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

Hydrogeology and Sources of Recharge to the Buffalo and Wahpeton Aquifers in the Southern Part of the Red River of the North Drainage Basin, West-Central Minnesota and Southeastern North Dakota

By M.E. Schoenberg

Water-Resources Investigations Report 97-4084

Prepared in cooperation with the Minnesota Department of Natural Resources and Moorhead Public Service

U.S. Department of the Interior

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Mounds View, Minnesota, 1998

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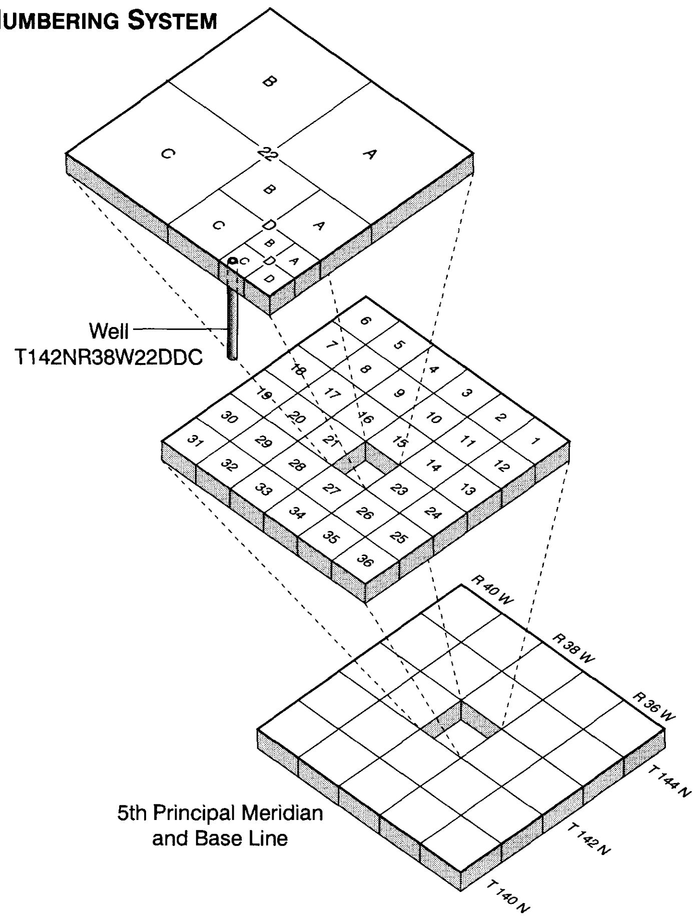
Conversion Factors and Vertical Datum

Multiply Inch-Pound Units	By	To Obtain Metric Unit
inch (in.)	25.4	millimeter
foot (ft)	.3048	meter
mile (mi)	1.609	kilometer
square foot (ft^2)	.09290	square meter
square mile (mi^2)	2.590	square kilometer
million gallons (Mgal)	3,785	cubic meter
foot per day (ft/d)	.3048	meter per day
	.0003528	centimeter per second
inch per year (in./yr)	2.54	centimeter per year
square foot per day (ft^2/d)	.09290	square meter per day
cubic foot per second (ft^3/s)	28.32	liter per second
cubic foot per day (ft^3/d)	28.32	liter per day
gallon per day (gal/d)	.003785	cubic meter per day
gallon per minute (gal/min)	.00006309	cubic meter per second
million gallons per year (Mgal/yr)	3,785	cubic meter per year

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

SITE LOCATION AND NUMBERING SYSTEM

The numbering system used to define the location of data collection sites is based on the Federal system of land subdivision (township, range, and section). The first number of the site location indicates the township (the N after the township number is an abbreviation for north); the second, the range (the W after the range number is an abbreviation for west); and the third the section. Uppercase letters after the section number indicate location within the section; the first letter denotes the 160-acre tract, the second the 40-acre tract, and the third the 10-acre tract. The number of uppercase letters indicates accuracy of the location number. For instance, if a point can be located within a 10-acre tract, three uppercase letters are shown in the location number. The number T142NR38W22DDC indicates the site is located in the SW 1/4 of the SE ¼ of the SE ¼, section 22, township 142 north, range 38 west, 5th principal meridian and base line.



Hydrogeology and Sources of Recharge to the Buffalo and Wahpeton Aquifers in the Southern Part of the Red River of the North Drainage Basin, West-Central Minnesota and Southeastern North Dakota

By M.E. Schoenberg

Abstract

Declining hydraulic heads in the Buffalo and Wahpeton aquifers are of concern to the Minnesota Department of Natural Resources and local water managers because of limited ground-water resources in the southern part of the Red River of the North drainage basin. The U.S. Geological Survey, in cooperation with the Minnesota Department of Natural Resources and Moorhead Public Service, investigated the hydrogeology of and sources of recharge to the Buffalo and Wahpeton aquifers.

The Buffalo aquifer is a complex, heterogeneous outwash deposit composed of medium to coarse sand and gravel. Part of the Buffalo aquifer is unconfined and part is confined. The direction of ground water flow in the Buffalo aquifer is from east to west. Water-level declines in observation wells near the Moorhead Public Service North Well Field extend beyond the eastern and western boundaries of the Buffalo aquifer. Transmissivity and storativity calculated from the drawdown part of an aquifer test ranged from 20,870 to 23,852 feet squared per day and from 3.0×10^{-5} to 3.2×10^{-2}, respectively. Transmissivity and hydraulic conductivity values of 29,090 and 28,450 feet squared per day and 272 and 266 feet per day were calculated from the recovery-phase data.

Potential recharge from the Buffalo River and its tributaries to the Buffalo aquifer ranged from 5 to 14 cubic feet per second. Recharge from precipitation where the Buffalo aquifer is unconfined was about 1.49×10^{5} cubic feet per day. Recharge per unit length of the Buffalo aquifer during an aquifer test near the Moorhead Public Service North Well Field ranged from 3.9×10^{-4} to 2.0×10^{-2} cubic feet per day.

The Wahpeton Shallow Sand, the Wahpeton Sand Plain, and the Wahpeton Buried Valley aquifers comprise the Wahpeton aquifers in order of increasing depth. All the aquifers are composed of fine- to coarse-grained sand mixed with gravel. Confining units are interleaved with the Wahpeton aquifers.

Ground-water-flow directions in the Wahpeton aquifers were changed by ground-water development. Before development, ground water flowed from the Wahpeton Buried Valley aquifer upward to the Wahpeton Sand Plain aquifer and the Wahpeton Shallow Sand aquifer. After development, ground water flowed from the Wahpeton Shallow Sand aquifer to the Wahpeton Sand Plain and the Wahpeton Buried Valley aquifers.

The potential sources of recharge to the Wahpeton aquifers investigated were the Red River of the North, and adjacent hydrogeologic units. The volume of ground water pumped from the Wahpeton aquifers provides an estimate of the upper limit for the volume of recharge to the aquifer. Based on pumpage from all of the Wapheton aquifers from 1990 to 1993, the upper limit is about 580 million gallons per year (2.4×10^{5} cubic feet per day).

Introduction

Ground water from the Buffalo and Wahpeton aquifers supplies municipal, agricultural-product processing, agricultural, and domestic needs in the southern part of the Red River of the North drainage basin in west-central Minnesota and southeastern North Dakota (fig. 1). The Buffalo aquifer is located in Clay and Wilkin Counties, Minnesota. The Wahpeton aquifers, in descending order, consist of the Wahpeton Shallow Sand, Wahpeton Sand Plain, and Wahpeton Buried Valley aquifers and are located in Wilkin County, Minnesota, and Richland County, North Dakota.

Declining hydraulic heads in the Buffalo and Wahpeton aquifers concern the Minnesota Department of Natural Resources (MDNR) and local water managers because ground-water resources are limited in the southern part of the Red River of the North drainage basin (Minnesota Department of Natural Resources, 1994, p. 15). Hydraulic head has declined by as much as 20 ft in the Buffalo aquifer since 1949 (G.B. Mitton, U.S. Geological Survey, written commun., 1993), and by as much as 60 ft in the Wahpeton Buried Valley aquifer since 1974 (D. Ripley, North Dakota State Water Commission, written commun., 1993). The MDNR is particularly concerned about the Buffalo and Wahpeton aquifers because these aquifers are susceptible to contamination, to hydraulic-head decline during drought, or to long-term withdrawals greater than long-term recharge (Minnesota Department of Natural Resources, 1994, p. 15). Some potential effects of declining hydraulic heads are the increased possibility of well interference between nearby wells, the induced recharge into aquifers of contaminated river water, and the uncertainty about long-term well yields.

Knowledge about the hydrogeology of the Buffalo and Wahpeton aquifers and the sources of recharge to these aquifers is necessary to manage the water resources in the southern Red River of the North drainage basin. Potential sources of ground-water recharge to the Buffalo and Wahpeton aquifers are the following: the induced leakage from nearby rivers, the vertical leakage of precipitation, and the horizontal leakage of ground water through adjacent hydrogeologic units. The amounts of ground-water recharge that the Buffalo and Wahpeton aquifers receive from each source of recharge are not well quantified because the hydraulic connections between each aquifer and the sources of ground-water recharge are not well known.

The U.S. Geological Survey (USGS) conducted this study in cooperation with the MDNR and Moorhead Public Service (MPS). The study focused on the hydrogeology of the Buffalo and Wahpeton aquifers, the potential sources of recharge to these aquifers, and the hydraulic connections between the aquifers and the sources of ground-water recharge.

Purpose and Scope

This report describes the hydrogeology and the sources of recharge to the Buffalo and Wahpeton aquifers in the southern Red River of the North drainage basin. Specifically, this report describes: (1) areal extents, recharge areas, and hydraulic properties of the Buffalo and Wahpeton aquifers; (2) hydraulic connections between the aquifers and the sources of recharge; and (3) recharge to the aquifers by induced leakage from nearby rivers, by vertical leakage from precipitation, and by horizontal leakage of ground water through adjacent hydrogeologic units.

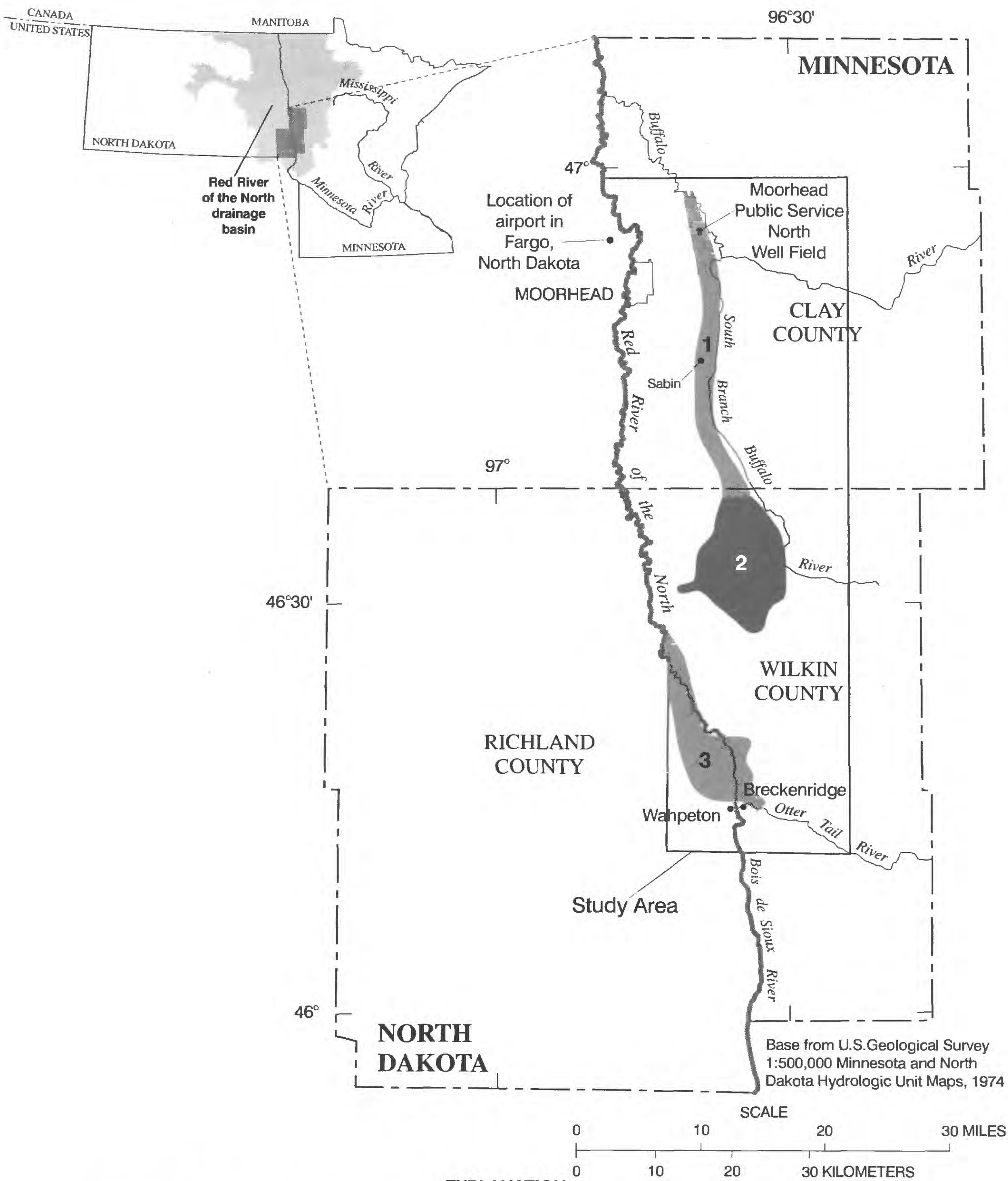
Previous Work

Maclay and others (1972) and Reeder (1978) described the water resources of the Red River of the North drainage basin. Byers and others (1946) and Dennis and others (1949) provide early scientific descriptions of the Buffalo aquifer near the Moorhead, Minnesota, area. William F. Guyton and Associates (1957) described the effect of ground-water withdrawals by MPS on the Buffalo aquifer. Bingham (1960) compiled basic geologic and ground-water data for Clay County, Minnesota. Zohdy and Bisdorf (1979) conducted a geo-electrical investigation of the Buffalo aquifer with geo-electrical-resistivity soundings. Wolf (1981) conducted the first study that concentrated on the hydrogeology of the Buffalo aquifer. Ulteig Engineers, Inc. (1987) described the drilling program and aquifer test associated with the MPS North Well Field in the Buffalo aquifer. Schmid (1970) documented an aquifer test of the Wahpeton Buried Valley and Wahpeton Sand Plain aquifers. Froelich (1974) described the hydrogeology of the Wahpeton aquifers near Wahpeton, North Dakota. Ripley (1988 and 1992) documented the effect of industrial development on the Wahpeton aquifers.

Methods of Investigation

Hydraulic-head and lithologic data were collected for this investigation to delineate the boundaries of the Buffalo and Wahpeton aquifers (fig. 1). Well logs and test holes in Minnesota were compiled from USGS and Minnesota Geological Survey (MGS) files. Published reports of the USGS, MDNR, MGS, North Dakota State Water Commission (NDSWC), and consultants provided additional data. New hydraulic-head and lithologic data were obtained from eight wells installed for this project. Individual test holes or wells are identified by a six-digit unique number assigned by the State of Minnesota or by a local well number assigned by the State of North Dakota (fig. 2).

Available water-use data for the study area were collected from published reports, from State agencies, and from municipalities in Minnesota and North Dakota. MPS provided monthly municipal water-use data for 1954 through 1993 for Moorhead, Minnesota (C. McClain, Moorhead Public Service, written commun., 1993 and 1994). The City of Breckenridge, Minnesota, provided annual municipal water-use data for 1978 through 1993 (J. Mueller, City of Breckenridge, oral commun., 1993 and 1994). The NDSWC provided municipal and agricultural-processing water-use data for the Wahpeton, North Dakota, area for 1974 through 1993 (D.P. Ripley, North Dakota State Water Commission, written commun., 1993 and 1994). The



EXPLANATION

1	Buffalo aquifer - Mapped by Wolf (1981).
2	Buffalo aquifer - Mapped for this report from available data.
3	Wahpeton aquifers - Combined outline of the Wahpeton Shallow Sand, Wahpeton Sand Plain, and Wahpeton Buried Valley aquifers; mapped for this report from maps and data from Froelick (1974), data from Ripley (1992), and well logs from the Minnesota County Well Index.

Figure 1. Location of Buffalo and Wahpeton aquifers, west-central Minnesota and southeastern North Dakota.

