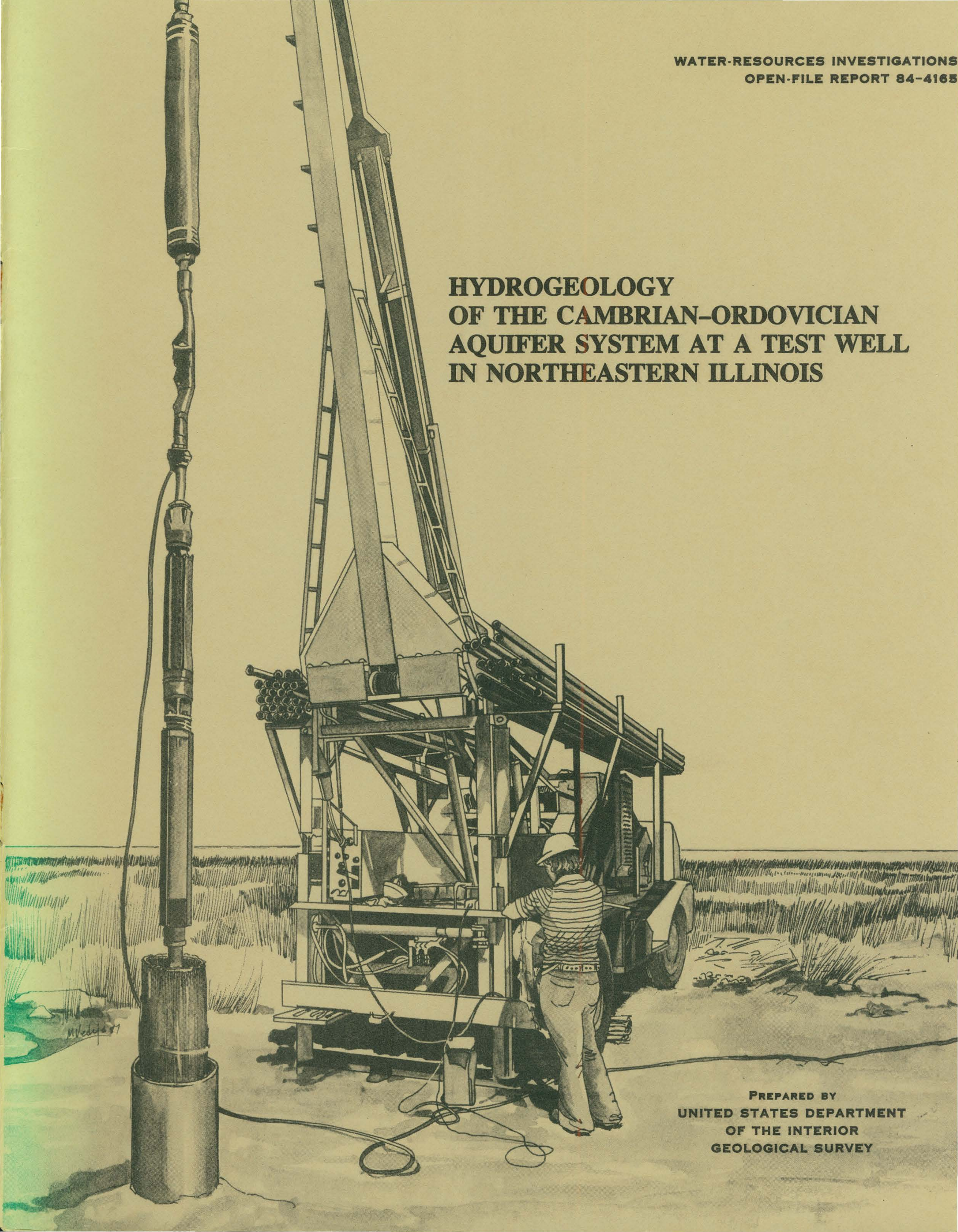
WATER-RESOURCES INVESTIGATIONS
OPEN-FILE REPORT 84-4165



HYDROGEOLOGY OF THE CAMBRIAN–ORDOVICIAN AQUIFER SYSTEM AT A TEST WELL IN NORTHEASTERN ILLINOIS

PREPARED BY
UNITED STATES DEPARTMENT
OF THE INTERIOR
GEOLOGICAL SURVEY

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BY
J. R. NICHOLAS, M. G. SHERRILL, AND H. L. YOUNG

U.S. GEOLOGICAL SURVEY

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URBANA, ILLINOIS
1987

UNITED STATES DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, *SECRETARY*

GEOLOGICAL SURVEY

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CONVERSION FACTORS AND RELATED INFORMATION

For the convenience of readers who may want to use the International System of Units (SI), the data may be converted by using the following factors:

Multiply inch-pound units	By	To obtain SI units
inch (in)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
gallon (gal)	3.785	liter (L)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
square foot per day (ft^2/d)	0.09290	square meter per day (m^2/d)
foot per day (ft/d)	0.3084	meter per day (m/d)
micromho per centimeter at 25° Celsius (μmho/cm at 25°C)	1.000	microsiemens per centimeter at 25° Celsius (μS/cm at 25°C)

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

$$°F = 9/5\ °C + 32$$

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

GLOSSARY

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

Aquifer system—A set of aquifers and their confining units.

Bedding plane—Any plane in sedimentary rock, along which sediment was deposited simultaneously.

Confining unit—Rock layers of low permeability lying directly above or below an aquifer. Its hydraulic conductivity may range from nearly zero to some value distinctly lower than that of the aquifer.

Digital computer model—A model of ground-water flow in which the aquifer system is described by numerical equations with specified values for boundary conditions which are solved on a digital computer.

Dolomite—A sedimentary rock consisting chiefly of the mineral dolomite, $CaMg(CO_3)_2$. Also called magnesian limestone.

Drawdown in a well—The vertical drop in water level in a well caused by pumping.

Fluid conductivity—The measured electrical conductance of a unit length and cross section of water, reported in micromhos per centimeter. Similar to specific conductance, but not standardized to 25° C.

