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Aquifer Test to Determine Hydraulic Properties of the Elm Aquifer near Aberdeen, South Dakota

Water-Resources Investigations Report 00-4264

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

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi)	0.1894	meter per kilometer
foot squared per day (ft^2/d)	0.0929	meter squared per day
gallon (gal)	3.785	liter
gallon per minute (gal/min)	0.06309	liter per second
gallon per day per foot squared [(gal/d)/ft^2)]	4.720×10^{-7}	meter per second
inch (in.)	2.54	centimeter
inch of mercury at 60° F (in Hg)	3.377	kilopascal
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

The Elm aquifer, which consists of sandy and gravelly glacial-outwash deposits, is present in several counties in northeastern South Dakota. An aquifer test was conducted northeast of Aberdeen during the fall of 1999 to determine the hydraulic properties of the Elm aquifer in that area. An improved understanding of the properties of the aquifer will be useful in the possible development of the aquifer as a water resource.

Historical water-level data indicate that the saturated thickness of the Elm aquifer can change considerably over time. From September 1977 through November 1985, water levels at three wells completed in the Elm aquifer near the aquifer test site varied by 5.1 ft, 9.50 ft, and 11.1 ft. From June 1982 through October 1999, water levels at five wells completed in the Elm aquifer near the aquifer test site varied by 8.7 ft, 11.4 ft, 13.2 ft, 13.8 ft, and 19.7 ft. The water levels during the fall of 1999 were among the highest on record, so the aquifer test was affected by portions of the aquifer being saturated that might not be saturated during drier times.

The aquifer test was conducted using five existing wells that had been installed prior to this study. Well A, the pumped well, has an operating irrigation pump and is centrally located among the wells. Wells B, C, D, and E are about 70 ft, 1,390 ft, 2,200 ft, and 3,100 ft, respectively, in different directions from Well A. Using vented pressure transducers and programmable data loggers, water-level data were collected at the five wells prior to, during, and after the pumping, which started on November 19, 1999, and continued a little over 72 hours.

Based on available drilling logs, the Elm aquifer near the test area was assumed to be unconfined. The Neuman (1974) method theoretical response curves that most closely match the observed water-level changes at Wells A and B were calculated using software (AQTESOLV for Windows Version 2.13-Professional) developed by Glenn M. Duffield of HydroSOLVE, Inc. These best fit theoretical response curves are based on a transmissivity of 24,000 ft^2/d or a hydraulic conductivity of about 600 ft/d, a storage coefficient of 0.05, a specific yield of 0.42, and vertical hydraulic conductivity equal to horizontal hydraulic conductivity.

The theoretical type curves match the observed data fairly closely at Wells A and B until about 2,500 minutes and 1,000 minutes, respectively, after pumping began. The increasing rate of drawdown after these breaks is an indication that a no-flow boundary (an area with much lower hydraulic conductivity) likely was encountered and that Wells A and B may be completed in a part of the Elm aquifer with limited hydraulic connection to the rest of the aquifer.

Additional analysis indicates that if different assumptions regarding the screened interval for Well B and aquifer anisotropy are used, type curves can be calculated that fit the observed data using a lower specific yield that is within the commonly accepted range. When the screened interval for Well B was reduced to 5 ft

near the top of the aquifer and horizontal hydraulic conductivity was set to 20 times vertical hydraulic conductivity, the type curves calculated using a specific yield of 0.1 and a transmissivity of 30,200 ft^2/d also matched the observed data from Wells A and B fairly well.

A version of the Theim equilibrium equation was used to calculate the theoretical drawdown in an idealized unconfined aquifer when a perfectly efficient well is being pumped at a constant rate. These calculations were performed for a range of pumping rates, drawdowns at the wells, and distances between wells that might be found in a production well field in the Elm aquifer.

Although the aquifer test indicates that hydraulic conductivity near the well may be adequate to support a production well, the comparison of drawdown and recovery curves indicates the possibility that heterogeneities may limit the productive capacity of specific locations in the Elm aquifer during certain times. Additional test hole drilling and geophysical studies could help characterize these heterogeneities in the aquifer.

INTRODUCTION

The City of Aberdeen is a growing municipality in northeastern South Dakota (fig. 1) that currently relies on a combination of surface water and ground water to meet its water-supply needs. Future residential and industrial growth may require additional water supplies, especially during drier times. The City of Aberdeen, which is interested in expanding its ground-water supply, could benefit from a better understanding of the hydraulic properties of the Elm aquifer, which is present in several counties in northeastern South Dakota. Information regarding its hydraulic properties will be useful for the possible development of the aquifer as a water resource.

The surficial deposits in the Aberdeen area are the result of glaciation and consist primarily of till and outwash. Only the more sandy and gravelly glacial-outwash deposits yield substantial quantities of water to wells. The outwash includes some beds of well-sorted sand and gravel, but most of these are small and discontinuous. The remaining deposits generally are either too clayey and silty or are too thin to serve as major sources of water except in very localized situations (Emmons, 1987). The three major outwash aquifers in the Aberdeen area are the Elm, Middle James, and the Deep James aquifers. These three aquifers generally are separated from each other by till and may be internally separated by till and thin clay and silt outwash layers (Emmons, 1987). Some flow may occur between and within these aquifers.

The Elm aquifer slopes to the west at about the same gradient as the topographic surface, which is about 15 ft/mi. The general direction of water movement is from northwest to southeast along a water-table gradient of about 10 ft/mi. Recharge is by percolation of precipitation, snowmelt, and surface water through overlying outwash, lake sediments, and till (Emmons, 1990).

Purpose and Scope

The purpose of this report is to provide information about the Elm aquifer that might be helpful in the possible development of the aquifer as a water resource. This is accomplished by describing historical water levels in the Elm aquifer, describing the aquifer test used to determine the general hydraulic properties of the Elm aquifer in the vicinity of Well A, and describing the analysis of the aquifer test. Also, the results of hypothetical equilibrium drawdown calculations based on a range of hydraulic properties and pumping scenarios are presented.

The scope of this report includes a description of the Elm aquifer and discussion of historical water levels in the Elm aquifer based on data from six wells (fig. 1) spanning a period from 1955 through 1999. The aquifer test is described in detail including descriptions of the wells, the pumping rate, and collection of water-level data. Analysis of the aquifer test is described, including descriptions of the processing of the water-level data, the computer software used for the analysis, the techniques applied and hydrologic situations simulated, and the results of the analysis. Hypothetical equilibrium drawdown values for distances of 50 ft, 100 ft, 250 ft, 500 ft, and 1,000 ft from the center of the pumping well are presented for pumping rates of 500, 1,000, and 1,500 gal/min for an aquifer with hydraulic conductivities of 500, 600, and 700 ft/d; with an initial saturated thickness of 40.29 ft; and with drawdown 1 ft from the center of the pumping well specified at 5, 10, and 15 ft.