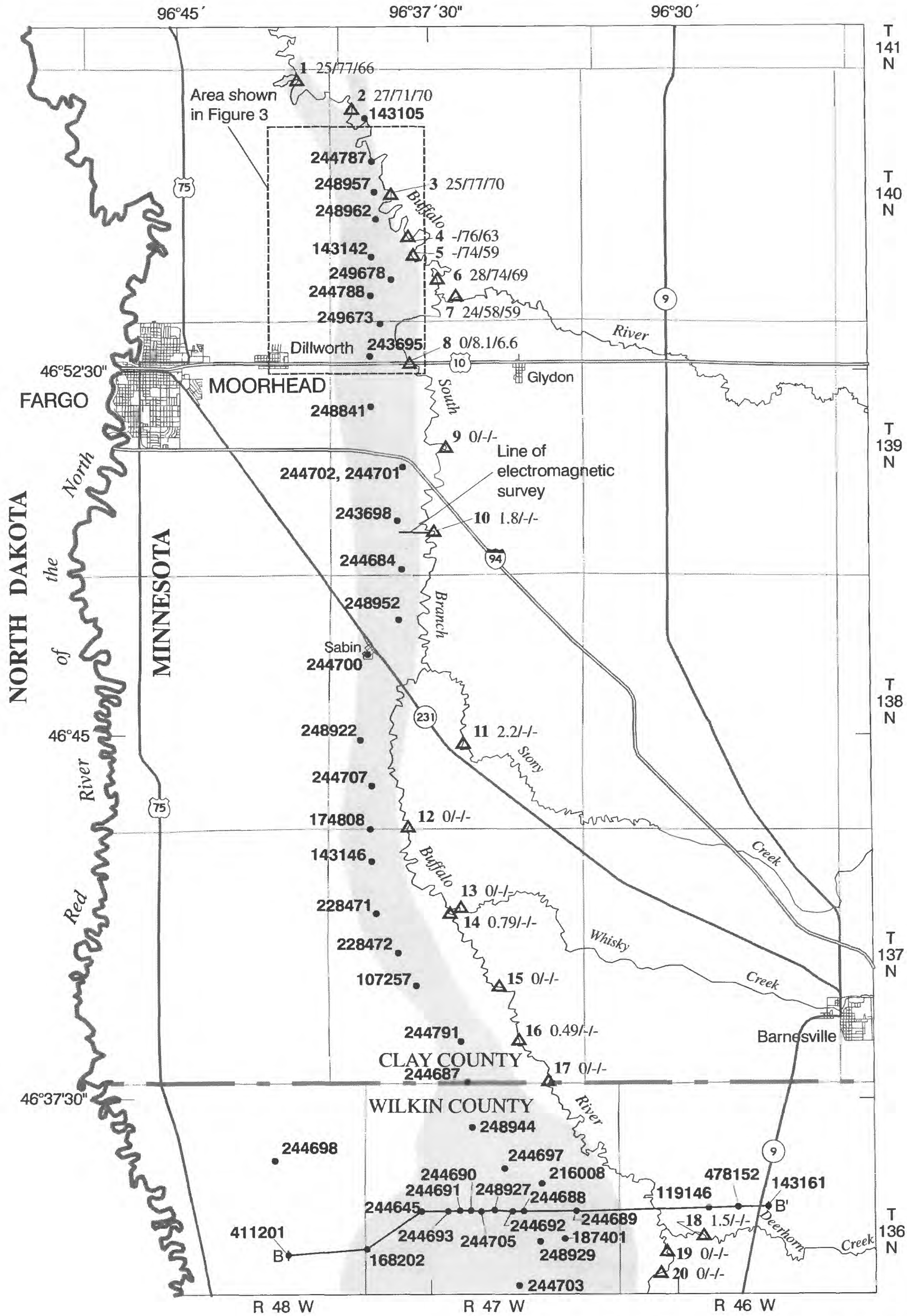
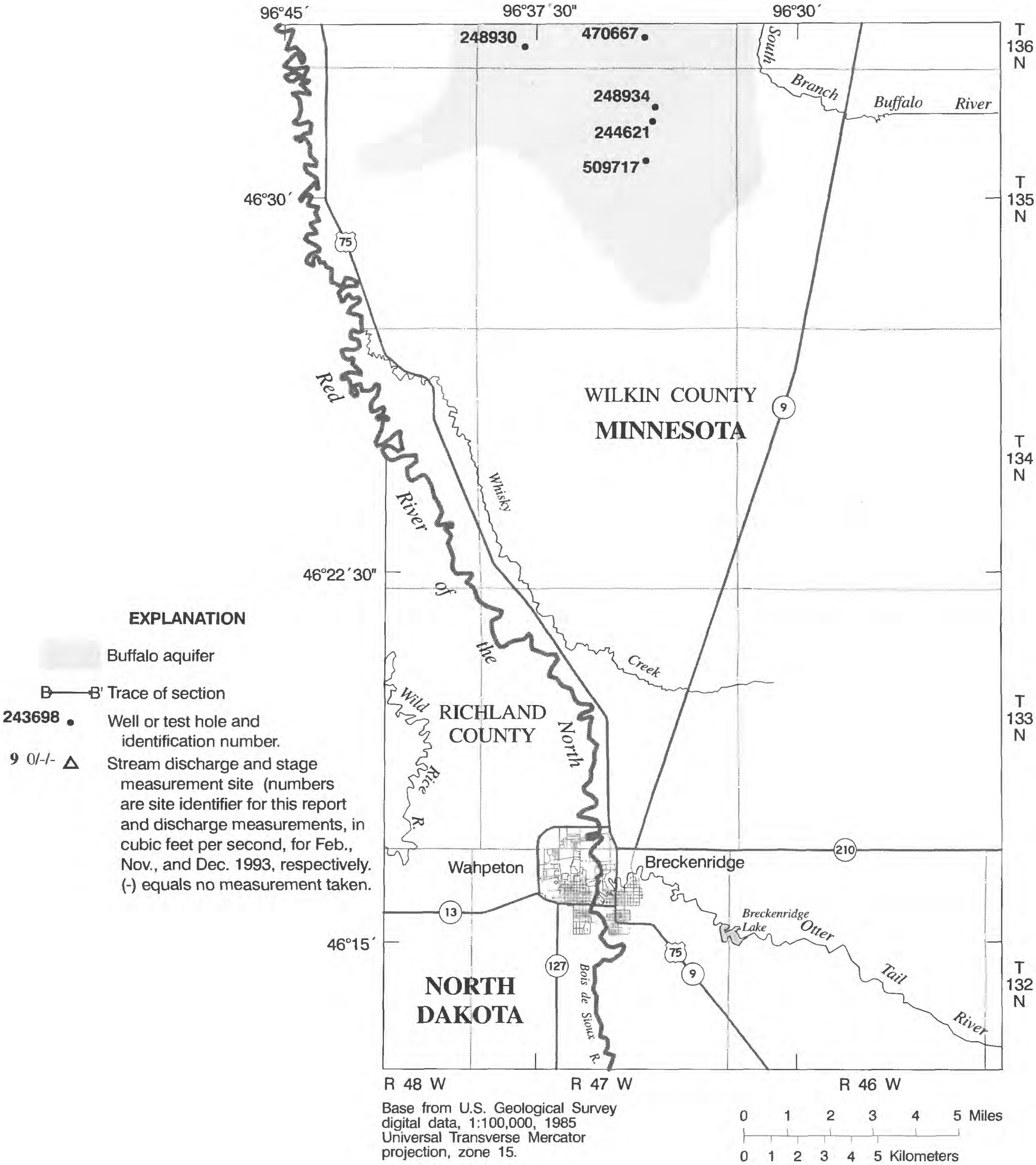


Figure 2. Buffalo aquifer study area and discharge



measurements along the Buffalo River and its tributaries.

MDNR provided annual water-use data for Clay and Wilkin Counties, Minnesota, for 1988 through 1992 (T. Nguyen, Minnesota Department of Natural Resources, written commun., 1994).

Eight test holes were drilled with hollow-stem-auger and mud-rotary drilling equipment. Observation wells were installed in seven of the test holes (fig. 3). Wells 244155, 244156, 244158, 244160, and 244161 were screened at the water table. Well 533055 was screened from about 100 to 105 ft below land surface. Well 533056 was screened from about 85 to 100 ft below land surface. Continual hydraulic-head measurements were made at 12 wells near the MPS North Well Field. Wells 511085 and 511086 located in the MPS North Well Field are municipal-supply wells and 10 wells were observation wells. Continual hydraulic-head measurements were made with transducers and electronic data loggers. Drill cuttings and cores were collected from wells 244156, 244161, 533055, and 533056. The drill cuttings were used to describe the lithology of the Buffalo aquifer and for particle-size analyses of Buffalo aquifer sediments and adjacent confining units.

Multiple methods were used to estimate hydraulic properties of the Buffalo aquifer and the adjacent confining units. Hydraulic properties were estimated based on grain-size analyses of core samples by the University of Minnesota-Duluth according to methods described by Folk (1974) and an aquifer test. Hydraulic properties of the adjacent confining units were also estimated based on grain-size analyses of core samples, laboratory permeameter tests, slug tests, and single-well aquifer tests. Hydraulic properties of the 44 core samples from the confining units were estimated using the equation of Puckett and others (1985).

Hydraulic conductivity and storativity of the Buffalo aquifer were determined from the drawdown part of an aquifer test at the MPS North Well Field (fig. 3). The data from two observations wells (247980 and 247985) and a municipal supply well (511085) were analyzed with the Hantusch (1960) curve-fitting method for an aquifer test in a leaky confined aquifer. Hydraulic conductivity was calculated by dividing the transmissivity by the thickness of the aquifer.

Hydraulic conductivity of the Buffalo aquifer was also determined from the recovery part of the aquifer test at the MPS North Well Field. The data from wells 511085 and 511086 were analyzed with the Theis recovery method (Kruseman and de Ridder, 1990, p. 194-196). Hydraulic conductivity was calculated by dividing the transmissivity by the thickness of the aquifer.

Hydraulic conductivity of confining units adjacent to the Buffalo aquifer was estimated with laboratory determinations of permeability that used undisturbed soil cores. The samples were obtained during the drilling of wells 244156, 244161, 533055, and 533056 by pushing a 4-in. diameter by 3-ft long thin-wall steel tube into the bottom of a test hole with the drill stem of the mud-rotary drill rig. Each core was kept saturated by sealing both ends of the steel tube with wax and a taped on cap immediately upon removal of the steel tube from the test hole. One sample was selected from each of three cores that had a uniform lithology. Two samples were selected from one core that had silt and silty clay. Permeability was determined by Twin Cities Testing Corporation according to methods described in the American Society for Testing Materials standard D5084-90 (American Society for Testing Materials, reapproved 1990).

Hydraulic conductivity of one of the confining units adjacent to the Buffalo aquifer was determined with a slug test in observation well 533055 and a single-well recovery test in well 533056. The slug test was analyzed with the method of Cooper and others (1967). The transmissivity of the aquifer was determined graphically. Hydraulic conductivity was calculated by dividing the transmissivity by the length of the well screen.The single-well recovery test was analyzed with the Theis recovery method (Kruseman and de Ridder, 1990, p. 194-196).

Electromagnetic-conductivity profiling was used to investigate the shape of the top of the Buffalo aquifer. The electromagnetic-conductivity profiling was conducted by MDNR and USGS personnel (T. Gullett, Minnesota Department of Natural Resources, written commun., 1993). Measurements were taken at stations along a 4,000-ft transect at intervals of about 66 ft (fig. 2) using a Geonics EM34-3 Ground Conductivity Meter (EM-34) and a Geonics EM31-D Ground Conductivity Meter (EM-31).

Seismic-refraction profiling was used to locate the water table for the placement of observation wells 244156 and 244161 (fig. 3). The wells were installed for this project and used to monitor the effects of the aquifer test at the MPS North Well Field. The profiling was conducted by MDNR and USGS personnel. Hanei (1986 and 1988) described the use of seismic-refraction profiling to delineate the water table in New England.

Recharge from Buffalo River and its tributaries to the Buffalo aquifer in response to pumpage in the aquifer was investigated by measuring stream discharge. Discharge in the Buffalo and South Branch Buffalo Rivers were measured once when ground water was pumped only from the MPS North Well Field and once when ground water was pumped only from the MPS South Well Field. Discharge in the Buffalo River, South Branch Buffalo River, Stony Creek, Whisky Creek, and Deerhorn Creek (fig. 2) was measured when both MPS well fields were being used (February, November, and December 1993). Stream-discharge measurements were determined according to the methods of Carter and Davidian (1968) and Rantz and others (1982).

Recharge from adjacent confining units to the Buffalo aquifer caused by pumpage was investigated by measuring the hydraulic-head response near the boundaries of the confining unit and the aquifer. Hydraulic heads in adjacent confining units were continually monitored near the MPS North Well Field at two well clusters. Observation wells 244155 and 533055 were located west of the Buffalo aquifer. Observation wells 244160 and 533056 were located east of the Buffalo aquifer (fig. 3).

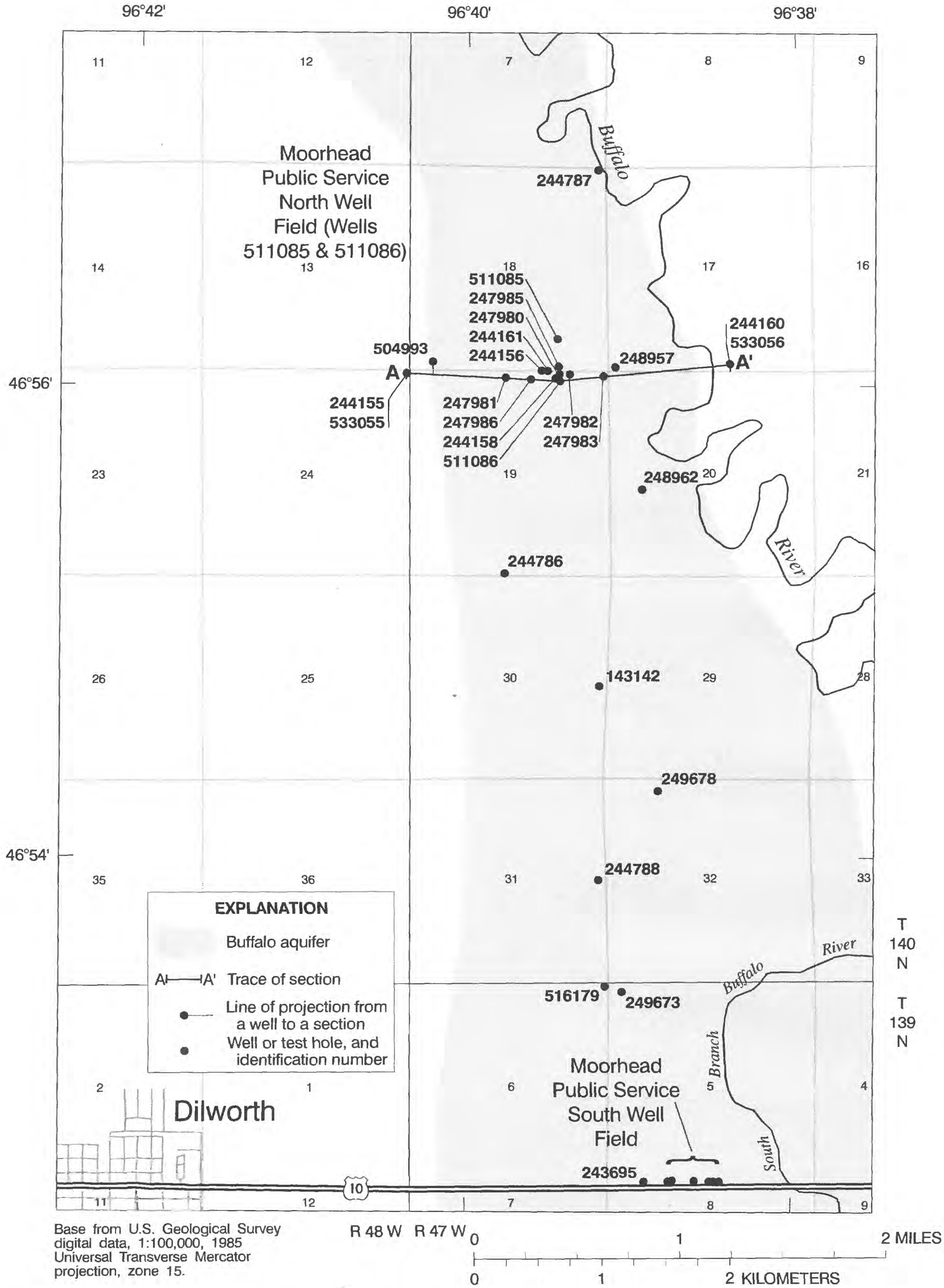


Figure 3. Location of wells, test holes, and hydrogeologic section, near Moorhead, Minnesota.

Recharge from precipitation was calculated from the response of the hydraulic head in wells to climatic events. Recharge from precipitation was calculated from hydrographs of wells 244693, 248927, and 248930 (fig. 2) between March 29, 1993 and June 20, 1993. Recharge was calculated by multiplying the change in hydraulic head on the hydrograph by the specific yield. The volume of areal recharge to the unconfined parts of the Buffalo and Wahpeton aquifers was calculated by multiplying the area of the unconfined aquifer by the recharge rate. The volume of recharge to the Buffalo aquifer through adjacent confining units and through the riverbeds of adjacent rivers was calculated with Darcy's Law.

Acknowledgments

The authors thank C. McClain, C. Moore, and others at Moorhead Public Service for their cooperation and assistance in conducting aquifer tests and collecting hydraulic-head data in the Buffalo aquifer, and for providing water-use data for the Moorhead Public Service wells in the Buffalo aquifer. The authors also thank D. Ripley from the North Dakota State Water Commission for hydraulic-head and water-use data for the Wahpeton, North Dakota, area; J. Mueller from the City of Breckenridge, Minnesota, for water-use data; and B. Popple of the Wilkin County Environmental Resources Management Office for measuring hydraulic heads in observation wells in Wilkin County, Minnesota, for the Minnesota Department of Natural Resources. The authors thank K. Harris and S. Benson of the Minnesota Geological Survey for advice and guidance in mapping the southern end of the Buffalo aquifer. Thanks also goes to the Minnesota Department of Natural Resources for providing potentiometric data and water-use data, and for conducting electromagnetic-conductivity and seismic-refraction profiling; and to the Minnesota Geological Survey for providing geologic data over the entire study area as part of the joint Minnesota Department of Natural Resources-Minnesota Geological Survey Regional Assessment Project.

Hydrogeology of the Buffalo Aquifer

The hydrogeology of the Buffalo aquifer is presented in terms of an aquifer description and hydraulic properties of the aquifer. The aquifer description includes a discussion of the physical setting of the aquifer and the recharge to and discharge from the aquifer. The physical setting of the aquifer includes the areal extent of the aquifer; grain-size distributions within the aquifer; unconfined and confined conditions; and hydraulic boundaries of the aquifer. Hydraulic properties of the aquifer include hydraulic conductivity and storativity of the aquifer.

Aquifer Description

The Buffalo aquifer is about 1-2 mi wide in the northern part of Clay County, Minnesota, extends southward about 36 mi, and is as much as 9 mi wide in southern Wilkin County, Minnesota (fig 2). The aquifer is a complex, heterogeneous mix of fine to coarse sand, clay, silt, and cobbly gravel. Wolf (1981) found that the aquifer becomes increasingly fine grained with increasing distance from its north-south axis. The aquifer grades from the silty fine to medium sand near the axis of the aquifer to very fine sand, silt, and clay at both the eastern and the western edges of the aquifer.

