Availability and Quality of Water from Drift Aquifers in Marshall, Pennington, Polk, and Red Lake Counties, Northwestern Minnesota

By R.J. Lindgren

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Conversion Factors, Vertical Datum, and Abbreviated Water Quality Units

Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	25.4	millimeter
foot (ft)	.3048	meter
mile (mi)	1.609	kilometer
foot per day (ft/d)	.3048	meter per day
	.0003528	centimeter per second
foot per mile (ft/mi)	.1894	meter per kilometer
cubic foot per second (ft^3/s)	.02832	cubic meter per second
foot squared per day (ft^2/d)	.09290	meter squared per day
gallon (gal)	.003785	cubic meter
gallon per minute (gal/min)	.06308	liter per second
million gallons per day (Mgal/d)	.04381	cubic meter per second
square mile (mi^2)	2.590	square kilometer

Chemical concentrations are given in metric units. Chemical concentrations of substances in water are given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million.

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 both the United States and Canada, formerly called "Sea Level Datum of 1929".

Glossary

The geologic and hydrologic terms pertinent to this report are defined as follows:

Aquifer: Formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells or springs.

Base flow: Sustained streamflow, consisting mainly of ground-water discharge to a stream.

Confined aquifer: Aquifer bounded above by a confining unit. An aquifer containing confined ground water. Synonymous with buried aquifer.

Confining unit: Body of material with low vertical permeability stratigraphically adjacent to one or more aquifers. Replaces the terms aquiclude, aquitard, and aquifuge.

Dissolved: Constituents in a representative water sample that pass through a 0.45-μm (micrometer)membrane filter. The dissolved constituents are determined from subsamples of the filtrate.

Drawdown: Vertical distance between the static (nonpumping) hydraulic head and hydraulic head caused by pumping.

Drift: General term applied to all material (clay, sand, gravel, and boulders) transported and deposited by glacial ice or melt water.

End moraine: A ridge-like accumulation that is being produced at the margin of an actively flowing glacier at any given time.

Evapotranspiration: Water discharged to the atmosphere by evaporation from water surfaces and moist soil and by plant transpiration.

Glacial lake sediments: Gravel, sand, silt, and clay deposited in or along the shoreline of a lake that derives much or all of its water from the melting of glacier ice.

Glacial lobe: A large, rounded, tongue-like projection from the margin of the main mass of a glacier.

Ground moraine: Accumulation of till deposited mainly from the bottom of a glacier as a more or less uniform blanket. Generally characterized by an undulating surface of hummocks or drumlins separated by swales.

Ground water: The part of subsurface water that is in the saturated zone.

Head, hydraulic: The height above a standard datum of the surface of a column of water that can be supported by the static pressure at a given point.

Hydraulic conductivity: Capacity of porous material to transmit water under pressure. It is the rate of flow of water passing through a unit section of area under a unit hydraulic gradient.

Hydraulic gradient: The change in hydraulic head per unit distance of flow in a given direction. Synonymous with potentiometric gradient.

Ice-contact deposit: Stratified drift deposited in contact with melting glacier ice.

Moraine: A mound, ridge, or other distinct accumulation of unsorted, unstratified drift, predominantly till, deposited chiefly by direct action of glacier ice.

Outwash: Washed, sorted, and stratified drift deposited by water from melting glacier ice.

Permeability: Measure of the relative ease with which a porous medium can transmit a fluid under a potential gradient.

Potentiometric surface: A surface that represents the static head of water in an aquifer; assuming no appreciable variation of head with depth in the aquifer. It is defined by the levels to which water will rise in tightly cased wells from a given point in an aquifer.

Reporting limit: The lowest measured concentration of a constituent that may be reliably reported using a given analytical method.

Saturated zone: The zone in which all voids are ideally filled with water. The water table is the upper limit of this zone. Water in the saturated zone is under pressure equal to or greater than atmospheric.

Specific capacity: The rate of discharge of water from a well divided by the drawdown of water level within the well.

Specific yield: The ratio of the volume of water that an aquifer material will yield by gravity drainage to the volume of the aquifer material.

Stagnation moraine: Accumulation of drift released by the melting of a glacier that has ceased flowing. Commonly occurs near ice margins. Typical landforms are Knob-and-Kettle topography. Stagnation moraine is transitional to end moraine.

Storage coefficient: The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. In an unconfined aquifer, it is the same as the specific yield.

Stratified drift: Drift consisting of sorted and layered material deposited by a meltwater stream or settled from suspension in a body of quiet water adjoining a glacier.

Surficial aquifer: The saturated zone between the water table and the first underlying confining unit; synonymous with unconfined aquifer.

Till: Unsorted, unstratified drift deposited directly by glacier ice.

Transmissivity: The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient.

Unconfined aquifer: The saturated zone between the water table and the first underlying confining unit; synonymous with surficial aquifer.

Water table: The surface in an unconfined ground-water body at which the water pressure is atmospheric. Generally, this is the upper potentiometric surface of the zone of saturation.

Availability and Quality of Water from Drift Aquifers in Marshall, Pennington, Polk, and Red Lake Counties, Northwestern Minnesota

By R.J. Lindgren

Abstract

Sand and gravel aquifers present within glacial deposits are important sources of water in Marshall, Pennington, Polk, and Red Lake Counties in northwestern Minnesota. Saturated thicknesses of the unconfined aquifers range from 0 to 30 feet. Estimated horizontal hydraulic conductivities range from 2.5 to 600 feet per day. Transmissivity of the unconfined aquifers ranges from 33 to greater than 3,910 feet squared per day. Theoretical maximum well yields for 6 wells with specific-capacity data range from 12 to 123 gallons per minute.

Saturated thicknesses of shallow confined aquifers (depth to top of the aquifer less than 100 feet below land surface) range from 0 to 150 feet. Thicknesses of intermediate, deep, and basal confined aquifers (depths to top of the aquifer from 100 to 199 feet, from 200 to 299 feet, and 300 feet or more below land surface, respectively) range from 0 to more than 126 feet. Transmissivity of the confined aquifers ranges from 2 to greater than 210,000 feet squared per day. Theoretical maximum well yields range from 3 to about 2,000 gallons per minute.

Recharge to ground water is predominantly from precipitation that percolates downward to the saturated zone. Recharge to unconfined aquifers in the study area ranged from 4.5 to 12.0 inches per year during 1991 and 1992, based on hydrograph analysis. Model simulations done for this study indicate that recharge rates from 8 to 9 inches per year to unconfined aquifers produce the best matches between model-simulated and measured water levels in wells.

Discharge from ground water occurs by seepage to streams, lakes and wetlands, ground-water evapotranspiration, and withdrawals through wells. In 1990, total ground-water withdrawals in the study area were 6.0 million gallons per day. All of the withdrawals were from drift aquifers.

Numerical models of ground-water flow were constructed to represent two beach-ridge aquifer systems under steady-state conditions. Beach-ridge aquifer systems were simulated in Pennington, Polk, and Red Lake County. Simulated recharge from the infiltration of precipitation accounts for most of the sources of water to the beach-ridge aquifer systems and simulated evapotranspiration accounts for all of the discharge other than ground-water withdrawals. The numerical-model simulations indicate that upward movement of water from underlying confined aquifers to overlying unconfined aquifers is an important component of ground-water flow within the beach-ridge aquifer systems. Simulated long-term, steady-state yields from the unconfined aquifers are generally less than 50 gallons per minute, due to the generally low saturated thickness of the aquifers and the relatively low hydraulic conductivity of the aquifer material.

Water from all the drift aquifers in the study area is very hard (more than 180 milligrams per liter of calcium carbonate). The predominant ions in water from the unconfined and shallow confined aquifers were generally calcium and bicarbonate. Water from the intermediate confined aquifers includes a variety of water types, including calcium bicarbonate, calcium sulfate, mixed calcium-sodium bicarbonate, and sodium chloride type waters. Waters from the deep confined aquifers are predominantly calcium bicarbonate, mixed calcium-sodium bicarbonate, and sodium chloride type waters.

Mean concentrations of calcium and magnesium generally decreased with depth below land surface. Mean concentrations of sodium and sulfate generally increased with depth. Mean chloride concentrations were greatest for the shallow and deep confined aquifers and least for the unconfined and intermediate confined aquifers.

The concentration and percentage (as percent of total cations) of sodium, and concentration of dissolved solids tend to increase from east to west along regional flow paths. Concentrations and percentages (as percent of total anions) of chloride tend to be greater in the western part of the study area than in the eastern part. These trends are

probably due to longer residence time of the water in the flow system, and upward leakage of water from the underlying Cretaceous and Paleozoic strata.

Waters from the drift aquifers underlying most of the study area generally are suitable for domestic consumption, crop irrigation, and most other uses. Water from 20 wells screened in unconfined and confined aquifers exceeded U.S. Environmental Protection Agency recommended limits for dissolved solids concentrations. Chemical analyses of waters from the unconfined and confined aquifers generally indicated a potentially low sodium hazard and a medium to high salinity hazard for irrigation.

Water samples analyzed for nitrate had nitrate concentrations below the reporting limit (0.05 milligrams per liter) in 10 out of 23 wells. Two samples had nitrate concentrations greater than 10 milligrams per liter. Pesticide concentrations in water samples from 17 wells screened in unconfined and shallow confined aquifers were below or only slightly above laboratory reporting limits.

Introduction

Aquifers in glacial deposits, hereinafter termed drift aquifers, are important sources of water in Marshall, Pennington, Polk, and Red Lake Counties in northwestern Minnesota. Ground-water withdrawals from drift aquifers are increasing due to increasing demands for water supplies. Drift aquifers include both unconfined and confined drift aquifers. Unconfined drift aquifers in the study area generally are limited to scattered surficial sand and gravel beach deposits formed by the ancient glacial Lake Agassiz (Bidwell and others, 1970). The unconfined drift aquifers, which are susceptible to land-surface contamination, could be significant areas of recharge for the underlying confined aquifers. Little is known about the thickness, areal extent, and hydraulic properties of the confined aquifers interbedded within the glacial deposits. High-salinity water from underlying Paleozoic and Cretaceous sedimentary rocks may have migrated into the drift aquifers, resulting in water-quality problems (Bidwell and others, 1970).

Managers and planners need additional information about the potential yields and water quality of the drift aquifers in the four-county area to help manage the ground-water resources. The U.S. Geological Survey, in cooperation with the Minnesota Department of Natural Resources (MDNR) and the Northwest Minnesota Ground-Water Study Steering Committee, conducted a 4-year study (October 1989-September 1993) to appraise the ground-water resources in Marshall, Pennington, Polk, and Red Lake Counties in northwestern Minnesota. This report presents the findings of that study.

Purpose and Scope

This report describes the availability and quality of ground water in drift aquifers in Marshall, Pennington, Polk, and Red Lake Counties in northwestern Minnesota. The report objectives are to (1) describe the areal extent, thickness, and water-bearing characteristics of drift aquifers, (2) estimate the potential yield from unconfined drift aquifers and the uppermost confined drift aquifer present in the glacial deposits, and (3) describe characteristics and trends in water quality along regional ground-water flow paths from areas of recharge to areas of discharge. The report provides baseline hydrologic and water-quality data for use in future assessments of long-term trends and defines the quality of ground water in relation to hydrogeologic conditions and land use.

The unconfined drift and uppermost confined drift aquifers are described in detail in this report. An uppermost confined aquifer is defined as the first confined drift aquifer present in the glacial deposits with increasing depth below land surface. Other aquifers may exist below the uppermost confined aquifers, but data for these deeper aquifers generally are limited so the extent and hydraulic properties of these deeper aquifers are described in lesser detail.

This study was conducted in two phases. The first phase included the entire study area and concentrated on regional mapping and description of the confined drift aquifers (hereinafter referred to as confined aquifers) in Marshall, Pennington, Polk, and Red Lake Counties. The second phase involved a more detailed study of the potential yield of unconfined drift aquifers (hereinafter referred to as unconfined aquifers) and underlying uppermost confined aquifers, the interaction between the unconfined and uppermost confined aquifers, and the ground-water quality in an area that coincides with beach and glacial-outwash deposits (fig. 1). The unconfined aquifers are present within the beach and glacial-outwash deposits. Two beach-ridge aquifer systems (including unconfined aquifers, underlying uppermost confined aquifers, and confining units)

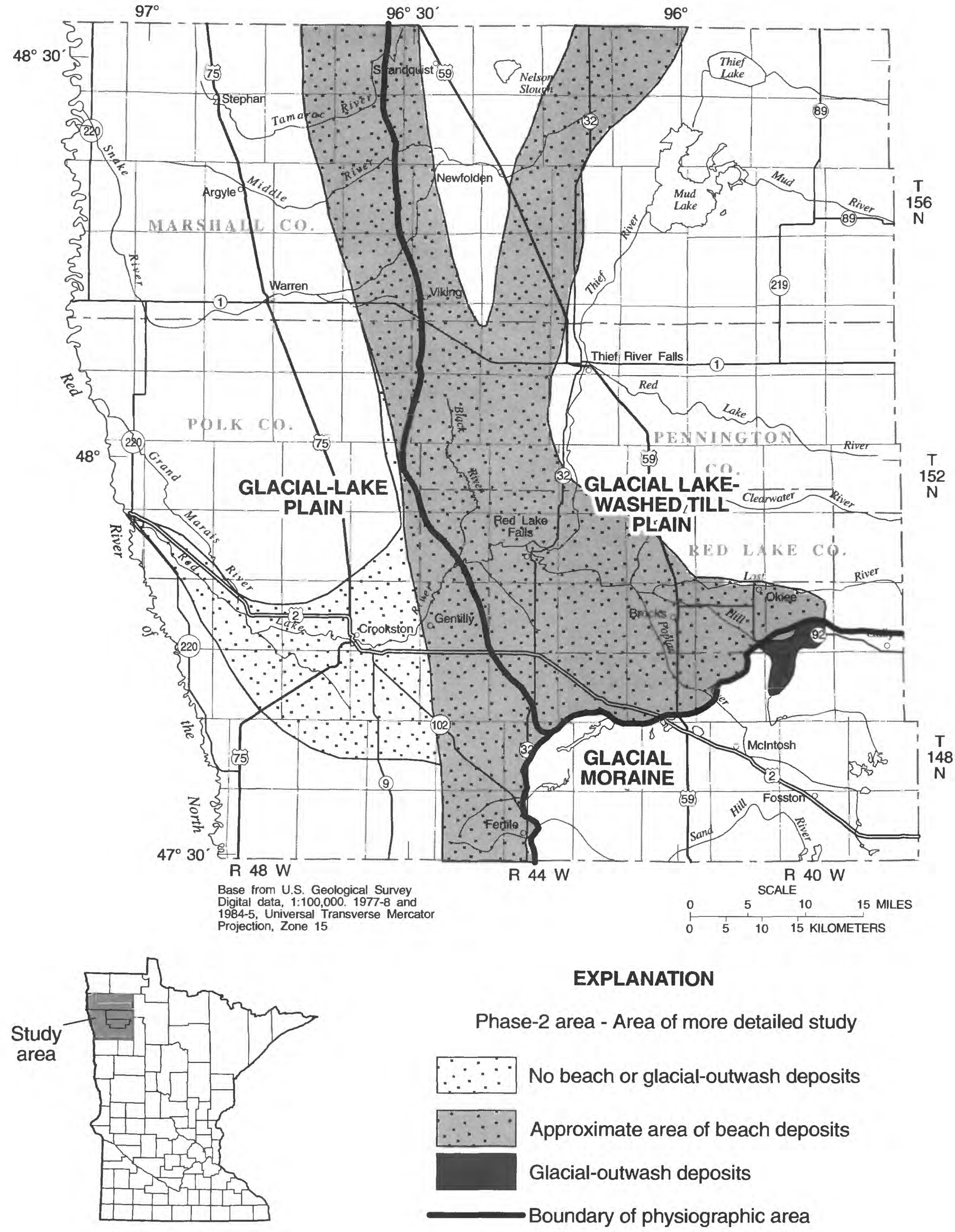


Figure 1. Location of study area, phase-2 area, physiographic areas, beach deposits, and glacial-outwash deposits.

associated with topographically defined beach ridges were investigated in detail.

Location and Description of Study Area

The study area covers approximately 4,810 mi^2 and includes Marshall, Pennington, Polk, and Red Lake Counties in northwestern Minnesota. The study area includes three general physiographic areas—glacial moraine, glacial lake-washed till plain, and glacial-lake plain (fig. 1). The glacial moraine is an area of hills and depressions that has local relief up to 150 ft and is present in the southeastern part of the study area. The glacial lake-washed till plain is a flat to very gently rolling area that has local relief up to 15 ft and includes approximately the eastern two-thirds of the study area, excluding the moraine area. The western part of the glacial lake-washed till plain is traversed by north-south and northeast-southwest trending, long, narrow beach ridges. The glacial-lake plain includes approximately the western one-third of the study area. The glacial-lake plain is extremely flat in the western part of its extent, sloping only a few feet per mile. In the eastern part, the slope increases and is traversed by north-south trending, long, narrow beach ridges as much as 20 ft high.

The study area is drained by tributaries of the Red River of the North. The Red Lake River and its tributaries, including the Clearwater and Thief Rivers, drain the central and eastern parts of the study area. The Middle, Tamarac, and Snake Rivers drain the northwestern part of the study area. The Sand Hill River, a tributary of the Wild Rice River (located south of the study area), drains the southern part of the study area.

Annual precipitation ranges from 21 to 26 in. in the study area (Baker and Kuehnast, 1978). Moisture is adequate for optimum plant growth in spring and early summer during a normal year but a moisture deficiency during August and September results in less than optimum growth. Annual precipitation varies widely from year to year; however, wet and dry years tend to occur in groups. Rural and municipal water shortages were common during droughts occurring in the 1930's and the 1980's. Potential annual evapotranspiration calculated by the Thornthwaite method is about 22 to 23 in. and annual runoff is about 3 to 5 in. (Baker and others, 1979).

Ground-water withdrawals presently constitute about 29 percent of the total water usage in the study area (Greg Mitton, U.S. Geological Survey, written commun., 1993). The primary consumptive use of ground water withdrawn from the drift aquifers is for domestic and municipal supply.

Previous Investigations

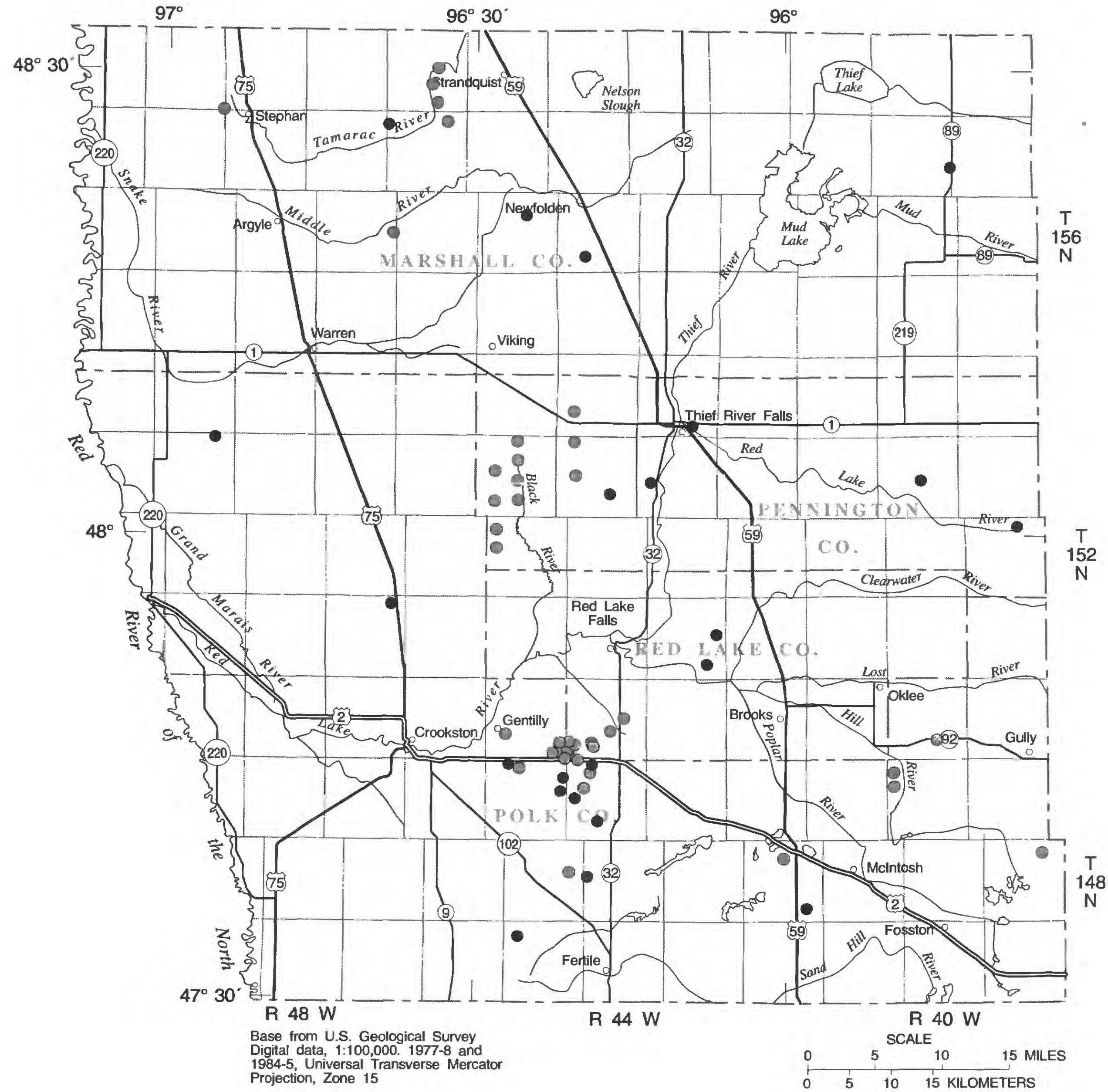
Wright and Ruhe (1965) and Wright (1972) have published works summarizing the general glacial history of Minnesota. Leverett (1932) and Hobbs and Goebel (1982) published maps of Minnesota's Quaternary geology.

Allison (1932) describes the geology and water resources of northwestern Minnesota. Bidwell and others (1970) discuss the water resources and hydrogeology of the Red Lake River watershed. Maclay and others (1965) discuss the water resources and hydrogeology of the Middle River watershed. Winter and others (1970) discuss the water resources and hydrogeology of the Wild Rice River watershed.

Methods of Investigation

Field work for this study was conducted from 1990-93. Hydrogeologic maps were prepared using reported data from about 1,800 wells and test holes obtained from files of the Minnesota Geological Survey (MGS) and the U.S. Geological Survey, and geologic logs from 146 test holes drilled for this study using hollow-stem augers for shallow holes (136 holes) and mud rotary drilling for deeper holes (10 holes). A well-log inventory using county plat books was used to verify the well locations given on the well logs. When the information from the well logs and plat books was incomplete or unclear, field visits to well sites were used to verify the well locations. Location, geologic, and hydrologic information from well and test-hole logs was entered into a relational computer data base. The data base was used to prepare maps showing the thickness, areal extent, and hydraulic properties of the drift aquifers and confining units. Thirty-two test holes drilled for this study were completed as observation wells to determine spatial and temporal changes in water levels in the drift aquifers and to collect water samples for chemical analysis. Water levels also were measured in 29 domestic wells. Water levels were measured periodically in 39 observation wells screened in unconfined aquifers and in 22 observation wells screened in confined aquifers (fig. 2). Water-use data were obtained from the Minnesota Water-Use Data System at the MDNR and also from the city of Crookston, Minnesota.

Two conceptually based, three-dimensional, finite-difference ground-water-flow models (McDonald and Harbaugh, 1988) simulated ground-water flow in beach-ridge aquifer systems. The models were developed to



EXPLANATION

- Observation well screened in unconfined aquifer
- Observation well screened in confined aquifer

Figure 2. Locations of observation wells.

better understand (1) ground-water flow in and recharge to the aquifer systems, (2) hydrologic budgets, and (3) the hydraulic properties of hydrogeologic units. The models were calibrated for steady-state conditions only and are not of sufficient detail to be used as predictive tools. Elevation surveys to an accuracy of 0.1 ft were conducted to determine the land-surface datum for all observation wells with measured water levels used to calibrate the models.

Horizontal hydraulic conductivity was estimated from slug tests conducted for this study at 21 wells screened in unconfined aquifers and at 4 wells screened in confined aquifers. Slug tests were conducted and the results analyzed using methods described by Bouwer and Rice (1976) and Bouwer (1989). Horizontal hydraulic conductivities of unconfined aquifer material from continuous cores (2-inch diameter) collected at 3 sites also were estimated based on the relation between grain size class and hydraulic conductivity as reported by Koch (1980, p. 15). Single-well recovery aquifer tests were conducted at 8 wells screened in unconfined aquifers. Transmissivity was estimated from the results of the aquifer tests using the Theis recovery method (Kruseman and de Ridder, 1990).

Specific-capacity information available from well logs for 6 wells screened in unconfined aquifers and for 464 wells screened in confined aquifers was used to estimate aquifer transmissivity (Heath, 1983, p. 60-61). Estimates for theoretical maximum well yields were computed by multiplying the specific capacity by the available drawdown. Selected data from commercial drillers' logs of wells in the study area used to estimate transmissivity and theoretical maximum well yield are given in table 19 in the Supplemental Information section.

Water samples were collected and analyzed to (1) establish baseline water-quality conditions, (2) define water-quality trends along regional ground-water flow paths, (3) determine seasonal changes in water chemistry, and (4) assess the quality of ground water in relation to land use. Water samples collected from 18 wells screened in unconfined aquifers and from 42 wells screened in confined aquifers during the summers of 1991 and 1992 established baseline water-quality conditions (fig. 3). Water samples were collected from 2 wells located in the valley of the Red River of the North for which no well logs were available. These 2 wells were assumed to be screened in confined aquifers. Water samples collected from 31 wells during August of 1991 along defined ground-water flow paths determined trends in water chemistry. Water samples collected from 3 wells screened in unconfined aquifers from August 1991 to October 1992 determined seasonal changes in water chemistry. Water samples from wells used to establish general water quality and baseline conditions were analyzed for an identical group of major common constituents (table 1). Water-quality data for all wells sampled for this study are given in tables 20 to 23 in the Supplemental Information section.

Water samples were collected during 1991 and 1992 from 23 wells screened in unconfined and shallow confined aquifers, and analyzed for nutrients to assess the quality of ground water in relation to land use. Water-quality data for wells sampled for nutrients are given in table 24 in the Supplemental Information section.

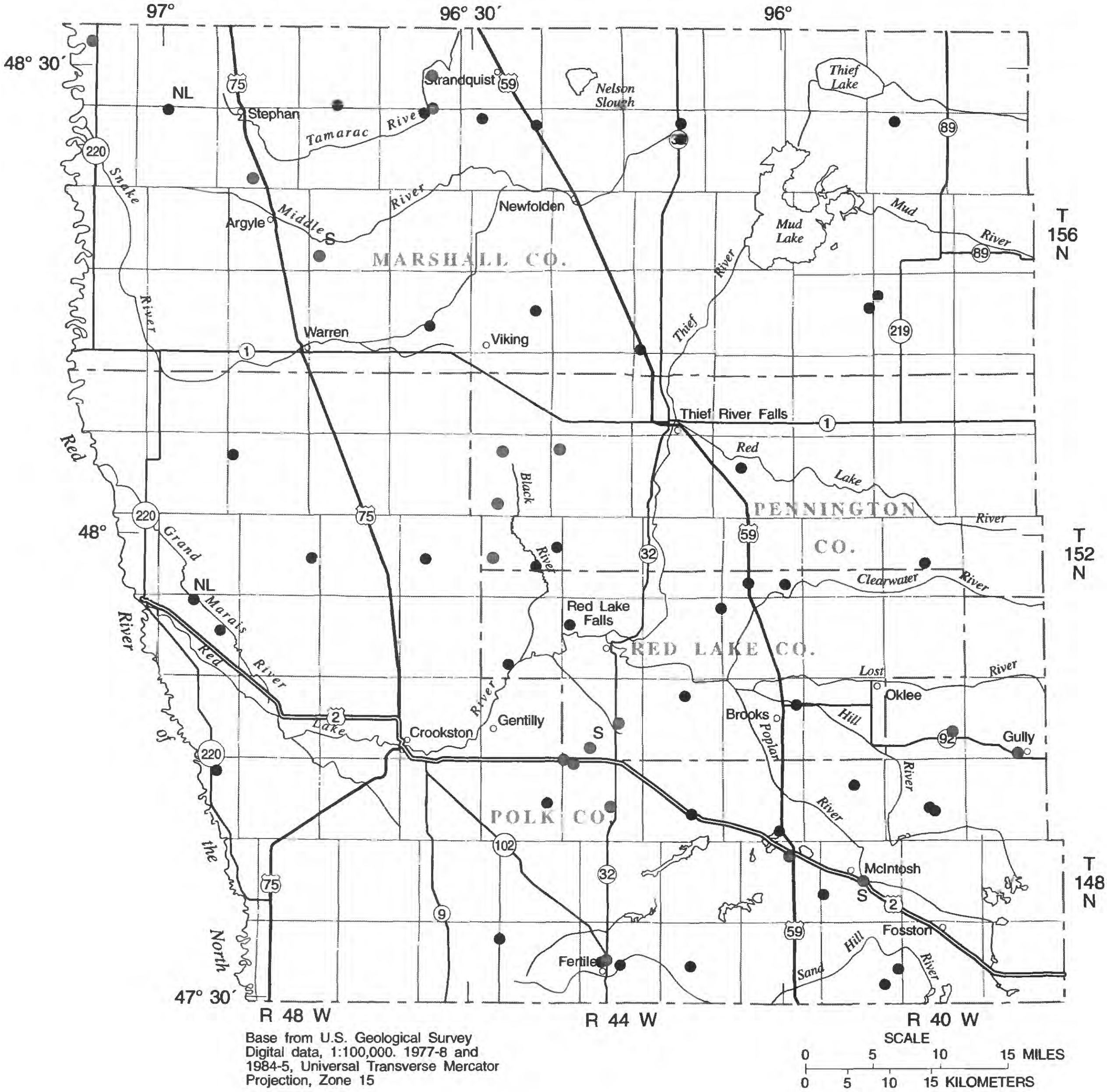
Eighty-three water samples were collected during August of 1992 from wells screened in unconfined and shallow confined aquifers and tested for the presence of the herbicide 2,4-D using immunoassay methods (fig. 4). The immunoassay method used is based on the use of polyclonal antibodies which bind both 2,4-D compounds and a 2,4-D enzyme conjugate (Millipore Corporation, written commun., 1992). The 2,4-D in the water sample competes with 2,4-D-enzyme conjugate for a limited number of antibody binding sites. Limitations of the method include (1) a lack of rigorous quantitative results, and (2) the chemical non-specificity of the test, which does not allow precise definition of which compound of the chemical family has elicited the response.

Water samples were collected during June to October 1992 from 18 wells screened in unconfined and shallow confined aquifers and analyzed for a wide spectrum of pesticides to assess the quality of ground water in relation to land use (table 2). The well sites were chosen based on the results of the immunoassay tests, proximity of the well site to cropland, and the direction of ground-water flow in the immediate vicinity of the well site.

The sampling procedures used were generally the same as those given in Rainwater and Thatcher (1960) and recommended by M.R. Have and L.H. Tornes (U.S. Geological Survey, written commun., 1985). Water samples were analyzed at the U.S. Geological Survey Laboratory in Arvada, Colorado. Inorganic constituents were analyzed by procedures outlined in Fishman and Friedman (1985). Pesticides were analyzed according to procedures in Wershaw and others (1983).

Test-Hole and Well-Numbering System

Two systems of numbering wells and test holes were used for this study. The first system used was the Minnesota Geological Survey (MGS) unique well



EXPLANATION

- Sampled well screened in unconfined aquifer
  - S indicates well was sampled seasonally
- Sampled well screened in confined aquifer
- NL Sampled well with no well log available
  - Assumed to be screened in confined aquifer

Figure 3. Water-quality sampling locations.

Table 1.—Constituents and properties for water samples from wells used to determine general ground-water quality and establish baseline conditions

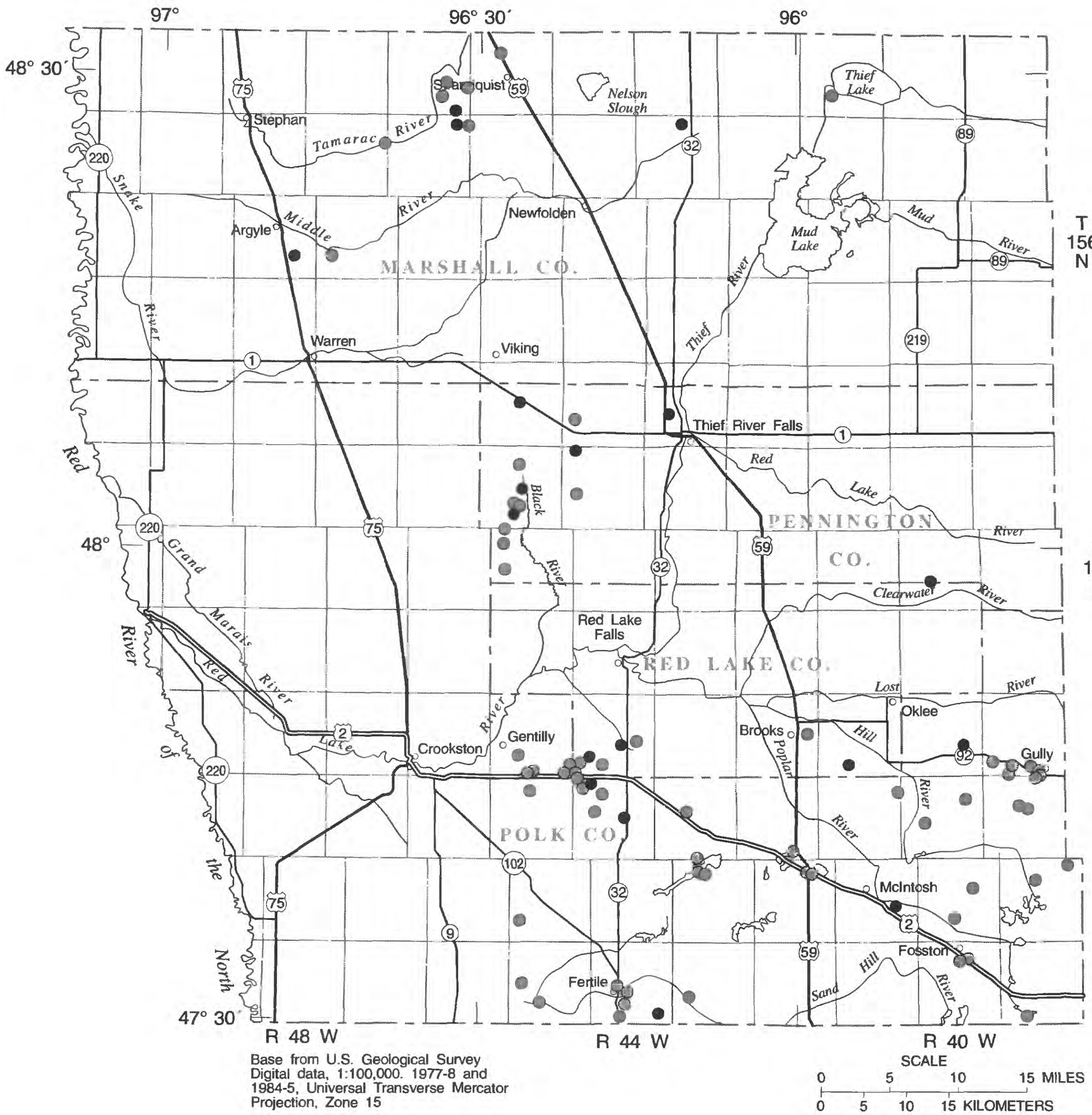
[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; field, determined at the sampling site]

Property or constituent	
Miscellaneous constituents and properties	
Specific conductance, field (µS/cm)	Oxygen, dissolved (mg/L)
pH, field (standard units)	Organic carbon, dissolved (mg/L as C)
Temperature, field (degrees Celsius)	Dissolved solids, residue at 180 degrees Celsius (mg/L)
Major inorganic constituents	
Hardness (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)
Calcium, dissolved (mg/L as Ca)	Chloride, dissolved (mg/L as Cl)
Magnesium, dissolved (mg/L as Mg)	Fluoride, dissolved (mg/L as F)
Sodium, dissolved (mg/L as Na)	Silica, dissolved (mg/L as SiO_2)
Potassium, dissolved (mg/L as K)	
Minor inorganic constituents	
Barium, dissolved (µg/L as Ba)	Lithium, dissolved (µg/L as Li)
Beryllium, dissolved (µg/L as Be)	Manganese, dissolved (µg/L as Mn)
Boron, dissolved (µg/L as B)	Molybdenum, dissolved (µg/L as Mo)
Cadmium, dissolved (µg/L as Cd)	Nickel, dissolved (µg/L as Ni)
Chromium, dissolved (µg/L as Cr)	Silver, dissolved (µg/L as Ag)
Cobalt, dissolved (µg/L as Co)	Strontium, dissolved (µg/L as Sr)
Copper, dissolved (µg/L as Cu)	Vanadium, dissolved (µg/L as V)
Iron, dissolved (µg/L as Fe)	Zinc, dissolved (µg/L as Zn)
Lead, dissolved (µg/L as Pb)	

number system that associates a well with an assigned unique number. The second system of numbering wells and test holes is based on the U.S. Bureau of Land Management's system of land subdivision (township, range, and section). Figure 5 illustrates the numbering system. The first numeral of a test hole or well number indicates the township, the second the range, and the third the section in which the well is located. Uppercase letters after the section number indicate the location of the well within the section; the first letter denotes the 160-acre tract, the second the 40-acre tract, the third the 10-acre tract, and the fourth the 2.5-acre tract. The letters A, B, C, and D are assigned in a counter clockwise direction, beginning in the northeast corner of each tract. The number of uppercase letters indicates the accuracy of the location number. Within a given 2.5-acre tract successive well numbers beginning with 1 are added as suffixes. For example, the number 150N46W22ADCC1 indicates the first test hole or well located in the SW1/4, SW1/4, SE1/4, NE1/4, Sec. 22, T150N, R46W.

Acknowledgments

The author is grateful to well owners, well drillers, and State and local agencies for data used in preparing this report. Thanks also go to land owners who permitted the drilling of test holes and the installation of observation wells, and to well owners who permitted sampling of their wells and measurement of water levels. Special thanks go to Greg Anderson, West Polk County Soil and Water Conservation District, for coordination of the project at the local level. Special thanks also go to Mike McDonald, Crookston Water Department, for providing geologic, water-level, and ground-water withdrawal data for the Crookston city well field.



EXPLANATION

- Sampled well with water sample analyzed for 2,4-D using immunoassay method

- Sampled well with water sample analyzed for 2,4-D using immunoassay method and for many pesticides at U.S. Geological Survey laboratory in Arvada, Colorado

Figure 4. Pesticide sampling locations (samples collected during June to October 1992).

Table 2.—Pesticides analyzed in water samples from wells used to establish effects of land use on ground-water quality

[All constituents in micrograms per liter]

Constituent	Reporting limit	Constituent	Reporting limit
Alachlor, dissolved	0.003	Methyl-parathion	0.005
Atrazine, dissolved	.002	Methylazinphos	.01
Benfluralin	.005	Metolachlor, dissolved	.002
Alpha BHC, dissolved	.01	Metribuzin, dissolved	.01
Butylate, dissolved	.002	Molinate	.005
Carbaryl	.008	Napropamide	.002
Carbofuran	.005	Parathion, dissolved	.005
Chlorpyrifos, dissolved	.002	Pebulate	.01
Cyanazine, dissolved	.01	Pendimethalin	.01
2,4-D, total	.01	Permethrin CIS	.01
DCPA	.002	Phorate	.02
P,P' DDE, dissolved	.002	Picloram, total	.01
Deethyl-atrazine, dissolved	.02	Prometon, dissolved	.005
Diazinon, dissolved	.005	Pronamide	.01
Dicamba, total	.01	Propanil	.005
Dieldrin, dissolved	.02	Propargite	.01
2,6-Diethyl-analine	.002	Propchlor, dissolved	.002
Dimethoate	.02	Silvex, total	.01
Disulfoton	.1	Simazine, dissolved	.005
2,4-DP, total	.01	2,4,5-T, total	.01
EPTC	.002	Tebuthiuron	.01
Ethalfluralin	.005	Terbacil	.01
Ethoprop	.005	Terbufos	.01
Fonofos, dissolved	.005	Thiobencarb	.008
Lindane, dissolved	.005	Triallate	.002
Linuron	.01	Trifluralin	.005
Malathion, dissolved	.01		

General Description of Bedrock

Precambrian crystalline rocks form the base of the geologic column in the study area. The crystalline rocks underlie Paleozoic and Cretaceous sediments and glacial deposits and are decomposed at the top of the formation to soft, gritty clays. These decomposition clays grade downward generally between 50 and 100 ft into hard rock. The upper part of Precambrian crystalline rocks is sufficiently weathered at some places to yield small amounts of water. Little is known about the composition of the solid crystalline rocks, but they apparently consist of granite and slate or schist (Bidwell and others, 1970). The surface of the crystalline rocks forms a large, broad, buried valley, with the axis trending northwest to southeast through central Marshall, Pennington, and Red Lake Counties and southeastern Polk County (Bidwell and others, 1970).

Paleozoic limestone and sandstone are present in the extreme western part of the study area near the Red River of the North. These sediments are probably discontinuous, generally less than 20 ft thick, and contain highly saline water (Bidwell and others, 1970).

Cretaceous bedrock underlies most of the study area. Cretaceous bedrock is not present in the southeastern part of the study area, including the moraine area, and near the eastern boundary. The Cretaceous strata are fairly continuous in the western

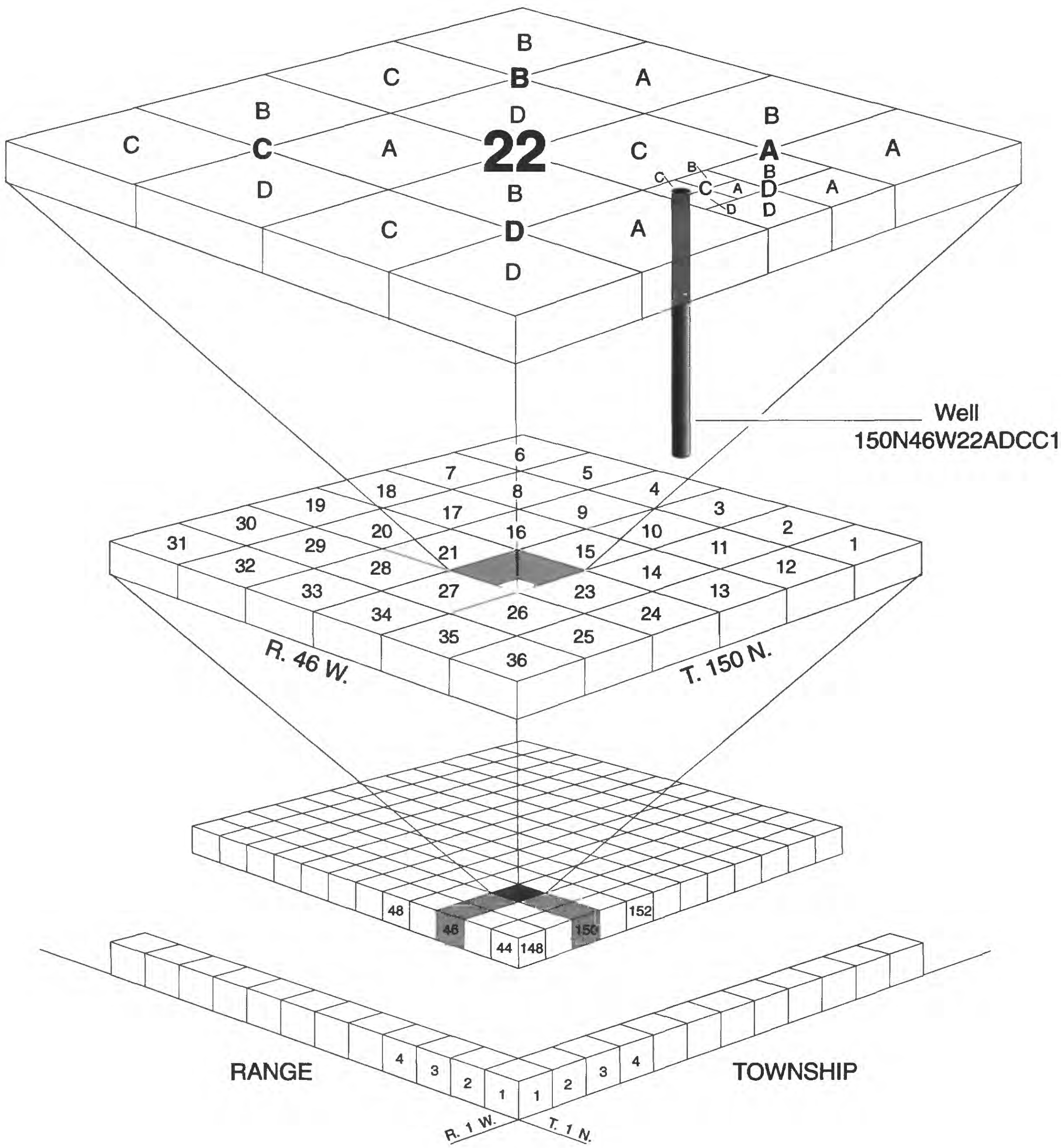


Figure 5. Test-hole and well-numbering system.

part of the study area, although some drill holes may not penetrate the strata even when most others in the vicinity do. The Cretaceous strata consist mainly of shale. However, where thin layers of fine to coarse sand are a part of these strata, wells yielding less than 50 gal/min can be developed. The thickness of the Cretaceous strata is extremely variable but is generally less than 50 ft. Water from the Cretaceous bedrock is generally highly mineralized with high concentrations of sodium and chloride, particularly in the western part of the study area.

General Description of Glacial Deposits

Glacial deposits cover the entire study area, ranging in thickness from about 100 to 350 ft. At least two major ice lobes of late Wisconsin age advanced over the study area--the Wadena lobe and the Des Moines lobe (including the St. Louis sublobe). The Wadena lobe progressed from the Winnipeg lowland in Canada southeastward into northwestern Minnesota (Wright, 1972). Later, the Des Moines lobe advanced from the northwest and progressed southward along the Red River lowland in northwestern Minnesota. The St. Louis sublobe spread east from the Red River lowland into the area previously occupied by the Wadena lobe. The Wadena lobe, Des Moines lobe, and St. Louis sublobe advanced and retreated separately as ice flowed through regional lowlands, generally corresponding to areas of less competent bedrock (Wright, 1972, and Wright and Ruhe, 1965). After the Des Moines lobe withdrew into the Red River lowland, water was ponded between the surrounding highlands and the ice front that blocked flow to the north, thus forming glacial Lake Agassiz. Lake Agassiz drained southward through a depression south of the study area, and later by an eastern outlet through northern Minnesota. Lake Agassiz covered all but the southeastern part of the study area. The only large remnants of Lake Agassiz left in the study area are Thief and Mud Lakes in Marshall County.

The two tills named in the study area are the Hewitt till derived from advances of the Wadena lobe and the New Ulm till derived from advances of the Des Moines lobe. Except in the extreme southeastern part of the study area, all of the till at the land surface is New Ulm till. In the extreme southeastern part of the study area, till at the land surface was deposited by the St. Louis sublobe. The New Ulm till is generally underlain by Hewitt till throughout the study area. Till deposited by the Wadena lobe is generally noncalcareous and lacks fragments of Cretaceous shale. Till deposited by the St. Louis sublobe of the Des Moines lobe is calcareous and contains fragments of Cretaceous shale (Wright, 1972). Mooers (1988) shows that the average composition of the Hewitt till is 60 percent sand, 28 percent silt, and 12 percent clay. The average composition of the New Ulm till is 46 percent sand, 33 percent silt, and 21 percent clay (Mooers, 1988). The New Ulm till may be highly fractured from weathering and ice unloading.

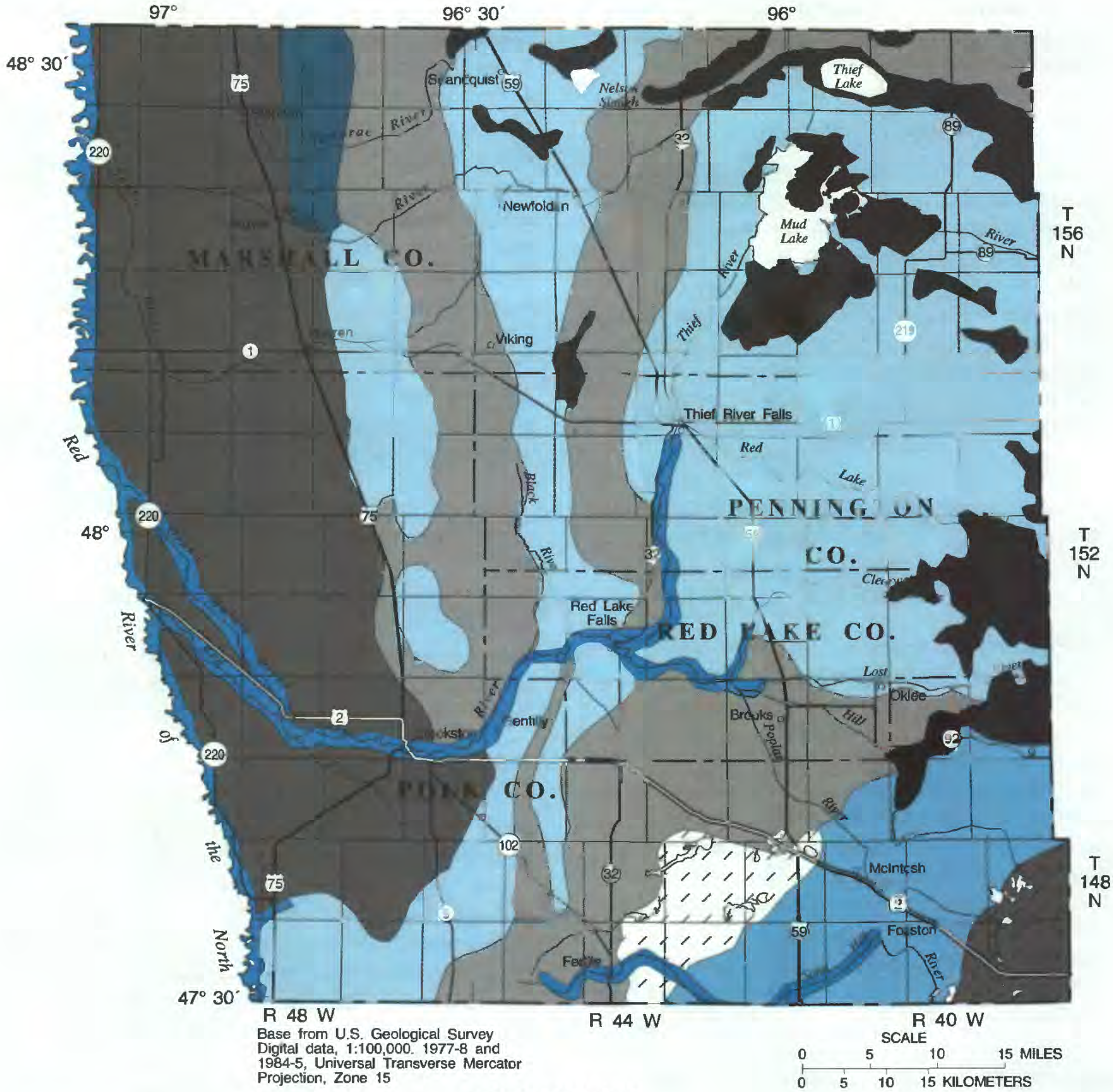
Hobbs and Goebel (1982) have mapped the surficial geology of the area using data from Minnesota soil atlases, interpretations of LANDSAT satellite imagery, and other published data. The surficial deposits consist primarily of peat, alluvium, lake-modified till, ground moraine, stagnation moraine, outwash, and glacial lake sediments (gravel, sand, silt, and clay). Figure 6 shows the distribution of the surficial deposits in the study area.

The glacial moraine physiographic area is bounded on the southeast and west by broad belts of hummocky hills deposited as stagnation moraines. These stagnation moraines have pronounced knob-and-kettle topography. Between these moraines, the area is a gently undulating till plain deposited as ground moraine.

All but the southeastern part of the study area was covered by the waters of Lake Agassiz and is characterized by the flat to very gently rolling topography of the glacial lake-washed till plain or the very flat topography of the glacial lake plain. Sediments deposited in glacial Lake Agassiz included ridges of sand and gravel washed up along the shore. Several sets of beach ridges were formed at successively lower elevations as the level of the lake declined. The beach ridges are generally about 5 to 20 ft high and are present predominantly in a north-to-south trending band through the center of the study area. The areal extent of beach deposits shown on figure 1 roughly coincides with the distribution of glacial lake sediment sand and gravel shown on figure 6.

Hydrogeologic Units Within the Glacial Deposits

Glacial deposits are divided into three hydrogeologic units for this study. These are (1) sand and gravel deposits exposed at land surface (unconfined aquifers), (2) fine-grained glacial till or lake deposits (confining units), and (3) buried sand and gravel deposits (confined aquifers). Confining units may be exposed at land surface, may separate unconfined aquifers and confined aquifers, or may separate confined aquifers at different depths. Previous regional studies indicate that the buried sand and gravel deposits that form confined aquifers beneath the study area are elongate in shape and trend in a general north-south direction. Such elongate aquifers have been mapped using detailed



EXPLANATION

- Peat (Holocene) - organic deposit in wetlands
- Alluvium (Holocene) - sand and gravel, silt, and clay deposited in channels and floodplains of modern streams

Deposits associated with the Des Moines Lobe (Pleistocene, late Wisconsinan) - gray calcareous drift (buff to brown where oxidized). Shale and limestone clasts generally common, derived from Manitoba and eastern North Dakota. Combined silt and clay typically exceeds 50 percent of till.

Erskine Moraine Assocation - limestone clasts common, but shale relatively uncommon. Generally clayey because of reworked lake sediment.

- Lake-Modified Till - wave-planed, mantled with thin and patchy lake sediments
- Ground Moraine
- Stagnation Moraine

Big Stone Moraine Assocation - contemporaneous with the St. Louis sublobe.

- Stagnation Moraine
- Outwash

Glacial lake sediment

- Sand and Gravel
- Silt and Fine Sand
- Clay and Clayey Silt

Figure 6. Distribution of surficial deposits in the study area. (modified from Hobbs and Goebel, 1982.)

drilling information in the northern part of the study area (Maclay and others, 1965) and to the south of the study area (Wolf, 1981).

Unconfined Aquifers

Unconfined aquifers in the study area generally are limited to scattered surficial sand and gravel beach deposits formed by Lake Agassiz (Bidwell and others, 1970). Maclay and Shiner (1962) speculated that many of the surficial beach deposits are reworkings of the deeper fluvial deposits. The unconfined aquifers could be significant areas of recharge for the underlying confined aquifers. Unconfined aquifers composed of coarse-grained beach deposits (Bidwell and others, 1970) are present in the central and southeastern parts of the study area.

Thick surficial sand deposits are present to the north and northeast of McIntosh in eastern Polk County. These deposits formed as glacial outwash and are of limited areal extent.

Test holes were drilled and observation wells were installed for this study to better define the extent, thickness, hydraulic characteristics, and water quality of unconfined aquifers in selected areas underlain by beach and glacial outwash deposits. Test drilling was areally distributed among the four counties and preference was given to the larger beach deposits based on topographic expression in the form of beach ridges. Test-drilling areas included (1) area A, northern and west-central Marshall County, (2) area B, southern Marshall and western Pennington Counties, (3) area C, southwestern Red Lake and central Polk Counties, and (4) area D, eastern Polk County (fig. 7). The boundaries and shapes of test-drilling areas A, B, C, and D shown on figure 7 were delineated to designate test-drilling areas for mapping purposes and only roughly coincide with the actual physical boundaries and shapes of aquifers or groups of aquifers. Saturated thicknesses of unconfined aquifers in western Marshall County (area A) ranged from 0 to 19 ft (fig. 8). Ten of the 28 test holes drilled (4 test holes completed as observation wells) had clay, silt, till, or dry sand at land surface; no unconfined aquifers were present at these locations.

Saturated thicknesses of unconfined aquifers in southern Marshall and western Pennington Counties (area B) ranged from 0 to at least 16 ft (fig. 9). Fifteen of the 56 test holes drilled (11 test holes completed as observation wells) had clay, silt, till, or dry sand at land surface. Fifteen of the 41 test-hole and observation-well locations with saturated surficial sand had a saturated thickness of 5 ft or less.

Saturated thicknesses of unconfined aquifers in southwestern Red Lake and central Polk Counties (area C) ranged from 0 to 30 ft (fig. 10). Eighteen of the 34 test holes drilled (8 test holes completed as observation wells) in the area underlain by the beach ridge traversing the Crookston city well field (Beach Ridge area on figure 10) had clay, silt, till, or dry sand at land surface. Seventeen of the test holes had dry sand at land surface. Test drilling was conducted in the relatively flat, low-lying Gentilly area (fig. 10), located west of the beach ridge traversing the Crookston city well field, to determine if surficial sand and gravel extends from the Beach Ridge area (fig. 10) to the Red Lake River. Eighteen of the 24 test holes drilled (3 test holes completed as observation wells) in the Gentilly area had clay, silt, or till at land surface.

