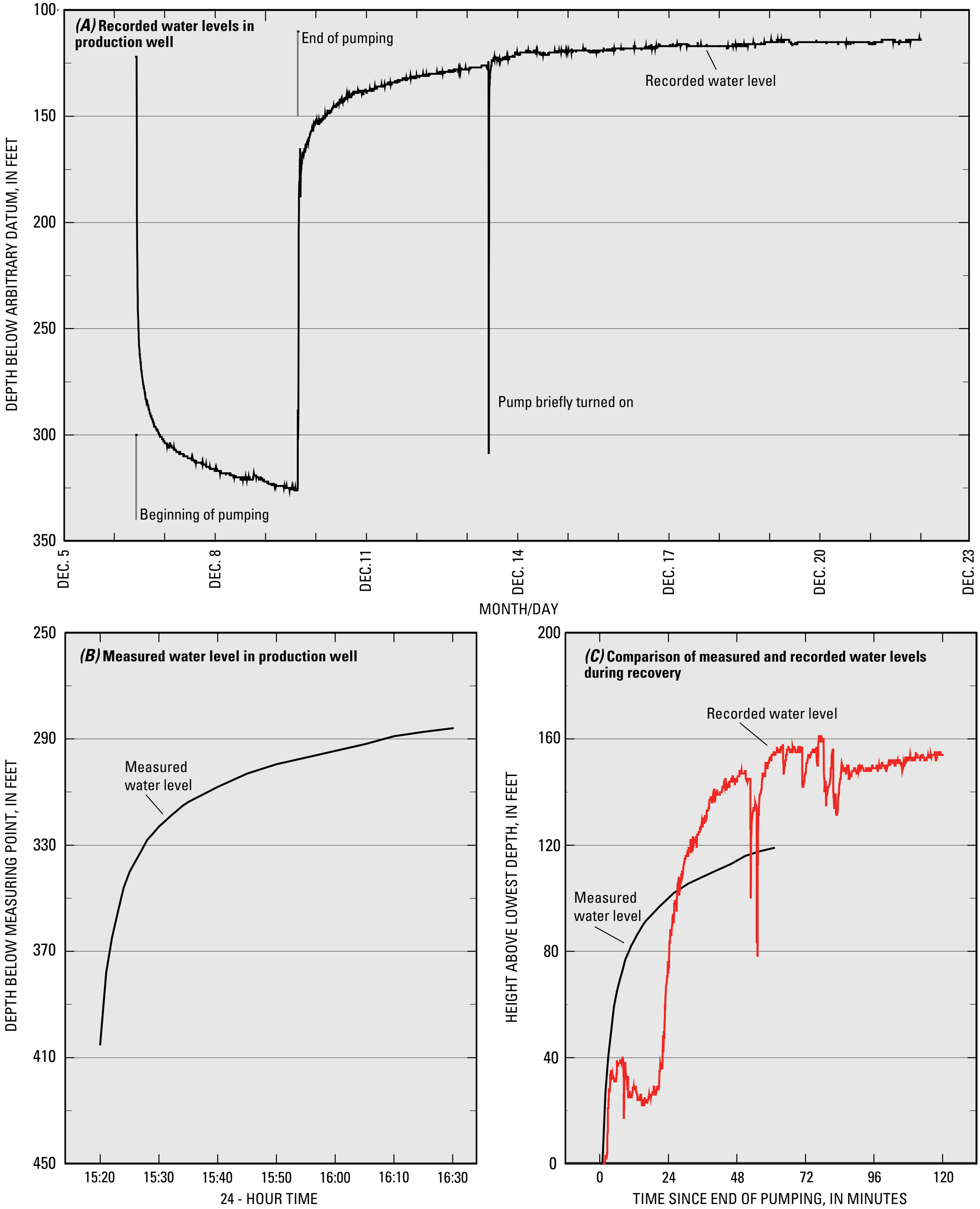

Figure 3. *(A)* Recorded water levels during aquifer test for production well, December 6–22, 2004, *(B)* measured water levels in production well, December 9, 2004, and *(C)* comparison of measured and recorded water levels during production well recovery, December 9, 2004.

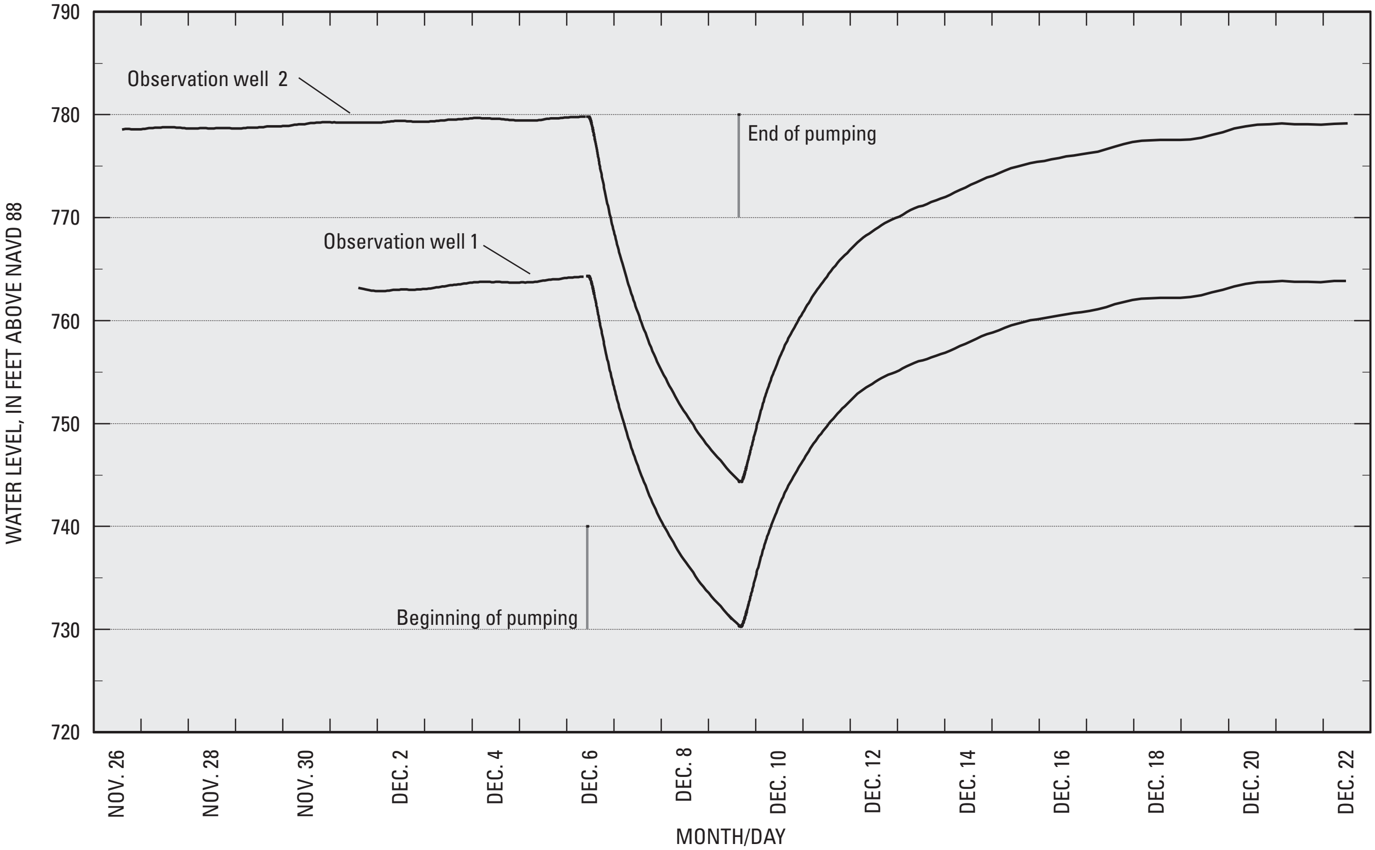

Figure 4. Recorded water levels in observation wells 1 and 2, November 26–December 22, 2004.

wells in these nearby communities were not pumped during the aquifer test (Lanya Ross, Shakopee Mdewakanton Sioux Community, oral commun., 2005).

Aquifer-Test Analysis and Hydraulic Properties of the Ironton and Galesville Sandstones

Four curve-fitting methods and two graphical methods were used to estimate the transmissivity and storage coefficient of the Ironton and Galesville Sandstones. The commercial software AQTESOLV (HydroSOLVE, 2000) was used to apply the six methods to the data collected during the aquifer test. The four curve-fitting methods were the Theis, Hantush, Hantush-Jacob, and Neumann-Witherspoon methods. These methods were applied to the drawdown and residual recovery curves of the observation wells. The two graphical methods were the Cooper-Jacob method and the Theis recovery method. The Cooper-Jacob method was applied to the drawdown curve of the production well and the drawdown curves of the two observation wells. The Theis recovery method was applied to the residual drawdown curves of the two observation wells.

All six methods were developed for very specific aquifer and ground-water flow conditions. The following conditions apply for all six methods (HydroSOLVE, 2000): (1) the aquifer has infinite areal extent, (2) the aquifer is homogenous, isotropic, and of uniform thickness, (3) the flow is unsteady, (4) water is released instantaneously from storage with decline of hydraulic head, and (5) the diameter of the pumped well is very small so that storage in the well can be neglected. The Theis, Cooper-Jacob, and Theis recovery methods were developed for confined aquifers that are not leaky; that is, water does not pass through the confining layers into the aquifer. The Hantush, Hantush-Jacob, and Neumann-Witherspoon methods were developed for leaky aquifers; that is, water moves through the confining layers into the aquifer from aquifers above or below it. Additional conditions for the use of the methods are mentioned in the discussion for each method.