At the MPS North Well Field (fig. 3), the Buffalo aquifer contains three horizons (fig. 4). The upper horizon consists of silty fine to coarse sand interlayered with sandy clay. The middle horizon, where present, consists of sand with clay. The lower horizon consists of cobbly gravel with medium to coarse sand. The aquifer is as much as 220-ft thick (fig. 4) where the long, narrow northern part of the aquifer fills a buried valley (Wolf, 1981, fig. 8). Wells 244156 and 244161 (fig. 3), near the north-south centerline of the aquifer, penetrated the upper horizon from 30 to 48 ft below the land surface. Test hole 247981 (fig. 4) penetrated the upper horizon from 55 to123 ft below land surface, the middle horizon from 123 to 148 ft below land surface, and the lower horizon from 148 to 152 ft below land surface. Ulteig Engineers, Inc. (1987) reported that test hole 247983 (fig. 4) penetrated the upper horizon from 60 to 120 ft below the land surface, the middle horizon from 120 to 135 ft below the land surface, and the lower horizon from 135 to 140 ft below the land surface. Ulteig Engineers, Inc. (1987) reported that top of the middle horizon was at 94 and 107 ft below the land surface in wells 247980 and 247985, respectively, and the top of the lower horizon was at 110 ft below the land surface and extended to 203 and 207 ft below the land surface, respectively. The middle horizon extends from well 511086 north almost to well 511085 (Ulteig Engineers, Inc., 1987). The middle horizon also extends east and west from well 511086 (fig. 4).

In the southern part of the Buffalo aquifer near test hole 244688 (fig. 2), grain size varies with depth. The aquifer coarsens from fine sand to coarse sand with depth from 5 to 24 ft. The sand overlies 67 ft of gravel. The gravel lies on gravely silty clay (till) (figs. 4 and 5). At test hole 244689 east of test hole 244688, the aquifer is about 10 ft thick and composed of fine to medium sand and underlies 36 ft of silty clay (glacial Lake Agassiz sediments). The aquifer overlies gravely silty clay (till) (fig. 5). At test hole 244692, west of test hole 244688, 7 ft of silty clay (glacial Lake Agassiz sediments) overlies the Buffalo aquifer. The aquifer at test hole 244692 is composed of two layers of sand separated by a layer of silty clay (till) (fig. 5). The upper part of the aquifer consists of 49 ft of fine to coarse sand with fine gravel and overlies a 28-ft thick layer of silty clay (till). The layer of silty clay (till) overlies 43 ft of sand. Drilling of the test hole stopped when a boulder was encountered at 127 ft below land surface (fig. 5).

The depth to the top of the Buffalo aquifer was investigated with a west-east electromagnetic-conductivity-profiling survey beginning at the north-south trending centerline of the aquifer. The survey indicated that for the first 650 ft of the profile, sand and silty sand was 5 to 10 ft below the land surface (T. Peterson, Minnesota Department of Natural Resources, written commun.,

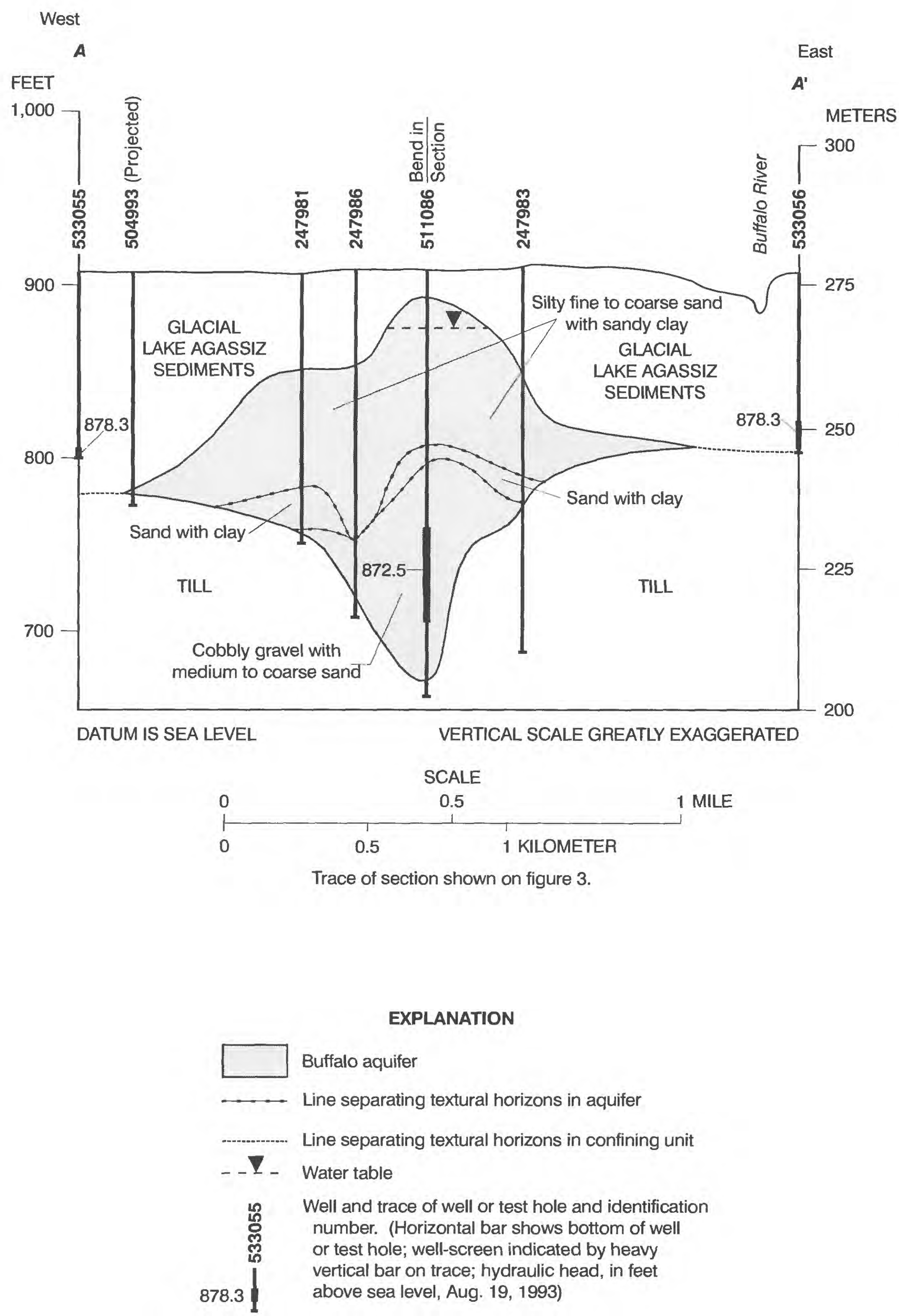


Figure 4. Hydrogeologic section *A-A'*, near Moorhead, Minnesota.

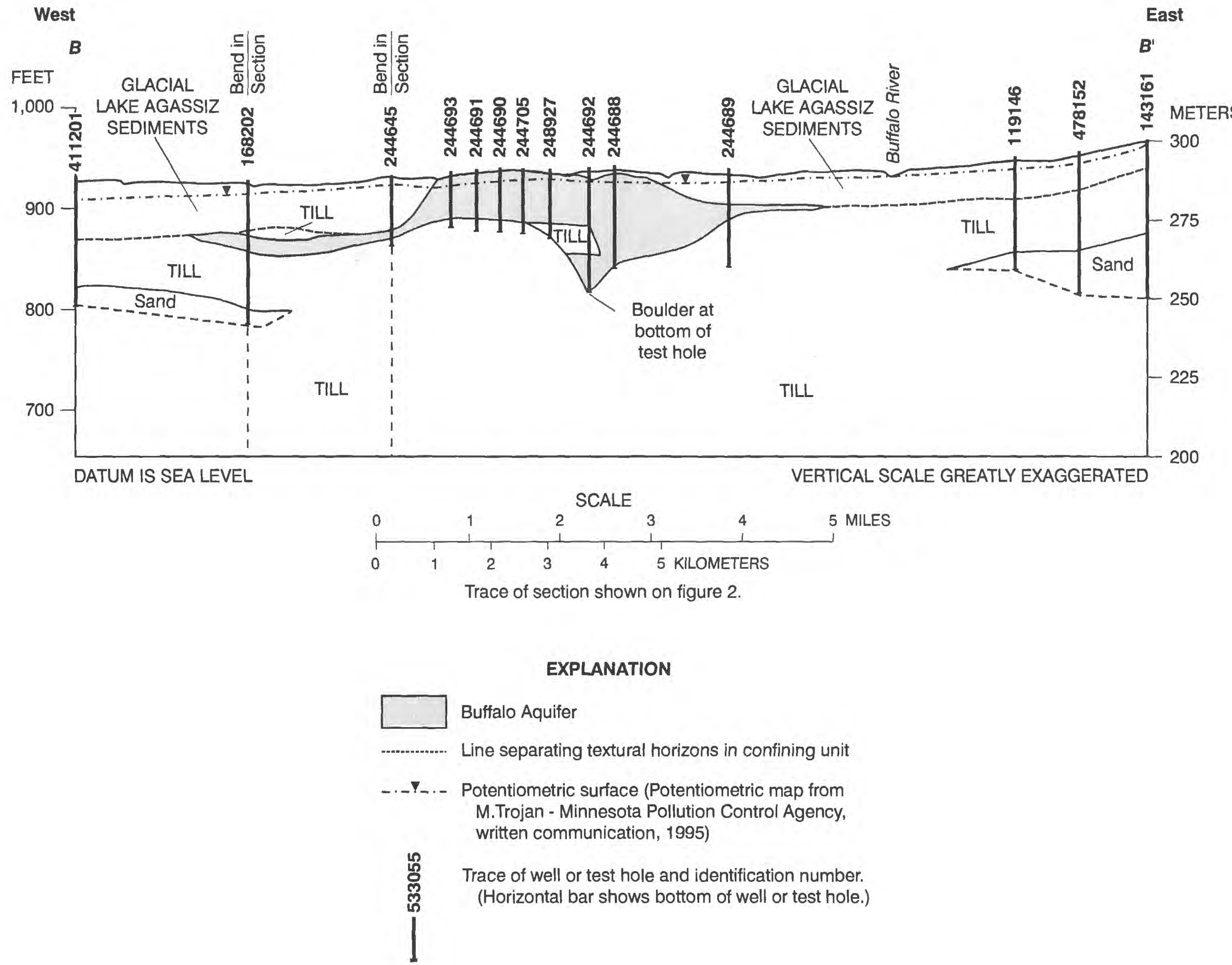


Figure 5. Hydrogeologic section *B-B'*, northern Wilkin County, Minnesota.

1994). The drillers' log for well 243698 (fig. 2) reports that sand is at 7 ft below land surface The electromagnetic-conductivity response from 1,300 ft to the end of the profile at about 4,000 ft indicates that the top of the Buffalo aquifer is between 50 and 100 ft below the land surface.

Zhody and Bisdorf (1979) conducted a geo-electrical-resistivity survey that shows the MPS North Well Field lies along a north-south trending of sand and gravel deposit that is aligned with the buried valley at the MPS North Well Field. The response is traceable at least 4 mi to the south of the MPS North Well Field. The same geo-electrical-resistivity survey shows that the MPS South Well Field lies along a separate north-south trending sand and gravel deposit.

Part of the Buffalo aquifer is unconfined and part is confined (Wolf, 1981). The aquifer is unconfined along parts of its north-south trending centerline (fig. 6), even though the aquifer is overlain by a potential confining unit composed of glacial Lake Agassiz sediments. The areal extent of the unconfined part of the aquifer is about 25 mi^2. Elsewhere, the overlying glacial Lake Agassiz sediments are a confining unit. The areal extent of the confined part of the aquifer is about 70 mi^2 (fig. 6). The entire aquifer is underlain by a confining unit (till).

A seismic-refraction survey was conducted from 60 ft to 700 ft west of the north-south trending centerline of the aquifer to determine the depth to the water table. Results of the survey indicated that the water table was 5-15 ft below the land surface 260 ft west of the north-south trending centerline of the aquifer, and was 30-40 ft below the land surface 410 ft west of the north-south trending centerline of the aquifer (T. Peterson, Minnesota Department of Natural Resources, written commun., 1994).

The MDNR and MGS collected hydraulic-head data during summer 1992 from wells open to glacial drift on the eastern side of the Red River of the North drainage basin in Clay and Wilkin Counties, Minnesota. A potentiometric map was constructed from data collected at wells open to the middle of the glacial drift thickness. The map shows ground-water flow through the glacial drift as a single unit that includes the Buffalo aquifer (fig. 7).

The potentiometric map (fig. 7) (M. Trojan, Minnesota Pollution Control Agency, written commun., 1995) shows that the regional ground-water flow in the glacial drift generally is from east to west in the study area. The direction of ground water flow in the Buffalo aquifer is from the east-southeast to the west-northwest, which indicates that recharge from the drift may occur along the aquifer's eastern margin, and discharge occurs along the aquifer's western margin to the adjacent till. Hydraulic head in the Buffalo aquifer ranges from about 960 ft above sea level along the southeastern boundary of the Buffalo aquifer in Wilkin County to about 840 ft above sea level along the northwestern boundary of the aquifer in Clay County (M. Trojan, Minnesota Department of Natural Resources, written commun., 1993).

Comparisons of hydrographs (fig. 8) from wells at the MPS North Well Field indicate the effects of ground-water pumpage on direction of ground-water flow. The hydrographs of wells 511085, 247985, 247980, and 511086 (fig. 8A-D) are screened in the lower horizon (cobbly gravel with sand) of the Buffalo aquifer. These hydrographs show that when well 511086 was pumped from August 9 to 19, 1993, the highest hydraulic head was at well 511085 and the lowest hydraulic head was at well 511086. The direction of ground-water flow between wells 511085 and 511086 was from north to south, perpendicular to the general direction of ground-water flow in the glacial drift. The hydrograph (fig. 8F) of well 244161 is screened in the upper horizon (silty fine to coarse sand with sandy clay to coarse sand) of the aquifer where the aquifer is under water table conditions. These hydrographs show that, when well 511086 was pumped from August 9 to 19, 1993, the water levels in well 244161 were higher than in well 511086. Thus, the direction of ground-water flow between well 244161 and well 511086 was from the upper horizon to the lower horizon. The hydraulic head measured in well 533055 (fig. 8E) screened in the adjacent glacial Lake Agassiz sediment was about 1 ft higher than the hydraulic head in well 511086 prior to pumping on August 9, 1993 (fig. 8D and 8E). From August 9 to 19, 1993, the hydraulic head measured at well 533055 declined 1 ft (fig. 8E). The head difference between the glacial Lake Agassiz sediments and the Buffalo aquifer indicates that leakage may occur from the glacial Lake Agassiz sediments to the Buffalo aquifer.

The first major use of ground water from the Buffalo aquifer was by MPS in 1948 at the MPS South Well Field (William F. Guyton and Associates, 1957). In January 1989, MPS began pumping water from the MPS North Well Field (C. McClain, Moorhead Public Service, written commun., 1993 and 1994).

The hydrograph of well 243695 (fig. 9) shows the long term (1946 to 1993) effect of withdrawals from the Buffalo aquifer on hydraulic head. Well 243695 is located adjacent to the MPS South Well Field and about 4 mi south of the MPS North Well Field (fig. 3). Prior to 1948, the Buffalo aquifer at well 243695 was confined. The hydraulic head in the aquifer was 905 ft above sea level on July 15, 1947 (Mitton and others, 1994). The top of the aquifer is about 897 ft above sea level (Bingham, 1960, p. 94). By 1949, the hydraulic head declined to about 895 ft above sea level, which is below the bottom of the overlying glacial Lake Agassiz sediments. The hydraulic head declined from 895 to 887 ft above sea level from 1950 to 1961. This head decline corresponds to drought conditions (Carlson and others, 1991; Ryan and Klapprod, 1991). From 1960 to 1968 the pumpage declined from about 450 to 180 Mgal/yr, which corresponded to a water level rise of about 7 ft over that period. From 1970 to 1990, the pumpage increase to as much as 720 Mgal/yr, which resulted in a water level decline of about 10 ft.

Hydraulic Properties

An aquifer test in the Buffalo aquifer was conducted for this project at the MPS North Well Field. One pumped well (well 511086) and three observation wells (247980, 247985, 511085) (fig. 3) were used in the aquifer test (table 1). Well 511086 was pumped at 1,090 gal/min for 10 days, from August 9 to 19, 1993.