Geophysical log—The graphical record of a physical characteristic of a rock, the fluid contained in a rock, or the construction of a well. Measured by lowering a sensing device into a well.

Gradient, hydraulic—The change of head per unit distance from one point to another in an aquifer.

Ground water—Water contained in the zone of saturation in the rock.

Head—Pressure, expressed as the height of a column of water than can be supported by the pressure.

Hydraulic conductivity—A medium has a hydraulic conductivity of unit length per unit time. It will transmit in unit time a unit volume of water at the prevailing viscosity through a cross section of unit area, measured at right angles to the direction of flow, under a hydraulic gradient of unit change in head through unit length of flow.

Hydrogeologic unit—A formation, part of a formation, or a group of formations in which there are similar hydrologic characteristics allowing for grouping into aquifers or confining units.

Joints—System of fractures in rocks along which there has been no movement parallel to the fracture surface.

Lithology—The physical character of a rock, particularly the type and size of minerals present.

Micromho—The unit used in reporting fluid conductivity and specific conductance (at 25° C) of water per centimeter.

Packer test—A type of aquifer test where inflatable packers are used in a well to hydraulically isolate a section of rock called the "packed interval."

Permeability (intrinsic)—A measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient.

Piezometer—A well, generally of small diameter, which is used to measure the elevation of the water table or potentiometric head. A piezometer generally has a short well screen through which water can enter.

Porosity (primary)—Interstices that were created at the time the rocks were formed.

Recovery of pumped well—When pumping from a well ceases, the water level rises (or recovers) to approximately the level before pumping.

Sandstone—A sedimentary rock composed predominantly of sand-size quartz grains.

Sedimentary rock—Rock formed by the deposition of sediment by water or air. The sediment may consist of rock fragments, the remains or products of animals or plants, the products of chemical action, or mixtures of these materials.

Shale—A laminated sedimentary rock consisting mainly of clay-size particles.

Specific conductance—The measured electrical conductance of a unit length and cross section of water, reported in micromhos (μmho) per centimeter at 25° C.

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.

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

Water type—A characterization of water based on the predominant major ion concentrations, for instance, a calcium bicarbonate water type or a sodium chloride water type.

HYDROGEOLOGY OF THE CAMBRIAN-ORDOVICIAN AQUIFER SYSTEM AT A TEST WELL IN NORTHEASTERN ILLINOIS

By

J. R. NICHOLAS, M. G. SHERRILL, AND H. L. YOUNG

ABSTRACT

A test well was drilled in 1980 near Lake Michigan, 1.7 miles south of the Illinois–Wisconsin State line, as part of the Northern Midwest Regional Aquifer-System Analysis. The well is 3,475 feet deep and penetrates the entire Cambrian–Ordovician aquifer system and 40 feet of Precambrian granite. From oldest to youngest, the aquifer system at this location consists of the following hydrogeologic units: Lower Mount Simon aquifer, Mount Simon confining unit, Elmhurst–Mount Simon aquifer, Eau Claire confining unit, Ironton–Galesville aquifer, Franconia confining unit, St. Peter aquifer, and an upper confining unit composed of the Glenwood Formation, Galena Dolomite, Platteville Limestone, and Maquoketa Shale.

Aquifer tests were performed on five hydrogeologic units that were isolated in the well with inflatable packers. Results indicate that the Ironton–Galesville aquifer has the highest hydraulic conductivity, 10 feet per day. The Elmhurst–Mount Simon and St. Peter aquifers have hydraulic conductivities of 1.5 and 1.8 feet per day, respectively. The Galena Dolomite and Platteville Limestone, which are part of a confining unit, could not sustain a yield of 15 gallons per minute and were not tested for hydraulic conductivity.

Geophysical logs, water-quality data, and head data show that 500 feet of interbedded shales in the upper part of the Mount Simon Sandstone form a confining unit. Beneath the Mount Simon confining unit, the water is a sodium chloride type, and dissolved solids exceed 55,000 milligrams per liter. The head in the Lower Mount Simon aquifer is at least 50 feet higher than heads in any of the younger Cambrian and Ordovician aquifers.

In 1981, piezometers were installed in the Lower Mount Simon, Elmhurst–Mount Simon, and Ironton–Galesville aquifers. A section of the well was left open to the St. Peter aquifer, Glenwood Formation, Galena Dolomite, and Platteville Limestone. Water-level fluctuations in the three piezometers and in the open section were similar over a 7-month period, and apparently responded to regional pumpage and recharge.

1.0 SUMMARY

AQUIFER SYSTEM COMPOSED OF FOUR AQUIFERS AND FOUR CONFINING UNITS

The Cambrian-Ordovician aquifer system is composed of four aquifers, each of which is overlain by a confining unit. From oldest to youngest, the hydrogeologic units are: Lower Mount Simon aquifer, Mount Simon confining unit, Elmhurst-Mount Simon aquifer, Eau Claire confining unit, Ironton-Galesville aquifer, Franconia confining unit, St. Peter aquifer, and an upper confining unit composed mainly of the Maquoketa Shale.

A test well was drilled by the U.S. Geological Survey in 1980 as part of the Northern Midwest Regional Aquifer-System Analysis. The well is located midway between major pumping centers in the Chicago and Milwaukee areas. Little information was available on the aquifer system at this location prior to drilling and testing this well. The well is 3,475 feet deep, penetrates the entire Cambrian–Ordovician aquifer system, and reaches Precambrian granite at a depth of 3,435 ft.

From oldest to youngest, the test well penetrates the following hydrogeologic units of the Cambrian–Ordovician aquifer system (fig. 1.0–1): Lower Mount Simon aquifer, Mount Simon confining unit, Elmhurst–Mount Simon aquifer, Eau Claire confining unit, Ironton–Galesville aquifer, Franconia confining unit, St. Peter aquifer, and an upper confining unit composed of the Glenwood Formation, Galena Dolomite, Platteville Limestone, and Maquoketa Shale. Aquifer tests were performed on five hydrogeologic units: Mount Simon confining unit, Elmhurst–Mount Simon aquifer, Ironton–Galesville aquifer, St. Peter aquifer, and the Galena–Platteville unit. Of these units, the Ironton–Galesville aquifer has the highest hydraulic conductivity, 10 ft per day, and the Galena–Platteville of the upper confining unit would not yield sufficient water to determine its hydraulic conductivity.