The Theis (Ferris and others, 1962; Todd, 1980; HydroSOLVE, 2000), Hantush (Hantush, 1960; HydroSOLVE, 2000), Hantush and Jacob (Hantush and Jacob, 1955; HydroSOLVE, 2000), and Neuman-Witherspoon (Neuman and Witherspoon, 1969; HydroSOLVE, 2000) methods were applied to the drawdown and recovery data for the two observation wells. The equations for each method are discussed briefly in following paragraphs.

Additional conditions necessary for use of the Theis method (HydroSOLVE, 2000) are: (1) the pumped well is

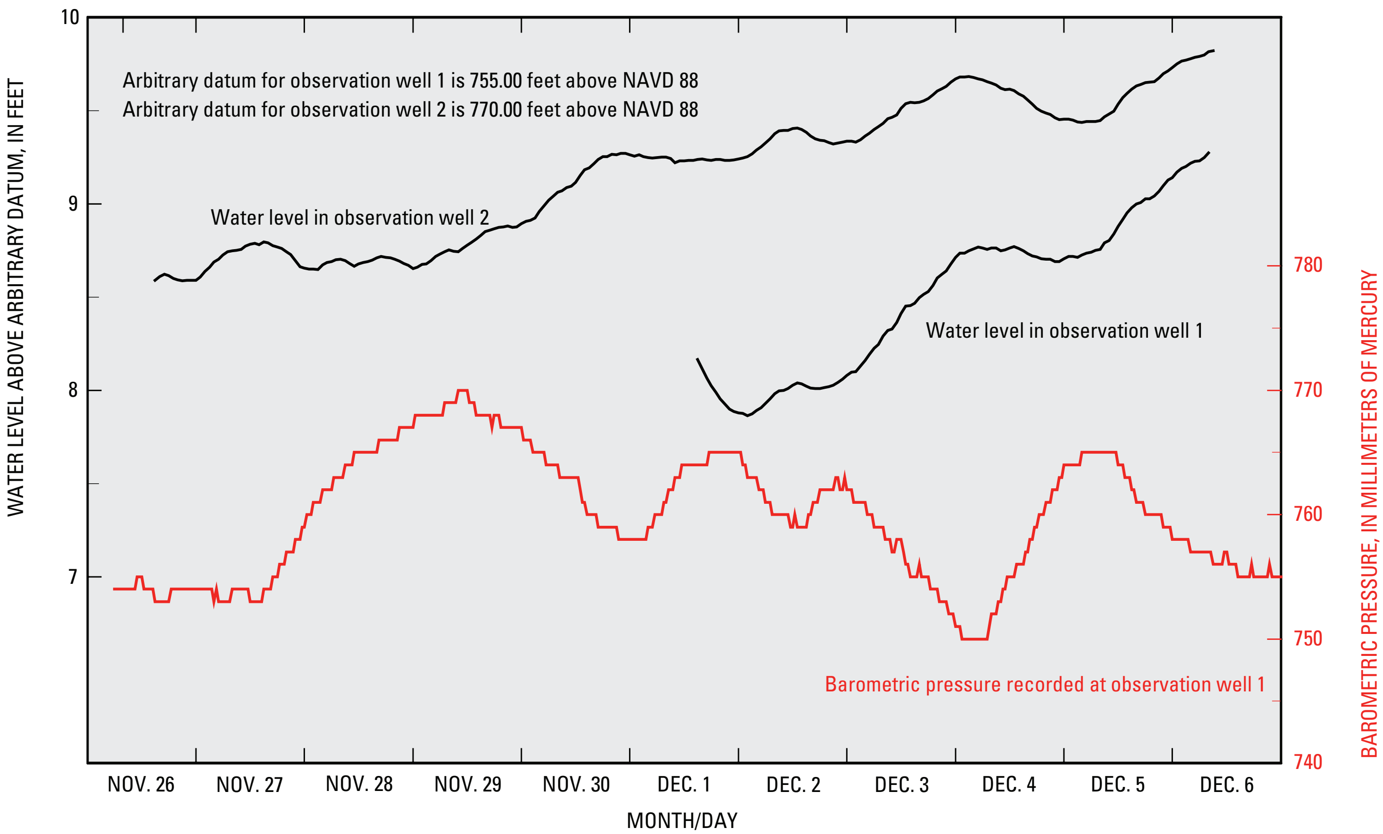

Figure 5. Recorded water levels in observation wells 1 and 2 and recorded barometric pressure at observation well 1 before aquifer test, November 26–December 6, 2004.

fully or partially penetrating, (2) flow to the pumped well is horizontal when the pumped well fully penetrates the aquifer, and (3) the aquifer is confined. The Theis method relates the drawdown (*s*) observed in a well as a result of pumping from another well at a discharge (*Q*) to the transmissivity (*T*) and storage coefficient (*S*) of an aquifer by the following equation:

$$s = \left(\frac{Q}{4\pi T}\right) W(u), \tag{2}$$

where *W(u)*, termed the well function, is a convenient symbolic form of the following integral:

$$\int_u^\infty \frac{e^{-u}du}{u}; \tag{3}$$

where

$$u = \frac{r^2 S}{4Tt}, \tag{4}$$

r is the radial distance from the pumped well, and *t* is the time since beginning of pumping (Todd, 1980, p. 123). The integral can be expanded as a convergent series (Todd, 1980, p. 124):

$$-0.5772 - \ln u + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} - \frac{u^4}{4 \cdot 4!} + \ldots . \tag{5}$$

Additional conditions necessary for use of the Hantush method are (HydroSOLVE, 2000): (1) the aquifer potentiometric surface is initially horizontal, (2) the pumped well fully or partially penetrates the aquifer, (3) flow to the pumped well is horizontal when the pumped well fully penetrates the aquifer, (4) the aquifer is leaky, (5) the confining bed(s) has infinite areal extent, uniform vertical hydraulic conductivity and storage coefficient, and uniform thickness, (6) confining bed(s) has uniform storage coefficient, (7) confining bed(s) is overlain or underlain by an infinite constant-head plane source, and (8) the flow in the confining bed(s) is vertical.

The drawdown curve given by Hantush (Hantush, 1960; HydroSOLVE, 2000) is

$$s = \frac{Q}{4\pi T} \int_u^\infty \frac{e^{-y}}{y}\, erfc \frac{\beta\sqrt{u}}{\sqrt{y(y-u)}}\, dy, \tag{6}$$

where

$$u = \frac{r^2 S}{4Tt}; \text{ and} \tag{7}$$

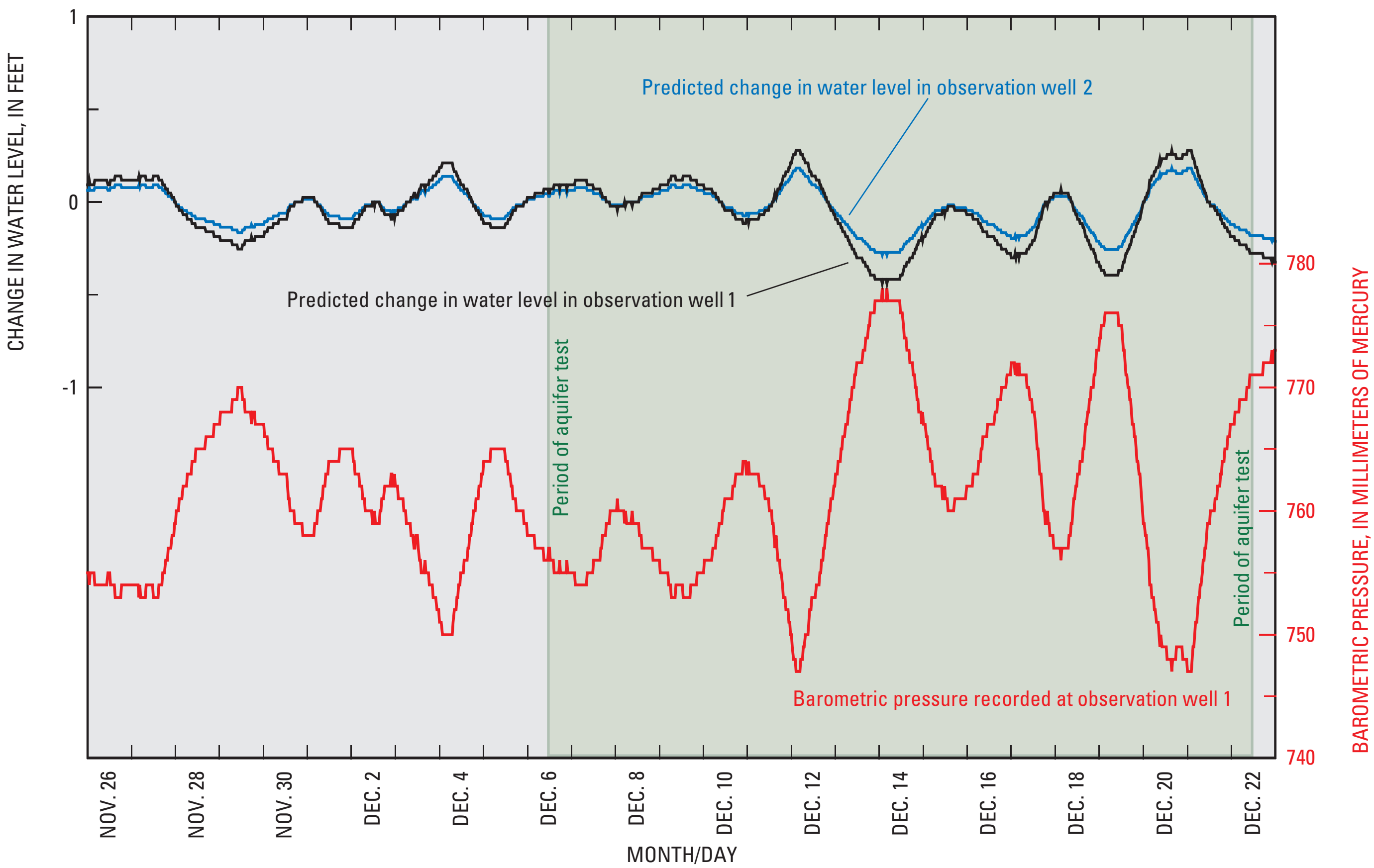

Figure 6. Predicted changes in water levels in observation wells 1 and 2 due to changes in barometric pressure during aquifer test, November 26–December 22, 2004.

$$\beta = \frac{r}{4}\left[\sqrt{\frac{K'/b'}{T}\frac{S'}{S}} + \sqrt{\frac{K''/b''}{T}\frac{S''}{S}}\right], \tag{8}$$

where y is the variable of integration;
b', b″ are the thickness of the confining layers;
K', K″ are the vertical hydraulic conductivities of the confining layers;
S', S″ are the storage coefficients of the confining layers;
and all other terms as previously defined.