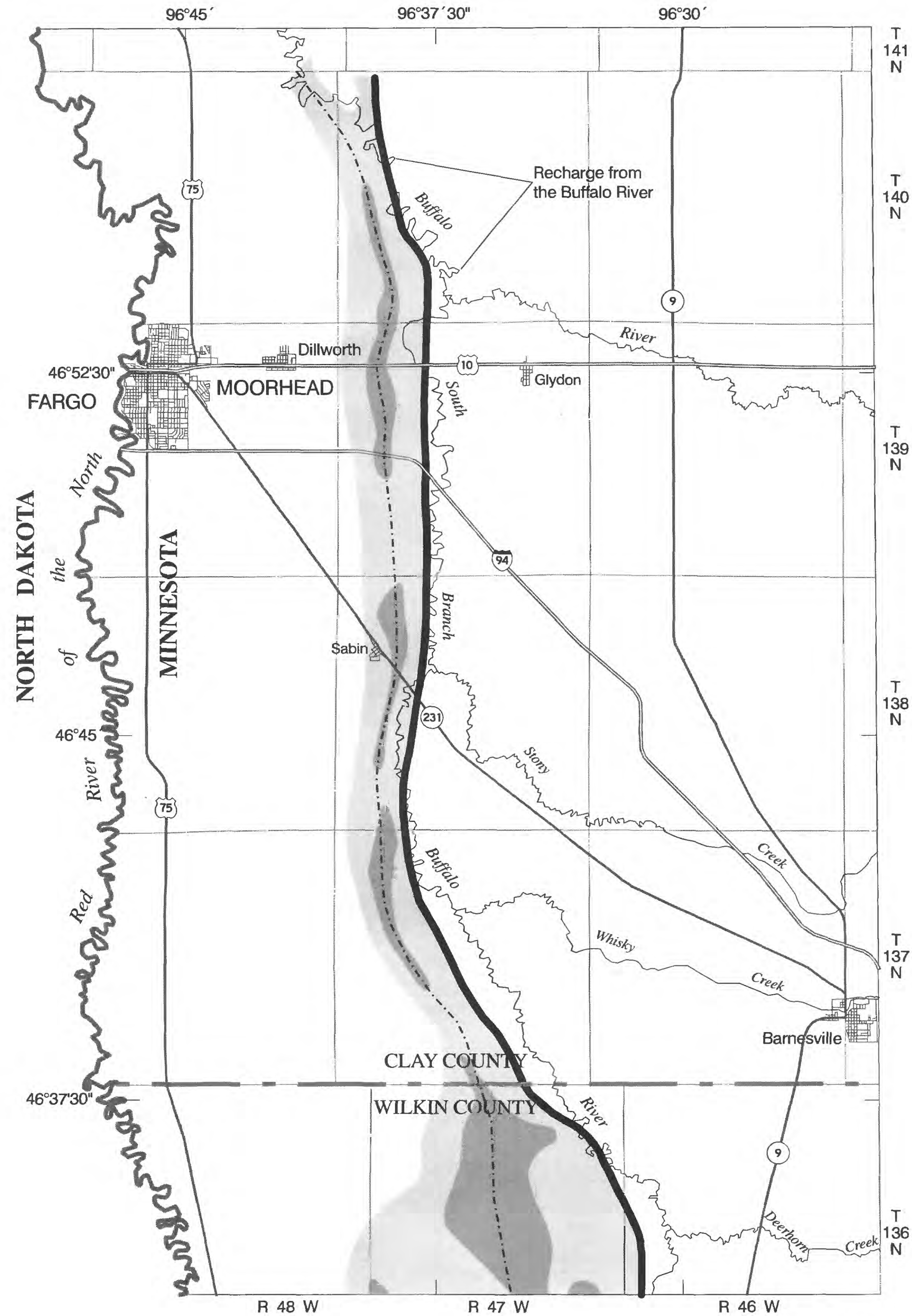
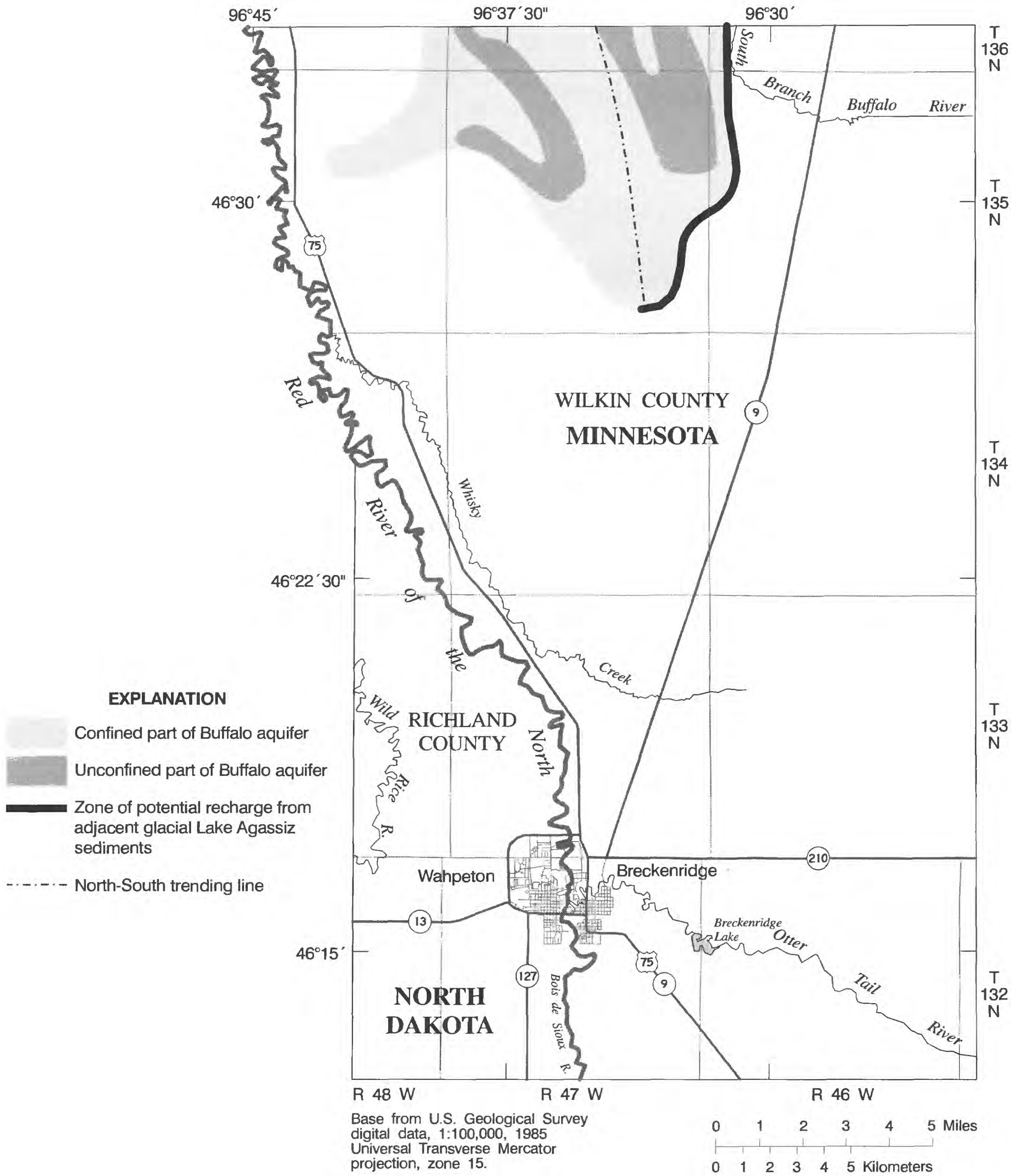


Figure 6. Zones of potential



recharge to the Buffalo Aquifer.

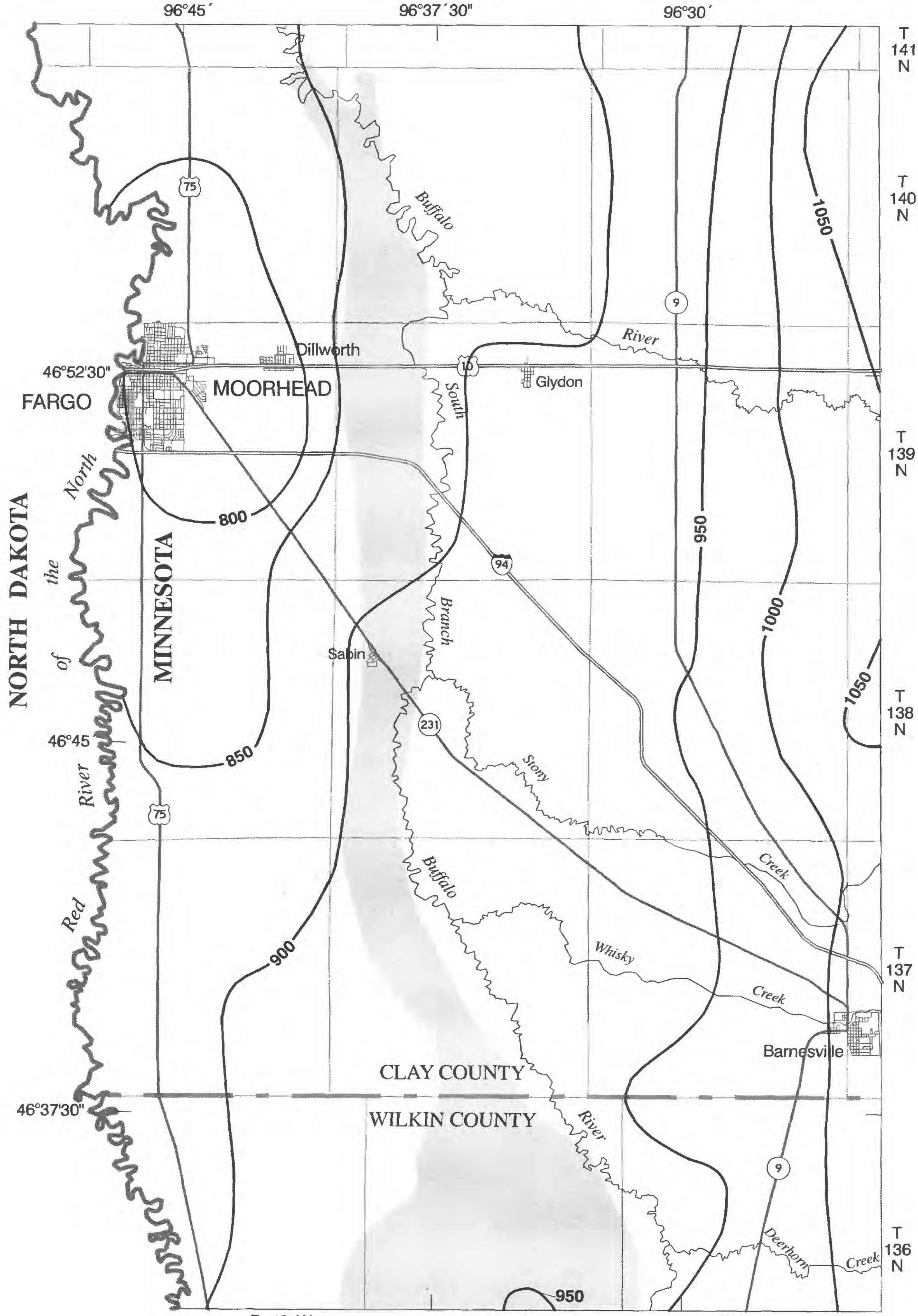
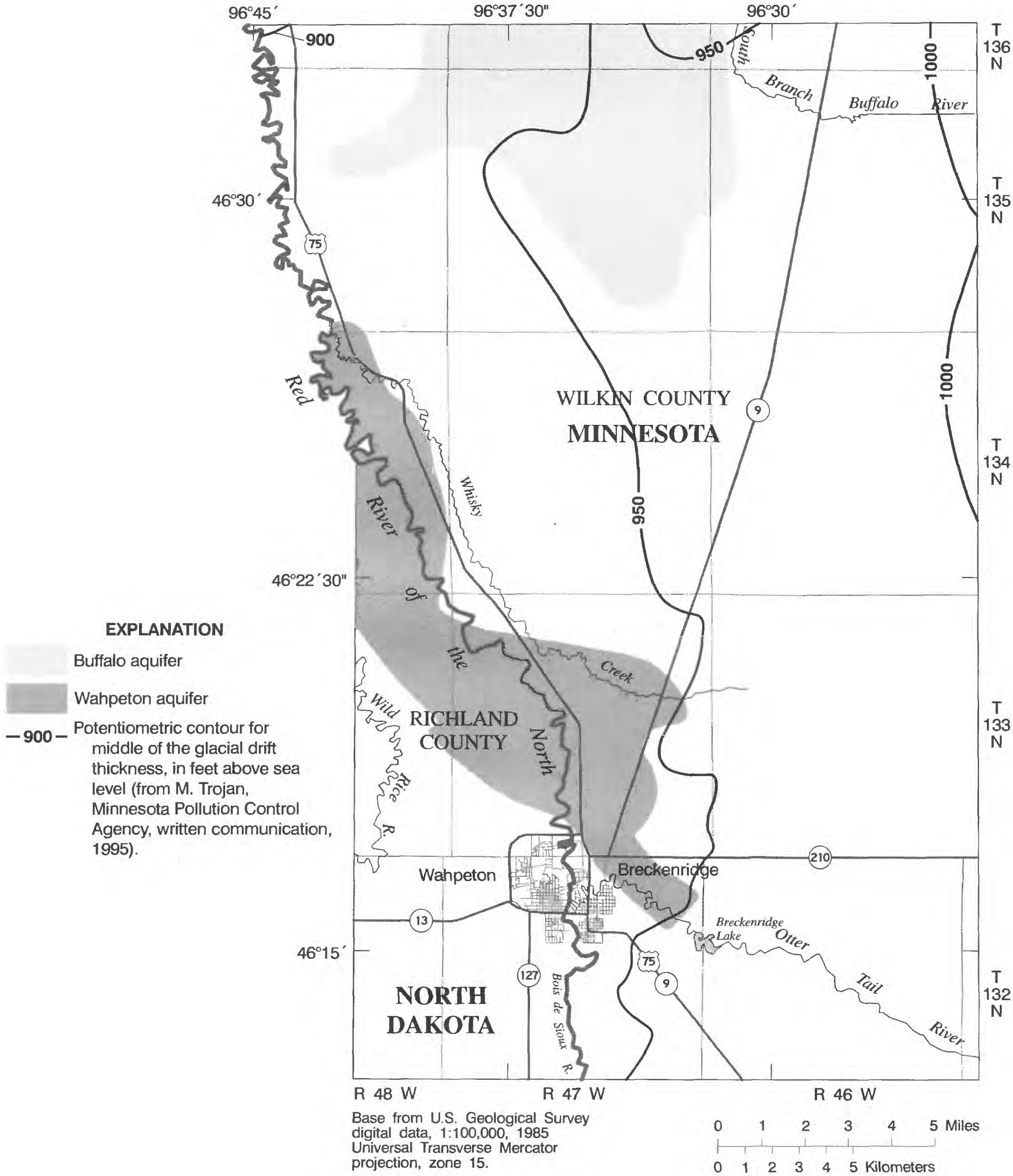


Figure 7. Potentiometric surface in the glacial drift, including the



Buffalo aquifer, Clay and Wilkins Counties, Minnesota, (August 1992).

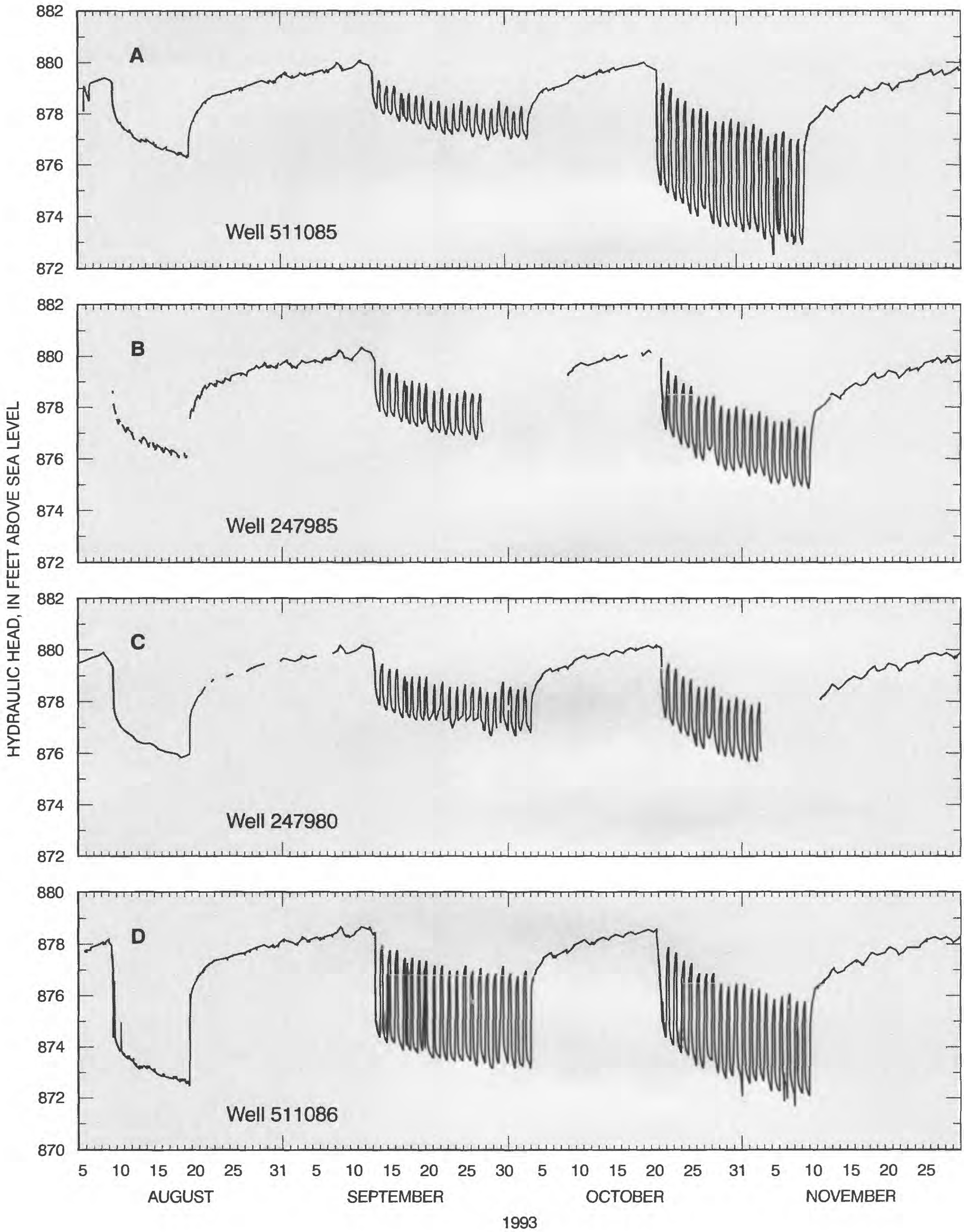


Figure 8. Hydraulic head in selected wells at the aquifer-test site, August through November, 1993, near Moorhead, Minnesota.