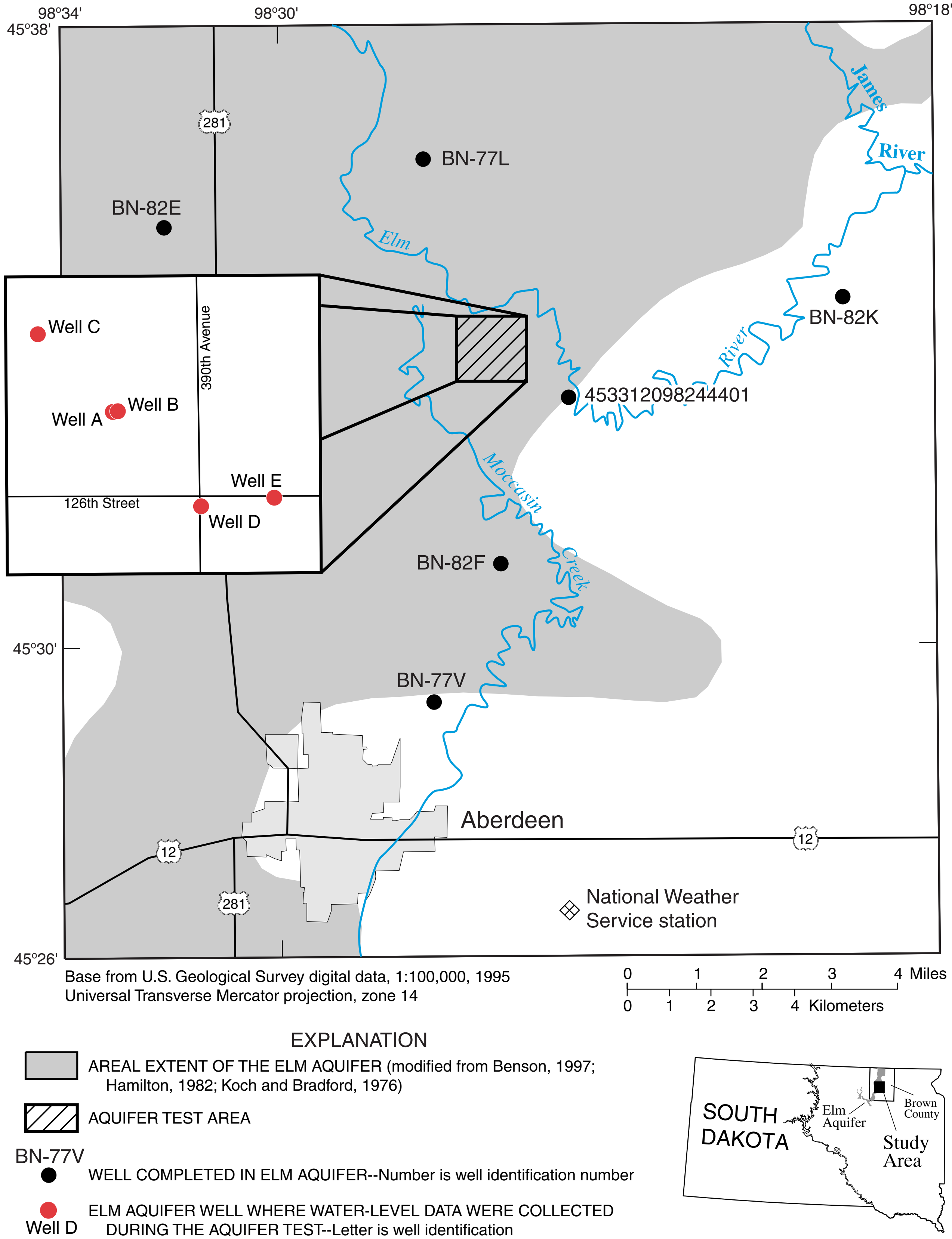

Figure 1. Location of aquifer test area in the regional study area.

Previous Studies

The Elm aquifer has been the subject of considerable study over the years by those interested in its potential as a source of water. Black and Veatch Consulting Engineers (1956) submitted a report to the City of Aberdeen that described the possibilities of additional sources of water supply, including the Elm aquifer. Several of the county reports published by the South Dakota Geological Survey, in cooperation with the U.S. Geological Survey, have described the location and some of the properties of the Elm aquifer in Brown County and beyond (Benson, 1997; Hamilton, 1974, 1982; Hamilton and Howells, 1996; Koch and others, 1973; and Koch and Bradford, 1976). Emmons (1987) studied the potential for artificial recharge of the Elm aquifer in the Aberdeen area as part of a Missouri River diversion project and concluded that some of the most suitable areas for spreading ponds were near the site of this study. A digital simulation of the glacial-aquifer system (Emmons, 1990), including the Elm aquifer, provided information about hydraulic properties, recharge rates, and inter-aquifer hydraulic connections. On the basis of extremely limited information, the model (Emmons, 1990) used an Elm aquifer thickness of 15 ft, a confining layer thickness of 20 ft, and a hydraulic conductivity of 250 ft/d for the 1/2-mi by 1/2-mi cell where the pumping well for the aquifer test is located.

Acknowledgments

The author gratefully acknowledges the efforts of all those involved in making the aquifer test possible. The landowner, N. Berbos, allowed access to the well and use of the irrigation pump already in place. R. Wahlen, Aberdeen water treatment superintendent, organized and led the efforts of many others during the aquifer test in keeping the pump running and removing the discharged water from the study site and into a pipeline to the Aberdeen water treatment plant. G. Nielsen and T. Kearns of the National Weather Service in Aberdeen provided information that was useful in assessing the effects of local precipitation and barometric pressure on water levels in the Elm aquifer.

HYDROGEOLOGY

Geologic Setting

The surficial deposits in the Aberdeen area are the result of glaciation and consist primarily of till and outwash. Only the more sandy and gravelly glacial-outwash deposits yield substantial quantities of water to wells. The outwash includes some beds of well-sorted sand and gravel, but most of these beds are small and discontinuous. The remaining deposits generally are either too clayey and silty or are too thin to serve as major sources of water except in very localized situations (Emmons, 1987).

The three major outwash aquifers in the Aberdeen area are the Elm, Middle James, and the Deep James aquifers. These three aquifers generally are separated from each other by till and may be internally separated by till and thin clay and silt outwash layers (Emmons, 1987). Some flow may occur between and within these aquifers. Exposures of the Elm aquifer just a few miles northwest of the aquifer test site show the extreme variability in grain size, bedding, and sorting characteristics of glacial outwash deposits.

The bedrock directly underlying the glacial drift in the study area consists of the Upper Cretaceous Pierre Shale, Niobrara Formation, and Carlile Shale. These units, which generally yield little or no water to wells, are considered to be confining beds.

Elm Aquifer

The Elm aquifer has been mapped, primarily on the basis of drilling information, in 492 mi^2 of Brown, Edmunds, Faulk, and Spink Counties in northeastern South Dakota (Benson, 1997; Hamilton, 1974, 1982; Hamilton and Howells, 1996; Koch and others, 1973; and Koch and Bradford, 1976). As defined in earlier studies, the Elm aquifer occurs between 1,225 and 1,400 ft above sea level or about 15 to 150 ft below land surface, but exploratory drilling near the site of the aquifer test encountered what is assumed to be the Elm aquifer at 2 ft below land surface. The top of the aquifer is deepest below land surface in topographically high areas. The aquifer slopes to the west at about the same gradient as the topographic surface, which is about 15 ft/mi (Emmons, 1990). The general direction of water movement is from northwest to southeast along a water-table gradient of about 10 ft/mi in the region of the study area. Recharge is by percolation of precipitation, snowmelt, and surface water through overlying outwash, lake sediments, and till. Recharge takes place rapidly in level areas where permeable sediments overlie the aquifer but slowly where till overlies the aquifer. Natural discharge is into the Elm River and Foot Creek (not shown on fig. 1), to the atmosphere by evapotranspiration, by leakage to the Middle James aquifer, and by eastward flow into lacustrine deposits underlying the Lake Dakota Plain (not shown on fig. 1).

In the northern three-fourths of Brown County, the Elm aquifer ranges in thickness from 0 to 113 ft, with an average of about 32 ft, and the overlying confining bed has an average thickness of about 20 ft (Emmons, 1990). Emmons assumed that where the overlying confining bed is less than 10 ft thick, the water in the Elm aquifer is under water-table or unconfined conditions, and where the overlying confining bed is greater than 10 ft thick, the water in the Elm aquifer is under confined or artesian conditions. Based on information published by Koch and Bradford (1976), the digital model constructed by Emmons (1990) has a limited area of hydraulic connection between the Elm aquifer and the Elm River and this area is near the site of the aquifer test.

Temporal Water-Level Fluctuations

Changes in the saturated thickness of the Elm aquifer affect the aquifer's water-producing capacity. Changes during a span of several years are of interest to water managers and changes during a span of a few weeks may affect an aquifer test. The water levels during the fall of 1999 were among the highest on record, so the aquifer test was affected by portions of the aquifer being saturated that might not be saturated during drier times.

Water-level data have been collected at several wells completed in the Elm aquifer near the site of the aquifer test (fig. 1). Figure 2 shows the elevation of the water table in the Elm aquifer at those selected wells. South Dakota Department of Environment and Natural Resources data in figure 2 are based on measurements made from about early summer through mid-fall at irregular time intervals. U.S. Geological Survey data in figure 2 are based on selected weekly values from a continuous recorder for the periods 1955-63 and 1965-85, and measurements at irregular time intervals in the fall of 1999 prior to, during, and after the aquifer test. Summary statistics for selected portions of the water-level data shown in figure 2 are presented in table 1. Figure 2 shows that not all the records for the wells span the same time periods, so the water-level data from the wells were grouped into two time periods (September 1977 through November 1985; June 1982

Table 1. Water-level data from selected wells completed in the Elm aquifer

[SD DENR, South Dakota Department of Environment and Natural Resources; USGS, U.S. Geological Survey]