Additional conditions necessary for use of the Hantush-Jacob method are (HydroSOLVE, 2000): (1) the aquifer potentiometric surface is initially horizontal, (2) pumped well fully or partially penetrates the aquifer, (3) the aquifer is leaky, (4) the confining bed(s) has infinite areal extent, uniform vertical hydraulic conductivity, and uniform thickness, (5) confining bed(s) is overlain or underlain by an infinite constant-head plane source, and (6) the flow in the confining bed(s) is vertical.

The drawdown curve given by Hantush and Jacob (1955) is:

$$s = \frac{Q}{4\pi T} w(u, r/B), \tag{9}$$

where w(*u,r/B*) is the Hantush function for leaky aquifers;

$$\int_u^\infty \frac{e^{-y-r^2/4B^2y}}{y}dy; \tag{10}$$

and

$$u = \frac{r^2 S}{4Tt}; \tag{11}$$

$$B = \sqrt{\frac{Tb'}{K'}}; \text{ and} \tag{12}$$

all other terms as previously defined.

Additional conditions necessary for use of the Neumann-Witherspoon method are (HydroSOLVE, 2000): (1) the aquifer potentiometric surface is initially horizontal, (2) the pumped well fully penetrates the aquifer, (3) flow to the pumped well is horizontal, (4) the aquifer is leaky, (5) the confining bed(s) has infinite areal extent, uniform vertical hydraulic conductivity, uniform storage coefficient, and uniform thickness, (6) confining bed(s) has uniform storage coefficient (7) confining bed(s) is overlain or underlain by an

Table 2. Measured pumping rate from production well, Shakopee Mdewakanton Sioux Community, southeastern Minnesota, December 6–9 , 2004.

[gal/min, gallons per minute]

Time from start of pumping (hours)	Measured pumping rate (gal/min)
1	644.5
2	637.0
3	630.0
4	630.0
5	627.0
21	612.0
22	613.0
23	611.0
24	611.0
25	609.4
26	610.0
28	609.8
29	609.2
45	604.4
46	604.4
49	603.8
50	603.2
53	602.2
54	603.0
69	600.0
70	599.8
72.75	599.2
Average	**610**

infinite constant-head plane source, and (8) the flow in the confining bed(s) is vertical.

The drawdown equation given by Neuman and Witherspoon (Neuman and Witherspoon, 1969; HydroSOLVE, 2000) is:

$$s = \frac{Q}{4\pi T}\int_0^\infty \left(1 - e^{-y\bar{t}_{D1}}\right)\left(\left[1 + G(y)\right]J_o\left[\omega_1(y)\right] + \left[1 - G(y)\right]J_o\left[\omega_2(y)\right]\right)\frac{dy}{y}, \quad (13)$$

where

b_i is the thickness of i^{th} aquifer;

b_j is thickness of j^{th} confining layer;

K_i is permeability of the i^{th} aquifer;

K_j is permeability of the j^{th} aquifer;

S_i is specific storage for the i^{th} aquifer;

S_j is specific storage for the j^{th} confining layer;

$$t_{Di} = \frac{K_i t}{Ss_i r^2}, \quad (14)$$

dimensionless time for pumped (i^{th}) aquifer;

$$\bar{t}_{D1} = \frac{t_{D1}\left(\frac{r}{B_{11}}\right)^4}{\left(4\beta_{11}\right)^2}; \quad (15)$$

$$\frac{r}{B_{ij}} = r\sqrt{\frac{K_j'}{T_i b_j'}}, \quad (16)$$

r/B$_{11}$ refers to the pumped aquifer, *r/B*$_{21}$ refers to the unpumped aquifer;

$$\beta_{ij} = \frac{r}{4b_i\sqrt{\frac{K'jS'sj}{K_i S_{si}}}}; \quad (17)$$

ß$_{11}$ refers to the pumped aquifer, ß$_{21}$ refers to the unpumped aquifer;

$$G(y) = \frac{M(y)}{F(y)}; \quad (18)$$

$$\omega_1^2(y) = \frac{1}{2}\left[N(y) + F(y)\right]; \quad (19)$$

$$G(y) = \frac{M(y)}{F(y)}; \quad (20)$$

$$F^2(y) = M^2(y) + \left[\frac{2\left(\frac{r}{B_{11}}\right)\left(\frac{r}{B_{21}}\right)y}{\sin y}\right]^2; \quad (21)$$

$$M(y)=\left[\frac{\left(\frac{r}{B_{11}}\right)^4}{(4\beta_{11})^2}-\frac{\left(\frac{r}{B_{21}}\right)^4}{(4\beta_{21})^2}\right]y^2- \left[\left(\frac{r}{B_{11}}\right)-\left(\frac{r}{B_{21}}\right)^2\right]y\cot y; \tag{22}$$

and all other terms are as previously defined. The fitted curves and recorded data are shown in figures 7 and 8, and the estimated aquifer transmissivities and storage coefficients are given in table 3.

The Cooper-Jacob method (Todd, 1980, p. 129–130) was applied to the drawdown curves of the production well and the two observation wells. The Theis recovery method (Ferris and others, 1962, p. 100–102; Jacob, 1963, p. 283; Todd, 1980, p. 131–133) was applied to the residual drawdown curves of the two observation wells.

Additional conditions necessary for use of the Cooper-Jacob method are (HydroSOLVE, 2000): (1) aquifer potentiometric surface is initially horizontal, (2) the pumped well fully penetrates the aquifer, (3) flow to the pumped well is horizontal, (4) the aquifer is confined, and (5) values of *u* are small. The Cooper-Jacob method is derived from the Theis equation for unsteady radial flow in a confined aquifer (Todd, 1980, p. 129). In this method a straight line is fitted to the straight portion of the drawdown curve plotted on semilogarithmic paper. The drawdown across one log cycle (s_{10}) is determined, and the transmissivity (*T*) and storage coefficient (*S*) are determined from the following two equations:

$$S=\frac{2.25Tt_o}{r^2}, \tag{23}$$

and

$$T=\frac{2.30Q}{4\pi s_{10}}, \tag{24}$$

where t_0 is the point where the fitted line crosses the time axis (the drawdown, *s*, is 0), *r* is the distance from the pumped well, and *Q* is the pumping rate. This method can be used when

$$u=\frac{r^2S}{4Tt}\leq 0.05, \tag{25}$$

(Heath, 1983).

The Cooper-Jacob method was applied to the drawdown record of the production well and the two observation wells (fig. 9). The storage coefficient was not computed for the production well because it is dependent on the radius of the production well chamber, which is not known. The value of *u* ranges from 0.06 to 0.24 for the observation wells and is less than 1 x 10^{-5} for the production well. The estimated aquifer transmissivities and storage coefficients are given in table 3.

The Theis recovery method is derived from the fact that if a well is pumped for a known period of time and then shut down and allowed to recover, the residual drawdown at any instant will be the same as if the discharge of the well had been continued and a recharge well with the same flow had been introduced at the same point at the instant the discharge stopped. The residual drawdown is the difference between the observed water level and the water level before pumping began. The residual water level is plotted on a semilogarithmic plot against $\frac{t}{t'}$, where *t* is the time since the aquifer test began and *t´* is the time since the pump was shut off (Todd, 1980, p. 133). A straight line is fitted to the straight portion of the curve, and the residual drawdown per log cycle ($\Delta s'$) is determined. The transmissivity is determined from:

$$T=\frac{2.30Q}{4\pi\Delta s'}. \tag{26}$$

The storage coefficient cannot be estimated using the Theis recovery method.

AQTESOLV was used to solve the Theis recovery method. It solves for a slightly different equation (HydroSOLVE, 2000):

$$s''=\frac{Q}{4\pi T}\left[\ln\left(\frac{t}{t'}\right)-\ln(S_r)\right], \tag{27}$$

where s'' is the residual displacement, and S_r is the ratio of storativity during pumping to storativity during recovery Equation 27 can be transformed into equation 26 if $\log_{10}$ is used instead of the natural log and the s'' is selected a log cycle apart. S_r is determined by where the straight line intercepts the $\log_{10}(t/t')$ axis. The value of S_r should be about 1 if there are no boundary effects (HydroSOLVE, 2000). If $S_r > 1$, there is indication of a recharge boundary during the aquifer test; $S_r < 1$ suggests the presence of a barrier or no-flow boundary (HydroSOLVE, 2000).

The Theis recovery method was applied to the residual drawdown data for both observation wells (fig. 10). The estimated transmissivities are shown in table 3.