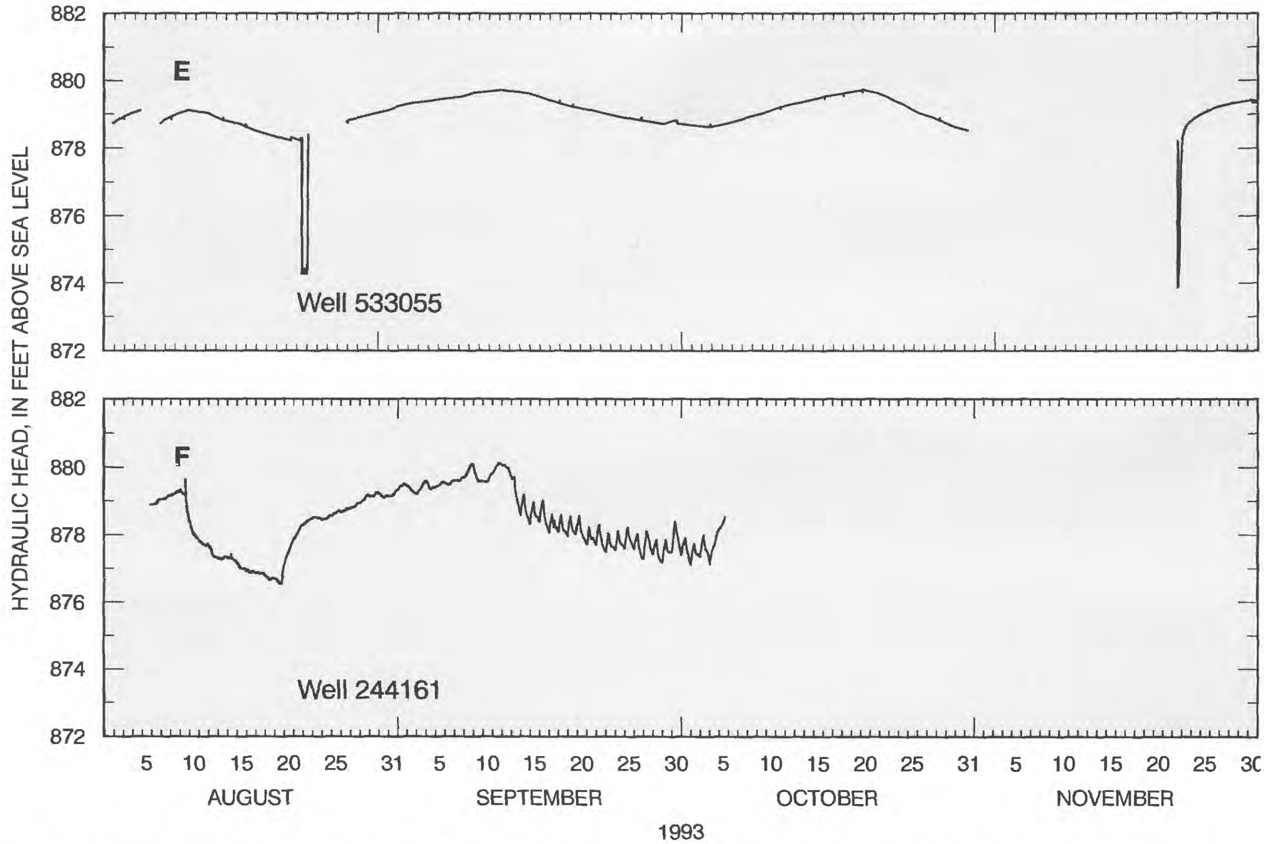


Figure 8 continued. Hydraulic head in selected wells at the aquifer-test site, August through November, 1993, near Moorhead, Minnesota.

Table 1.--Well characteristics at the Moorhead Public Service North Well Field, Clay County, Minnesota. (Data from LTP, Inc.,written commun., 1993)

Well number	Use of well during aquifer test	Hole depth (in feet below land surface)	Casing radius (in feet)	Screened interval (in feet below land surface)	Distance north of pumped well (in feet)
511086	Pumped	243	0.917	147 - 203	0
247980	Observation	203	.083	170 - 181	65
247985	Observation	207	.083	202 - 207	175.5
511085	Observation	205	.917	148 - 190	920

The hydraulic head in the MPS North Well Field was allowed to recover for 20 days, from August 19 to September 12, 1993. Water levels in observation wells 244786 and 516179, located between the two MPS well fields, showed no response to pumpage.

The transmissivity and storativity of the Buffalo aquifer was determined for the drawdown phase of the aquifer test. Transmissivity and storativity was 21,400, 23,852, and 20,870 ft^2/d; and 3.2 x 10^{-2}, 2.6 x 10^{-3}, and 3.0 x $10^{-5}$from wells 247980, 247985, 511085, respectively (table 2). Transmissivity of the aquifer was determined for the recovery phase of the aquifer test. Transmissivity values of 29,090 and 28,450 ft^2/d were calculated at wells 511086 and 511085, respectively. Hydraulic-conductivity values were 266 and 272 ft/d (table 2) at wells 511085 and 511086, respectively.

Ulteig Engineers, Inc. (1987) conducted aquifer tests at the MPS North Well Field when the supply wells were installed. They reported values for hydraulic conductivity of 270-280 ft/d on drawdown and 335-378 ft/d on recovery and values of storativity of 1.4 x 10^{-2}-8.2 x 10^{-2} on drawdown and 7 x 10^{-3}-4.2 x 10^{-2} on recovery (table 2).

The hydraulic conductivity of the aquifer was estimated from the analysis of grain-size distributions from three samples from well 244161. The hydraulic conductivity of the upper horizon of the Buffalo aquifer at the MPS North Well Field ranged from 11

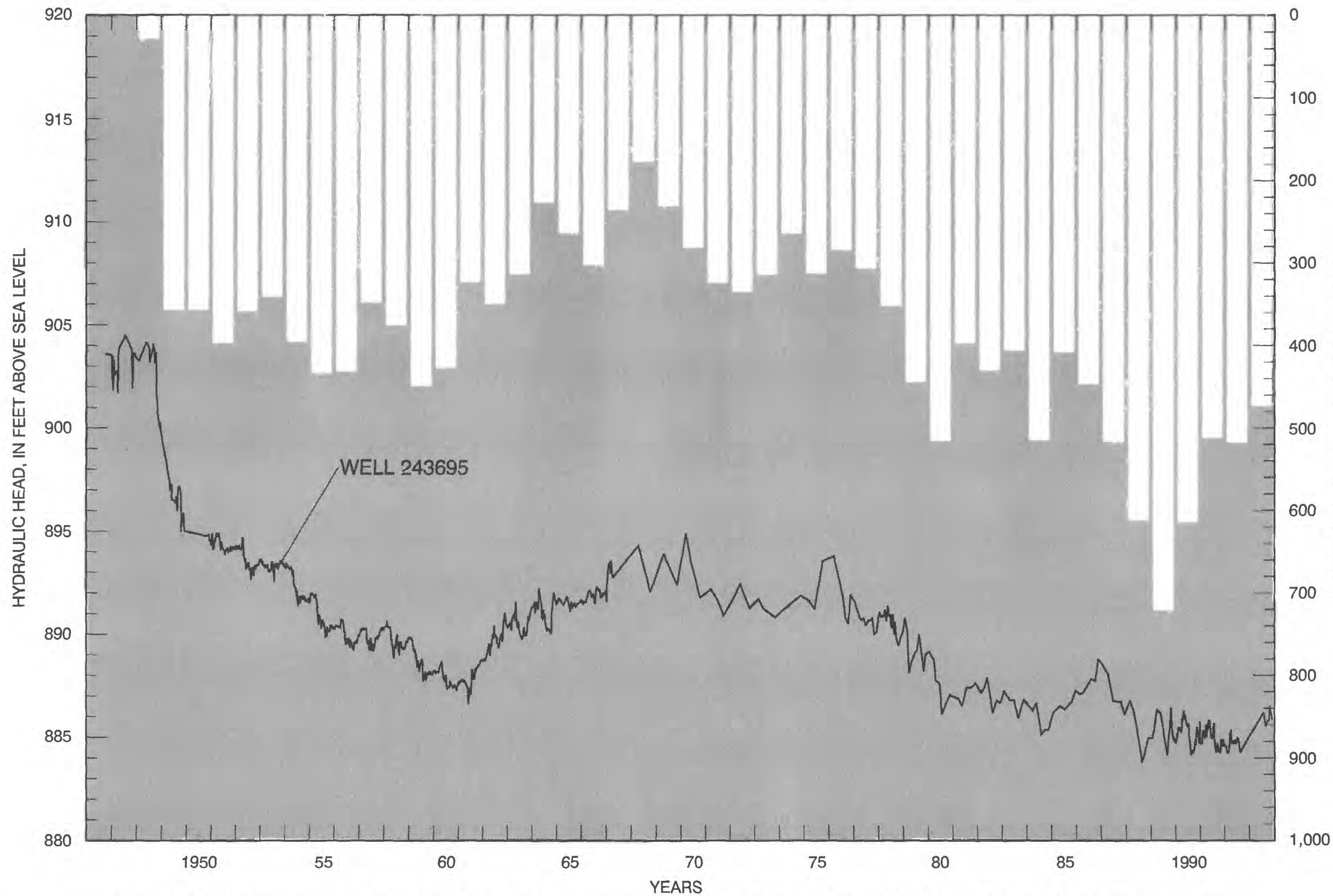


Figure 9. Hydraulic head in well 243695 completed in the Buffalo aquifer and Moorhead Public Service withdrawals from the Buffalo aquifer near Moorhead, Minnesota, 1946-93 (Water-use data from C. McClain, Moorhead Public Service, written communication, 1993-94).

Table 2.--Measured and reported hydraulic properties of the Buffalo and Wahpeton aquifers, west-central Minnesota and southeastern North Dakota
[ft^2/day, feet squared per day; ft/day, feet per day; --, no value]

Hydrogeologic unit	Type of test	Area or site	Position in hydrogeologic unit	Transmissivity (in ft^2/day)	Horizontal hydraulic conductivity (in ft/day)	Storativity	Source of data
Buffalo aquifer	Aquifer test (drawdown)	Moorhead Public Service North Well Field	Lower (confined)	[a]20,870 - 23,852	[b]195-223	3.0×10^{-5} - 3.2×10^{-2}	This study
				25,000 -26,000	[c]270-280	1.4×10^{-2} - 8.2×10^{-2}	Ulteig Engineers, Inc. (1987)
	Aquifer test (recovery)	Moorhead Public Service North Well Field	Lower (confined)	[d]28,450 - 29,090	266-272	--	This study
				31,000 - 35,000	335-378	7.0×10^{-3} - 4.2×10^{-2}	Ulteig Engineers, Inc. (1987)
	Aquifer test (drawdown)	Moorhead Public Service South Well Field	Full thickness	40,000	430	1×10^{-1}	Ulteig Engineers, Inc. (1987)
	Maps based on well-log analysis	Clay and Wilkin Counties, Minnesota	Full thickness	2,500 - 50,000	20 - 500	--	Wolf (1981, figures 17 and 18)
	Aquifer test (drawdown)	Well 244703	Full thickness	19,500	384 - 400	8.2×10^{-2} - 1.06×10^{-1}	Wolf (1981, p. 29)
	Grain-size analysis[e]	Well 244161	Upper	--	11-36	--	This study
Wahpeton Buried Valley aquifer	Aquifer test (drawdown)	Wahpeton, North Dakota	Full thickness	29,000 -52,000	200-370	5×10^{-4} - 9×10^{-4}	Schmid (1970)
Wahpeton Sand Plain aquifer	Aquifer test (drawdown)	Wahpeton, North Dakota	Full thickness	13,800	150	5×10^{-4}	Schmid (1970)

[a]Method of analysis used was the Hantusch type-curve method (Hantusch, 1960).
[b]Thickness of aquifer used in calculation for this study was 107 feet.
[c]Thickness of aquifer used in calculation by Ulteig Engineers Inc. (1987) was 92.6 feet.
[d]Method of analysis used was the Theis recovery method (Kruseman and de Ridder, 1990, p. 194-196).
[e]Hydraulic conductivity calculated from grain-size distributions with equation of Krumbein and Monk (1943).

to 36 ft/d (table 2) (H. Mooers, University of Minnesota-Duluth, written commun., 1993). Hydraulic properties of the Buffalo aquifer were determined by Wolf (1981) near well 244703 (fig. 2 and table 2).

Sources of Recharge to the Buffalo Aquifer

There are three potential sources of recharge to the Buffalo aquifer: the Buffalo River and its tributaries, recharge from precipitation where the aquifer is at or near land surface, and leakage from overlying glacial Lake Agassiz sediments and adjacent till.

Buffalo River and its Tributaries

Recharge from the Buffalo River and its tributaries to the Buffalo aquifer depends on two conditions: the stage in the river must be higher than the hydraulic head in the aquifer, and the river must be hydraulically connected to the aquifer. The stage in the Buffalo River and its tributaries is higher than hydraulic head in the aquifer for about 45 miles of river length (fig. 10). River length is the actual distance a river flows along the bends and turns in a river. The hydraulic connection is direct where the river is incised into the aquifer. Where the river is not incised into the aquifer, river water must flow through the sediment from the river to the aquifer.

Recharge from the Buffalo River and its tributaries to the Buffalo aquifer was investigated using three river-discharge measurement periods conducted February 8-10, November 1-2, and December 6-7, 1993. Stream discharge and stage measurement sites are shown on figure 2. Locations of possible recharge areas to the Buffalo aquifer are stream reaches where river discharge decreases. Withdrawals from the Buffalo aquifer may affect discharge to the Buffalo River; thus, discharge was measured in conjunction with controlled withdrawals from the two MPS well fields during the November and December measurement periods. These measurements were used to locate reaches of the Buffalo River and its tributaries where discharges decreased in the downstream direction.

During February, measurements were made at 18 sites along the Buffalo River and its tributaries (South Branch Buffalo River, Stony Creek, Whisky Creek, and Deerhorn Creek), while both MPS well fields in the Buffalo aquifer were being pumped. Discharge in the South Branch of the Buffalo River and its tributaries was much less than the Buffalo River. Discharge along the South Branch Buffalo River and its tributaries ranged from 0.0 to 2.2 ft^3/s. Discharge in the Buffalo River ranged from 24 to 28 ft^3/s. Discharge decreased in the Buffalo River along two reaches. Between stations 2 and 1, discharge decreased by about 2 ft^3/s. From stations 6 to 3, discharge decreased by about 3 ft^3/s. Reaches where the streamflow gain or loss is 4 ft^3/s or less would be within the 5 percent streamflow measurement error.

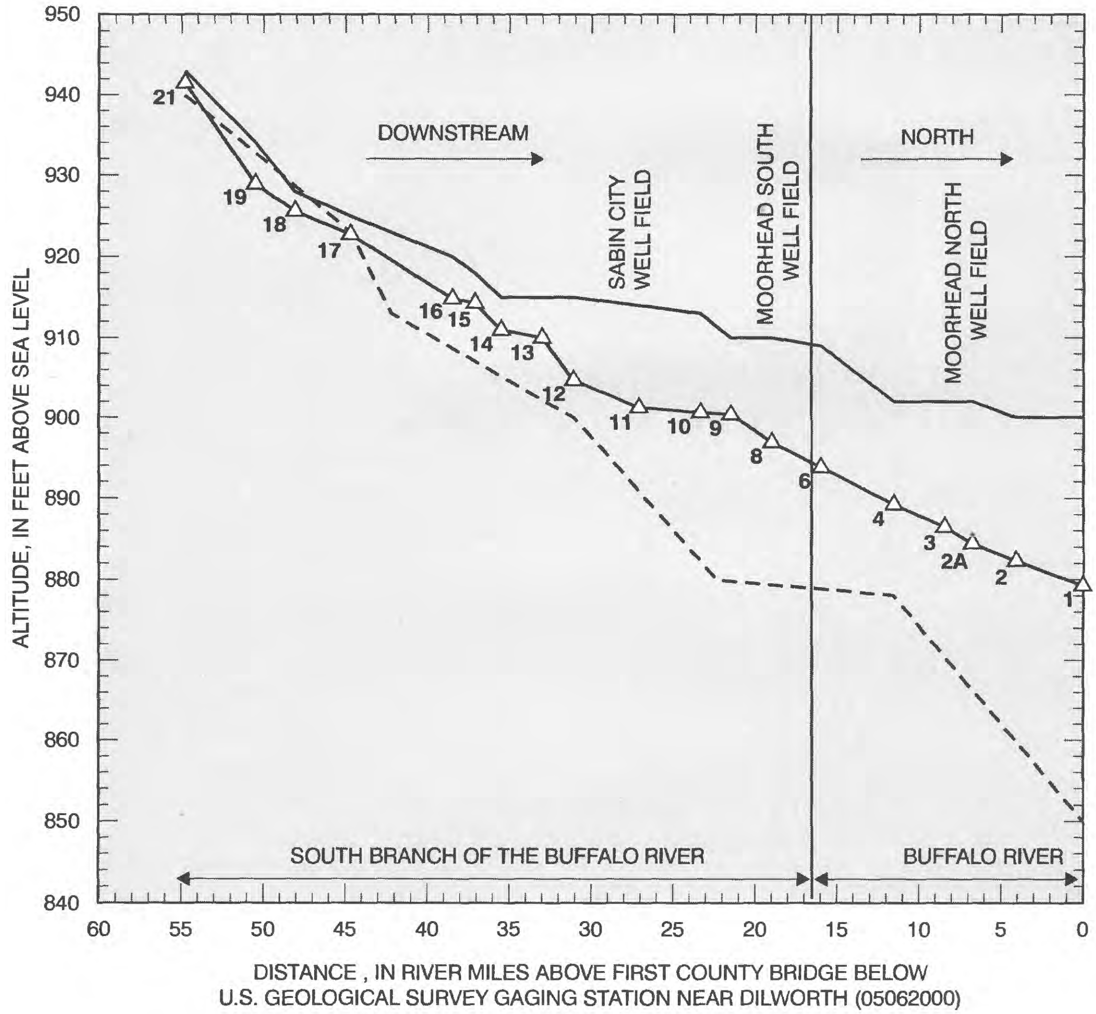
Measurements were made at seven sites along the Buffalo River and one site along the South Branch Buffalo River during November 1-2, 1993 and December 6-7, 1993. During November, discharge was measured when ground water was pumped only from the MPS North Well Field. Discharge decreased 6 ft^3/s from stations 3 to 2, but increased 6 ft^3/s from stations 2 to 1 (fig. 2). During December, discharge was measured when ground water was pumped from the MPS South Well Field. Discharge in the Buffalo River decreased from 70 to 66 ft^3/s from stations 2 to 1 and decreased 10 ft^3/s from stations 6 to 5. The discharge increased 11 ft^3/s from stations 5 to 3.

The measurements show the relation of discharge and river-mile distance of the February, November and December set of streamflow measurements and the gaining and losing reaches of the stream. The measured streamflow loss in the stream reaches provides a plausible range of recharge to the Buffalo aquifer; however, the only reaches that showed losses greater than the measurement error were from stations 3 to 2 and from 6 to 5. The discharge decreases and increases in the measured reaches of the Buffalo River changed when the pumping pattern for the MPS well fields changed. During the three discharge-measurement periods, potential recharge from the Buffalo River and its tributaries to the Buffalo aquifer ranged from 5 to 14 ft^3/s (table 3).