Chemical analysis of water samples show that three water types are present in the aquifer system. The lower Mount Simon aquifer has a sodium chloride water type, the Mount Simon confining unit has a sodium sulfate water type, and the St. Peter aquifer has a calcium bicarbonate water type. Intermediate water types may be present in the Ironton–Galesville and Elmhurst–Mount Simon aquifers, but representative water samples could not be collected from these aquifers.

Water-level measurements in the four aquifers indicate that the Ironton–Galesville aquifer has the lowest potentiometric head in the aquifer system. On October 22, 1982, heads in the Lower Mount Simon, Elmhurst–Mount Simon, and St. Peter aquifers were about 57, 6, and 3 ft higher, respectively, than the head in the Ironton–Galesville aquifer. Water-level measurements show fluctuations in all four aquifers that are responses to regional pumpage.

A significant finding in the study is the presence of the Mount Simon confining unit. Geophysical logs, water-quality data, and water-level measurements show that a 500-ft section of interbedded shales in the upper part of the Mount Simon Sandstone form a major confining unit in the aquifer system. Water beneath the Mount Simon confining unit has the highest head in the aquifer system and is very saline.

HYDROGEOLOGIC UNITS	WATER TYPE	POTENTIOMETRIC HEAD (Feet above sea level, October 22, 1982)
● UPPER CONFINING UNIT		
● ST. PETER AQUIFER	■ CALCIUM BICARBONATE	368
● FRANCONIA CONFINING UNIT		
● IRONTON-GALESVILLE AQUIFER		365
● EAU CLAIRE CONFINING UNIT		
● ELMHURST-MOUNT SIMON AQUIFER		371
● MOUNT SIMON CONFINING UNIT	■ SODIUM SULFATE	
● LOWER MOUNT SIMON AQUIFER	■ SODIUM CHLORIDE	422

2.0 INTRODUCTION

TEST WELL AIDS REGIONAL STUDY OF CAMBRIAN-ORDOVICIAN AQUIFER SYSTEM

The test well provides geologic, hydrologic, and water-quality data for units of the Cambrian-Ordovician aquifer system—focus of the Northern Midwest Regional Aquifer-System Analysis.

The Northern Midwest Regional Aquifer-System Analysis (RASA) began in 1978. It is part of a nationwide program of regional aquifer studies by the U.S. Geological Survey. The program was authorized by Congress in 1978 to develop a comprehensive understanding of regional aquifer systems in the United States. The purpose of the Northern Midwest RASA is to study the Cambrian–Ordovician aquifer system in a six-state area (fig. 2.0–1). This aquifer system supplies a major part of water needs in the Northern Midwest (Steinhilber and Young, 1979). Many metropolitan areas depend on the aquifer system for all or part of their water supplies. Protection and management of the aquifer system are important concerns of state and local planning, regulatory, and water-management agencies. The goal of the Northern Midwest RASA is a comprehensive understanding of the aquifer system—its physical dimension, hydrologic characteristics, water availability, water quality, and the effects of past and future pumping from the aquifer system.

One effort of the Northern Midwest RASA in Illinois was to drill a deep test well in the Camp Logan day-use addition of Illinois Beach State Park north of Zion, Illinois. The test well is located 1.7 mi south of the Illinois–Wisconsin State line near the Lake Michigan shore (fig. 2.0–1). The potentiometric head in the aquifer system has declined hundreds of feet in the Chicago–Milwaukee area (Sasman and others, 1982; Young, 1976). Projections of future water needs indicate continuing or increasing demands in this area, and therefore, continuing water-level declines (Schicht and others, 1976; Visocky, 1982). The test well is located midway between Chicago and Milwaukee, where little information was available on the aquifer system. The test well was drilled to determine (1) depth to Precambrian rock, (2) the thickness of the Cambrian–Ordovician aquifer system, (3) the vertical distribution of hydraulic properties, and (4) the character and distribution of highly mineralized water in the Mount Simon Sandstone.

The authors appreciate the cooperation of Robert Grosso, Park Superintendent, Illinois Beach State Park. Michael Sargent, Illinois State Geological Survey, and Robert Ringler, formerly with the Illinois State Geological Survey and now with the Montana Department of State Land, assisted in collecting and identifying rock cuttings. Robert Gilkeson, Illinois State Geological Survey, assisted in the field measurement of water quality and the collection of water samples. Most of the work of performing packer tests and installing piezometers was done by Russell Gifford, Alan MacKenzie, and Mark Hansen of the Northern Midwest RASA staff, Madison, Wisconsin, and by Darwin Evans of the Iowa Geological Survey.