Well name	Data collection agency	Period of analysis	Number of measurements	Minimum measured water level (feet)	Maximum measured water level (feet)	Mean measured water level (feet)	Median measured water level (feet)	Standard deviation (feet)
BN-77L	SD DENR	09/1977 - 11/1985	88	1,328.2	1,339.3	1,332.6	1,332.4	2.5
		06/1982 - 10/1999	170	1,329.8	1,343.0	1,335.8	1,335.0	3.7
BN-77V	SD DENR	09/1977 - 11/1985	36	1,286.2	1,291.3	1,288.8	1,288.9	1.4
		06/1982 - 10/1999	98	1,288.5	1,299.9	1,292.0	1,290.7	3.1
BN-82E	SD DENR	06/1982 - 10/1999	173	1,339.4	1,359.1	1,345.5	1342.4	5.8
BN-82F	SD DENR	06/1982 - 10/1999	161	1,292.5	1,301.2	1,295.0	1,294.2	2.2
BN-82K	SD DENR	06/1982 - 10/1999	93	1,283.5	1,297.3	1,288.7	1,286.7	4.1
453312098244401	USGS	09/1977 - 11/1985	178	1,293.47	1,302.97	1,296.33	1,296.17	1.12

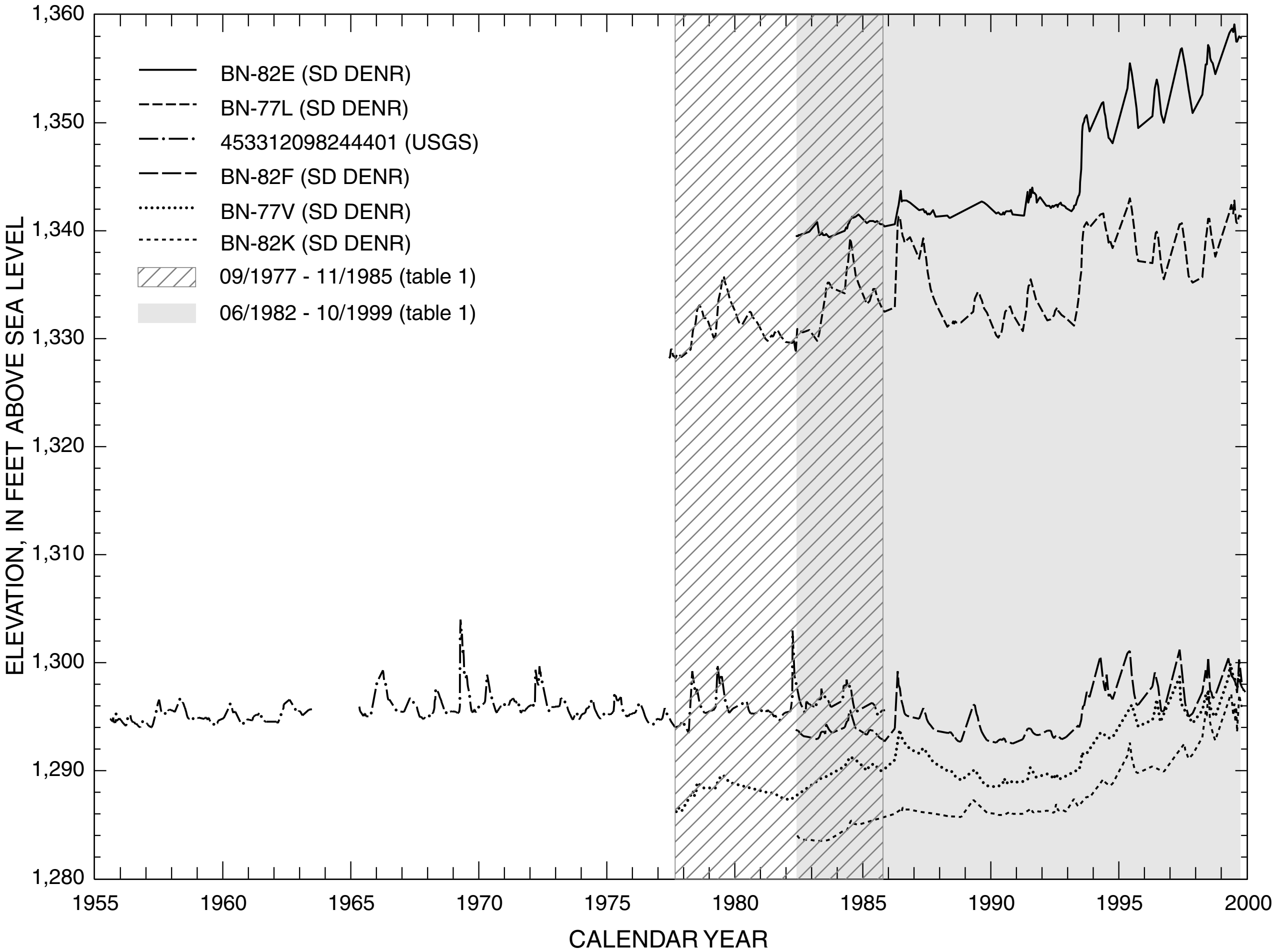

Figure 2. Water-level elevations in selected wells completed in the Elm aquifer.

through October 1999) to make comparisons more meaningful. From September 1977 through November 1985, water levels at Wells BN-77L, BN-77V, and 453312098244401, varied by 11.1 ft, 5.1 ft, and 9.50 ft, respectively. From June 1982 through October 1999, water levels at Wells BN-77L, BN-77V, BN-82E, BN-82F, and BN-82K, varied by 13.2 ft, 11.4 ft, 19.7 ft, 8.7 ft, and 13.8 ft, respectively.

Koch and Bradford (1976) found that from 1947 through 1972, the water levels in the unconfined part of the Elm aquifer were positively correlated with precipitation with a short, but unspecified, time lag. Prior to and during the aquifer test, there was very little precipitation to affect water levels in the Elm aquifer. During October 1999, only 0.15 in. of precipitation was recorded at the National Weather Service Station at the Aberdeen airport (fig. 1), and no measurable precipitation was recorded during November 1999 (G. Nielsen and T. Kearns, National Weather Service, written commun., 1999). Based on data from Wells C, D, and E (fig. 3), water levels in the Elm aquifer beyond the influence of the pumping well, decreased by about 0.01 ft/d from November 19 through November 30 (fig. 3).

Barometric pressure recorded at the National Weather Service station (fig. 1) a few miles from the aquifer test site was compared to several weeks of water levels recorded at Wells A, B, C, D, and E prior to the aquifer test. It does not appear that changes in barometric pressure have any significant effect on water levels in the Elm aquifer near the aquifer test site. The weather was relatively stable during the time of the aquifer test and barometric pressure varied less than 0.6 in. of Hg.