Precipitation

Recharge from precipitation to the Buffalo aquifer takes place where the aquifer is at or near land surface. Recharge from precipitation to the Buffalo aquifer was investigated with hydraulic-head measurements in water-table wells. Changes in hydraulic head in wells 244693, 248927, and 248930 indicate that the aquifer received from 3.6 to 5.5 in. of recharge during spring 1993. In well 244693 (fig. 2), the water levels rose from 9.96 to 8.45 ft below land surface from April 5 to June 20, 1993. In wells 248927 and 248930 (fig. 2), the water levels rose from 11.40 to 9.10 ft and from 12.40 to 10.20 ft below land surface, respectively, from March 29 to June 20, 1993. Recharge was estimated by multiplying the water-level change by a specific yield of 0.2 (Freeze and Cherry 1979, p. 81). The estimated recharge was 3.6 in. at well 244693 from April 5 to June 20, 1993, and 5.5 and 5.3 in. at wells 248927 and 248930, respectively, from March 29 to June 20, 1993.

The hydraulic heads in wells 244693, 248927, and 248930 rose monotonically in spring 1993. Wolf (1981, fig. 22) showed that recharge occurred from March 1978 to May 1978 and determined that the annual recharge rate from 1965 to 1978 was 4.7 in. (table 3). The average recharge measured at wells 244693, 248927, and 248930 for this investigation was 4.8 in. The estimated daily volume of recharge to the unconfined part of the aquifer (25 mi^2) was 1.49×10^5 ft^3/d (table 3).



EXPLANATION

- - - - Potentiometric profile of the Buffalo aquifer for August 1993, in feet above sea level; estimated along river profile from potentiometric map by M. Trojan, (Minnesota Pollution Control Agency, written communication, 1995).

—△— 11 River profile for river stage measured on October 29, 1993, in feet above sea level. Numbers are station numbers at stage-measurement sites; locations shown on figure 2.

——— Topographic profile of top of river embankment, in feet above seal level; elevations estimated from 7.5 minute topographic maps: Dilworth, Glyndon North, Glyndon South, Sabin, Comstock, Baker, and Wolverton SE Quadrangles.

Figure 10. Topographic profile, potentiometric profile of the Buffalo aquifer (August 1993), and river profile of the Buffalo River and South Branch of the Buffalo River (October 29, 1993), Clay and Wilkin Counties, Minnesota.

Table 3.--Contributions from sources of water to the Buffalo aquifer, Clay and Wilkin Counties, Minnesota

[ft^3/s, cubic feet per second; ft^2, square feet; mi^2, square miles; ft/d, feet per day; in./yr, inches per year; ft^3/d, cubic feet per day; --, no value; nc, inadequate data to calculate]

Source of water	Range of loss of river discharge along losing reaches, in ft^3/s	Calculated cross-sectional area through which ground water leaks[a], in ft^2	Measured surface area[b], in mi^2	Hydraulic conductivity, in ft/d	Hydraulic head difference, in feet	Distance over which hydraulic head difference acts[c], in feet	Recharge rate[d], in./yr	Estimated daily volume of water leaking into aquifer (rounded), in ft^3/d
Losing reaches along the Buffalo River	5 - 14	--	--	--	--	--	--	$4.32 \times 10^5 - 1.21 \times 10^6$
Induced leakage through glacial Lake Agassiz sediments from the east near the Moorhead Public Service North Well Field per foot of boundary of aquifer in response to pumpage	--	15	--	$4 \times 10^{-2} - 1 \times 10^0$	[e]5.8	4,280	--	$8.1 \times 10^{-4} - 2.0 \times 10^{-2}$
Induced leakage through glacial Lake Agassiz sediments from the west near the Moorhead Public Service North Well Field per foot of boundary of aquifer in response to pumpage	--	35	--	$8 \times 10^{-3} - 8 \times 10^{-1}$	5.8	4,080	--	$3.9 \times 10^{-4} - 3.9 \times 10^{-2}$
Recharge where confined	--	--	70	$4 \times 10^{-5} - 7 \times 10^{-5}$	variable	variable	--	nc
Recharge where unconfined	--	--	25	--	--	--	4.7	1.49×10^5

[a]The cross-sectional area through which water leaks from the confining unit to the aquifer is taken as the thickness of the part of the confining unit through which the ground-water flows and is normal to the hydraulic gradient times a unit width of the boundary between the confining unit and the aquifer (1 foot).

[b]Rounded to the nearest 5 square miles.

[c]The approximate distances over which the hydraulic-head differences acted was the distance between observation wells (wells 533055 and 533056) and the pumped well (well 511086).

[d]Wolf (1981, p. 39)

[e]Hydraulic-head data from August 19, 1993.

Lake Agassiz Sediments

The Buffalo aquifer is confined by till or the glacial Lake Agassiz sediments over about 70 mi^2 of the study area (fig. 6). Near the MPS North Well Field, the glacial Lake Agassiz sediments overlay the Buffalo aquifer. The glacial Lake Agassiz sediments are composed silty sand, silt, and silty clay. Grain-size analyses of samples collected during the drilling of well 533055 (fig. 11) indicate that the sediments are composed of an upper layer of clayey silt from about 5 to 16 ft below the land surface; a middle layer of silty clay from 16 to 90 ft and a bottom layer of silty clay and sandy silt from 90 to 105 ft below the land surface. At well 533056 the sediments are composed of silt to clayey silt from 2 to 25 ft, silty clay from 25 to 75 ft, clayey silt from about 75 to 85 ft, and silty sand from about 85 to 100 ft below the land surface. The thickness of the glacial Lake Agassiz sediments range from 1 to as much as 130 ft (Wolf, 1981). The thickness ranges from 25 ft in well 511086 near the center of the aquifer (fig. 4) to as much as 130 ft in well 504993 near the western edge of the aquifer. Along section B-B' (fig. 5), glacial Lake Agassiz sediments range in thickness from 0 to 36 ft.

Recharge by leakage from the adjacent glacial Lake Agassiz sediments to the Buffalo aquifer was estimated from the hydraulic-head difference between glacial Lake Agassiz sediments and the Buffalo aquifer, and the cross sectional area and the hydraulic conductivity of the glacial Lake Agassiz sediments. Hydraulic head in the Buffalo aquifer is lower than the hydraulic head in the glacial Lake Agassiz sediments along the eastern boundary of the Buffalo aquifer. Hydraulic-conductivity data was not available for the glacial till; thus, leakage was estimated in areas where the aquifer was confined by the glacial Lake Agassiz sediments. Hydraulic-head differences near the MPS North Well Field are shown in figure 8. Hydraulic head of the glacial Lake Agassiz sediments were measured near the boundary of the Buffalo aquifer from August 1993 through November 1993 (fig. 8). Near the western aquifer boundary, well 244155 was screened at the water table of the glacial Lake Agassiz sediments and well 533055 (fig. 8) was screened from 100 to 105 ft below the land surface. Wells 511085 and 511086 (figs. 8A and 8D) were screened in the Buffalo aquifer and the prepumping hydraulic head was 20 to 25 feet lower than in well 244155 screened at the water table. The prepumping hydraulic head in wells 511085 and 511086 was similar to well 533055 (fig. 8). The seismic-refraction survey conducted near the MPS North Well Field corresponded well with the observation well information and indicated that the water table difference between the Buffalo aquifer and the glacial Lake Agassiz sediments was about 25 ft.

Hydraulic conductivity of the glacial Lake Agassiz sediments was determined by measurement of laboratory permeability from drill cuttings, one slug test of a well completed in the sediments (533055), a single-well recovery test (533056), and laboratory determination for grain-size distributions (244161, 533055, and 533056) (table 4). Laboratory measurements of permeabilities were conducted on four samples collected during the drilling of wells 244156, 244161, 533055, and 533056. The vertical hydraulic conductivity of the silty clay ranges from 4 x 10^{-5} ft/d for samples from well 533055 to 7 x 10^{-5} ft/d for samples from wells 244161 and 533055. The transmissivity computed from the slug test of well 533055 for the glacial Lake Agassiz sediments was 4 x 10^{-2} ft^2/d. The horizontal hydraulic conductivity was 8 x 10^{-3} ft/d (4 x 10^{-2} ft^2/d divided by 5 ft, the well-screen length) (table 4). The transmissivity for the single-well recovery test in well 533056 was determined graphically. Horizontal hydraulic conductivity of about 1 x 10^{-1} ft/d (table 4) was calculated by dividing the transmissivity by the length of the well screen, 15 ft. The horizontal hydraulic conductivity value is only an estimate because of well-bore storage effects during the test (K. Mueller, U.S. Geological Survey, written commun., 1994). Grain-size distributions were determined for 44 drill cutting samples collected from the installation of wells 533055, 533056, and 244161 (H. Mooers, University of Minnesota-Duluth, written commun., 1993). The horizontal hydraulic conductivity for the silty clay ranged from 2 x 10^{-7} to 3 x 10^{-4} ft/d (table 4). The horizontal hydraulic conductivity for the clayey silt ranged from 8 x 10^{-4} to 1 x 10^{-1} ft/d. The horizontal hydraulic conductivity for the silt was 5 ft/d. The horizontal hydraulic conductivity for the silty sand ranged from 4 x 10^{-2} to 1 ft/d (table 4). The horizontal hydraulic conductivity for the sandy silt ranged from 8 x 10^{-1} to 3 ft/d.

The hydraulic gradient used to estimate recharge to the Buffalo aquifer from the glacial Lake Agassiz sediments at the MPS North Well Field is the difference in hydraulic head divided by distance in the direction of ground-water flow. Hydraulic-head difference and the distance over which that head acts are affected by the layers in the glacial Lake Agassiz sediments and the shape of the aquifer-confining unit boundary. The hydrograph for well 533055 (fig. 8E) to the west of the aquifer shows that the effect of ground-water pumpage from the MPS North Well Field caused a water level decline in the glacial Lake Agassiz sediments. The hydraulic-head difference between wells 533055 and well 511086 was about 5.8 ft at the end of 10 days of continuous pumping. The approximate distances over which the hydraulic-head differences acted between wells 533055 and 511086 was about 4,080 ft. The hydraulic gradients between wells 533055 and 511086 are about 1.42 x 10^{-3} ft/ft.

Recharge to the Buffalo aquifer from the adjacent confining unit is probably from the bottom layer of the glacial Lake Agassiz sediments. The cross-sectional area normal to the hydraulic gradient through which recharge water leaks is determined by the thickness of the glacial Lake Agassiz sediments multiplied by the length of the edge of the Buffalo aquifer. The thickness of the bottom layer of the glacial Lake Agassiz sediments, however, was determined only at wells 533055 and 533056. Recharge to the Buffalo aquifer, hence, was calculated for unit lengths (1 ft) of the edge of the aquifer along the western and eastern sides of the aquifer near the MPS North Well Field. At wells 533055 and 533056. the thickness of the bottom layer in the glacial Lake Agassiz sediment was 35 and 15 ft, respectively. The depth to the bottom of the glacial Lake Agassiz sediments at well 533055 was estimated from the well

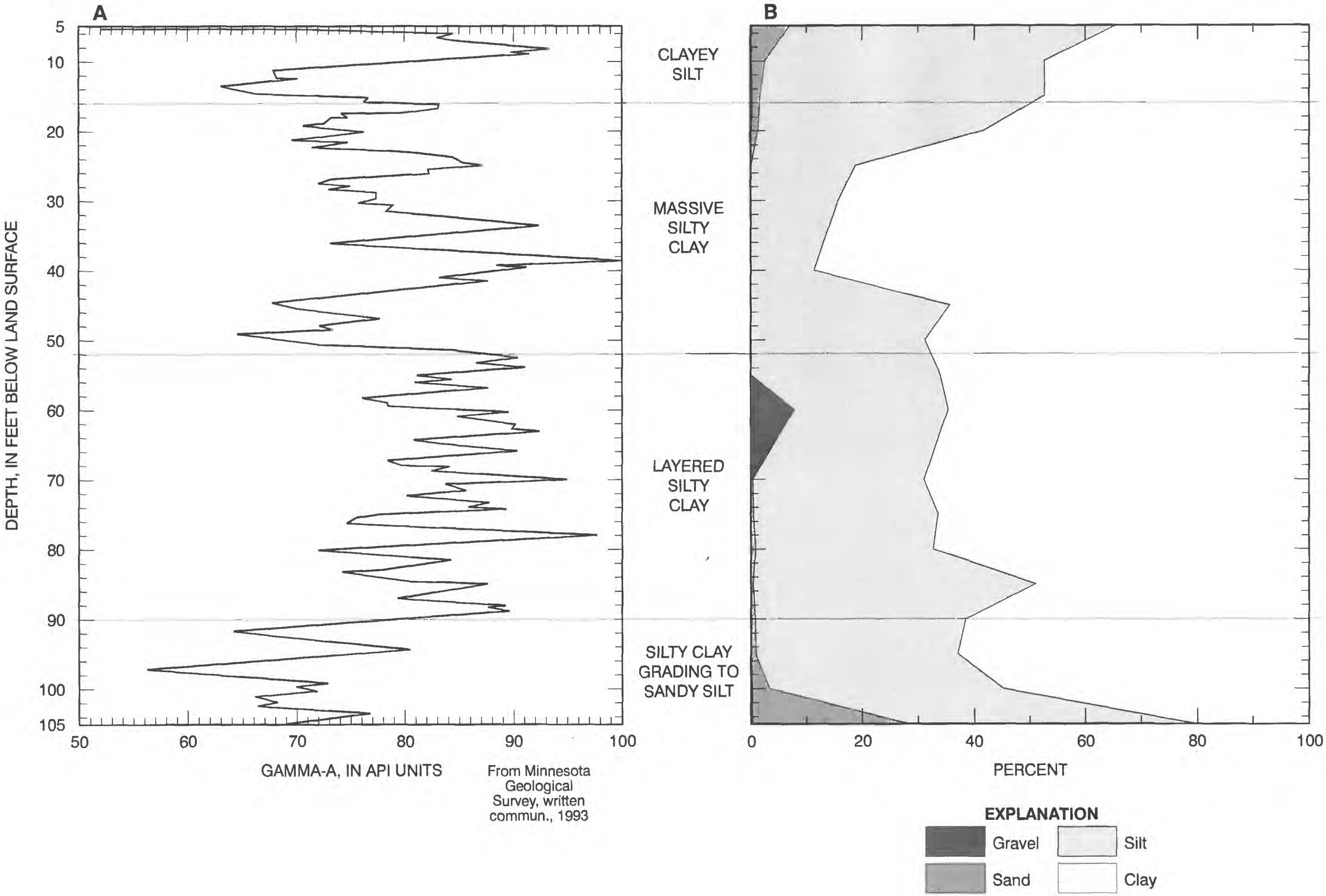


Figure 11. (A) Gamma log and (B) log of grain-size analyses showing percentage of gravel, sand, silt, and clay for well 533055 near Moorhead, Minnesota.

Table 4.--Measured hydraulic conductivity of glacial Lake Agassiz sediments, Clay County, Minnesota

[-, no value]

Type of test	Well	Number of tests or samples	Texture	Horizontal hydraulic conductivity, in feet/day	Vertical hydraulic conductivity, in feet/day
Slug test[a]	533055	1	Sandy silt	8×10^{-3}	-
Recovery test[b]	533056	1	Silty sand	[c]about 1×10^{-1}	-
Grain-size analysis[d]	244161	5	Clayey silt	6×10^{-3} - 2×10^{-2}	-
		1	Silty clay	3×10^{-4}	-
	533055	1	Sandy silt	8×10^{-1}	-
		4	Clayey silt	8×10^{-4}-1×10^{-2}	-
		14	Silty clay	3×10^{-7} - 2×10^{-4}	-
	533056	1	Silt	5×10^{0}	-
		1	Sandy silt	3×10^{0}	-
		3	Silty sand	4×10^{-2}-1×10^{0}	
		4	Clayey silt	3×10^{-3} - 1×10^{-1}	-
		10	Silty clay	2×10^{-7} - 2×10^{-4}	-
Permeameter[e]	244156	1	Clayey silt	-	2×10^{-3}
	244161	1	Silty clay	-	7×10^{-5}
	533055	2	Silty clay	-	4×10^{-5} - 7×10^{-5}
	533056	1	Silty clay	-	4×10^{-5}

[a]Method of analysis used was from Cooper and others (1967).
[b]Method of analysis used was the Theis recovery method (Kruseman and de Ridder, 1990)
[c]Rough estimate because of well-bore storage effects (K. Mueller, U.S. Geological Survey, written commun., 1994).
[d]Hydraulic conductivity calculated from grain-size distributions with the equation of Puckett and others (1985).
[e]Method used described in D5084-90 (American Society of Testing Materials, reapproved 1990)

log of a nearby well, well 504993. The cross-sectional area along the western and eastern edges of the Buffalo aquifer through which recharge water flowed were 35 and 15 ft^2, respectively. Recharge per unit length of the aquifer margin along the western and eastern boundaries at the MPS North Well Field was calculated using Darcy's Law. The estimated daily volume of water leaking to the Buffalo aquifer from the glacial Lake Agassiz sediments is listed in table 3.

Hydrogeology of the Wahpeton Aquifers

The Wahpeton Shallow Sand, the Wahpeton Sand Plain, and the Wahpeton Buried Valley aquifers compose the Wahpeton aquifers in order of increasing depth (Froelich, 1974; Ripley 1988). These aquifers also have been called the Wahpeton Buried Valley aquifer system (Ripley, 1992). The Wahpeton aquifers are near Wahpeton in eastern Richland County, North Dakota, and near Breckenridge in western Wilkin County, Minnesota (fig. 12).

The contents and interpretations in this section and the next section, Sources of recharge to the Wahpeton aquifers, are based on data collected by others. Most of the data have not been previously interpreted. The discussions of the physical settings of the aquifers are based on well-log data from Froelich (1974), Ripley (1992), and the Minnesota County Well Index, maintained by the MGS. The discussions of the movement of water within the aquifers are based on potentiometric maps from Froelich (1974) and Trojan (M. Trojan, Minnesota Pollution Control Agency, written commun., 1995); hydraulic-head data from Ripley (1992) and Ripley (North Dakota State Water Commission, written commun., 1993, 1994); and water-use data from Ripley (North Dakota State Water Commission, written commun., 1993, 1994) and Mueller (City of Breckenridge, oral commun., 1993, 1994).