The transmissivity estimated using the six methods ranged from 450 to 650 ft^2/d (table 3). As shown in table 3, the average transmissivity for the fitted methods (Theis, Hantush, Hantush-Jacob, and Neuman-Witherspoon) was 510 ft^2/d; the average transmissivity for the Cooper-Jacob and Theis recovery graphical methods was 600 ft^2/d; and the average transmissivity for all six methods was 540 ft^2/d. The average transmissivity for the three methods developed for nonleaky aquifers, Theis, Cooper-Jacob, and Theis recovery, was 590 ft^2/d. The

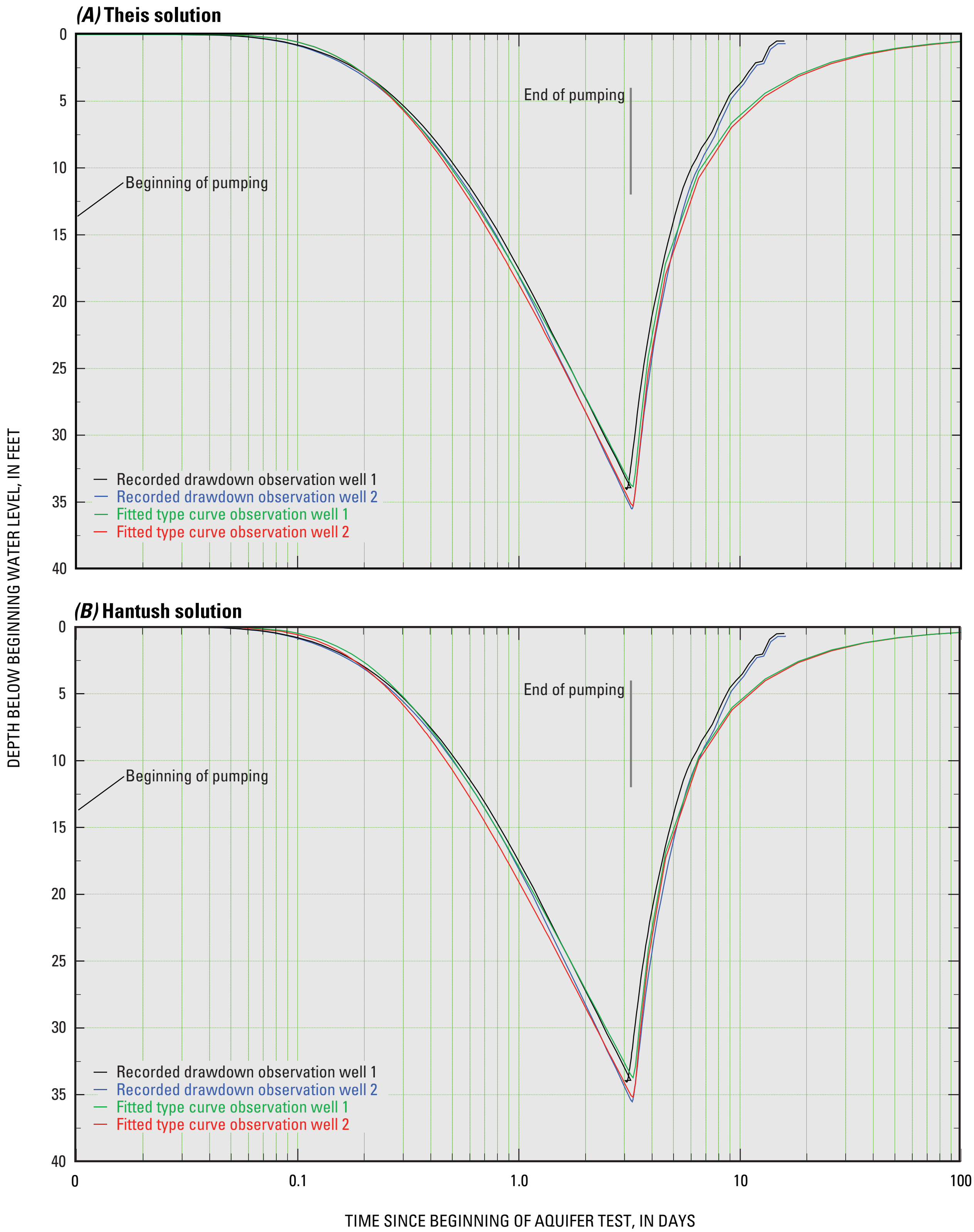

Figure 7. ***(A)*** Theis and ***(B)*** Hantush fitted type curves and recorded water levels for observation wells 1 and 2, December 6–22, 2004.

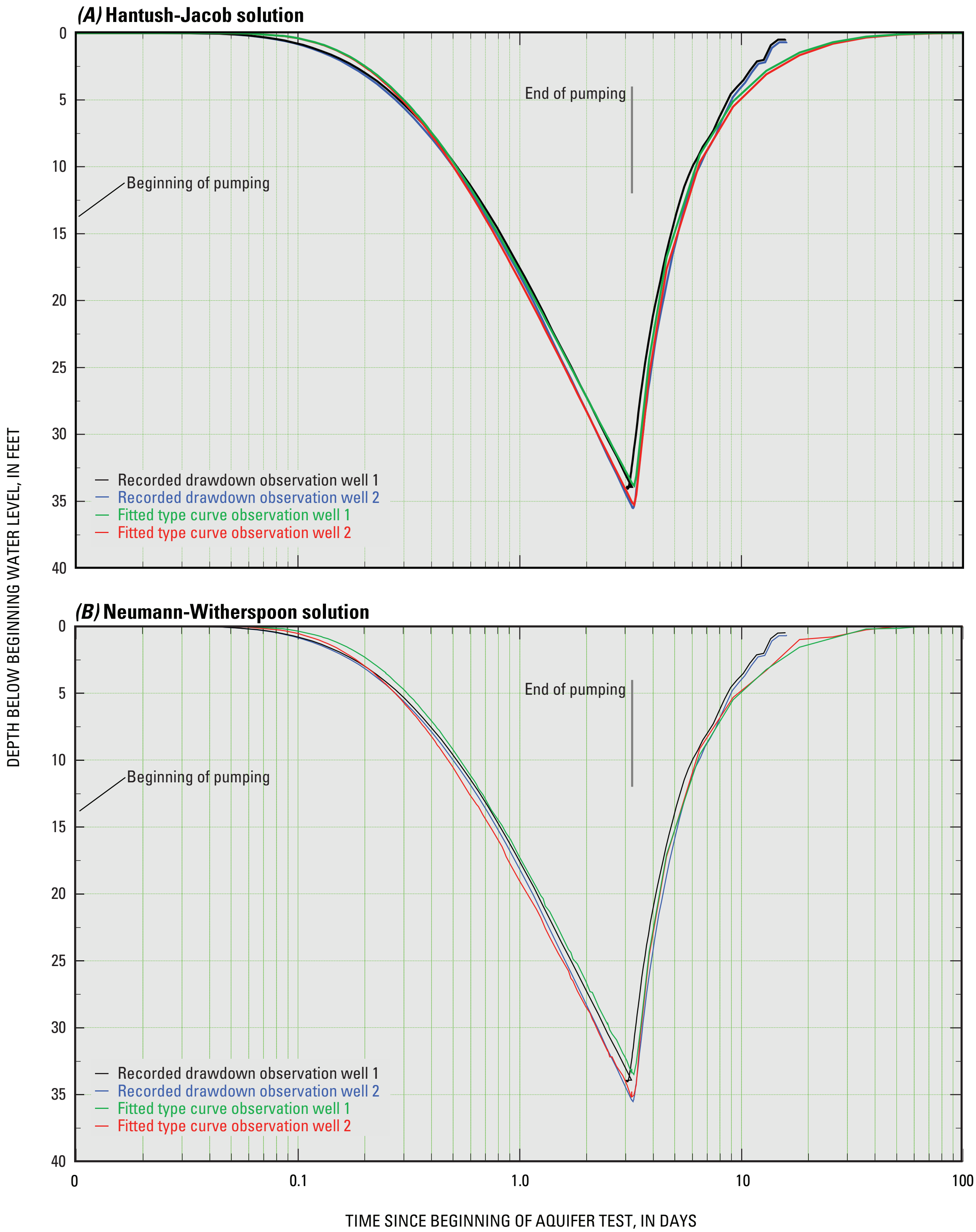

Figure 8. ***(A)*** Hantush-Jacob and ***(B)*** Neumann-Witherspoon fitted type curves and recorded water levels in observation wells 1 and 2, December 6–22, 2004.

Table 3. Estimated aquifer properties of Ironton and Galesville Sandstones, Shakopee Mdewakanton Sioux Community, southeastern Minnesota.