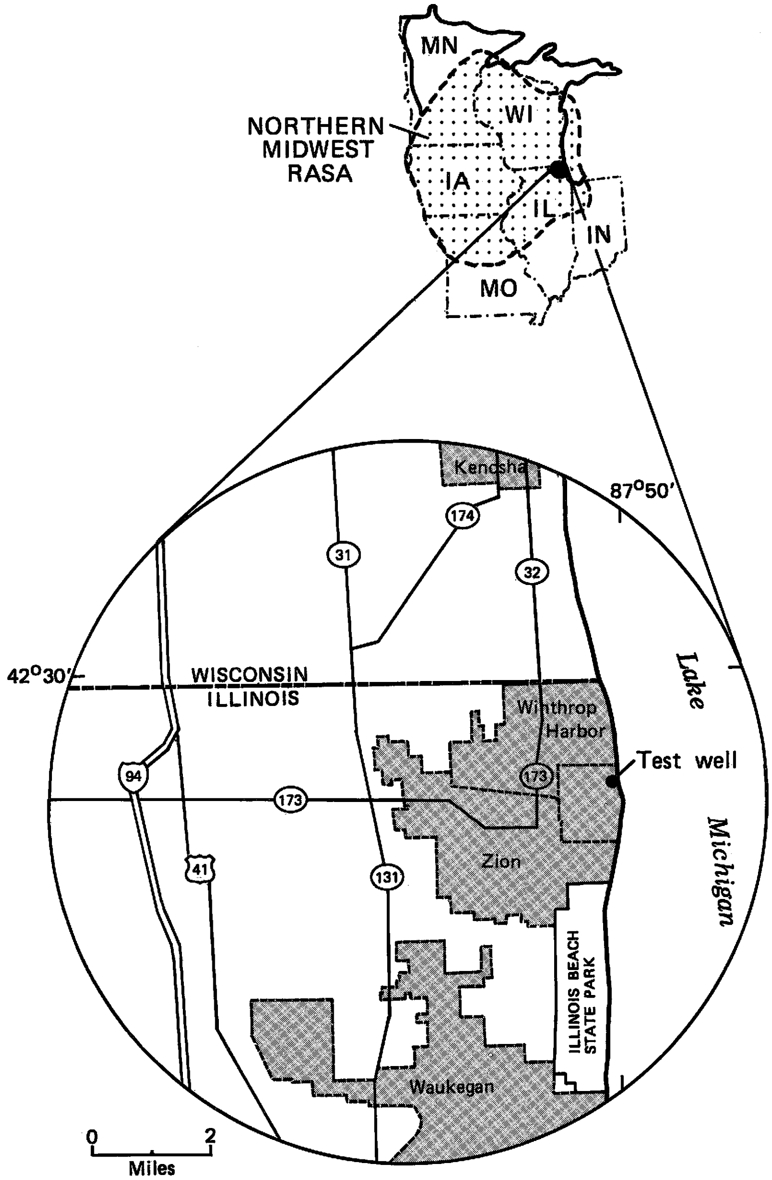


Figure 2.0–1 Location of test well and boundary of Northern Midwest Regional Aquifer-System Analysis.

2.0 INTRODUCTION

CAMBRIAN-ORDOVICIAN AQUIFER SYSTEM COMPOSED OF FOUR AQUIFERS AND FOUR CONFINING UNITS

Aquifers of Cambrian and Ordovician age at the well site are the St. Peter, Ironton-Galesville, Elmhurst-Mount Simon, and Lower Mount Simon. Confining units separating the aquifers are shales, carbonates, and siltstones of the Maquoketa Shale, Galena Dolomite, Platteville Limestone, Franconia Formation, Eau Claire Formation, and Mount Simon Sandstone.

Cambrian and Ordovician sedimentary rocks penetrated by the well are primarily sandstone, shale, and siltstone, with lesser amounts of dolomite and limestone. The sandstone aquifers alternate with shale, siltstone, or dolomite confining units (fig. 3.1–1).

The Maquoketa Shale, Galena Dolomite, Platteville Limestone, and Glenwood Formation comprise the upper confining unit of the Cambrian–Ordovician aquifer system at the test-well site. The Maquoketa Shale is composed of shale and shaly dolomite and forms a confining unit of regional extent throughout a large part of the Northern Midwest RASA study area. Where the Maquoketa confining unit is present, the underlying Galena–Platteville unit yields little water. Underlying the Galena–Platteville is the Glenwood Formation, a sandy siltstone. The Glenwood Formation also is a confining unit.

The St. Peter Sandstone is an aquifer composed of clean, rounded, well-sorted, friable sand. Many wells in northeastern Illinois are open to the St. Peter aquifer; however, it is often cased out because of problems with caving. A thin shale unit at the base of the St. Peter Sandstone and the underlying Franconia Formation form a confining unit.

The Franconia Formation is composed of sandy siltstone and shaly dolomite. The top of the Franconia Formation is an unconformity.

The Ironton and Galesville Sandstones are composed of clean, well-sorted, fine-to-coarse-grained sand. They form the most permeable and productive aquifer in northeastern Illinois. Most public water supplies that withdraw water from the Cambrian–Ordovician aquifer system in northeastern Illinois have wells that are open to the Ironton–Galesville aquifer.

The Eau Claire Formation underlies the Ironton–Galesville aquifer. This formation is composed of three members, as classified by the Illinois State Geological Survey. The youngest member, the Proviso Siltstone Member, is a confining unit throughout northern Illinois. In northeastern Illinois, the Lombard Dolomite Member is also a confining unit. The oldest member, the Elmhurst Sandstone Member, is a part of the Elmhurst–Mount Simon aquifer, a productive aquifer throughout most of the RASA study area.

The Mount Simon Sandstone is composed of sandstone, siltstone, and shale. This formation is thick, accounting for over half of the depth of the test well. The upper 140 ft is sandstone and is part of the Elmhurst–Mount Simon aquifer. Below this aquifer, the sandstone is interbedded with red shale for about 500 ft, resulting in a confining unit (fig. 3.1–1). The areal extent and continuity of the Mount Simon confining unit is not known. The Lower Mount Simon aquifer underlies this confining unit. Although this aquifer is thick and permeable, it is seldom used because of high dissolved-solids concentrations.