Aquifer Description

The Wahpeton Buried Valley, Wahpeton Sand Plain, and Wahpeton Shallow Sand aquifers are composed of fine-grained to coarse-grained sand mixed with gravel, based on lithologic descriptions from Froelich (1974) and Ripley (1992). The Wahpeton Buried Valley aquifer is fine grained at the top to very coarse grained at the bottom, and covers about 8 mi^2 (fig. 12), based on available well-log data (Froelich, 1974; Ripley, 1992; data from Minnesota County Well Index, MGS, 1993). The Wahpeton Buried Valley aquifer fills a steep-sided buried valley (fig. 13), cuts into till and Cretaceous bedrock, and is as much as 125 ft thick (fig. 13). In well 133N47W18ADA, 82 ft of sand and gravel overlie a sandstone aquifer, the top of which is at 720 ft above sea level (Froelich, 1974, p. 53). The Wahpeton Sand Plain aquifer covers about 24 mi^2 (fig. 12), based on available well-log data (Froelich, 1974; Ripley, 1992; data from Minnesota County Well Index, MGS, 1993) and is as much as 80 ft thick at well 133N47W20ABB. The bottom of the aquifer ranges from 100 to 195 ft below land surface. The top of the aquifer ranges from 65 to 185 ft below land surface. The extent of the Wahpeton Shallow Sand aquifer is about 29 mi^2 (fig. 12), and overlies till (Froelich, 1974; Ripley, 1992; data from Minnesota County Well Index, MGS, 1993). The Wahpeton Shallow Sand aquifer ranges from 28 ft below land surface at well 133N47W28ABB to 130 ft below land surface at well 221779. The thickness of the Wahpeton Shallow Sand aquifer ranges from about 11 to 115 ft. In places, the Wahpeton Shallow Sand aquifer is composed of two parts separated by silt (fig. 13).

Confining units are interleaved with the Wahpeton aquifers (fig. 13). Glacial Lake Agassiz sediments and till overlie the Wahpeton Shallow Sand aquifer, except where the Wahpeton Shallow Sand aquifer (Ripley, 1988, p. 125) is found near the land surface. Till separates the Wahpeton Shallow Sand aquifer from the Wahpeton Sand Plain aquifer (Ripley, 1988).

The ground-water resources in the Wahpeton aquifers have been used extensively since 1974. The City of Wahpeton, North Dakota, became the first major user of ground water from the Wahpeton Sand Plain and Wahpeton Buried Valley aquifers in 1974 (D. Ripley, North Dakota State Water Commission, written commun., 1993). The City of Breckenridge, Minnesota, began using the Wahpeton Buried Valley aquifer for municipal supply in 1978 (J. Mueller, City of Breckenridge, oral commun., 1993). Agricultural-processing use from the Wahpeton Sand Plain and Wahpeton Buried Valley aquifers began in 1986 (table 5) and from the Wahpeton Shallow Sand aquifer began in 1990 (D. Ripley, North Dakota State Water Commission, written commun., 1993).

Prior to the development of ground-water resources in the Wahpeton aquifers in 1974, ground water flowed upward from the Wahpeton Buried Valley aquifer to the Wahpeton Sand Plain and the Shallow Sand aquifers (Froelich, 1974, plates 5 and 6). Froelich (1974, p. 24) estimated that in 1970 about 2×10^5 gal/d flowed from the Wahpeton Buried Valley aquifer. Ground water from the Wahpeton Sand Plain aquifer discharged as "natural underflow to adjacent areas, to streams and evapotranspiration processes, and to wells" (Froelich, 1974, p. 31).

Ground water in the Wahpeton Sand Plain aquifer in North Dakota flowed in three directions from the potentiometric high in an area directly over the Wahpeton Buried Valley aquifer (Froelich, 1974, plate 6). Ground water flowed northeast from the potentiometric high to the Red River of the North (Froelich, 1974, plate 6). Ground water flowed southwest from the potentiometric high to potentiometric lows ranging from 930 to 935 ft above sea level along Wild Rice Creek (Froelich, 1974, plate 6). Froelich (1974, plate 6) showed that ground water flowed northwest from the potentiometric high to potentiometric lows ranging from 910 to 920 ft above sea level near the northern end of the study area in North Dakota.

Froelich (1974, plate 5) showed that hydraulic heads in the Wahpeton Buried Valley aquifer ranged from as much as about 960 ft above sea level at the Minnesota-North Dakota border to about 955 ft above sea level at the western edge of the study area. This hydraulic-head distribution indicates that ground water in the Wahpeton Buried Valley aquifer flowed northwest from Minnesota into North Dakota. The highest hydraulic head in the Wahpeton Sand Plain aquifer in North Dakota was about 957 ft above sea level on January 31, 1972, at well 133N47W17CCC1 (fig. 12) (Ripley, 1992, p. 199) in an area that is directly over the Wahpeton Buried Valley aquifer (Froelich, 1974, plates 5 and 6). In that same area, Froelich (1974, plate 6) shows hydraulic heads ranging from 950 to 952 ft above sea level. Predevelopment hydraulic-head data were not available for the Wahpeton Shallow Sand aquifer. About one year after ground-water withdrawals from the Wahpeton Buried Valley aquifer began, however, hydraulic heads on September 7, 1975, in three wells screened in the Wahpeton Shallow Sand aquifer (wells 133N47W20BCD1, 133N47W20BBA2, and 133N47W20BBA3) (fig. 12) were about 957 ft above sea level (Ripley, 1992, p. 247, 248, and 258).

Artesian conditions were observed in 1970 in the Wahpeton Buried Valley aquifer at wells 133N48W3ABB and 133N48W12BAA, and test holes 133N48W2BBC, 134N48W21BBB, and 134N48W33AAA (Froelich, 1974). Discharge from all of the aquifers occurred by uncontrolled (flowing) wells. Artesian conditions were observed in 1970 in the Wahpeton Sand Plain aquifer at well 133N48W2ADA and test hole 133N48W1DDD (fig. 12) (Froelich, 1974).

Following development of ground-water resources in the Wahpeton aquifers, the predevelopment direction of ground-water flow reversed from the Wahpeton Shallow Sand aquifer to the Wahpeton Sand Plain and the Wahpeton Buried Valley aquifers. Hydraulic heads in the Wahpeton Shallow Sand aquifer have declined 22 ft from 1975 to 1990 (Ripley, 1992, p. 247). Hydraulic heads in the Wahpeton Sand Plain aquifer declined 51 ft from 1971 to 1990 (Ripley, 1992, p. 189-190). Hydraulic heads in the Wahpeton Buried Valley aquifer declined 51 ft from 1969 to 1990 (Ripley, 1992, p. 212-213). Hydraulic heads in the Wahpeton Buried Valley aquifer have declined 50 ft from 1970 to 1993.

The hydrograph of well 133N47W20DDD1 is shown on figure 14. The average annual pumpage from the Wahpeton Buried Valley aquifer was about 300 Mgal/yr during 1974-79 and about 560 Mgal/yr during 1980-93 (D. Ripley, North Dakota State Water Commission, written commun., 1993, 1994; J. Mueller, City of Breckenridge, oral commun., 1993, 1994).

The general direction of ground-water flow in the Wahpeton Buried Valley aquifer is southeast to northwest, from potentiometric highs in Minnesota to potentiometric lows near Wahpeton, North Dakota (D. Zwilling, Minnesota Department of Natural Resources, written commun., 1993). Hydraulic heads in the glacial drift near the Wahpeton aquifers in Minnesota were measured during summer 1992 by staff from the MDNR and the MGS. The general direction of ground-water flow in the glacial drift in Minnesota in summer 1992 was from east to west toward the Wahpeton aquifers (M. Trojan, Minnesota Pollution Control Agency, written commun., 1995). The hydraulic head in the glacial drift near the Wahpeton aquifers in summer 1992 was about 950 ft above sea level (fig. 7).

Ground water has been pumped from the Wahpeton Sand Plain and Wahpeton Shallow Sand aquifers since 1986 and 1990, respectively, for self-supplied industrial use (D. Ripley, North Dakota State Water Commission, written commun., 1993, 1994). The average annual water use from the Wahpeton Sand Plain aquifer from 1986 to 1993 was about 90 Mgal (D. Ripley, North Dakota State Water Commission, written commun., 1993, 1994). The average annual use from the Wahpeton Shallow Sand aquifer from 1990 to 1993 was about 26 Mgal (D. Ripley, North Dakota State Water Commission, written commun., 1993, 1994).

Table 5.--Data for wells open to the Wahpeton Sand Plain and Wahpeton Buried Valley aquifers near Breckenridge, Minnesota, and Wahpeton, North Dakota

[ND, North Dakota; MN, Minnesota; O, observation well; M, municipal supply well; A, agricultural-processing supply well; SP, Wahpeton Sand Plain aquifer; BV, Wahpeton Buried Valley aquifer]

State	Use	Well number	Date completed	Well diameter (in inches)	Interval of well screen (in feet below land surface)	Aquifer	Approximate distance from well 133N47W20DDD1 (in miles)
ND[a]	O	133N47W20DDD1	August 16, 1969	1.25	248 - 254	SP-BV	0
	M	133N47W20ADD	August 10, 1973	12	250 - 290	SP-BV	0.5
	M	133N47W20ABD	July 18, 1973	12	240 - 300	SP-BV	.75
	M	133N47W20BBA	July 9, 1973,	12	240 - 300	SP-BV	1.27
	A	133N47W20ABDAC1	September 22, 1986	12	175 - 275	SP-BV	.75
MN[b]	M	130573	January 6, 1977	12	245 - 300	BV	1.15
	M	130574	January 6, 1977	12	245 - 300	BV	1.3

[a]Data for sites in North Dakota from Ripley (1992)

[b]Data for sites in Minnesota from Minnesota County Well Index, MGS, 1993

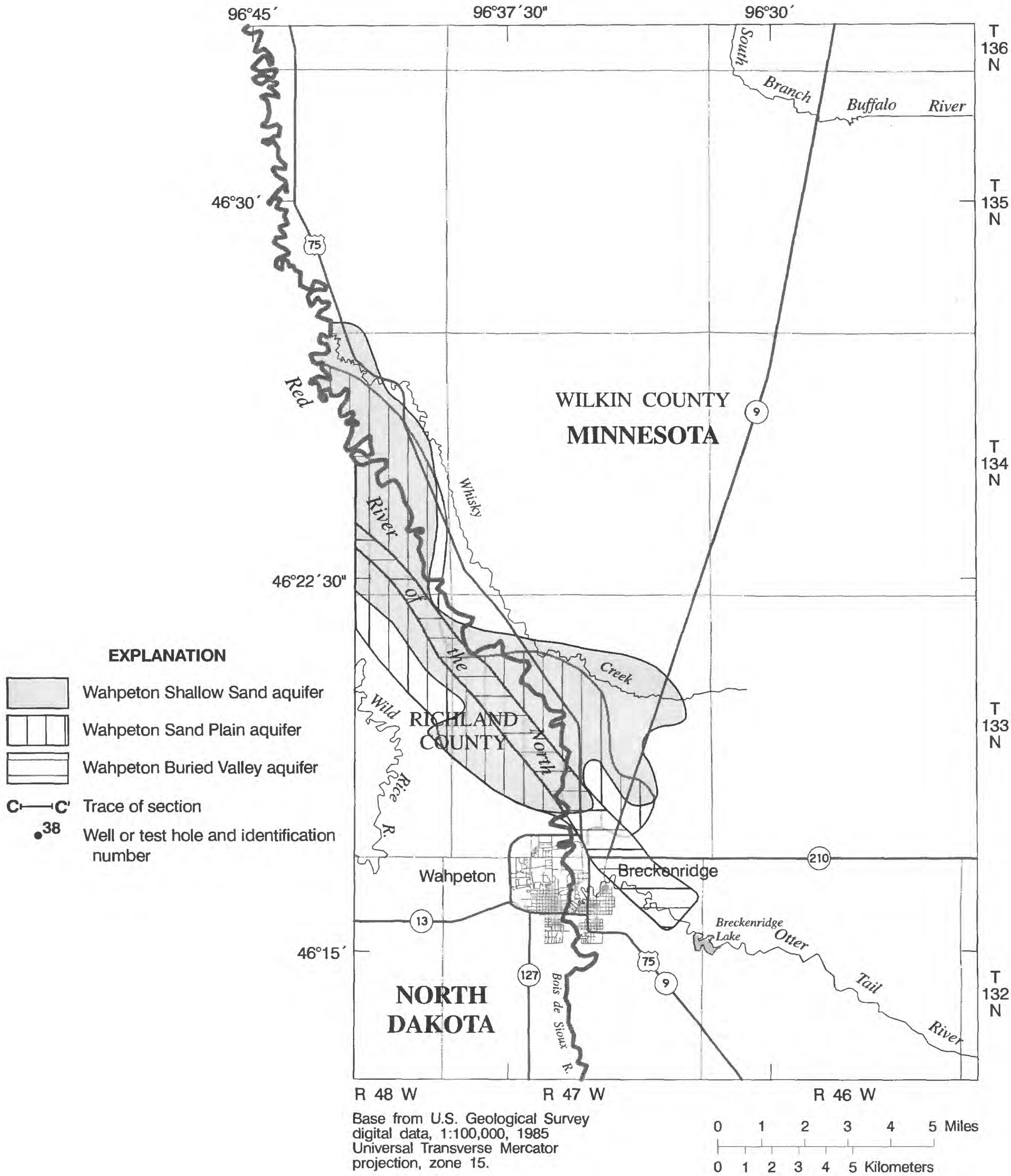
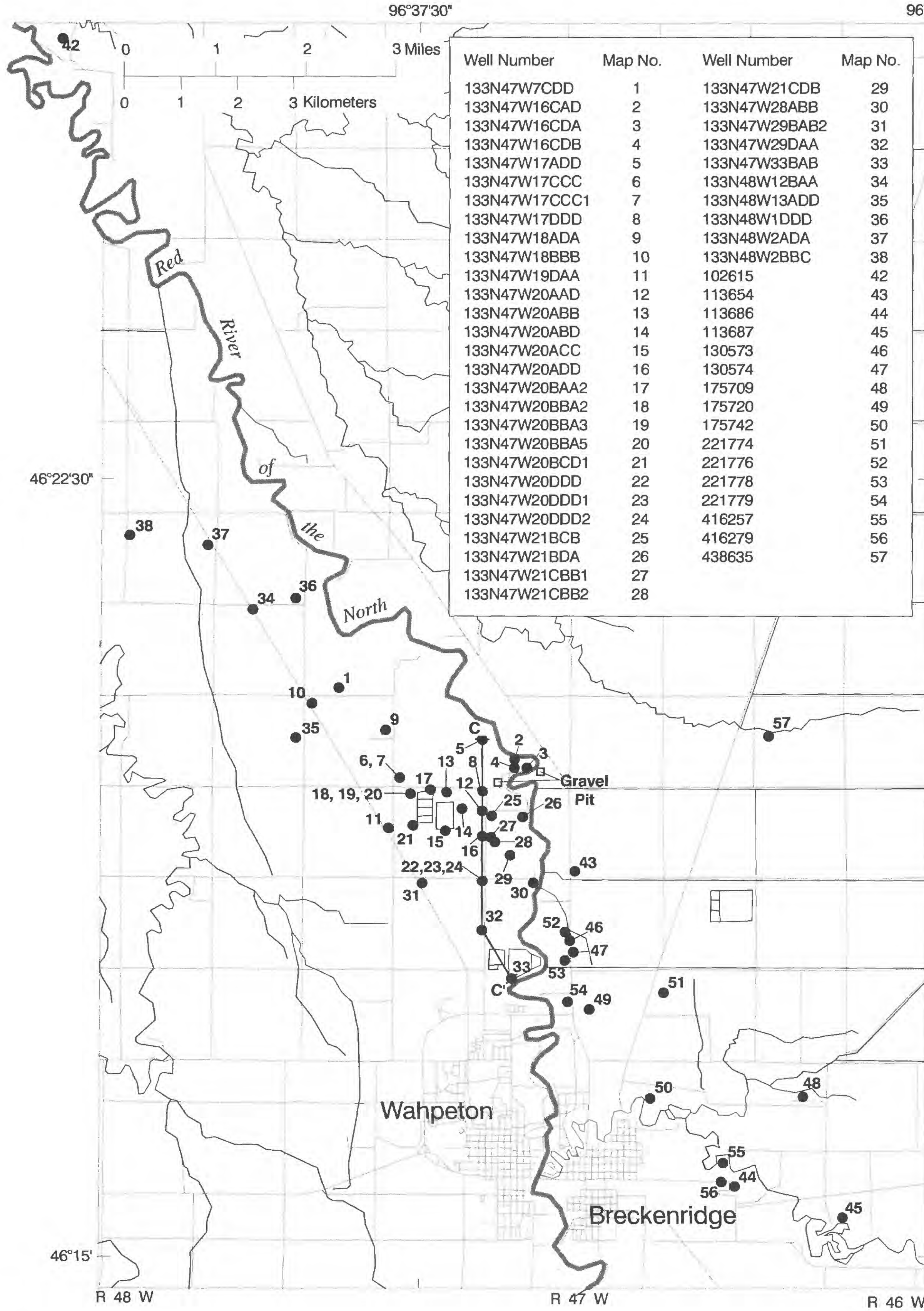


Figure 12. Areal extent



Well Number	Map No.	Well Number	Map No.
133N47W7CDD	1	133N47W21CDB	29
133N47W16CAD	2	133N47W28ABB	30
133N47W16CDA	3	133N47W29BAB2	31
133N47W16CDB	4	133N47W29DAA	32
133N47W17ADD	5	133N47W33BAB	33
133N47W17CCC	6	133N48W12BAA	34
133N47W17CCC1	7	133N48W13ADD	35
133N47W17DDD	8	133N48W1DDD	36
133N47W18ADA	9	133N48W2ADA	37
133N47W18BBB	10	133N48W2BBC	38
133N47W19DAA	11	102615	42
133N47W20AAD	12	113654	43
133N47W20ABB	13	113686	44
133N47W20ABD	14	113687	45
133N47W20ACC	15	130573	46
133N47W20ADD	16	130574	47
133N47W20BAA2	17	175709	48
133N47W20BBA2	18	175720	49
133N47W20BBA3	19	175742	50
133N47W20BBA5	20	221774	51
133N47W20BCD1	21	221776	52
133N47W20DDD	22	221778	53
133N47W20DDD1	23	221779	54
133N47W20DDD2	24	416257	55
133N47W21BCB	25	416279	56
133N47W21BDA	26	438635	57
133N47W21CBB1	27		
133N47W21CBB2	28		

of Wahpeton aquifers.