[*Sr*, ratio of storativity during pumping to storativity during recovery; *r/B*, dimensionless leakage factor; *B*, leakage factor; *T'* , vertical transmissivity in confining unit overlying aquifer; *S'*, coefficient of storage in confining unit overlying aquifer; K_v/K_x, ratio of vertical hydraulic conductivity to horizontal hydraulic conductivity; *b*, thickness of aquifer; ft²/d, feet squared per day; ft, feet; ft/d, feet per day; --, not applicable]

Method used to estimate aquifer properties	Well(s) for which estimates were made	Transmissivity, T, (ft²/d)	Storage coefficient, S (dimensionless)	Sr	r/B	B	T′ (ft²/d)	S′	K_v/K_x	b (ft)	Hydraulic conductivity, K (ft/d)
Theis	Observation well 1	590	5.1 x 10-5	--	--	--	--	--	0.1	45	13.1
	Observation well 2	560	5.6 x 10-5	--	--	--	--	--	.1	45	12.4
Hantush	Observation well 1	450	4.3 x 10-5	--	--	0.0767	--	--	.1	45	10.0
	Observation well 2	480	4.8 x 10-5	--	--	.0530	--	--	.1	45	10.7
Hantush-Jacob	Observation well 1	520	5.2 x 10-5	--	0.2319	--	--	--	.1	45	11.6
	Observation well 2	500	5.7 x 10-5	--	.2218	--	--	--	.1	45	11.1
Neuman-Witherspoon	Observation well 1	490	5.0 x 10-5	--	.2496	.0400	1.0 x 10-5	0.0591	--	--	10.9
	Observation well 2	490	5.0 x 10-5	--	.2496	.0400	1.0 x 10-5	.0591	--	--	10.9
Average fitted methods		510	5.1 x 10-5								11.3
Cooper-Jacob	Observation well 1	650	4.2 x 10-5	--	--	--	--	--	--	--	14.4
	Observation well 2	620	4.6 x 10-5	--	--	--	--	--	--	--	13.8
	Production well	590	--	--	--	--	--	--	--	--	13.1
Theis recovery	Observation well 1	580	--	1.105	--	--	--	--	--	--	12.9
	Observation well 2	540	--	1.111	--	--	--	--	--	--	12.0
Average graphical methods		600	4.4 x 10-5								13.2
Average all methods		540	5.0 x 10-5								12.1

average transmissivity for the other three methods, which were developed for leaky aquifers, was 490 ft²/d.

The storage coefficient estimated using the six methods ranged from 4.2 to 5.7 x 10^{-5}. As shown in table 3, the average storage coefficient for the fitted methods, Theis, Hantush, Hantush-Jacob, and Neuman-Witherspoon, was 5.1 x 10^{-5}; the average storage coefficient for the Cooper-Jacob graphical method was 4.4 x 10^{-5}; and the average storage coefficient for all six methods was 5.0 x 10^{-5}. The average storage coefficient for the two methods developed for nonleaky aquifers, Theis and Cooper-Jacob, was 4.9 x 10^{-5}. The average storage coefficient for the other three methods with estimated values, which were developed for leaky aquifers, was 5.0 x 10^{-5}.

The hydraulic conductivity was estimated by dividing the estimated transmissivity by 45 ft, which is the thickness of the aquifer at the production well. As shown in table 3, it ranged from 10.0 to 14.4 ft/d. The average hydraulic conductivity for all six methods was 12.1 ft/d.

Summary

The U.S. Geological Survey, in cooperation with the Shakopee Mdewakanton Sioux Community, conducted an aquifer test December 6–22, 2004, to improve definition of the hydraulic properties of the Ironton and Galesville Sandstones

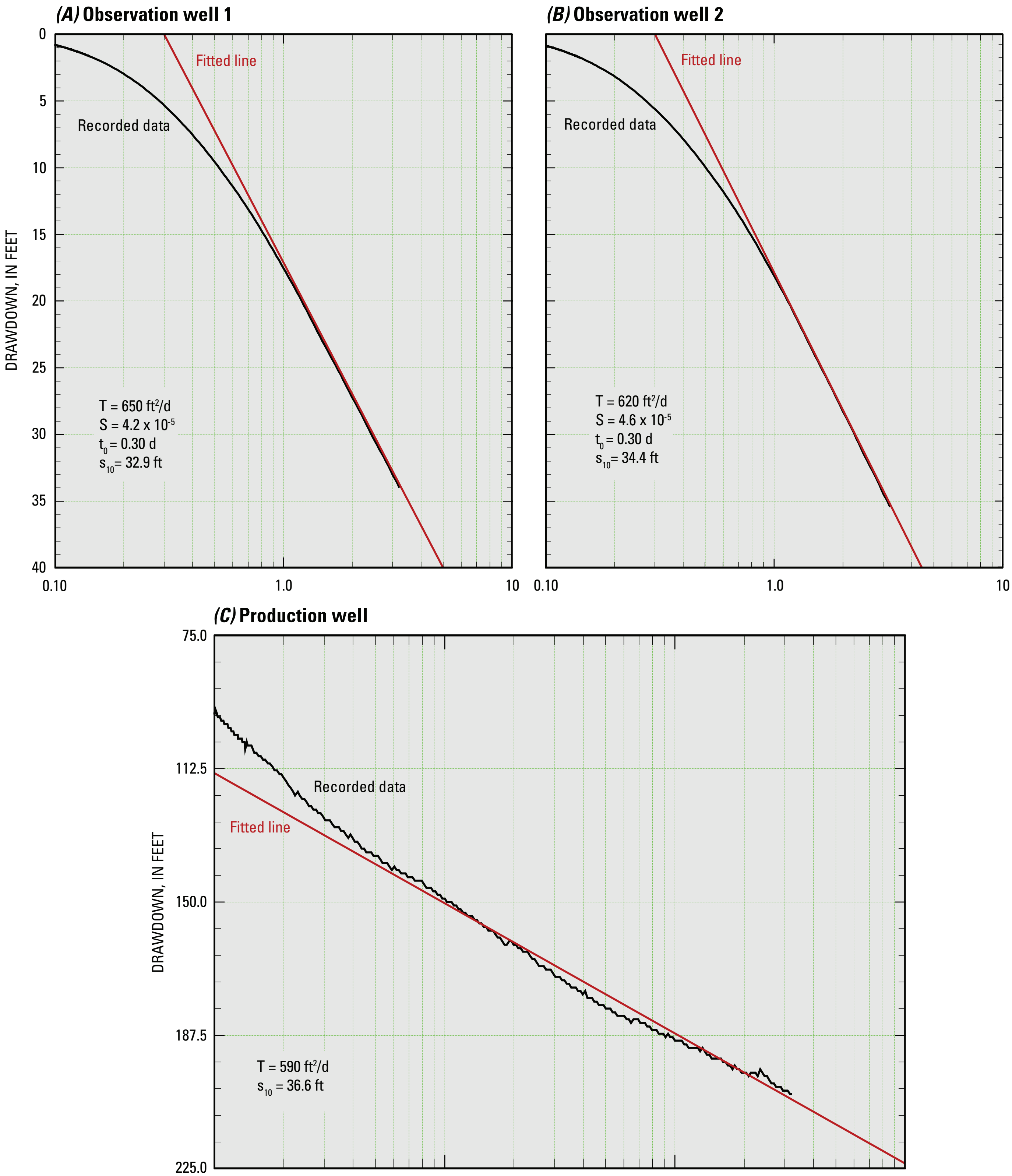

Figure 9. Cooper-Jacob method of solution applied to recorded drawdown of ***(A)*** observation well 1, ***(B)*** observation well 2, and ***(C)*** production well, December 6–9, 2004. [T = transmissivity; S = storage coefficient; t_o = point where line crosses axis at 0 drawdown; S_{10} = drawdown across one log cycle]

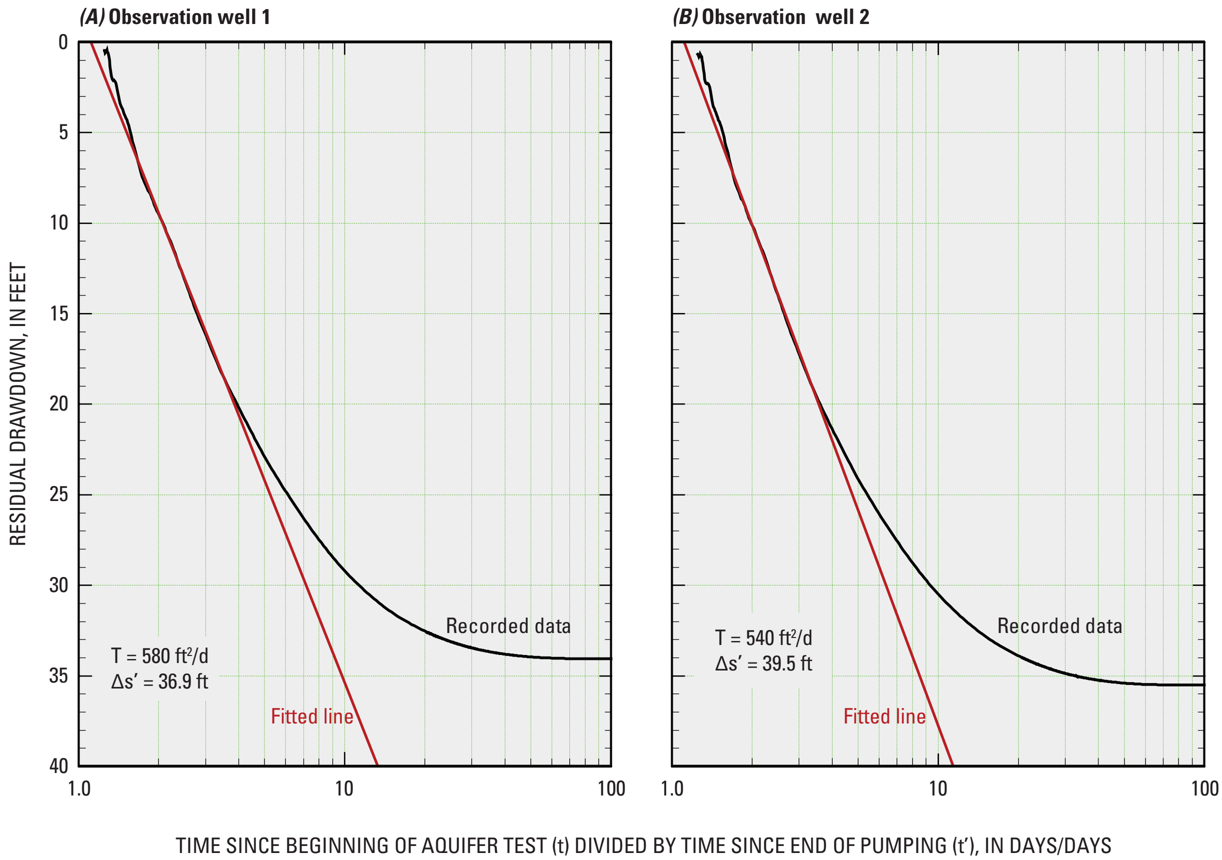

Figure 10. Theis recovery method applied to residual recovery curves for ***(A)*** observation well 1 and ***(B)*** observation well 2, December 9–22, 2004. [T = transmissivity drawdown per log cycle; Δs´ = change in coefficient of storage]