Surficial sand deposits as much as 150 ft thick are present to the north and northeast of McIntosh in eastern Polk County (Bidwell and others, 1970). Saturated thicknesses for unconfined aquifers in glacial outwash at 3 observation wells in eastern Polk County (area D) ranged from 14 to more than 20 ft (fig. 11). Depths to the water table in the 3 observation wells ranged from 30 to 58 ft.

Estimates of horizontal hydraulic conductivity for the unconfined aquifers were derived from (1) slug tests, (2) single-well recover aquifer tests, (3) grain-size analyses of aquifer material, and (4) results of the ground-water-flow models for this study. Estimates of horizontal hydraulic conductivity derived from slug tests at 21 sites ranged from 2.5 to 79 ft/d. Twelve of the 21 estimated hydraulic conductivities for the unconfined aquifers were less than 10 ft/d. Estimated hydraulic conductivities for the unconfined aquifers were greater than 20 ft/d at two wells in Marshall County (test-drilling area A), at one well in Pennington County (test-drilling area B), and at 2 wells in Polk County (test-drilling area C). Estimates of horizontal hydraulic conductivity derived from single-well recovery aquifer tests at 8 sites ranged from 20 to 202 ft/d. Based on grain-size analyses of aquifer material from 3 cores (figs. 8 and 10), horizontal hydraulic conductivity ranges from 50 to 600 ft/d. The results of the numerical ground-water-flow models (discussed later in this report) indicated that hydraulic conductivities for unconfined aquifers in beach deposits range from 50 to 300 ft/d.

Estimates of transmissivity for unconfined aquifers derived from slug tests ranged from 33 to 693 ft^2/d (fig.12). Estimates of transmissivity derived from

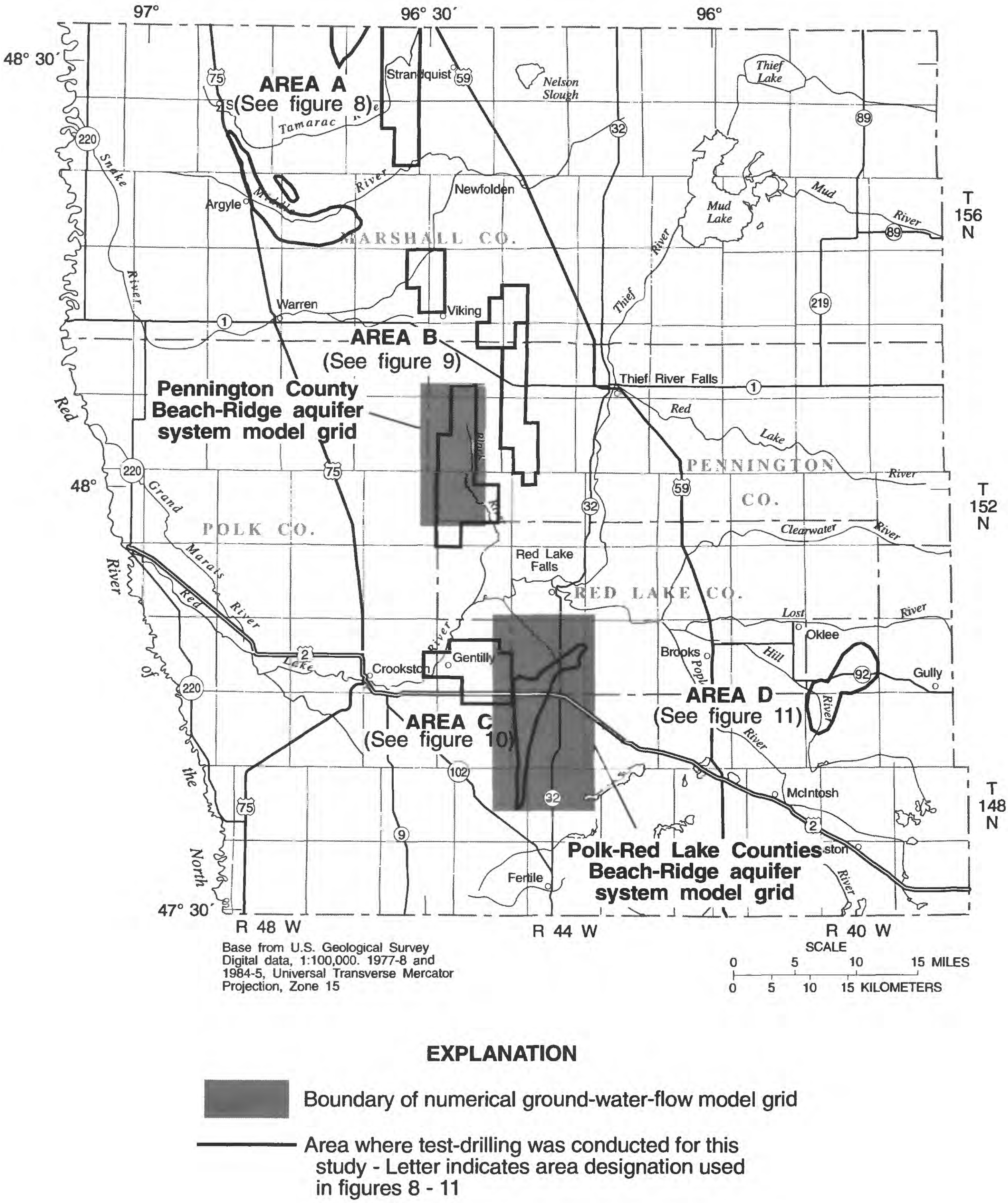
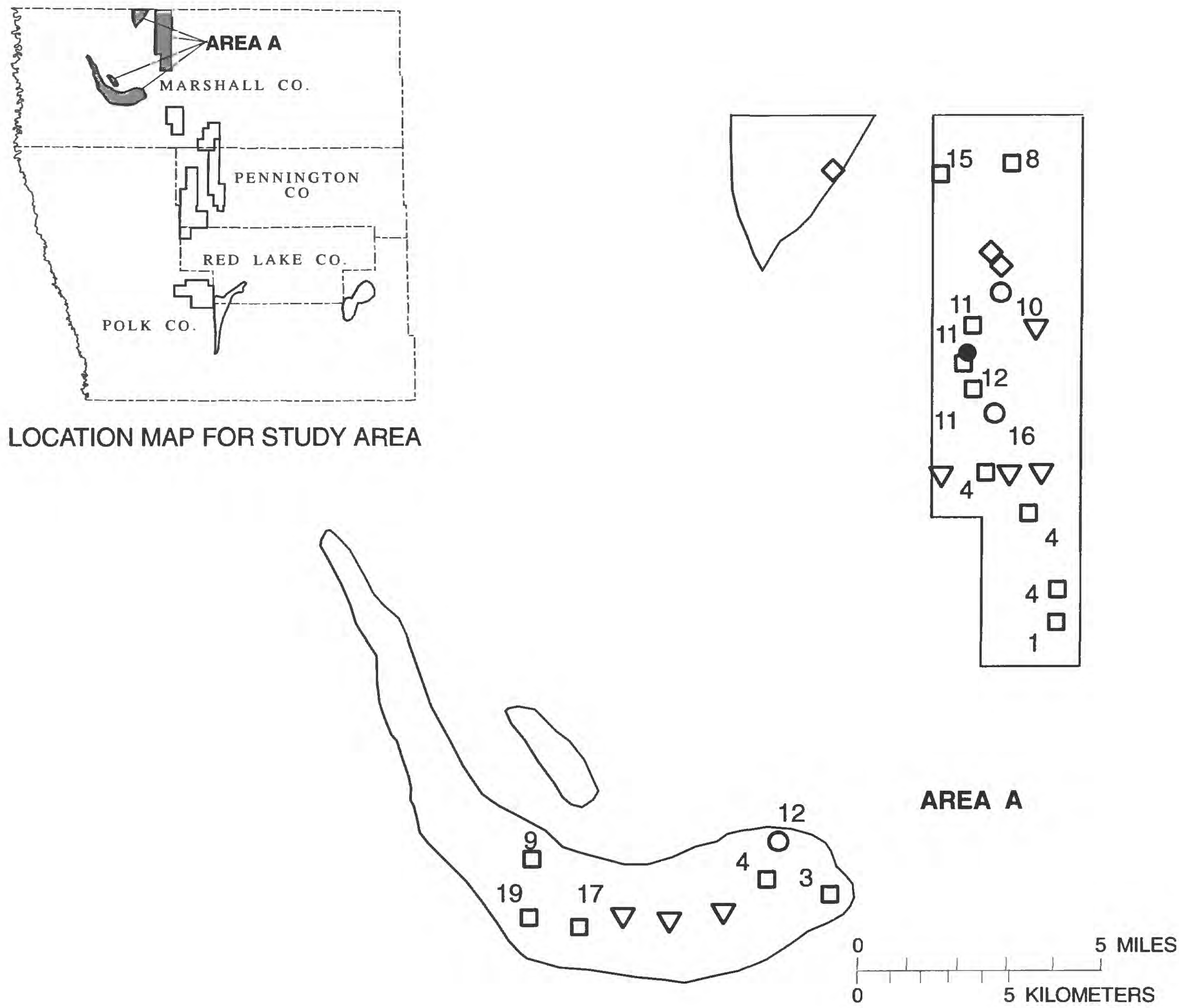


Figure 7. Locations of areas where test drilling was conducted for this study.



EXPLANATION

11 ● Observation well - Number indicates saturated thickness, in feet. Continous cores collected

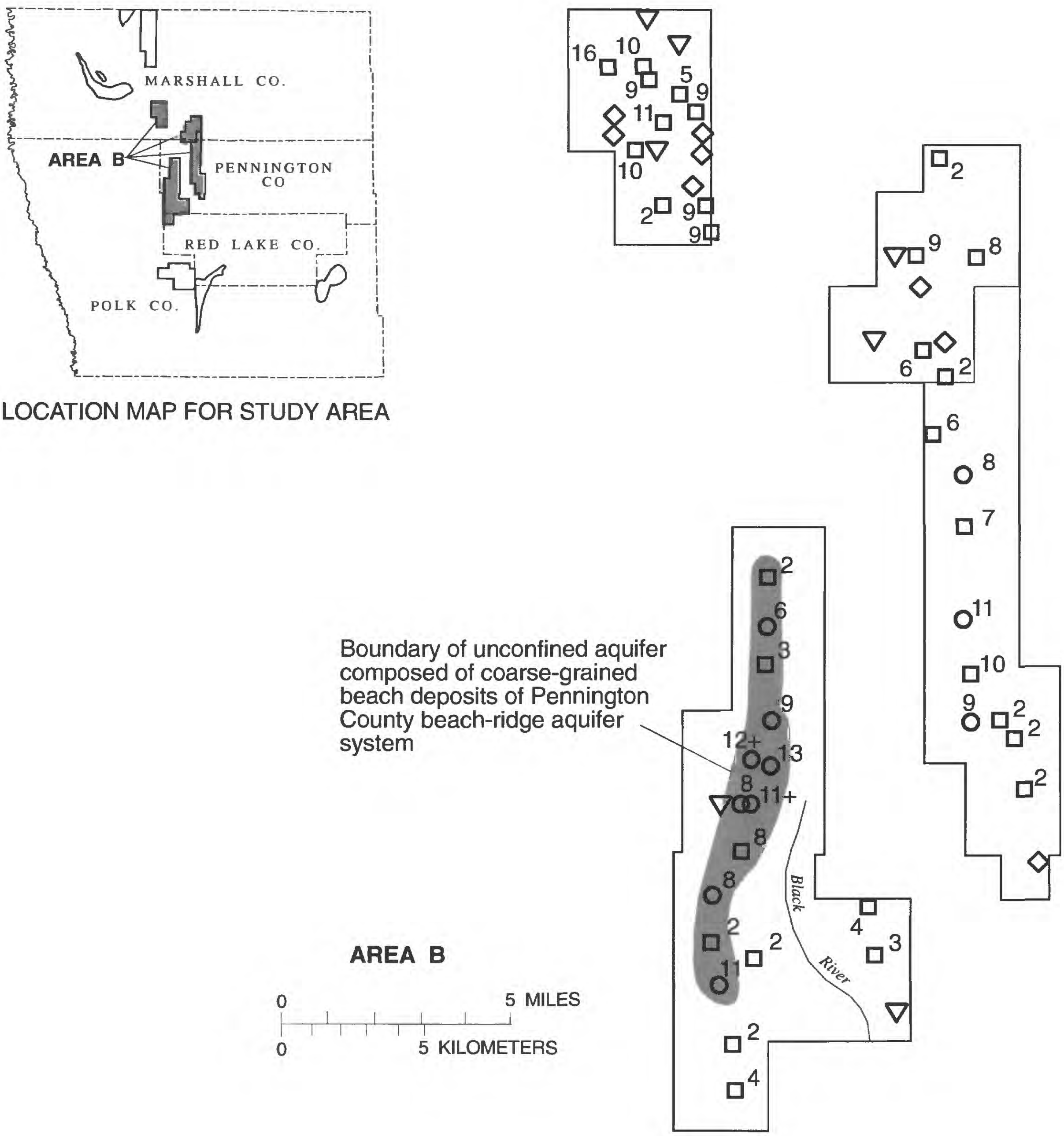
12 ○ Observation well - Number indicates saturated thickness, in feet

19 □ Test hole - Number indicates saturated thickness, in feet

▽ Test hole - Clay, silt, or till present at land surface

◇ Test hole - Dry sand at land surface underlaid by clay or till

Figure 8. Saturated thicknesses of unconfined aquifers in western Marshall County.



EXPLANATION

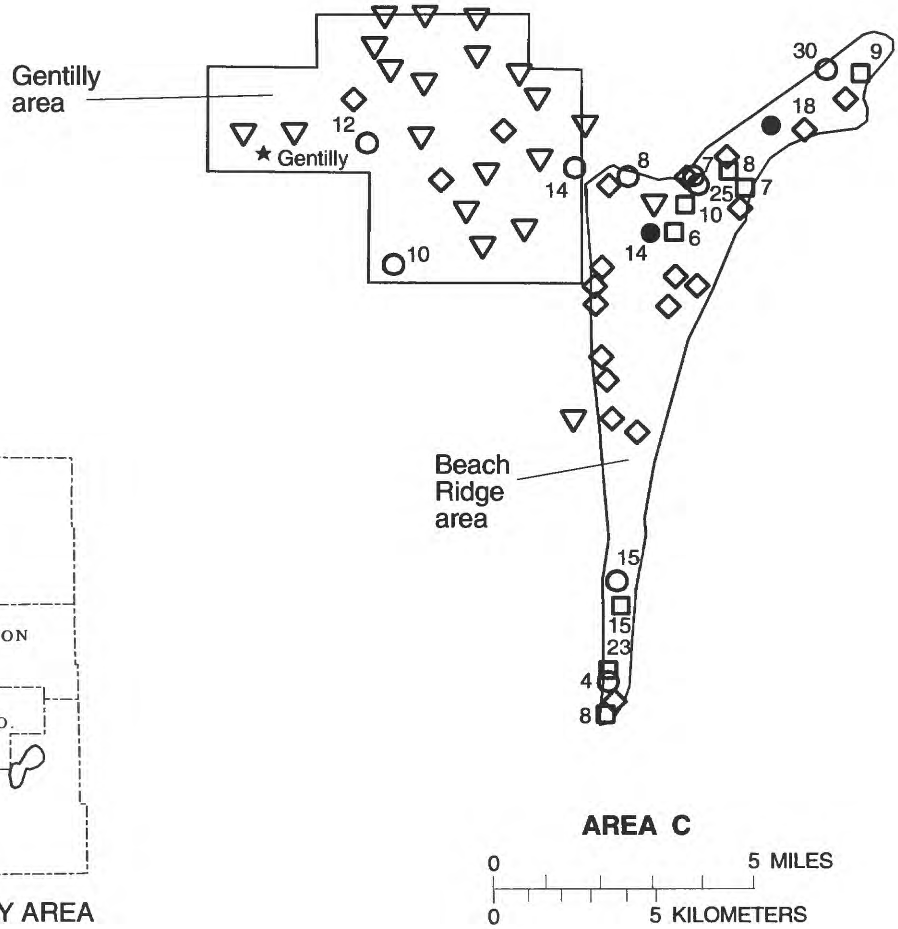
12+ ○ Observation well - Number indicates saturated thickness, in feet. (+) indicates that the hole did not penetrate to the bottom of the aquifer

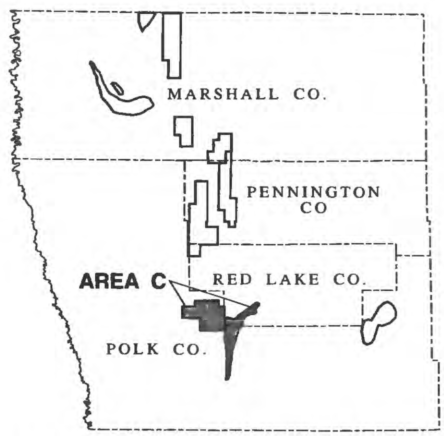
8 □ Test hole - Number indicates saturated thickness, in feet

▽ Test hole - Clay, silt, or till present at land surface

◇ Test hole - Dry sand at land surface underlaid by clay or till

Figure 9. Saturated thicknesses of unconfined aquifers in southern Marshall and western Pennington Counties.





LOCATION MAP FOR STUDY AREA

EXPLANATION

14 ● Observation well - Number indicates saturated thickness, in feet. Continous cores collected

10 ○ Observation well - Number indicates saturated thickness, in feet

7 □ Test hole - Number indicates saturated thickness, in feet

▽ Test hole - Clay, silt, or till present at land surface

◇ Test hole - Dry sand at land surface underlaid by clay or till

Figure 10. Saturated thicknesses of unconfined aquifers in southwestern Red Lake and central Polk Counties.

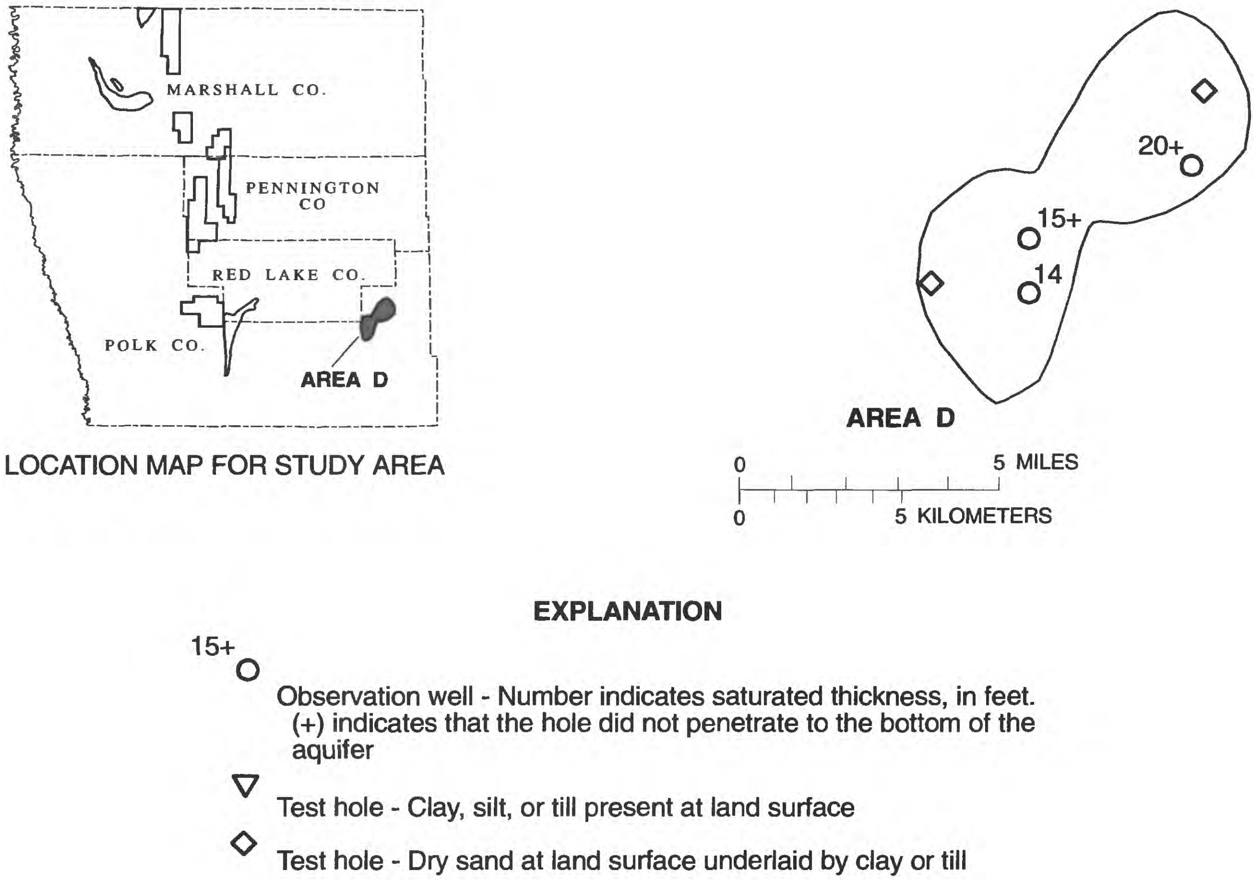
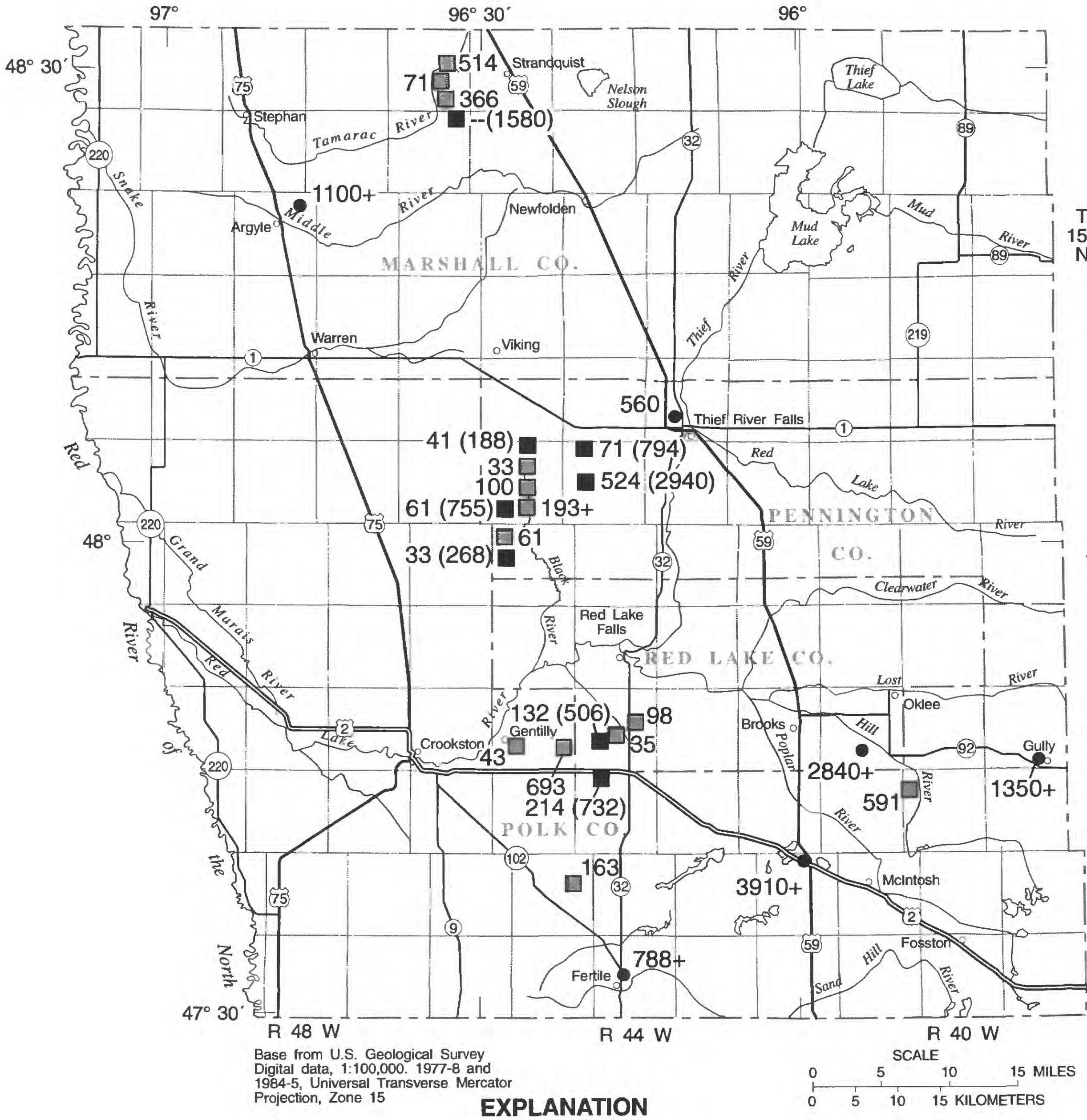


Figure 11. Saturated thicknesses of unconfined aquifers in eastern Polk County.

single-well recovery aquifer tests at 8 sites ranged from 188 to 2,940 ft^2/d (fig. 12). At well sites where both a slug test and an aquifer test were conducted, the estimated transmissivities derived from the aquifer tests were about 3 to 10 times greater than those derived from the slug tests. Slug-test results represent aquifer material in the immediate vicinity of a borehole, whereas aquifer tests represent aquifer material in a larger area surrounding the borehole. The consistently lower estimated transmissivity values from slug tests may indicate an envelope of fine-grained aquifer material in the immediate vicinity of the boreholes, due to well-construction and well-development methods. The estimated transmissivities derived from aquifer tests are considered to be more representative of the aquifer as a whole.

Values of specific capacity, available for many domestic wells for which aquifer-test data are not available, can be used to estimate transmissivity. Estimates of transmissivity for unconfined aquifers derived from specific-capacity data for 6 wells range from 560 to greater than 3,910 ft^2/d (fig. 12). Five of the well borings did not penetrate to the bottom of the aquifer. The largest transmissivities are for wells that are screened in unconfined aquifers in the southeastern part of the study area. The estimated transmissivities derived from specific-capacity data generally are greater than the transmissivities derived from slug tests and aquifer tests.

Reported well yields for unconfined aquifers composed of coarse-grained beach deposits generally are about 5 to 10 gal/min and are sufficient for rural domestic and livestock supplies. The saturated thickness of these aquifers limits the potential productivity of the aquifers as a source of ground water to wells. Theoretical maximum well yields for the 6



EXPLANATION

193+ ■ Slug-test site - Number is transmissivity of unconfined aquifer estimated from slug test, in feet squared per day. (+) indicates that the hole did not penetrate to the bottom of the aquifer

--(1580) ■ Slug-test and aquifer-test site - First number is transmissivity of unconfined aquifer estimated from slug test, in feet squared per day. -- indicates a slug test was not done. Number in parentheses is transmissivity of unconfined aquifer estimated from aquifer test

1100+ ● Domestic well - Number is transmissivity derived from specific capacity data, in feet squared per day. (+) indicates that the hole did not penetrate to the bottom of the aquifer.

Figure 12. Locations of slug-test and aquifer-test sites and estimated transmissivity for unconfined aquifers.

wells with specific-capacity data ranged from 12 to 123 gal/min. The maximum value of 123 gal/min was computed for a well screened in an unconfined aquifer in the southeastern part of the study area. The areas of greatest theoretical maximum yield coincide with areas of greatest transmissivity. Local variations in aquifer properties, recharge, proximity of the well to other pumping wells, effects of hydrologic boundaries, well diameter and efficiency, and duration of pumping will cause local deviations from theoretical maximum yields.

Confined Aquifers

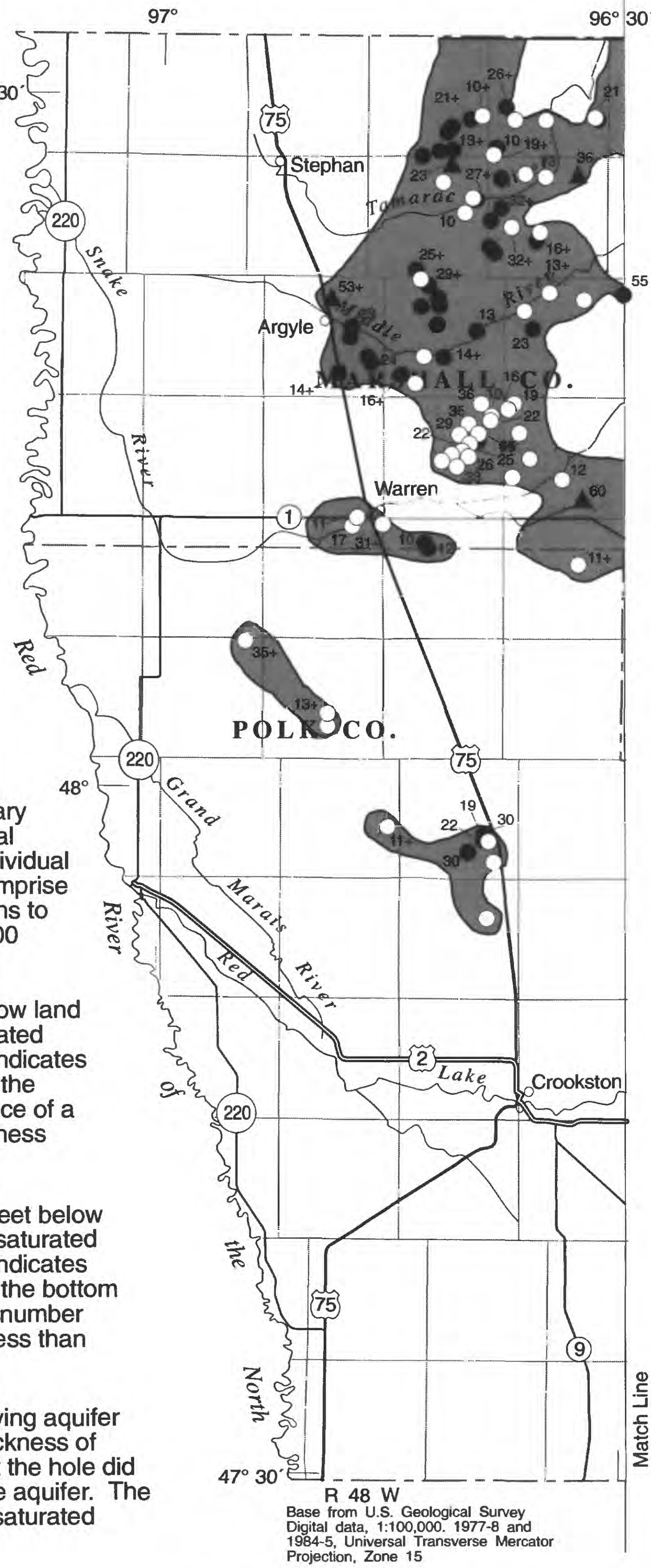
Confined aquifers in the study area were mapped using (1) existing test-hole and well-log information and (2) nine test holes drilled for this study that penetrated confining units in Pennington, Polk, and Red Lake Counties. The confined aquifers were grouped and mapped based on the depth from land surface to the top of the aquifer. All buried sand and gravel deposits supplying water to wells, based on available well-log information, with depths to the top of the deposits less than 100 ft were designated as shallow confined aquifers. Buried sand and gravel deposits penetrated by test holes that could be correlated to nearby water-supplying buried sand and gravel deposits and with depths to the top of the deposits less than 100 ft were also designated as shallow confined aquifers. The locations of all test holes and well logs penetrating a shallow confined aquifer were plotted on a map and the areal extent of shallow confined aquifers in the study area delineated. For the purposes of this report, the areal extent of the shallow confined aquifers represents the areal extent of a grouping of many aquifers, not a single aquifer. Similarly, all sand and gravel deposits with depths to the top of the deposit of 100 to 199 ft were designated as intermediate confined aquifers. All sand and gravel deposits with depths to the top of the deposit of 200 to 299 ft were designated as deep confined aquifers. All sand and gravel deposits with depths to the top of the deposit 300 ft or more were designated as basal confined aquifers. For mapping purposes and the display of thickness, transmissivity, and theoretical maximum well-yield values, each aquifer grouping was further subdivided into 50 ft intervals. The 50 ft intervals give additional detail in the vertical dimension for the presence or absence of aquifers and the variation in aquifer thickness, transmissivity, and theoretical maximum well yield. The uppermost confined aquifer at a given location may be a shallow, intermediate, deep, or basal confined aquifer.

Defining and designating the confined aquifers solely on the basis of the depth from land surface to the top of the aquifer is a conceptual simplification of a very complex sequence of aquifers and confining units both vertically and horizontally. The conceptual simplification was necessary because the available data are insufficient to define and designate individual aquifers based on the lithology, history of deposition, and degree of physical and hydraulic connection of the buried sand and gravel deposits. The discussions of shallow, intermediate, deep, and basal confined aquifers in this report represent grouping of individual sand and gravel deposits that comprise many separate aquifers within each group. Within a relatively small area, such as a township or a section, the sand and gravel deposits within a particular aquifer grouping, such as the shallow confined aquifers, may or may not comprise a single aquifer, depending on the degree of physical and hydraulic connection between the deposits.

The method used to define and designate the confined aquifers could potentially result in a single aquifer being included in two different aquifer groupings. For example, if a well boring penetrated a sand and gravel deposit (aquifer) with a depth to the top of the deposit of 95 ft at one location and a second well boring penetrated the same sand and gravel deposit with a depth to the top of the deposit of 105 ft at a different location, the same aquifer would be included in both the shallow and intermediate confined aquifers groupings. This type of duplication could result from a slope in the altitude of the top of the aquifer or of the land surface. The available data are insufficient to avoid this type of potential duplication.

Shallow confined aquifers

Shallow confined aquifers generally are present in much of the eastern two-thirds of the study area (fig. 13). The saturated thickness of the aquifers ranges from 0 to 150 ft (fig. 13). The thickness values shown on figure 13 represent the thickness of one aquifer only, not multiple aquifers. At locations having a thickness value in the upper 50 ft depth interval, one or more aquifers may exist below in the second 50 ft depth interval. The presence or absence of underlying aquifers at these locations is generally not known with certainty because the well borings often do not penetrate deeper than the upper 50 ft depth interval. The presence or absence of underlying aquifers, however, may be inferred from nearby deeper test holes and well borings. At locations having a thickness value in the second 50 ft depth interval only, no sand and gravel deposits (aquifers) were penetrated at those locations in the first 50 ft depth interval. At a given location, available test holes and well borings penetrated no more than one water-supplying aquifer within each 100 ft depth interval.



EXPLANATION

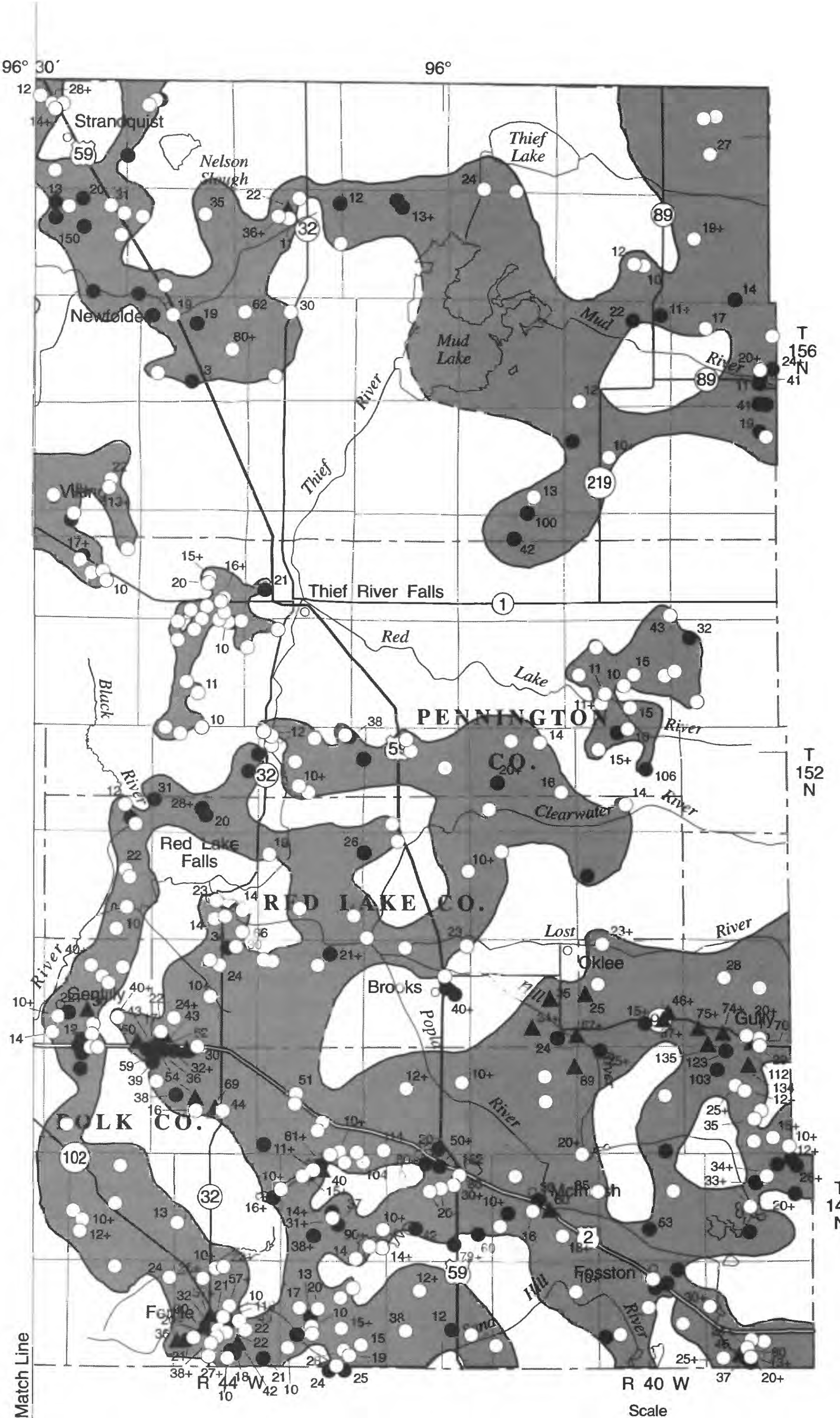
Shallow confined aquifers - Boundary dashed where approximate. Areal extent represents grouping of individual sand and gravel deposits that comprise many different aquifers with depths to the top of the aquifer less than 100 feet below land surface

●13+ Top of aquifer less than 50 feet below land surface - Number indicates saturated thickness of aquifer, in feet. (+) indicates that the hole did not penetrate to the bottom of the aquifer. The absence of a number indicates saturated thickness less than 10 feet

○32+ Top of aquifer 50 to less than 100 feet below land surface - Number indicates saturated thickness of aquifer, in feet. (+) indicates that the hole did not penetrate to the bottom of the aquifer. The absence of a number indicates saturated thickness is less than 10 feet

▲74+ No confining unit (clay or till) overlying aquifer - Number indicates saturated thickness of aquifer, in feet. (+) indicates that the hole did not penetrate to the bottom of the aquifer. The absence of a number indicates saturated thickness is less than 10 feet

Figure 13. Areal extent and saturated



thickness of shallow confined aquifers.

Saturated thicknesses greater than 100 ft are present in the southeastern part of the study area and at one test hole in north-central Marshall County. Shallow confined aquifers extend to the land surface at isolated locations. These aquifers may be unconfined locally.

Estimates of transmissivity for shallow confined aquifers, derived from specific-capacity data for 98 wells, ranged from 12 to more than 46,000 ft^2/d. Fifty-nine percent of the estimated values were less than 1,000 ft^2/d. Eight percent of the estimated values were greater than 5,000 ft^2/d. Transmissivity for shallow confined aquifers is shown in figure 14.

Theoretical maximum well yields for the 98 wells with specific-capacity data (fig. 15) ranged from 3 to 538 gal/min. As indicated on figure 15, seven of the well logs with specific-capacity data reported no measurable drawdown in the pumping wells during development. The lack of measurable drawdown in the wells may indicate that the wells are screened in the most transmissive portions of the aquifers. The specific-capacity data for these wells, however, do not permit the calculation of theoretical maximum well yields. Therefore, theoretical maximum well yields at some locations are potentially much larger than 538 gal/min. Wells with theoretical maximum well yields greater than 300 gal/min are present (1) northeast of Warren and near Newfolden in Marshall County, (2) near the Clearwater River in the central part of Red Lake County and in the southwestern corner of T150N, R44W, and (3) south of Gentilly and west of McIntosh in Polk County (fig. 15). Figures 14 and 15 indicate that both transmissivity and theoretical maximum well yield commonly varies greatly within short distances.

Intermediate confined aquifers

The intermediate confined aquifers are not present in about 40 percent of the western one-third of the study area (fig. 16). The available data are sparse in the west-central and northwestern parts of the study area, however. Where the aquifers are present, thicknesses range from less than 10 to more than 125 ft (fig. 16). Thicknesses greater than 100 ft are present in southwestern Polk and eastern Pennington Counties.

Estimates of transmissivity for an intermediate confined aquifer in southwestern Red Lake and central Polk Counties (a component of the Polk-Red Lake Counties beach-ridge aquifer system that includes unconfined aquifers, underlying uppermost confined aquifers, and confining units and is discussed later in the text) are shown in figure 17. The estimates of transmissivity derived from slug tests range from 155 to 936 ft^2/d.

Estimates of transmissivity for the intermediate confined aquifers, derived from specific-capacity data for 204 wells, ranged from 2 to more than 190,000 ft^2/d. Fifty-nine percent of the estimated values were less than 1,000 ft^2/d. Five percent of the estimated values were greater than 5,000 ft^2/d. Transmissivity derived from specific-capacity data for intermediate confined aquifers is shown in figure 18.

Theoretical maximum well yields for the 204 wells with specific-capacity data ranged from 4 to greater than 16,300 gal/min. Eight of the well logs with specific-capacity data reported no measurable drawdown in the pumping wells during development. These wells may be screened in the most transmissive portions of the aquifers, with theoretical maximum well yields potentially much larger than those calculated for wells with measurable drawdowns during development. Wells with theoretical maximum well yields greater than 300 gal/min are present in (1) south-central and east-central Marshall County, (2) most of Pennington County, excluding range 39W, (3) east of Red Lake Falls and the northeast corner of Red Lake County, and (4) T149N R48W,T149N R44W, T149N R42W, and T151N R39W, in Polk County (fig. 19). Estimated theoretical maximum well yields greater than about 2,000 gal/min are probably unrealistically large. Unrealistically large values for theoretical maximum well yields could result from inaccuracies in reported drawdowns and pumping rates used for calculating specific capacity. Also, inaccuracies in reported static water levels and aquifer thickness could result in available drawdown being overestimated. Figures 18 and 19 indicate that both transmissivity and theoretical maximum well yield commonly vary greatly within short distances.

Deep confined aquifers

Available test-hole and well-log information indicates that deep confined aquifers are generally not present in the northwest, north-central, and central parts of the study area (fig. 20). Where the aquifers are present, thicknesses range from less than 10 to more than 126 ft (fig. 20). The greatest thicknesses are present in eastern Pennington County.

Estimates of transmissivity for the deep confined aquifers, derived from specific-capacity data for 128 wells, ranged from 3 to greater than 210,000 ft^2/d. Seventy-six percent of the estimated values were less than 1,000 ft^2/d. Seven percent of the estimated values were greater than 5,000 ft^2/d. Transmissivity for deep confined aquifers is shown in figure 21.

Theoretical maximum well yields for the 128 wells with specific-capacity data ranged from 4 to 71,460 gal/min. Three of the well logs with specific-capacity data reported no measurable drawdown in the pumping wells during development. Wells with theoretical maximum well yields greater than 300 gal/min are present in (1) south-central Marshall County, (2) east and southeast of Thief River Falls and T153N R40W in Pennington County, (3) range 42W and the west-central part of Red Lake County, and (4) most of Polk County where data are available (fig. 22). Estimated theoretical maximum well yields greater than about 2,000 gal/min are probably unrealistically large, possibly due to inaccuracies in reported drawdowns, pumping rates, static water levels, or aquifer thickness. Figures 21 and 22 indicate that both transmissivity and theoretical maximum well yield commonly varies greatly within short distances.

Basal confined aquifers

Basal confined aquifers are most utilized as a source of water in central Marshall and western Pennington Counties. In these areas, shallower overlying aquifers are often absent and the basal confined aquifers are the first aquifers encountered in the geologic column. The areal extent of the basal confined aquifers may be greater than shown in figure 23, but for most of the study area, few test holes or well borings penetrate to depths of 300 ft or more below land surface. The basal confined aquifers are absent in an area where the bedrock surface is high in northwestern Marshall County and in west-central Pennington County (fig. 23). The thickness of the aquifers ranges from 0 to more than 70 ft (fig. 23).

Estimates of transmissivity for the basal confined aquifers, derived from specific-capacity data for 34 wells, ranged from 6 to 48,900 ft^2/d. Seventy-four percent of the estimated values were less than 1,000 ft^2/d. Six percent of the estimated values were greater than 5,000 ft^2/d. Transmissivity for basal confined aquifers is shown in figure 24.

Theoretical maximum well yields for the 34 wells with specific-capacity data ranged from 6 to 10,700 gal/min. One of the well logs with specific-capacity data reported no measurable drawdown in the pumping well during development. Wells with theoretical maximum well yields greater than 300 gal/min are present in (1) north-central and south-central Marshall County, (2) western Pennington County, and (3) western and southeastern Polk County (fig. 25). Estimated theoretical maximum well yields greater than about 2,000 gal/min are probably unrealistically large, possibly due to inaccuracies in reported drawdowns, pumping rates, static water levels, or aquifer thickness.

Confining Units

Confining units physically and hydraulically separate successive aquifers in the geologic column. In areas where unconfined aquifers are absent, confining units are present at land surface. In this case, the confining unit prevents or impedes the downward leakage of precipitation to uppermost confined aquifers. In general, individual confining units cannot be mapped due to the limited areal extent and discontinuities of the confined aquifers, which are present as lenses within the matrix of the confining units. The rate of vertical flow of water through a confining unit depends on (1) the thickness and vertical hydraulic conductivity of the confining unit, and (2) differences in hydraulic head of the aquifers above and below the confining unit. In the case where a confining unit is present at land surface, the controlling difference in hydraulic heads is the difference between the hydraulic head of the water table in the confining unit and the hydraulic head of the uppermost confined aquifer. Although significant volumes of water flow through confining units to confined aquifers on a regional scale, confining units serve as an effective barrier to the rapid movement of water to uppermost confined aquifers or between aquifers.

The thickness and hydraulic properties of confining units vary from point to point. The degree to which confining units impede flow between aquifer units or between land surface and uppermost confined aquifers is a function of these properties. The thickness of uppermost confining units ranges from 0 to greater than 300 ft in the study area (fig. 26). Confining units in figure 26 represent a composite of the shallowest deposits of till or lake clay at a given location and do not represent a single hydraulically homogenous confining unit. The confining units include all non-aquifer material, undifferentiated as to origin or lithology, that stratigraphically overlies uppermost confined aquifers. The thickness of uppermost confining units is generally greatest in the western one-third of the study area and least in the southeastern part.

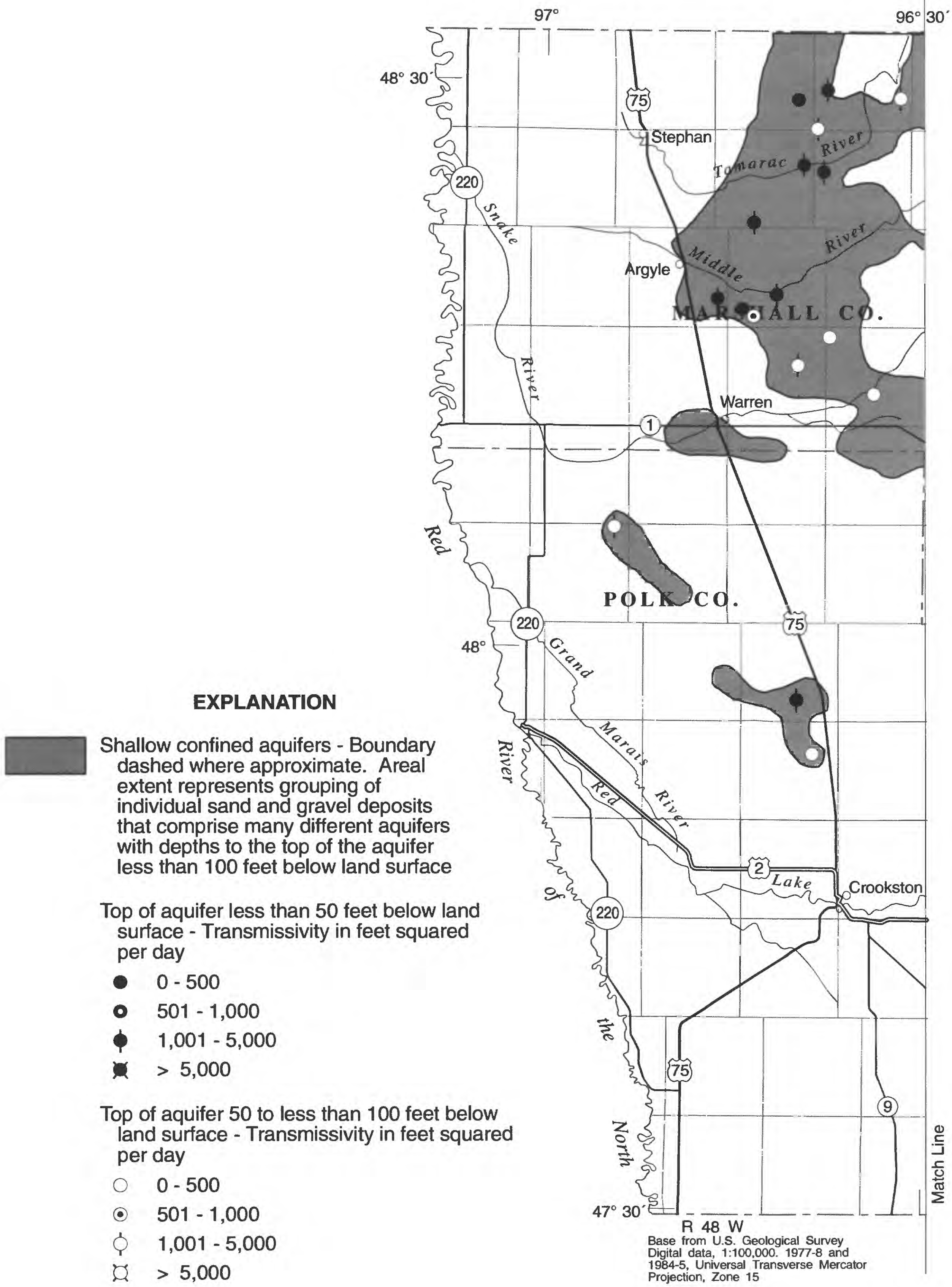
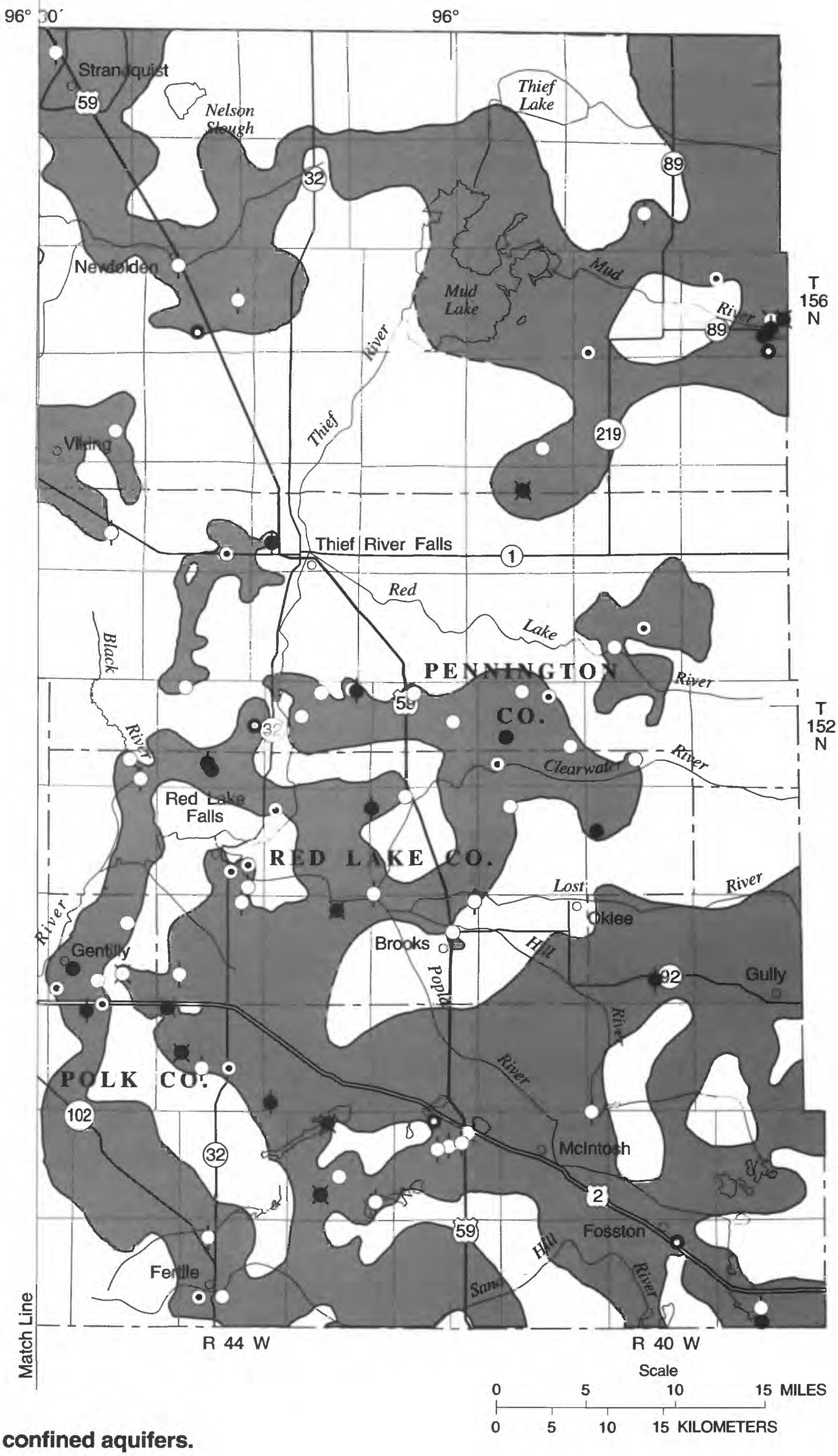
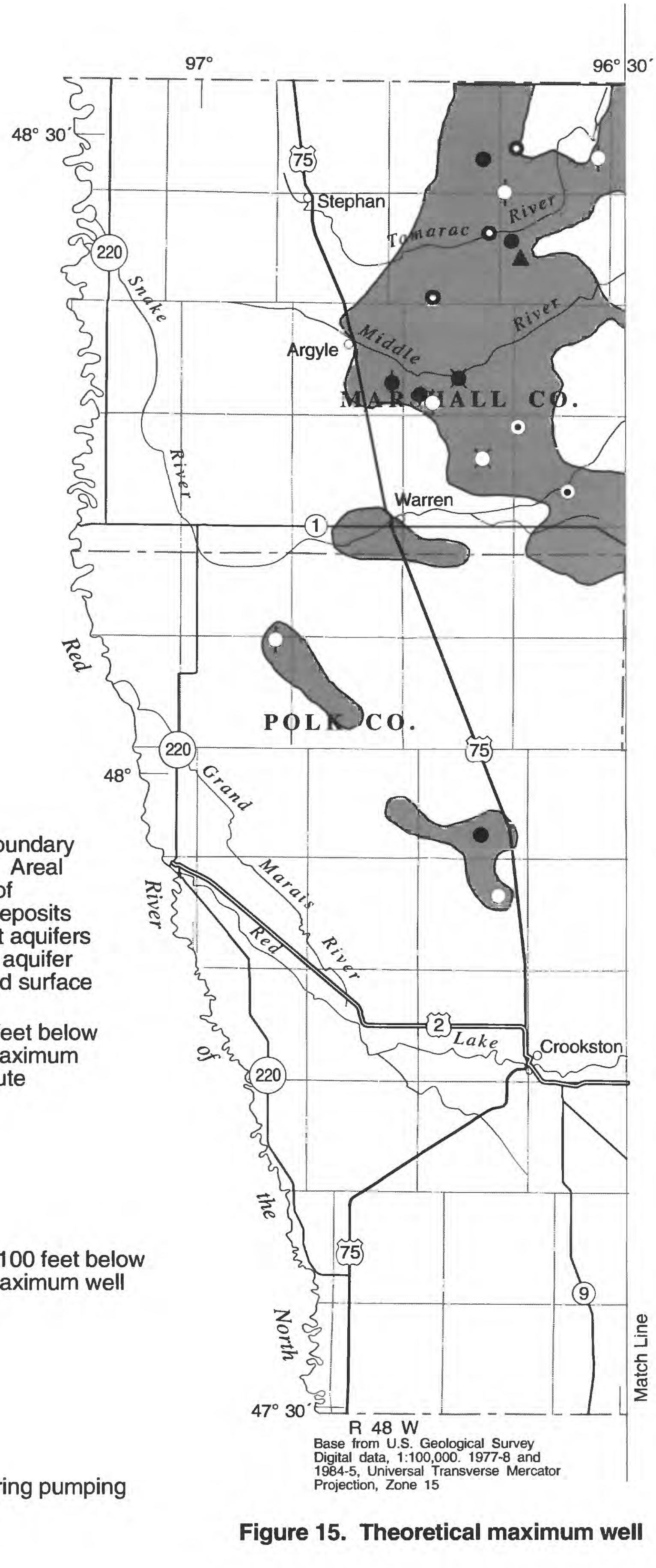


Figure 14. Transmissivity for



shallow confined aquifers.