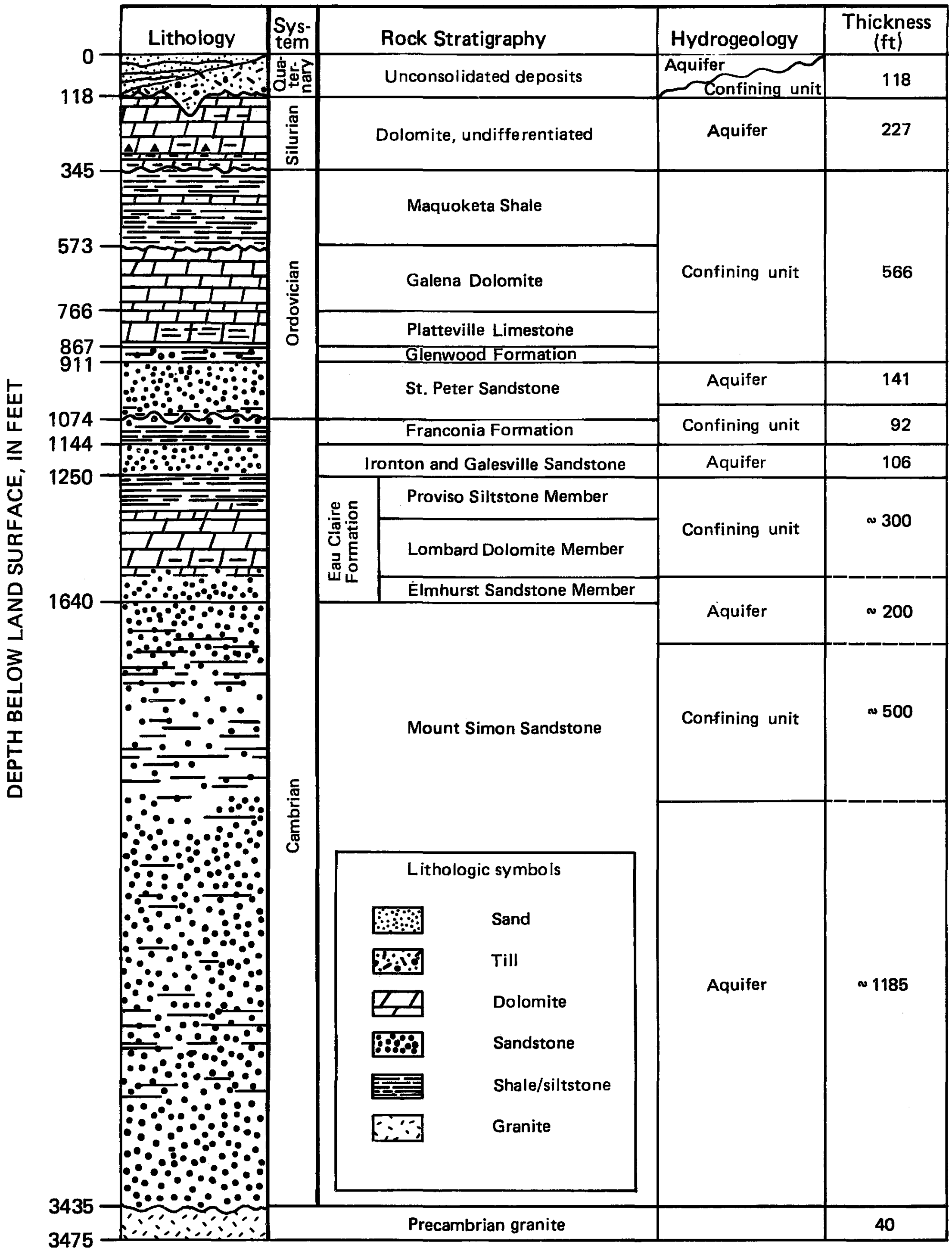


Figure 3.1–1 Lithology, rock stratigraphy, hydrogeology, and thickness of rocks penetrated by the test well. (Altitude of land surface is 586 feet above sea level).

CAMBRIAN-ORDOVICIAN AQUIFER SYSTEM BOUNDED BY SILURIAN DOLOMITE ABOVE AND PRECAMBRIAN GRANITE BELOW

Unconsolidated Quaternary deposits and Silurian dolomite overlie the Cambrian-Ordovician aquifer system. Relatively impermeable Precambrian granite underlies the aquifer system.

The 118 ft of unconsolidated Quaternary deposits encountered at the test site (fig. 3.2–1) are composed of 27 ft of sand underlain by 91 ft of glacial drift. The glacial drift is mostly till with some sand and gravel lenses. Quaternary deposits form productive aquifers in much of northeastern Illinois.

The Silurian dolomite is 227 ft thick. This dolomite is a productive aquifer in northeastern Illinois, where water can be produced from solutionally developed openings in joints and bedding planes (Suter and others, 1959).

Little is known about the Precambrian granite that underlies the aquifer system. Because granite is a rock that has extremely low primary permeability, it forms an impermeable boundary at the base of the aquifer system.

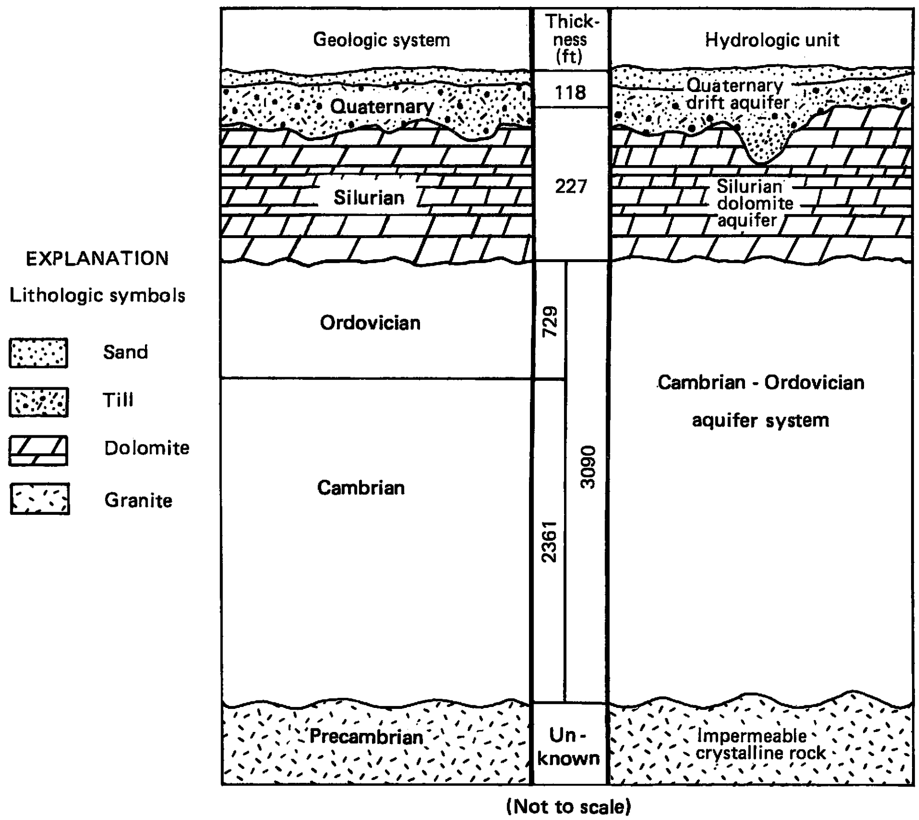


Figure 3.2–1 Relation of Cambrian–Ordovician aquifer system to other geologic units.