beneath the Shakopee Community in southeastern Minnesota. One production well and two observation wells were used in the aquifer test. The production well, Franconia-Ironton-Galesville Well No. 2, is cased with a 20-in. diameter steel casing from 0 to 179 ft and a 16-in. diameter steel casing from 170 to 570 ft, and is an open hole from 570 to 667 ft. The casing ends about 25 ft above the bottom of the Franconia Formation. The bottom of the pump is at a depth of 465 ft. Observation well 1 is located 3,247 ft northwest of the production well. The well is cased with an 8-in. diameter steel casing from 0 to 145 ft, a 4-in. diameter steel casing from 145 to 520 ft, and is a 4-in. diameter open hole from 520 to 620 ft. Observation well 2 is located 3,049 ft southeast of the production well. The well is cased with a 8-in. diameter steel casing from 0 to 252 ft, a 4-in. diameter steel casing from 252 to 623 ft, and is a 4-in. diameter open hole from 623 to 712 ft. Both observation wells were cased to about the same elevation as the production well so that they were open to the same formations.

The aquifer test began at 10:30 a.m. December 6, 2004. The production well was pumped at about 600 gal/min. The pump was shut off December 9, 2004, at 3:26 p.m. Drawdown and recovery were recorded in the production well and both observation wells December 6–22.

Four curve-fitting methods and two graphical methods were used to estimate the transmissivity and storage coefficient of the Ironton and Galesville Sandstones. The four curve-fitting methods were the Theis, Hantush, Hantush-Jacob, and Neumann-Witherspoon methods. These methods were applied to the drawdown and residual recovery curves of the observation wells. The two graphical methods were the Cooper-Jacob method and the Theis recovery method. The Cooper-Jacob method was applied to the drawdown curve of the production well and the drawdown curves of the two observation wells. The Theis recovery method was applied to the residual drawdown curves of the two observation wells

The transmissivity estimated using the six methods ranged from 450 to 650 ft^2/d. The average transmissivity for the fitted methods, Theis, Hantush, Hantush-Jacob, and Neuman-Witherspoon, was 510 ft^2/d; the average transmissivity for the Cooper-Jacob and Theis recovery graphical methods was 600 ft^2/d; and the average transmissivity for all six methods was 540 ft^2/d. The average transmissivity for the three methods developed for nonleaky aquifers, Theis, Cooper-Jacob, and Theis recovery, was 590 ft^2/d. The average transmissivity for the other three methods, which were developed for leaky aquifers, was 490 ft^2/d.

The storage coefficient estimated using the six methods ranged from 4.2 to 5.7 x 10^{-5}. The average storage coefficient for the fitted methods, Theis, Hantush, Hantush-Jacob, and Neuman-Witherspoon, was 5.1 x 10^{-5}; the average storage coefficient for the Cooper-Jacob graphical method was 4.4 x 10^{-5}; and the average storage coefficient for all six methods was 5.0 x 10^{-5}. The average storage coefficient for the two methods developed for nonleaky aquifers, Theis and Cooper-Jacob, was 4.9 x 10^{-5} . The average storage coefficient for the other three methods with estimated values, which were developed for leaky aquifers, was 5.0 x 10^{-5}.

The hydraulic conductivity was estimated by dividing the estimated transmissivity by 45 ft. It ranged from 10.0 to 14.4 ft/d. The average hydraulic conductivity for all six methods was 12.1 ft/d.

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Appendix

Table A1. Recorded water levels in production well, Shakopee Mdewakanton Sioux Community, December 6–22, 2004.

[Aquifer test began at 10:30 a.m., December 6, 2004]

Time since beginning of pumping, in days	Recorded water level, in feet below datum	Time since beginning of pumping, in days	Recorded water level, in feet below datum	Time since beginning of pumping, in days	Recorded water level, in feet below datum	Time since beginning of pumping, in days	Recorded water level, in feet below datum
0	122	0.022	241	0.101	272	0.499	302
.001	146	.023	242	.108	273	.526	303
.001	163	.024	243	.114	274	.550	304
.002	178	.025	244	.119	275	.597	305
.003	190	.026	245	.126	276	.631	306
.003	194	.027	246	.133	277	.731	307
.005	195	.029	247	.140	278	.783	308
.006	198	.030	248	.148	279	.833	309
.006	203	.031	249	.156	280	.915	310
.007	206	.033	250	.163	281	.974	311
.008	209	.034	251	.167	282	1.079	312
.008	213	.036	252	.174	283	1.136	313
.009	216	.037	253	.181	284	1.285	314
.01	217	.038	254	.205	285	1.355	315
.010	220	.041	256	.215	286	1.417	316
.011	222	.044	257	.229	287	1.545	317
.012	223	.046	258	.238	288	1.650	318
.013	225	.049	259	.251	289	1.767	319
.013	226	.053	260	.258	290	1.906	320
.014	227	.054	261	.272	291	2.061	321
.015	228	.057	262	.288	292	2.294	322
.015	230	.059	263	.302	293	2.587	323
.016	231	.065	264	.321	294	2.678	324
.017	232	.068	265	.333	295	2.904	325
.017	233	.074	266	.345	296	3.032	326
.018	235	.081	267	.376	297	3.190	326
.020	236	.083	268	.392	298	3.191	339
.020	237	.087	269	.416	299	3.192	325
.021	238	.090	270	.436	300	3.192	305
.022	240	.097	271	.463	301	3.193	291

Table A1. Recorded water levels in production well, Shakopee Mdewakanton Sioux Community, December 6–22, 2004.—Continued

[Aquifer test began at 10:30 a.m., December 6, 2004]

Time since beginning of pumping, in days	Recorded water level, in feet below datum	Time since beginning of pumping, in days	Recorded water level, in feet below datum	Time since beginning of pumping, in days	Recorded water level, in feet below datum	Time since beginning of pumping, in days	Recorded water level, in feet below datum
3.194	294	3.215	199	3.245	184	3.914	144
3.194	292	3.216	195	3.246	184	3.990	143
3.195	288	3.217	193	3.247	177	4.008	142
3.196	287	3.217	188	3.247	188	4.078	141
3.197	288	3.218	185	3.248	195	4.156	140
3.197	293	3.220	184	3.249	183	4.235	139
3.198	301	3.221	182	3.249	176	4.301	138
3.199	297	3.223	181	3.250	177	4.392	137
3.199	299	3.224	178	3.251	176	4.724	136
3.200	302	3.226	181	3.251	180	4.824	135
3.201	304	3.227	219	3.252	178	4.944	134
3.201	303	3.228	192	3.343	164	5.107	133
3.202	302	3.229	187	3.351	163	5.272	132
3.203	301	3.230	181	3.367	162	5.419	131
3.203	297	3.231	180	3.387	161	5.647	130
3.204	298	3.231	175	3.405	160	5.953	129
3.205	292	3.232	173	3.415	159	6.167	128
3.206	290	3.233	171	3.437	157	6.433	127
3.206	266	3.234	170	3.461	156	6.743	126
3.207	250	3.236	174	3.472	155	6.958	125
3.208	240	3.236	170	3.494	154	6.959	124
3.208	235	3.238	169	3.506	153	6.981	305
3.209	231	3.238	171	3.529	152	6.981	309
3.210	223	3.240	177	3.558	151	6.982	298
3.210	216	3.240	179	3.695	150	6.983	305
3.211	211	3.241	172	3.709	149	6.983	306
3.212	208	3.242	171	3.752	148	6.984	141
3.212	204	3.243	174	3.784	147	6.985	232
3.214	203	3.244	165	3.863	146	6.985	171
3.215	201	3.244	166	3.879	145	6.986	182

Table A1. Recorded water levels in production well, Shakopee Mdewakanton Sioux Community, December 6–22, 2004.—Continued

[Aquifer test began at 10:30 a.m., December 6, 2004]

Time since beginning of pumping, in days	Recorded water level, in feet below datum	Time since beginning of pumping, in days	Recorded water level, in feet below datum	Time since beginning of pumping, in days	Recorded water level, in feet below datum	Time since beginning of pumping, in days	Recorded water level, in feet below datum
6.987	193	6.994	140	7.020	128	10.210	116
6.988	200	6.994	138	7.021	127	10.210	115
6.988	204	6.995	136	7.022	126	11.128	114
6.989	190	6.997	135	7.920	117	15.483	113
6.990	167	7.000	134	7.040	123	15.555	114
6.990	154	7.002	133	7.079	122		
6.991	151	7.003	132	7.442	121		
6.992	149	7.007	131	7.503	120		
6.992	145	7.009	130	7.506	119		
6.993	142	7.010	129	7.765	118		

Table A2. Measured water levels in production well, Shakopee Mdewakanton Sioux Community, southeastern Minnesota, December 9, 2004.