EXPLANATION

Shallow confined aquifers - Boundary dashed where approximate. Areal extent represents grouping of individual sand and gravel deposits that comprise many different aquifers with depths to the top of the aquifer less than 100 feet below land surface

Top of aquifer is less than 50 feet below land surface - Theoretical maximum well yield in gallons per minute

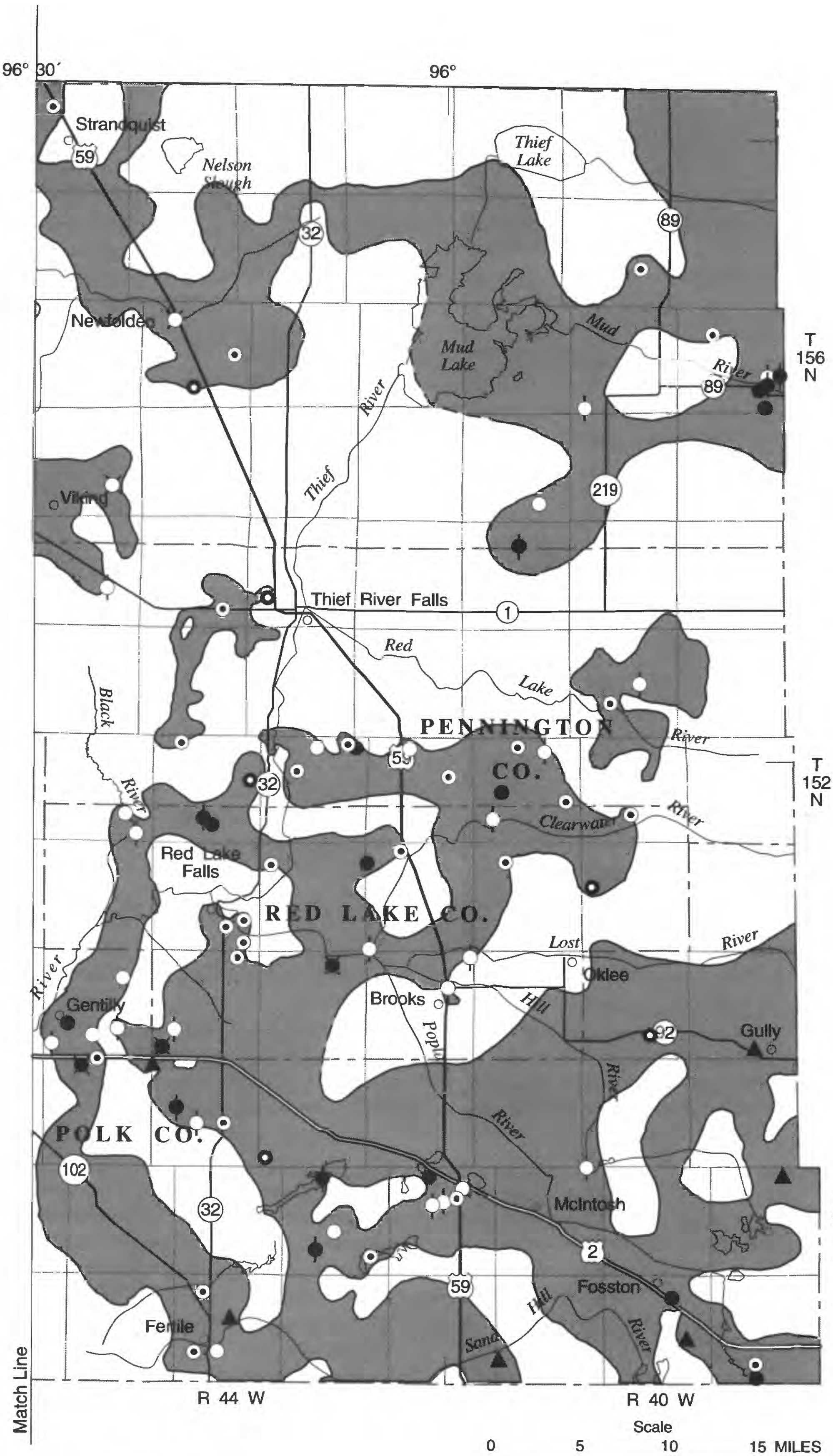
- ● 0 - 25
- 26 - 100
- 101 - 300
- > 300

Top of aquifer 50 to less than 100 feet below land surface - Theoretical maximum well yield in gallons per minute

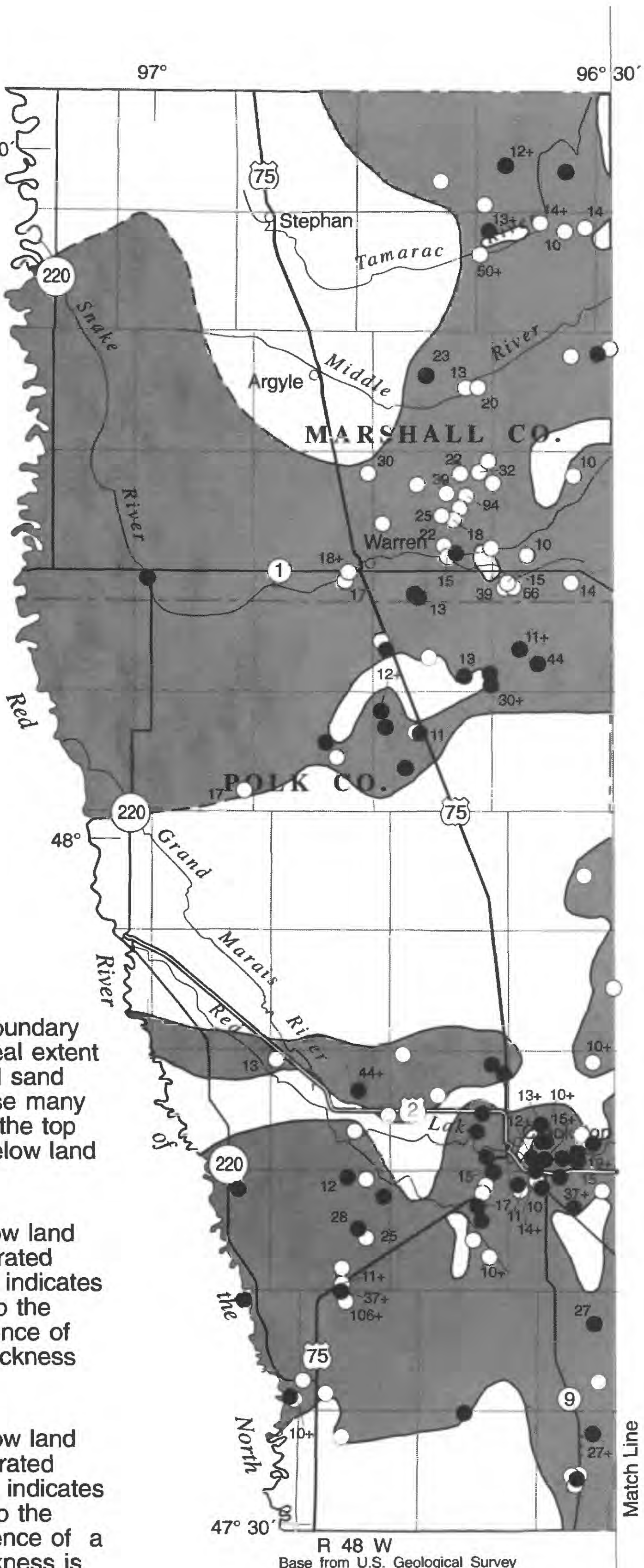
- ○ 0 - 25
- 26 - 100
- 101 - 300
- > 300

▲ No measurable drawdown during pumping

Figure 15. Theoretical maximum well



yield for shallow confined aquifers.



EXPLANATION

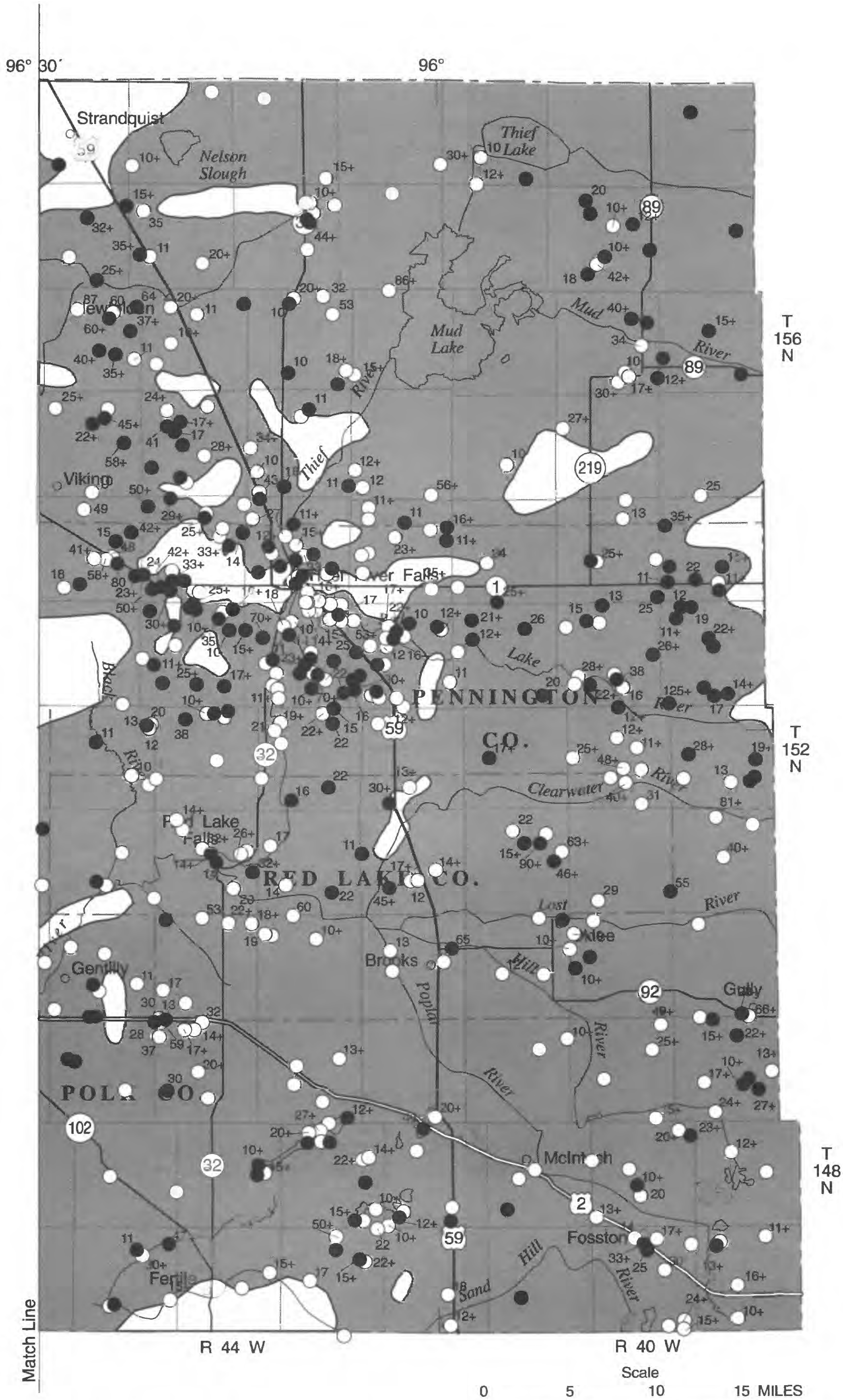
Intermediate confined aquifers - Boundary dashed where approximate. Areal extent represents grouping of individual sand and gravel deposits that comprise many different aquifers with depths to the top of the aquifer 100 to 199 feet below land surface

○ 18+ Top of aquifer 100 to 149 feet below land surface - Number indicates saturated thickness of aquifer, in feet. (+) indicates that the hole did not penetrate to the bottom of the aquifer. The absence of a number indicates saturated thickness less than 10 feet

● 12+ Top of aquifer 150 to 199 feet below land surface - Number indicates saturated thickness of aquifer, in feet. (+) indicates that the hole did not penetrate to the bottom of the aquifer. The absence of a number indicates saturated thickness is less than 10 feet

Base from U.S. Geological Survey Digital data, 1:100,000. 1977-8 and 1984-5, Universal Transverse Mercator Projection, Zone 15

Figure 16. Areal extent and thickness



of intermediate confined aquifers.

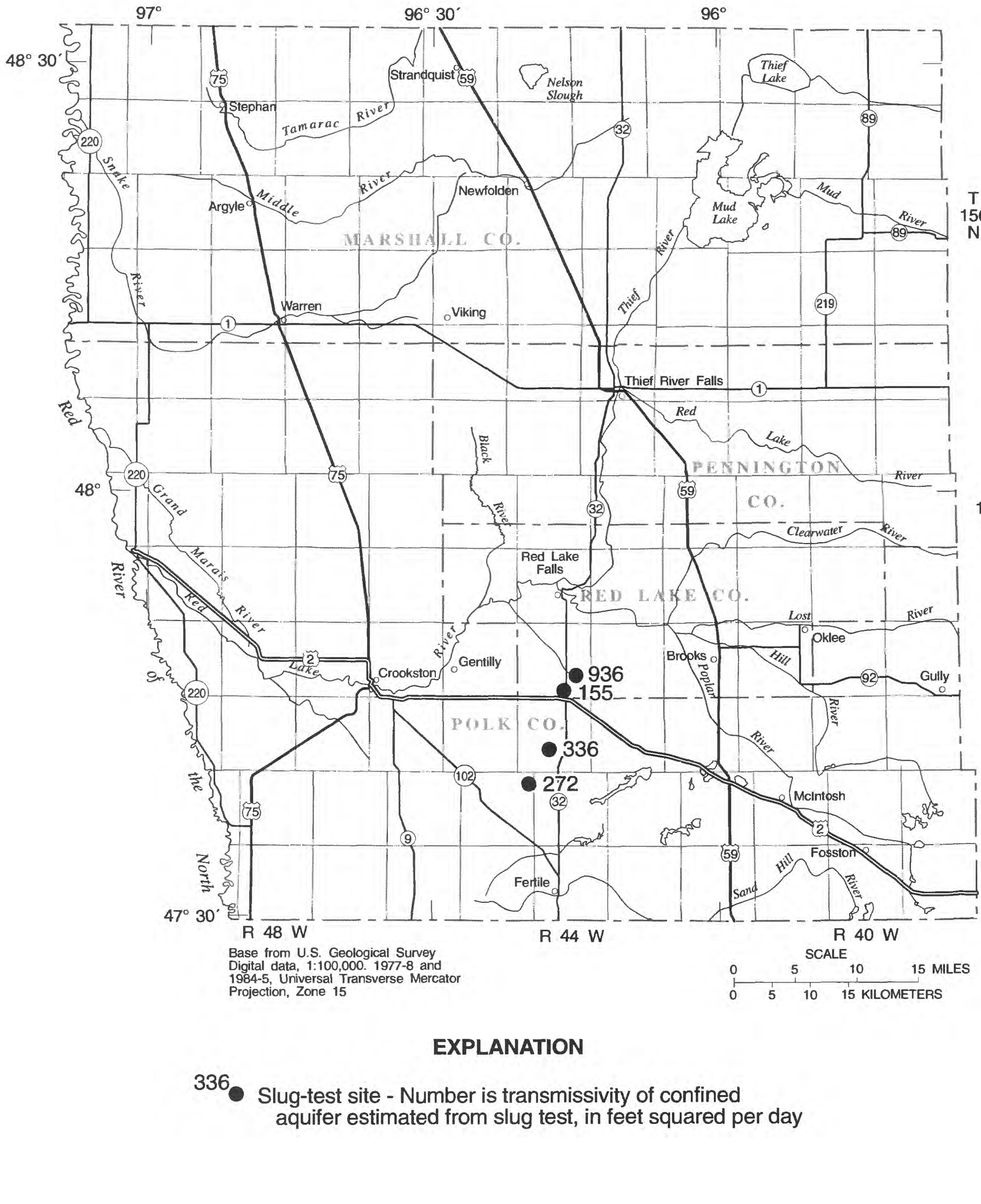


Figure 17. Locations of slug-test sites and estimated transmissivity for an intermediate confined aquifer.

No field tests were conducted for this study to determine the hydraulic properties of confining units. Based on previous studies and the modeling results for this study, however, the horizontal hydraulic conductivity of tills and lake clays in the study area is probably in a range from 0.1 to 2.0 ft/d. Model analyses of beach-ridge aquifer systems for this study (discussed later in this report) indicated that values from 0.5 to 2.0 ft/d are reasonable values of horizontal hydraulic conductivity for the uppermost confining units in the model areas, with a value of 1.0 ft/d producing the best matches between model-simulated and measured water levels. A value of 1 ft/d for the horizontal hydraulic conductivity of alluvial clay in the Arkansas River Valley in Colorado was given by Lohman (1972, p. 53). A value of 1 ft/d is also at the upper limit for horizontal hydraulic conductivity values for till (location not specified) given by Heath (1983, p. 13). Stark and others (1991) reported that ground-water-flow model analysis indicated that values from 0.1 to 1.0 ft/d are reasonable values of horizontal hydraulic conductivity for the uppermost confining unit in the Bemidji-Bagley, Minn. area. The uppermost confining unit in the Bemidji-Bagley area generally consists of Hewitt till. Hewitt till is sandier than the New Ulm till that generally comprises the uppermost confining units in the study area.

The vertical hydraulic conductivity of till and glacial-lake deposits (confining units) generally is much lower than the horizontal hydraulic conductivity. On the basis of analysis of 12 aquifer tests, Delin (1986) estimated the mean vertical hydraulic conductivity of till in the area of Morris, Minnesota, to be 0.025 ft/d. This compares favorably with the value of 0.018 ft/d for the vertical hydraulic conductivity of till in the Detroit Lakes area in Minnesota (Miller, 1982). Permeameter tests conducted by Prudic (1982) indicate that the vertical hydraulic conductivity of till in New York ranges from 0.000031 to 0.00043 ft/d. These values, from laboratory tests, are about 2 to 3 orders of magnitude lower than the cited values for Minnesota till, which are based on aquifer tests. Fetter (1988), however, reports that differences between field and laboratory measurements of hydraulic conductivity in till can differ more than 3 orders of magnitude due to till fractures and macrostructures (layers of better-sorted sediments). The values for vertical hydraulic conductivity of uppermost confining units determined by model analyses done for this study (discussed later in this report) that produced the best matches between model-simulated and measured water levels ranged from 0.001 to 0.02 ft/d.

In the study area, relatively fine-grained New Ulm till overlies relatively coarse-grained Hewitt till. Surficial tills are often weathered rather deeply (10-20 ft), producing fractures and macropores. The vertical hydraulic conductivity of till is largely controlled by texture, the degree of weathering and fracturing, and the presence of sand or silt seams. The combination of fractured, fine-grained New Ulm till underlain by coarse-grained Hewitt till could result in relatively high vertical hydraulic conductivity for till in the study area.

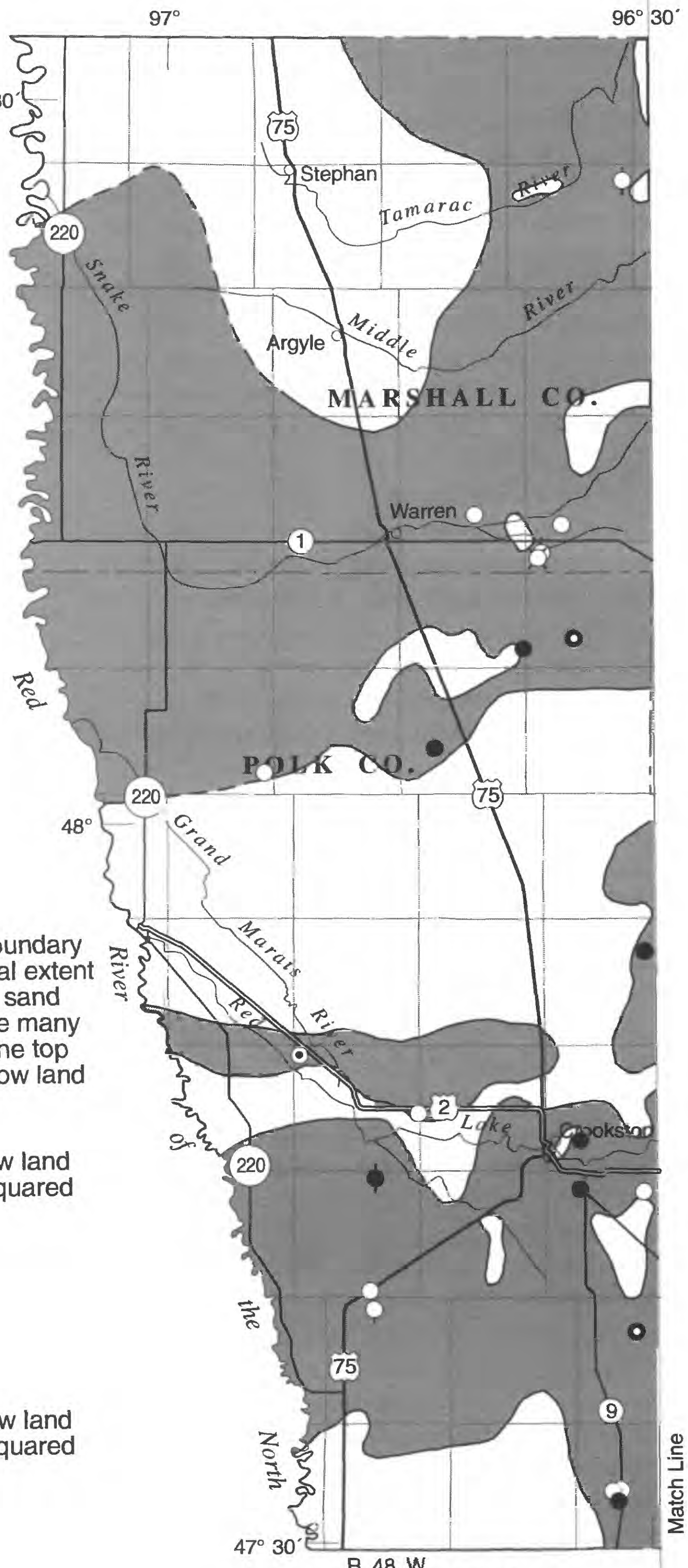
Beach-Ridge Aquifer Systems

One of the primary objectives of this study and report is to estimate the potential yield from unconfined and uppermost confined aquifers in the study area. Two beach-ridge aquifer systems associated with topographically defined beach ridges were investigated in detail, including numerical ground-water-flow modeling analyses. The two aquifer systems are hereinafter termed the Polk-Red Lake Counties beach-ridge aquifer system and the Pennington County beach-ridge aquifer system.

Polk-Red Lake Counties Beach-Ridge Aquifer System

The Polk-Red Lake Counties beach-ridge aquifer system (fig. 7) underlies a beach ridge that is about 14 mi in length and generally less than 0.5 mi in width located in central Polk County and southwestern Red Lake County (fig. 27). The areal extent of this beach ridge was previously mapped by Bidwell and others (1970). The Polk-Red Lake Counties beach-ridge aquifer system consists of an unconfined aquifer, a partially confined aquifer, an uppermost confined aquifer, and overlying and interbedded uppermost confining units (figs. 27 and 28). The areal extent of the unconfined aquifer is less than the areal extent of the beach ridge. Water-supply wells for the city of Crookston are screened in the partially confined (2 wells) and uppermost confined (2 wells) aquifers.

The saturated thickness of the unconfined aquifer present within the beach deposits ranges from 0 to 30 ft (fig. 29). During test drilling for this study, till and clay were penetrated directly underlying a thin, unsaturated sand and gravel unit in 17 of the 34 test holes drilled on the beach ridge (fig. 10).



Base from U.S. Geological Survey Digital data, 1:100,000. 1977-8 and 1984-5, Universal Transverse Mercator Projection, Zone 15

EXPLANATION

Intermediate confined aquifers - Boundary dashed where approximate. Areal extent represents grouping of individual sand and gravel deposits that comprise many different aquifers with depths to the top of the aquifer 100 to 199 feet below land surface

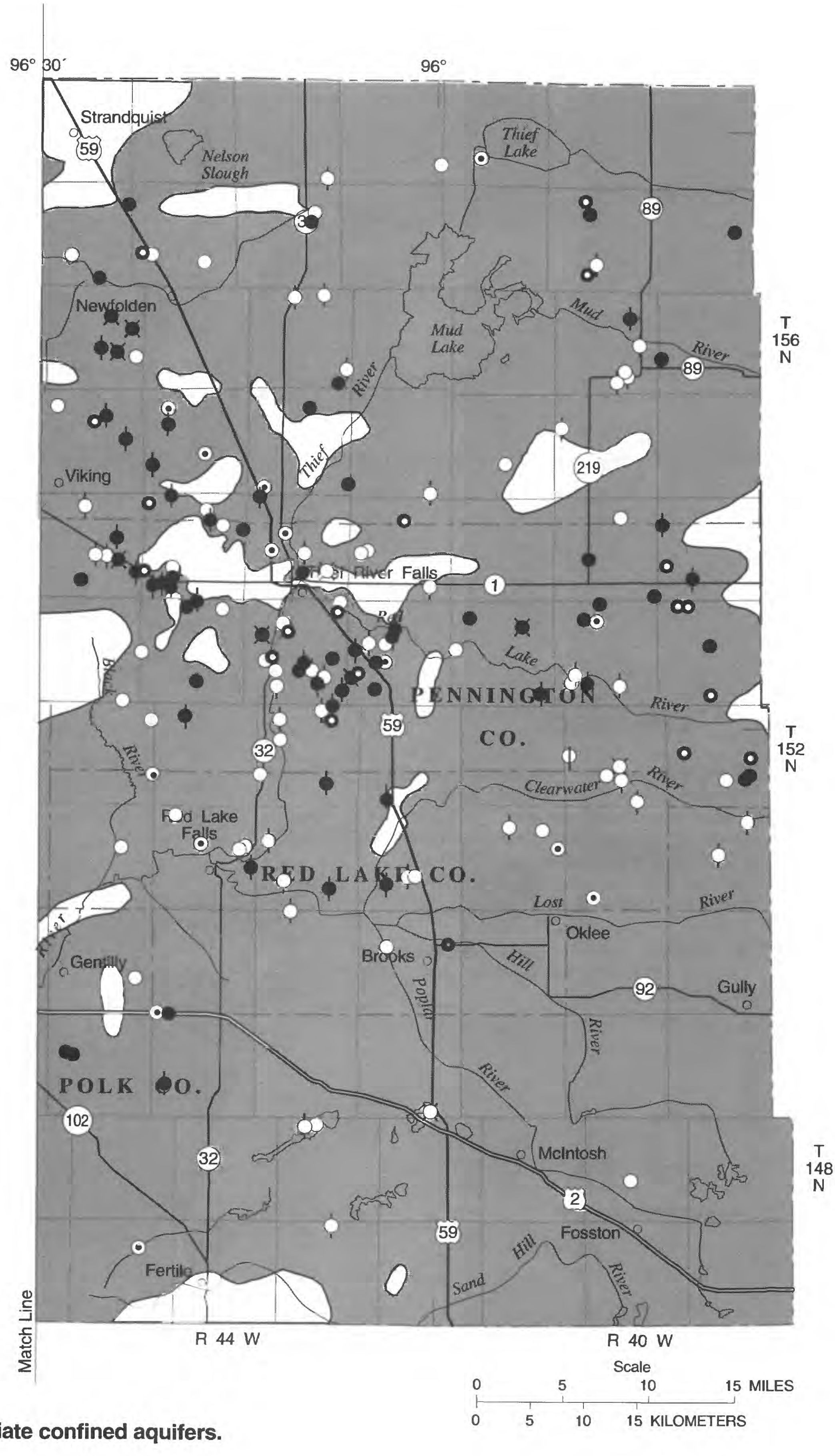
Top of aquifer 100 to 149 feet below land surface - Transmissivity in feet squared per day

- 0 - 500
- 501 - 1,000
- 1,001 - 5,000
- > 5,000

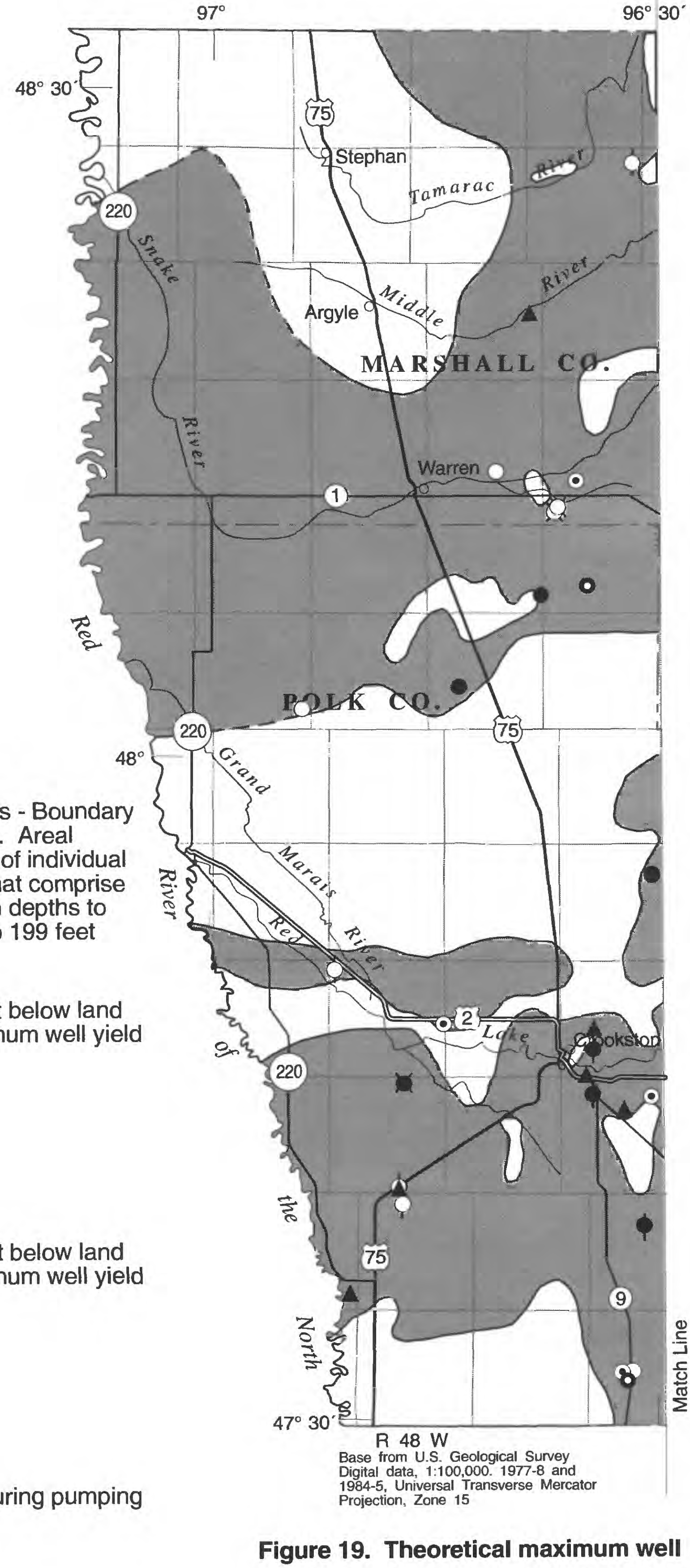
Top of aquifer 150 to 199 feet below land surface - Transmissivity in feet squared per day

- 0 - 500
- 501 - 1,000
- 1,001 - 5,000
- > 5,000

Figure 18. Transmissivity for



intermediate confined aquifers.



EXPLANATION

Intermediate confined aquifers - Boundary dashed where approximate. Areal extent represents grouping of individual sand and gravel deposits that comprise many different aquifers with depths to the top of the aquifer 100 to 199 feet below land surface

Top of aquifer 100 to 149 feet below land surface - Theoretical maximum well yield in gallons per minute

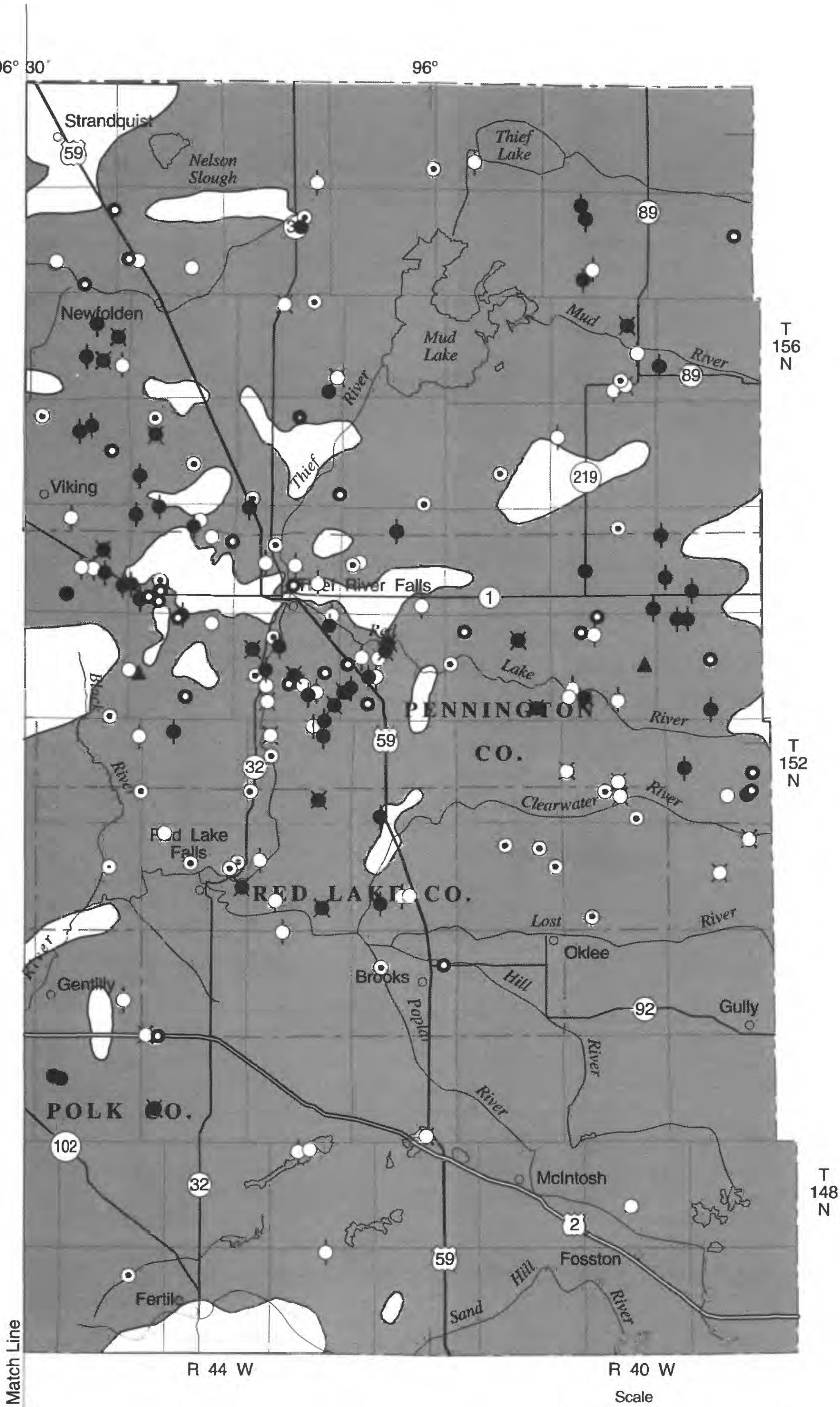
- 0 - 25
- 26 - 100
- 101 - 300
- > 300

Top of aquifer 150 to 199 feet below land surface - Theoretical maximum well yield in gallons per minute

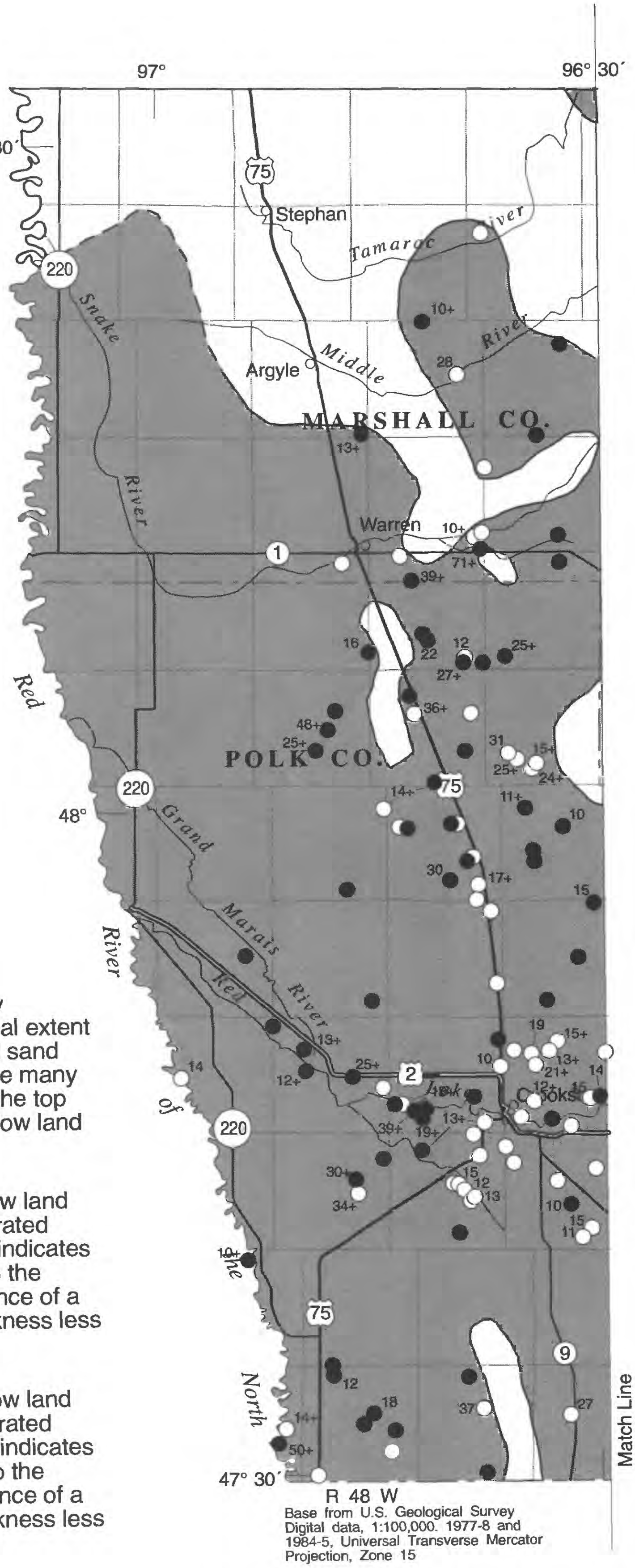
- 0 - 25
- 26 - 100
- 101 - 300
- > 300

▲ No measurable drawdown during pumping

Figure 19. Theoretical maximum well



yield for intermediate confined aquifers.



Base from U.S. Geological Survey Digital data, 1:100,000. 1977-8 and 1984-5, Universal Transverse Mercator Projection, Zone 15

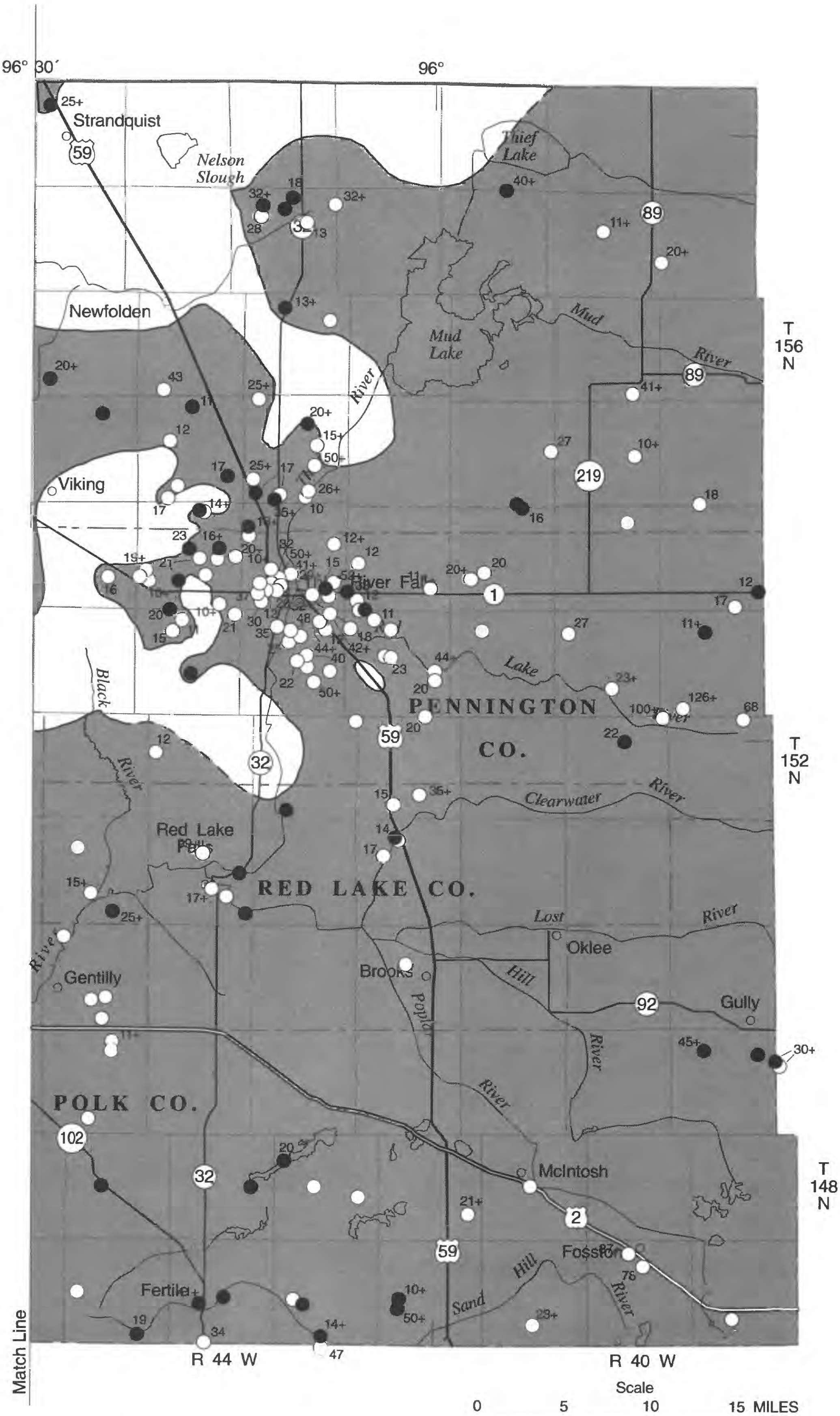
EXPLANATION

Deep confined aquifers - Boundary dashed where approximate. Areal extent represents grouping of individual sand and gravel deposits that comprise many different aquifers with depths to the top of the aquifer 200 to 299 feet below land surface

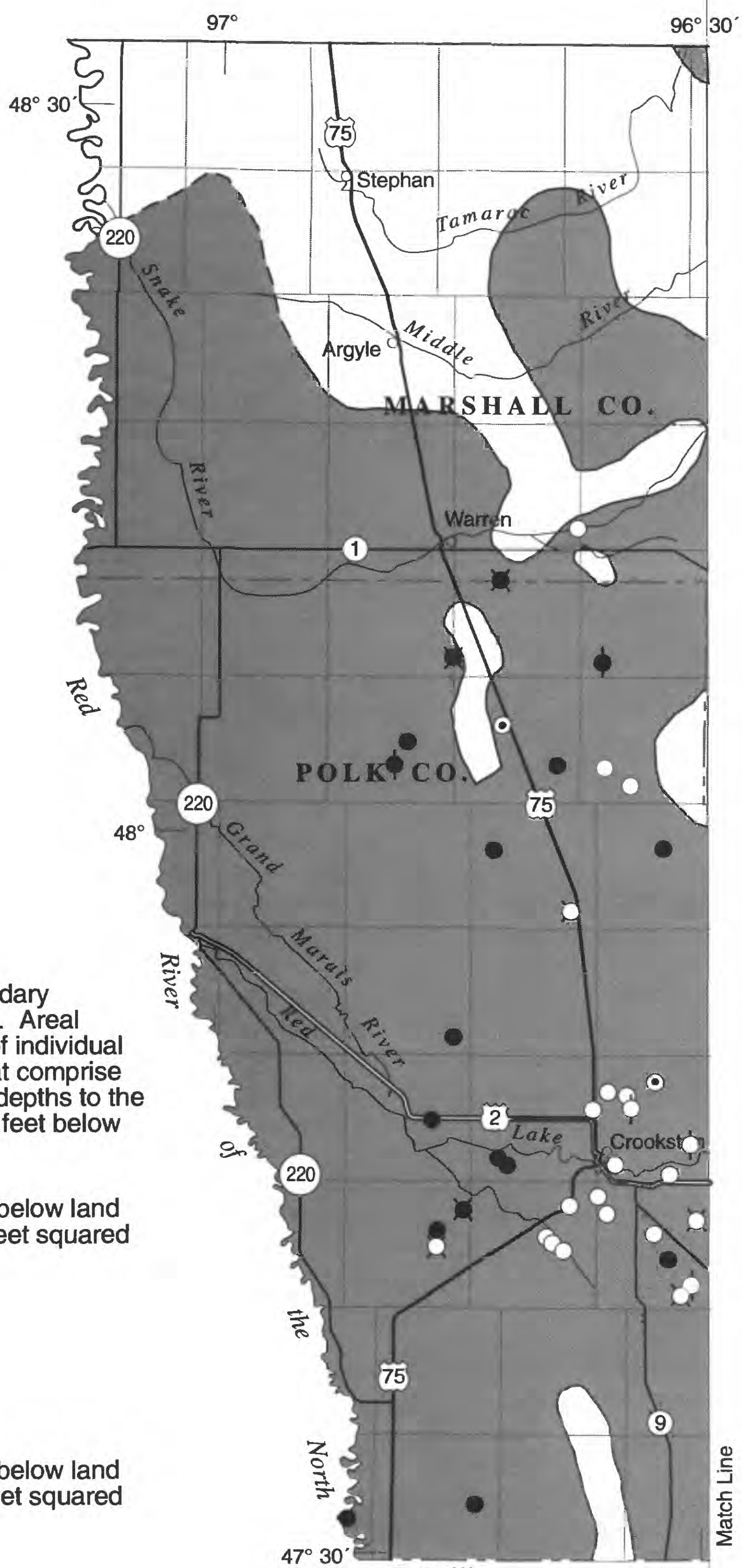
○ 10+ Top of aquifer 200 to 249 feet below land surface - Number indicates saturated thickness of aquifer, in feet. (+) indicates that the hole did not penetrate to the bottom of the aquifer. The absence of a number indicates saturated thickness less than 10 feet

● 25+ Top of aquifer 250 to 299 feet below land surface - Number indicates saturated thickness of aquifer, in feet. (+) indicates that the hole did not penetrate to the bottom of the aquifer. The absence of a number indicates saturated thickness less than 10 feet

Figure 20. Areal extent and thickness



of deep confined aquifers.



Base from U.S. Geological Survey Digital data, 1:100,000. 1977-8 and 1984-5, Universal Transverse Mercator Projection, Zone 15

EXPLANATION

Deep confined aquifers - Boundary dashed where approximate. Areal extent represents grouping of individual sand and gravel deposits that comprise many different aquifers with depths to the top of the aquifer 200 to 299 feet below land surface

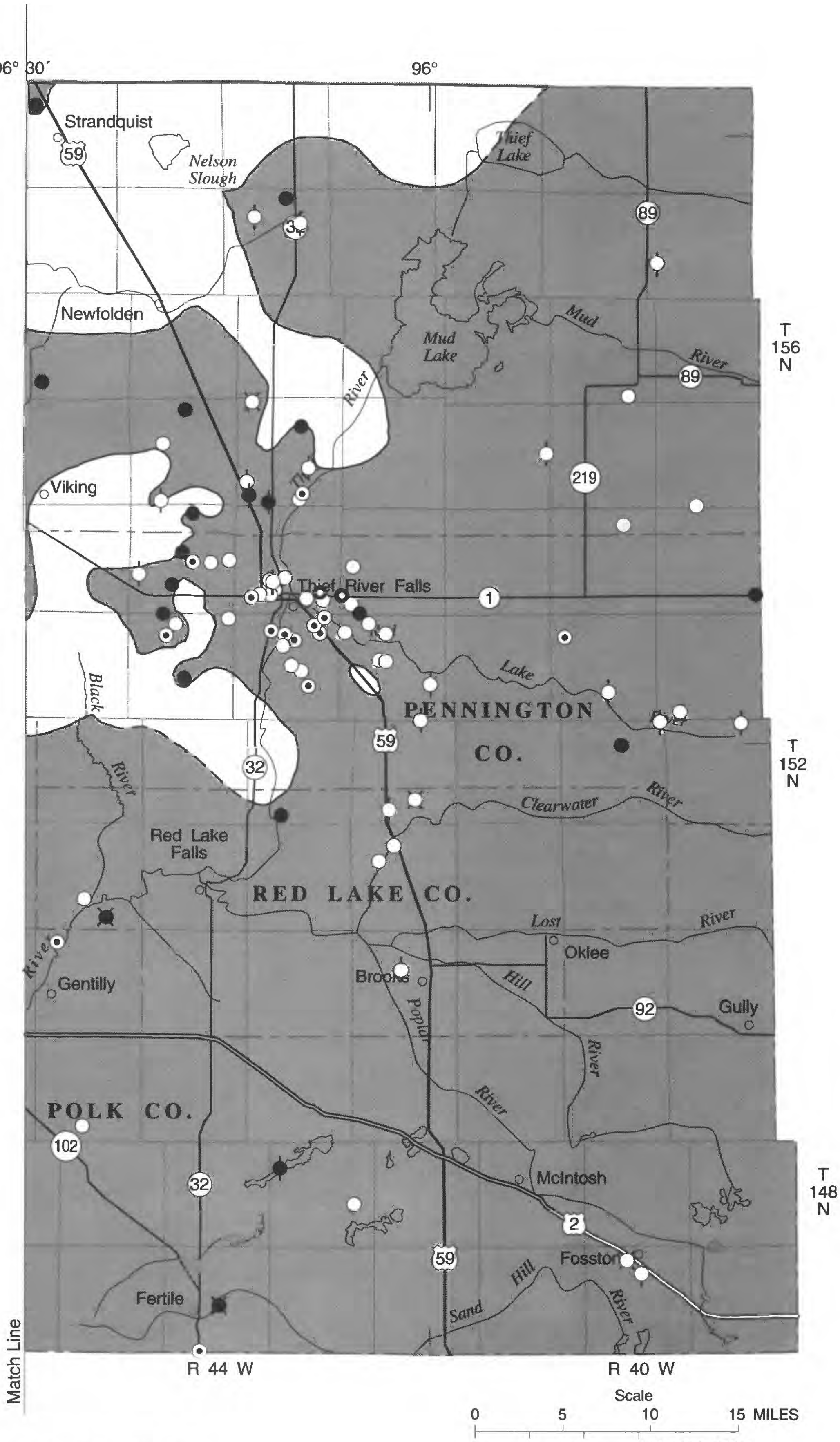
Top of aquifer 200 to 249 feet below land surface - Transmissivity in feet squared per day

- 0 - 500
- 501 - 1,000
- 1,001 - 5,000
- > 5,000

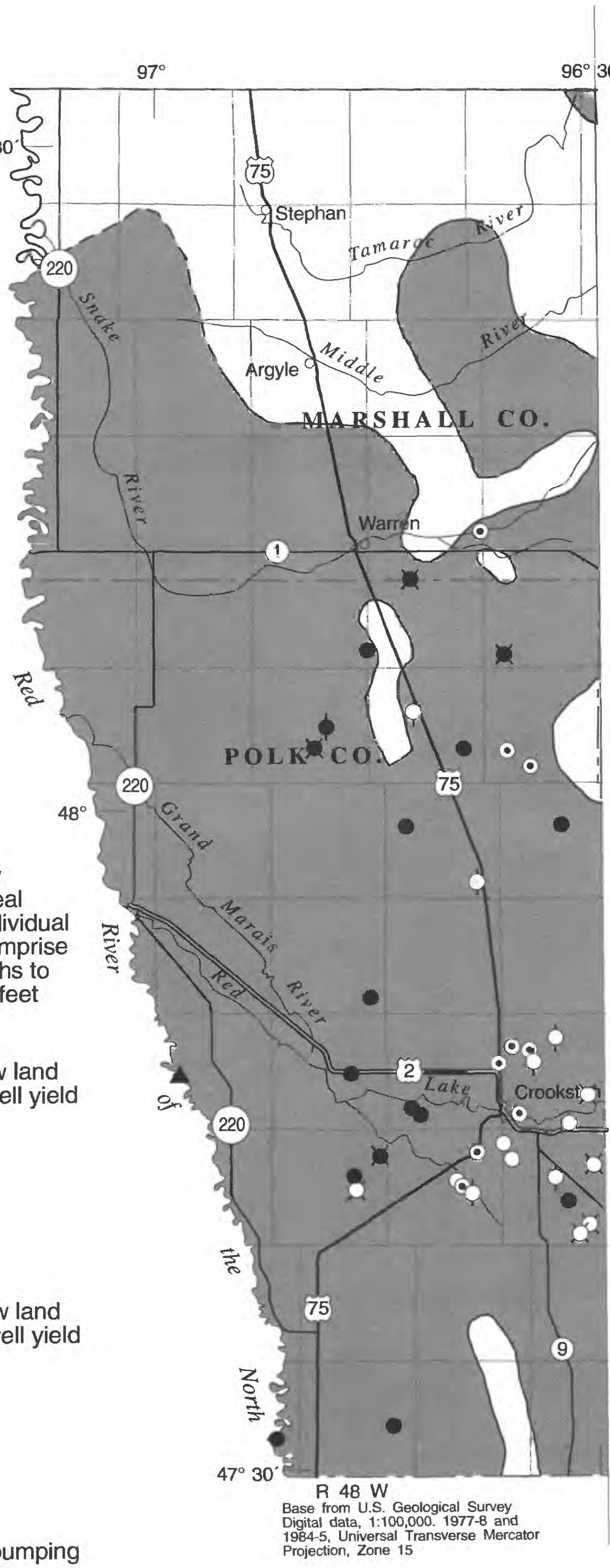
Top of aquifer 250 to 299 feet below land surface - Transmissivity in feet squared per day

- 0 - 500
- 501 - 1,000
- 1,001 - 5,000
- > 5,000

Figure 21. Transmissivity



for deep confined aquifers.