4.0 TEST-WELL DESIGN

TEST WELL COMPLETED IN FIVE STAGES

Data-collection schemes required that the well be completed in five stages.

The test well was drilled with an air-rotary drill rig. A bentonite-water mixture was used while drilling in the unconsolidated Quaternary deposits to remove drill cuttings and to keep the borehole wall from collapsing. Once consolidated rock was reached, a biodegradable polymer foam mixed with Lake Michigan water was used to remove rock cuttings from the borehole. The advantage of the foam over bentonite was that it would not form a mud cake on the walls of the borehole, which would decrease aquifer permeability and interfere with packer tests and geophysical logging.

The test well was completed in five stages. The first stage consisted of drilling through the Quaternary deposits and then installing and grouting 123 ft of 16-in. diameter steel casing 5 ft into the Silurian rock (fig. 4.0–1). The casing prevented unconsolidated deposits from caving into the well. The grout sealed the casing, preventing movement of water in the annular space.

The second stage consisted of drilling through the Silurian dolomite and the Maquoketa Shale and installing and grouting 589 ft of 10-in. diameter steel casing 16 ft into the Galena Dolomite. The casing and grout sealed off the Silurian rock and kept the Maquoketa Shale from swelling and collapsing into the well.

The remainder of the Ordovician rocks and upper part of the Cambrian rocks were drilled to a 10-in. diameter in the third stage. Drilling was suspended at 1,932 ft when water-quality changes occurred that would affect water sampling and geophysical logging in the rock units above. Geophysical logs were run in the well to determine the intervals in which to perform packer tests. Packer tests were performed in the Ironton–Galesville and Elmhurst–Mount Simon aquifers, and water samples were collected for laboratory analysis.

The fourth stage consisted of drilling the remainder of the Mount Simon Sandstone and 40 ft of Precambrian rock. The diameter of the well was reduced from 10 to 6.5 in. at 2,269 ft and to 6 in. at 2,784 ft. After drilling was completed, geophysical logs were run and packer tests were made in the Galena–Platteville unit and in the St. Peter Sandstone. Water samples were collected during the packer tests and then at three different depths in the open well using a 2-liter sampler lowered with the logging equipment.

The fifth stage, begun one year after completion of drilling, consisted of implacing piezometers to measure water levels in and to collect water samples from specific locations in the well. Three 20-ft long, 1.25-in. diameter, stainless steel well screens were attached to plastic pipe and set at depths of 2,264, 1,684, and 1,203 ft. Below a depth of 940 ft, the well was backfilled with gravel and grouted to seal off each screen. The result is 3 piezometers plus a section of open hole from 589 to 940 ft (fig. 4.0–1). Water levels have been measured in and water samples have been collected from the piezometers and open hole. However, this initial water quality is not representative because considerable interformational flow occurred in the open well and treated municipal water was used to tremie the gravel pack into place for each piezometer.