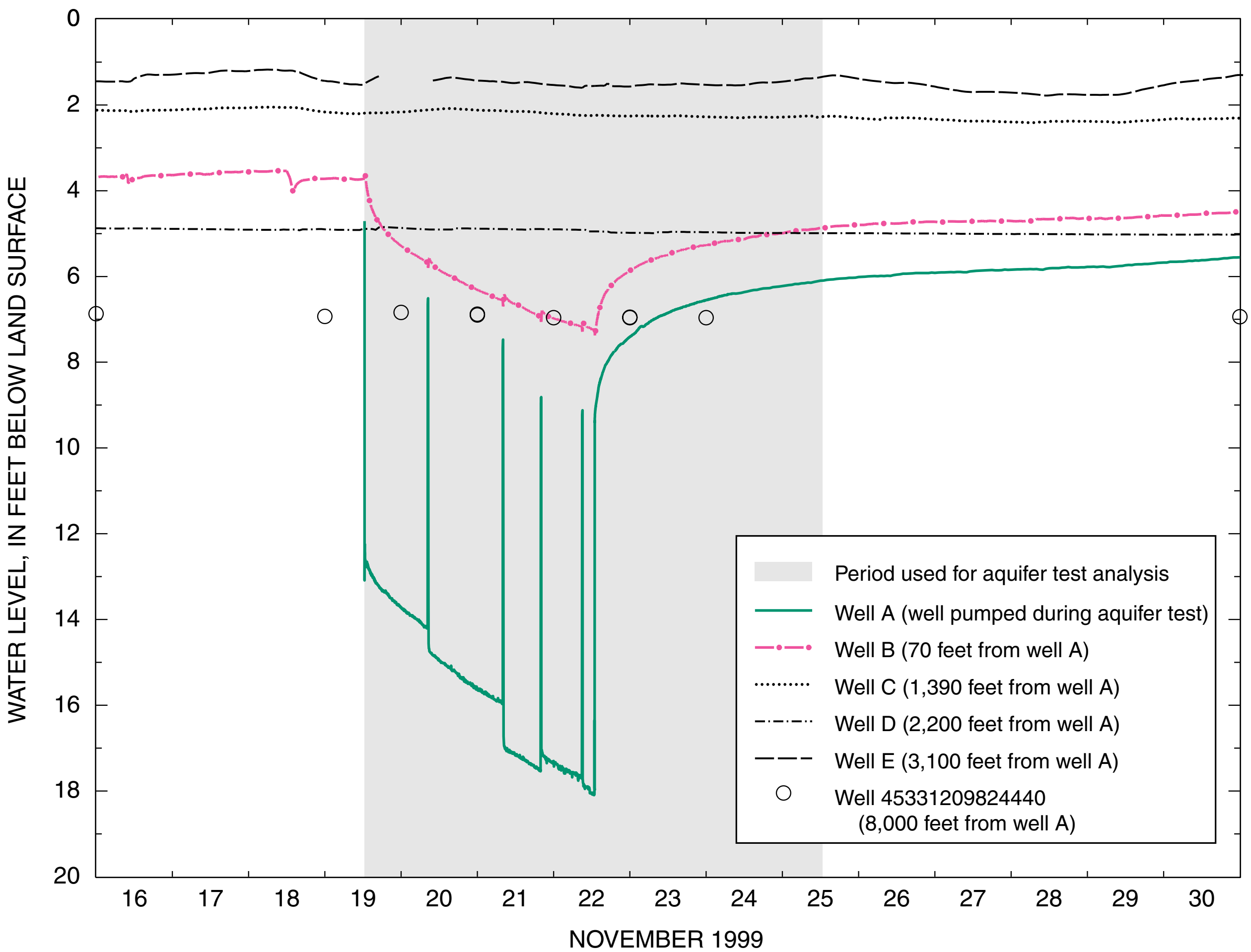

Figure 3. Water levels at selected wells in the aquifer test area.

AQUIFER TEST DESIGN

The potential of the Elm aquifer as a reliable and economic source of water is affected by the hydraulic properties of the aquifer, including the ability to store and transmit water. Several methods have been developed to determine hydraulic properties, but many of these methods require conditions, such as moving a small amount of disturbed aquifer material to a laboratory or using short time scales, that do little to advance the understanding of how the aquifer functions under natural conditions. A useful way to determine the hydraulic properties over a large aquifer volume is to conduct a controlled pumping episode over an extended period of time and observe the effects on water levels within the aquifer. Estimates of hydraulic properties over a large area are based on comparisons of the observed drawdown data with theoretical type curves.

Methods

The aquifer test was conducted using five existing wells (fig. 1) that had been installed prior to the study. Well A, which has an operating irrigation pump, is centrally located among the wells. Wells B, C, D, and E are about 70 ft, 1,390 ft, 2,200 ft, and 3,100 ft, respectively, from Well A.

Using vented pressure transducers and programmable data loggers, water-level data were collected at the five wells prior to, during, and after the pumping (fig. 3). The collection of water-level data at Well A was interrupted because the pressure transducer had to be removed from the well when the pipeline was installed to transport the pumped water from the test area.

The time intervals between recorded water levels varied from 1 minute to 1 hour, depending on the distances between the observation wells and Well A and on the time interval since pumping began. Tables 3, 4, and 5 in the Supplemental Information section at the end of the report contain the pumping data for Well A, the water-level data recorded at Well A, and the water-level data recorded at Well B, respectively, used for the aquifer test analysis.

On November 16, 1999, an attempt was made to conduct the aquifer test, but the test was stopped because of equipment difficulties. Two days later, the pump was run for a short time to assess the repairs that had been made. The effects on ground-water levels of these short pumping episodes were recorded at Well B (fig. 3). At the same time the repairs were made, an access hole to Well A was enlarged enough to allow the re-installation of the pressure transducer and the collection of water-level data at Well A was resumed.

For a little over 72 hours, the pump at Well A was used to remove approximately 1,000 gal/min from the aquifer (table 3). The pumping rate was measured by a flow meter within the pipeline, which was used to transport the water from the study area to the Aberdeen water filtration plant. The pump was stopped periodically to allow maintenance inspections and refueling of the generator, which supplied power to the pump.

Data Collection

Geologic logs (from files of the South Dakota Department of Environment and Natural Resources) of exploratory drilling done in 1990 indicate that the confining layer overlying the Elm aquifer is about 2 ft thick and that the upper part of the Elm aquifer near Wells A and B is about 43 ft thick. Geologic logs are not available for any of the five wells used for this study, but construction logs are available for Wells A and C, which were meant to serve as irrigation wells. Both of these wells are 45 ft deep with screens in the bottom 25 ft. The saturated thickness of the Elm aquifer at the start of the aquifer test is assumed to be 45 ft minus the 4.71-ft distance from the land surface to the water table, or 40.29 ft. Measurements indicate that the bottom 2 ft of the screen at Well A has silted in, so the effective screened interval is assumed to be from 20 to 43 ft below land surface. Well B is believed to have been installed as a monitoring well for Well A, but no written records or reliable eyewitness accounts were discovered. For the purposes of the analysis, Well B is assumed to have the same screened interval as Well A. Water levels at Well B were affected by the pumping well, but it does not appear that the pumping affected water levels at Wells C, D, or E.

During the aquifer test, much more data were collected (much of it at 1- and 5-minute intervals) than was needed for the analysis of the aquifer test. Thus, the large data files were selectively edited to reduce computation times to arrive at solutions. Tables 4 and 5 contain the elapsed times and the changes in water levels for Wells A and B, respectively, used for the aquifer test analysis.

Water-level data recorded at Wells A and B were adjusted to negate the effect of regional water-level declines in the Elm aquifer of about 0.01 ft/d from November 16 through November 30. There was a small time difference between the data loggers at Well A and Well B, so the data recorded at Well A were assumed to have been recorded at the correct times and the difference (2 minutes and 32 seconds) was subtracted from the recorded times for the Well B data. The elapsed times in table 5 are reported to the nearest hundredth of a minute because of this correction.

AQUIFER TEST RESULTS

Software (AQTESOLV for Windows Version 2.13-Professional) developed by Glenn M. Duffield of HydroSOLVE, Inc. was used to calculate the best fit theoretical response curves based on the pumping record of the aquifer test and the assumption that the Elm aquifer is unconfined in the area near Wells A and B. The solution calculated for unsteady flow to a partially penetrating well in an unconfined aquifer with delayed gravity response using analytical solutions developed by Neuman (1974) matched the observed data best when transmissivity was 24,000 ft^2/d, the storage coefficient was 0.05, and the specific yield was 0.42.

Figure 4 shows drawdown versus elapsed time at Wells A and B during the pumping phase of the aquifer test and the Neuman type curve traces. The type curves match the observed data fairly well until about 2,500 minutes have elapsed at Well A and about 1,000 minutes have elapsed at Well B. The increasing rate of drawdown after these breaks is an indication that a no-flow boundary (an area with much lower hydraulic conductivity) likely was encountered and that Wells A and B may be completed in a part of the Elm aquifer with limited hydraulic connection to the rest of the aquifer.

Figure 5 shows modified data from Wells A and B during the recovery phase of the aquifer and