EXPLANATION

Deep confined aquifers - Boundary dashed where approximate. Areal extent represents grouping of individual sand and gravel deposits that comprise many different aquifers with depths to the top of the aquifer 200 to 299 feet below land surface

Top of aquifer 200 to 249 feet below land surface - Theoretical maximum well yield in gallons per minute

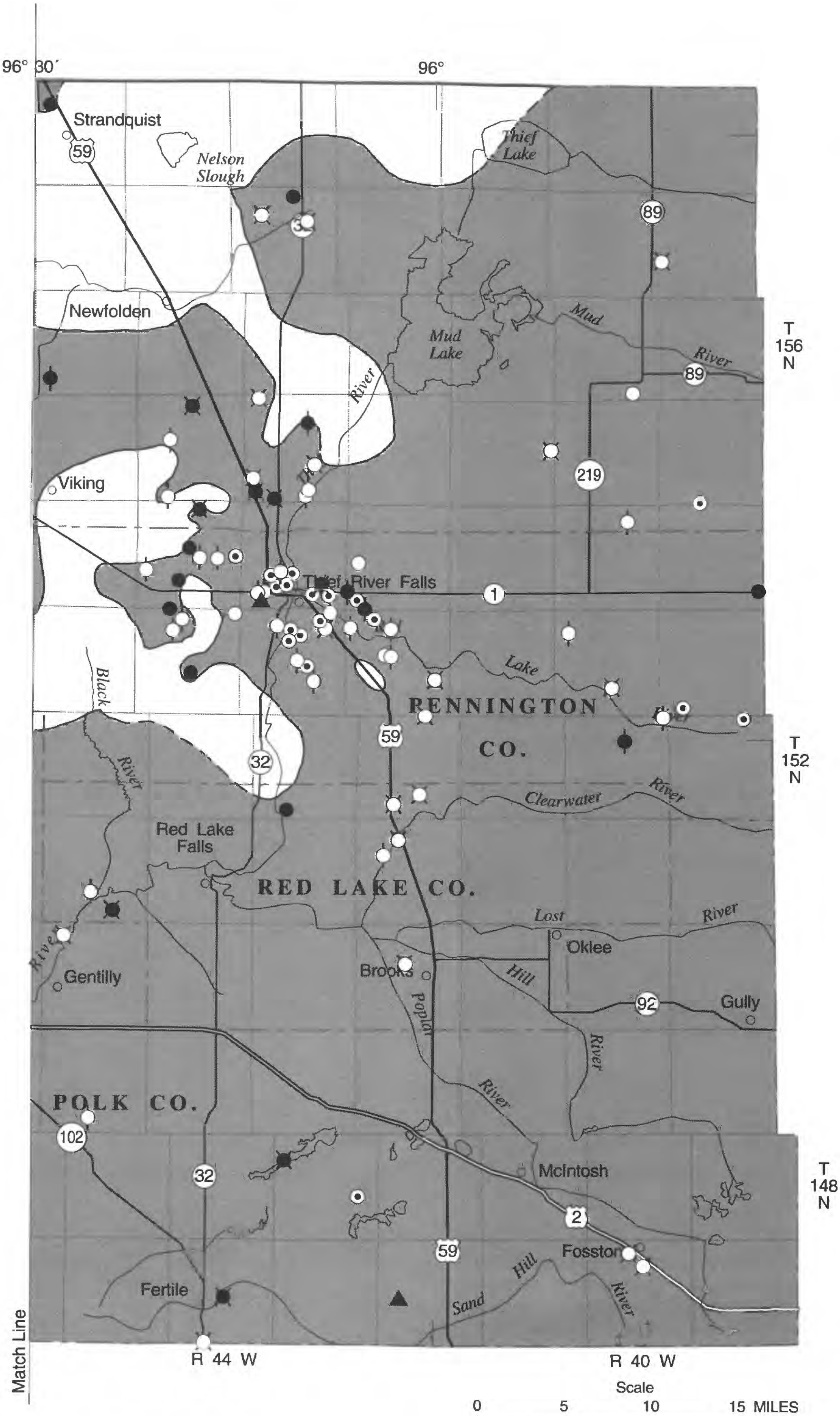
- 0 - 25
- 26 - 100
- 101 - 300
- > 300

Top of aquifer 250 to 299 feet below land surface - Theoretical maximum well yield in gallons per minute

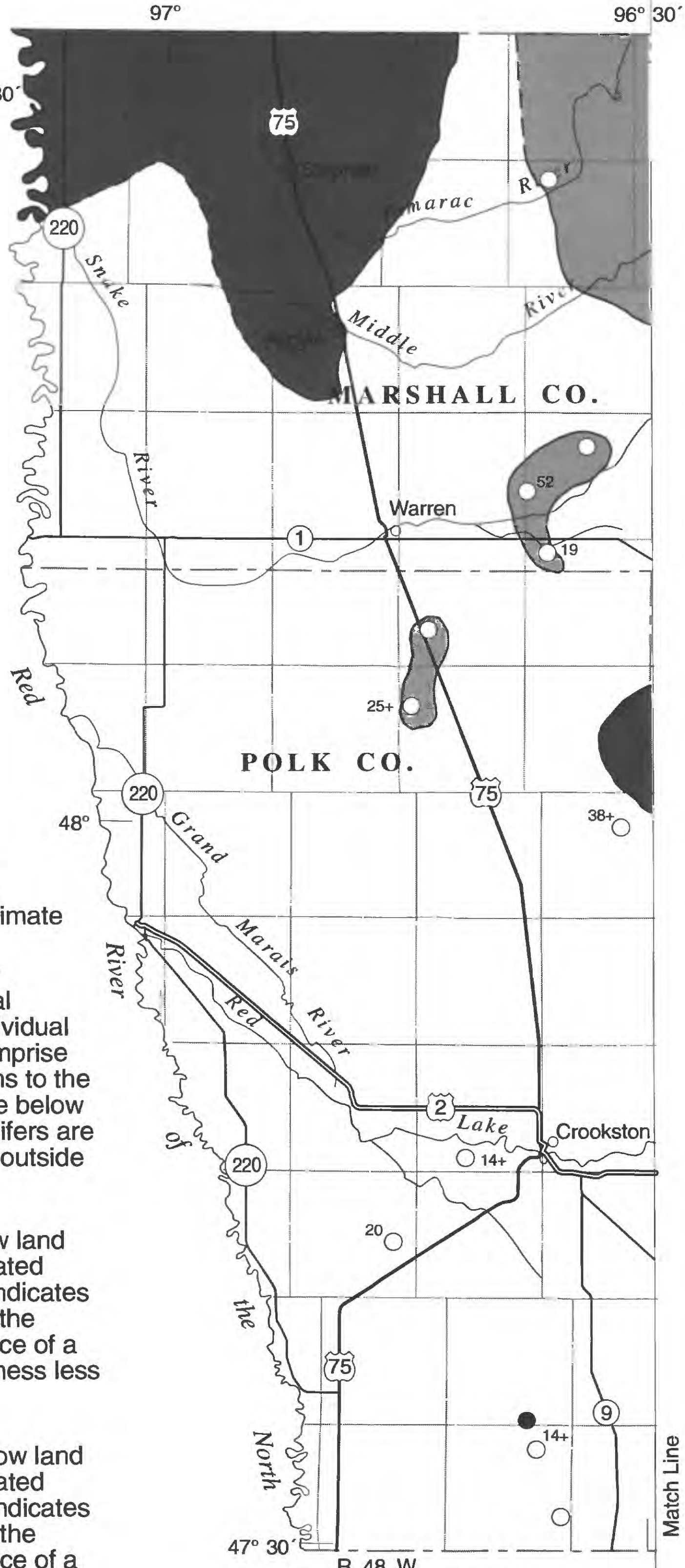
- 0 - 25
- 26 - 100
- 101 - 300
- > 300

▲ No measurable drawdown during pumping

Figure 22. Theoretical maximum well



yield for deep confined aquifers.



Base from U.S. Geological Survey Digital data, 1:100,000. 1977-8 and 1984-5, Universal Transverse Mercator Projection, Zone 15

EXPLANATION

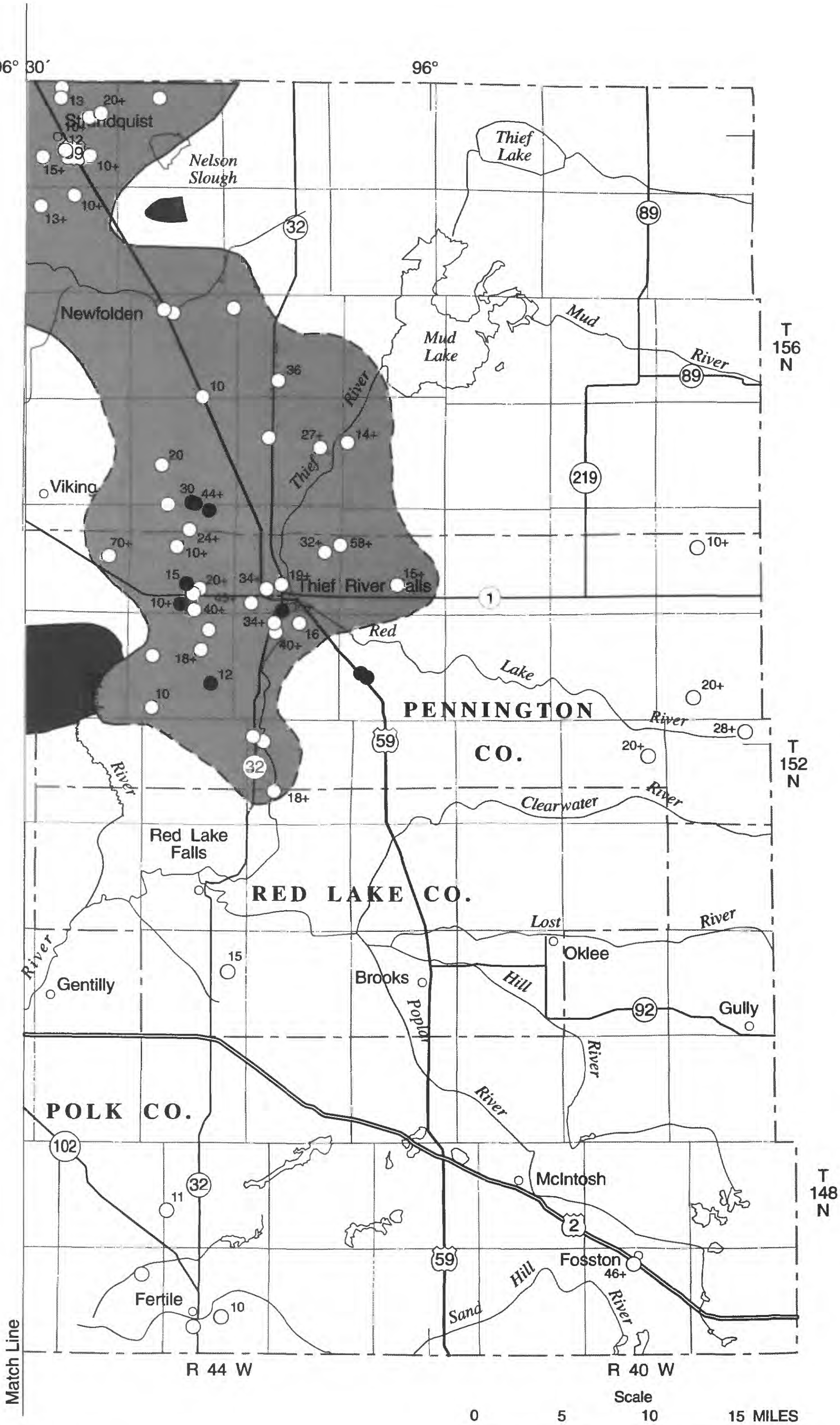
No glacial-deposit aquifers present - Boundary dashed where approximate

Basal confined aquifers - Boundary dashed where approximate. Areal extent represents grouping of individual sand and gravel deposits that comprise many different aquifers with depths to the top of the aquifer 300 feet or more below land surface. Basal confined aquifers are also present at isolated locations outside shaded areas

● 16+ Top of aquifer 300 to 399 feet below land surface - Number indicates saturated thickness of aquifer, in feet. (+) indicates that the hole did not penetrate to the bottom of the aquifer. The absence of a number indicates saturated thickness less than 10 feet

○ 15+ Top of aquifer 400 or more feet below land surface - Number indicates saturated thickness of aquifer, in feet. (+) indicates that the hole did not penetrate to the bottom of the aquifer. The absence of a number indicates saturated thickness is less than 10 feet

Figure 23. Areal extent and thickness



of basal confined aquifers.

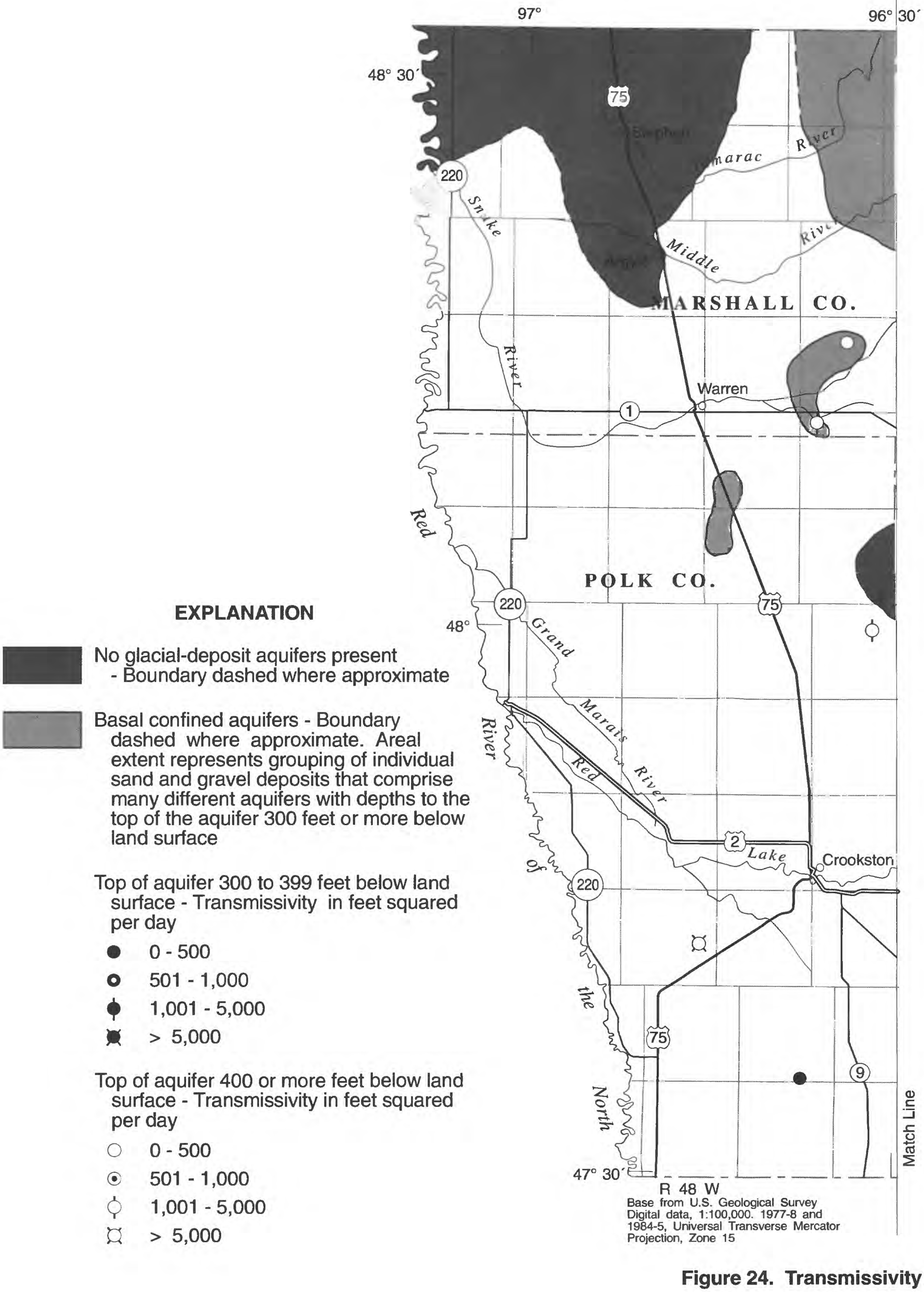
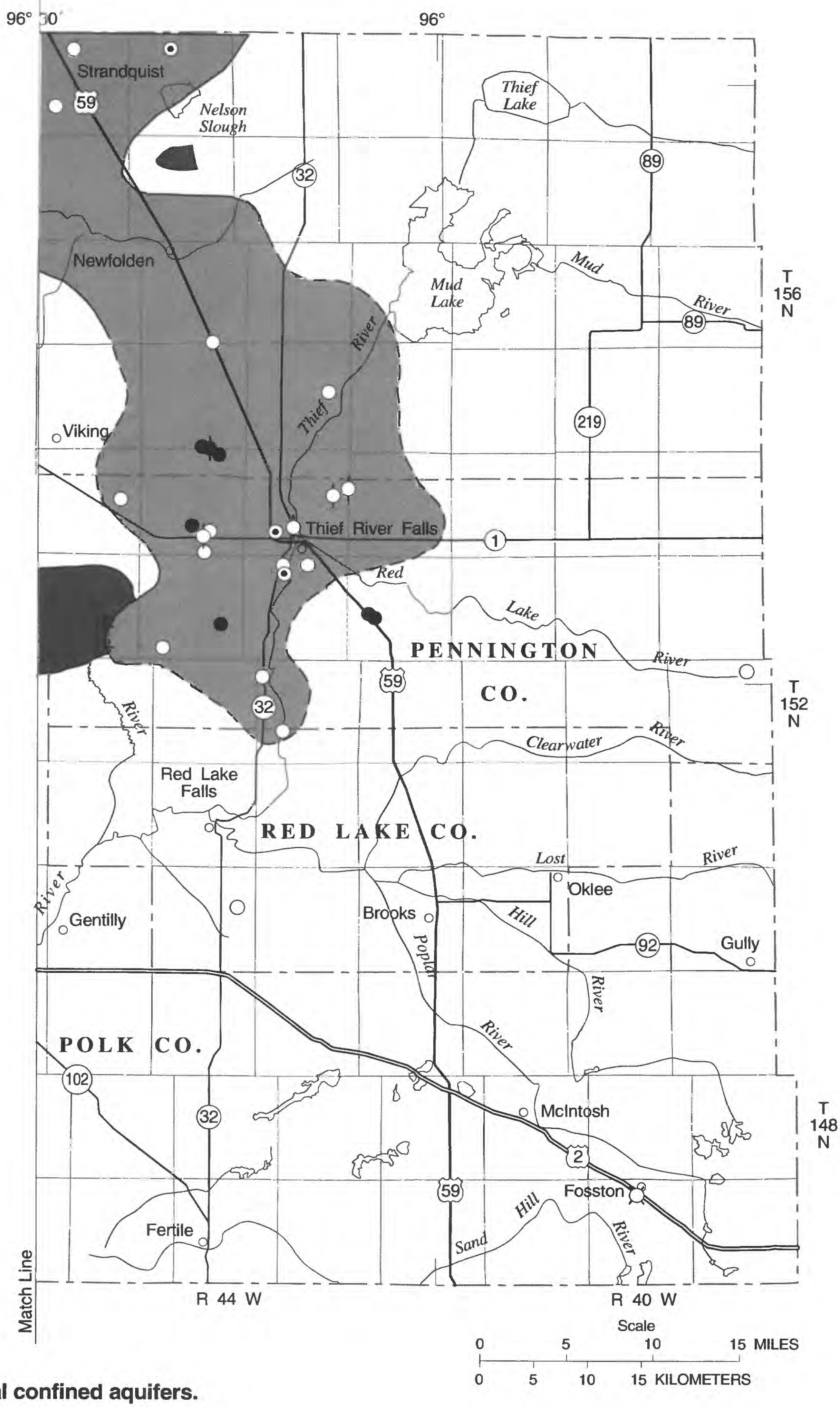


Figure 24. Transmissivity



for basal confined aquifers.

EXPLANATION

- No glacial-deposit aquifers present - Boundary dashed where approximate

- Basal confined aquifers - Boundary dashed where approximate. Areal extent represents grouping of individual sand and gravel deposits that comprise many different aquifers with depths to the top of the aquifer 300 feet or more below land surface

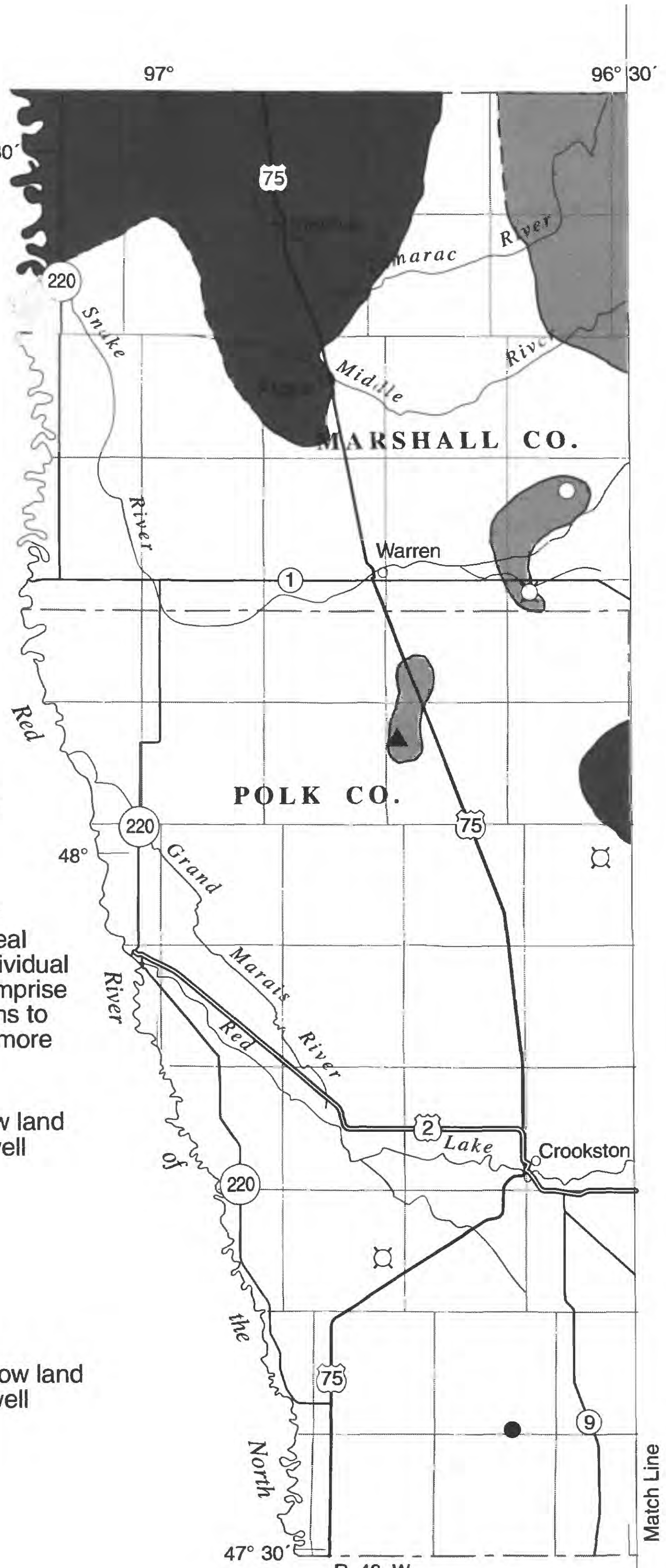
Top of aquifer 300 to 399 feet below land surface - Theoretical maximum well yield in gallons per minute

- ● 0 - 25
- 26 - 100
- 101 - 300
- > 300

Top of aquifer 400 or more feet below land surface - Theoretical maximum well yield in gallons per minute

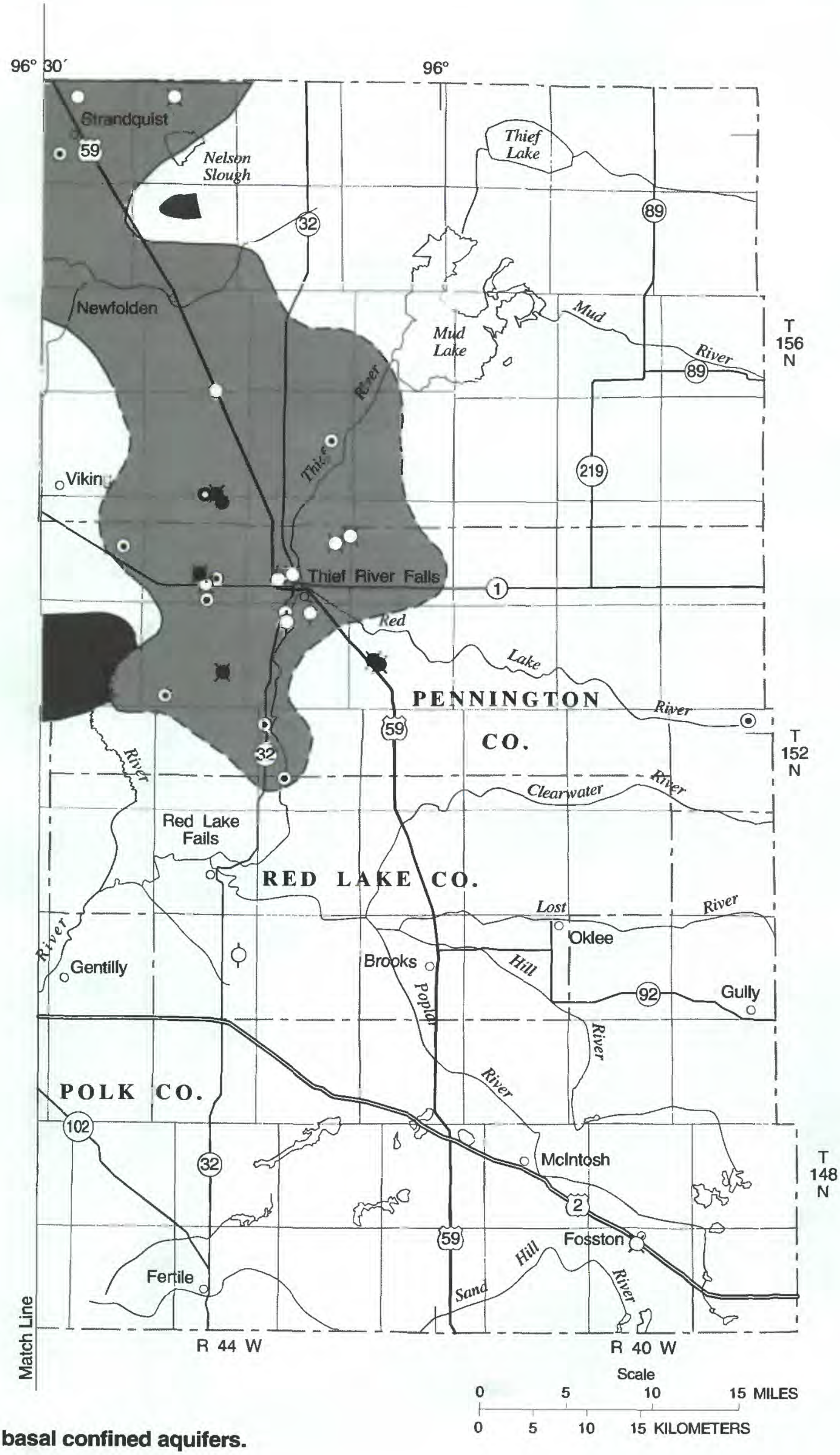
- ○ 0 - 25
- ⊙ 26 - 100
- 101 - 300
- > 300

▲ No measurable drawdown during pumping



Base from U.S. Geological Survey Digital data, 1:100,000. 1977-8 and 1984-5, Universal Transverse Mercator Projection, Zone 15

Figure 25. Theoretical maximum well

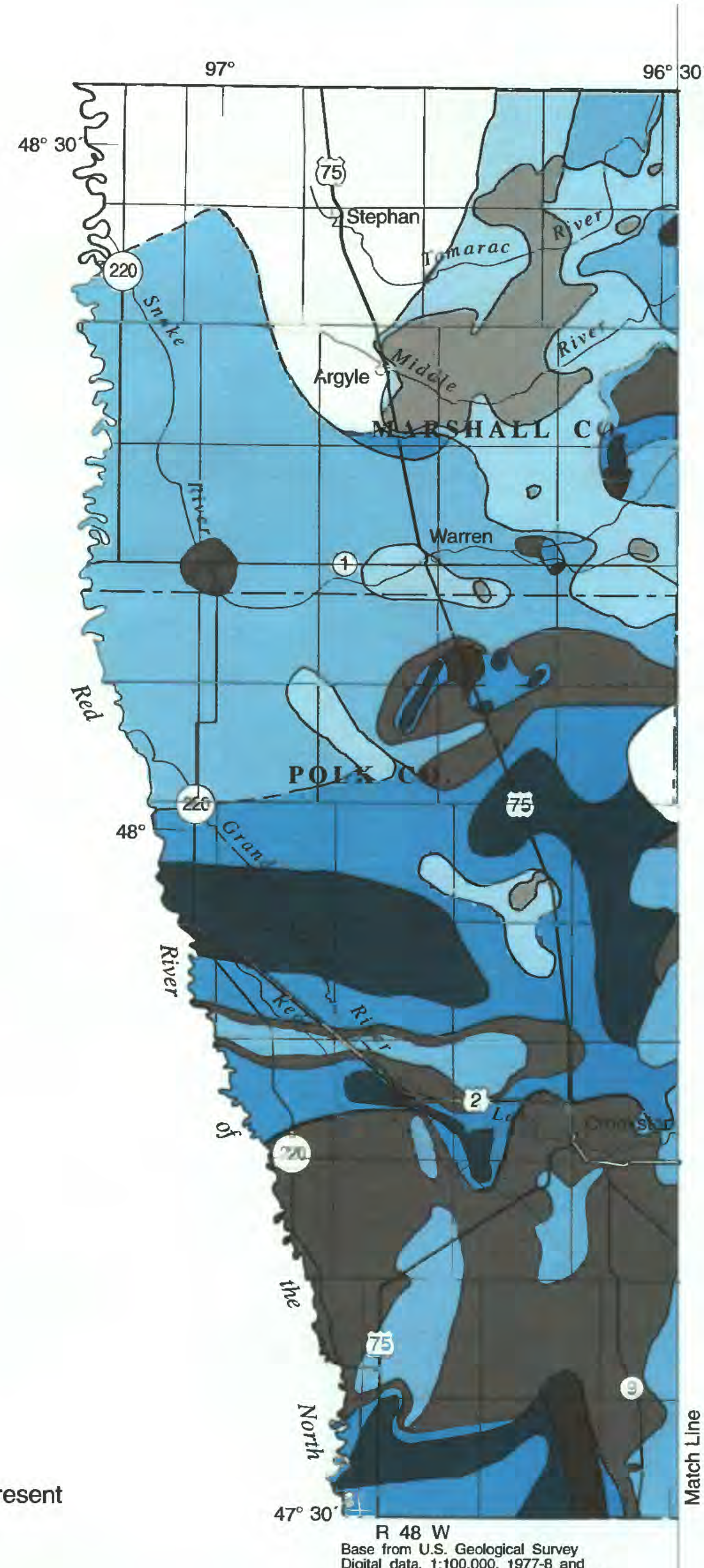


yield for basal confined aquifers.

EXPLANATION

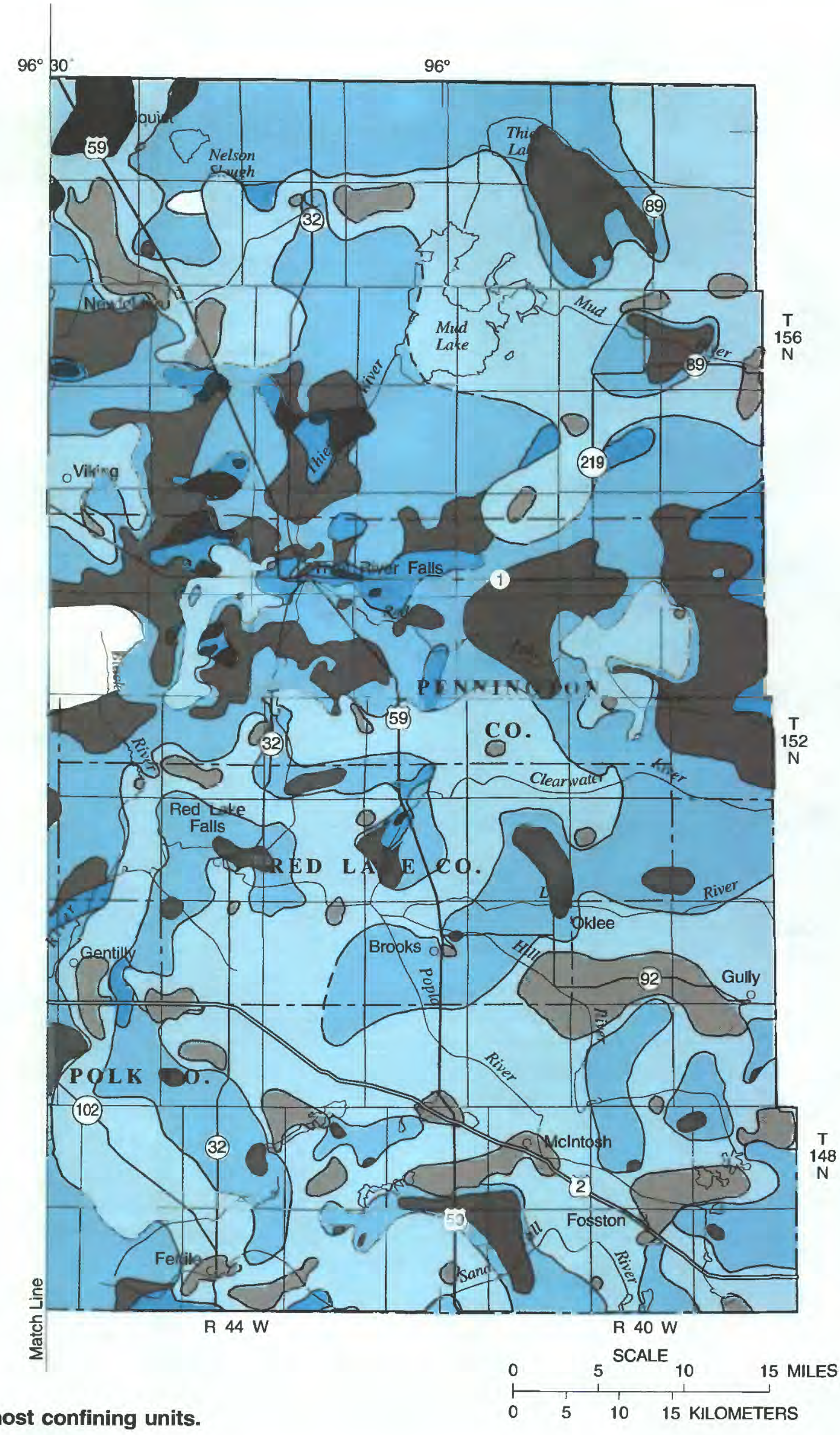
Thickness of uppermost confining units, in feet:

- 0 - 49
- 50 - 99
- 100 - 149
- 150 - 199
- 200 - 249
- 250 - 299
- > 300
- No glacial-deposit aquifers present



Base from U.S. Geological Survey Digital data, 1:100,000. 1977-8 and 1984-5, Universal Transverse Mercator Projection, Zone 15

Figure 26. Thickness of



uppermost confining units.

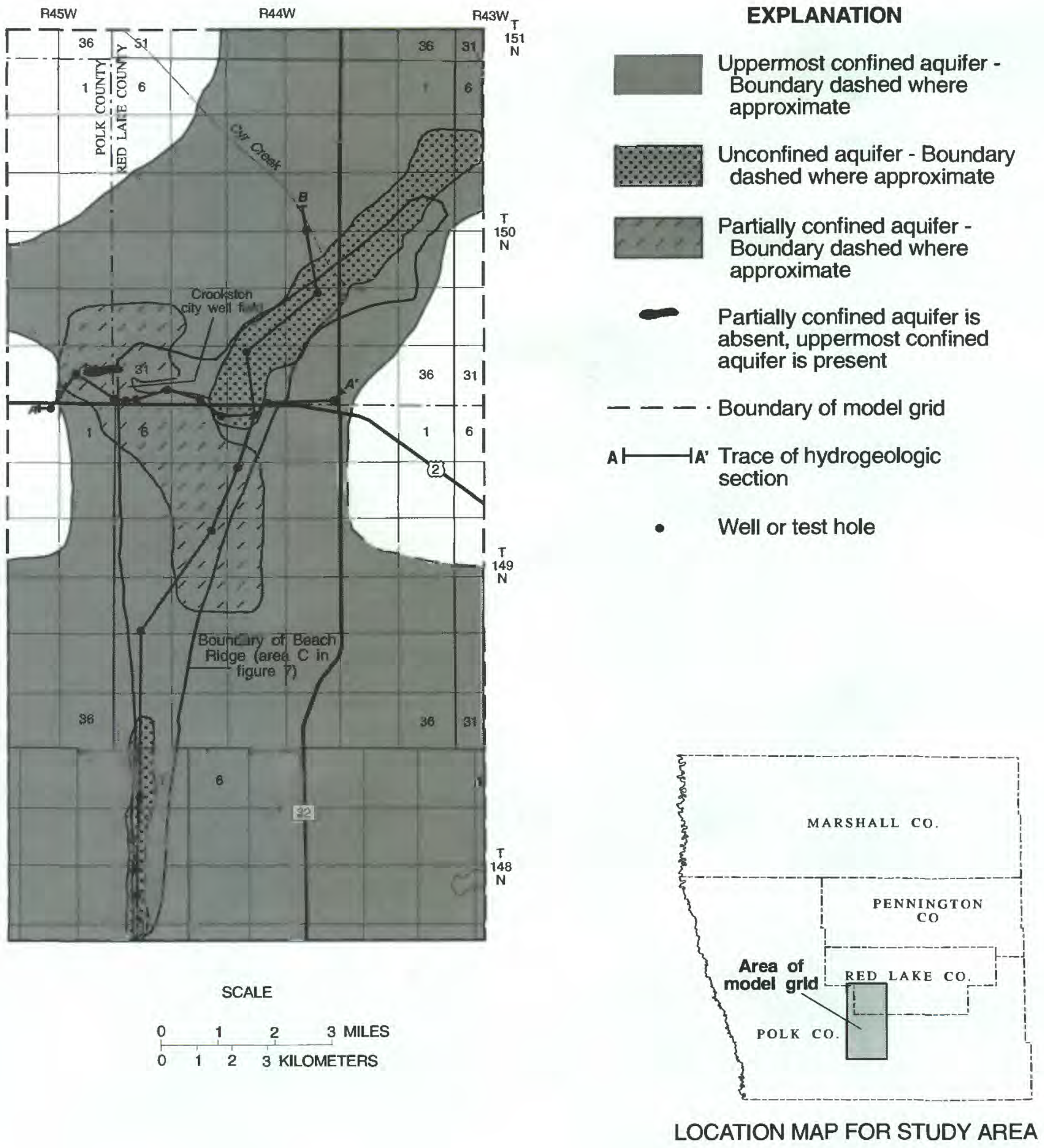


Figure 27. Areal extent of unconfined, partially confined, and uppermost confined aquifers of Polk-Red Lake Counties beach-ridge aquifer system and traces of hydrogeologic sections.

The partially confined aquifer is overlain by 0 to 30 ft of till and clay. In the context of the previous discussion of confined aquifers based on depth below land surface to the top of the aquifer, the partially confined aquifer is categorized as a shallow confined aquifer. The aquifer is predominantly under confined conditions but is under unconfined conditions in small isolated areas where sand and gravel are present at land surface. The saturated thickness of the partially confined aquifer ranges from 0 to 54 ft, but is from 24 to 54 ft thick in the area underlying the Crookston city well field (fig. 29).

The unconfined and partially confined aquifers are physically and hydraulically separated from the underlying uppermost confined aquifer by a confining unit (uppermost confining unit on fig. 28) composed of till and lake clay that is 80 to 140 ft thick. In the context of the previous discussion of confined aquifers based on depth below land surface to the top of the aquifer, the uppermost confined aquifer of the Polk-Red Lake Counties beach-ridge aquifer system is categorized as an intermediate confined aquifer. The uppermost confined aquifer is about 20 to 40 ft thick.

Pennington County Beach-Ridge Aquifer System

The Pennington County beach-ridge aquifer system underlies a beach ridge that is approximately 10 mi in length and 1 mi wide located in western Pennington County (fig. 9). The beach ridge is bounded on the south, east, and west by well-defined wetland, lowland areas. The unconfined aquifer consists of coarse-grained beach deposits that compare the beach-ridge landform and a fine surficial sand underlying the lowland between the beach-ridge and the Black River. Available test-hole logs indicate no significant hydraulic connection between the unconfined aquifer and the Black River. The saturated thickness of the unconfined aquifer ranges from 0 to 13 ft (fig. 9). Saturated thickness in the central part of the aquifer (along the beach-ridge axis) range from 8 to 13 ft (fig. 9). The northern one-quarter of the beach ridge is underlain by an uppermost confined aquifer at a depth of about 90 ft below land surface. The unconfined aquifer is probably in hydraulic connection with part of the underlying uppermost confined aquifer in this area. Hydraulic heads in this uppermost confined aquifer are greater than land surface altitude and wells screened in the aquifer in the area flow. The southern three-quarters of the beach ridge is underlain by confined aquifers at depths below land surface greater than 200 ft, if present at all. The unconfined aquifer underlying the southern three-quarters of the beach-ridge is probably not in hydraulic connection with any underlying confined aquifers.

Recharge, Discharge, and Ground-Water Flow

Recharge

Recharge to ground water predominantly is from precipitation that percolates downward to the saturated zone. Seepage from lakes and streams and underflow from the east are minor sources of recharge to ground water in the study area. Recharge to the aquifers is greatest and most rapid in areas where the unconfined aquifers are present at land surface. Recharge and hydraulic heads in the aquifers tend to follow a short-term cyclic pattern of seasonal fluctuations (fig. 30). Hydraulic heads generally are highest in the spring, during maximum recharge from snowmelt and rainfall; decline during the summer, when evapotranspiration losses are high and the amount of precipitation is less; decline less rapidly, but continue downward, during the fall; are lowest in winter, when potential recharge from precipitation is stored at land surface as snow; and rise again in the spring, to complete the cycle. Variations in the amount and timing of precipitation may result in deviations from this generalized cyclic pattern of fluctuations (fig. 30). Autumn rainfall often results in significant recharge to ground water.

Recharge rates can be estimated from continuous water-level measurements from observation wells (Rasmussen and Andreasen, 1959). The method assumes that all water-level rises in the well result from recharge to the aquifer. The rate of recharge per year equals the sum of individual water-level rises within the year multiplied by the specific yield of the aquifer. The water-level rise calculated by this method is based on a lower line projecting the recession line of the hydrograph to the date at which the peak occurred (fig. 31). Hydrographs for 14 observation wells were analyzed to estimate recharge to unconfined aquifers in the study area. Estimated recharge to unconfined aquifers in Polk and Red Lake Counties ranged from 6.0 to 12.0 in. during 1991 based on data from 3 observation wells, and from 4.5 to 10.6 in. during 1992, based on data from 6 observation wells (estimated recharge values for 1992 are shown in figure 32). Based on hydrograph analysis for 2 wells located in north-central Marshall County, recharge to the unconfined aquifers ranged from 4.7 to 6.5 in. during 1992. Observation wells were installed in Pennington County in May 1992; therefore, an annual recharge rate based on hydrograph analysis could not be determined. Hydrograph analysis indicated that major recharge to the unconfined aquifers

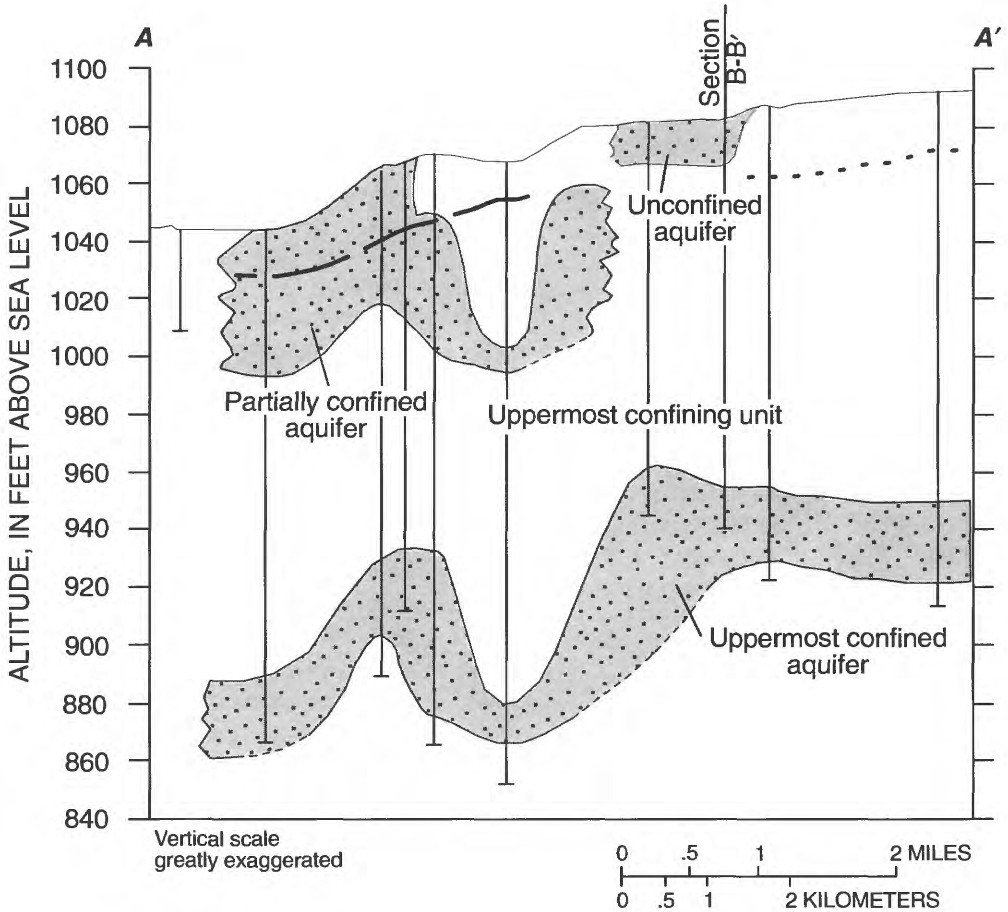
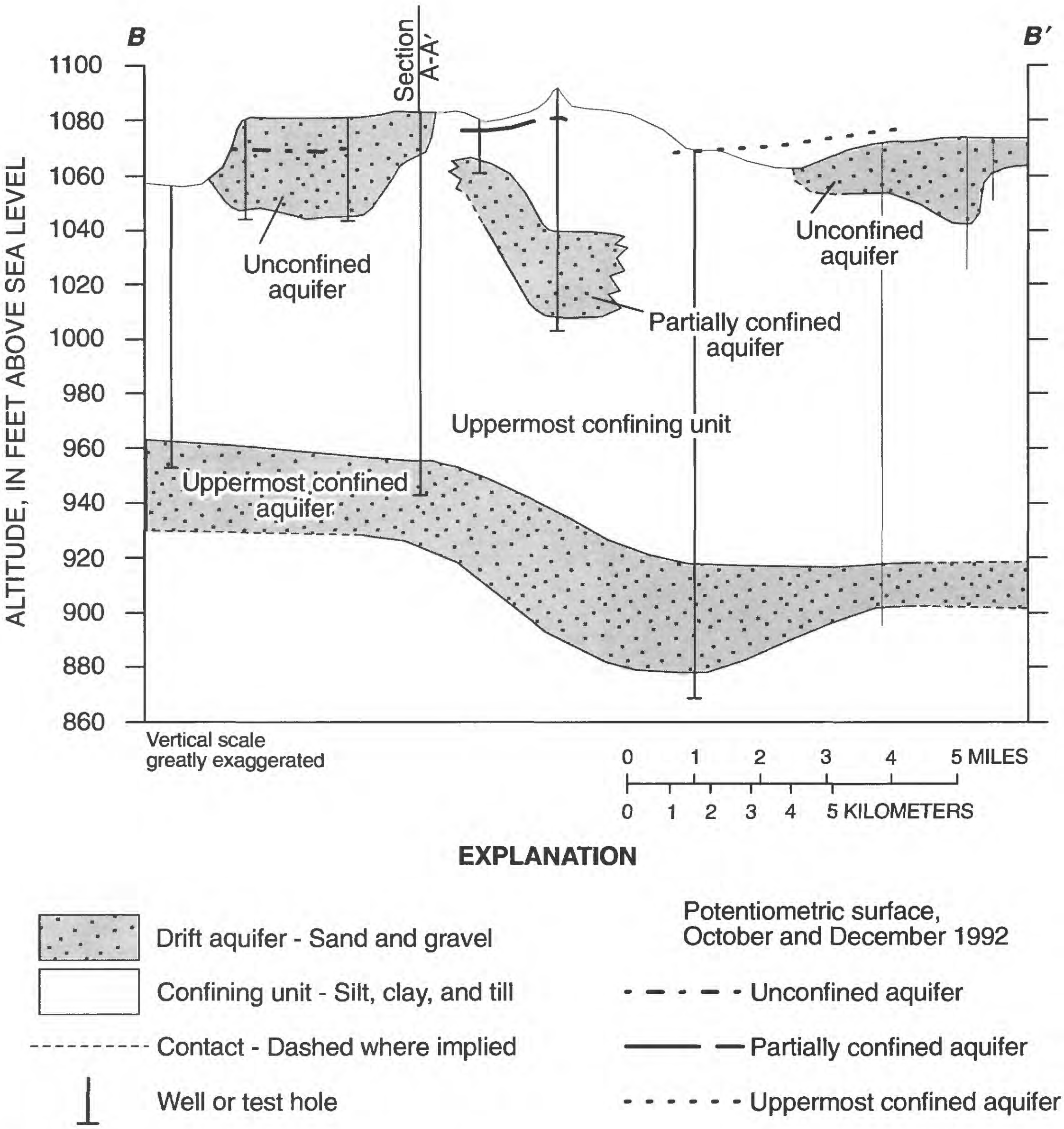


Figure 28. Hydrogeologic sections of Polk-Red (trace of sections

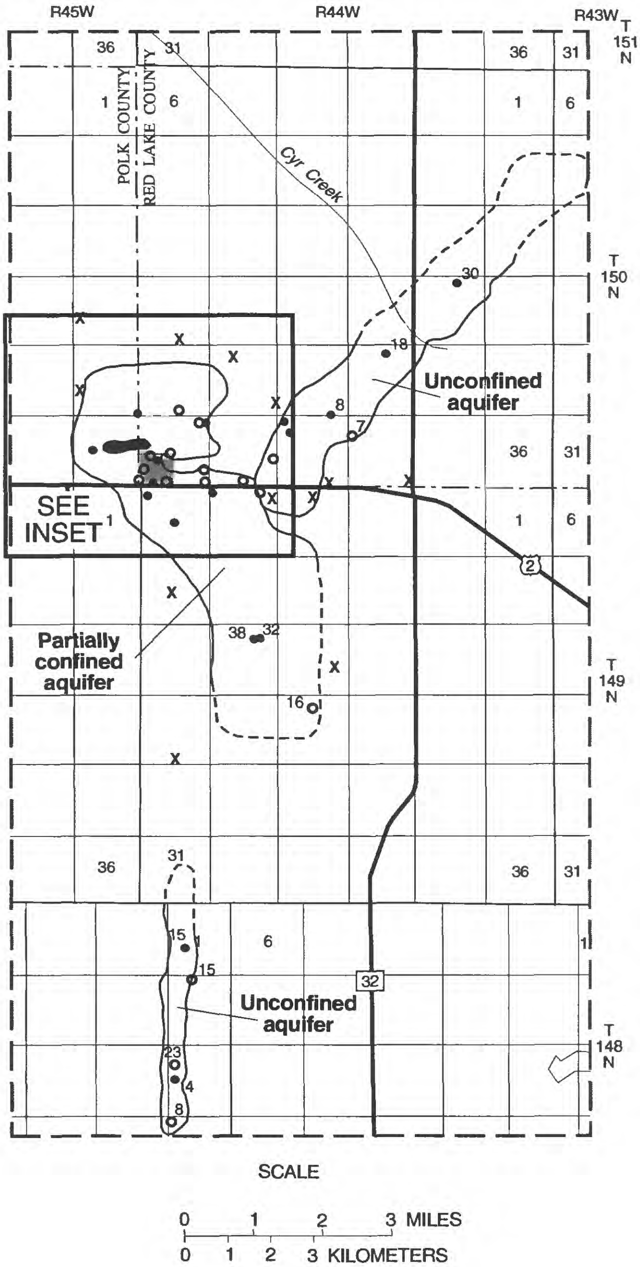
occurred during the spring (March to May) and during fall (late August to October) in 1991 and 1992. Estimated recharge to unconfined aquifers in Pennington County during the fall in 1992 ranged from 1.4 to 5.0 in., based on hydrograph analysis for 6 observation wells. Results from model simulations done for this study (discussed later in this report) indicate that a long-term average recharge rate from 8 to 9 in./yr (inches per year) to unconfined aquifers produce the best matches between model-simulated and measured water levels.

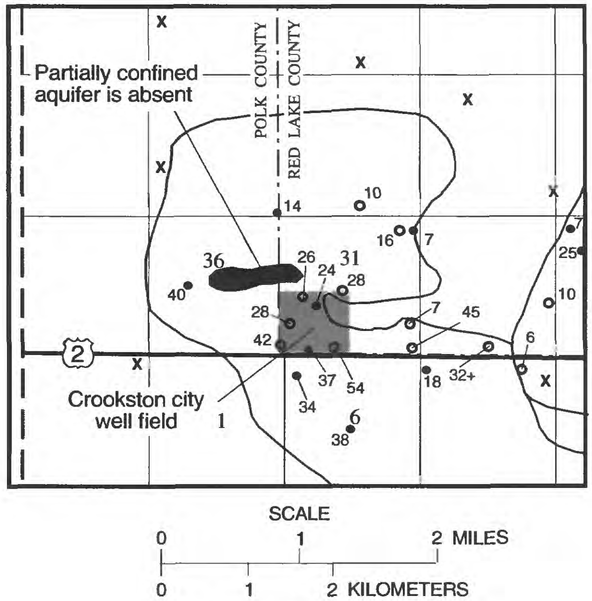
Recharge to ground water also occurs where till or lake clays (of uppermost confining units) are present at land surface. In morainal or lakebed areas, water flows vertically downward through till or lake clays to uppermost confined aquifers. However, because till and lake clays have much lower hydraulic conductivities than sand, recharge is much less in these areas than in areas underlain by sand and gravel. Recharge to uppermost confined aquifers in these areas is greatest where (1) the uppermost confining unit is thin, or (2) the vertical hydraulic conductivity of the confining unit



Lake Counties beach-ridge aquifer system shown on figure 27).

material is comparatively high (sandy or highly-fractured till). Stark and others (1991) reported long-term average recharge rates in the Bemidji-Bagley area of (1) 4 to 8 in./yr in areas where Wadena lobe (Hewitt) till is exposed at land surface, and (2) 0 to 4 in./yr in areas where Des Moines lobe till is exposed at land surface. Leakage rates through till of 0.06 to 1.60 in./yr were computed at nine sites in the Brooten-Belgrade area in west-central Minnesota by Delin (1988). Lindgren (1990) reported a leakage rate of 2.0 in./yr to confined aquifers in the Twin Cities metropolitan area in east-central Minnesota. Delin (1990) reported that recharge rates of 0 to 2.5 in./yr in areas where the thickness of glacial deposits is greater than about 100 ft produced the best match between measured and simulated hydraulic heads in the Rochester area in southeastern Minnesota. Results from model simulations done for this study (discussed later in this report) indicate that a long-term average recharge rate from 4.0 to 4.5 in./yr for sandy till and clay exposed at land surface produce the best matches between model-simulated and measured water levels.





EXPLANATION

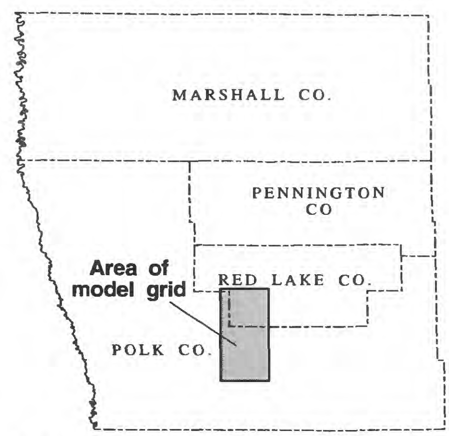
Aquifer boundary - Dashed where approximate

Boundary of model grid

$\bullet^{14}$ Observation well - Number indicates saturated thickness, in feet

$\circ^{32+}$ Test hole - Number indicates saturated thickness, in feet. (+) indicates that the test hole did not penetrate to the bottom of the aquifer

x Partially confined aquifer is absent



LOCATION MAP FOR STUDY AREA

Figure 29. Saturated thickness of unconfined and partially confined aquifers of Polk-Red Lake Counties beach-ridge aquifer system.

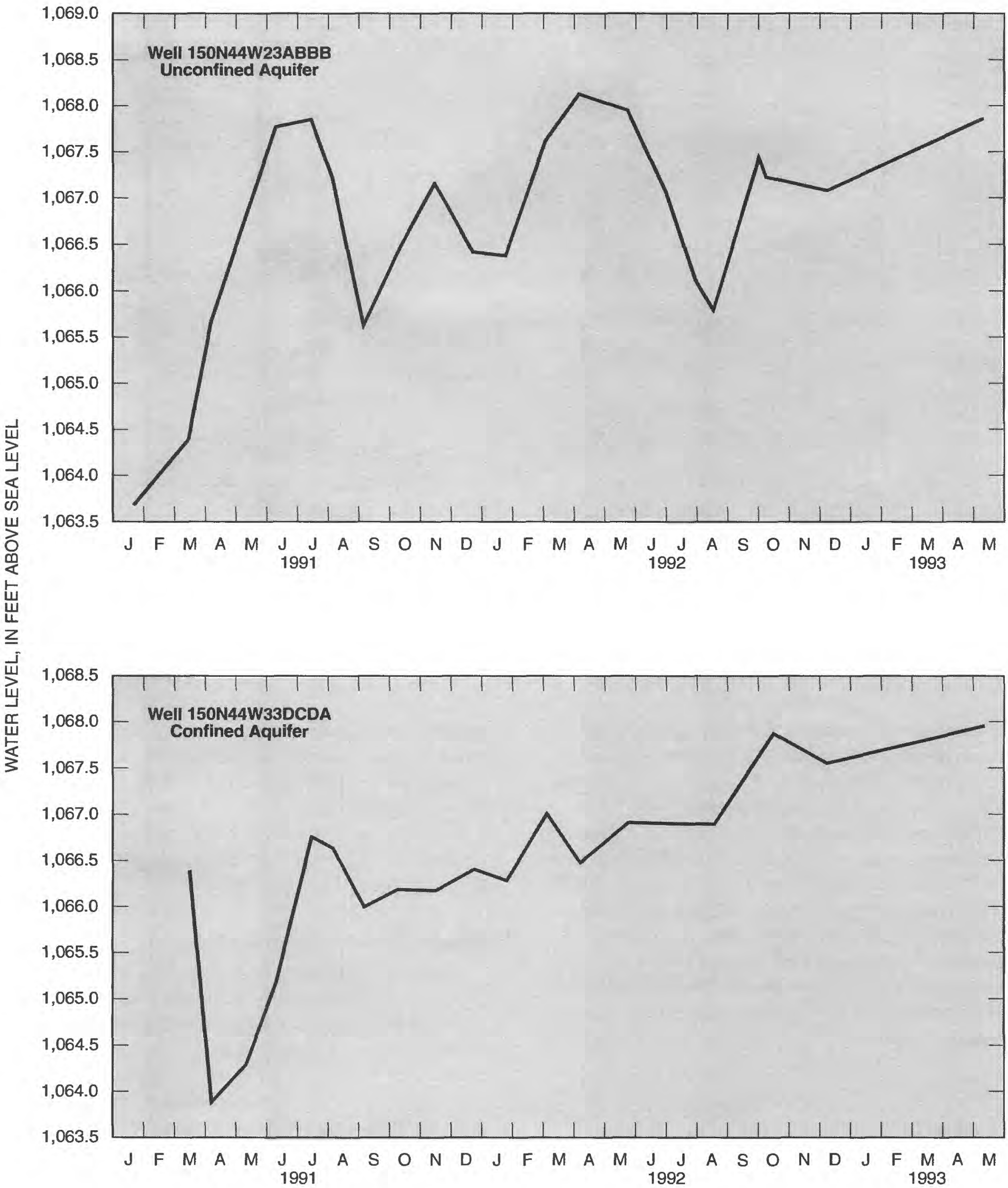


Figure 30. Water-level fluctuations in wells screened in unconfined and confined aquifers.