Time (24-hour)	Water level below top of casing (feet)	Water-surface elevation (feet above North American Vertical Datum of 1988)
15:25	405	580
15:27	378	607
15:28	365	620
15:29	355	630
15:30	346	639
15:31	340	645
15:32	336	649
15:33	332	653
15:34	328	657
15:35	325.5	659.5
15:36	323	662
15:37	321	664
15:38	319	666
15:39	317.1	667.9
15:40	315.2	669.8
15:41	313.7	671.3
15:46	308	677
15:51	303	682
15:56	299.5	685.5
16:01	297	688
16:06	294.5	690.5
16:11	292	693
16:16	289	696
16:21	287.3	697.7
16:26	286	699

Table A3. Measured water levels in observation well 1 and observation well 2, Shakopee Mdewakanton Sioux Community, southeastern Minnesota, December 6–22, 2004.

[Aquifer test began 10:30 a.m., December 6, 2004. Pump was turned off 3:26 p.m., December 9, 2004. Water level was measured in observation well 1 until 10:27 a.m., December 22, 2004. Water level was measured in observation well 2 until 11:55 a.m., December 22, 2004. --, no data]

Observation well 1				Observation well 2			
Time since beginning of aquifer test (days)	Draw-down (feet)	Recovery (feet)	Elevation above North American Vertical Datum of 1988 (feet)	Time since beginning of aquifer test (days)	Draw-down (feet)	Recovery (feet)	Elevation (feet)
0	0	--	764.32	0	0	--	779.82
.034	0	--	764.32	.036	0	--	779.81
.035	.01	--	764.31	.037	.01	--	779.80
.036	.01	--	764.31	.038	.01	--	779.80
.037	.02	--	764.30	.039	.02	--	779.80
.039	.02	--	764.30	.040	.02	--	779.79
.040	.02	--	764.30	.041	.03	--	779.79
.041	.03	--	764.30	.042	.03	--	779.78
.042	.04	--	764.29	.043	.04	--	779.77
.043	.04	--	764.28	.044	.04	--	779.77
.044	.05	--	764.27	.046	.06	--	779.75
.045	.05	--	764.27	.050	.09	--	779.73
.046	.06	--	764.26	.054	.13	--	779.68
.047	.07	--	764.25	.058	.18	--	779.64
.048	.08	--	764.24	.063	.24	--	779.58
.049	.08	--	764.24	.069	.31	--	779.51
.050	.09	--	764.24	.074	.39	--	779.43
.051	.10	--	764.22	.080	.48	--	779.34
.052	.11	--	764.21	.086	.58	--	779.24
.053	.12	--	764.20	.093	.71	--	779.11
.054	.13	--	764.19	.100	.85	--	778.97
.055	.14	--	764.18	.108	1.02	--	778.80
.056	.15	--	764.17	.117	1.20	--	778.62
.057	.16	--	764.16	.126	1.40	--	778.41
.058	.17	--	764.15	.136	1.63	--	778.19
.059	.18	--	764.14	.147	1.87	--	777.94
.060	.19	--	764.14	.159	2.16	--	777.66
.062	.21	--	764.11	.171	2.45	--	777.37
.064	.23	--	764.09	.185	2.80	--	777.02
.066	.26	--	764.06	.200	3.14	--	776.68

Table A3. Measured water levels in observation well 1 and observation well 2, Shakopee Mdewakanton Sioux Community, southeastern Minnesota, December 6–22, 2004.—Continued

[Aquifer test began 10:30 a.m., December 6, 2004. Pump was turned off 3:26 p.m., December 9, 2004. Water level was measured in observation well 1 until 10:27 a.m., December 22, 2004. Water level was measured in observation well 2 until 11:55 a.m., December 22, 2004. --, no data]

Observation well 1				Observation well 2			
Time since beginning of aquifer test (days)	Draw-down (feet)	Recovery (feet)	Elevation above North American Vertical Datum of 1988 (feet)	Time since beginning of aquifer test (days)	Draw-down (feet)	Recovery (feet)	Elevation (feet)
0.068	0.29	--	764.04	0.216	3.53	--	776.28
.071	.33	--	764.00	.233	3.96	--	775.86
.074	.37	--	763.96	.251	4.41	--	775.41
.078	.42	--	763.90	.272	4.90	--	774.91
.081	.47	--	763.86	.293	5.42	--	774.40
.084	.52	--	763.80	.317	5.98	--	773.84
.088	.58	--	763.74	.342	6.56	--	773.26
.093	.67	--	763.65	.369	7.17	--	772.64
.097	.75	--	763.58	.398	7.82	--	771.99
.102	.84	--	763.48	.430	8.52	--	771.30
.108	.93	--	763.39	.464	9.23	--	770.59
.114	1.05	--	763.27	.501	9.98	--	769.84
.120	1.18	--	763.14	.541	10.76	--	769.06
.127	1.32	--	763.00	.585	11.55	--	768.27
.134	1.48	--	762.84	.631	12.38	--	767.44
.142	1.65	--	762.68	.681	13.26	--	766.56
.151	1.84	--	762.49	.736	14.16	--	765.66
.160	2.05	--	762.28	.795	15.11	--	764.71
.170	2.27	--	762.05	.858	16.08	--	763.73
.181	2.52	--	761.81	.926	17.10	--	762.72
.193	2.78	--	761.54	1.000	18.11	--	761.71
.205	3.08	--	761.24	1.080	19.17	--	760.65
.219	3.41	--	760.91	1.166	20.22	--	759.59
.234	3.76	--	760.56	1.260	21.37	--	758.45
.250	4.14	--	760.19	1.360	22.52	--	757.30
.267	4.54	--	759.78	1.468	23.68	--	756.14
.285	4.97	--	759.35	1.585	24.79	--	755.02
.305	5.44	--	758.88	1.712	25.89	--	753.93
.327	5.94	--	758.39	1.848	27.06	--	752.76
.350	6.46	--	757.87	1.996	28.24	--	751.57

Table A3. Measured water levels in observation well 1 and observation well 2, Shakopee Mdewakanton Sioux Community, southeastern Minnesota, December 6–22, 2004.—Continued

[Aquifer test began 10:30 a.m., December 6, 2004. Pump was turned off 3:26 p.m., December 9, 2004. Water level was measured in observation well 1 until 10:27 a.m., December 22, 2004. Water level was measured in observation well 2 until 11:55 a.m., December 22, 2004. --, no data]

Observation well 1				Observation well 2			
Time since beginning of aquifer test (days)	Draw-down (feet)	Recovery (feet)	Elevation above North American Vertical Datum of 1988 (feet)	Time since beginning of aquifer test (days)	Draw-down (feet)	Recovery (feet)	Elevation (feet)
0.403	7.60	--	756.72	2.154	29.34	--	750.47
.432	8.21	--	756.11	2.327	30.55	--	749.26
.464	8.86	--	755.46	2.513	31.74	--	748.07
.499	9.55	--	754.78	2.712	32.84	--	746.97
.536	10.26	--	754.06	2.929	34.03	--	745.78
0.575	10.98	--	753.34	3.162	35.16	--	744.65
.618	11.73	--	752.59	3.205	35.38	--	744.44
.665	12.53	--	751.79	3.207	35.38	-0	744.44
.716	13.36	--	750.96	3.208	35.39	-.01	744.43
.770	14.23	--	750.09	3.209	35.40	-.02	744.42
.829	15.13	--	749.20	3.210	35.40	-.02	744.42
.892	16.07	--	748.25	3.211	35.40	-.02	744.42
.961	17.01	--	747.31	3.212	35.40	-.03	744.41
1.034	17.97	--	746.35	3.213	35.41	-.03	744.41
1.114	18.95	--	745.37	3.214	35.41	-.04	744.40
1.201	19.98	--	744.34	3.215	35.42	-.04	744.40
1.293	21.06	--	743.27	3.216	35.43	-.05	744.39
1.393	22.14	--	742.19	3.217	35.43	-.05	744.39
1.503	23.21	--	741.11	3.218	35.43	-.06	744.38
1.619	24.24	--	740.08	3.219	35.44	-.06	744.38
1.745	25.27	--	739.06	3.220	35.45	-.07	744.37
1.882	26.36	--	737.96	3.221	35.45	-.07	744.37
2.030	27.44	--	736.89	3.222	35.46	-.08	744.36
2.189	28.47	--	735.85	3.223	35.46	-.08	744.36
2.361	29.60	--	734.72	3.224	35.46	-.09	744.36
2.546	30.68	--	733.64	3.225	35.47	-.09	744.35
2.746	31.69	--	732.63	3.226	35.47	-.09	744.35
3.020	33.10	--	731.22	3.227	35.48	-.10	744.34
3.196	33.88	--	730.44	3.228	35.48	-.10	744.34
3.205	33.92	--	730.40	3.229	35.48	-.10	744.34

Table A3. Measured water levels in observation well 1 and observation well 2, Shakopee Mdewakanton Sioux Community, southeastern Minnesota, December 6–22, 2004.—Continued

[Aquifer test began 10:30 a.m., December 6, 2004. Pump was turned off 3:26 p.m., December 9, 2004. Water level was measured in observation well 1 until 10:27 a.m., December 22, 2004. Water level was measured in observation well 2 until 11:55 a.m., December 22, 2004. --, no data]