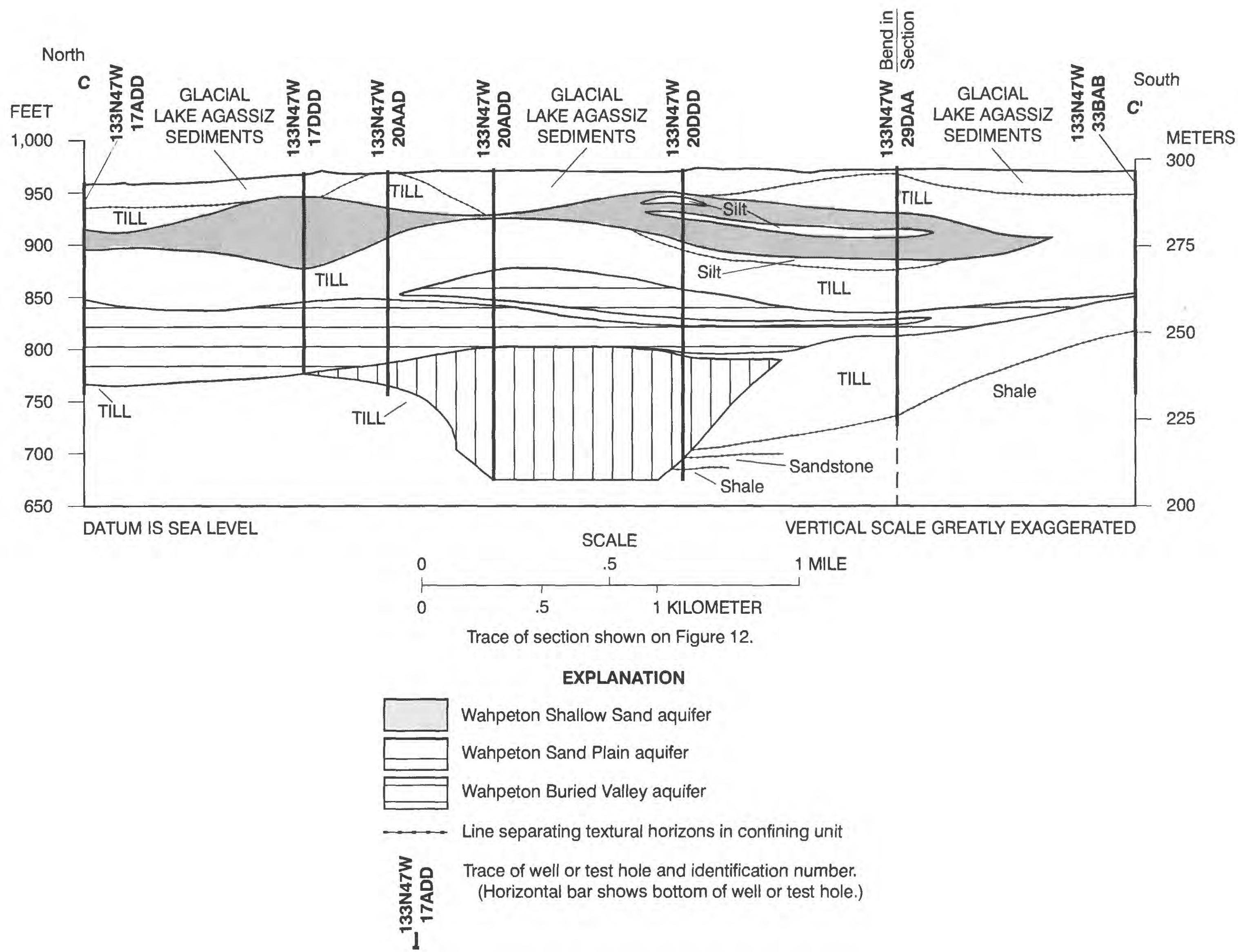


Figure 13. Hydrogeologic section C-C', Wahpeton, North Dakota.

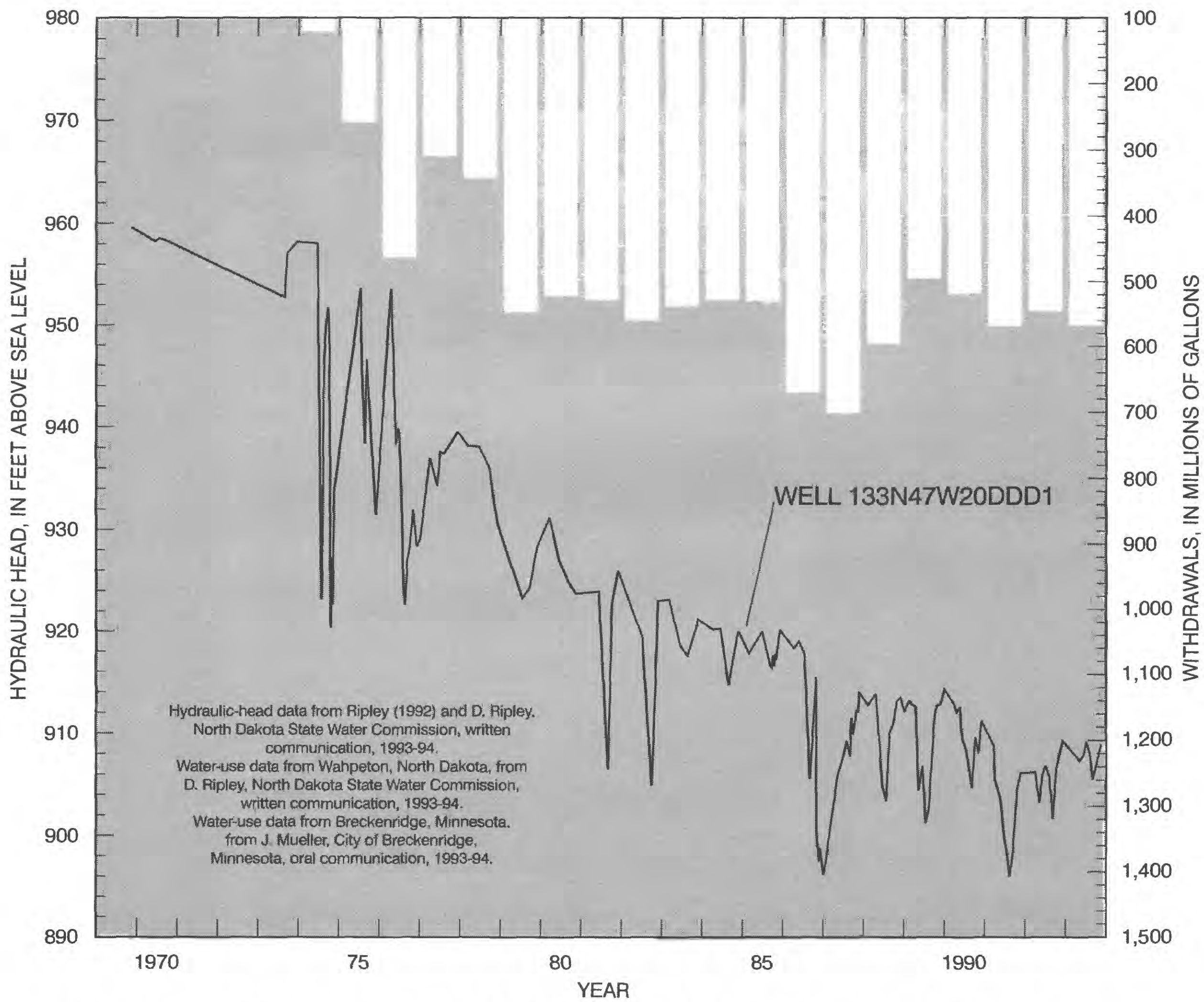


Figure 14. Hydraulic head in well 133N47W20DDD1 in the Wahpeton Buried Valley aquifer near Wahpeton, North Dakota, and withdrawals from Wahpeton Buried Valley aquifer near Wahpeton, North Dakota, and Breckenridge, Minnesota, 1969-93.

Hydraulic Properties

Data from one aquifer test were available for the Wahpeton Buried Valley aquifer (Schmid, 1970). The wells used in the test are listed in table 6. There were no available measurements of hydraulic properties in the Wahpeton Shallow Sand and Wahpeton Sand Plain aquifers.

Sources of Recharge to the Wahpeton Aquifers

The potential sources of recharge to the Wahpeton aquifers were from the Red River of the North and adjacent confining units. For the purpose of this report, the confining units include the glacial Lake Agassiz sediments, till, and Cretaceous bedrock. Data are not available to differentiate the effects of ground-water flow through the separate confining units and aquifers.

Red River of the North

Recharge from the Red River of the North to the Wahpeton aquifers depends on two conditions: (1) the stage in the river must be higher than the hydraulic head in the aquifers; and (2) the river must be hydraulically connected to the aquifer. The stage of the Red River of the North near Wahpeton, North Dakota, and Breckenridge, Minnesota, is controlled at low flow by a flat-topped, low-head dam. The altitude of the top of the dam is about 943 ft above sea level. Measured hydraulic head at well 133N47W20DDD2 (fig. 12) in the Wahpeton Shallow Sand aquifer declined from about 952 to 942 ft above sea level between September 17, 1974 and June 23, 1988. From June 23, 1988, to the end of data collection in June 1990, hydraulic head varied between about 941 and 942 ft above sea level (Ripley, 1992, p. 262-263). Hydraulic head at wells 133N47W17CCC1 and 133N47W20BAA2 (fig. 12) in the Wahpeton Sand Plain aquifer have been lower than the altitude of the dam (Ripley, 1992, p. 199-200, 240-241). Hydraulic heads at wells

Table 6.--Wells used in and transmissivity values from an aquifer test, September 24-30, 1969, near Wahpeton, North Dakota (Schmid, 1970)

[nc, not calculated]

Use of well	Well number	Well and screen diameter (in inches)	Screened interval (in feet above sea level)	Distance from pumped well (in feet)	Transmissivity (in feet^2 per day)	
					Calculated with the Jacob method[a]	Calculated with the Theis method[b]
Observation	133N47W18ADA	1.25	724-730	8,500	5,300	6,000
	133N47W17ADD	1.25	802-808	5,500	14,000	nc
	133N47W28ABB	1.25	771-775	3,900	3,300	nc
	133N47W20ABB	1.25	780-786	3,800	3,700	52,000
	133N47W20ACC	1.25	724-730	2,700	3,500	nc
	133N47W20ACA	1.25	708-714	1,800	3,500	36,000
	133N47W21BCB	1.25	772-778	1,400	3,300	14,000
	133N47W21CDB	1.25	703-706	900	4,100	29,000
	133N47W21CBB2	1.25	715-718	400	2,900	21,000
Pumped	133N47W21CBB3	12 for 207 feet of casing 6 for 25 feet of casing 6 for 50 feet of screen	688-738	0	nc	nc

[a]Cooper and Jacobs (1946)

133N47W18ADA, 133N47W20ABB, and 133N47W20DDD1 (fig.12) in the Wahpeton Buried Valley aquifer have been lower than the altitude of the dam since 1976 (Ripley, 1992, p. 203-204, 212-213, 206-261).

The recharge area where water from the Red River of the North leaks into the Wahpeton aquifers was not directly determined with river-discharge measurements. Recharge from the Red River of the North to the Wahpeton aquifers is most probable where the aquifers are shallow. This condition is most likely met for the Wahpeton Shallow Sand aquifer. The most likely locations for a hydraulic connection between the Wahpeton Shallow Sand aquifer and the Red River of the North are areas where the aquifer is at or near land surface and adjacent to the river. These areas would include wells 133N47W16CAD, 133N47W16CDA, 133N47W28ABB, and 133N47W21BDA, near two sand and gravel pits (fig. 12) next to the Red River of the North (Froelich, 1974).

Recharge from the Red River of the North to the Wahpeton aquifers was not estimated. The texture of the riverbed sediments of the Red River of the North, aquifer thicknesses, and their hydraulic properties are not known.

Adjacent Units

Ground water leaks into the Wahpeton aquifers from the adjacent units where the hydraulic head in the Wahpeton aquifers are lower than the hydraulic head in the adjacent units.

Ground water leaks horizontally into the Wahpeton aquifers at the boundary of the aquifers and adjacent units. The area though which recharge moves is a product of the thickness of the aquifers around the boundary multiplied by the length of that boundary. Data on the thickness of the aquifers around the perimeter, however, are not available.

The relation between the volume of ground water pumped from the Wahpeton Buried Valley aquifer near Wapheton, North Dakota, and Breckenridge, Minnesota, and hydraulic head in well 133N47W20DDD1 (fig. 14) provides an estimate of the upper limit for the volume of recharge to the aquifer at that location. The decline in hydraulic head between 1974 and 1993 indicates that pumpage has exceeded recharge in the Wahpeton Buried Valley aquifer. The pumpage from 1979 to 1993 averaged 560 Mgal/yr, or about 2.0 x 10^5 ft^3/d.

The estimated volume of recharge does not take into account pumpage from the Wahpeton Shallow Sand and Wahpeton Sand Plain aquifers. An estimate of recharge, based on pumpage from all of the Wapheton aquifers from 1990 to 1993, is about 580 Mgal/yr or about 2.4 x 10^5 ft^3/d.

Summary

The Buffalo and Wahpeton aquifers are the primary source of water for municipal, agricultural-product processing, agricultural, and domestic use in the southern Red River of the North drainage basin. Declining hydraulic heads in the Buffalo and Wahpeton aquifers are of concern to Minnesota Department of Natural Resources (MDNR) and local water managers because ground-water resources are limited in the southern part of the Red River of the North drainage basin. The MDNR is particularly concerned about the Buffalo and Wahpeton aquifers because these aquifers are susceptible to contamination, to hydraulic-head decline during drought, or to long-term withdrawals greater than long-term recharge.

The Buffalo aquifer is a narrow, 36 mile long, 1-2 mile wide sand and gravel deposit located in Clay County and northern Wilkin County. Part of the Buffalo aquifer is unconfined and part is confined. The aquifer is unconfined along parts of its north-south trending centerline. At the MPS North Well Field, the middle horizon (sand with clay), where present, acts as a leaky confining unit within the aquifer, separating the upper horizon (silty fine to coarse sand with sandy clay) from the lower horizon (cobbly gravel with sand). The direction of ground water flow in the Buffalo aquifer is from the east to the west.

Major use of ground water from the Buffalo aquifer began in 1948. Hydraulic head declined from 1950 to 1961, which corresponds in time to drought conditions for most of that period. During that time MPS pumped ground water from the Buffalo aquifer at an almost constant rate, averaging 386 Mgal/yr for 1951 to 1960.

Transmissivity and storativity determined from the drawdown part of an aquifer test in the Buffalo aquifer were calculated as 21,400, 23,852, and 20,870 ft^2/d and 3.2×10^{-2}, 2.6×10^{-3}, and 3.0×10^{-5} from the data from wells 247980, 247985, 511085, respectively. From the recovery part of the aquifer test, transmissivity values of 29,090 and 28,450 ft^2/d were calculated at wells 511086 and 511085, respectively. The hydraulic conductivity of the upper horizon of the Buffalo aquifer at the MPS North Well Field, estimated from grain-size distributions from three samples, ranged from 11 to 36 ft/d.

Recharge from the Buffalo River and its tributaries to the Buffalo aquifer ranged from 5 to 14 ft^3/s. Recharge from precipitation to the unconfined part of the Buffalo aquifer was determined to be about 1.49×10^5 ft^3/d. Recharge per unit length of the margins of the aquifer along the western and eastern sides of the aquifer during an aquifer test near the MPS North Well Field ranged from 3.9×10^{-4} to 2.0×10^{-2} ft^3/d and from 8.1×10^{-4} to 20×10^{-2} ft^3/d, respectively.

The Wahpeton Shallow Sand, the Wahpeton Sand Plain, and the Wahpeton Buried Valley aquifers comprise the Wahpeton aquifers in order of increasing depth. The aquifers are composed of fine-grained to coarse-grained sand mixed with gravel. The Wahpeton Shallow Sand aquifer has an irregular thickness. The extent of the Wahpeton Shallow Sand aquifer is about 29 mi^2. The bottom of the aquifer ranges from about 100 to 195 ft below land surface and is underlain by till. The extent of the Wahpeton Sand Plain aquifer is about 24 mi^2. The extent of the Wahpeton Buried Valley aquifer is about 8 mi^2 and fills a steep-sided buried valley. The top of the Wahpeton Buried Valley aquifer ranges from about 65 to 240 ft below land surface. Confining units are interleaved within the Wahpeton aquifers, and are composed of till and Cretaceous bedrock.

Development of ground-water resources in the Wahpeton aquifers began in 1974. Prior to 1974, ground water flowed from the Wahpeton Buried Valley aquifer upward to the Wahpeton Sand Plain aquifer and the Wahpeton Shallow Sand aquifer. Development of the aquifers reversed the predevelopment direction of vertical flow.

The general direction of ground-water flow in the glacial drift in Minnesota in summer 1992 was from east to west toward the Wahpeton aquifers. The direction of horizontal ground-water flow in the Wahpeton Buried Valley aquifer is from potentiometric highs in Minnesota to potentiometric lows in North Dakota.

Hydraulic head in the Wahpeton Buried Valley aquifer has declined since 1974 in response first to increasing pumpage (1974-79) and then almost constant pumpage (1980-93). The average annual pumpage from the Wahpeton Buried Valley aquifer was about 300 Mgal/yr during 1974-79 and about 560 Mgal/yr during 1980-93. Ground water has been pumped from the Wahpeton Sand Plain and Wahpeton Shallow Sand aquifers since 1986 and 1990, respectively. The average annual water use from the Wahpeton Sand Plain aquifer from 1986 to 1993 was about 90 Mgal. The average annual water use from the Wahpeton Shallow Sand aquifer from 1990 to 1993 was about 26 Mgal.

The volume of ground water pumped from the Wahpeton aquifers from 1990 to 1993 near Wahpeton, North Dakota, and Breckenridge, Minnesota, provides an estimate of the upper limit of recharge to the aquifer (about 580 Mgal/yr or about 2.4×10^5 ft^3/d).

Recharge from the Red River of the North to the Wahpeton aquifers most likely occurs where the aquifer is at or near land surface, such as near two sand and gravel pits next to the Red River of the North. Vertical recharge from precipitation must first move through the confining unit overlying the Wahpeton Shallow Sand aquifer to recharge the Wahpeton aquifers. Ground water leaks into the Wahpeton aquifers from the adjacent confining units where the hydraulic heads in the Wahpeton aquifers are lower than the hydraulic heads in the adjacent confining units.

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