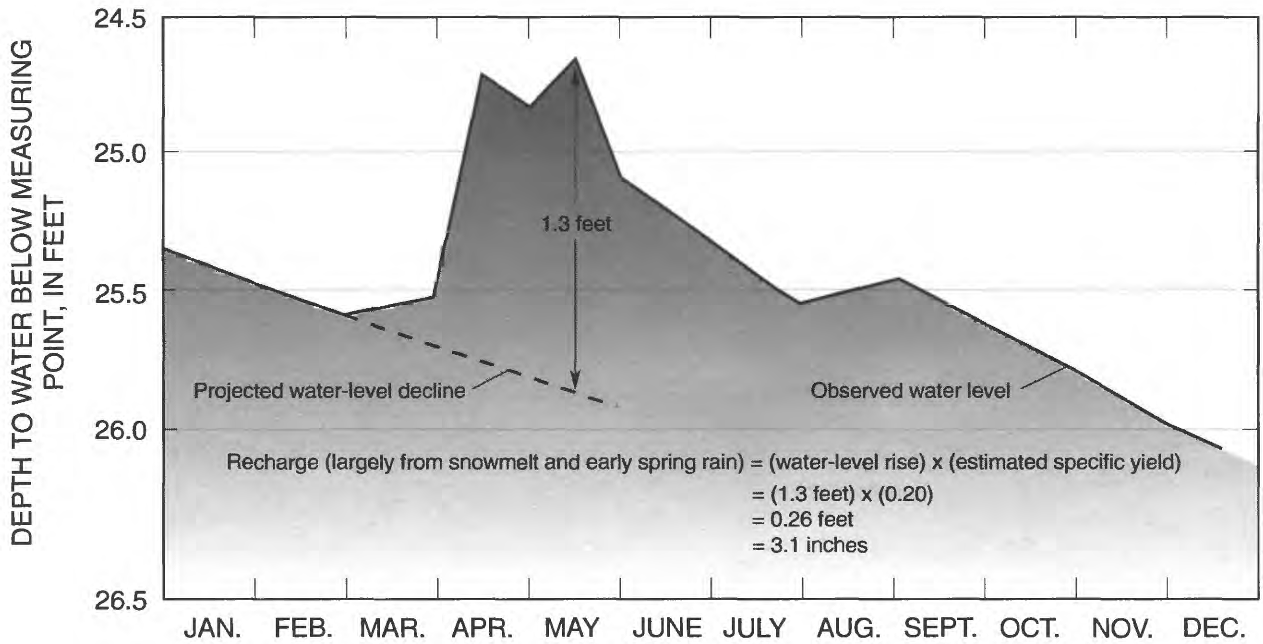


Figure 31. Hydrograph demonstrating method of estimating recharge during spring to the unconfined aquifers (Rasmussen and Andreasen, 1959).

The seasonal pattern of fluctuations in hydraulic heads observed in confined aquifers generally are of lesser magnitude and delayed in time as compared to fluctuations in unconfined aquifers (fig. 30). The differences in the magnitude and timing of fluctuations are caused by the presence of the confining units of low hydraulic conductivity overlying the confined aquifers. The fluctuations generally are of lesser magnitude because less recharge water reaches the confined aquifers. Also, the generally longer flowpaths, with a greater resistance to flow, through fine-grained material require more time for recharge water to leak to the confined aquifers.

Discharge

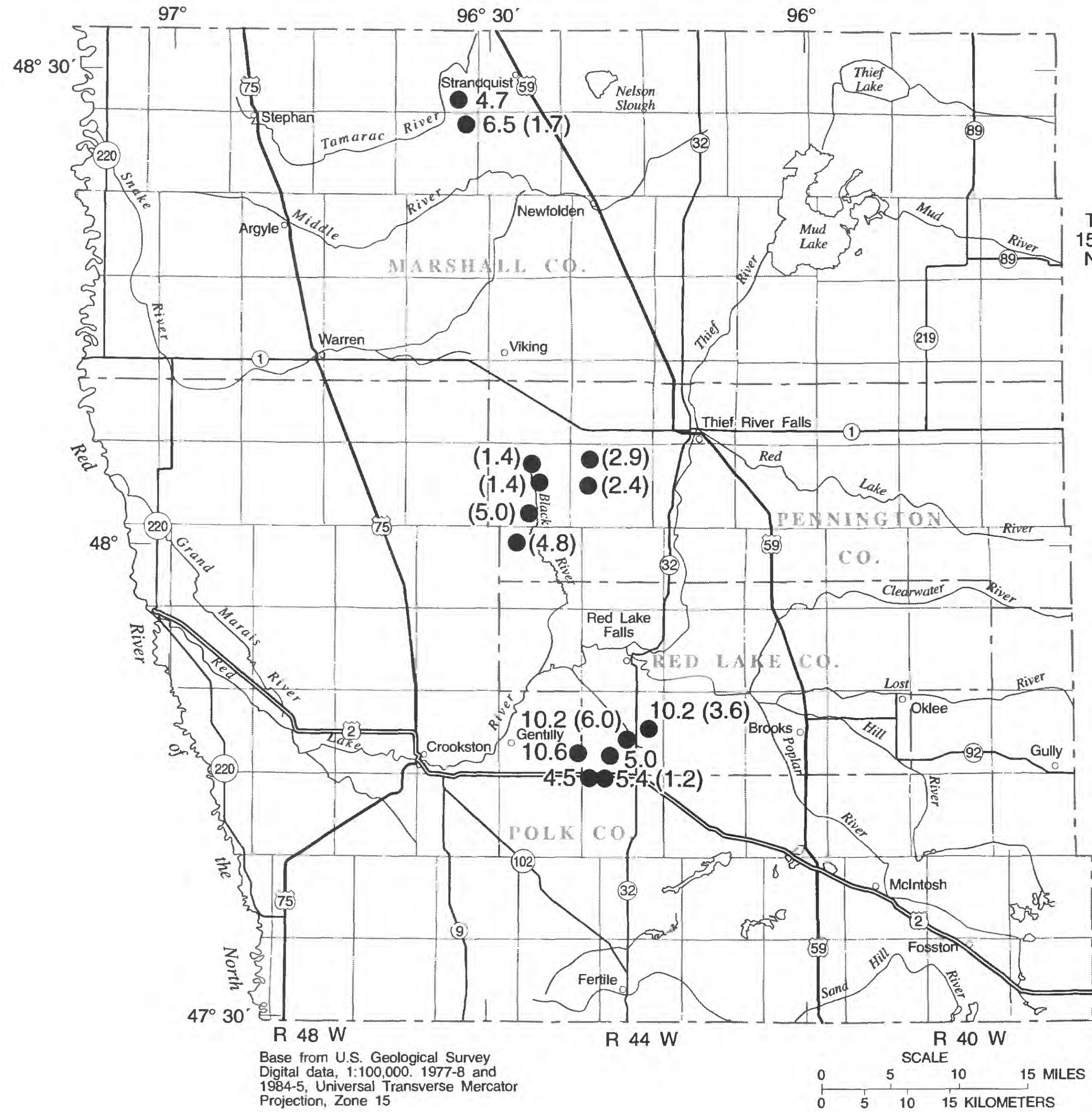
Discharge from ground water occurs by (1) seepage to streams, lakes, and wetlands, (2) ground-water evapotranspiration, and (3) withdrawals through wells.

Seepage to streams, lakes, and wetlands

Discharge from ground water to streams, lakes, and wetlands is a major component of ground-water flow in the study area. The Red River of the North, which constitutes the western boundary of the study area, is a regional ground-water discharge area. Substantial ground-water discharge occurs to large areas of wetlands near the northeastern Polk and eastern Pennington County lines and much of the eastern one-third of Marshall County. Ground water also discharges to wetlands that commonly border beach ridges composed of coarse-grained beach deposits (fig. 1) in the central part of the study area.

Ground-water evapotranspiration

Where the water table is at or near the land surface, such as in wetland areas, or where the water table is above the root zone or within reach of roots through capillary attraction, ground water discharges by direct evaporation from the water table and by transpiration by vegetation. Ground-water evapotranspiration is a function of the depth of the water table below land surface. As the depth to the water table increases, fewer plants have roots that extend deep enough to extract water from the water table and the evapotranspiration rate, therefore, decreases. Direct evaporation from the water table also decreases. Ground-water evapotranspiration is maximum where the water table is at land surface and decreases to zero where the water table is below the root-zone depth. The approximate maximum root-zone depth for vegetation in the study area is about 5 to 10 ft. The rate of ground-water



EXPLANATION

5.4 (1.2) ● Observation well screened in unconfined aquifer - Number without parentheses is estimated annual recharge, in inches, for 1992. Number in parentheses is estimated recharge, in inches, for fall (late August through October) of 1992.

Figure 32. Estimated recharge to unconfined aquifers.

evapotranspiration is assumed to be a maximum of 28 to 37 in./yr in the study area (Baker and others, 1979) where water levels are at land surface, based on mean annual pan evaporation rates. The amount of ground-water loss to evapotranspiration also depends on solar energy supplied, air temperature, and humidity of the air.

Large quantities of water are discharged from ground water through evapotranspiration during the summer. These losses decrease rapidly in the fall and are near zero in the winter. This seasonal variation in ground-water loss to evapotranspiration is approximately the same from year to year, provided the vegetation does not change significantly. Ground-water losses to evapotranspiration are probably greatest where large surface-water bodies are present and depth to ground water is shallow. Large ground-water losses to evapotranspiration occur from the wetland areas bordering beach ridges in the study area.

Withdrawals

Ground water is withdrawn in the study area primarily for public water supply, rural-domestic and livestock use, and irrigation. All of the withdrawals are from the drift aquifers. Ground-water use during 1985 and 1990 for the four counties in the study area is given in table 3. In 1990 total ground-water withdrawals in the study area were 6.0 Mgal/d. There were approximately 61,330 people living in the study area in 1990. About 37 percent of the people (22,950) were supplied through private wells, accounting for 2.11 Mgal/d of ground water. Public water suppliers (24) and private water suppliers (2) withdrew 2.46 Mgal/d of ground water. All but 5 percent of this water withdrawn by public and private water suppliers went to residential use, with commercial and industrial users splitting the remaining 5 percent.

Livestock operations used 0.85 Mgal/d of ground water in 1990. Pivot irrigation used 0.50 Mgal/d. Crop irrigation used 0.49 Mgal/d and other irrigation, primarily golf courses, used 0.01 Mgal/d. Other large ground-water users were self-supplied industrial, 0.04 Mgal/d, and commercial, 0.02 Mgal/d, interests.

Consumptive water use is that portion of withdrawals that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise not returned to the environment for immediate re-use. In 1990 consumptive water use, as a percentage of withdrawal, by category, was as follows: (1) livestock - 100 percent; (2) irrigation - 88 percent; (3) residential, self-supply - 85 percent; (4) residential, public supply - 15 percent; and (5) industrial - 0 percent (Gregory Mitton, U.S. Geological Survey, written commun., 1993). These percentages change little from year to year. Rural-domestic users (residential, self-supply) have a relatively high consumptive water use (85 percent) compared to users on public supply (15 percent). Most of the rural-domestic water used is piped to a septic system and is lost to the water supply because it is bound by soil particles or consumed by plants. Water used in a public supply system usually is returned to a sewer system and eventually to a water-supply source such as a river.

Ground-Water Flow

The regional direction of ground-water flow in the study area is from glacial moraine and glacial lake-washed till plain areas in the east to the Red River of the North at the western boundary. Ground-water flow in drift aquifers within and underlying beach deposits was investigated. Conceptually-based, numerical ground-water-flow models for two beach-ridge aquifer systems were constructed to gain a better understanding of ground-water flow and recharge to these local aquifer systems.

Regional flow

The general pattern of ground-water flow in the drift aquifers in the study area may be summarized in terms of entry of water to, movement within, and discharge of water from the study area. Water enters the drift aquifers by infiltration of precipitation and underflow from the east. Water moves through the study area predominantly from east to west in the aquifers. Water discharges from the drift aquifers by seepage to the Red River of the North, ground-water evapotranspiration, and withdrawals through wells.

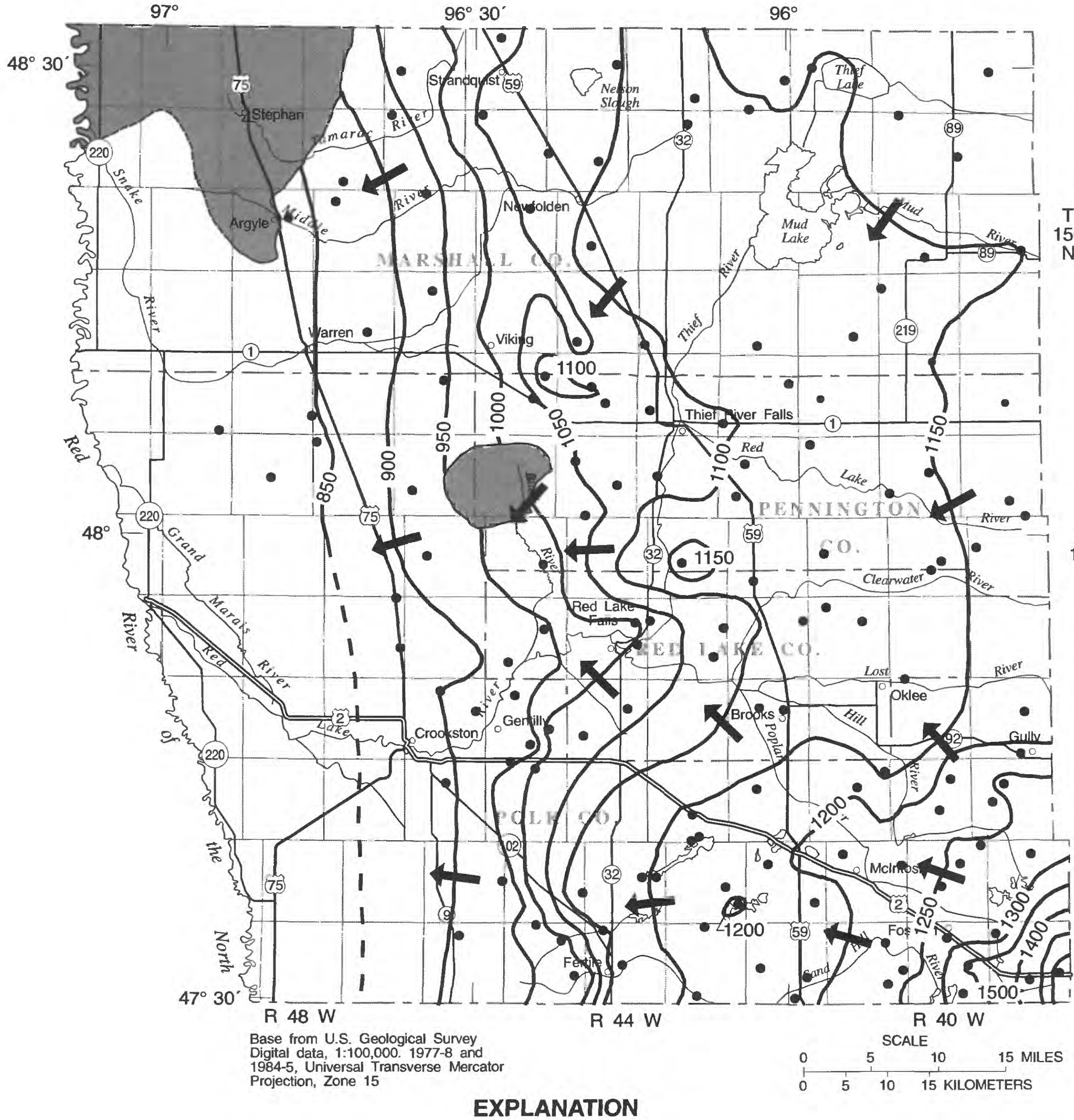
Ground water moves into the study area primarily where confined aquifers extend eastward beyond the boundaries of the study area. Some underflow into the study area through the unconfined aquifers may occur where small isolated surficial sand units are present at the boundaries (near Gully in eastern Polk County (Bidwell and others, 1970)).

Measured hydraulic heads in the confined aquifers indicate that the regional direction of ground-water flow is from east to west across the study area toward the Red River of the North (fig. 33). In Polk and Red Lake Counties in the southeastern part of the study area, ground water flows in a northwesterly direction toward the Clearwater and Red Lake Rivers.

Table 3.—Water use in study area during 1985 and 1990

[All water use in million gallons per day. PS, public supply; SS, self supply, <, less than]

County	Category of water use		1985	1990
Marshall	(population)		(12,800)	(10,990)
	Residential	- PS	0.45	0.49
	Rural-domestic	- SS	.31	.19
	Livestock	- SS	.19	.19
	Irrigation	- SS	<.01	<.01
	Industrial	- PS	.06	0
		- SS	<.01	<.01
	Commercial	- PS	.02	0
		- SS	.01	.01
Pennington	(population)		(13,880)	(13,310)
	Residential	- PS	.04	.02
	Rural-domestic	- SS	.29	.25
	Livestock	- SS	.16	.14
	Irrigation	- SS	<.01	<.01
	Industrial	- PS	<.01	0
		- SS	.01	<.01
	Commercial	- PS	<.01	<.01
		- SS	<.01	<.01
Polk	(population)		(34,200)	(32,500)
	Residential	- PS	.48	1.07
	Rural-domestic	- SS	1.72	1.50
	Livestock	- SS	.38	.35
	Irrigation	- SS	.09	.50
	Industrial	- PS	.06	.06
		- SS	.06	.02
	Commercial	- PS	.03	.03
		- SS	<.01	.01
Red Lake	(population)		(5,150)	(4,530)
	Residential	- PS	1.10	.80
	Rural-domestic	- SS	.22	.17
	Livestock	- SS	.15	.17
	Irrigation	- SS	<.01	<.01
	Industrial	- PS	.13	0
		- SS	<.01	<.01
	Commercial	- PS	.07	<.01
		- SS	<.01	<.01



EXPLANATION

No glacial-deposit aquifers present - Boundary dashed where approximate

Potentiometric contour - Shows altitude at which water level would have stood in tightly cased wells open to confined aquifers. Dashed where inferred. Contour interval 50 feet. Datum is sea level

Generalized direction of ground-water flow

Well log used for control

Figure 33. Composite potentiometric surface of shallow, intermediate, deep, and basal confined aquifers, December 1991 to February 1992.

The horizontal hydraulic gradient in the confined aquifers ranges from about 2 to 50 ft/mi in the study area, as inferred from the spacing of the potentiometric-surface contours (fig. 33). The largest hydraulic gradients are in the glacial moraine areas in southeastern and south-central Polk County, corresponding with large changes in land surface elevations. The smallest hydraulic gradients are in the extremely flat glacial lake plain area in the western part of the study area and in flat to very gently rolling glacial lake-washed till plain and peat areas in the northeastern and east-central parts of the study area.

Hydraulic heads in the confined aquifers in some areas are above land-surface altitude and wells screened in confined aquifers in these areas will flow. Flowing artesian wells are numerous in the lowland areas of Polk County. They are particularly common just below the prominent slopes near the beach ridges. In Red Lake County, wells situated in low areas in the valley of the Red Lake River or its tributaries will flow. In Pennington County, some wells located between or west of the beach ridges will flow. In Marshall County, flowing wells are present west and southwest of Newfolden and near Strandquist. The wells are located in depressions that are occupied by the Tamarack, Middle, and Snake Rivers. Flowing wells are also common in the western townships of Marshall County; upward seepage of water from the underlying Cretaceous bedrock probably increases the hydraulic head of water from the confined aquifers.

Flow in aquifers is predominantly horizontal, whereas flow in confining units is predominantly vertical, due to differences in grain size and hydraulic conductivities for the materials comprising the units. Water moves vertically upward from deeper to more shallow aquifers in areas of regional discharge, including the area underlying the Red River of the North.

Local flow in beach-ridge aquifer systems

Numerical models of ground-water flow were constructed to represent the Polk-Red Lake Counties and Pennington County beach-ridge aquifer systems. The computer code used in this study was the U.S. Geological Survey modular three-dimensional finite-difference ground-water-flow model developed by McDonald and Harbaugh (1988). The model uses finite-difference methods to obtain approximate solutions to partial-differential equations of ground-water flow. The model incorporates horizontal- and vertical-flow equations, hydraulic characteristics of aquifers, and rates of recharge to and discharge from the aquifer system to determine hydraulic heads in the aquifers. The model was used to simulate steady-state conditions only. Under steady-state conditions there are no long-term changes in storage in the aquifer system.

Polk-Red Lake Counties beach-ridge aquifer system

A conceptual model—a qualitative description of the known characteristics and functioning of the aquifer system—was formulated from knowledge of the hydrogeologic setting, aquifer characteristics, distribution and amount of recharge and discharge, and aquifer boundaries. A numerical model of ground-water flow was constructed based on the conceptual model of the aquifer system.

Model description The study area was subdivided into rectangular finite-difference grid cells within which the properties of the hydrogeologic unit represented are assumed to be uniform. The center of a grid cell is referred to as a node and represents the location for which the hydraulic head is computed by the model. Properties of the hydrogeologic units and stresses are assigned to the cells and are assumed to represent average conditions within grid cells.The variably-spaced finite-difference grid used to spatially discretize the model area has 57 rows and 59 columns (fig. 34). Notation of the form (11, 24) where the first number in parentheses indicates the row and the second number indicates the column, is used to refer to the location of an individual cell within the grid. The dimensions of the grid cells, ranging from 660 to 2,220 ft along rows and from 1,320 to 4,450 ft along columns, increase toward the edges of the model area; therefore, hydrologic properties assigned to the outer cells are averaged over larger areas than for cells near the center of the model area. The smallest cells are in the central part of the grid, where the most detailed hydrogeologic information is available.

The beach-ridge aquifer system in the model area was subdivided vertically into 3 layers, corresponding to generally horizontal hydrogeologic units. The thickness of a cell representing a hydrogeologic unit is incorporated in the transmissivity term for the cell.

Simulation of water leakage between model layers is dependent on the thicknesses and vertical hydraulic conductivities of adjacent layers and the hydraulic head difference between adjacent layers. A more detailed discussion of leakage of water between model layers is given in the Supplemental Information section at the end of this report.

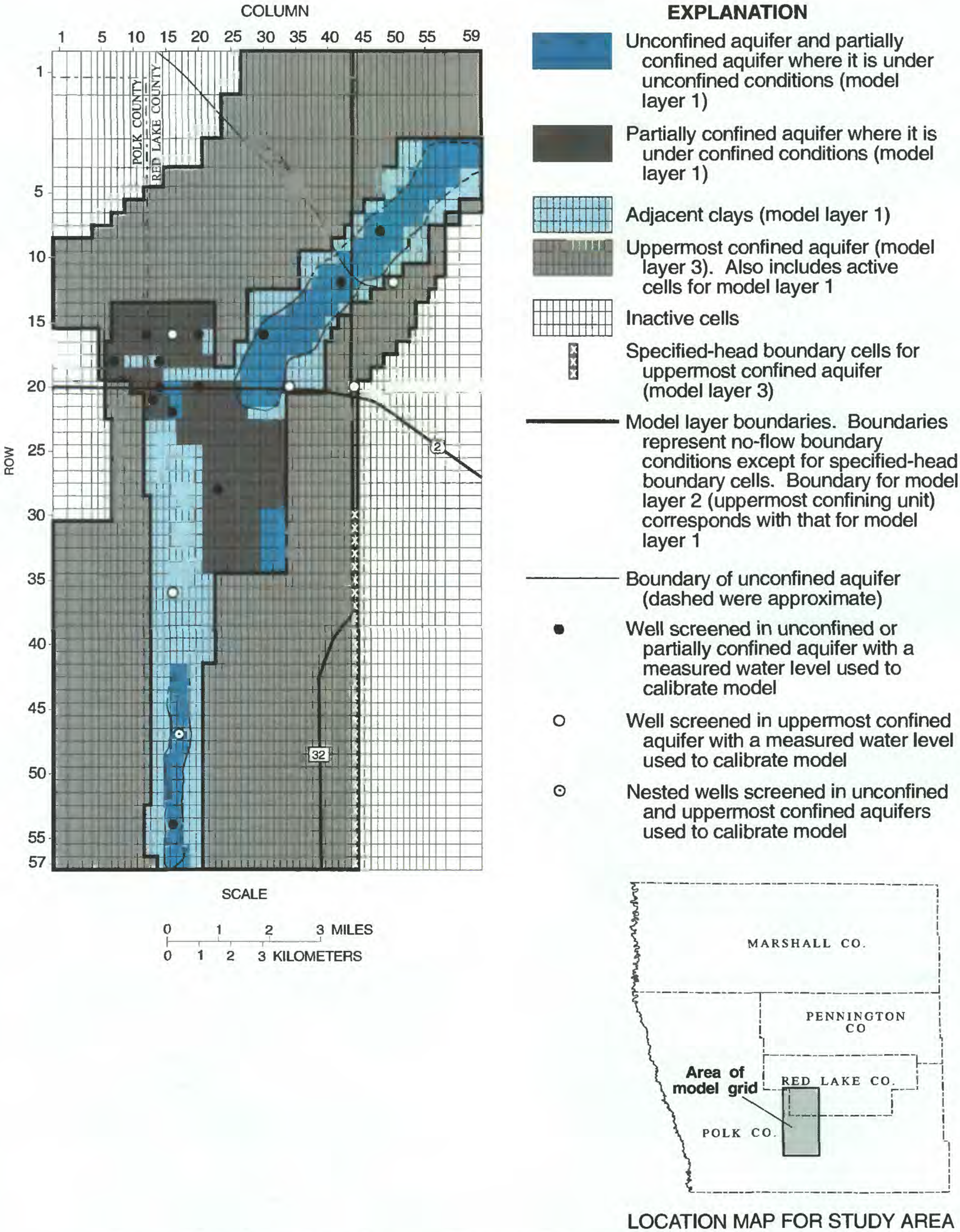


Figure 34. Grid and boundary conditions for finite-difference ground-water-flow model of Polk-Red Lake Counties beach-ridge aquifer system.

The hydrogeologic units represented in the ground-water-flow model are (1) the unconfined aquifer and laterally adjacent low-permeability deposits and the partially confined aquifer (model layer 1), (2) the uppermost confining unit (model layer 2), and (3) the uppermost confined aquifer (model layer 3). The low-permeability deposits laterally adjacent to the unconfined aquifer are hereinafter referred to as the adjacent clays. These adjacent clays consist of clayey to sandy till, silt, and clay and are a source of water to the adjoining sand and gravel aquifer by lateral flow. The top of the partially confined aquifer coincides with the water-table surface in areas where it is unconfined, and with the altitude of the base of the overlying confining unit in areas where it is under confined conditions. The effects of the confining unit overlying the partially confined aquifer are incorporated in the model by reducing the amount of simulated recharge to the model cells representing the aquifer in areas where it is under confined conditions. The uppermost confining unit impedes the leakage of water between the unconfined and partially confined aquifers and the uppermost confined aquifer.

The transmissivities associated with the model cells representing the unconfined aquifer and adjacent clays and the partially confined aquifer, where it is under unconfined conditions, vary as the saturated thicknesses varies. The transmissivities assigned to the model cells representing the uppermost confining unit and uppermost confined aquifer are constant in time.

A number of simplifying assumptions about the beach-ridge aquifer system and boundary condition specifications were required to make mathematical representation of the aquifer system possible:

1. The volume of water that moves vertically across the bottom of the uppermost confined aquifer is small relative to lateral flow.

2. The hydraulic heads at arbitrarily imposed lateral boundaries where the natural hydrologic boundaries lie outside the model area during the winter months (December to February) represent steady-state conditions.

3. Ground-water flow is predominantly horizontal in the aquifers. Ground-water flow is vertical in the confining units and the low-permeability deposits laterally adjacent to the unconfined aquifer (adjacent clays, model layer 1).

4. Ground-water evapotranspiration is a linear function of the depth of the water table below land surface.

The volume of water that moves vertically through the base of the uppermost confined aquifer is considered small, relative to lateral flow in that aquifer, and its base is treated as a no-flow boundary. Significant movement of water vertically through the base of the uppermost confined aquifer, violating the assumption of a no-flow boundary, could result in the simulated mass fluxes being too high or too low. For example, if leakage of water downward through the base of the uppermost confined aquifer actually does occur, the areal recharge required for reasonable simulation of hydraulic heads by the model could be too low. Simulated hydraulic heads would be relatively insensitive to possible leakage through the base of the simulated beach-ridge aquifer system.

Ideally, all model boundaries should be located at the physical limits of the aquifer system or at other hydrologic boundaries, such as a major river. Practical considerations, such as limitations concerning the size of the area modeled may necessitate the use of arbitrarily imposed model boundaries where the natural hydrologic boundaries lie outside the model area. The simulated boundaries for the unconfined and partially confined aquifers are located at the physical limits of the aquifers. However, model layer 1 includes the low-permeability deposits laterally adjacent to the unconfined aquifer. The outer boundaries for these deposits were arbitrarily imposed and do not coincide with the physical limits of the deposits. Simulated horizontal ground-water flow between the adjacent clays and the unconfined aquifer is dependent on the hydraulic heads and hydraulic conductivities assigned to the adjacent model cells. The boundaries for model layer 2, representing the uppermost confining unit, are arbitrarily imposed to coincide with the boundaries for model layer 1. Because flow in confining units is predominantly vertical, no-flow boundary conditions were used for all lateral boundaries for model layer 2. Figure 34 shows the modeled extents and boundary conditions for the unconfined aquifer and adjacent clays and the partially confined aquifer (model layer 1).

The northern and western boundaries and the northern part of the eastern boundary for model layer 3, representing the uppermost confined aquifer, represent the approximate physical extent of the aquifer and therefore no-flow boundary conditions were used. The southern boundary is also represented using a no-flow boundary because the predominant direction of flow near the boundary is from east to west, parallel to the boundary. The southern part of the eastern boundary is arbitrarily imposed and specified-head boundary conditions were used. The hydraulic heads at these boundary cells were held constant because the available data indicate that long-term changes in ground-water levels are not significant in these areas. The southern part of the eastern boundary was located to coincide with locations where hydraulic head information was available. Figure 34 shows the modeled extent and boundary conditions for model layer 3.

The effect of the use of no-flow boundary conditions at the arbitrary lateral boundaries for model layer 1 on hydraulic heads and fluxes in the beach-ridge aquifer system was investigated by using specified-head boundaries in place of no-flow boundaries for steady-state conditions. Changing from no-flow boundaries to specified-head boundaries for model layer 1 had little effect on the simulated hydraulic heads. The changes in hydraulic heads in model layer 1 and in model layer 3 were 1 ft or less. Changes in the simulated water budget indicated that using specified-head boundaries resulted in water flowing both into and out of the beach-ridge aquifer system through model-layer-1 boundaries. Water entered the beach-ridge aquifer system through model-layer-1 boundaries at a rate of 0.9 ft^3/s, compared to 7.0 ft^3/s for recharge from infiltration of precipitation. Water discharged from the beach-ridge aquifer system through model-layer-1 boundaries at a rate of 2.3 ft^3/s. Most of the boundary inflow through model layer 1 occurred in the northern part of the beach-ridge aquifer system and most of the boundary outflow occurred in the southern part. The net boundary flow using specified-head boundaries for model layer 1 was -1.4 ft^3/s, compared to a net boundary flow of 0.0 ft^3/s using no-flow boundaries.

The effect of the use of specified-head boundary conditions for the southern part of the eastern boundary of model layer 3 on hydraulic heads and fluxes in the beach-ridge aquifer system was investigated by using no-flow boundaries in place of specified-head boundaries for steady-state conditions. Changing from a specified-head boundary to a no-flow boundary for the southern part of the eastern boundary of model layer 3 resulted in declines in hydraulic heads of as much as (1) 15 ft in model layer 1 with a mean decline of 4.7 ft, and (2) 55 ft in model layer 3 with a mean decline of 12.4 ft. Declines in hydraulic head resulting from the change in boundary conditions were 5 ft or less north of model rows 22 and 21 for model layer 1 and model layer 3, respectively. Ground-water inflow from the southeast is a significant source of water to the Polk-Red Lake Counties beach-ridge aquifer system.

A specified-flux boundary was used to represent recharge by the infiltration of precipitation to the unconfined aquifer and adjacent clays and to the partially confined aquifer in areas where it is under unconfined conditions (model layer 1). A specified-flux boundary was also used to represent leakage to the partially confined aquifer (model layer 1) through overlying till and clay in areas where it is under confined conditions and leakage from overlying deposits to the uppermost confined aquifer (model layer 3). Leakage to model layer 3 was specified only for the area outside the boundaries of model layers 1 and 2.

Discharge is by evapotranspiration from the unconfined aquifer and adjacent clays and from the partially confined aquifer in areas where it is under unconfined conditions (model layer 1). The model simulates evapotranspiration from the saturated zone only; it does not simulate evapotranspiration of soil water in the unsaturated zone. The assumption was made that evaporation from lakes was a reasonable estimate of the maximum ground-water evapotranspiration rate that occurs when the water table is at the land surface. A commonly accepted estimate for lake evaporation rates is about 75 percent of the observed class A pan-evaporation rates (National Oceanic and Atmospheric Administration, 1982). In the model area, the mean annual pan-evaporation rate is about 35 in. (Baker and others, 1979), which corresponds to an estimated average annual lake-evaporation rate of 26.25 in. The initial maximum ground-water evapotranspiration rate specified in the model, therefore, was 26.25 in./yr. The ground-water evapotranspiration rate in the model decreases linearly with depth below land surface and becomes zero at the extinction depth. As the depth to the water table increases, fewer plants have roots that extend deep enough to extract water from the saturated zone and the evapotranspiration rate, therefore, decreases. The extinction depth corresponds to a depth below land surface minimally greater than the rooting depth of the plants present. The plausible range for evapotranspiration extinction depth was assumed to be from 5 to 10 ft with an average value of 7 ft. The elevation of the land surface for each cell was determined from U.S. Geological Survey 7.5-minute topographic quadrangle maps.

The initial values of hydraulic properties and fluxes represented in the model are listed in table 4. Initial values for hydraulic conductivity for each hydrogeologic unit were based on slug tests, aquifer tests, and grain-size analyses done for this study, and published values in the literature (table 4). Initial values for recharge assigned to the model cells representing the unconfined and partially confined aquifers (model layer 1) were estimated using hydrograph analysis. Recharge

Table 4.—Initial and final (best-match) calibration values of hydraulic properties and fluxes in steady-state simulation of Polk-Red Lake Counties beach-ridge aquifer system

[ft, feet; ft/d, feet per day; ft^2/d, feet squared per day; in./yr, inches per year]

Hydraulic property or flux and hydrogeologic unit	Initial value	Final calibration value
Recharge or leakage (in./yr)		
Unconfined aquifer	8.0	8.0
Adjacent clays	4.0	4.5
Partially confined aquifer		
Areas where aquifer is unconfined	8.0	8.0
Areas where aquifer is confined	4.0	0
Uppermost confined aquifer	2.0	0
Horizontal hydraulic conductivity (ft/d)		
Unconfined aquifer	150	200-300
Adjacent clays	10-20	10-50
Partially confined aquifer	550	100-550
Uppermost confining unit	1.0	1.0
Uppermost confined aquifer	50-100	50-300
Transmissivity (ft^2/d)		
Uppermost confining unit	100	100
Uppermost confined aquifer	600-1,200	600-3,600
Vertical hydraulic conductivity (ft/d)		
Unconfined aquifer	15	20-30
Adjacent clays	.1-.2	.1-.5
Partially confined aquifer	55	10-55
Uppermost confining unit	.02	.02-.001
Uppermost confined aquifer	5-10	5-30
Evapotranspiration rate (in./yr)	26.25	22.75
Extinction depth (ft)	7	5

assigned to the cells representing the adjacent clays (model layer 1) was estimated to be 4 in./yr (table 4), based on recharge rates for Des Moines lobe till reported by Stark and others (1991, p. 45). Leakage to the uppermost confined aquifer (model layer 3) was estimated to be 2 in./yr (table 4), based on leakage rates reported by Delin (1988, 1990) and Lindgren (1990).

Model calibration Model calibration is the process in which initial estimates of aquifer properties and boundary conditions are adjusted until simulated hydraulic heads and ground-water flows adequately match measured water levels and flows. Calibration and evaluation of the ground-water-flow model were conducted for steady-state (equilibrium), or long-term average, conditions. No storage terms are included in the steady-state simulation. Under steady-state conditions, the amount of water entering the aquifer system equals the amount of water leaving the system and there are no long-term changes in storage. Measured hydraulic heads in the beach-ridge aquifer system during December 1992 were used to define boundary conditions and calibrate the model in the steady-state simulation. Measured hydraulic heads in the aquifers during the winter months (December to February) are assumed to be representative of steady-state conditions. Available measurements indicate that hydraulic heads in the aquifers generally recover quickly to about the same level during the winter months each year following the lessening of withdrawals by wells in the late summer and fall.

The model was calibrated by varying, within reasonable limits, the simulated values of hydraulic properties of the beach-ridge aquifer system (horizontal and vertical hydraulic conductivity), recharge to the model cells representing the low-permeability deposits laterally adjacent to the unconfined aquifer (adjacent clays, model layer 1), leakage to the model cells representing the partially confined aquifer (model layer 1) and uppermost confined aquifer (model layer 3), and the simulated evapotranspiration rate and extinction depth until simulated hydraulic heads acceptably matched measured water levels. The values of simulated hydraulic properties and fluxes resulting in the best match between measured water levels and simulated hydraulic heads are listed in table 4. The initially uniform horizontal hydraulic conductivity of 550 ft/d for model cells representing the partially confined aquifer (model layer 1) was changed to a variable distribution ranging from 100 to 550 ft/d. The horizontal hydraulic conductivity for model cells representing the unconfined aquifer (model layer 1) was decreased from 300 to 200 ft/d in model rows 42 to 50. The horizontal hydraulic conductivity for cells representing the adjacent clays (model layer 1) was increased to 50 ft/d in an area east of the Crookston city well field and to 25 ft/d south of the well field. The vertical hydraulic conductivity of the uppermost confining unit (model layer 2) was decreased by factors of 10 to 20 in the southern part of the beach-ridge aquifer system. The transmissivity of the uppermost confined aquifer (model layer 3) was increased by factors of 1.5 to 3.0 in the southern part of the model area. Recharge to the model cells representing the adjacent clays was increased from 4.0 to 4.5 in./yr. The maximum evapotranspiration rate was reduced to 22.75 in./yr and the extinction depth was changed from 7 ft to 5 ft.

Leakage to model cells representing the partially confined aquifer (model layer 1) in areas where it is under confined conditions and to the uppermost confined aquifer (model layer 3) was reduced to 0.0 in./yr to produce a better match between simulated hydraulic heads and measured water levels. The calibration best-match value for leakage of 0.0 in./yr may represent the net recharge to model layer 3. If leakage of water downward through the base of the uppermost confined aquifer actually does occur, violating the assumption of a no-flow boundary used in the model simulations, leakage to the aquifer could be greater than 0.0 in./yr. For example, 1.0 in./yr of leakage through the base of the uppermost confined aquifer would, in effect, negate 1.0 in./yr of simulated leakage to the aquifer from overlying deposits. The net amount of water added to the aquifer would be 0.0 in./yr. However, no local recharge (leakage through till) to a confined aquifer overlain by 50 to 100 ft of till is not unreasonable.

The effect of treating the base of the uppermost confined aquifer (model layer 3) as a no-flow boundary on fluxes in the aquifer system was investigated by adding hypothetical hydrogeologic units to the model. A hypothetical confining unit (model layer 4) and a hypothetical aquifer (model layer 5) were added to the model underlying the uppermost confined aquifer (model layer 3). The simulated fluxes through the bottom of model layer 3, representing the uppermost confined aquifer, were about 4 ft^3/s (0.8 in./yr) in both an upward and downward direction. The net flux was downward at a rate of only 0.09 ft^3/s, or less than 0.02 in./yr, indicating little net leakage through the base of model layer 3.

The simulated hydraulic heads for the model cells representing the unconfined and partially confined aquifers (model layer 1) are within 3 ft of measured water levels in 14 wells for which water-level data were available. The absolute value of the average difference between simulated and measured hydraulic heads for the 14 wells is 1.93 ft. The simulated hydraulic heads for model cells representing the uppermost confined aquifer (model layer 3) are within 5 ft of measured water levels in 6 wells for which water-level data were available. The absolute value of the average difference between simulated and measured hydraulic heads for the 6 wells is 3.17 ft.

Simulated water budget and flow The simulated water budget is shown in table 5. Recharge from infiltration of precipitation accounts for about 73 percent of the sources of water to the Polk-Red Lake Counties aquifer system and boundary inflow accounts for the remaining 27 percent. About 86 percent of the discharge from the beach-ridge aquifer system is by evapotranspiration and about 14 percent is by withdrawals from wells. Water flows vertically through the uppermost confining unit (model layer 2) in

Table 5.—Simulated water budget for steady-state simulation of Polk-Red Lake Counties beach-ridge aquifer system

[Numbers in parentheses are percentages of total sources or of total discharges; --, not applicable]

Budget component	Source (cubic feet per second)	Discharge (cubic feet per second)
Recharge (from precipitation) to layer 1	8.33 (73)	--
Flow from specified-head boundary		
Layer 3	3.07 (27)	--
Evapotranspiration	--	9.75 (86)
Pumpage		
Layer 1	--	.68 (6)
Layer 3	--	.97 (8)
Subtotal	--	1.65 (14)
Total	11.40	11.40
Leakage between model layers through uppermost confining unit		
Layer 1	3.63	1.54
Layer 3	1.49	3.58
Total	5.12	5.12

both downward and upward directions. The model simulation indicates a net leakage of 2.09 ft^3/s to model cells representing the unconfined aquifer, adjacent clays, and partially confined aquifer (model layer 1), from model cells representing the uppermost confined aquifer (model layer 3), through model cells representing the uppermost confining unit (model layer 2). The simulation indicates more water is leaking upward from the uppermost confined aquifer to the overlying aquifers in the Polk-Red Lake Counties beach-ridge aquifer system than is leaking downward from the overlying aquifers to the uppermost confined aquifer.

Figure 35 shows the directions of simulated vertical ground-water flow between model layer 1and model layer 3. The vertical direction of ground-water flow is generally downward in the northern part of the beach-ridge aquifer system and generally upward in the southern part. Comparative measured potentiometric surfaces of the aquifers resulting in the simulated flow directions are shown on the hydrogeologic sections in figure 28.

Sensitivity analysis A model-sensitivity analysis, wherein a single hydraulic property or flux is varied while all other properties and fluxes are held constant, was done to identify the relative effect of adjustments of hydraulic properties and fluxes on simulated hydraulic heads. The degree to which the properties and fluxes can be adjusted is related to the uncertainty associated with each. Adjustments were kept within reported or plausible ranges of values (tables 6 and 7). With the exception of changes in ground-water withdrawals, simulated hydraulic heads were most sensitive to changes in (1) recharge from precipitation, (2) horizontal hydraulic conductivity for model layer 1, representing the unconfined aquifer, adjacent clays, and partially confined aquifer, and (3) transmissivity for the uppermost confined aquifer (model layer 3). Simulated hydraulic heads in model layer 3 were most sensitive to a decrease (by a factor of 0.1) in the vertical

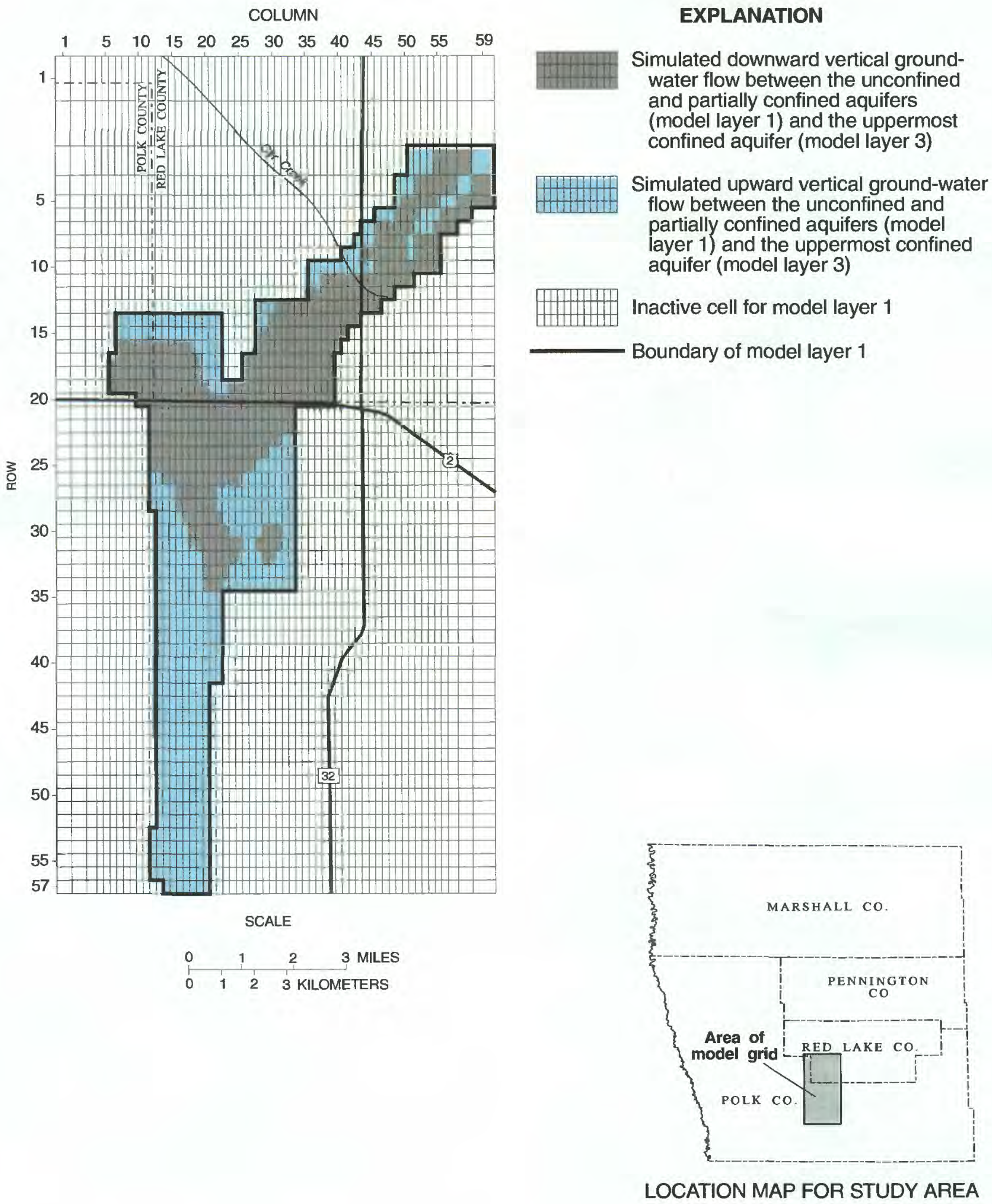


Figure 35. Directions of simulated vertical ground-water flow between the unconfined and partially confined aquifers (model layer 1), and the uppermost confined aquifer (model layer 3).

Table 6.—Sensitivity of hydraulic heads in the unconfined aquifer, adjacent clays, and partially confined aquifer (model layer 1) to changes in values of hydraulic properties and fluxes in steady-state simulation for Polk-Red Lake Counties beach-ridge aquifer system

[Absolute value of mean deviation of hydraulic heads from values calculated by best-match simulation; deviation calculated at all active cells for model layer 1; --, all deviations of hydraulic heads from values calculated by best-match simulation are positive or all deviations are negative]

Hydraulic property or flux	Multiplied by factor of	Absolute value of mean deviation of hydraulic heads (feet)	Maximum positive deviation (feet)	Maximum negative deviation (feet)
Recharge (from precipitation) to layer 1	1.5	3.0	6.0	--
Recharge (from precipitation) to layer 1	.5	3.6	--	7.0
Horizontal hydraulic conductivity of layer 1	2.0	2.1	5.0	6.0
Horizontal hydraulic conductivity of layer 1	.5	2.3	6.0	11.0
Transmissivity of layer 2	2.0	.1	1.0	1.0
Transmissivity of layer 2	.5	.1	1.0	1.0
Transmissivity of layer 3	2.0	2.1	10.0	1.0
Transmissivity of layer 3	.5	1.5	1.0	8.0
Vertical hydraulic conductivity of layer 2	10.	1.2	8.0	5.0
Vertical hydraulic conductivity of layer 2	.1	1.1	4.0	5.0
Evapotranspiration rate	1.2	.7	--	5.0
Evapotranspiration rate	.8	1.3	7.0	--
Withdrawals from layers 1 and 3	1.5	2.0	--	12.0

hydraulic conductivity of model layer 2, representing the uppermost confining unit. Simulated hydraulic heads in the aquifer system were relatively insensitive to changes in the transmissivity of the uppermost confining unit.

The effects on hydraulic heads of increasing withdrawals from the Polk-Red Lake Counties aquifer system were also investigated. Increasing withdrawals by a factor of 2.0 from all 4 wells of the Crookston city well field resulted in hydraulic heads in model cells representing the partially confined aquifer (model layer 1) and uppermost confined aquifer (model layer 3) declining below the bottoms of the aquifers in the model cells in a large area around the pumping wells. The simulation indicates that doubling the withdrawals by the current Crookston city wells would not be feasible. A second simulation was done by increasing withdrawals from all 4 wells of the Crookston city well field by a factor of 1.5. This simulation resulted in a mean increased decline in hydraulic heads from the best-match simulation of 2.0 ft for model layer 1 and 1.7 ft for model layer 3 (tables 6 and 7). The maximum increased decline in hydraulic head (as compared to best-match simulation hydraulic heads) was 12 ft for model layer 1 and 40.5 ft for model layer 3. The areal distributions of increased drawdowns resulting from the increased simulated withdrawals are shown in figures 36 and 37. A third simulation was done by increasing withdrawals from the 2 wells of the Crookston city well field, screened in the partially confined aquifer (model layer 1), by a factor of 1.5 resulted in a maximum increased decline in hydraulic head of 6.0 ft in model layer 1 and 3.0 ft in model layer 3. A fourth simulation was done by increasing ground-water withdrawals from the 2 wells of the Crookston city well field, screened in

Table 7.—Sensitivity of hydraulic heads in the uppermost confined aquifer (model layer 3) to changes in values of hydraulic properties and fluxes in steady-state simulation for Polk-Red Lake Counties beach-ridge aquifer system

[Absolute value of mean deviation of hydraulic heads from values calculated by best-match simulation; deviation calculated at all active cells for model layer 3; --, indicates all deviations of hydraulic heads from values calculated by best-match simulation are positive or all deviations are negative]

Hydraulic property or flux	Multiplied by factor of	Absolute value of mean deviation of hydraulic heads (feet)	Maximum positive deviation (feet)	Maximum negative deviation (feet)
Recharge (from precipitation) to layer 1	1.5	2.4	5.0	--
Recharge (from precipitation) to layer 1	.5	2.6	--	6.0
Horizontal hydraulic conductivity of layer 1	2.0	1.1	4.0	6.0
Horizontal hydraulic conductivity of layer 1	.5	1.2	5.0	7.0
Transmissivity of layer 2	2.0	.1	2.0	1.0
Transmissivity of layer 2	.5	.1	1.0	1.0
Transmissivity of layer 3	2.0	3.5	29.1	1.0
Transmissivity of layer 3	.5	2.7	1.0	42.6
Vertical hydraulic conductivity of layer 2	10.0	2.7	31.1	8.0
Vertical hydraulic conductivity of layer 2	.1	6.4	15.0	33.6
Evapotranspiration rate	1.2	.7	--	3.0
Evapotranspiration rate	.8	1.2	5.0	--
Withdrawals from layers 1 and 3	1.5	1.7	--	40.5

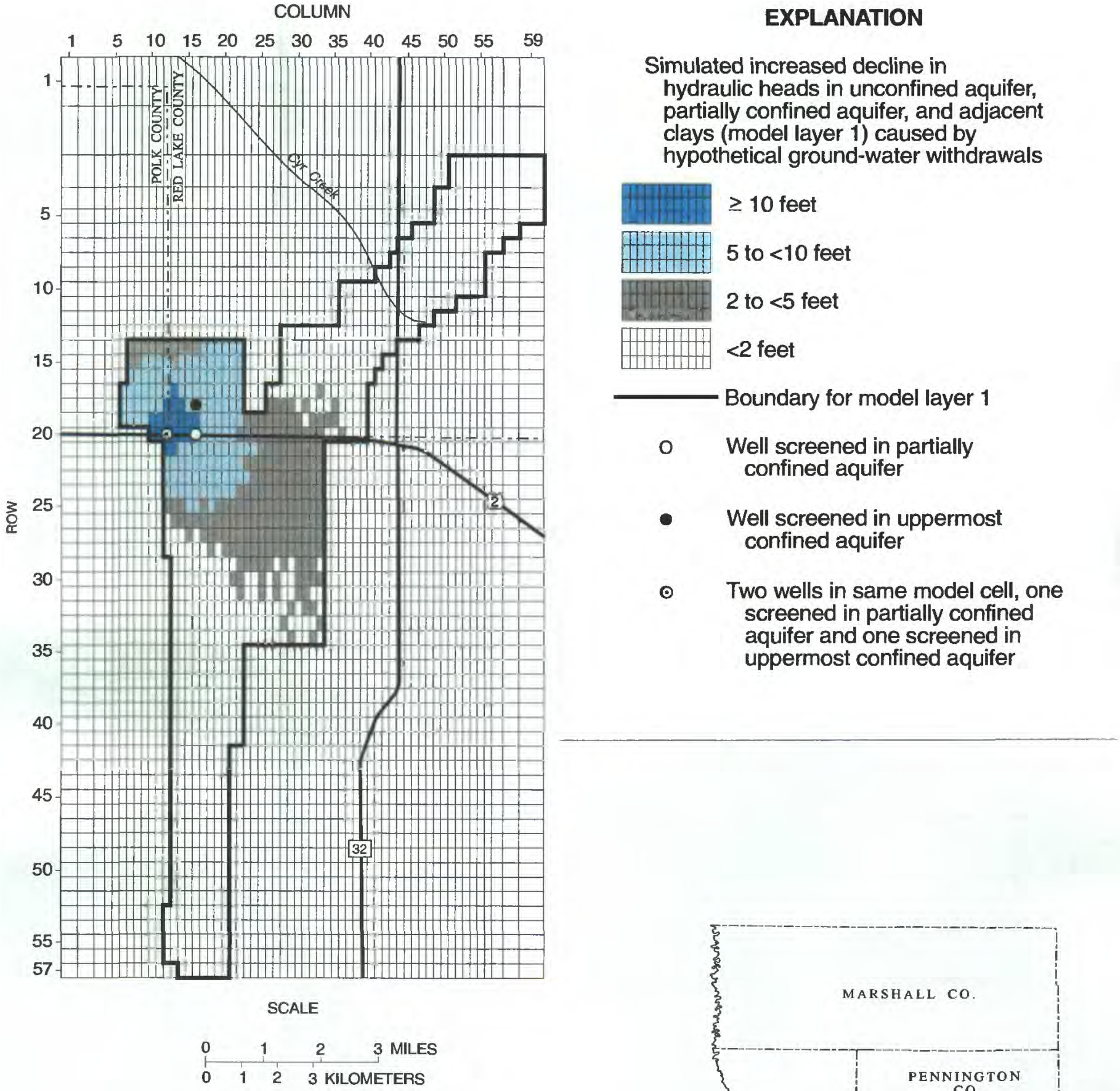
the uppermost confined aquifer (model layer 3), by a factor of 1.5 resulted in a maximum increased decline in hydraulic head of 5.0 ft in model layer 1 and 36.2 ft in model layer 3.