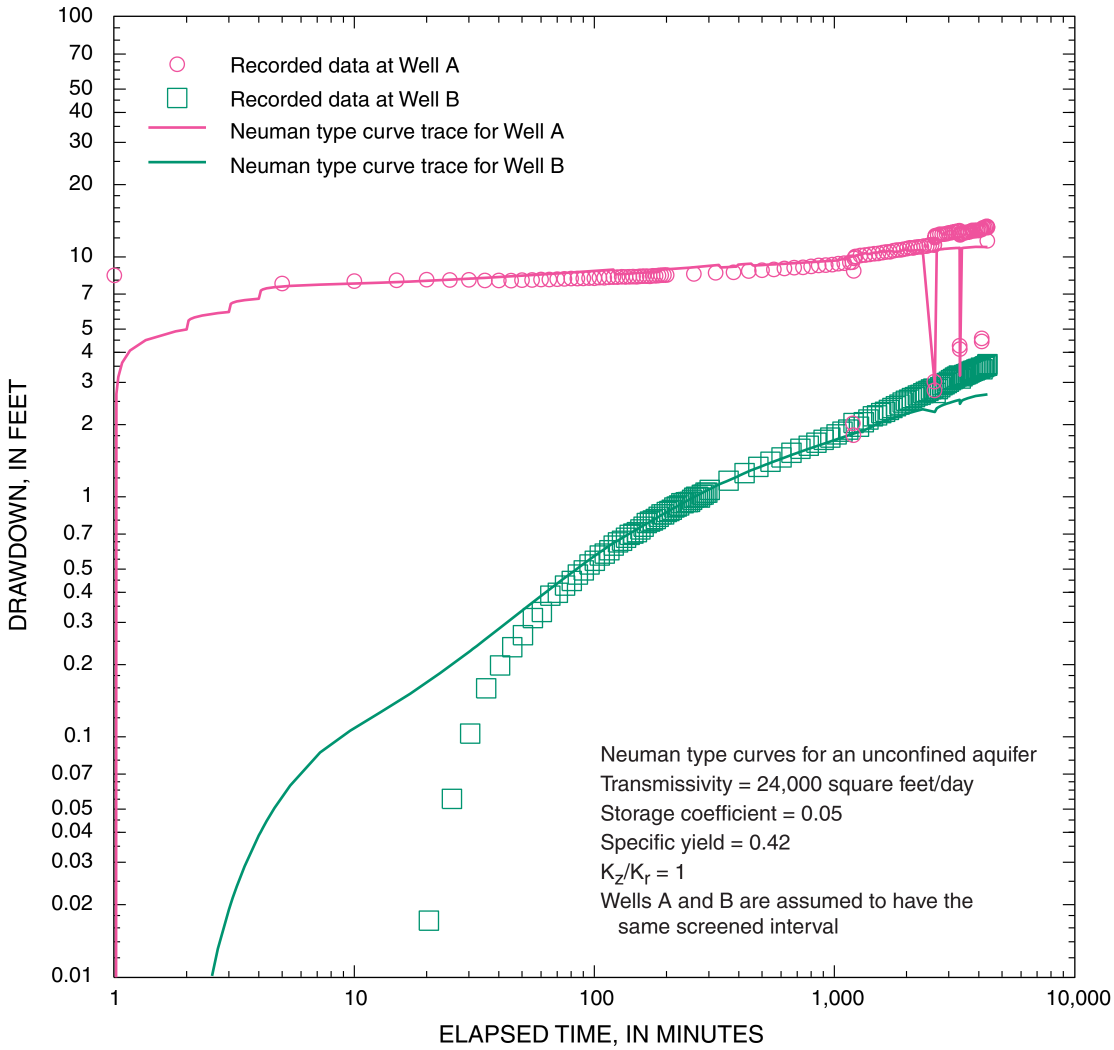

Figure 4. Best fit type curve matches to the drawdown data at Wells A and B during pumping.

Neuman type curve traces similar to those shown in figure 4. The after-pumping data at Wells A and B were modified to make them similar to the data collected during pumping. The elapsed times were adjusted so that the time when the pumping stopped appeared to coincide with the time the pumping started and drawdowns were adjusted by constants and multiplied by negative one to make them comparable to drawdowns during the pumping part of the test. The Neuman type curve traces were calculated using the same aquifer parameters as used for figure 4, but with pumping data modified by removing the intervals when the pump was stopped. These type curve traces fit the modified recovery data fairly well.

Figures 4 and 5 show that the same set of aquifer properties can be used to calculate theoretical type curves to fit the changes in water levels with time during the pumping and the recovery parts of the aquifer test. However, the specific yield typically ranges from 0.1 to 0.3 in unconfined aquifers (Freeze and Cherry, 1979) and the specific yield value of 0.42 used for these type curves is probably too high. Some of the assumptions used to simulate the conditions of the aquifer test may have been wrong. The variable glacial deposits of the Elm aquifer may have a lower vertical hydraulic conductivity (K_z) than horizontal hydraulic conductivity (K_r) or the screened interval of Well B may be less than that of Well A.

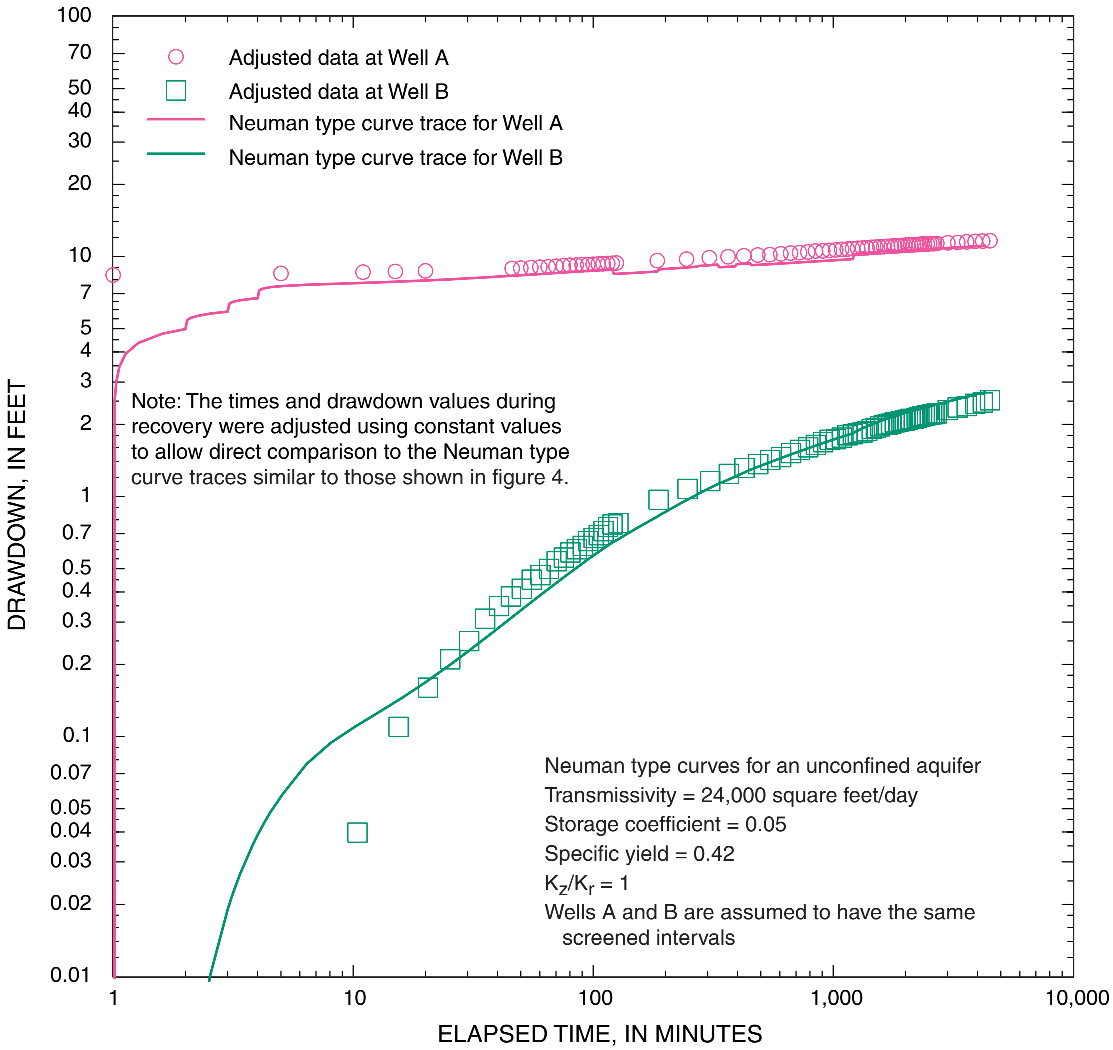

Figure 5. Comparison of the best fit type curve matches to the drawdown data for Wells A and B during recovery.

Figure 6 shows the same modified data from Wells A and B as in figure 5, but this time in comparison to Neuman type curve traces calculated using a different set of hydraulic properties and a smaller screened interval for Well B. The transmissivity is increased to 30,200 ft^2/d, the specific yield is decreased to 0.1, and the ratio of K_z/K_r is 0.05. The screened interval for Well B was reduced to 5 ft near the top of the aquifer. This combination of relatively extreme changes in some parameters produces type curves that match the modified data from Wells A and B fairly well with relatively little change in transmissivity. Further study might indicate that specific yield is closer to 0.3, the ratio of K_z/K_r is closer to 1, the screened interval in Well B is more than 5 ft, and therefore, the transmissivity of the Elm aquifer in the study area may be closer to 24,000 ft^2/d than 30,200 ft^2/d.