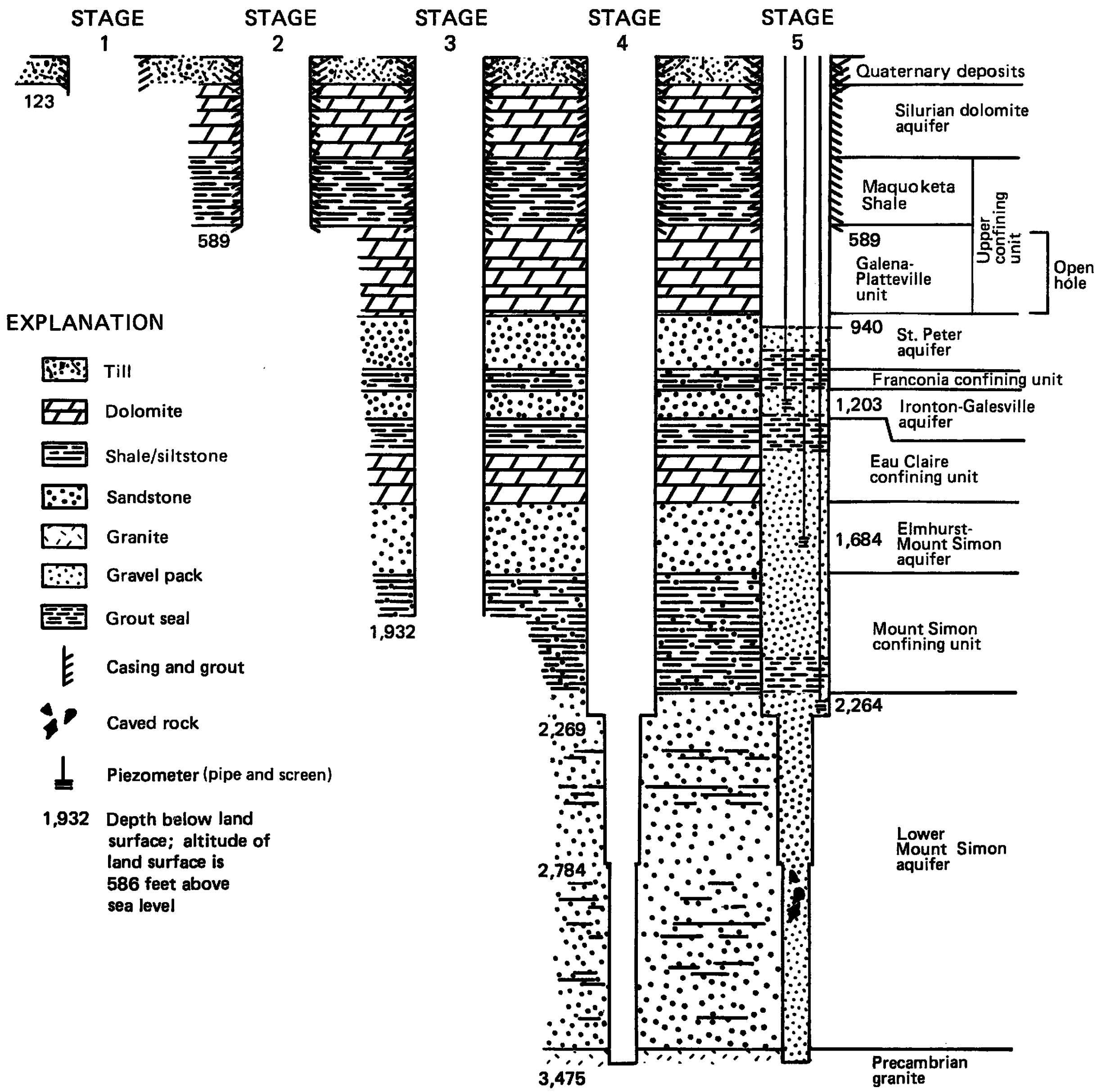


Figure 4.0-1 Test-well design and stages of completion.

GEOPHYSICAL LOGS AID IN INTERPRETING HYDROGEOLOGY

Eleven types of geophysical logs were run in the test well. The logs aid in the identification of litholgy, borehole characteristics, and quality of water.

Eleven types of geophysical logs were run in the test well (table 5.0–1). They can be divided into three categories: electric logs, borehole-condition logs, and nuclear logs. The electric logs are spontaneous potential, single-point resistance, lateral, and normal. The spontaneous-potential log records natural potential developed between the borehole fluid and the surrounding rock (Keys and MacCary, 1971). The other electric logs induce currents in rock and record resistance. Electric logs aid in identification of lithology, stratigraphic contacts, and freshwater-saltwater interfaces.

Logs that identify borehole conditions are caliper, temperature, fluid conductivity, and flowmeter. Caliper logs measure borehole diameter and are necessary for interpreting electric and nuclear logs and for planning packer settings. The remaining logs identify properties and movement of fluid in the borehole. The temperature and fluid-conductivity logs are discussed in section 7.0.

Nuclear logs consist of gamma-gamma, neutron, and natural gamma. Gamma-gamma and neutron logging probes contain a nuclear source that bombards the surrounding rocks. The log is a record of the response of the rock and fluid to this bombardment. If rock and fluid density are derived from laboratory analysis, then bulk density of the rock can be determined from gamma-gamma logs (Keys and MacCary, 1971). The neutron logging probe provides output that is a function of the hydrogen content of the borehole environment, and, as such, can measure the total porosity of the rock below the water table. Quantitative interpretations of the gamma-gamma and neutron logs run in the test well have not been made.

The natural-gamma log is the most useful log for qualitative hydrogeologic interpretation in this well because confining beds and aquifers are clearly indicated (fig. 5.0–1). Deflections to the right indicate higher natural radioactivity, which is a function of clay content. Shales and siltstones, which are confining beds that commonly contain clay, show as right deflections. The log is affected by casing and borehole diameter. Where the well is cased, above a depth of 589 ft, the signal is weaker; thus, the signal for the Maquoketa confining bed does not deflect as far to the right as it would if casing were not present. In the small-diameter section of the well, below a depth of 2,265 ft, the signal is stronger; thus the record of the sandstones there deflects farther to the right than it does above this depth.

Other information is obtainable from these geophysical logs. Logs are available for inspection at the Illinois District Office of the U.S. Geological Survey in Urbana, Illinois.

Table 5.0–1 Geophysical log run in test well

LOG TYPE	DATE	DEPTH, IN FEET	EQUIPMENT[1]
NATURAL GAMMA	12-80	10 - 1920	WR[2]
	9-81	0 - 2780	MS
	10-81	2700 - 3372	MS
CALIPER	12-80	296 - 1920	WR
	9-81	2260 - 2778	MS
	9-81	600 - 2770	MS
	10-81	2700 - 3370	MS
	10-81	530 - 2800	WR
TEMPERATURE	1-81	216 - 3122	WR
	9-81	220 - 2781	MS
	10-81	600 - 3365	MS
FLUID CONDUCTIVITY	1-81	216 - 3122	WR
	9-81	220 - 2701	MS
	10-81	600 - 3365	MS
FLOWMETER	1-81	300 - 3100	WR
	1-81	170 - 3100	WR
	1-81	220 - 3100	WR
	1-81	290 - 3100	WR
SPONTANEOUS POTENTIAL AND RESISTIVITY	9-81	600 - 2270	MS
	10-81	2700 - 3372	MS
LATERAL LOG	9-81	600 - 2770	MS
	10-81	2700 - 3370	MS
SHORT NORMAL(16-INCH) LONG NORMAL (64-INCH)	9-81	600 - 2770	MS
	10-81	2700 - 3370	MS
GAMMA-GAMMA	9-81	0 - 2770	MS
	10-81	2700 - 3370	MS
NEUTRON	9-81	0 - 2778	MS
	10-81	2700 - 3370	MS