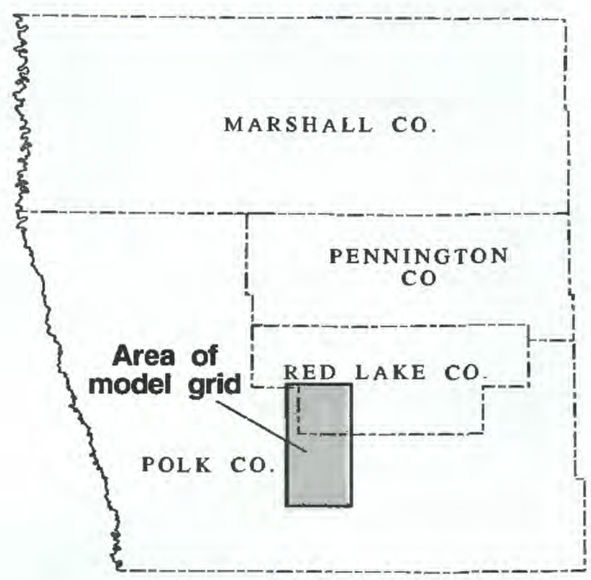
The indicated declines in hydraulic heads due to increasing ground-water withdrawals represent average, steady-state drawdowns resulting from simulated withdrawal rates distributed evenly over the year. Seasonal drawdowns resulting from temporally variable withdrawal rates would probably be much greater during periods of large withdrawals or low recharge to the aquifers. The simulated drawdowns illustrate general long-term trends only and should not be regarded as predictive or used for well-field management.

Pennington County beach-ridge aquifer system

The Pennington County beach-ridge aquifer system is less complex than the Polk-Red Lake Counties beach-ridge aquifer system because there is no partially confined aquifer. Also, the unconfined aquifer is hydraulically connected to an underlying uppermost confined aquifer only in the northern part of the Pennington County beach ridge. The uppermost confined aquifer is absent in the southern part of the Pennington County beach ridge.

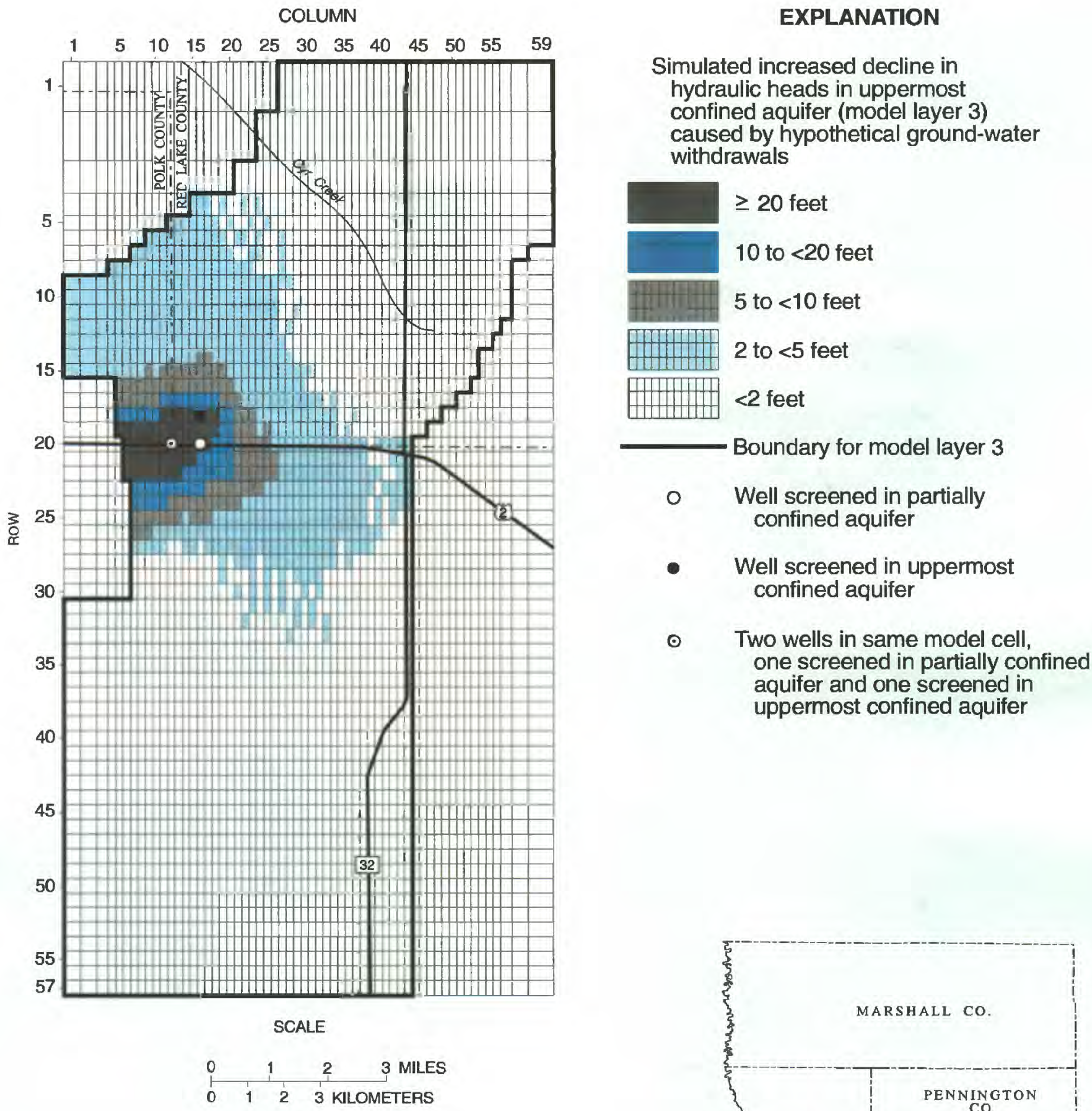
Model description The uniform finite-difference grid used to spatially discretize the model area has 46 rows and 42 columns (fig. 38). The dimensions of the grid cells are 660 ft along rows and 1,320 ft along columns.

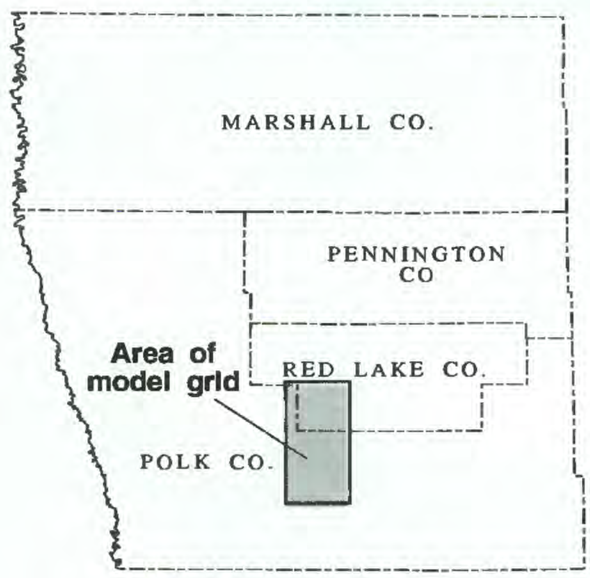




LOCATION MAP FOR STUDY AREA

Figure 36. Simulated increased declines in hydraulic heads in the unconfined aquifer, partially confined aquifer, and adjacent clays (model layer 1) in the Polk-Red Lake Counties beach-ridge aquifer system for steady-state simulation of additional ground-water withdrawals from the partially confined and uppermost confined aquifers.





LOCATION MAP FOR STUDY AREA

Figure 37. Simulated increased declines in hydraulic heads in the uppermost confined aquifer (model layer 3) in the Polk-Red Lake Counties beach-ridge aquifer system for steady-state simulation of additional ground-water withdrawals from the partially confined and uppermost confined aquifers.

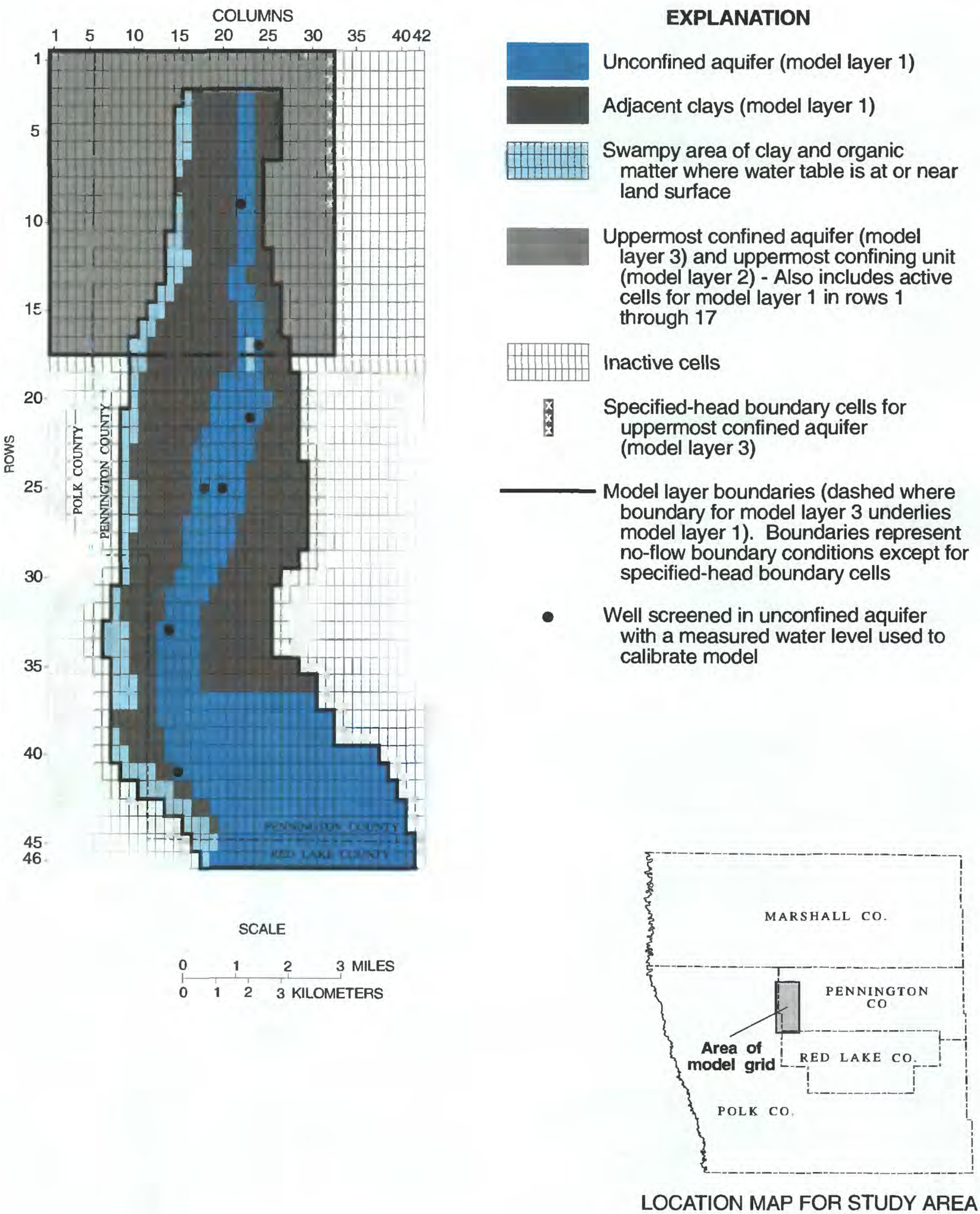


Figure 38. Grid and boundary conditions for finite-difference ground-water-flow model of Pennington County beach-ridge aquifer system.

The hydrologic units represented in the ground-water-flow model are (1) the unconfined aquifer and laterally adjacent low-permeability deposits (model layer 1), (2) the uppermost confining unit (model layer 2), and (3) the uppermost confined aquifer (model layer 3). The low-permeability deposits laterally adjacent to the unconfined aquifer are hereinafter referred to as the adjacent clays. These adjacent clays consist of clayey to sandy till, silt, and clay and are a source of water to the adjoining sand and gravel aquifer by lateral flow in some areas. The uppermost confining unit and the uppermost confined aquifer are present only in the northern one-third of the model area.

Simplifying assumptions about the aquifer system included:

1. The volume of water that moves vertically through the bottom of the uppermost confined aquifer (model layer 3) in the northern part of the beach ridge, and through the bottom of the unconfined aquifer (model layer 1) in the southern part is small relative to lateral flow.

2. The hydraulic heads at arbitrarily imposed lateral boundaries where the natural hydrologic boundaries lie outside the model area during the winter months (December to February) represent steady-state conditions.

3. Ground-water flow is predominantly horizontal in the aquifers. Ground-water flow is predominantly vertical in the confining units and the low permeability deposits laterally adjacent to the unconfined aquifer (adjacent clays, model layer 1).

4. Ground-water evapotranspiration is a linear function of the depth of the water table below land surface. Discharge by evapotranspiration occurs from the unconfined aquifer and adjacent clays (model layer 1).

The aquifer bottoms for the uppermost confined aquifer in the northern part of the beach ridge and for the unconfined aquifer in the southern part are represented as no-flow boundaries. Significant movement of water vertically through the base of the aquifers, violating the assumption of a no-flow boundary, could result in the simulated mass fluxes being too high or too low.

The simulated boundaries for the unconfined aquifer are located at the physical limits of the aquifer. However, model layer 1 includes the low-permeability deposits laterally adjacent to the unconfined aquifer (adjacent clays). The outer boundaries for these deposits were arbitrarily imposed and do not coincide with the physical limits of the deposits. Ground-water flow in low-permeability units is predominantly vertical; therefore, no-flow boundary conditions were used for the outer lateral boundaries of model layer 1, representing the adjacent clays. The boundaries for model layer 2, representing the uppermost confining unit, were arbitrarily imposed to coincide with the boundaries of model layer 3, representing the uppermost confined aquifer. Because ground-water flow in confining units is predominantly vertical, no-flow boundary conditions were used for all lateral boundaries for model layer 2.

The southern and western boundaries for the uppermost confined aquifer (model layer 3) represent the approximate physical extent of the aquifer and are therefore no-flow boundaries. The northern boundary is also represented using a no-flow boundary because the predominant direction of flow near the boundary is from east to west parallel to the boundary. The eastern boundary of the uppermost confined aquifer lies outside the model area. A specified-head boundary, adjusted to measured values for the appropriate time period, was used for this boundary. Figure 38 shows the modeled extents and boundary conditions for the unconfined aquifer and adjacent clays (model layer 1) and for the uppermost confined aquifer (model layer 3).

The effect of the use of no-flow boundary conditions at the arbitrary lateral boundaries for model layer 1, representing the unconfined aquifer and adjacent clays, on hydraulic heads and fluxes in the aquifers was investigated by using specified-head boundaries in place of no-flow boundaries for steady-state conditions and comparing the results. Changing from no-flow boundaries to specified-head boundaries for model layer 1 had little effect on the simulated hydraulic heads. The changes in hydraulic heads for model layer 1 and for model layer 3 were 1 ft or less, with mean changes less than 0.1 ft. Changes in the simulated water budget indicated that using specified-head boundaries resulted in water flowing both into and out of the beach-ridge aquifer system through model-layer-1 boundaries. Water entered the beach-ridge aquifer system through model-layer-1 boundaries at a rate of only 0.07 ft^3/s, however, compared to discharging through model-layer-1 boundaries at a rate of 0.77 ft^3/s. The net flow through model layer 1 boundaries was -0.70 ft^3/s, compared to 12 ft^3/s for recharge from infiltration of precipitation.

The effect of the use of specified-head boundary conditions for the eastern boundary of model layer 3, representing the uppermost confined aquifer, on hydraulic heads in the beach-ridge aquifer system was investigated by using no-flow boundaries in place of specified-head boundaries for steady-state conditions and comparing the results. Changing from a specified-head boundary to a no-flow boundary for the eastern boundary of model layer 3 resulted in declines in hydraulic heads as much as 2.0 ft for model layer 1, with a mean decline of 0.2 ft; and as much as 38.0 ft for model layer 3 with a mean decline of 23.5 ft. The simulation indicates that ground-water inflow from the east to the uppermost confined aquifer has a large effect on hydraulic heads in the uppermost confined aquifer, but only a minor effect on hydraulic heads in the overlying unconfined aquifer.

Some uncertainty exists regarding the extent or lack of the uppermost confined aquifer underlying the southern two-thirds of the model area, due to a lack of test-hole data. Therefore, a simulation was done with the extent of the uppermost confined aquifer (model layer 3) expanded to underlie the entire model area. Increasing the extent of model layer 3 had little effect on simulated hydraulic heads for model layer 1. The changes in hydraulic heads in model layer 1 were 1 ft or less, with a mean change of 0.2 ft.

Recharge to the unconfined aquifer and adjacent clays (model layer 1) simulated in the numerical model represents the net difference between infiltration of precipitation and evapotranspiration losses occurring above the water table. Flow to the uppermost confined aquifer (model layer 3) occurs by leakage down through overlying deposits.

Recharge by infiltration of precipitation to the unconfined aquifer and adjacent clays (model layer 1), and leakage from overlying deposits to the uppermost confining unit (model layer 2), were represented by a specified-flux boundary. Leakage to model layer 2 was specified only for areas outside the boundaries of model layer 1.

In the model area, the mean annual pan-evaporation rate is about 32 in., which corresponds to an estimated average annual lake-evaporation rate of 24 in. The initial evapotranspiration extinction depth used was 7 ft.

The initial values of hydraulic properties and fluxes represented in the model are listed in table 8. Initial simulated values for hydraulic conductivity for each hydrogeologic unit were based on slug tests, aquifer tests, and grain-size analyses done for this study, and published values in the literature (table 8). Initial values for recharge to the unconfined aquifer and adjacent clays (model layer 1), were assumed to be the same as the corresponding values used for the Polk-Red Lake Counties beach-ridge aquifer system. The initial value for leakage to model layer 2, representing the uppermost confining unit, was assumed to be the same as recharge from precipitation to the adjacent clays.

Model calibration Calibration and evaluation of the ground-water-flow model for the Pennington County beach-ridge aquifer system was conducted for steady-state (equilibrium) conditions. Measured hydraulic heads in the aquifers during December 1992 were used to define boundary conditions and calibrate the model in the steady-state simulation. Measured hydraulic heads in the aquifers during the winter months (December to February) are assumed to be representative of steady-state conditions.

The model was calibrated by varying, within reasonable limits, the simulated values of hydraulic properties of the beach-ridge aquifer system, adjacent clays, and uppermost confining unit (horizontal and vertical hydraulic conductivity), recharge to model layer 1, representing the unconfined aquifer and adjacent clays, leakage to model layer 2, representing the uppermost confining unit, and the simulated evapotranspiration rate and extinction depth until simulated hydraulic heads acceptably matched measured water levels. The values of simulated hydraulic properties and fluxes resulting in the best match between measured water levels and simulated hydraulic heads are listed in table 8. The horizontal hydraulic conductivity of model cells representing the unconfined aquifer (model layer 1) was decreased from 100 to 75 ft/d in the northern part of the model area and from 100 to 50 ft/d in the southern part. The transmissivity of model cells representing the uppermost confined aquifer (model layer 3) was increased from 2,000 to 4,000 ft^2/d in the northern part of the model grid. Recharge from infiltration of precipitation to the model cells representing the unconfined aquifer (model layer 1) was increased to 9.0 in./yr. Leakage to model layer 2 was reduced to zero. The evapotranspiration rate was reduced to 20.8 in./yr and the extinction depth changed to 5 ft.

The simulated hydraulic heads for model cells representing the unconfined aquifer are within 2 ft of measured water levels in 7 wells for which water-level data were available. The mean of the differences between simulated and measured hydraulic heads for the 7 wells is 1.29 ft. The very limited water-level information available for the uppermost confined aquifer indicates that wells screened in the uppermost confined aquifer flow in the northern part of the model

Table 8.—Initial and final (best-match) calibration values of hydraulic properties and fluxes in steady-state simulation of Pennington County beach-ridge aquifer system

[ft, feet; ft/d, feet per day; ft^2/d, feet squared per day; in./yr, inches per year; --, not applicable]

Hydraulic property or flux and hydrogeologic unit	Initial value	Final calibration value
Recharge or leakage (in./yr)		
Unconfined aquifer	8.0	9.0
Adjacent clays	4.0	4.5
Uppermost confining unit	4.0	0
Horizontal hydraulic conductivity (ft/d)		
Unconfined aquifer	100-200	50-200
Adjacent clays	5-25	7-25
Uppermost confining unit	1.0	1.0
Uppermost confined aquifer	80-160	80-320
Transmissivity (ft^2/d)		
Uppermost confining unit	100	100
Uppermost confined aquifer	1600	1600-4000
Vertical hydraulic conductivity (ft/d)		
Unconfined aquifer	10-20	5-20
Adjacent clays	.5-2.5	.7-2.5
Uppermost confining unit	.02	.02
Uppermost confined aquifer	8-16	8-32
Evapotranspiration rate (in./yr)	24.0	20.8
Extinction depth (ft)	7	5

area. Water levels are below land surface near the southern boundary of the aquifer.

Simulated water budget and flow The simulated water budget is shown in table 9. Recharge from the infiltration of precipitation accounts for about 94 percent of the sources of water to the Pennington County beach-ridge aquifer system, and boundary inflow to the uppermost confined aquifer (model layer 3) accounts for about 6 percent. All of the discharge from the beach-ridge aquifer system is by evapotranspiration. Water flows vertically through the uppermost confining unit (model layer 2) in the northern part of the model area from the uppermost confined aquifer (model layer 3) to the unconfined aquifer and adjacent clays (model layer 1). Water flows vertically upward because hydraulic heads in the uppermost confined aquifer are higher than hydraulic heads in the unconfined aquifer, as indicated by reported water levels in wells in the area. A well located in T154N, R45W, section 9 and screened in the uppermost confined aquifer is reported to flow at a rate of about 100 gal/min.

Sensitivity analysis A model-sensitivity analysis, wherein a single hydraulic property or flux is varied while all other properties are held constant, was done to identify the relative effect of adjustments of hydraulic properties and fluxes on simulated hydraulic heads. Adjustments were kept within reported or plausible ranges of values (tables 10 and 11). With the exception of changes in ground-water withdrawals, hydraulic heads in the unconfined aquifer and adjacent clays (model layer 1) were found to be most sensitive

Table 9.—Simulated water budget for steady-state simulation of Pennington County beach-ridge aquifer system

[Numbers in parentheses are percentages of total sources or of total discharges; --, not applicable]

Budget component	Source (cubic feet per second)	Discharge (cubic feet per second)
Recharge (from precipitation) to layer 1	13.46 (94)	--
Flow from specified-head boundary		
Layer 3	.92 (6)	--
Evapotranspiration	--	14.38 (100)
Total	14.38	14.38
Leakage between model layers through uppermost confining unit		
Layer 1	.93	0
Layer 3	0	.93
Total	.93	.93

to changes in (1) recharge from precipitation, (2) horizontal hydraulic conductivity for model layer 1, and (3) evapotranspiration rate.

With the exception of changes in ground-water withdrawals, hydraulic heads in the uppermost confined aquifer (model layer 3) were found to be most sensitive to changes in the transmissivity of the uppermost confined aquifer (model layer 3) and the vertical hydraulic conductivity of the uppermost confining unit (model layer 2). Changing the vertical hydraulic conductivity of model cells representing the uppermost confining unit (model layer 2) by factors of 10 and 0.1 ft resulted in much larger mean deviations of hydraulic heads from hydraulic heads calculated by the best-match simulation in model layer 3 than in model layer 1.

The effects on hydraulic heads of increasing withdrawals from the Pennington County beach-ridge aquifer system were also investigated. Adding withdrawals equal to the 1990 water use for the city of Thief River Falls equally divided between 4 cells located in the most transmissive part of the unconfined aquifer (model layer 1) in the central part of the model area (model rows 22 to 25) resulted in hydraulic heads declining below the aquifer bottoms (the cells went dry) in the pumped and adjacent cells. Adding withdrawals equal to one-fourth of the 1990 water use of the city of Thief River Falls equally divided between the same 4 cells resulted in a maximum increased decline in hydraulic head from the best-match simulation of 8 ft (table 10). A simulation was done using the same withdrawal rates from the same 4 cells, but with specified-head boundary conditions for model layer 1 (unconfined aquifer and adjacent clays). The maximum increased decline in hydraulic head from the best-match simulation was 8 ft, as for the simulation using no-flow boundary conditions for model layer 1. The maximum withdrawal rate that could be sustained from a single model cell (cell 25, 20) in the most transmissive part of the unconfined aquifer (model layer 1) was about 0.25 ft^3/s, based on the results of the simulations.

Adding withdrawals equal to 0.10 ft^3/s from the unconfined aquifer in the northern part of the model area (model rows 8 to 11) to 4 adjacent cells (total withdrawals of 0.40 ft^3/s) caused simulated hydraulic heads in the pumped and adjacent cells to decline below the aquifer bottom. Adding withdrawals of 0.05 ft^3/s to each of the same 4 northern cells resulted in a maximum increased decline in hydraulic head from the best-match simulation of 4 ft (table 10).

Table 10.—Sensitivity of hydraulic heads in unconfined aquifer and adjacent clays (model layer 1) to changes in values of hydraulic properties and fluxes in steady-state simulation for Pennington County beach-ridge aquifer system

[Absolute value of mean deviation of hydraulic heads from values calculated by best-match simulation; deviation calculated at all active cells for model layer 1; --, indicates all deviations of hydraulic heads from values calculated by best-match simulation are positive or all deviations are negative]

Hydraulic property or flux	Multiplied by factor of	Absolute value of mean deviation of hydraulic heads (feet)	Maximum positive deviation (feet)	Maximum negative deviation (feet)
Recharge (from precipitation) to layer 1	1.5	1.4	4.0	--
Recharge (from precipitation) to layer 1	.5	1.7	--	5.0
Horizontal hydraulic conductivity of layer 1	2.0	.9	1.4	3.0
Horizontal hydraulic conductivity of layer 1; variable	.5, .75	[1].6	3.0	[1]5.2
Transmissivity of layer 2	2.0	0	1.0	--
Transmissivity of layer 2	.5	0	--	1.0
Transmissivity of layer 3	2.0	0	1.0	--
Transmissivity of layer 3	.5	0	--	1.0
Vertical hydraulic conductivity of layer 2	10.	.3	6.7	2.0
Vertical hydraulic conductivity of layer 2	.1	[2].1	5.0	[2]8.6
Evapotranspiration rate	1.2	[3].5	3.0	[3]13.1
Evapotranspiration rate	.8	.6	2.0	--
Withdrawals from layer 1; 4 cells, rows 22-25	[4].40	.2	--	8.0
Withdrawals from layer 1; 4 cells, rows 8-11	[4].20	.1	--	4.0

[1] Does not include 114 cells that went dry where only adjacent clays are present (unconfined aquifer absent).
[2] Does not include 42 cells that went dry where only adjacent clays are present (unconfined aquifer absent).
[3] Does not include 33 cells that went dry where only adjacent clays are present (unconfined aquifer absent).
[4] Added ground-water withdrawals in cubic feet per second.

Summary and comparison of model simulations

The calibration best-match values for hydraulic properties of the hydrogeologic units, recharge, and evapotranspiration for the Polk-Red Lake Counties and Pennington County beach-ridge aquifer systems are similar. The simulated horizontal hydraulic conductivities of the uppermost confined aquifers and adjacent clays exhibit relatively wide ranges in values (50-300 ft/d and 7-50 ft/d, respectively), but are similar for both beach-ridge aquifer systems. The simulated transmissivities of the uppermost confined aquifers and the vertical hydraulic conductivities of the confining units are also similar for both beach-ridge aquifer systems. The calibration best-match values for simulated recharge to the unconfined aquifers were 8.0 and 9.0 in./yr for the two beach-ridge aquifer systems, reflecting relatively small differences in average annual precipitation. The relatively small differences in simulated ground-water evapotranspiration rates for the two beach-ridge aquifer systems reflect differences in pan evaporation rates for the two areas. The similarities between the simulated hydraulic properties of the hydrogeologic units, and simulated recharge and ground-water evapotranspiration rates for the two

Table 11.—Sensitivity of hydraulic heads in the uppermost confined aquifer (model layer 3) to changes in values of hydraulic properties and fluxes in steady-state simulation for Pennington County beach-ridge aquifer system

[Absolute value of mean deviation of hydraulic heads from values calculated by best-match simulation; deviation calculated at all active cells for model layer 3; --, indicates all deviations of hydraulic heads from values calculated by best-match simulation are positive or all deviations are negative]

Hydraulic property or flux	Multiplied by factor of	Absolute value of mean deviation of hydraulic heads (feet)	Maximum positive deviation (feet)	Maximum negative deviation (feet)
Recharge (from precipitation) to layer 1	1.5	0.4	1.0	--
Recharge (from precipitation) to layer 1	.5	.4	--	1.0
Horizontal hydraulic conductivity of layer 1	2.0	.1	--	1.0
Horizontal hydraulic conductivity of layer 1; variable	.5, .75	.4	1.0	--
Transmissivity of layer 2	2.0	.2	1.0	1.0
Transmissivity of layer 2	.5	.2	1.0	--
Transmissivity of layer 3	2.0	4.8	8.0	--
Transmissivity of layer 3	.5	5.5	--	8.0
Vertical hydraulic conductivity of layer 2	1.0	14.4	--	21.0
Vertical hydraulic conductivity of layer 2	.1	11.3	18.0	--
Evapotranspiration rate	1.2	.5	1.0	1.0
Evapotranspiration rate	.8	.3	1.0	--
Withdrawals from layer 1; 4 cells, rows 22-25	[1].4	0	--	0
Withdrawals from layer 1; 4 cells, rows 8-11	[1].2	.1	--	1.0

[1] Added ground-water withdrawals in cubic feet per second.

beach-ridge aquifer systems indicate that the values of hydraulic properties and fluxes and results of the simulations are transferable to other beach-ridge aquifer systems within the study area.

Sensitivity analyses indicated that simulated hydraulic heads in the unconfined aquifers for both beach-ridge aquifer systems were most sensitive to changes in simulated recharge rates and the simulated hydraulic conductivity of the unconfined aquifers and adjacent clays. Simulated hydraulic heads in the uppermost confined aquifers were most sensitive to changes in the simulated transmissivity of the uppermost confined aquifers and the simulated vertical hydraulic conductivity of the confining units. Further investigation would be best directed toward better defining recharge and these hydraulic properties.

The model simulations indicated that vertical ground-water flow through confining units between the unconfined (and partially confined) and uppermost confined aquifers occurs in both upward and downward directions. In the case of the Polk-Red Lake Counties beach-ridge aquifer system, about 18 percent of the simulated recharge by infiltration of precipitation to the unconfined aquifer and adjacent clays leaks downward to the underlying uppermost confined aquifer. In the southern part of this aquifer system, hydraulic heads in the deeper aquifers are higher than those in the surficial deposits and ground water moves vertically upward from the uppermost confined aquifer to the overlying unconfined aquifer. The surficial beach deposits (unconfined aquifer and adjacent clays) are a source of water to the underlying deeper aquifers in some areas and a potential discharge area for the deeper aquifers in other areas.

Implications can be drawn from the model simulations regarding the potential yield of beach-ridge aquifer systems in the study area. The potential yield of unconfined aquifers composed of coarse-grained beach deposits is limited due to the generally low saturated thickness of the aquifers and the relatively low hydraulic conductivity of the aquifer material. The model simulations indicated that maximum long-term steady-state yields from parts of the unconfined aquifers the size of a model grid cell (about 20 acres) are generally about 100 gal/min, with yields for most areas of the aquifers of the same size (about 20 acres) being less than 50 gal/min. Greater long-term yields are possible from the uppermost confined aquifers. The model simulations indicated that long-term steady-state yields of about 450 to 650 gal/min are possible from parts of the partially confined and uppermost confined aquifers about 20 acres in size for the Polk-Red Lake Counties beach-ridge aquifer system. However, due to their generally limited areal extent and variable transmissivity, extensive exploratory test-drilling and aquifer tests are needed to adequately define appropriate locations for the development of water supplies.

Ground-Water Quality

The chemical nature of water is determined by the type and quantity of substances dissolved in it. Chemical constituents dissolved in ground water are derived mainly from the materials (soil, glacial drift, and rock) through which water flows. Ground-water quality varies in response to changes in residence time, length of flow path, temperature, precipitation, and chemical reactions with minerals and aquifer materials. Ground-water quality can also be influenced by chemicals introduced to ground-water systems by human activity such as direct discharges of chemicals to the ground-water system or nonpoint sources of chemicals related to land-use activities. Chemical constituents occurring naturally in ground water can, in some instances, be the same as those introduced from human activities. Other chemicals, particularly man-made organic chemicals such as pesticides, herbicides, and solvents, have no naturally occurring source, and can be solely attributed to specific human activities.

The U.S. Environmental Protection Agency (USEPA) has set maximum contaminant levels (MCL's) and secondary maximum contaminant levels (SMCL's) for some constituents in drinking water (U.S. Environmental Protection Agency, 1986) (tables 12 and 13). MCL's generally are set because elevated concentrations of these constituents may cause adverse health effects. SMCL's generally are set for aesthetic reasons; elevated concentrations of these constituents may impart an undesirable taste or odor to water.

Water samples were collected from observation wells and domestic-supply wells screened in unconfined and confined aquifers (figs. 3 and 4). Ground-water samples were collected to (1) determine general ground-water quality, (2) provide baseline water-quality data for use in future assessments of long-term trends, (3) determine seasonal changes in water chemistry, and (4) determine if ground-water quality has been affected by land-use practices.

General Water Quality

A description of the general quality of ground water includes general properties, major and minor ions and constituents, nutrients, and its suitability for various uses.

General properties

General properties of water include specific conductance, dissolved solids, pH, alkalinity, and hardness. Specific conductance, pH, and alkalinity are generally determined on site at the time a water sample is taken.

Specific conductance is a measurement of the ability of water to conduct an electric current. It is expressed in units of microsiemens per centimeter (μS/cm) at 25 degrees Celsius. The mean specific conductance of water from the unconfined aquifers was less than the mean specific conductance of water from any of the confined aquifers (tables 14-17). The specific conductance of water from a well screened in a basal confined aquifer was 649 μS/cm.

Specific conductance is directly related to the concentration of dissolved solids; the greater the concentration of dissolved solids, the higher the specific conductance. High concentrations of dissolved solids in ground water can cause well-screen encrustation and reduced yields to wells. The mean concentration of dissolved solids (residue at 180 degrees Celsius) in water from the unconfined aquifers was less than the mean concentration of dissolved solids in water from any of the confined aquifers (tables 14-17). The mean specific conductance and mean concentration of dissolved solids in water from the confined aquifers were least for the deep confined aquifers and greatest for the shallow confined aquifers (tables 15-17). The dissolved solids concentration of water from a well screened in a basal confined aquifer was 405 mg/L.

Table 12.—Recommended limits for concentrations of selected constituents in ground water and numbers of wells screened in unconfined and shallow confined aquifers sampled where concentrations exceeded the limits

[a, the Maximum Contaminant Level established by the U.S. Environmental Protection Agency (1986); b, the Secondary Maximum Contaminant Level established by the U.S. Environmental Protection Agency (1986); c, the arbitrary limit suggested for pubic, livestock, and irrigation uses by the National Academy of Sciences and National Academy of Engineering (1974); mg/L, milligrams per liter; µg/L, micrograms per liter; --, not analyzed]

			Unconfined aquifers		Shallow confined aquifers	
Constituent	Recommended limits	Source	Number of wells sampled	Number of samples exceeding limits	Number of wells sampled	Number of samples exceeding limits
Sodium	270 mg/L	c	18	0	14	2
Sulfate	250 mg/L	b	18	0	14	2
Chloride	250 mg/L	c	18	0	14	2
Fluoride	4 mg/L	a	18	0	14	0
	2 mg/L	b	18	0	14	0
Silica	50 mg/L	c	18	0	14	0
Dissolved solids	500 mg/L	b	18	3	14	6
Nitrate (nitrate plus nitrite as N)	10 mg/L	a	18	2	5	0
Arsenic	50 µg/L	a	--	--	--	--
Boron	750 µg/L	c	18	1	14	1
Cadmium	10 µg/L	a	18	0	14	0
Chromium	50 µg/L	a	18	0	14	0
Copper	1 mg/L	a	18	0	14	0
Iron	300 µg/L	b	18	7	14	12
Lead	50 µg/L	a	18	0	14	0
Manganese	50 µg/L	b	18	10	14	11
Mercury	2 µg/L	a	--	--	--	--
Zinc	5 mg/L	b	18	0	14	0

The pH of a water sample is a measurement of the activity of hydrogen ions in water and is expressed in logarithmic units. A pH of 7 is defined as neutral. Water with a pH less than 7 is acidic; water with a pH greater than 7 is basic. The pH of distilled water is 5.6. The median pH of water from the drift aquifers ranged from 7.25 to 7.6. The pH of water from a well screened in a basal confined aquifer was 8.1.

The alkalinity of water is the capacity for solutes contained to react with and to neutralize acid. Alkalinity is produced by dissolved carbon dioxide, bicarbonate, and carbonate and is expressed in terms of an equivalent amount of calcium carbonate. The mean alkalinity of water from the drift aquifers was least for the unconfined aquifers and greatest for the intermediate confined aquifers (tables 14-17). The alkalinity of water from a well screened in a basal confined aquifer was 297 mg/L.

Hardness of water is caused by the presence of alkaline earth elements, chiefly calcium and magnesium. Hard water inhibits the lathering of soap and causes the formation of encrustations when water is heated. These effects are the result of the formation of insoluble compounds. Hardness is expressed in equivalent concentrations of calcium carbonate. Hardness is classified by Durfor and Becker (1964, p.

Table 13.—Recommended limits for concentrations of selected constituents in ground water and numbers of wells screened in intermediate confined and deep confined aquifers sampled where concentrations exceeded the limits

[a, the Maximum Contaminant Level established by the U.S. Environmental Protection Agency (1986); b, the Secondary Maximum Contaminant Level established by the U.S. Environmental Protection Agency (1986); c, the arbitrary limit suggested for pubic, livestock, and irrigation uses by the National Academy of Sciences and National Academy of Engineering (1974); mg/L, milligrams per liter; µg/L, micrograms per liter; --, not analyzed]

			Intermediate confined aquifers		Deep confined aquifers	
Constituent	Recommended limits	Source	Number of wells sampled	Number of samples exceeding limits	Number of wells sampled	Number of samples exceeding limits
Sodium	270 mg/L	c	19	1	8	0
Sulfate	250 mg/L	b	19	2	8	0
Chloride	250 mg/L	c	19	1	8	0
Fluoride	4 mg/L	a	19	0	8	0
	2 mg/L	b	19	0	8	0
Silica	50 mg/L	c	19	0	8	0
Dissolved solids	500 mg/L	b	19	8	8	3
Nitrate (nitrate plus nitrite as N)	10 mg/L	a	--	--	--	--
Arsenic	50 µg/L	a	4	0	--	--
Boron	750 µg/L	c	19	2	8	0
Cadmium	10 µg/L	a	19	0	8	0
Chromium	50 µg/L	a	19	0	8	0
Copper	1 mg/L	a	19	0	8	0
Iron	300 µg/L	b	19	16	8	6
Lead	50 µg/L	a	19	0	8	0
Manganese	50 µg/L	b	19	8	8	3
Mercury	2 µg/L	a	4	0	--	--
Zinc	5 mg/L	b	19	0	8	0

27) as: soft, 0-60 mg/L; moderately hard, 61-120 mg/L; hard, 121-180 mg/L; very hard, more than 180 mg/L. Based on mean hardness, water from both the unconfined and confined aquifers in the study area is very hard (tables 14-17). The hardness of water from a well screened in a basal confined aquifer was 58 mg/L.

Major and minor ions and constituents

Major ions and constituents dissolved from soil and rock make up most of the dissolved solutes in ground water; the remainder comes mostly from constituents dissolved in precipitation. Most chloride in ground water is dissolved from natural sources. However, elevated concentrations of chloride may be caused by human activities, such as highway deicing, fertilizing, and septic system drainage.

A common graphical technique for presenting water-chemistry data is a Piper diagram (Freeze and Cherry, 1979). These diagrams permit the representation of common cation and anion compositions of many samples on a single graph. The relative chemistry of water from wells screened in the unconfined and confined aquifers is shown in figure 39. The points representing cation and anion data from two separate trilinear diagrams (not shown on fig. 39) are extended to the parallelogram (Freeze and Cherry, 1979) to indicate the general type of water indicated by concentrations of

Table 14.—Statistical summary of water-quality data for wells screened in unconfined aquifers

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25°C (degrees Celsius); <, less than; FET, fixed endpoint titration; field, value determined at sampling site; lab, value determined in laboratory]

Constituent	Number of samples	Maximum	Minimum	Mean
Specific conductance, field (µS/cm)	15	1300	284	600
Specific conductance, lab (µS/cm)	18	1270	394	619
pH, field (standard units)	15	9.0	6.6	7.3
pH, lab (standard units)	18	8.8	6.7	7.6
Oxygen, dissolved (mg/L)	14	13.5	.04	2.0
Hardness (mg/L as $CaCO_3$)	18	790	86	372
Calcium, dissolved (mg/L as Ca)	18	200	6.3	78
Magnesium, dissolved (mg/L as Mg)	18	70	15	30
Sodium, dissolved (mg/L as Na)	18	43	.7	8.8
Sodium, percent	18	50	1.0	6.3
Sodium adsorption ratio (SAR)	18	2.0	0	.25
Potassium, dissolved (mg/L as K)	18	6.0	.8	2.9
Alkalinity, FET, field (mg/L as $CaCO_3$)	18	746	148	294
Sulfate, dissolved (mg/L as SO_4)	18	100	.3	31
Chloride, dissolved (mg/L as Cl)	18	910	.5	11.6
Fluoride, dissolved (mg/L as F)	18	0.2	.1	.16
Silica, dissolved (mg/L as SiO_2)	18	27	1.3	18
Dissolved solids, residue at 180°C (mg/L)	18	868	222	371
Dissolved solids, sum of constituents (mg/L)	18	829	179	361
Barium, dissolved (µg/L as Ba)	18	330	27	117
Boron, dissolved (µg/L as B)	18	2600	10	200
Iron, dissolved (µg/L as Fe)	18	8500	7.0	1118
Manganese, dissolved (µg/L as Mn)	18	690	<1.0	128
Strontium, dissolved (µg/L as Sr)	18	480	37	143
Zinc, dissolved (µg/L as Zn)	18	450	3.0	67
Carbon, organic, dissolved (mg/L as C)	17	27.0	90	4.6

cations and anions.

The predominant ions in water from both the unconfined and shallow confined aquifers are generally calcium and bicarbonate, derived primarily from soil and rock weathering (Hem, 1985). Sodium percentages (as percentage of total cations) are generally higher in water from the shallow confined aquifers compared to water from the unconfined aquifers. Waters from the intermediate confined aquifers are a variety of water types, including calcium bicarbonate, calcium sulfate, mixed calcium-sodium bicarbonate, and sodium chloride type waters. Sodium percentages are generally higher in waters from the intermediate confined aquifers than in waters from the shallow confined aquifers. Waters from the deep confined aquifers are predominantly calcium bicarbonate, mixed calcium-sodium bicarbonate, and sodium chloride type waters. Water from a well screened in a basal confined aquifer is a sodium bicarbonate type water. Sodium bicarbonate type water results from natural softening of calcium bicarbonate or calcium sulfate waters by ion exchange and is generally associated with the clayey Cretaceous strata. Sodium chloride type water is water associated with strata of marine origin, both Cretaceous and Paleozoic. The increase in sodium and chloride concentrations (as a percentage of total cations and

Table 15.—Statistical summary of water-quality data for wells screened in shallow confined aquifers

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25°C (degrees Celsius); <, less than; FET, fixed endpoint titration; field, value determined at sampling site; lab, value determined in laboratory]

Constituent	Number of samples	Maximum	Minimum	Mean
Specific conductance, field (µS/cm)	12	2780	500	1152
Specific conductance, lab (µS/cm)	14	3400	486	1138
pH, field (standard units)	12	7.6	6.7	7.2
pH, lab (standard units)	14	7.9	7.1	7.5
Oxygen, dissolved (mg/L)	4	.15	.05	.08
Hardness (mg/L as $CaCO_3$)	14	1000	180	414
Calcium, dissolved (mg/L as Ca)	14	220	39	97
Magnesium, dissolved (mg/L as Mg)	14	110	19	41
Sodium, dissolved (mg/L as Na)	14	390	2.2	82
Sodium, percent	14	69	2	24
Sodium adsorption ratio (SAR)	14	9	.10	1.8
Potassium, dissolved (mg/L as K)	14	11	1.3	5.8
Alkalinity, FET, field (mg/L as $CaCO_3$)	14	491	228	340
Sulfate, dissolved (mg/L as SO_4)	14	880	<.1	137
Chloride, dissolved (mg/L as Cl)	14	910	.3	119
Fluoride, dissolved (mg/L as F)	14	.50	.1	.31
Silica, dissolved (mg/L as SiO_2)	14	34	20	28
Dissolved solids, residue at 180°C, (mg/L)	14	2040	294	711
Dissolved solids, sum of constituents (mg/L)	12	1800	304	764
Barium, dissolved (µg/L as Ba)	14	900	17	176
Boron, dissolved (µg/L as B)	14	860	20	266
Iron, dissolved (µg/L as Fe)	14	8900	62	2071
Manganese, dissolved (µg/L as Mn)	14	220	28	118
Strontium, dissolved (µg/L as Sr)	14	1600	86	579
Zinc, dissolved (µg/L as Zn)	14	130	3	29
Carbon, organic, dissolved (mg/L as C)	12	8.5	1.3	3.3

anions, respectively) with increasing depth below land surface is probably due to mixing with water from the underlying Cretaceous and Paleozoic strata (Bidwell and others, 1970).

Mean concentrations of calcium and magnesium generally decreased with depth below land surface and were lowest for the deep confined aquifers (tables 14-17). The mean concentration of sodium was much lower for the unconfined aquifers (8.8 mg/L) than for the shallow, intermediate, and deep confined aquifers (74-82 mg/L). Mean sulfate concentrations were much greater for the shallow and intermediate confined aquifers (greater than 115 mg/L) than for the unconfined and deep confined aquifers. Mean chloride concentrations were greater for the shallow and deep confined aquifers (greater than 50 mg/L) than for the unconfined and intermediate confined aquifers (less than 40 mg/L). Water from a well screened in a basal confined aquifer had comparatively low calcium, magnesium, and sulfate concentrations (less than 15 mg/L) and comparatively high chloride and sodium concentrations (greater than 60 mg/L).

Higher concentrations of naturally occurring constituents in waters from confined aquifers compared to waters from unconfined aquifers may occur because of the longer flow paths and longer residence times of

Table 16.—Statistical summary of water-quality data for wells screened in intermediate confined aquifers

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25°C (degrees Celsius); <, less than; FET, fixed endpoint titration; field, value determined at sampling site; lab, value determined in laboratory]

Constituent	Number of samples	Maximum	Minimum	Mean
Specific conductance, field (µS/cm)	17	2050	502	925
Specific conductance, lab (µS/cm)	19	2060	541	907
pH, field (standard units)	17	8.2	6.8	7.5
pH, lab (standard units)	19	8.7	7.3	7.7
Oxygen, dissolved (mg/L)	10	1.8	.04	.2
Hardness (mg/L as $CaCO_3$)	19	950	67	330
Calcium, dissolved (mg/L as Ca)	19	190	13	72
Magnesium, dissolved (mg/L as Mg)	19	120	8.3	36
Sodium, dissolved (mg/L as Na)	19	290	14	74
Sodium percent	19	86	9	32
Sodium adsorption ratio (SAR)	19	10	.3	2.06
Potassium, dissolved (mg/L as K)	19	8.9	1.9	4.2
Alkalinity, FET, field (mg/L as $CaCO_3$)	19	502	241	342
Sulfate, dissolved (mg/L as SO_4)	19	750	.1	117
Chloride, dissolved (mg/L as Cl)	19	390	1.2	37
Fluoride, dissolved (mg/L as F)	19	.9	.2	.35
Silica, dissolved (mg/L as SiO_2)	19	39	15	25
Dissolved solids, residue at 180°C, (mg/L)	19	1420	300	570
Dissolved solids, sum of constituents, (mg/L)	18	1340	311	576
Barium, dissolved (µg/L as Ba)	19	330	15	111
Boron, dissolved (µg/L as B)	19	920	50	266
Iron, dissolved (µg/L as Fe)	19	4000	11	1463
Manganese, dissolved (µg/L as Mn)	19	210	5	70
Strontium, dissolved (µg/L as Sr)	19	1100	110	414
Zinc, dissolved (µg/L as Zn)	19	660	3.2	83
Carbon, organic, dissolved (mg/L as C)	17	10	1.5	3.7

water in the confined aquifers (Hem, 1985). Longer residence times in the confined aquifers compared to the unconfined aquifers may result from (1) the discontinuity of the confined aquifers and the low ground-water-flow velocities produced by these discontinuities, (2) the greater depth of burial of the aquifers that results in long flow paths, and (3) recharge to the confined aquifers through till in highland (morainal) areas. The combined effect of these factors is to increase the water-mineral contact time, thereby increasing mineral dissolution and the concentrations of chemical constituents in the ground water.

Metals and other trace constituents typically are present in concentrations less than 1 mg/L in natural waters (Hem, 1985). Iron and manganese are usually present in ground water. Most of the metals and other trace constituents in natural ground water are leached from the soil or dissolved from the underlying bedrock in very small quantities by circulating ground water; some are present in precipitation.

The mean concentrations of iron and manganese in water from the drift aquifers were least for the deep confined aquifers (tables 14-17). Iron and manganese concentrations were 44 and 5 µg/L, respectively, in water from a well screened in a basal confined aquifer.

Table 17.—Statistical summary of water-quality data for wells screened in deep confined aquifers

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25°C (degrees Celsius); <, less than; FET, fixed endpoint titration; field, value determined at sampling site; lab, value determined in laboratory]

Constituent	Number of samples	Maximum	Minimum	Mean
Specific conductance, field (µS/cm)	8	939	562	758
Specific conductance, lab (µS/cm)	8	1030	601	791
pH, field (standard units)	8	7.9	7.1	7.6
pH, lab (standard units)	8	7.9	7.5	7.7
Oxygen, dissolved (mg/L)	5	5.0	.05	1.4
Hardness (mg/L as $CaCO_3$)	8	380	170	238
Calcium, dissolved (mg/L as Ca)	8	82	35	50
Magnesium, dissolved (mg/L as Mg)	8	42	19	27
Sodium, dissolved (mg/L as Na)	8	150	41	82
Sodium percent	8	66	19	42
Sodium adsorption ratio (SAR)	8	5	.9	2.4
Potassium, dissolved (mg/L as K)	8	5.3	2.4	3.8
Alkalinity, FET, field (mg/L as $CaCO_3$)	8	406	220	300
Sulfate, dissolved (mg/L as SO_4)	8	87	2.9	52
Chloride, dissolved (mg/L as Cl)	8	190	7.4	53
Fluoride, dissolved (mg/L as F)	8	1.7	.3	.58
Silica, dissolved (mg/L as SiO_2)	8	26	17	23
Dissolved solids, residue at 180°C, (mg/L)	8	570	335	457
Dissolved solids, sum of constituents, (mg/L)	8	606	353	472
Barium, dissolved (µg/L as Ba)	8	170	32	99
Boron, dissolved (µg/L as B)	8	520	140	258
Iron, dissolved (µg/L as Fe)	8	3300	10	809
Manganese, dissolved (µg/L as Mn)	8	110	11	39
Strontium, dissolved (µg/L as Sr)	8	530	250	374
Zinc, dissolved (µg/L as Zn)	8	89	8	26
Carbon, organic, dissolved (mg/L as C)	7	3.5	2	2.7

Sources of iron in well water include minerals in the bedrock such as pyroxenes, amphiboles, hematite, magnetite, and pyrite; and corrosion of iron well casings (Hem, 1985). Concentrations may be elevated by bacterial activity. Sources of manganese in ground water include minerals in the bedrock, such as biotite and hornblende, and bioaccumulation by plants (Hem, 1985).

Mean concentrations of zinc ranged from 26 µg/L for the deep confined aquifers to 83 µg/L for the intermediate confined aquifers. Mean concentrations of boron ranged from 200 µg/L for the unconfined aquifers to 266 µg/L for the shallow and intermediate confined aquifers. Zinc and boron concentrations were 11 and 780 µg/L, respectively, in water from a well screened in a basal confined aquifer.

Water from four wells screened in intermediate confined aquifers was analyzed for mercury, selenium, and arsenic. Concentrations in water from all four wells were below detection limits for these constituents.

Waters from the unconfined and confined aquifers underlying most of the study area generally are suitable for domestic consumption, crop irrigation, and most other uses. Water from 17, 43, 42, and 38 percent of sampled wells screened in unconfined (3 wells), shallow

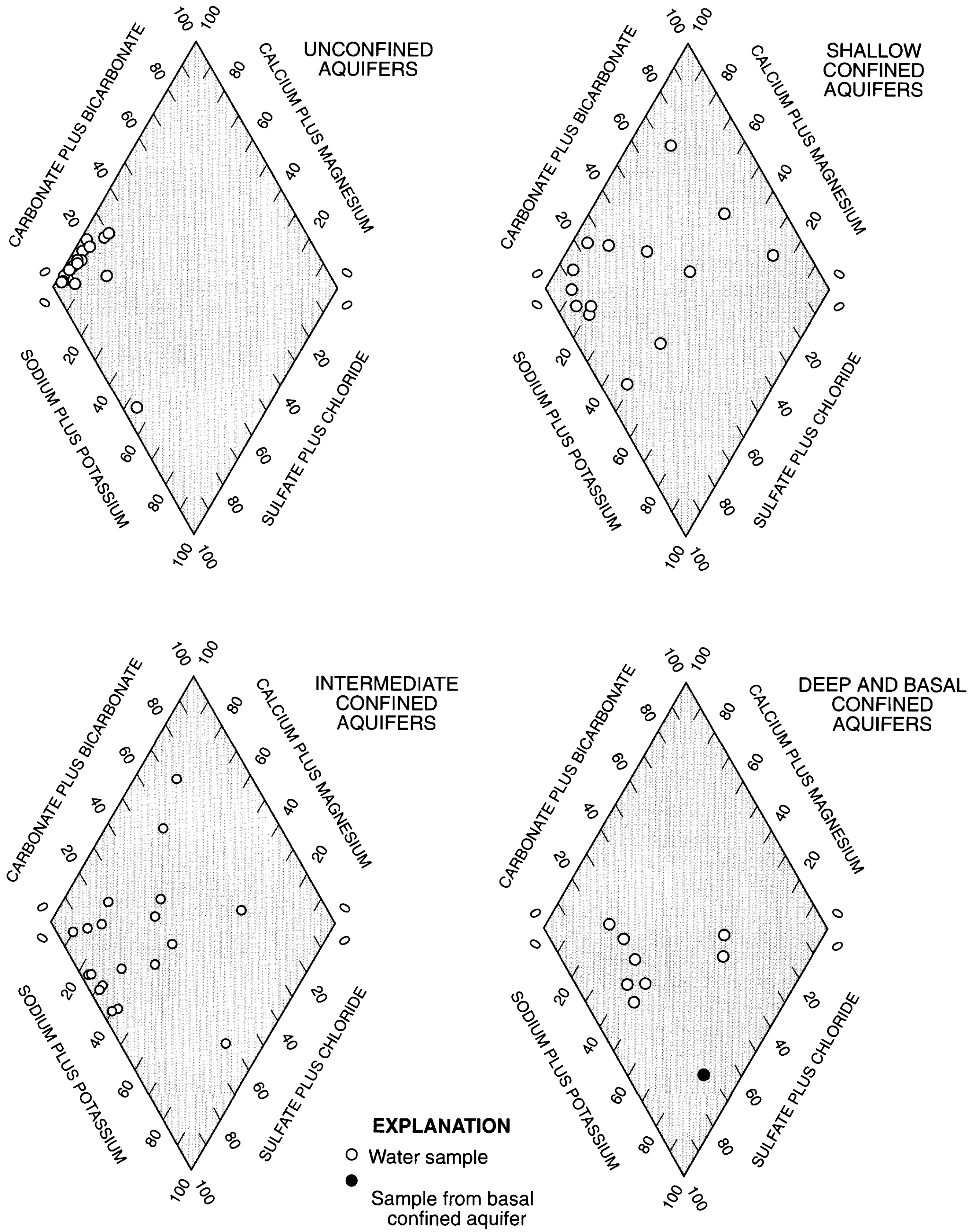


Figure 39. Major-ion chemical characteristics of water in unconfined and confined aquifers.

confined (6 wells), intermediate confined (8 wells), and deep confined aquifers (3 wells), respectively, exceeded the USEPA-established SMCL for dissolved-solids concentrations (tables 12 and 13). Water from 14 percent of sampled wells screened in shallow confined aquifers had sodium, sulfate, and chloride concentrations that exceeded the USEPA-established SMCL or limits suggested by the National Academy of Sciences and National Academy of Engineering (table 12). Water from 11 percent of sampled wells screened in intermediate confined aquifers had sulfate concentrations exceeding the USEPA-established SMCL. Water from one well screened in intermediate confined aquifers (5 percent of sampled wells) exceeded limits suggested by the National Academy of Sciences and National Academy of Engineering for sodium and chloride concentrations (table 13). The wells with water exceeding the recommended limits for sodium and chloride are located in the western part of the study area near the Red River of the North.

Concentrations of iron and manganese in water from the unconfined and confined aquifers frequently exceeded the USEPA-established SMCL's (tables 12 and 13). The SMCL's for iron were exceeded in 39 and 83 percent of the wells sampled for the unconfined and confined aquifers, respectively. The SMCL's for manganese were exceeded in 56 and 54 percent of the wells sampled for the unconfined and confined aquifers, respectively. Iron and manganese are essential to plants and animals, but may cause objectionable taste, odors, and staining of plumbing fixtures at high concentrations. High concentrations of these constituents do not adversely affect plants, but treatment of the water may be necessary prior to domestic use.