Transmissivity

In an unconfined aquifer, such as the Elm aquifer in the vicinity of the pumping well, transmissivity is defined as the hydraulic conductivity times the saturated thickness of the aquifer. It is a measure of the ability of the aquifer to transmit water. Based on the analysis shown in figures 4 and 5, the transmissivity of the Elm aquifer in the test area is about 24,000 ft^2/d, and hydraulic conductivity is about 600 ft/d. The Big Sioux aquifer, located in the eastern part of South

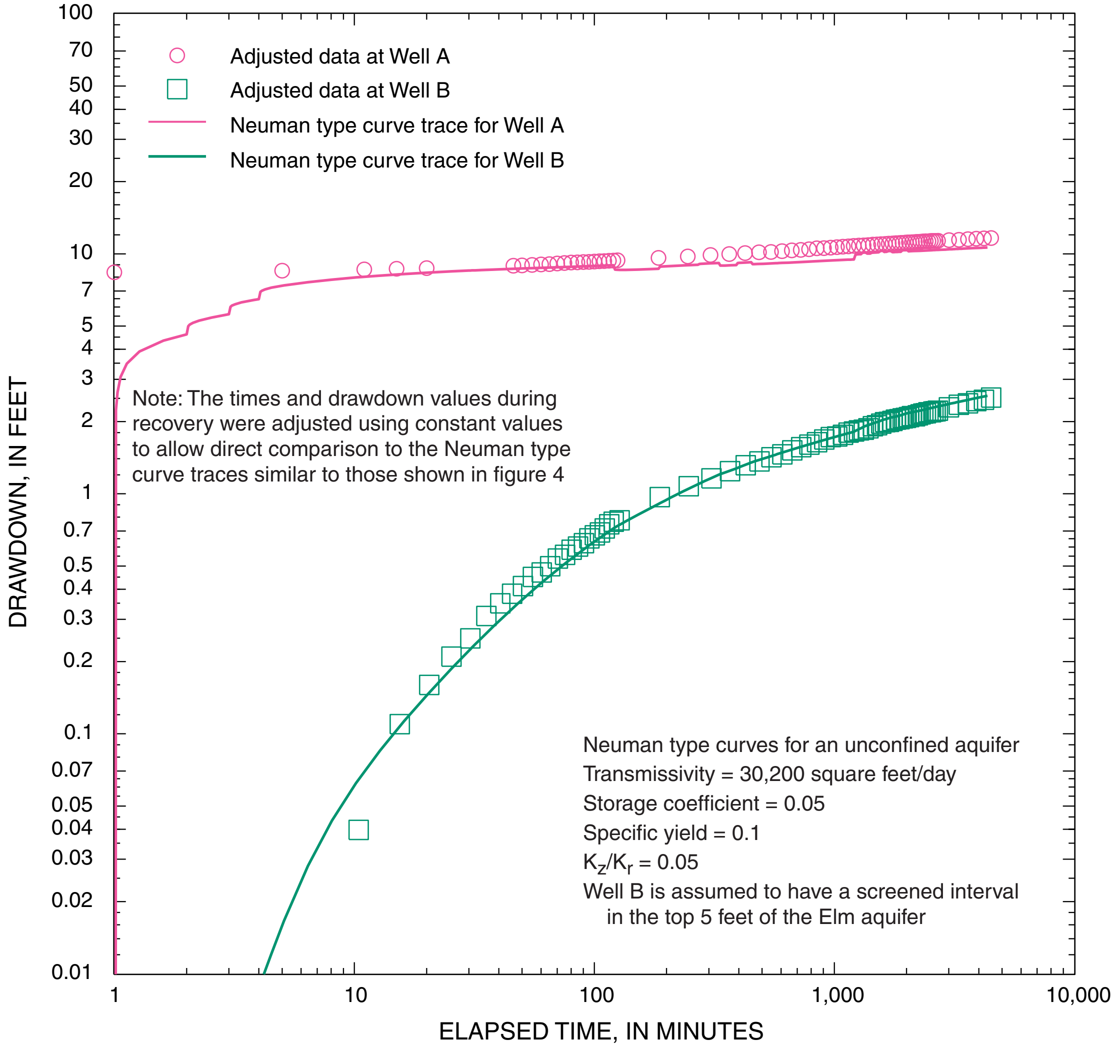

Figure 6. Comparison of the best fit type curve matches to the drawdown data during recovery assuming a different screened interval for Well B.

Dakota, is geologically similar to the Elm aquifer and numerous aquifer tests of the Big Sioux aquifer have yielded hydraulic conductivity values between 300 and 800 ft/d (Putnam and Thompson, 1996).

Storage

The storage coefficient is defined as the volume of water that an aquifer releases from storage per unit surface area of aquifer per unit decline in potentiometric surface. It is a measure of the ability of the aquifer to release water that is in storage, and it is usually associated with confined aquifers. Storativity of confined aquifers (storage coefficient) typically ranges from 10^{-5} to 10^{-3}. In unconfined aquifers, the storativity is virtually equivalent to the specific yield, which typically ranges from 0.1 to 0.3 (Freeze and Cherry, 1979).

The Neuman method of analysis for an unconfined aquifer assumes the first part of the drawdown curve (type A) approximates the response of a confined aquifer. The storativity determined from this part of the curve should yield a value that is somewhat less than what would be determined from the analysis of the type B curve (Domenico and Schwartz, 1990). The best fit theoretical response curve shown in figures 4 and 5 is based on a storage coefficient of 0.05 and a specific yield of 0.42.

Calculated Hypothetical Equilibrium Drawdown

A version of the Theim equilibrium equation (Driscoll, 1986, p. 215) can be used to calculate the hypothetical equilibrium drawdown in an idealized unconfined aquifer when a perfectly efficient well is being pumped at a constant rate. The equation is:

$$K = \frac{1,055 \cdot Q \cdot \log(r_2 / r_1)}{h_2^{\ 2} - h_1^{\ 2}} \qquad (1)$$

where

K = hydraulic conductivity in gallons per day per foot squared;
Q = pumping rate, in gallons per minute;
r_2 = distance to the farthest observation point, in feet;
r_1 = distance to the nearest observation point, in feet;
h_2 = saturated thickness of the aquifer at the farthest observation point, in feet; and
h_1 = saturated thickness of the aquifer at the nearest observation point, in feet.

Although no situation can fully meet the simplifying assumptions used to develop the equation, the average hydraulic conductivity determined from aquifer tests has proven to be an be an adequate substitute for the uniform hydraulic conductivity assumed for the idealized aquifer (Driscoll, 1986, p. 214). The mathematical relationships expressed in the equation can be used to develop a general understanding of how the water levels in the aquifer might react to different pumping rates.

Equation 1 can be re-written, as shown below, to allow the calculation of drawdown at a specified distance from the well. Equation 2 was used to calculate the hypothetical equilibrium drawdown values shown in table 2.

$$h_2 = \sqrt{h_1^{\ 2} + \frac{1,055 \cdot Q \cdot \log(r_2 / r_1)}{K}} \qquad (2)$$

where the variables are defined as above for equation 1.

The drawdown-at-a-distance values presented in table 2 were calculated for a range of possible situations, depending on pumping rate, hydraulic conductivity, and drawdown near the well at equilibrium. The specified pumping rates of 500, 1,000, and 1,500 gal/min span a range of production that might be needed to justify a municipal production well or an irrigation well. The specified hydraulic conductivity values are based on the results of the aquifer test. The best fit estimate of transmissivity (24,000 ft^2/d) divided by the saturated thickness of the Elm aquifer at the start of the test (40.29 ft) indicates that the average hydraulic conductivity is about 600 ft/d. Drawdown 1 ft from the center of the pumping well might be approximately the same level of drawdown in the well, depending on well construction, and the specified drawdowns of 5, 10, and 15 ft at this distance may be within the range of acceptable operating drawdowns, depending on distances between wells and saturated aquifer thickness at different times and in different locations.

Figure 7 is a graph of calculated drawdown of water levels in an unconfined aquifer versus distance from the center of the pumping well when the pumping rate is 1,000 gal/min, the hydraulic conductivity is 600 ft/d, and drawdown at 1 ft from the center of the pumping well is specified at 5, 10, and 15 ft. The greater the drawdown near the pumping well, the greater the area affected by pumping. For these three hypothetical drawdown conditions at the pumping well, drawdown at 1,000 ft from the center of the pumping well would be less than 0.01 ft, 0.01 ft, and 3.62 ft, respectively (table 2).