Observation well 1				Observation well 2			
Time since beginning of aquifer test (days)	Draw-down (feet)	Recovery (feet)	Elevation above North American Vertical Datum of 1988 (feet)	Time since beginning of aquifer test (days)	Draw-down (feet)	Recovery (feet)	Elevation (feet)
3.206	33.92	0	730.40	3.230	35.49	-0.11	744.33
3.207	33.93	-.01	730.39	3.231	35.49	-.11	744.33
3.208	33.93	-.01	730.39	3.232	35.49	-.12	744.32
3.209	33.94	-.02	730.38	3.233	35.49	-.12	744.32
3.212	33.95	-.03	730.37	3.234	35.50	-.12	744.32
3.214	33.96	-.04	730.36	3.235	35.50	-.12	744.32
3.215	33.96	-.04	730.36	3.236	35.50	-.13	744.31
3.216	33.97	-.05	730.35	3.237	35.51	-.13	744.31
3.217	33.97	-.05	730.35	3.238	35.51	-.13	744.31
3.218	33.97	-.06	730.34	3.239	35.51	-.13	744.31
3.219	33.98	-0.06	730.34	3.240	35.51	-0.13	744.31
3.220	33.99	-.07	730.33	3.241	35.51	-.13	744.31
3.221	33.99	-.07	730.33	3.242	35.51	-.14	744.30
3.222	34.00	-.08	730.32	3.245	35.51	-.13	744.31
3.223	34.00	-.08	730.32	3.248	35.51	-.13	744.31
3.224	34.00	-.08	730.32	3.253	35.50	-.13	744.31
3.225	34.01	-.09	730.31	3.256	35.49	-.12	744.32
3.226	34.01	-.09	730.31	3.260	35.48	-.10	744.34
3.227	34.01	-.09	730.31	3.264	35.46	-.08	744.36
3.228	34.02	-.10	730.30	3.268	35.43	-.05	744.39
3.229	34.02	-.10	730.30	3.273	35.39	-.01	744.43
3.230	34.03	-.11	730.30	3.279	35.33	.04	744.48
3.231	34.03	-.11	730.29	3.285	35.28	.10	744.54
3.232	34.03	-.11	730.29	3.291	35.21	.17	744.61
3.233	34.03	-.12	730.28	3.298	35.12	.25	744.69
3.234	34.04	-.12	730.28	3.305	35.02	.36	744.80
3.235	34.04	-.12	730.28	3.313	34.91	.47	744.91
3.236	34.04	-.12	730.28	3.322	34.78	.60	745.04
3.237	34.04	-.12	730.28	3.331	34.63	.75	745.19
3.239	34.05	-.13	730.27	3.341	34.47	.91	745.35

Table A3. Measured water levels in observation well 1 and observation well 2, Shakopee Mdewakanton Sioux Community, southeastern Minnesota, December 6–22, 2004.—Continued

[Aquifer test began 10:30 a.m., December 6, 2004. Pump was turned off 3:26 p.m., December 9, 2004. Water level was measured in observation well 1 until 10:27 a.m., December 22, 2004. Water level was measured in observation well 2 until 11:55 a.m., December 22, 2004. --, no data]

Observation well 1				Observation well 2			
Time since beginning of aquifer test (days)	Draw-down (feet)	Recovery (feet)	Elevation above North American Vertical Datum of 1988 (feet)	Time since beginning of aquifer test (days)	Draw-down (feet)	Recovery (feet)	Elevation (feet)
3.239	34.05	-0.13	730.27	3.352	34.27	1.10	745.54
3.240	34.05	-.13	730.27	3.364	34.07	1.30	745.74
3.241	34.05	-.13	730.27	3.376	33.85	1.53	745.97
3.243	34.05	-.13	730.27	3.390	33.61	1.77	746.21
3.246	34.05	-.13	730.27	3.405	33.33	2.04	746.48
3.249	34.05	-.13	730.27	3.421	33.05	2.32	746.76
3.256	34.03	-.12	730.29	3.438	32.74	2.64	747.08
3.260	34.02	-.10	730.30	3.457	32.39	2.99	747.43
3.264	34.00	-.08	730.33	3.476	32.02	3.36	747.80
3.269	33.97	-.05	730.36	3.498	31.62	3.76	748.20
3.274	33.93	-0.01	730.39	3.522	31.20	4.18	748.62
3.280	33.88	.04	730.44	3.547	30.74	4.63	749.07
3.285	33.83	.09	730.49	3.574	30.26	5.12	749.56
3.292	33.76	.16	730.57	3.603	29.75	5.62	750.06
3.298	33.69	.23	730.64	3.635	29.21	6.17	750.61
3.306	33.59	.33	730.73	3.670	28.63	6.74	751.18
3.314	33.48	.44	730.84	3.706	28.05	7.33	751.77
3.322	33.36	.56	730.96	3.746	27.44	7.93	752.37
3.332	33.22	.69	731.10	3.790	26.82	8.56	753.00
3.342	33.07	.85	731.25	3.836	26.19	9.19	753.63
3.353	32.89	1.03	731.43	3.887	25.53	9.85	754.29
3.364	32.70	1.21	731.62	3.941	24.87	10.51	754.95
3.377	32.49	1.43	731.83	4.000	24.20	11.18	755.62
3.391	--	1.67	732.07	4.063	23.47	11.91	756.35
3.405	31.99	1.93	732.33	4.132	22.73	12.65	757.09
3.421	31.72	2.20	732.60	4.205	21.99	13.38	757.82
3.438	31.42	2.50	732.91	4.285	21.25	14.12	758.56
3.457	31.08	2.83	733.24	4.371	20.54	14.84	759.28
3.477	30.71	3.21	733.61	4.465	19.78	15.59	760.04
3.498	30.33	3.59	734.00	4.565	18.99	16.39	760.83

Table A3. Measured water levels in observation well 1 and observation well 2, Shakopee Mdewakanton Sioux Community, southeastern Minnesota, December 6–22, 2004.—Continued

[Aquifer test began 10:30 a.m., December 6, 2004. Pump was turned off 3:26 p.m., December 9, 2004. Water level was measured in observation well 1 until 10:27 a.m., December 22, 2004. Water level was measured in observation well 2 until 11:55 a.m., December 22, 2004. --, no data]

Observation well 1				Observation well 2			
Time since beginning of aquifer test (days)	Draw-down (feet)	Recovery (feet)	Elevation above North American Vertical Datum of 1988 (feet)	Time since beginning of aquifer test (days)	Draw-down (feet)	Recovery (feet)	Elevation (feet)
3.522	29.90	4.02	734.42	4.673	18.16	17.21	761.66
3.547	29.46	4.46	734.87	4.790	17.30	18.08	762.52
3.574	28.98	4.94	735.34	4.917	16.47	18.90	763.34
3.604	28.48	5.44	735.85	5.054	15.64	19.74	764.18
3.636	27.94	5.98	736.39	5.200	14.75	20.63	765.07
3.670	27.37	6.55	736.95	5.360	13.88	21.50	765.94
3.707	26.78	7.13	737.54	5.532	13.08	22.30	766.74
3.747	26.17	7.75	738.15	5.717	12.21	23.17	767.61
3.790	25.56	8.36	738.77	5.917	11.48	23.90	768.34
3.837	24.94	8.98	739.39	6.134	10.80	24.58	769.02
3.887	24.29	9.63	740.03	6.368	10.17	25.21	769.65
3.942	23.63	10.29	740.70	6.620	9.63	25.74	770.18
4.001	22.97	10.95	741.35	6.892	8.95	26.42	770.86
4.064	22.25	11.67	742.08	7.187	8.48	26.89	771.33
4.132	21.53	12.39	742.79	7.507	7.92	27.46	771.90
4.206	20.81	13.11	743.52	7.851	7.18	28.20	772.64
4.286	20.08	13.84	744.24	8.226	6.39	28.99	773.43
4.372	19.38	14.54	744.94	8.622	5.68	29.70	774.14
4.465	18.65	15.27	745.67	9.049	4.91	30.47	774.91
4.565	17.89	16.03	746.43	9.517	4.39	30.99	775.43
4.673	17.09	16.83	747.23	10.028	3.97	31.41	775.85
4.791	16.25	17.67	748.08	10.570	3.59	31.79	776.23
4.917	15.47	18.45	748.85	11.153	2.90	32.48	776.92
5.054	14.68	19.24	749.64	11.788	2.32	33.06	777.50
5.202	13.83	20.09	750.50	12.476	2.28	33.10	777.54
5.360	13.00	20.92	751.32	13.215	1.75	33.62	778.06
5.533	12.25	21.67	752.07	14.007	.89	34.48	778.93
5.718	11.43	22.48	752.89	14.872	.72	34.65	779.09
5.918	10.75	23.17	753.57	15.799	.68	34.69	779.13
6.134	10.13	23.79	754.19	16.059	.66	34.71	779.15

Table A3. Measured water levels in observation well 1 and observation well 2, Shakopee Mdewakanton Sioux Community, southeastern Minnesota, December 6–22, 2004.—Continued

[Aquifer test began 10:30 a.m., December 6, 2004. Pump was turned off 3:26 p.m., December 9, 2004. Water level was measured in observation well 1 until 10:27 a.m., December 22, 2004. Water level was measured in observation well 2 until 11:55 a.m., December 22, 2004. --, no data]

Observation well 1				Observation well 2			
Time since beginning of aquifer test (days)	Draw-down (feet)	Recovery (feet)	Elevation above North American Vertical Datum of 1988 (feet)	Time since beginning of aquifer test (days)	Draw-down (feet)	Recovery (feet)	Elevation (feet)
6.368	9.57	24.35	754.75				
6.620	9.08	24.84	755.24				
6.893	8.46	25.46	755.86				
7.187	8.04	25.88	756.28				
7.509	7.54	26.37	756.78				
7.852	6.85	27.07	757.47				
8.227	6.10	27.82	758.23				
8.623	5.42	28.50	758.91				
9.050	4.68	29.24	759.65				
9.519	4.18	29.74	760.14				
10.019	3.78	30.14	760.54				
10.571	3.42	30.50	760.90				
11.155	2.72	31.20	761.60				
11.790	2.15	31.77	762.18				
12.467	2.12	31.80	762.21				
13.207	1.59	32.33	762.73				
14.009	.71	33.21	763.61				
14.873	.53	33.39	763.80				
15.800	.47	33.44	763.85				
16.019	.47	33.45	763.86				