Limits suggested by the National Academy of Sciences and National Academy of Engineering for boron concentrations were exceeded in one well screened in unconfined, shallow confined, and basal confined aquifers and in two wells screened in intermediate confined aquifers (tables 12 and 13). Boron concentrations affect the suitability of water for irrigation. Small amounts of boron are essential to plant growth. Greater concentrations of boron in soil and in irrigation water are harmful, however, and for some plants the toxic concentration is as low as 1 mg/L (Hem, 1985, p. 129).

The suitability of water for irrigation commonly is determined by relating conductivity of the water to the sodium-adsorption ratio (SAR), which can be used to classify the water in terms of its sodium and salinity hazards. This classification system was developed by the U.S. Salinity Laboratory (1954). The SAR is determined by the following relation where constituent concentrations are expressed in milliequivalents per liter:

$$SAR = \frac{Sodium}{\sqrt{\frac{(Calcium + Magnesium)}{2}}}$$

A high SAR value indicates that irrigation can destroy soil structure and thereby reduce permeability. Salinity is directly related to the dissolved solids in water. High salinity concentrations endanger plants by reducing the amount of water absorbed by roots. Waters from the unconfined and confined aquifers underlying most of the study area have a potentially low sodium hazard and a medium to high salinity hazard (fig. 40). Water from two wells screened in intermediate confined aquifers and from one well screened in basal confined aquifers had a medium sodium hazard. Water from two wells screened in shallow confined aquifers had a very high salinity hazard and a medium to high sodium hazard.

Nutrients

Nutrients include nitrogen and phosphorus species. Nitrogen is found in water principally as nitrate (NO_3), nitrite (NO_2), and ammonia (NH_4). Madison and Brunett (1984) evaluated nitrate concentrations nationwide and determined that concentration ranges of nitrate as nitrogen may indicate differences between human and natural activities. Nitrate concentrations less than 3 mg/L as nitrogen may indicate natural or ambient concentrations from naturally occurring soil nitrogen or geologic deposits. Concentrations larger than 3 mg/L as nitrogen may indicate effects from human activities. Significant human sources of nitrate in ground water include septic systems, agricultural activities (fertilizers, irrigation, dryland farming, and livestock wastes), land disposal of wastes, and industrial wastes.

Unconfined aquifers are closer to land surface and lack overlying low-permeability materials that could isolate the aquifers from direct infiltration of recharge and land surface sources of nutrients. Anderson (1987) found that nitrate concentrations exceeded the Minnesota drinking-water standard of 10 mg/L in 50 percent of 56 wells screened in surficial sand-plain aquifers that underlie west-central Minnesota. A study conducted by Detroy and others (1988) in Iowa reported that the percentage of water samples that had nitrate concentrations greater than 10 mg/L as nitrogen increased with decreasing well depth, based on 50-foot increments of well depth for wells less than 200 ft deep. The largest percentage of samples with nitrate

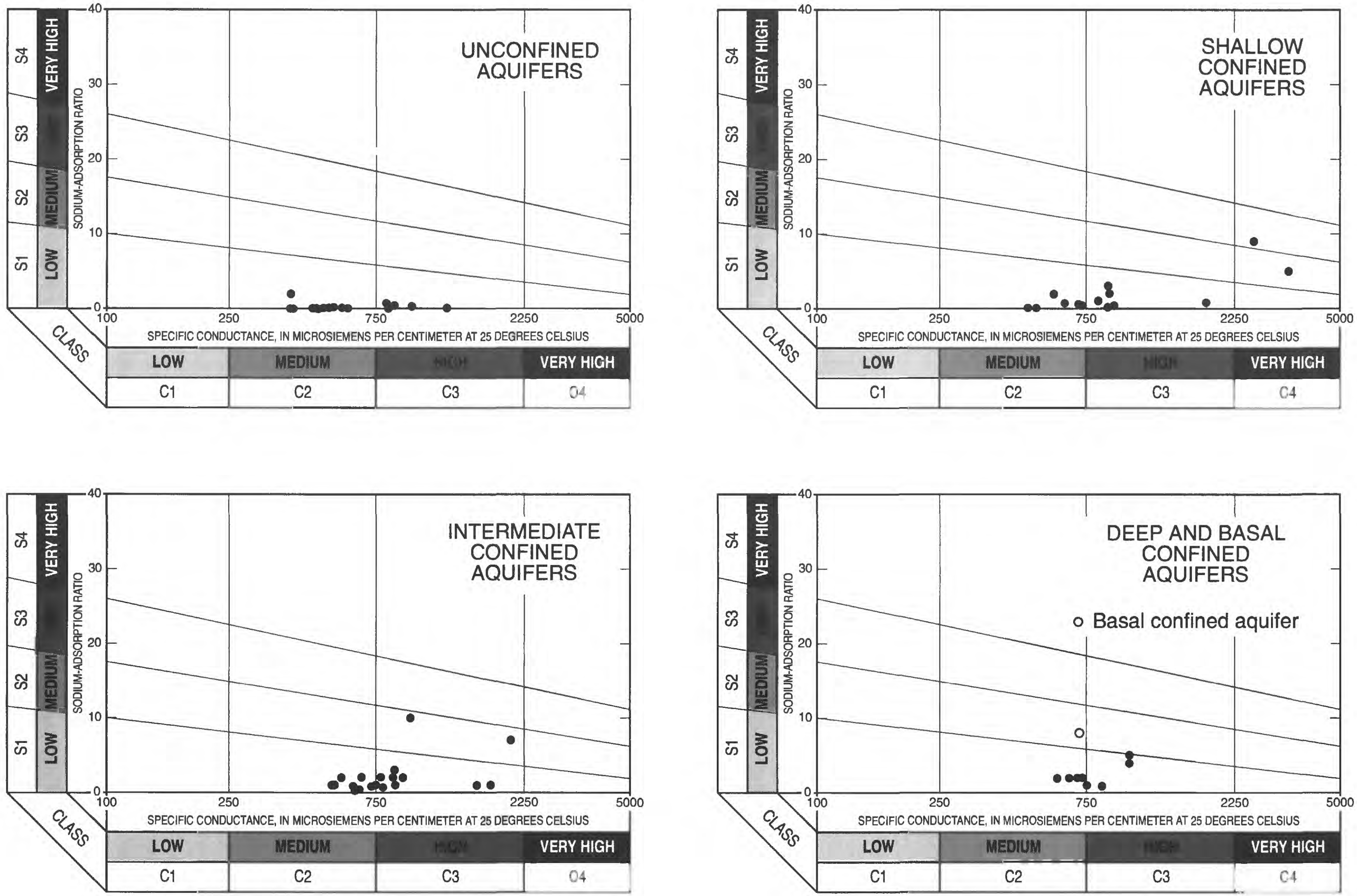


Figure 40. Suitability of water from unconfined and confined aquifers for irrigation in terms of sodium and salinity hazards.

concentrations greater than 10 mg/L were collected from the depth interval between 1 and 50 ft. The data indicated that water from the shallowest wells tends to be most affected by increased concentrations of nitrate. Studies conducted by Myette (1984) near Staples, Minnesota, indicate that concentrations of nitrate and chloride generally are greatest in water samples from the shallowest part of the unconfined aquifer (near the water table). Vertical mixing is generally limited within unconfined aquifers because of anisotropy and the relatively short flow paths in these systems.

Twenty-three water samples were collected for this study from wells screened in unconfined and shallow confined aquifers and analyzed for nitrate. Ten of the samples had nitrate concentrations below the reporting limit (0.05 mg/L) (fig. 41). Six of the samples had nitrate concentrations between 0.05 and 3.0 mg/L and five samples between 3.0 and 10 mg/L. Two samples had nitrate concentrations greater than the USEPA established MCL of 10 mg/L (22 and 44 mg/L). Nitrate concentrations in water from the shallow confined aquifers were all 2.0 mg/L or less. About 30 percent of the samples (all from wells screened in unconfined aquifers) had nitrate concentrations greater than 3.0 mg/L, indicating effects on ground water from human activities.

Trends in Ground-Water Quality

Changes in water quality along regional flow paths

Water samples were collected during August 1991 from wells screened in drift aquifers and located along regional ground-water flow paths (fig. 33) to determine possible trends in water quality with relative age and position of the water in the flow system (fig. 42). Concentrations of dissolved solids in the drift aquifers tend to increase from east to west along flow paths (fig. 42), probably due to longer residence times and upward leakage of water from the Cretaceous and Paleozoic strata.

Figures 43, 44, and 45 show geologic sections along the regional ground-water-flow paths and Stiff diagrams for water samples from wells screened in confined aquifers at various depths below land surface. The Stiff diagram is a graphical representation of the cations and anions of an analysis in milliequivalents per liter. The Stiff plotting technique uses parallel horizontal axes extending on each side of a vertical zero axis (Hem, 1985, p. 175). Concentrations of the cations are plotted to the left of the vertical axis and anions to the right. The points are then connected and an irregular pattern results providing a relatively distinctive method of showing water-composition differences and similarities. The concentration and percentage (as percent of total cations) of sodium tended to increase with well depth and increased from east to west along regional flow paths (figs. 43 and 44). Concentrations and percentages (as percent of total anions) of chloride were greater in the western part of the study area than in the eastern part. The increased concentrations and percentages of sodium and chloride are probably due to a combination of longer residence time of the water in the flow system, and upward leakage of water from the underlying Cretaceous and Paleozoic strata. The Cretaceous and Paleozoic strata pinch out and are not present in the eastern part of the study area (Bidwell and others, 1970; Maclay and others, 1965). Sulfate concentrations were comparatively high (greater than 15 milliequivalents per liter) for shallow confined aquifers in the southeastern part of the study area (fig. 45, section E-E'). The conditions causing these high sulfate concentrations are not known, but they may be due to a high positive redox potential of the waters within the ground-water reservoir and consequently little reduction of the sulfate ion, or to less permeable deposits than in other parts of the study area, allowing greater time in contact with sulfate-producing minerals.

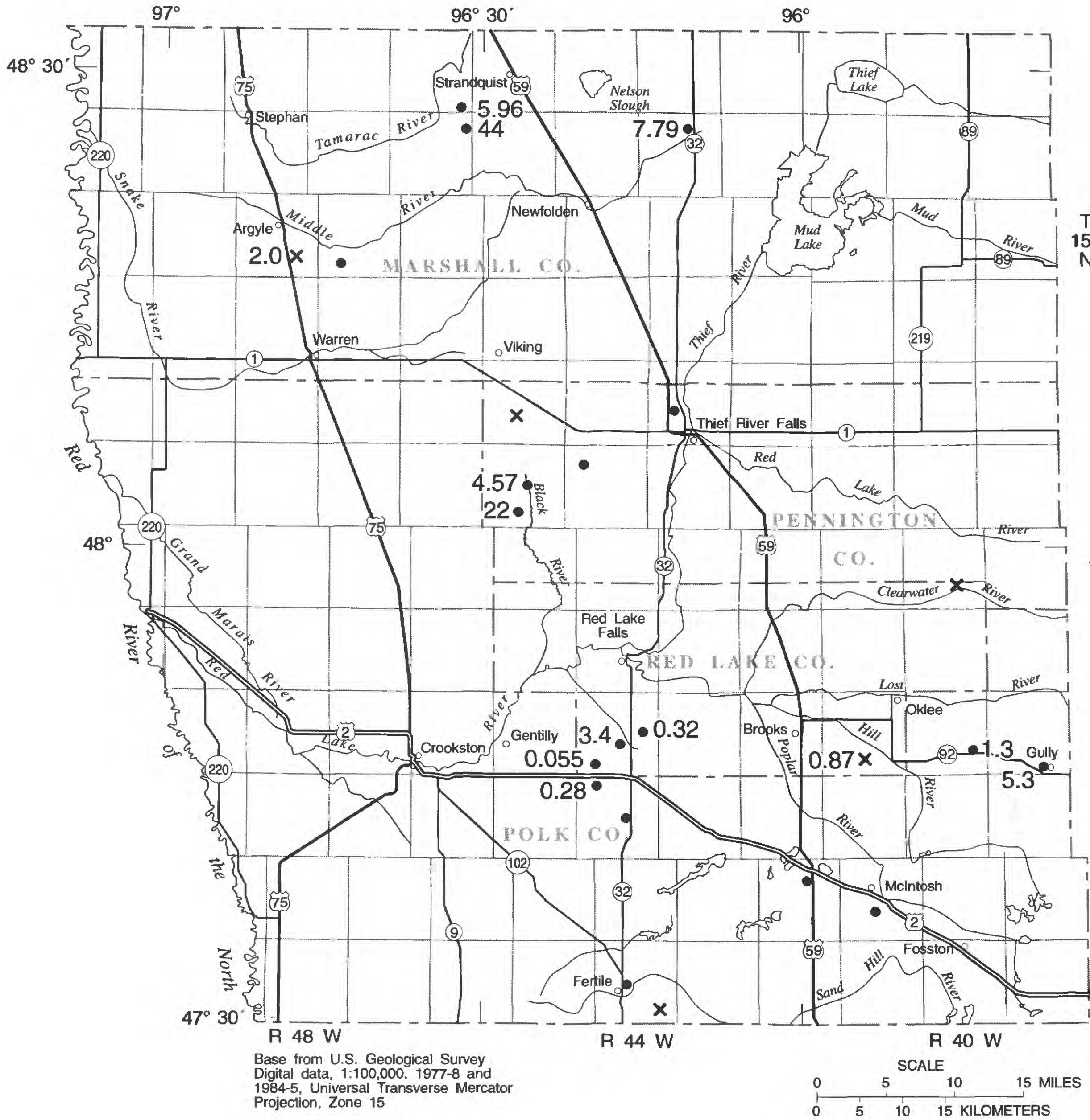
Seasonal variability in water quality

Three wells screened in unconfined aquifers were sampled during 1991-92 to determine the effect of seasonal changes on concentrations of chemical constituents (table 18). Seasonal changes in concentrations of chemical constituents are generally small, based on the data from the wells sampled.

Ground-Water Quality Related to Land Uses

Because the unconfined and shallow confined aquifers are most susceptible to contamination by land-surface activities, samples were collected from these aquifers and analyzed for constituents that might be related to prevalent land uses in the study area. The predominant land use in the study area is agriculture; therefore, water samples were analyzed for pesticides.

An immunoassay method was used as a screening tool prior to laboratory analysis for a broad spectrum of pesticides. Water samples were collected from 83 wells screened in unconfined and shallow confined aquifers (fig. 4) and immunoassay analyses were done to determine the presence of 2,4-D. The immunoassay analyses indicated the presence of 2,4-D for 4 of the samples at concentration levels of about 0.5 part per billion.



EXPLANATION

5.96 ● Sampled well screened in unconfined aquifer - Number denotes concentration of nitrate in milligrams per liter. No number indicates concentration of nitrate is below detection level (0.05 milligrams per liter)

2.0 × Sampled well screened in shall confined aquifer - Number denotes concentration of nitrate in milligrams per liter. No number indicates concentration of nitrate is below detection level (0.05 milligrams per liter)

Figure 41. Nitrate concentrations in water from unconfined and shallow confined aquifers.

EXPLANATION

Trace of hydrogeologic section

434 — Sampled well screened in confined aquifer - Number is dissolved-solids concentration, in milligrams per liter

5490 — Sampled well screened in confined aquifer and water analyzed for arsenic, mercury, and selenium - Number is dissolved-solids concentration, in milligrams per liter

Figure 42. Water-quality sampling locations along regional ground-water-flow paths, traces of hydrogeologic sections, and dissolved-solids concentrations in water from confined aquifers.

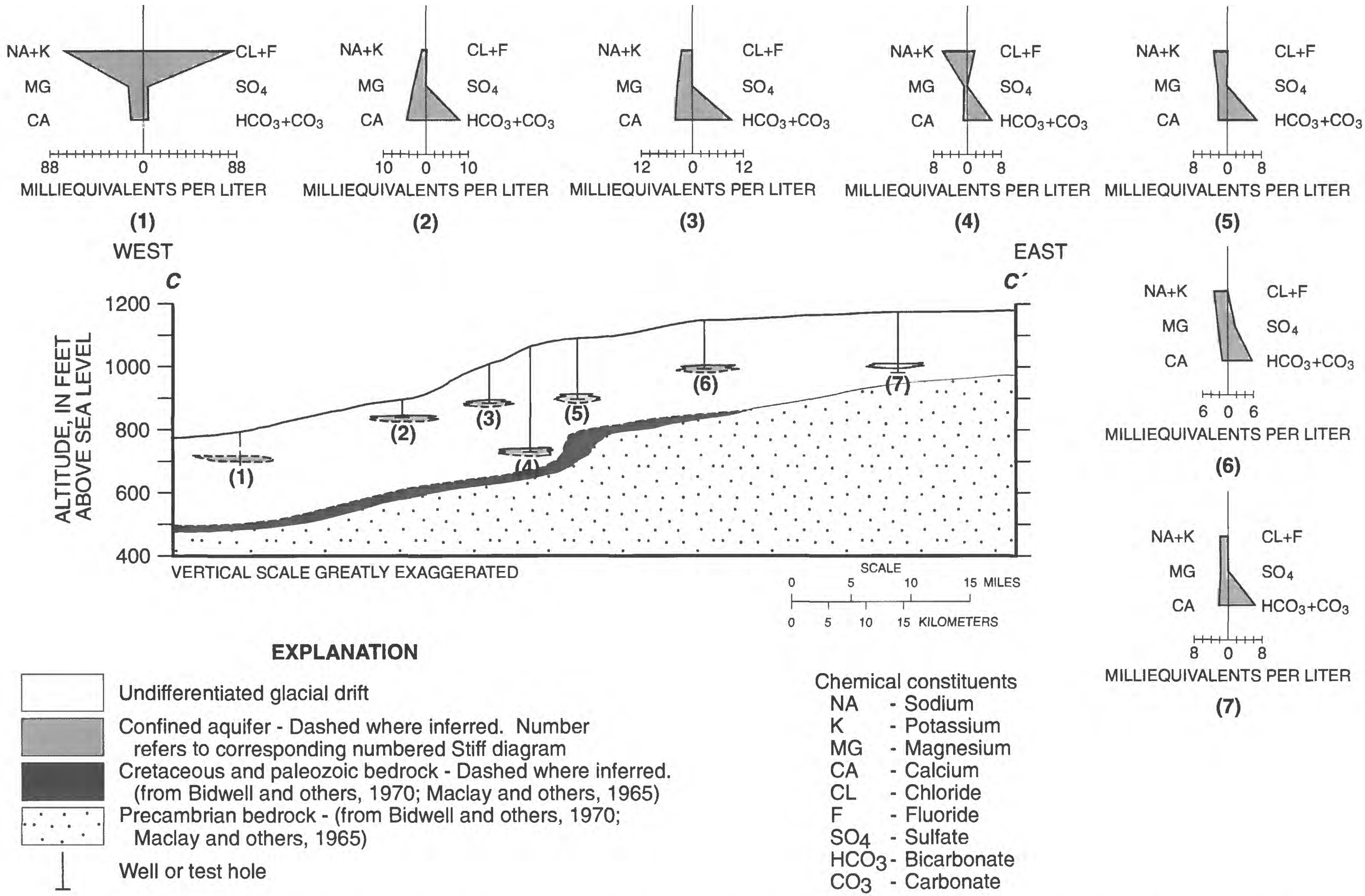


Figure 43. Hydrogeologic section C - C´along regional ground-water-flow path and Stiff diagrams showing predominant chemical constituents in water from confined aquifers (trace of section shown on figure 42).

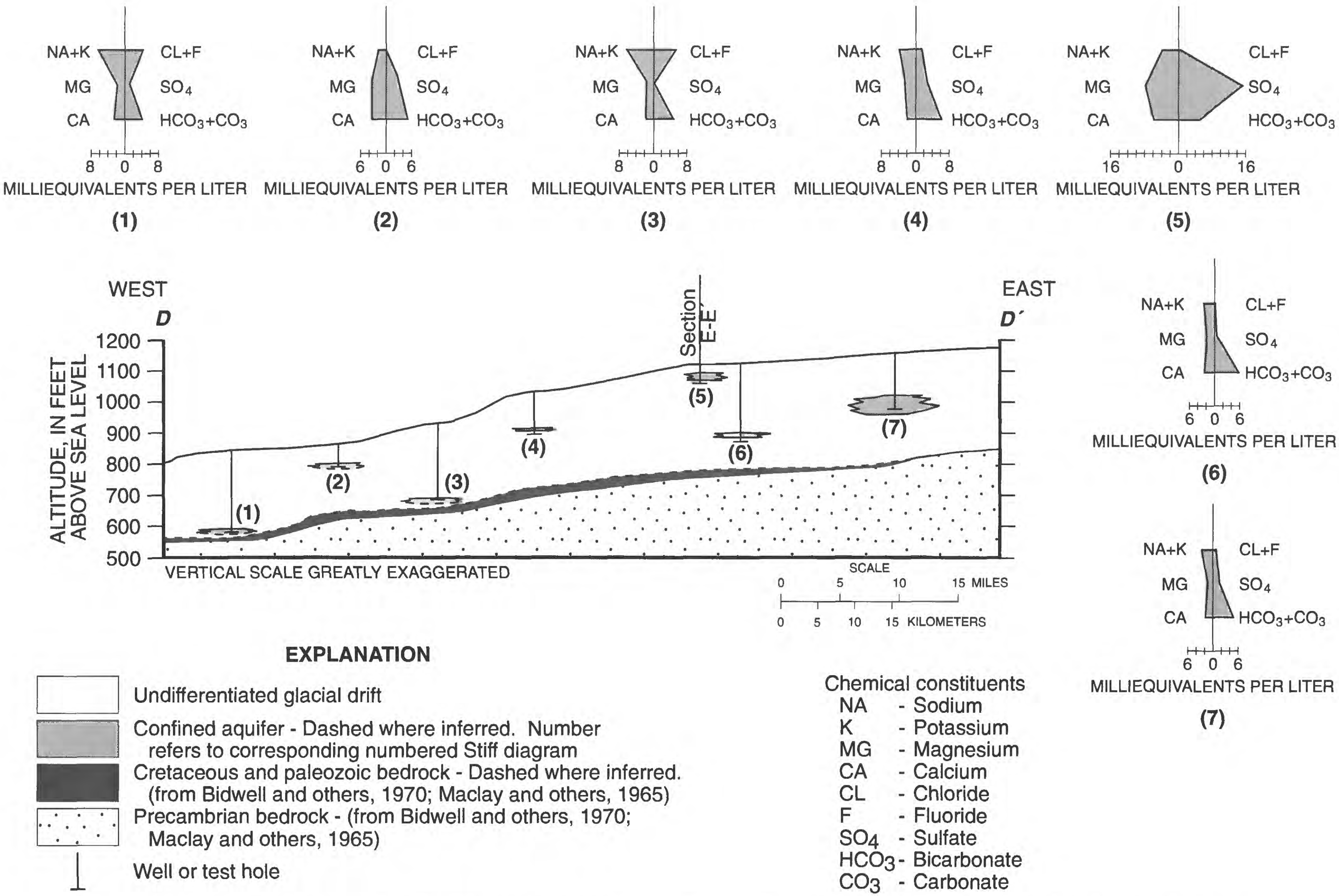


Figure 44. Hydrogeologic section D - D´ along regional ground-water-flow path and Stiff diagrams showing predominant chemical constituents in water from confined aquifers (trace of section shown on figure 42).

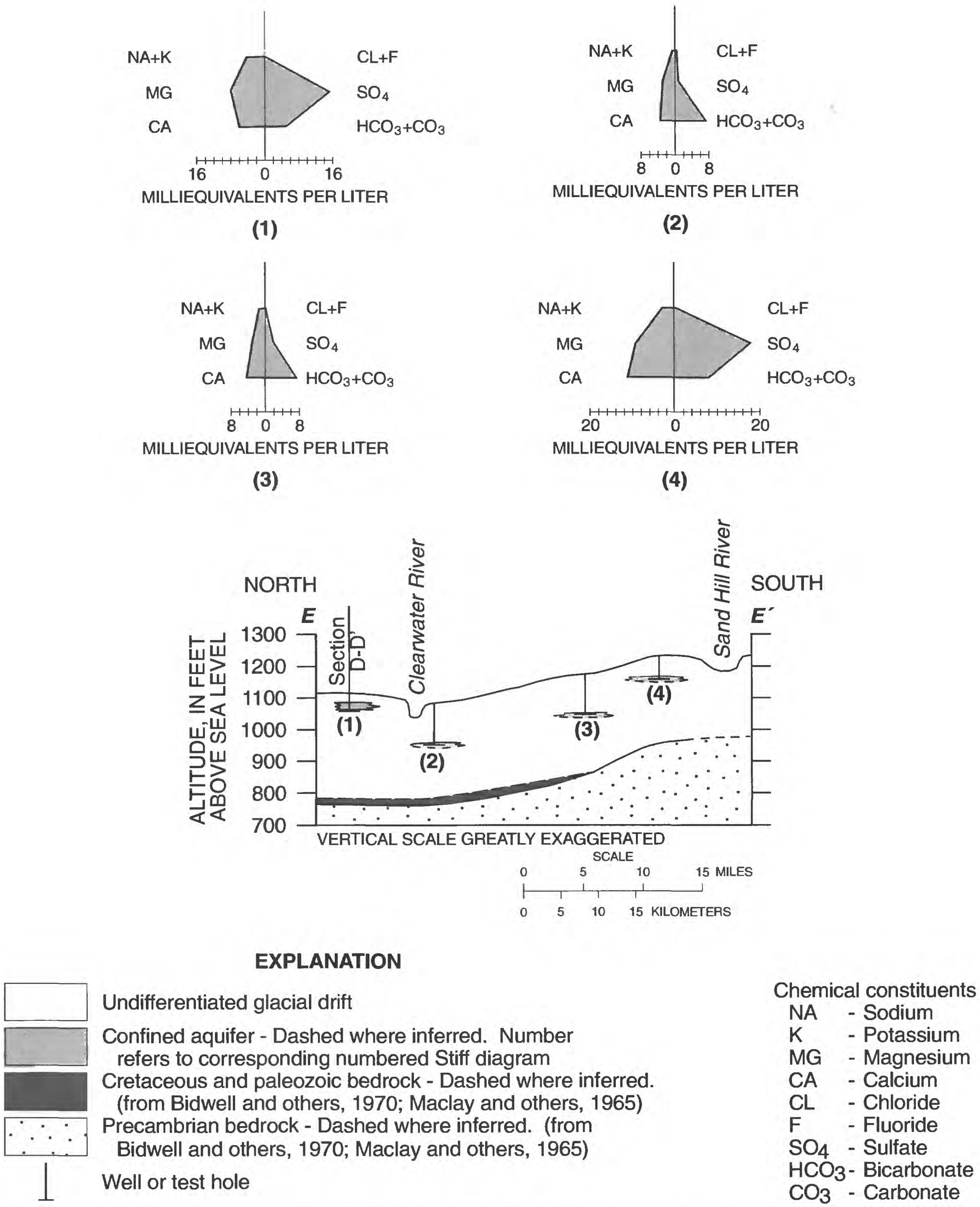


Figure 45. Hydrogeologic section E - E´ along regional ground-water-flow path and Stiff diagrams showing predominant chemical constituents in water from confined aquifers (trace of section shown on figure 42).

Table 18.—Seasonal water-quality data for samples collected from selected wells completed in unconfined aquifers

[mg/L, milligrams per liter; µg/L, micrograms per liter; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; --, not sampled; <, less than: FET, fixed endpoint titration; field, value determined at sampling site; lab, value determined in a laboratory]

Station number	Date	Depth of water level below land surface (feet)	Depth of well, total (feet)	Elevation of land surface datum (feet above sea level)	Temperature, water (°C)	Specific conductance, field (µS/cm)	Specific conductance, lab (µS/cm)	pH, field (standard units)	pH, lab (standard units)	Oxygen, dissolved (mg/L)
473752095521401	03-28-91	6.0	60	1212	12	748	808	7.2	7.6	0.5
	04-29-92	--	60	1212	--	--	816	--	7.5	--
474629096180400	08-13-91	9.4	15	1050	13	284	394	7.5	7.8	13.5
	04-29-92	--	15	1050	--	--	428	--	7.7	--
	11-12-92	--	15	1050	--	--	426	--	7.8	--
481807096430801	08-22-91	7.0	32	853	12	739	821	6.8	7.2	0
	04-28-92	--	32	853	--	--	827	--	7.2	--
	11-13-92	--	32	853	--	--	829	--	7.4	--

Station number	Date	Hardness, total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Sodium, percent	Sodium adsorption ratio (SAR)	Potassium, dissolved (mg/L as K)	Alkalinity, total FET, field (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)
473752095521401	03-28-91	380	89	37	31	15	0.7	5.7	355	87
	04-29-92	350	82	36	28	15	.6	4.7	--	91
474629096180400	08-13-91	190	51	15	.7	1	0	1.3	148	7.9
	04-29-92	210	56	17	.6	1	0	.9	--	7.9
	11-12-92	200	51	18	1.3	1	0	1.3	170	6.0
481807096430801	08-22-91	460	87	58	6.6	3	.1	3.3	464	23
	04-28-92	420	80	54	6.8	3	.1	3.5	--	25
	11-13-92	420	79	54	6.5	3	.1	3.6	428	24

Table 18.—Seasonal water-quality data for samples collected from selected wells completed in unconfined aquifers—Continued

Station number	Date	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Solids, residue at 180°C, dissolved (mg/L)	Solids, sum of constituents, dissolved (mg/L)	Barium, dissolved (µg/L as Ba)	Beryllium, dissolved (µg/L as Be)	Boron, dissolved (µg/L as B)	Cadmium, dissolved (µg/L as Cd)
473752095521401	03-28-91	2.2	0.2	26	505	493	40	<0.5	180	<1.0
	04-29-92	1.0	.2	26	493	--	35	<.5	190	<1
474629096180400	08-13-91	.5	.1	14	240	179	37	<.5	20	<1
	04-29-92	.8	.1	13	260	--	34	<.5	10	<1
	11-12-92	.9	.1	13	246	194	34	<.5	20	<1
481807096430801	08-22-91	6.6	.2	24	478	492	320	<.5	30	<1
	04-28-92	7.9	.2	23	481	--	280	<.5	30	<1
	11-13-92	2.9	.2	22	485	450	250	<.5	30	1

Station number	Date	Chromium, dissolved (µg/L as Cr)	Cobalt, dissolved (µg/L as Co)	Copper, dissolved (µg/L as Cu)	Iron, dissolved (µg/L as Fe)	Lead, dissolved (µg/L as Pb)	Lithium, dissolved (µg/L as Li)	Manganese, dissolved (µg/L as Mn)	Molybdenum, dissolved (µg/L as Mo)	Nickel, dissolved (µg/L as Ni)
473752095521401	03-28-91	<5	<3	<10	1800	<10	44	76	<10	<10
	04-29-92	<5	<3	<10	1100	<10	43	66	20	<10
474629096180400	08-13-91	<5	<3	<10	10	<10	5	17	<10	<10
	04-29-92	<5	<3	<10	160	<10	<4	13	<10	<10
	11-12-92	<5	<3	<10	15	<10	<4	18	<10	<10
481807096430801	08-22-91	<5	<3	<10	4500	<10	18	170	<10	<10
	04-28-92	<5	<3	<10	2300	<10	15	150	10	<10
	11-13-92	<5	<3	<10	23	<10	15	150	20	<10

Table 18.—Seasonal water-quality data for samples collected from selected wells completed in unconfined aquifers—Continued

Station number	Date	Silver, dissolved (µg/L as Ag)	Strontium, dissolved (µg/L as Sr)	Vanadium, dissolved (µg/L as V)	Zinc, dissolved (µg/L as Zn)	Carbon, organic dissolved (mg/L as C)
473752095521401	03-28-91	<1	480	<6	25	2.0
	04-29-92	<1	490	<6	58	1.9
474629096180400	08-13-91	<1	37	<6	13	1.9
	04-29-92	1	41	<6	8	1.2
	11-12-92	<1	61	<6	43	--
481807096430801	08-22-91	<1	190	<6	7	6.1
	04-28-92	<1	180	<6	52	5.9
	11-13-92	<1	180	<6	16	--

A smaller set of 18 water samples, from wells previously sampled for immunoassay analysis, was collected and sent to the U.S. Geological Survey laboratory in Arvada, Colorado to be analyzed for nutrients and a broad spectrum of pesticides (fig. 4, table 2). The wells to be sampled were selected based on (1) the results of the immunoassay analyses, (2) the proximity of the well to cropland, and (3) known or inferred directions of ground-water flow in the vicinity of the well. One well was sampled three times during the summer and fall of 1992 to determine temporal changes in pesticide concentrations. The laboratory results indicated that pesticide concentrations in the water samples were below or only slightly above reporting limits, indicating no significant pesticide concentrations in the ground water. The repeated sampling at one well during the summer and fall of 1992 indicated only small temporal changes in pesticide concentrations.

Summary

Aquifers in glacial deposits are important sources of water in Marshall, Pennington, Polk, and Red Lake Counties in northwestern Minnesota. Unconfined aquifers are generally limited to scattered surficial sand and gravel beach deposits formed by the ancient glacial Lake Agassiz. Saturated thicknesses for the unconfined aquifers range from 0 to 30 ft.

Estimates of horizontal hydraulic conductivity for the unconfined aquifers were derived from (1) slug tests, (2) single-well recovery aquifer tests, (3) grain-size analyses of aquifer material, and (4) results from numerical ground-water-flow models. The estimated horizontal hydraulic conductivity ranged from 2.5 to 600 ft/d. Transmissivity of the unconfined aquifers derived from slug tests and single-well recovery aquifer tests ranged from 33 to 2,940 ft^2/d. Transmissivity derived from specific-capacity data ranged from 560 to greater than 3,910 ft^2/d.

Reported well yields for unconfined aquifers within beach deposits are generally about 5 to 10 gal/min and are sufficient for rural domestic and livestock supplies. Theoretical maximum well yields for wells with specific-capacity data ranged from 12 to 123 gal/min. Areas of greatest theoretical maximum yield coincide with areas of greatest transmissivity.

Confined aquifers consist of sand and gravel deposits that are bounded above by confining units of till or lake deposits. The confined aquifers were grouped and mapped for this study on the basis of depth from land surface to the top of the aquifer. All buried sand and gravel deposits supplying water to wells with depths to the top of the deposits less than 100 ft were designated as shallow confined aquifers. Similarly, all sand and gravel deposits with depths to the top of the deposit from 100 to 199 ft were designated as intermediate confined aquifers. All sand and gravel deposits with depths to the top of the deposit from 200 to 299 ft were designated as deep confined aquifers. All sand and gravel deposits with depths to the top of the deposit 300 ft or more were designated as basal confined aquifers.

Shallow confined aquifers are generally present in much of the eastern two-thirds of the study area. The saturated thickness of the aquifers ranges from 0 to 150 ft. Transmissivity derived from specific-capacity data ranges from 12 to greater than 46,000 ft^2/d. Theoretical maximum well yields range from 3 to 538 gal/min.

The intermediate confined aquifers are not present in about 40 percent of the western one-third of the study area. Where the aquifers are present, thicknesses range from less than 10 to more than 125 ft and are greatest in southwestern Polk and eastern Pennington Counties. Transmissivity derived from specific-capacity data ranges from 2 to greater than 190,000 ft^2/d. Theoretical maximum well yields range from 4 to greater than 16,300 gal/min.

The deep confined aquifers are generally not present in the northwest, north-central, and central parts of the study area. Where the aquifers are present, thicknesses range from less than 10 to more than 126 ft and are greatest in eastern Pennington County. Transmissivity derived from specific-capacity data ranges from 3 to greater than 210,000 ft^2/d. Theoretical maximum well yields range from 4 to 71,460 gal/min.

The basal confined aquifers are most utilized as a source of water in central Marshall and western Pennington Counties. The thickness of the aquifers ranges from 0 to more than 70 ft. Transmissivity derived from specific-capacity data ranges from 6 to 48,900 ft^2/d. Theoretical maximum well yields range from 6 to 10,700 gal/min.

Confining units physically and hydraulically separate unconfined and uppermost confined aquifers and successive confined aquifers in the geologic column. The rate of vertical flow of water through a confining unit depends on the thickness and vertical hydraulic conductivity of the confining unit, and differences in hydraulic head of the aquifers above and below the confining unit. The thicknesses of uppermost confining units in the study area range from 0 to greater than 300 ft.

Recharge to ground water is predominantly from precipitation that percolates downward to the saturated zone. Recharge to the aquifers is greatest and most rapid in areas where the unconfined aquifers are present at land surface. Recharge to unconfined aquifers in the study area ranged from 4.5 to 12.0 in./yr during 1991 and 1992, based on hydrograph analysis.

Discharge from ground water occurs by seepage to streams, lakes, and wetlands, evapotranspiration, and withdrawals through wells. The Red River of the North, which is the western boundary of the study area, is also the regional ground-water discharge area. The rate of ground-water evapotranspiration is assumed to be a maximum of 28 to 37 in./yr in the study area where water levels are at land surface (based on mean annual pan evaporation rates) and decreases to zero where the water table is below the root-zone depth. In 1990 total ground-water withdrawals in the study area were 6.0 Mgal/d. All of the withdrawals are from the drift aquifers. Ground-water is withdrawn in the study area primarily for public water supply, rural-domestic and livestock, and irrigation.

The regional direction of ground-water flow in the study area is from morainal areas in the eastern part toward the Red River of the North at the western boundary. In Polk and Red Lake Counties in the southeastern part of the study area, ground water flows in a southeast to northwest direction toward the Clearwater and Red Lake Rivers. The horizontal hydraulic gradient in the confined aquifers ranges from 2 to 50 ft/mi.

Numerical models of ground-water flow were constructed for beach-ridge aquifer systems in Polk and Red Lake Counties and in Pennington County. Simulated recharge from the infiltration of precipitation accounts for most of the sources of water to the beach-ridge aquifer systems and simulated evapotranspiration accounts for all of the discharges other than ground-water withdrawals. The values for vertical hydraulic conductivity of uppermost confining units determined by model analyses that produced the best matches between model-simulated and measured water levels ranged from 0.001 to 0.02 ft/d. The calibration best-match values for long-term average recharge to the unconfined aquifers by infiltration of precipitation for the two beach-ridge aquifer systems were 8.0 and 9.0 in./yr. Model simulations also indicate that a long-term average recharge rate from 4.0 to 4.5 in./yr is reasonable for sandy till and clay exposed at land surface in the study area. The similarities between the calibration best-match values for the hydraulic properties of the hydrogeologic units and hydrologic fluxes for the two beach-ridge aquifer systems indicate that the values of hydraulic properties and hydrologic fluxes and the results of the simulations are transferable to other beach-ridge aquifer systems within the study area.

The numerical-model simulations indicated that the surficial beach deposits (unconfined aquifer and adjacent clays) are a source of water to the underlying deeper aquifers in some areas and a potential discharge area for the deeper aquifers in other areas. Implications can also be drawn from the model simulations regarding the potential yield of beach-ridge aquifer systems in the study area. Simulated long-term, steady-state yields from parts of the unconfined aquifers, the size of a model grid cell (about 20 acres), are generally less than 50 gal/min, due to the generally low saturated thickness of the aquifers and the relatively low hydraulic conductivity of the aquifer material.

Ground-water samples were collected to (1) determine general ground-water quality, (2) provide baseline water-quality data for use in future assessments of long-term trends, (3) determine seasonal changes in water chemistry, and (4) determine if ground-water quality has been affected by land-use practices. General properties of water include specific conductance, dissolved solids, pH, alkalinity, and hardness. The mean concentration of dissolved solids was least in water from the unconfined aquifers and greatest in water from the shallow confined aquifers. The mean alkalinity was least for water from the unconfined and basal confined aquifers and was greatest for water from the shallow and intermediate confined aquifers. Water from the shallow, intermediate, and deep confined aquifers in the study area is very hard (more than 180 mg/L).

The predominant ions in water from the unconfined and shallow confined aquifers were generally calcium and bicarbonate. Sodium percentages (as percentage of total cations) were generally higher in water from the shallow confined aquifers compared to water from the unconfined aquifers. Chemical analyses of water from the intermediate confined aquifers indicated a variety of water types, including calcium bicarbonate, calcium sulfate, mixed calcium-sodium bicarbonate, and sodium chloride type waters. Analyses of water from the deep confined aquifers indicated that the predominant water types are calcium bicarbonate, mixed calcium-sodium bicarbonate, and sodium chloride type waters. The probable reason for the increase in sodium and chloride, as a percentage of total cations and anions, with increasing depth below land surface is mixing with water from the underlying Cretaceous and Paleozoic strata.

Mean concentrations of calcium and magnesium in water from the drift aquifers generally decreased with depth below land surface. The mean concentration of sodium was much lower for the unconfined aquifers (8.8 mg/L) than for the shallow, intermediate, and deep confined aquifer (74-82 mg/L). Mean chloride concentrations were greater for the shallow and deep confined aquifers than for the unconfined and intermediate confined aquifers. Mean dissolved iron concentrations were least for the deep confined aquifers and greatest for the shallow confined aquifers. Water from a well screened in a basal confined aquifer had comparatively low calcium, magnesium, and sulfate concentrations and comparatively high chloride and sodium concentrations.

Water from the drift aquifers underlying most of the study area are generally suitable for domestic consumption, crop irrigation, and most other uses. Water from 34 percent of sampled wells screened in unconfined and confined aquifers exceeded USEPA recommended limits for dissolved-solids concentrations. Water from 14 percent of sampled wells screened in shallow confined aquifers had sodium, sulfate, and chloride concentrations that exceeded USEPA recommended limits. The SMCL's for iron were exceeded in 39 and 83 percent of the wells sampled for the unconfined and confined aquifers, respectively. Water from the unconfined and confined aquifers generally have a potentially low sodium hazard and a medium to high salinity hazard for irrigation.

Twenty-three water samples were collected for this study from wells screened in unconfined and shallow confined aquifers and analyzed for nitrate. Ten of the samples had a nitrate concentration below the reporting limit (0.05 mg/L). Two samples had nitrate concentrations greater than the MCL of 10 mg/L.

Water samples were collected from wells screened in drift aquifers and located along regional ground-water-flow paths to determine possible trends in water quality with relative age and position of the water in the flow system. The concentration and percentage (as percent of total cations) of sodium and concentration of dissolved solids tend to increase from east to west along regional flow paths. Concentrations and percentages (as percent of total anions) of chloride tend to be greater in the western part of the study area than in the eastern part. These trends are probably due to a combination of longer residence time of the water in the flow system, and upward leakage of water from the underlying Cretaceous and Paleozoic strata.

Because the unconfined and shallow confined aquifers are most susceptible to contamination by land-surface activities, samples were collected from these aquifers and analyzed for a broad spectrum of pesticides. The laboratory results indicated that pesticide concentrations in the water samples were below or only slightly above reporting limits, indicating no significant pesticide concentrations in the ground water at the sites tested.

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Supplemental Information Section

Well-Log Data

Table 19.—Selected data from commercial drillers' logs of wells in study area used to estimate transmissivity and theoretical maximum well yield

[ft, feet; gal/min, gallons per minute; hr, hours; in., inches; gal/min/ft, gallons per minute per foot of drawdown; -, indicates static water level is above land surface]

Location	Static water level below land surface (ft)	Pumping water level below land surface (ft)	Pumping rate (gal/min)	Pumping time (hr)	Well diameter (in.)	Well screen length (ft)	Specific capacity (gal/min/ft)
147N39W24CDB	80	96	30	3.0	3.0	8.0	2
147N39W28CBDB	55	58	10	2	4	9	3
147N39W28CDCD	43	47	19	10	3.5	5	5
147N39W33BDB	0	50	4	1	2	4	.1
147N40W03DCC	17	30	12	6	3.5	8	.9
147N40W04BDDB	25	40	500	10.5	10	35	33
147N40W04DBDA	28	58	513	8	12	36.8	17
147N40W10BBBB1	29.7	112	220	24	10	34.5	3
147N43W03BBDA2	20	70	100	2	4	8	2
147N44W05DACA	21	80	50	2	4	4	.8
147N44W16CCCB	12	57	25	.5	2	6	.6
147N44W22BBAB	14.8	15.3	150	3.5	4	5	300
147N44W28BADC	21	97	18	1	3	5	.2
147N44W29BBA	20	40	25	3	4	8	1
147N44W33CBCA	20	75	110	5	2	20	2
147N45W11BBCC	29	170	45	2.5	2	5	.3
147N46W16CCDD	0	62	43	16	4	8	.7
147N46W16CDDA2	7	94	4	3.5	2	8	.05
147N46W21BABA	1.5	97	40	11.2	4	4	.4
147N48W24BBAD	18	160	30	5	4	9	.2
147N49W24CCD	16	309	90	2	2	10	.3
148N40W21DDC	48	93.5	8	3	4	10	.2
148N42W02CCBA	47.8	95	150	4	4	8	3
148N42W03DADA	49	50.7	20	4.5	4	5	12
148N42W03DDAB	46	80	100	4	4	8	3
148N42W04BABC2	8.5	50	13	4	3	10	.3
148N42W09CDA	20	55	90	2	4	4	3
148N42W10ADC	22	45	35	2	4	4	2
148N42W10CBB	20	45	75	1	4	4	3
148N43W04BABD	5	65	15	2	4	4	.2
148N43W04BACD2	10	60	100	3	4	4	2
148N43W05ABBB	10	15	12	2	2	6	2
148N43W07ABCA	35	120	150	3	4	8	2
148N43W21AADA	30	60	18	3	4	10	.6
148N43W22CABC	30	45	50	2	4	8	3
148N43W23AAAC	30	100	30	6	4	4	.4
148N43W25CBCC	21	150	75	2.5	2	5	.6
148N43W29AACD	39	45	45	1.5	4	8	8

Table 19.—Selected data from commercial drillers' logs of wells in study area used to estimate transmissivity and theoretical maximum well yield—Continued

Location	Static water level below land surface (ft)	Pumping water level below land surface (ft)	Pumping rate (gal/min)	Pumping time (hr)	Well diameter (in.)	Well screen length (ft)	Specific capacity (gal/min/ft)
148N46W10BDDC	2.0	148	150	5	4	8.7	1
148N47W35BCDD	60	313	5	1.7	4	5	.02
148N48W04ABAB	28	206	200	5	4	13	1
149N40W31CCA	25	32	35	1.5	4	8	5
149N42W35BBDC	1	2	150	2	4	4	150
149N43W31BAAD	14	30	12	2	3	5	.8
149N44W06ACC	12	48	100	2	4	4	3
149N44W06CBCD	17	20	50	3.5	4	4	17
149N44W17ABCB	5.4	18	90	6	4	10	7
149N44W19DDDD	7.4	23	102	4.5	2	20	7
149N44W21ABCB	6	35	50	4	4	4	2
149N44W23BBBC	12	80	75	8	4	13.5	1
149N45W04BBAB	9.3	13.6	80	0.5	4	12	19
149N45W17ABDD	18	199	18	8	4	4	.1
149N45W17BABA	12	196	20	8	4	4	.1
149N45W28DDBD	27	104	85	5	4	4	1
149N46W01CBCB	22	155	110	7	4	13	.8
149N46W04CBBB	-1	80	60	5.5	4	6	.7
149N46W06BDAD	13	180	10	12	4	5	.06
149N46W07AAAA	10	233	5	15	4	8	.02
149N46W12BCCC	17.9	20	100	2.5	4	5	48
149N46W15BBBB	3	211	125	7	4	4.3	.6
149N46W22ADDA	7	266	45	30	4	8.7	.2
149N46W26DAAA	0	50	150	1.5	4	8	3
149N46W35BAAA	-1	3	200	4	4	6	50
149N47W01CCBD	6	170	25	5	4	4	.2
149N47W07BBAB	32.5	39	120	2.8	4	6	18
149N47W14BCBC	-3	160	9	13	4	8	.06
149N47W14CAAB	33	110	25	8	4	8	.3
149N47W14DDDC	5	82	60	5.2	4	6	.8
149N48W02BABA	31	45	100	3	4	5	7
149N48W14ABAA	22	284	80	8	4	12.8	.3
149N48W14DDAD	23.5	25	180	2	4	5	120
149N48W24BBAB	24.4	27	100	2	4	4	38
149N48W35BCC2	25	60	40	1	4	8	1
150N39W35CBBC	20	55	15	3	4	4	.4
150N40W26ADBB	21.9	28.2	147	2	12	10	23
150N40W27ACBC	10	20	35	2	4	8	4
150N41W27CDA	2	30	50	1	4	4	2
150N42W01ABB	4	50	150	3	4	8	3
150N42W08DCCB	5	148	75	8	4	9	.5

Table 19.—Selected data from commercial drillers' logs of wells in study area used to estimate transmissivity and theoretical maximum well yield—Continued

Location	Static water level below land surface (ft)	Pumping water level below land surface (ft)	Pumping rate (gal/min)	Pumping time (hr)	Well diameter (in.)	Well screen length (ft)	Specific capacity (gal/min/ft)
150N42W09DDCD	33	100	120	3	4	8	2
150N42W11CDAA	1	85	7	4	2	4	.08
150N42W12CCB	5	110	40	4	4	8	.4
150N43W02BCBC	10	20	140	2	4	12	14
150N44W02ABAB	55	80	40	6	4	12	2
150N44W14AAAA	35	150	75	6	4	8	.6
150N44W29BABA	20	80	125	3	4	8	2
150N44W31CAAC2	12.7	122.8	350	72	12	29	3
150N44W31CCCC5	3.2	41.1	575	72	12	15	15
150N44W31CDDC2	3.9	45.1	700	72	12	20	17
150N44W31DDAD	14.5	99.6	30	3.8	2	15	.4
150N44W31DDDD2	6	8	60	3	4	6	30
150N45W05BDCD2	40	110	150	8	4	8	2
150N45W15ABCB	12	82	20	8	4	4.3	.3
150N45W20DCCB	8	46	12	3	4	4	.3
150N45W24CBBD	4	80	75	4	4	8	.9
150N45W26BBAA	16	95	150	4	4	4	2
150N45W28DAAB	15	63	10	5	4	4.3	.2
150N45W30DCCD	12	100	180	7	4	12	2
150N45W33DAAA	6	70	60	6	4	4	.9
150N45W33DADB	12	69	30	2	4	8	.5
150N45W34CCCD	28	102	40	8	4	4.3	.5
150N46W03CCDC	42	72	32	2	4	5	1
150N46W07ADAD	15	100	25	4	4	8	.3
150N46W08DAAC	25	237	30	30	4	13	.1
150N46W16BBBC	25	100	75	6	4	4	1
150N46W18BBDD2	14	110	30	4	4	6	.3
150N46W23DDDC	30	90	200	4	4	8	3
150N46W28BCCC	1.5	170	150	6	4	4	.9
150N46W29CDCC	12	241	60	8	4	5	.3
150N46W34AADC2	9	200	8	6.5	4	5	.04
150N47W18CDDD	23.6	77.6	20	7.5	4	9	.4
150N47W28CCDD	31	297	50	5	4	17	.2
150N47W29DBAA	31	70	10	1	4	8	.3
150N48W06AABC	26	44.4	55	9	6	12	3
150N48W14DCCA	23	307	30	2	4	8	.1
151N39W02ACCB	4	30	125	4	4	4	5
151N39W16ADDD	0	50	150	3	4	8	3
151N40W18BAAA	16	40	20	3	4	4	.8
151N40W29DCCC	12	80	20	3	4	4	.3

Table 19.—Selected data from commercial drillers' logs of wells in study area used to estimate transmissivity and theoretical maximum well yield—Continued

Location	Static water level below land surface (ft)	Pumping water level below land surface (ft)	Pumping rate (gal/min)	Pumping time (hr)	Well diameter (in.)	Well screen length (ft)	Specific capacity (gal/min/ft)
151N41W04DDC	15	70	50	3	4	4	0.9
151N41W05DCCC	12	60	45	5	4	8	.9
151N41W11ABB	18	85	40	3	4	4	.6
151N41W13BAA	16	80	25	3	4	8	.4
151N42W04CDAC	36	110	120	3	4	4	2
151N42W05AAA	20	70	60	3	4	4	1
151N42W06CBC	20	30	15	2	4	8	2
151N42W08DCCA	25	150	100	3	4	8	.8
151N42W21DADD	20	70	125	3	4	4	2
151N42W22CBD	35	90	9	3	4	8	.2
151N42W29ABBC	14	100	125	3	4	8	1
151N42W31CBC	15	60	140	3	4	4	3
151N43W06DCDD	25	60	45	6	4	12	1
151N43W07DADB	35	85	90	6	4	8	2
151N43W20DCDD	55	110	125	4	4	4	2
151N43W26BDAC	11	80	180	3	4	8	3
151N43W33CBCB	30	100	125	5	4	12	2
151N44W05DBA	47	100	9	3	4	4	.2
151N44W09DDD	40	100	35	3	4	8	.6
151N44W12CDDC	64.	85	17	3	4	4	.8
151N44W13BBBA	25	70	20	4	4	8	.4
151N44W24ABDD	35	70	100	3	4	8	3
151N44W25BBA	33	60	50	4	4	8	2
151N44W26BCCA	70	85	15	3	4	12	1
151N44W36BBD	45	100	60	4	4	12	1
151N45W14BBBB	43.	100	20	5	4	4	.4
151N45W21DDD	35	100	60	2	4	12	.9
151N45W35BBB	17	21	100	2	4	8	25
151N46W01DDBA	38	130	3	11	2	10	.03
151N47W11DAA	11	66	3	1	4	4	.05
151N48W25DCDA	24	173	9	5.8	4	8	.06
152N39W02BACA	9	80	15	8	4	8	.2
152N39W14DDCA	-.6	168	80	6	4	4	.5
152N39W18DABD	6	80	60	6	4	8	.8
152N39W23DDCC	1	160	100	6	4	4	.6
152N39W26ABB	3	170	25	8	4	8	.2
152N39W27BAB	6	110	20	3	4	8	.2
152N40W10BAAC	20	140	130	6	4	12	1
152N40W18CBDB	10	60	200	4	4	8	4
152N40W21CDDD	12	90	50	8	4	4	.6

Table 19.—Selected data from commercial drillers' logs of wells in study area used to estimate transmissivity and theoretical maximum well yield—Continued

Location	Static water level below land surface (ft)	Pumping water level below land surface (ft)	Pumping rate (gal/min)	Pumping time (hr)	Well diameter (in.)	Well screen length (ft)	Specific capacity (gal/min/ft)
152N40W22BCCB	10	60	200	3	4	8	4
152N40W27BABB	7	70	175	6	4	8	3
152N40W28ABAA	12	60	30	3	4	8	.6
152N40W35BCB	42	120	50	5	4	4	.6
152N41W03DAAB	20	60	60	3	4	8	2
152N41W04BCDA	6	40	30	4	4	4	.9
152N41W17CDDA1	6	25	12	3	4	8	.6
152N41W24CBBB	7	55	35	3	4	8	.7
152N41W29BCC	7	60	75	4	4	4	1
152N42W04BAD	10	60	6	3	4	4	.1
152N42W14ABBA	20	60	30	3	4	4	.8
152N42W27ABDB	2	60	145	3	4	4	2
152N42W28CCCD	0	60	200	3	4	8	3
152N42W32ABDD	13	188	200	4	4	4	1
152N43W01BBDB	20	38	50	2	4	8	3
152N43W02AAB	12	70	25	2	4	4	.4
152N43W02CAAD	6	80	100	3	4	8	1
152N43W03ABAB	9	100	175	4	4	8	2
152N43W03BCBC	12	70	12	4	4	4	.2
152N43W05CBBA	-1	40	150	3	4	4	4
152N43W06CDA	9	190	18	12	4	8	.1
152N43W08CDBD	10	85	30	3	4	8	.4
152N43W09CBB	21	60	20	4	4	4	.5
152N43W19CCDA2	5	80	25	4	4	8	.3
152N43W20DCDA	2	343	100	3	4	9	.3
152N43W26BCAD	11	80	180	3	4	8	3
152N43W33BBBC	35	110	15	6	4	4	.2
152N44W05ABBA	30	65	35	6	4	8	1
152N44W05ADDA	30	110	500	5	8	30	6
152N44W13BAAA	25	40	30	6	4	8	2
152N44W27BCBD	2	40	15	4	4	8	.4
152N44W28ADA	5	25	50	2	4	8	2
152N45W01DDCC	35	110	75	4	4	12	1
152N45W25AADB	60	80	30	3	4	4	2
152N45W26ABBB	45	55	10	3	4	8	1
152N45W36BBBC	28	50	75	3	4	4	3
152N46W10DCCD	22	288	100	8	4	9	.4
152N46W11BCCC	23	110	150	2	4	12	2
152N47W08DCCC	4	265	20	15	4	4	.08
152N47W25CBD	1	100	75	2	4	12	.8

Table 19.—Selected data from commercial drillers' logs of wells in study area used to estimate transmissivity and theoretical maximum well yield—Continued