Table 2. Calculated hypothetical equilibrium drawdown

[<, less than]

Pumping rate (gallons per minute)	Hydraulic conductivity (feet per day)	Drawdown, in feet, in the aquifer at the specified distance from the pumping well					
		Specified	Calculated				
		1	50	100	250	500	1,000
500	500	5	1.75	1.21	0.50	<0.01	<0.01
		10	6.27	5.66	4.86	4.26	3.68
		15	10.64	9.93	9.02	8.35	7.69
	600	5	2.28	1.81	1.21	.76	.32
		10	6.87	6.34	5.66	5.15	4.65
		15	11.32	10.72	9.94	9.36	8.79
	700	5	2.65	2.25	1.73	1.34	.95
		10	7.30	6.84	6.25	5.80	5.37
		15	11.82	11.29	10.61	10.10	9.60
1,000	500	5	<.01	<.01	<.01	<.01	<.01
		10	2.92	1.80	.37	<.01	<.01
		15	6.84	5.60	4.02	2.86	1.75
	600	5	<.01	<.01	<.01	<.01	<.01
		10	4.00	3.04	1.81	.90	.01
		15	8.06	6.98	5.60	4.60	3.62
	700	5	.45	<.01	<.01	<.01	<.01
		10	4.80	3.95	2.87	2.06	1.28
		15	8.96	8.00	6.78	5.89	5.02
1,500	500	5	<.01	<.01	<.01	<.01	<.01
		10	<.01	<.01	<.01	<.01	<.01
		15	3.44	1.75	<.01	<.01	<.01
	600	5	<.01	<.01	<.01	<.01	<.01
		10	1.35	.01	<.01	<.01	<.01
		15	5.10	3.62	1.76	.40	<.01
	700	5	<.01	<.01	<.01	<.01	<.01
		10	2.46	1.28	<.01	<.01	<.01
		15	6.34	5.02	3.36	2.14	.97

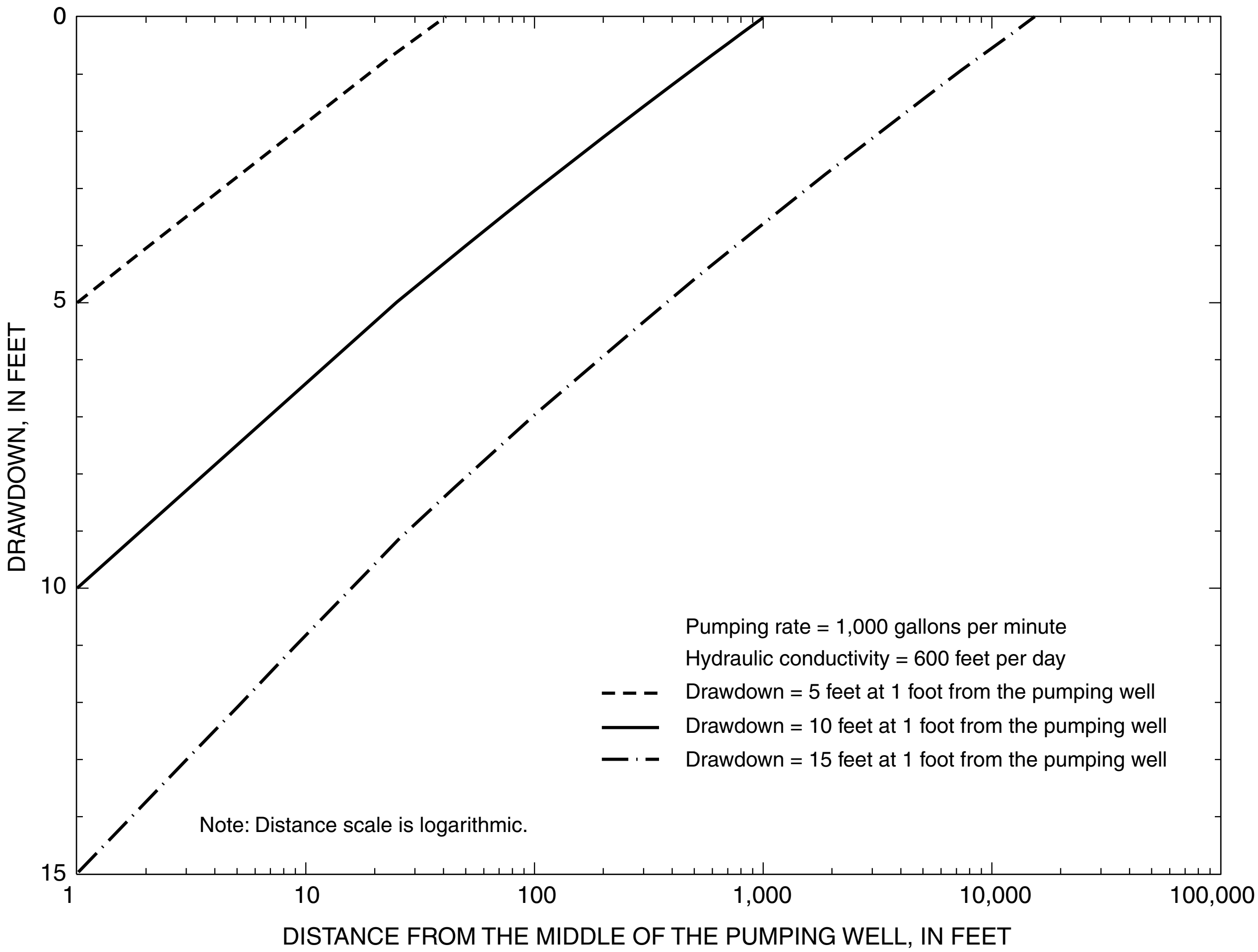

Figure 7. Calculated drawdown versus distance for 3 hypothetical equilibrium scenarios.

SUMMARY AND CONCLUSIONS

The City of Aberdeen is a growing municipality in northeastern South Dakota that currently relies on a combination of surface water and ground water to meet its water-supply needs. Future residential and industrial growth may require additional water supplies, especially during drier times. Aberdeen is interested in expanding its ground-water supply and needs a better understanding of the hydraulic properties of the Elm aquifer.

The Elm aquifer consists of sandy and gravelly glacial-outwash deposits. It slopes to the west at about the same gradient as the topographic surface, about 15 ft/mi, and the general direction of water movement is from northwest to southeast along a water-table gradient of about 10 ft/mi (Emmons, 1990). The Elm aquifer is present in several counties in eastern South Dakota and information regarding its hydraulic properties will be useful for the possible development of the aquifer as a water resource.

Historical water-level data indicate that the saturated thickness of the Elm aquifer can change considerably over time. From September 1977 through November 1985, water levels at three wells completed in the Elm aquifer near the aquifer test site varied by 5.1 ft, 9.50 ft, and 11.1 ft. From June 1982 through October 1999, water levels at five wells completed in the Elm aquifer near the aquifer test site varied by 8.7 ft, 11.4 ft, 13.2 ft, 13.8 ft, and 19.7 ft. The water levels during the fall of 1999 were among the highest on record, so the aquifer test was affected by portions of the aquifer being saturated that might not be saturated during drier times.

The aquifer test was conducted using five existing wells that had been installed prior to the study. Well A, which has an operating irrigation pump, is centrally located among the wells. Wells B, C, D, and E are about 70 ft, 1,390 ft, 2,200 ft, and 3,100 ft, respectively, from Well A. Using vented pressure transducers and programmable data loggers, water-level data were collected at the five wells prior to, during, and after the pumping, which started on November 19, 1999, and lasted a little over 72 hours.

The Neuman (1974) method theoretical response curves that most closely match the observed water-level changes at Wells A and B were calculated using software (AQTESOLV for Windows Version 2.13-Professional) developed by Glenn M. Duffield of HydroSOLVE, Inc. These best fit theoretical response curves are based on a transmissivity of 24,000 ft^2/d or a hydraulic conductivity of about 600 ft/d, a storage coefficient of 0.05, a specific yield of 0.42, and $K_z/K_r = 1$.

The theoretical type curves match the observed data fairly closely at Wells A and B until about 2,500 minutes and 1,000 minutes, respectively, after pumping began. The increasing rate of drawdown after these breaks is an indication that a no-flow boundary (an area with much lower hydraulic conductivity) likely was encountered and that Wells A and B may be completed in a part of the Elm aquifer with limited hydraulic connection to the rest of the aquifer.

Additional analysis indicates that if different assumptions regarding the screened interval for Well B and aquifer anisotropy are used, type curves can be calculated that fit the observed data using a lower specific yield that is within the commonly accepted range. When the screened interval for Well B was reduced to 5 ft near the top of the aquifer and K_z/K_r was set to 0.05, the type curves calculated using a specific yield of 0.1 and a transmissivity of 30,200 ft^2/d also matched the modified data from Wells A and B fairly well.

A version of the Theim equilibrium equation (Driscoll, 1986, p. 215) was used to calculate the theoretical drawdown in an idealized unconfined aquifer when a perfectly efficient well is being pumped at a constant rate. When these calculations were done with an assumed pumping rate of 1,000 gal/min, a hydraulic conductivity of 600 ft/d, and drawdown at 1 ft from the center of the pumping well of 5, 10, and 15 ft, drawdown at 1,000 ft from the center of the pumping well would be less than 0.01 ft, 0.01 ft, and 3.62 ft, respectively.