Location	Static water level below land surface (ft)	Pumping water level below land surface (ft)	Pumping rate (gal/min)	Pumping time (hr)	Well diameter (in.)	Well screen length (ft)	Specific capacity (gal/min/ft)
152N47W27AADC	9.5	19	15	5	4	5	2
153N39W05ABB	10	80	110	2	4	8	2
153N39W05BBB	20	80	100	4	4	8	2
153N39W09DCD	17	184	100	3	4	9	.6
153N39W31CCAA	13	300	200	4	4	8	.7
153N39W32BBAC	10	160	15	24	4	24	.2
153N39W33AAA	10	90	135	3	4	8	2
153N39W35DCD	5	298	100	5	4	4	.3
153N40N04CDDC	34	90	90	3	4	4	2
153N40W05DCDD	10	100	25	6	4	8	.3
153N40W06DCDD	28	120	60	3	4	8	.6
153N40W15DDDB	19	65	70	5	4	8	2
153N40W20CCC	20	80	100	3	4	4	2
153N40W21CCCD	17	60	35	3	4	8	.8
153N40W27ACC	20	90	100	5	4	4	1
153N40W27BBAA	6	60	150	4	4	8	3
153N40W29ADDB	12	70	200	2	4	4	3
153N40W30ADAD	4	150	20	6	4	4	.1
153N41W05CCBB	22	192	50	16	4	8.7	.3
153N41W11BBAC	20	70	150	3	4	4	3
153N41W18BCAA	15	90	45	8	4	4	.6
153N41W36BBBB	6	60	150	4	4	8	3
153N42W04DBC	30	120	75	6	4	4	.8
153N42W05ABA	35	120	20	4	4	8	.2
153N42W06CADD	31	100	60	6	4	9	.9
153N42W09ADB	25	75	110	3	4	4	2
153N42W09DCBB	23	60	140	3	4	8	4
153N42W16ABBC	30	120	50	6	4	8	.6
153N42W16BABB1	34	85	15	6	4	8	.3
153N42W16BABB2	60	150	10	6	4	4	.1
153N42W17BBAB	27	140	180	4	4	8	2
153N42W18CAAA	42	100	50	3	4	4	.9
153N42W19DCC	35	100	75	6	4	4	1
153N42W20ABC1	38	110	100	3	4	8	1
153N42W20ABC2	2	5	100	10	4	8	1
153N42W20BBAA	5	100	70	6	4	8	.7
153N42W21BBB	39	90	75	3	4	4	1
153N42W24BCBD	25	90	130	3	4	8	2
153N42W25ABD	25	85	60	4	4	4	1
153N42W29DCAD	23	205	75	5	4	8	.4

Table 19.—Selected data from commercial drillers' logs of wells in study area used to estimate transmissivity and theoretical maximum well yield—Continued

Location	Static water level below land surface (ft)	Pumping water level below land surface (ft)	Pumping rate (gal/min)	Pumping time (hr)	Well diameter (in.)	Well screen length (ft)	Specific capacity (gal/min/ft)
153N42W30BBAD	30	50	150	2	4	4	8
153N42W35DBBB	12	80	175	3	4	8	3
153N43W01BDDD	35	100	80	5	4	8	1
153N43W02ACA	35	100	25	8	4	8	.4
153N43W02DADC	35	110	110	6	4	8	1
153N43W03ABCD	37	110	30	6	4	12	.4
153N43W04BDD	38	180	50	8	4	8	.4
153N43W04CAA	31	90	40	4	4	8	.7
153N43W04CDBC	38	349	200	3	4	8	.6
153N43W04DDD	37	100	22	4	4	8	.4
153N43W08CCCC	34	85	175	3	4	8	3
153N43W09ADCA	40	100	15	6	4	8	.2
153N43W09BAAB	30	80	50	4	4	4	1
153N43W09DBCC	35	100	100	3	4	8	2
153N43W10BAAA	33	90	30	4	4	8	.5
153N43W15CBA	30	120	75	4	4	12	.8
153N43W15DDDD	30	120	40	6	4	8	.4
153N43W20AABA	35	120	125	6	4	8	1
153N43W20ABDB	35	85	20	6	4	4	.4
153N43W20DAA	36	80	10	2	4	8	.2
153N43W22ABCB2	29	80	175	3	4	4	3
153N43W22CCA	30	100	40	6	4	8	.6
153N43W22DDA	38	95	125	3	4	4	2
153N43W23CAC	27	247	125	5	4	8.7	.6
153N43W23CCAB	26	215	150	6	4	9	.8
153N43W24BBA	35	100	35	7	4	4	.5
153N43W25DDDD	22	70	160	3	4	4	3
153N43W26ABB	36	85	110	3	4	8	2
153N43W29DADD	20	70	170	2	4	4	3
153N43W36CCD	33	100	150	3	4	8	2
153N44W02AACD	60	120	5	5	4	4	.08
153N44W04AAAA	60	100	25	3	4	4	.6
153N44W04AAAD	90	140	50	3	4	8	1
153N44W04CCD	85	160	125	6	4	8	2
153N44W18CCDA	31	85	12	3	4	4	.2
153N44W22BACA	60	120	8	4	4	12	.1
153N44W23DDDB	55	140	80	6	4	8	.9
153N44W27BDDD	30	100	12	6	4	8	.2
153N44W32BAAB	20	332	100	6	4	9	.3
153N45W36CBBC	-3	50	25	3	4	4	.5

Table 19.—Selected data from commercial drillers' logs of wells in study area used to estimate transmissivity and theoretical maximum well yield—Continued

Location	Static water level below land surface (ft)	Pumping water level below land surface (ft)	Pumping rate (gal/min)	Pumping time (hr)	Well diameter (in.)	Well screen length (ft)	Specific capacity (gal/min/ft)
153N46W20DCCD	4	244	100	10	4	13	0.4
153N46W28DDBD	3	244	100	6	4	9	.4
153N47W09DDC	1	249	200	6	4	8.7	.8
153N47W21CBBD	63	140	8	11	4	4	.1
153N47W24CDCC	15	286	12	10	4	4	.04
153N48W14CDD	2	312	200	4	4	13	.6
153N48W22DDCC	-1	39	100	11.5	4	10	3
153N48W30BCB	1	139	20	6	4	4	.1
154N39W07BCDB	12	196	200	6	4	8	1
154N39W19CDD	15	70	100	3	4	4	2
154N39W25DCCB	15	285	8	12	4	9	.03
154N39W29DAA	5	80	125	3	4	8	2
154N40W02CBBB	10	85	100	3	4	8	1
154N40W03DDC	25	70	20	6	4	8	.4
154N40W20ADDD	20	100	10	8	4	8	.1
154N40W33DCC	15	80	25	12	4	8	.4
154N40W36ADBA	18	177	125	6	4	13	.8
154N41W10BBAB	15	60	100	2	4	4	2
154N42W10BBAA	30	90	60	6	4	4	1
154N42W17CCA	35	85	15	6	4	4	.3
154N42W18DDCC1	25	226	6	8	4	12	.03
154N42W18DDCC2	28	137	100	8	4	8.7	.9
154N42W26DDCC	38	80	125	3	4	8	3
154N42W30CCBA	35	150	100	6	4	8	.9
154N42W31ABAA1	32	100	10	6	4	12	.2
154N42W32CBAA	15	100	40	3	4	4	.5
154N43W09CACA	35	80	25	4	4	4	.6
154N43W12DDDD	37	140	110	3	4	8	1
154N43W13BBCC	35	90	125	4	4	4	2
154N43W17CDD	43	80	75	1	4	4	2
154N43W20DCCC	10	20	15	2	4	8	2
154N43W21CCBC	34	100	30	5	4	8	.4
154N43W21CCDC	36	115	90	4	4	8	1
154N43W21DDAD	38	110	25	5	4	8	.4
154N43W22BAAA	30	85	90	3	4	4	2
154N43W25CCCD	42	110	20	7	4	8	.3
154N43W26ABA	35	80	125	3	4	4	3
154N43W26CCCC	35	120	35	6	4	8	.4
154N43W26DAA2	35	100	125	5	4	8	2
154N43W27BACC	40	90	20	5	4	4	.4

Table 19.—Selected data from commercial drillers' logs of wells in study area used to estimate transmissivity and theoretical maximum well yield—Continued

Location	Static water level below land surface (ft)	Pumping water level below land surface (ft)	Pumping rate (gal/min)	Pumping time (hr)	Well diameter (in.)	Well screen length (ft)	Specific capacity (gal/min/ft)
154N43W28ACAD	40	100	125	3	4	4	2
154N43W28BDDD	40	240	75	8	4	13	.4
154N43W28CBBC	35	110	10	8	4	8	.1
154N43W29ADAD	30	350	150	3	4	8	.5
154N43W29BBA	6	25	30	3	4	8	2
154N43W29CBCC	35	115	85	3	4	12	1
154N43W29DBBB	42	110	45	5	4	8	.7
154N43W36CCAD3	35	120	50	5	4	8	.6
154N43W36DCCA	36	85	65	8	4	8	1
154N44W02ABB	52	408	20	12	4	9	.06
154N44W03ABDD	65	100	60	5	4	4	2
154N44W03DBBC	65	90	10	5	4	4	.4
154N44W06BADD	60	217	150	20	4	21.5	1
154N44W10ABBB	80	120	125	4	4	8	3
154N44W11DBAB	80	100	5	3	4	4	.2
154N44W12DADA	52	120	40	4	4	8	.6
154N44W13DAC	66	225	100	5	4	8.7	.6
154N44W14DCDC	65	90	30	4	4	4	1
154N44W15BCCC	58	266	40	7	4	8.7	.2
154N44W15DDCB	70	120	75	4	4	12	2
154N44W19DBAA	85	120	70	3	4	8	2
154N44W20DDDC	63	85	15	4	4	4	7
154N44W26CBBB	60	378	30	10	4	8	.09
154N44W26DDCB	35	55	45	6	4	8	2
154N44W27BACA	64	140	85	6	4	12	1
154N44W27DDB	70	120	125	4	4	12	2
154N44W28ABDC	59	306	50	14	4	13	.2
154N44W29CDCC	70	205	60	8	4	4	.4
154N44W29DAAA	75	205	50	8	4	9	.4
154N44W30BBDD	60	110	55	3	4	8	1
154N44W31AAB	80	140	125	3	4	12	2
154N44W32AAA	80	222	100	4	4	4	.7
154N44W33CCB	84	175	30	3	4	16	.3
154N44W34CCCD	55	100	60	4	4	8	1
154N44W34DABD	72	392	100	5	4	13	.3
154N44W36DDCD	60	180	12	6	4	8	.1
154N45W04ADCD	1	60	120	3	4	8	2
154N45W14ACB	30	70	100	3	4	8	2
154N45W14DAAA2	30	405	30	5	4	16	.08
154N45W22BAC	5	168	200	6	4	4	1

Table 19.—Selected data from commercial drillers' logs of wells in study area used to estimate transmissivity and theoretical maximum well yield—Continued

Location	Static water level below land surface (ft)	Pumping water level below land surface (ft)	Pumping rate (gal/min)	Pumping time (hr)	Well diameter (in.)	Well screen length (ft)	Specific capacity (gal/min/ft)
154N45W23BBCD	18	187	150	6	4	8	0.9
154N45W23CAAD	16	65	100	3	4	4	2
154N45W23DBBB	25	85	100	3	4	4	2
154N45W25ACAB	36	191	200	5	4	4	1
154N45W28DCA	5	110	15	8	4	4	.1
154N46W05BCAD	35	41.4	60	1.5	4	17	9
154N46W05BCCC	11.8	15.9	110	24	4	12	22
154N46W05BDAD	38	49	50	3	4	10	4
154N46W28ACCD	0	140	50	8	4	8	.4
154N46W30CDCC	15	150	10	5	4	8	.07
154N46W32ABBB	4	60	75	5	4	8	2
154N47W09ABBA	2.5	25	608	119	12	30	27
154N47W30CDDD	7	303	100	5	4	12	.3
154N49W36DCDD	0.5	101	150	2	4	12	1
155N39W33BCDC	18	100	25	8	4	4	.3
155N40W07BDCB	10	8	110	3	4	8	2
155N41W13ADB	12	80	150	3	4	8	2
155N41W22CBB	20	90	40	8	4	8	.6
155N41W26CCCD	22	60	12	10	4	8	.3
155N42W35ADDC	19	80	50	1	4	9	.8
155N43W03DCDB	20	100	50	20	4	8	.6
155N43W10ACDD	38	306	150	3	4	4	.6
155N43W14ADAC	30	323	75	8	4	9	.3
155N43W23BCCB	40	120	150	3	4	12	2
155N43W27DDDC	35	110	125	4	4	16	2
155N43W30ABAC	80	130	106	4	4	8	2
155N43W31ABA	68	120	100	3	4	8	2
155N43W31ACCA	80	11	40	3	4	8	1
155N43W31DCDC	45	120	90	4	4	4	1
155N43W32DACC	34	110	100	4	4	8	1
155N43W34ACAB	20	90	100	4	4	8	1
155N43W36AAA	25	80	30	3	4	8	.6
155N44W03BCBD	36	70	95	2	4	8	3
155N44W05CDA	17	125	100	6	4	9	.9
155N44W08CDCB	18	90	150	2	4	8	2
155N44W17AAAB	20	100	50	4	4	8	.6
155N44W22ACC	41	140	60	8	4	8	.6
155N44W30ABBA	60	206	150	6	4	9	1
155N44W32ADDC	80	120	75	4	4	8	2
155N44W32DCD	80	130	100	3	4	8	2

Table 19.—Selected data from commercial drillers' logs of wells in study area used to estimate transmissivity and theoretical maximum well yield—Continued

Location	Static water level below land surface (ft)	Pumping water level below land surface (ft)	Pumping rate (gal/min)	Pumping time (hr)	Well diameter (in.)	Well screen length (ft)	Specific capacity (gal/min/ft)
155N44W34DCAA	80	450	75	7	4	13	0.2
155N44W34DDBA	45	110	100	4	4	12	2
155N45W05CBAC	30	100	35	3	4	8	.5
155N45W10CAAC	30	110	75	4	4	8	.9
155N45W11BBCC	27	200	150	6	4	8.7	.9
155N45W13CCBB	39	207	100	6	4	8.6	.6
155N45W26BABB	30	80	20	4	4	8	.4
155N46W06ACC	12	60	25	3	4	8	.5
155N46W10BDAC	39	348	20	6	4	8	.06
155N46W22CDCC	1	30	30	4	4	8	1
155N46W28CCC	38	100	75	3	4	8	1
155N46W30CAAA	30	110	40	4	4	4	.5
155N47W14ABBB	35	72.5	350	24	10	25	9
155N47W26BCC	20	80	12	6	4	8	.2
156N39W08ADA	15	60	40	3	4	4	.9
156N39W19CBCC	8	80	60	3	4	4	.8
156N39W23DDA	8	40	125	3	4	4	4
156N39W24DBBB	4	20	110	4	4	4	7
156N39W26AAAD	10	30	60	2	4	8	3
156N39W26ADDD	10	35	20	3	4	8	.8
156N39W35DAAD	10	40	15	4	4	8	.5
156N40W11BCDD	8	70	110	3	4	12	2
156N40W14DDCD	5	60	100	3	4	8	2
156N40W26CBBC	1	5	25	4	4	10	6
156N40W27DAAA	12	80	60	3	4	8	.9
156N40W31ACCA	8	50	90	2	4	8	2
156N40W34BAAA	11	90	100	4	4	8	1
156N40W35BACA	8	140	12	8	4	12	.09
156N43W02BBAB	20	80	75	4	4	4	1
156N43W04ABCA	36	50	50	5	4	4	4
156N43W25DBD	30	60	125	3	4	4	4
156N43W31DDDD	20	35	50	3	4	4	3
156N43W36BCCD	30	130	15	8	4	8	.2
156N44W05DDCD	15	70	300	21	8	15	5
156N44W13CCCD	25	40	17	5	4	6	1
156N44W28DAAA	13	31	40	3	4	8	2
156N44W35CCCC	50	190	9	6	4	8	.06
156N45W11CBBD	-1	15	30	3	4	4	2
156N45W13BADD	8	12	100	2	3	6	25
156N45W22ADB	4	187	150	4	4	8	.8

Table 19.—Selected data from commercial drillers' logs of wells in study area used to estimate transmissivity and theoretical maximum well yield—Continued

Location	Static water level below land surface (ft)	Pumping water level below land surface (ft)	Pumping rate (gal/min)	Pumping time (hr)	Well diameter (in.)	Well screen length (ft)	Specific capacity (gal/min/ft)
156N45W23DBBD	1	20	80	4	3	4	4
156N45W24DDC	30	75	50	4	4	8	1
156N45W29CCBD	5	276	300	4	4	13	1
156N47W22CADB	6	10	50	4	4	10	12
156N47W29CAD	7	20	6	3	6	10	.5
156N47W33BBB	5	60	125	6	4	8	2
156N48W03DDDC1	8	30	15	2	4	4.5	.7
156N48W24DDDD	4.3	19.9	89	2	4	8	6
157N39W14ADAB	2	100	35	6	4	8	.4
157N39W19CADD	20	60	180	3	4	8	4
157N40W04CBBB	15	90	120	4	4	12	2
157N40W09BDD	20	110	65	4	4	4	.7
157N40W23CACA	10	50	65	3	4	4	2
157N40W28AABA	16	100	75	3	4	8	.9
157N40W28CCDA	14	80	85	3	4	8	1
157N43W03ABCB	65	170	15	4	4	8	.1
157N43W08AABC	30	80	110	3	4	8	2
157N43W11ABCA	30	100	50	6	4	4	.7
157N43W11BCDD	27	58.5	166	6.5	6	13	5
157N43W14BBAA	30	100	10	4	4	8	.1
157N44W19DCDA	21	205	100	6	4	8	.5
157N44W20CCD	25	120	12	6	4	8	.1
157N44W26BBCD	28	155	10	8	4	9	.08
157N45W12AAAA	13	100	45	2	4	7	.5
157N45W21DDCC	4	75	10	3	4	8	.1
157N45W35BCD	1	178	100	4	4	8	.6
157N46W01DAAA	25	45	50	4	4	9	2
157N46W17BBCB	17	30	15	2	4	8	1
157N47W12DDDC	21.5	31	40	4	4	12	4
157N47W33ADAD	4	20	50	3	4	8	3
158N41W28BBC	18	60	120	4	4	8	3
158N42W25DAAA2	20	80	30	5	4	16	.5
158N43W36BCCD	23	40	65	2	4	6	4
158N44W04CDDD	6	110	150	3	4	4	1
158N45W04DDDD	28	264	5	10.5	4	8	.02
158N45W08AAAA	15	40	20	2.5	4	5	.8
158N45W08AAAC	16	180	8	3	4	4	.05
158N45W29AAAA	-2	220	35	3	4	4	.2
158N46W20BCDD	7	30	50	2	4	8	2
158N46W24DDCD	13	18	25	4.5	4	6	5

Table 19.—Selected data from commercial drillers' logs of wells in study area used to estimate transmissivity and theoretical maximum well yield—Continued

Location	Static water level below land surface (ft)	Pumping water level below land surface (ft)	Pumping rate (gal/min)	Pumping time (hr)	Well diameter (in.)	Well screen length (ft)	Specific capacity (gal/min/ft)
158N46W31DCA	5	30	125	2	4	8	5
158N47W24DCC	8	35	3	2	3.25	8	.1

Water-Quality Data

Table 20.—Water-quality data for wells screened in unconfined aquifers

[ft, feet; mg/L, milligrams per liter; µg/L, micrograms per liter; ∞°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; --, not analyzed; <, less than; FET, fixed endpoint titration; field, value determined at sampling site; lab, value determined in a laboratory]

Station number	Date	Depth below land surface (water level) (ft)	Depth of well, total (ft)	Elevation of land surface datum (ft above sea level)	Specific conductance, field (µS/cm)	Specific conductance, lab (µS/cm)	pH, field (standard units)	pH, lab (standard units)	Temperature, water (°C)	Oxygen, dissolved (mg/L)
473042096151800	08-13-91	5	12	1040	396	465	7.3	7.7	14.0	3.9
473241096164401	08-29-91	12	51	1139	508	541	7.1	7.5	12.0	0
473752095521401	08-28-91	6	60	1212	748	808	7.2	7.6	12.0	.5
473944095590800	08-14-91	46	96	1240	508	525	7.2	7.5	11.0	.1
474252096160800	08-22-91	6	53	1135	395	397	9.0	8.8	8.5	0
474537096195200	08-13-91	19	32	1125	443	477	7.5	7.7	9.5	1.8
474538096205000	08-13-91	--	--	1070	485	505	7.4	7.6	9.5	0
474608095372600	08-13-91	10	48	1263	922	978	6.8	7.3	10.5	2.9
474629096180400	08-13-91	9	15	1050	284	394	7.5	7.8	13.0	13.5
474728095434501	08-28-91	22	46	1220	467	479	7.1	7.5	12.0	3.7
475815096273500	06-09-92	--	22	1010	641	606	7.4	7.7	9.0	.2
480211096265200	06-09-92	--	22	1035	--	579	--	7.8	--	--
480537096205800	06-17-92	--	13	1103	1300	1270	6.6	6.7	8.0	--
480537096263000	06-09-92	--	17	1030	--	544	--	7.8	--	--
481807096430801	08-22-91	7	32	853	739	821	6.8	7.2	12.0	0
482725096332201	04-28-92	--	23	1048	359	401	7.8	7.7	9.5	1.9
482935096332101	04-28-92	--	22	1052	--	488	--	7.5	--	--
483145097062201	08-27-91	4	16	800	798	856	7.4	7.7	11.0	0

Table 20.—Water-quality data for wells screened in unconfined aquifers—Continued

Station number	Date	Hardness, total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Sodium, percent	Sodium, adsorption ratio	Potassium, dissolved (mg/L as K)	Alkalinity, FET total (mg/L as $CaCO_3$)
473042096151800	08-13-91	270	72	21	2.6	2	0.1	2.0	251
473241096164401	08-29-91	290	78	23	2.3	2	.1	1.3	245
473752095521401	08-28-91	380	89	37	31	15	.7	5.7	355
473944095590800	08-14-91	270	69	24	4.3	3	.1	2.6	248
474252096160800	08-22-91	86	6.3	17	43	50	2	5.7	221
474537096195200	08-13-91	260	65	23	2.7	2	.1	1.8	210
474538096205000	08-13-91	270	64	27	4.2	3	.1	3.1	233
474608095372600	08-13-91	480	130	38	17	7	.3	3.4	351
474629096180400	08-13-91	190	51	15	.7	1	0	1.3	148
474728095434501	08-28-91	250	67	21	1.7	1	0	2.2	244
475815096273500	06-09-92	340	83	31	3.6	2	.1	2.2	304
480211096265200	06-09-92	300	73	28	3.7	3	.1	2.8	204
480537096205800	06-17-92	790	200	70	5.1	1	.1	6.0	746
480537096263000	06-09-92	280	82	19	8.9	6	.2	2.1	262
481807096430801	08-22-91	460	87	58	6.6	3	.1	3.3	464
482725096332201	04-28-92	200	53	17	1.5	2	0	.8	198
482935096332101	04-28-92	240	60	23	1.9	2	0	1.6	260
483145097062201	08-27-91	440	95	49	17	8	.4	4.0	345

Table 20.—Water-quality data for wells screened in unconfined aquifers—Continued

Station number	Date	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissoved (mg/L as SiO_2)	Solids, residue at 180 C, dissolved (mg/L)	Solids, sum of constituents, dissolved (mg/L)	Barium, dissolved (µg/L as Ba)	Beryllium, dissolved (µg/L as Be)
473042096151800	08-13-91	23	5.0	0.2	20	290	298	54	<0.5
473241096164401	08-29-91	54	6.9	.2	26	334	341	280	<.5
473752095521401	08-28-91	87	2.2	.2	26	505	493	40	<.5
473944095590800	08-14-91	32	7.8	.1	27	312	318	290	<.5
474252096160800	08-22-91	0.3	7.7	.2	1.3	236	214	41	<.5
474537096195200	08-13-91	32	7.2	.1	16	267	275	79	<.5
474538096205000	08-13-91	50	6.3	.2	15	301	311	46	<.5
474608095372600	08-13-91	31	60	.1	26	581	540	220	<.5
474629096180400	08-13-91	7.9	.5	.1	14	240	179	37	<.5
474728095434501	08-28-91	16	1.9	.1	21	272	277	71	<.5
475815096273500	06-09-92	29	13	.2	19	357	364	56	<.5
480211096265200	06-09-92	13	12	.2	17	329	272	50	<.5
480537096205800	06-17-92	42	22	.2	26	868	829	330	<.5
480537096263000	06-09-92	9.4	10	.1	14	321	305	55	<.5
481807096430801	08-22-91	23	6.6	.2	24	478	492	320	<.5
482725096332201	04-28-92	5.4	1.6	.1	10	222	208	27	<.5
482935096332101	04-28-92	5.2	5.3	.1	8.1	260	261	30	<.5
483145097062201	08-27-91	100	32	.2	19	515	525	79	<.5

Table 20.—Water-quality data for wells screened in unconfined aquifers—Continued

Station number	Date	Boron, dissolved (µg/L as B)	Cadmium, dissolved (µg/L as Cd)	Chromium, dissolved (µg/L as Cr)	Cobalt, dissolved (µg/L as Co)	Copper, dissolved (µg/L as Cu)	Iron, dissolved (µg/L as Fe)	Lead, dissolved (µg/L as Pb)	Lithium, dissolved (µg/L as Li)
473042096151800	08-13-91	20	<1	<5	<3	<10	33	<10	8
473241096164401	08-29-91	20	<1	<5	<3	<10	1400	<10	8
473752095521401	08-28-91	180	<1	<5	<3	<10	1800	<10	44
473944095590800	08-14-91	20	<1	<5	<3	<10	2200	<10	11
474252096160800	08-22-91	130	<1	<5	<3	<10	38	<10	19
474537096195200	08-13-91	10	<1	<5	<3	<10	99	<10	8
474538096205000	08-13-91	20	<1	<5	<3	<10	890	<10	11
474608095372600	08-13-91	80	<1	<5	<3	<10	12	<10	18
474629096180400	08-13-91	20	<1	<5	<3	<10	10	<10	5
474728095434501	08-28-91	20	<1	<5	<3	<10	23	<10	10
475815096273500	06-09-92	100	<1	<5	<3	<10	9	<10	7
480211096265200	06-09-92	230	<1	<5	<3	<10	7	<10	5
480537096205800	06-17-92	40	<1	8	<3	<10	8500	<10	21
480537096263000	06-09-92	2600	<1	<5	<3	<10	20	<10	4
481807096430801	08-22-91	30	<1	<5	<3	<10	4500	<10	18
482725096332201	04-28-92	10	<1	<5	<3	<10	20	<10	<4
482935096332101	04-28-92	20	<1	<5	<3	<10	11	<10	<4
483145097062201	08-27-91	50	<1	<5	<3	<10	550	<10	44

Table 20.—Water-quality data for wells screened in unconfined aquifers—Continued

Station number	Date	Manganese, dissolved (µg/ L as Mn)	Molybdenum, dissolved (µg/ L as Mo)	Nickel, dissolved (µg/ L as Ni)	Silver, dissolved (µg/ L as Ag)	Strontium, dissolved (µg/ L as Sr)	Vanadium, dissolved (µg/ L as V)	Zinc, dissolved (µg/ L as Zn)	Carbon, organic, dissolved (mg/ L as C)
473042096151800	08-13-91	26	<10	20	<1	82	<6	140	2.6
473241096164401	08-29-91	140	<10	<10	<1	100	<6	9	1.2
473752095521401	08-28-91	76	<10	<10	<1	480	<6	25	2.0
473944095590800	08-14-91	220	<10	<10	<1	110	<6	18	2.1
474252096160800	08-22-91	10	<10	<10	<1	160	<6	5	15
474537096195200	08-13-91	64	<10	<10	<1	68	<6	98	--
474538096205000	08-13-91	54	<10	<10	<1	110	<6	3	1.6
474608095372600	08-13-91	<1	<10	<10	<1	180	<6	230	1.9
474629096180400	08-13-91	17	<10	<10	<1	37	<6	13	1.9
474728095434501	08-28-91	8	<10	<10	<1	85	<6	63	.9
475815096273500	06-09-92	440	<10	<10	<1	100	<6	11	4.3
480211096265200	06-09-92	51	<10	<10	<1	77	<6	8	2.0
480537096205800	06-17-92	690	<10	<10	<1	380	7	33	27
480537096263000	06-09-92	12	<10	10	<1	68	<6	6	4.2
481807096430801	08-22-91	170	<10	<10	<1	190	<6	7	6.1
482725096332201	04-28-92	7	<10	<10	<1	43	<6	80	1.3
482935096332101	04-28-92	20	<10	<10	<1	44	<6	11	2.5
483145097062201	08-27-91	300	<10	<10	<1	260	<6	450	2.0

Table 21.—Water-quality data for wells screened in shallow confined aquifers

[ft, feet; mg/L, milligrams per liter; µg/L, micrograms per liter; ∞°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; --, not analyzed; <, less than; FET, fixed endpoint titration; field, value determined at sampling site; lab, value determined in a laboratory]

Station number	Date	Depth below land surface (water level) (ft)	Depth of well, total (ft)	Elevation of land surface datum (ft above sea level)	Specific conductance, field (µS/cm)	Specific conductance, lab (µS/cm)	pH, field (standard units)	pH, lab (standard units)	Temperature, water (°C)	Oxygen, dissolved (mg/L)
473214095484500	06-19-92	--	78	1280	910	923	7.3	7.3	8.5	--
473229096083400	07-13-92	--	83	1190	750	711	7.6	7.6	7.5	--
473238096165300	06-11-92	--	59	1133	585	515	7.3	7.6	8.5	0.2
473712095554701	08-14-91	--	78	1240	1690	1840	6.8	7.2	9.5	0
474207096083000	07-13-92	--	86	1161	680	639	7.5	7.7	11.0	--
474224095451400	06-30-92	--	84	1280	850	882	7.2	7.3	8.0	--
474356095525100	06-30-92	--	75	1200	500	486	7.2	7.5	8.0	--
475702095592300	06-29-92	--	45	1130	900	821	7.5	7.6	9.0	--
475924096211300	06-10-92	--	74	1037	--	588	--	7.8	--	--
480512096520700	06-10-92	--	101	840	2560	2630	7.6	7.6	9.0	--
480540096263000	11-12-92	--	95	1026	--	890	--	7.9	--	--
481332096342900	06-08-92	--	86	946	950	883	7.1	7.3	9.0	--
482300096503801	08-22-91	--	--	--	2780	3400	6.7	7.1	11.0	.1
482729096423101	08-20-91	7	51	850	668	730	7.1	7.4	8.5	0

Table 21.—Water-quality data for wells screened in shallow confined aquifers—Continued

Station number	Date	Hardness, total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Sodium, percent	Sodium, adsorption ratio	Potassium, dissolved (mg/L as K)	Alkalinity, FET total (mg/L as $CaCO_3$)
473214095484500	06-19-92	490	120	46	22	9	0.4	5.8	385
473229096083400	07-13-92	350	86	32	27	14	.6	7.7	372
473238096165300	06-11-92	290	79	22	2.2	2	.1	1.3	236
473712095554701	08-14-91	1000	220	110	57	11	.8	8.1	397
474207096083000	07-13-92	310	72	31	27	16	.7	5.7	336
474224095451400	06-30-92	510	120	50	12	5	.2	6.2	491
474356095525100	06-30-92	270	67	24	2.3	2	.1	2.0	252
475702095592300	06-29-92	370	83	40	54	24	1	4.6	310
475924096211300	06-10-92	180	39	19	64	43	2	4.6	314
480512096520700	06-10-92	370	85	38	390	69	9	8.9	228
480540096263000	11-12-92	240	43	33	84	42	2	6.8	246
481332096342900	06-08-92	230	57	20	94	47	3	5.0	354
482300096503801	08-22-91	840	200	81	300	44	5	11	428
482729096423101	08-20-91	350	86	33	18	10	.4	4.2	408

Table 21.—Baseline water-quality data for wells screened in shallow confined aquifers—Continued

Station number	Date	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluroide, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Solids, residue at 180 °C, dissolved (mg/L)	Solids, sum of constituents, dissolved (mg/L)	Barium, dissolved (µg/L as Ba)	Beryllium, dissolved (µg/L as Be)
473214095484500	06-19-92	140	0.9	0.2	29	603	597	33	<0.5
473229096083400	07-13-92	35	.3	.3	28	417	441	94	<.5
473238096165300	06-11-92	53	4.4	.2	27	314	332	150	<.5
473712095554701	08-14-91	880	1.3	.2	27	1520	1550	17	<.5
474207096083000	07-13-92	23	.5	.4	30	358	393	96	<.5
474224095451400	06-30-92	28	.6	.2	30	521	545	170	<.5
474356095525100	06-30-92	27	.6	<.1	28	294	304	200	<.5
475702095592300	06-29-92	190	6.6	.3	27	577	592	38	<.5
475924096211300	06-10-92	<.1	14	.4	25	338	--	120	<.5
480512096520700	06-10-92	320	600	.5	26	1470	1610	21	<1
480540096263000	11-12-92	220	20	.5	20	572	576	67	<.5
481332096342900	06-08-92	<.1	88	.4	34	504	--	300	<.5
482300096503801	08-22-91	.2	910	.5	32	2040	1800	900	<2
482729096423101	08-20-91	.1	12	.2	29	427	434	260	<.5

Table 21.—Baseline water-quality data for wells screened in shallow confined aquifers—Continued

Station number	Date	Boron, dissolved (µg/L as B)	Cadmium, dissolved (µg/L as Cd)	Chromium, dissolved (µg/L as Cr)	Cobalt, dissolved (µg/L as Co)	Copper, dissolved (µg/L as Cu)	Iron, dissolved (µg/L as Fe)	Lead, dissolved (µg/L as Pb)	Lithium, dissolved (µg/L as Li)
473214095484500	06-19-92	200	<1	<5	<3	<10	1100	<10	74
473229096083400	07-13-92	240	<1	<5	5	<10	810	<10	71
473238096165300	06-11-92	20	<1	<5	4	<10	800	<10	5
473712095554701	08-14-91	680	<1	<5	<3	<10	2300	<10	220
474207096083000	07-13-92	170	<1	<5	4	<10	780	<10	38
474224095451400	06-30-92	130	1	<5	10	<10	2200	<10	52
474356095525100	06-30-92	20	1	<5	7	<10	1800	<10	9
475702095592300	06-29-92	160	<1	<5	<3	<10	68	<10	24
475924096211300	06-10-92	320	<1	<5	<3	<10	62	<10	20
480512096520700	06-10-92	860	<2	<10	<6	<20	1000	<20	100
480540096263000	11-12-92	230	<1	<5	<3	<10	570	<10	19
481332096342900	06-08-92	170	<1	<5	9	<10	2600	<10	15
482300096503801	08-22-91	480	<3	<20	<9	<30	8900	<30	96
482729096423101	08-20-91	50	<1	<5	<3	<10	6000	<10	18

Table 21.—Baseline water-quality data for wells screened in shallow confined aquifers—Continued

Station number	Date	Manganese, dissolved (µg/L as Mn)	Molybdenum, dissolved (µg/L as Mo)	Nickel, dissolved (µg/L as Ni)	Silver, dissolved (µg/L as Ag)	Strontium, dissolved (µg/L as Sr)	Vanadium, dissolved (µg/L as V)	Zinc, dissolved (µg/L as Zn)	Carbon, organic, dissolved (mg/L as C)
473214095484500	06-19-92	110	<10	<10	<1	610	<6	20	2.1
473229096083400	07-13-92	65	<10	<10	<1	640	<6	130	2.0
473238096165300	06-11-92	170	<10	<10	<1	86	<6	3	1.3
473712095554701	08-14-91	200	<10	<10	<1	1600	<6	23	--
474207096083000	07-13-92	47	<10	<10	2	380	<6	9	2.0
474224095451400	06-30-92	75	<10	<10	1	660	<6	<3	2.7
474356095525100	06-30-92	170	<10	<10	<1	110	<6	6	1.4
475702095592300	06-29-92	220	<10	<10	<1	400	<6	7	2.3
475924096211300	06-10-92	48	<10	<10	<1	280	<6	41	5.0
480512096520700	06-10-92	110	<20	<20	<2	1000	<12	9	2.4
480540096263000	11-12-92	28	10	<10	<1	420	<6	6	--
481332096342900	06-08-92	72	<10	<10	<1	220	<6	45	8.5
482300096503801	08-22-91	170	<30	<30	<3	1400	<18	87	7.0
482729096423101	08-20-91	160	<10	<10	<1	300	<6	15	3.1

Table 22.—Water-quality data for wells screened in intermediate confined aquifers

[ft, feet; mg/L, milligrams per liter; µg/L, micrograms per liter; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; --, not analyzed; <, less than; FET, fixed endpoint titration; field, value determined at sampling site; lab, value determined in a laboratory]

Station number	Date	Depth below land surface (water level) (ft)	Depth of well, total (ft)	Elevation of land surface datum (ft above sea level)	Specific conductance, field (µS/cm)	Specific conductance, lab (µS/cm)	pH, field (standard units)	pH, lab (standard units)	Temperature, water (°C)	Oxygen, dissolved (mg/L)
474113096001300	08-14-91	1	130	1179	754	790	7.4	7.6	9.0	0.0
474241095454900	06-30-92	--	170	1290	725	727	7.5	7.8	8.0	--
474258096222000	06-29-92	--	121	1040	810	779	7.9	7.8	9.0	--
474450096532300	06-11-92	--	158	852	2050	2060	6.9	7.6	8.0	1.8
474537096134400	10-30-92	--	165	1105	--	633	--	7.8	--	--
474537096160300	10-30-92	--	172	1095	--	541	--	8.7	--	--
474913095582600	06-18-92	--	191	1131	720	662	7.6	7.5	9.0	--
474954096090501	08-21-91	33	136	1090	595	641	7.5	7.6	8.5	0
475145096255000	06-10-92	--	200	905	996	972	7.9	8.2	8.5	.1
475421096195600	06-10-92	--	220	1025	1635	1600	6.8	7.3	8.0	0
475819096225400	08-15-91	55	128	1030	754	862	7.5	7.8	8.5	.2
475823095462401	08-21-91	10	171	1157	553	581	7.8	7.9	11.0	0
480440096034100	06-08-92	--	114	1130	825	749	7.5	7.6	8.5	--
481200096133000	06-04-92	--	180	1165	1650	1770	7.4	7.5	9.0	--
481437096232700	06-05-92	--	207	1075	900	852	7.6	7.7	8.5	--
481537095504800	06-05-92	--	118	1155	925	917	8.2	7.6	9.0	--
482633096231401	08-20-91	13	193	1091	580	675	7.5	7.6	10.0	0
482642096481301	08-27-91	15	179	1175	502	552	7.3	7.7	12.0	0
482717096342001	08-20-91	12	124	1010	752	867	7.2	7.4	9.5	0

Table 22.—Water-quality data for wells screened in intermediate confined aquifers—Continued

Station number	Date	Hardness, total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Sodium, percent	Sodium, adsorption ratio	Potassium, dissolved (mg/L as K)	Alkalinity, FET total (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)
474113096001300	08-14-91	370	86	37	30	15	0.7	4.1	353	99
474241095454900	06-30-92	350	86	33	33	17	.8	5.1	347	69
474258096222000	06-29-92	260	54	30	76	39	2	3.8	426	4.4
474450096532300	06-11-92	350	94	29	290	63	7	8.9	302	130
474537096134400	10-30-92	240	51	28	34	23	.9	2.4	360	2.4
474537096160300	10-30-92	180	45	17	41	32	1	5.0	245	34
474913095582600	06-18-92	320	80	29	22	13	.5	3.5	382	46
474954096090501	08-21-91	320	68	37	14	9	.3	3.4	350	18
475145096255000	06-10-92	67	13	8.3	190	86	10	1.9	309	24
475421096195600	06-10-92	770	190	72	87	20	1	6.6	396	480
475819096225400	08-15-91	230	41	32	94	46	3	2.8	304	130
475823095462401	08-21-91	170	39	18	63	44	2	2.9	241	73
480440096034100	06-08-92	280	61	32	56	30	1	4.8	413	.3
481200096133000	06-04-92	950	180	120	71	14	1	8.7	292	750
481437096232700	06-05-92	300	56	38	73	35	2	3.3	290	150
481537095504800	06-05-92	340	70	40	78	33	2	3.4	305	210
482633096231401	08-20-91	210	42	26	67	40	2	2.2	370	.3
482642096481301	08-27-91	210	44	24	42	30	1	2.1	320	.3
482717096342001	08-20-91	360	76	42	52	23	1	5.3	502	<.1

Table 22.—Water-quality data for wells screened in intermediate confined aquifers—Continued

Station number	Date	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Solids, residue at 180 °C, dissolved (mg/L)	Solids, sum of constituents, dissolved (mg/L)	Arsenic, dissolved (µg/L as As)	Barium, dissolved (µg/L as Ba)	Beryllium, dissolved (µg/L as Be)	Boron, dissolved (µg/L as B)
474113096001300	08-14-91	6.5	0.3	27	471	505	--	47	<0.5	140
474241095454900	06-30-92	1.2	.2	27	437	464	--	44	<.5	180
474258096222000	06-29-92	7.4	.3	33	457	465	--	180	<.5	240
474450096532300	06-11-92	390	.4	28	1160	1150	--	30	<1	910
474537096134400	10-30-92	5.0	.3	20	343	360	--	110	<.5	130
474537096160300	10-30-92	5.8	.5	15	300	311	--	54	<.5	90
474913095582600	06-18-92	1.2	.2	27	393	440	--	99	<.5	100
474954096090501	08-21-91	1.7	.3	22	379	377	--	110	<.5	50
475145096255000	06-10-92	110	.9	19	572	554	--	44	<.5	920
475421096195600	06-10-92	37	.4	31	1240	1150	--	15	<.5	390
475819096225400	08-15-91	37	.4	21	532	542	<1	140	<.5	370
475823095462401	08-21-91	12	.4	18	338	374	<1	120	<.5	110
480440096034100	06-08-92	16	.3	21	431	444	--	140	<.5	170
481200096133000	06-04-92	4.0	.3	23	1420	1340	--	20	<.5	290
481437096232700	06-05-92	14	.4	22	539	532	--	83	<.5	260
481537095504800	06-05-92	9.7	.2	26	594	622	--	89	<.5	180
482633096231401	08-20-91	16	.3	24	412	402	<1	280	<.5	230
482642096481301	08-27-91	8.1	.3	25	304	339	<1	170	<.5	130
482717096342001	08-20-91	13	.3	39	517	--	--	330	<.5	160

Table 22.—Water-quality data for wells screened in intermediate confined aquifers—Continued

Station number	Date	Cadmium, dissolved (µg/L as Cd)	Chromium, dissolved (µg/L as Cr)	Cobalt, dissolved (µg/L as Co)	Copper, dissolved (µg/L as Cu)	Iron, dissolved (µg/L as Fe)	Lead, dissolved (µg/L as Pb)	Lithium, dissolved (µg/L as Li)	Manganese, dissolved (µg/L as Mn)	Mercury, dissolved (µg/L as Hg)
474113096001300	08-14-91	<1.0	<5	<3	<10	3000	<10	24	94	--
474241095454900	06-30-92	<1.0	<5	<3	<10	720	10	27	89	--
474258096222000	06-29-92	<1.0	<5	<3	<10	45	<10	25	28	--
474450096532300	06-11-92	<2.0	<10	<6	<20	730	<20	95	130	--
474537096134400	10-30-92	<1.0	<5	<3	<10	670	<10	16	29	--
474537096160300	10-30-92	<1.0	<5	<3	<10	11	<10	15	48	--
474913095582600	06-18-92	1.0	<5	<3	<10	1400	<10	15	58	--
474954096090501	08-21-91	<1.0	<5	<3	<10	2600	<10	23	45	--
475145096255000	06-10-92	<1.0	<5	<3	<10	100	<10	17	5	--
475421096195600	06-10-92	<1.0	<5	10	<10	3700	10	110	190	--
475819096225400	08-15-91	<1.0	<5	<3	<10	440	<10	25	18	<0.1
475823095462401	08-21-91	<1.0	<5	<3	<10	2100	<10	9	210	<.1
480440096034100	06-08-92	<1.0	<5	10	<10	4000	<10	13	18	--
481200096133000	06-04-92	<1.0	<5	4	<10	1700	<10	110	110	--
481437096232700	06-05-92	<1.0	<5	<3	<10	630	<10	28	50	--
481537095504800	06-05-92	<1.0	<5	<3	<10	770	<10	18	45	--
482633096231401	08-20-91	<1.0	<5	<3	<10	1300	<10	13	49	<.1
482642096481301	08-27-91	<1.0	<5	<3	<10	690	<10	17	29	<.1
482717096342001	08-20-91	<1.0	<5	<3	<10	3200	<10	22	76	--

Table 22.—Water-quality data for wells screened in intermediate confined aquifers—Continued

Station number	Date	Molybdenum, dissolved (µg/L as Mo)	Nickel, dissolved (µg/L as Ni)	Selenium, dissolved (µg/L as Se)	Silver, dissolved (µg/L as Ag)	Strontium, dissolved (µg/L as Sr)	Vanadium, dissolved (µg/L as V)	Zinc, dissolved (µg/L as Zn)	Carbon, organic, dissolved (mg/L as C)
474113096001300	08-14-91	<10	<10	--	<1	350	<6	3	2.1
474241095454900	06-30-92	<10	<10	--	<1	380	<6	14	2.1
474258096222000	06-29-92	<10	<10	--	<1	440	<6	8	5.3
474450096532300	06-11-92	<20	<20	--	<2	560	<12	660	2.0
474537096134400	10-30-92	<10	<10	--	<1	360	<6	220	--
474537096160300	10-30-92	<10	<10	--	1	110	<6	490	--
474913095582600	06-18-92	10	<10	--	2	270	<6	11	1.8
474954096090501	08-21-91	<10	<10	--	<1	310	<6	3	1.6
475145096255000	06-10-92	<10	<10	--	<1	180	<6	<3	3.9
475421096195600	06-10-92	<10	<10	--	<1	770	<6	13	2.1
475819096225400	08-15-91	<10	<10	<1	<1	410	<6	19	4.3
475823095462401	08-21-91	10	<10	<1	<1	220	<6	<3	1.5
480440096034100	06-08-92	<10	<10	--	<1	350	<6	8	7.8
481200096133000	06-04-92	<10	<10	--	<1	1100	<6	8	3.5
481437096232700	06-05-92	<10	<10	--	<1	480	<6	68	3.5
481537095504800	06-05-92	<10	<10	--	<1	460	<6	3	3.4
482633096231401	08-20-91	<10	<10	<1	<1	370	<6	<3	5.2
482642096481301	08-27-91	<10	<10	<1	1	270	<6	17	2.5
482717096342001	08-20-91	<10	<10	--	<1	480	<6	24	10

Table 23.—Water-quality data for wells screened in deep and basal confined aquifers

[ft, feet; mg/L, milligrams per liter; µg/L, micrograms per liter; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; --, not analyzed; <, less than; FET, fixed endpoint titration; field, value determined at sampling site; lab, value determined in a laboratory]

Station number	Date	Depth below land surface (water level) (ft)	Depth of well, total (ft)	Elevation of land surface datum (ft above sea level)	Specific conductance, field (µS/cm)	Specific conductance, lab (µS/cm)	pH, field (standard units)	pH, lab (standard units)	Temperature, water (°C)	Oxygen, dissolved (mg/L)
Deep confined aquifers										
473119095500500	06-22-92	--	237	1251	760	750	7.5	7.5	8.0	--
473233096152100	06-11-92	--	260	1125	904	841	7.1	7.5	8.5	0.1
473412096263200	06-11-92	--	210	933	796	721	7.6	7.8	8.5	1.7
475356096532200	08-15-91	33	260	840	939	1030	7.4	7.6	13.0	5.0
475747096030701	08-21-91	0	240	1123	562	601	7.5	7.8	9.0	0
475838096335400	08-15-91	10	245	927	892	1030	7.8	7.9	13.0	.1
481452095512700	06-04-92	--	236	1153	610	658	7.9	7.9	8.0	--
482447096094300	06-04-92	--	218	1145	600	697	7.7	7.8	8.0	--
Basal confined aquifer										
482649096284001	08-20-91	4	324	1065	649	711	8.1	7.7	8.5	.1

Table 23.—Water-quality data for wells screened in deep and basal confined aquifers—Continued

Station number	Date	Hardness, total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Sodium, percent	Sodium, adsorption ratio	Potassium, dissolved (mg/L as K)	Alkalinity, FET total (mg/L as $CaCO_3$)
				Deep confined aquifers					
473119095500500	06-22-92	290	69	29	50	27	1	4.6	327
473233096152100	06-11-92	380	82	42	41	19	.9	4.8	406
473412096263200	06-11-92	220	46	25	79	44	2	4.3	362
475356096532200	08-15-91	190	43	19	140	61	4	5.3	220
475747096030701	08-21-91	200	44	22	57	38	2	2.5	278
475838096335400	08-15-91	170	35	19	150	66	5	3.2	232
481452095512700	06-04-92	200	41	24	74	44	2	2.4	281
482447096094300	06-04-92	250	36	38	63	35	2	3.2	296
				Basal confined aquifer					
482649096284001	08-20-91	58	13	6.2	140	83	8	3.7	297

Table 23.—Water-quality data for wells screened in deep and basal confined aquifers—Continued

Station number	Date	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Solids, residue at 180 C, dissolved (mg/L)	Solids, sum of constituents, dissolved (mg/L)	Barium, dissolved (μg/L as Ba)	Beryllium, dissolved (μg/L as Be)
				Deep confined aquifers					
473119095500500	06-22-92	70	15	0.30	21	454	457	65	<0.5
473233096152100	06-11-92	87	7.4	.70	25	523	537	32	<.5
473412096263200	06-11-92	34	14	.40	26	427	447	170	<.5
475356096532200	08-15-91	78	160	1.7	26	565	606	45	<.5
475747096030701	08-21-91	24	15	.30	21	335	353	100	<.5
475838096335400	08-15-91	2.9	190	.40	17	570	558	110	<.5
481452095512700	06-04-92	55	12	.30	26	384	404	140	<.5
482447096094300	06-04-92	63	13	.50	21	401	417	130	<.5
				Basal confined aquifer					
482649096284001	08-20-91	<.10	62	1.1	13	405	--	66	<.5

Table 23.—Water-quality data for wells screened in deep and basal confined aquifers—Continued

Station number	Date	Boron, dissolved (µg/L as B)	Cadmium, dissolved (µg/L as Cd)	Chromium, dissolved (µg/L as Cr)	Cobalt, dissolved (µg/L as Co)	Copper, dissolved (µg/L as Cu)	Iron, dissolved (µg/L as Fe)	Lead, dissolved (µg/L as Pb)	Lithium, dissolved (µg/L as Li)
Deep confined aquifers									
473119095500500	06-22-92	190	<1.0	<5	<3	<10	1100	<10	25
473233096152100	06-11-92	230	<1.0	<5	10	<10	3300	<10	43
473412096263200	06-11-92	360	<1.0	<5	<3	<10	180	<10	29
475356096532200	08-15-91	520	<1.0	<5	<3	50	10	<10	55
475747096030701	08-21-91	140	<1.0	<5	<3	<10	420	<10	17
475838096335400	08-15-91	260	1.0	<5	<3	<10	540	<10	14
481452095512700	06-04-92	180	<1.0	<5	<3	<10	310	<10	22
482447096094300	06-04-92	180	<1.0	<5	3	<10	610	<10	22
Basal confined aquifers									
482649096284001	08-20-91	780	<1.0	<5	<3	<10	44	<10	31

Table 23.—Water-quality data for wells screened in deep and basal confined aquifers—Continued

Station number	Date	Manganese, dissolved (µg/L as Mn)	Molybdenum, dissolved (µg/L as Mo)	Nickel, dissolved (µg/L as Ni)	Silver, dissolved (µg/L as Ag)	Strontium, dissolved (µg/L as Sr)	Vanadium, dissolved (µg/L as V)	Zinc, dissolved (µg/L as Zn)	Carbon, organic, dissolved (mg/L as C)
Deep confined aquifers									
473119095500500	06-22-92	110	<10	<10	<1.0	360	<6	8	2.3
473233096152100	06-11-92	54	<10	<10	<1.0	440	<6	16	--
473412096263200	06-11-92	14	<10	<10	<1.0	410	<6	29	3.3
475356096532200	08-15-91	24	20	<10	<1.0	380	<6	89	2.0
475747096030701	08-21-91	51	<10	<10	<1.0	250	<6	26	2.0
475838096335400	08-15-91	27	<10	<10	1.0	330	<6	14	2.7
481452095512700	06-04-92	18	<10	<10	<1.0	290	<6	13	3.5
482447096094300	06-04-92	11	<10	<10	<1.0	530	<6	11	2.9
Basal confined aquifer									
482649096284001	08-20-91	5	<10	<10	<1.0	190	<6	11	3.3

Table 24.—Water-quality data for wells sampled for nutrients

[mg/L, milligrams per liter; --, not analyzed; <, less than]

Station number	Date	Nitrogen, organic, dissolved (mg/L as N)	Nitrogen, ammonia, dissolved (mg/L as N)	Nitrogen, nitrite, dissolved (mg/L as N)	Nitrogen, nitrate, dissolved (mg/L as N)	Nitrogen ammonia + organic, dissolved (mg/L as N)	Nitrogen, $NO_2 + NO_3$, dissolved (mg/L as N)	Phosphate, ortho, dissolved (mg/L as PO_4)	Phosphorus, dissolved (mg/L as P)	Phosphorus, ortho, dissolved (mg/L as P)	Nitrogen ammonia, dissolved (mg/L as NH_4)
473042096151800	08-13-91	0.26	0.04	<0.01	--	0.30	0.32	--	<0.01	<0.01	0.05
473048096124300	08-27-92	--	.16	<.01	--	--	<.05	0.15	.04	.05	.21
473241096164401	08-29-91	.43	.07	<.01	--	.50	<.05	--	.05	<.01	.09
473752095521401	08-25-92	--	.76	<.01	--	--	<.05	--	<.01	<.01	.98
473944095590800	08-14-91	.18	.02	<.01	--	.20	<.05	.03	.02	.01	.03
474252096160800	08-19-92	--	1.6	<.01	--	--	<.05	.12	.02	.04	2.1
474537096195200	08-13-91	.25	.05	<.01	--	.30	.28	--	.01	<.01	.06
Do.	06-16-92	--	.05	<.01	--	--	.21	--	.01	<.01	.06
Do.	08-24-92	--	.07	<.01	--	--	<.05	.03	<.01	.01	.09
474608095372600	08-13-91	--	.05	<.01	--	--	5.3	--	<.01	<.01	.06
474628096195300	08-26-92	--	.41	<.01	--	--	.05	--	<.01	<.01	.53
474638095532800	08-21-92	--	.03	.09	0.87	--	.96	.09	<.01	.03	.04
474719096163100	08-19-92	--	.04	<.01	--	--	3.4	--	.01	<.01	.05
474728095434501	08-25-92	--	.04	<.01	--	--	1.3	--	<.01	<.01	.05
475758095465700	08-21-92	--	.54	<.01	--	--	<.05	.15	.03	.05	.70
480211096265200	09-03-92	--	.04	<.01	--	--	22	--	<.01	<.01	.05
480354096261000	08-26-92	--	.13	.73	4.57	--	5.3	--	<.01	<.01	.17
480537096205800	08-20-92	--	.76	<.01	--	--	<.05	--	.04	<.01	.98
480815096122500	08-20-92	--	.20	<.01	--	--	<.05	--	.12	<.01	.26
480937096261300	08-25-92	--	1.0	<.01	--	--	<.05	.18	.06	.06	1.3
481807096430801	08-22-91	.39	.11	<.01	--	.50	<0.05	.03	.04	.01	.14
481820096401700	08-19-92	--	.45	<.01	--	--	2.0	--	.02	<.01	.58
482634096111000	08-20-92	--	.05	.11	7.79	--	7.9	--	<.01	<.01	.06
482634096324101	08-20-92	--	.02	.04	44	--	44	.03	<.01	.01	.03
482725096332201	08-26-92	--	.04	.04	5.96	--	6.0	--	<.01	<.01	.05

Leakage Between Model Layers

Leakage of water between model layers is dependent on the thicknesses and vertical hydraulic conductivities of adjacent layers and the hydraulic head difference between adjacent layers. Vertical conductance terms are calculated within the model using data from an input array which incorporates both thickness and vertical hydraulic conductivity into a single term, and using horizontal areas calculated from cell dimensions. The input array contains values of vertical hydraulic conductivity divided by thickness, termed the vertical leakance, for each cell in a model layer. Each value of vertical leakance is for the interval between a layer and the layer below it; therefore, vertical leakance is not specified for the lowermost layer in the model. The expression for vertical leakance for the case in which two adjacent model layers are used to represent two vertically adjacent hydrogeologic units is (McDonald and Harbaugh, 1988):

$$\mathrm{Vcont}_{i,\,j,\,k+\frac{1}{2}} = \frac{1}{\dfrac{\left(\dfrac{\Delta v_k}{2}\right)}{K_{Zi,\,j,\,k}} + \dfrac{\left(\dfrac{\Delta v_{k+1}}{2}\right)}{K_{Zi,\,j,\,k+1}}}$$

where $\mathrm{Vcont}_{i,j,k+1/2}$ = the vertical leakance term for leakage between model layers k and k+1;

Δv_k = the thickness of model layer k;

Δv_{k+1} = the thickness of model layer k+1;

$K_{Zi,j,k}$ = the vertical hydraulic conductivity of the upper layer in cell i,j,k; and

$K_{Zi,j,k+1}$ = the vertical hydraulic conductivity of the lower layer in cell i,j,k+1.

The above relation was used to calculate vertical leakance terms for each layer and cell in the models where model layer 3 was overlain by model layer 1.

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