Additional aquifer tests could provide enhanced information about the hydraulic properties of the Elm aquifer. Aquifer tests at the same location might be enhanced by collecting water-level data at observation wells between 70 ft and 1,390 ft from Well A and pumping the well at a rate and duration similar to that of a municipal production well. Aquifer tests conducted in other areas of the aquifer could indicate the spatial variability of the hydraulic properties of the Elm aquifer.

Although the aquifer test indicates that hydraulic conductivity near the well may be adequate to support a production well, the comparison of drawdown and recovery curves indicates the possibility that heterogeneities may limit the productive capacity at specific locations in the Elm aquifer during certain times. Additional test hole drilling and geophysical studies could help characterize these heterogeneities in the aquifer.

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SUPPLEMENTAL INFORMATION

Table 3. Pumping rate at Well A

[Pumping started on November 19, 1999, at 12:30 PM]

Elapsed time (minutes)	Pumping rate (gallons per minute)	Elapsed time (minutes)	Pumping rate (gallons per minute)	Elapsed time (minutes)	Pumping rate (gallons per minute)
0	0	1,290	1,020	3,015	1,000
1	700	1,350	1,000	3,088	1,000
2	800	1,410	1,010	3,162	1,000
3	900	1,530	1,025	3,210	1,000
4	1,000	1,590	1,010	3,270	1,000
30	1,000	1,650	1,020	3,325	1,000
120	950	1,720	1,000	3,330	0
185	975	1,770	1,000	3,335	0
270	980	1,830	1,000	3,337	1,000
330	950	1,890	1,020	4,005	1,000
390	975	1,950	1,020	4,105	1,000
450	950	2,010	1,000	4,106	0
510	950	2,550	1,000	4,114	0
570	950	2,610	1,000	4,115	1,000
1,140	950	2,611	0	4,295	1,000
1,170	950	2,623	0	4,340	1,000
1,193	950	2,624	1,000	4,341	0
1,195	0	2,790	1,000	4,342	1,000
1,200	0	2,850	1,000	4,345	1,000
1,207	1,000	2,910	1,000	4,346	0
1,270	1,000	2,970	1,000		

Table 4. Drawdown at Well A

[Pumping started on November 19, 1999, at 12:30 PM]

Elapsed time (minutes)	Drawdown (feet)	Elapsed time (minutes)	Drawdown (feet)	Elapsed time (minutes)	Drawdown (feet)
0	0.00	165	8.31	1,465	10.31
1	8.38	170	8.30	1,525	10.34
5	7.75	175	8.34	1,585	10.41
10	7.92	180	8.34	1,645	10.47
15	7.99	185	8.36	1,705	10.50
20	8.04	190	8.39	1,765	10.62
25	8.01	195	8.41	1,825	10.68
30	8.03	200	8.40	1,885	10.70
35	7.98	260	8.49	1,945	10.75
40	7.97	320	8.58	2,005	10.82
45	7.96	380	8.63	2,065	10.90
50	8.00	440	8.72	2,125	10.90
55	8.01	500	8.79	2,185	10.97
60	8.04	560	8.86	2,245	11.01
65	8.05	620	8.94	2,305	11.01
70	8.07	680	9.01	2,365	11.10
75	8.10	740	9.05	2,425	11.09
80	8.12	800	9.13	2,485	11.19
85	8.12	860	9.21	2,545	11.23
90	8.13	920	9.24	2,605	11.20
95	8.16	980	9.28	2,610	11.25
100	8.14	1,040	9.36	2,611	3.02
105	8.20	1,100	9.42	2,615	2.78
110	8.18	1,160	9.49	2,625	12.03
115	8.22	1,190	9.50	2,630	12.18
120	8.24	1,195	2.02	2,635	12.25
125	8.24	1,200	1.81	2,695	12.32
130	8.26	1,205	8.74	2,755	12.42
135	8.25	1,210	9.86	2,815	12.43
140	8.26	1,220	9.99	2,875	12.45
145	8.27	1,225	10.04	2,935	12.49
150	8.27	1,285	10.13	2,995	12.58
155	8.30	1,345	10.17	3,055	12.59
160	8.31	1,405	10.24	3,115	12.67

Table 4. Drawdown at Well A—Continued

[Pumping started on November 19, 1999, at 12:30 PM]

Elapsed time (minutes)	Drawdown (feet)	Elapsed time (minutes)	Drawdown (feet)	Elapsed time (minutes)	Drawdown (feet)
3,175	12.71	4,360	4.40	5,490	2.31
3,235	12.77	4,365	4.35	5,550	2.27
3,295	12.81	4,391	4.14	5,610	2.24
3,325	12.85	4,395	4.12	5,670	2.21
3,330	4.26	4,400	4.07	5,730	2.18
3,335	4.13	4,405	4.03	5,790	2.14
3,340	12.49	4,410	4.00	5,850	2.12
3,345	12.35	4,415	3.94	5,910	2.09
3,405	12.52	4,420	3.91	5,970	2.07
3,465	12.56	4,425	3.86	6,030	2.04
3,525	12.64	4,430	3.85	6,090	2.02
3,585	12.68	4,435	3.82	6,150	1.99
3,645	12.70	4,440	3.80	6,210	1.97
3,705	12.79	4,445	3.78	6,270	1.94
3,765	12.89	4,450	3.74	6,330	1.92
3,825	12.83	4,455	3.73	6,390	1.91
3,885	12.91	4,460	3.70	6,450	1.88
3,945	12.89	4,465	3.69	6,510	1.87
4,005	12.90	4,470	3.67	6,570	1.85
4,065	12.95	4,530	3.45	6,630	1.83
4,105	13.03	4,590	3.31	6,690	1.80
4,110	4.57	4,650	3.17	6,750	1.79
4,115	4.44	4,710	3.08	6,810	1.77
4,120	13.03	4,770	2.99	6,870	1.75
4,125	13.13	4,830	2.91	6,930	1.74
4,185	13.23	4,890	2.88	6,990	1.74
4,245	13.25	4,950	2.80	7,050	1.73
4,305	13.40	5,010	2.73	7,350	1.66
4,340	13.38	5,070	2.68	7,650	1.61
4,341	11.67	5,130	2.62	7,950	1.56
4,342	13.24	5,190	2.52	8,250	1.51
4,345	13.30	5,250	2.49	8,550	1.46
4,346	4.69	5,310	2.45	8,850	1.42
4,350	4.56	5,370	2.40		
4,356	4.45	5,430	2.35		

Table 5. Drawdown at Well B

[Pumping started on November 19, 1999, at 12:30 PM]

Elapsed time (minutes)	Drawdown (feet)	Elapsed time (minutes)	Drawdown (feet)	Elapsed time (minutes)	Drawdown (feet)
20.45	0.02	190.51	0.85	1,022.40	1.82
25.49	.06	195.41	.85	1,082.45	1.87
30.38	.10	200.45	.86	1,142.50	1.91
35.42	.16	205.49	.87	1,202.40	2.03
40.46	.20	210.38	.88	1,267.49	1.96
45.50	.24	215.42	.90	1,327.39	2.05
50.40	.27	220.46	.91	1,387.44	2.10
55.44	.31	225.50	.92	1,447.49	2.17
60.48	.33	230.40	.94	1,507.39	2.18
65.52	.39	235.44	.94	1,567.44	2.23
70.42	.40	240.48	.95	1,627.49	2.26
75.46	.43	245.52	.95	1,687.39	2.30
80.50	.45	250.42	.95	1,747.44	2.35
85.39	.47	255.46	.97	1,807.49	2.39
90.43	.49	260.50	.99	1,867.39	2.42
95.47	.52	265.39	1.00	1,927.44	2.47
100.51	.54	270.43	1.00	1,987.49	2.51
105.41	.57	275.47	.99	2,047.39	2.54
110.45	.58	280.51	1.02	2,107.44	2.58
115.49	.60	285.41	1.02	2,167.49	2.60
120.38	.63	290.45	1.04	2,227.39	2.64
125.42	.65	295.49	1.04	2,287.44	2.66
130.46	.66	302.40	1.07	2,347.49	2.70
135.50	.67	362.45	1.17	2,407.39	2.74
140.40	.69	422.50	1.25	2,467.44	2.77
145.44	.70	482.40	1.33	2,527.49	2.80
150.48	.71	542.45	1.40	2,587.39	2.83
155.52	.73	602.50	1.46	2,642.40	2.71
160.42	.75	662.40	1.53	2,702.45	2.81
165.46	.78	722.45	1.59	2,762.50	2.86
170.50	.79	782.50	1.63	2,822.40	2.92
175.39	.80	842.40	1.68	2,882.45	2.94
180.43	.81	902.45	1.73	2,942.50	2.98
185.47	.83	962.50	1.77	3,002.40	3.02