[1] Use of brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

[2] WR-Well Reconnaisance
MS-Mt. Sopris

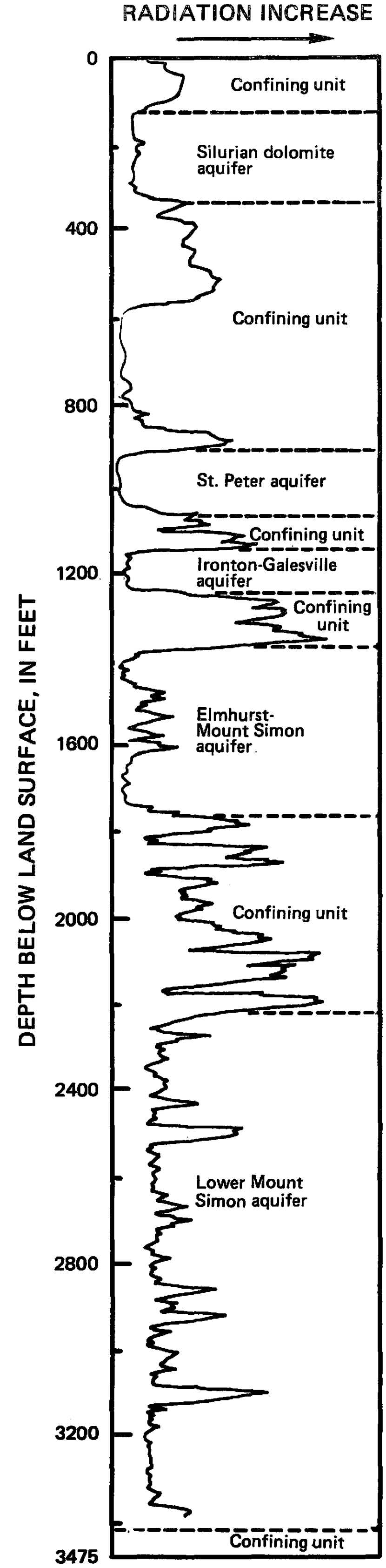


Figure 5.0–1 Natural-gamma log from test well. (Altitude of land surface is 586 feet above sea level).

AQUIFER TESTS PERFORMED AT SIX DEPTH INTERVALS

Inflatable rubber packers were used to isolate five hydrogeologic units in the test well for aquifer tests and hydraulic-head measurements.

Six intervals were isolated in the test well with a pair of inflatable rubber packers and test pumped with a submersible pump between the packers (fig. 6.1–1) in order to determine the hydraulic properties of five hydrogeologic units (fig. 6.1–2). The length of the packed interval was adjusted in each case to set the packers within confining units above and below the aquifer to be tested. Potentiometric head in the packed zone and below the lower packer was recorded from pressure transducers. The water level above the top packer was measured with an electric tape. Thus, for each test, time-drawdown data were collected in the packed interval and potentiometric heads were measured above and below the interval during the pumping period and a recovery period. Heads above and below the packed interval were monitored closely for the presence of drawdown from pumping; no drawdown ensured that the packers were tightly sealed against the borehole wall.

It is difficult to obtain hydraulic properties of individual aquifers in the Cambrian–Ordovician aquifer system from deep wells in the Chicago–Milwaukee area because most wells are open to more than one aquifer. Therefore, most existing water-level and transmissivity data, as well as water-quality data, represent the composite aquifer system.

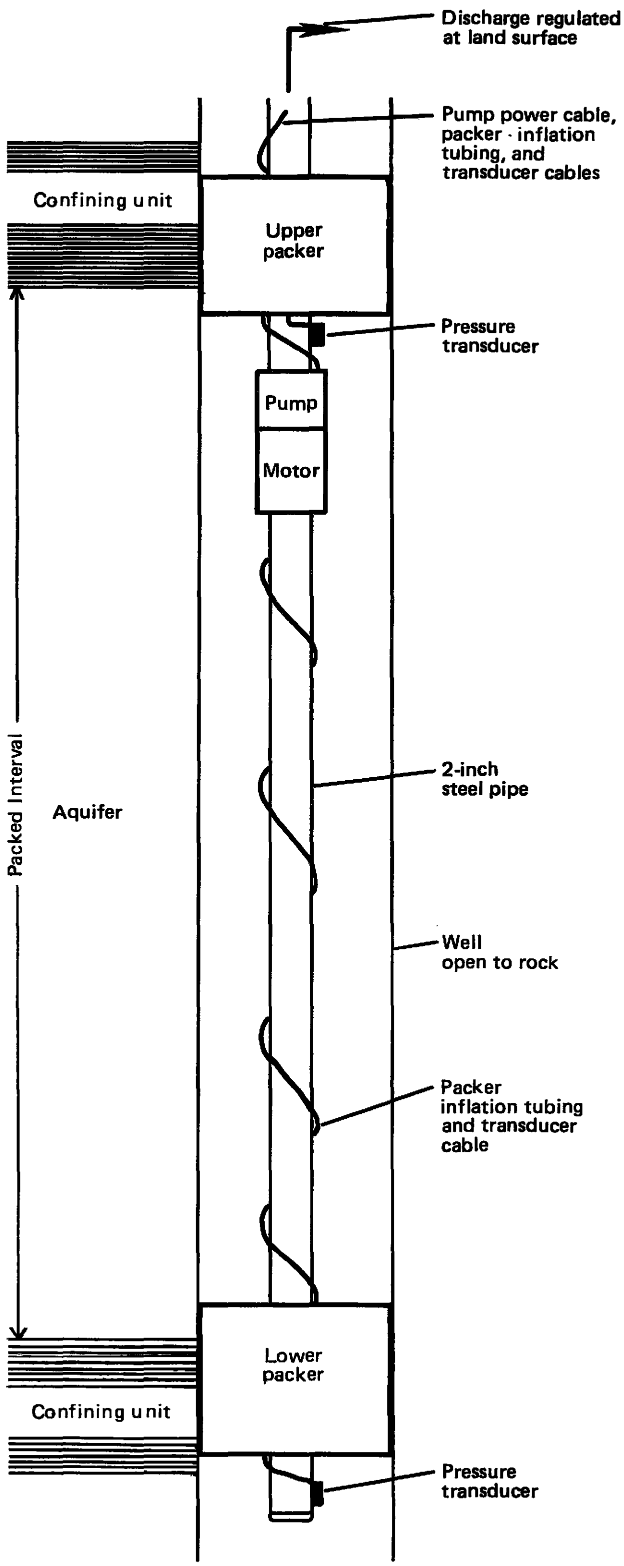


Figure 6.1–1 Configuration of equipment during packer tests in the well.

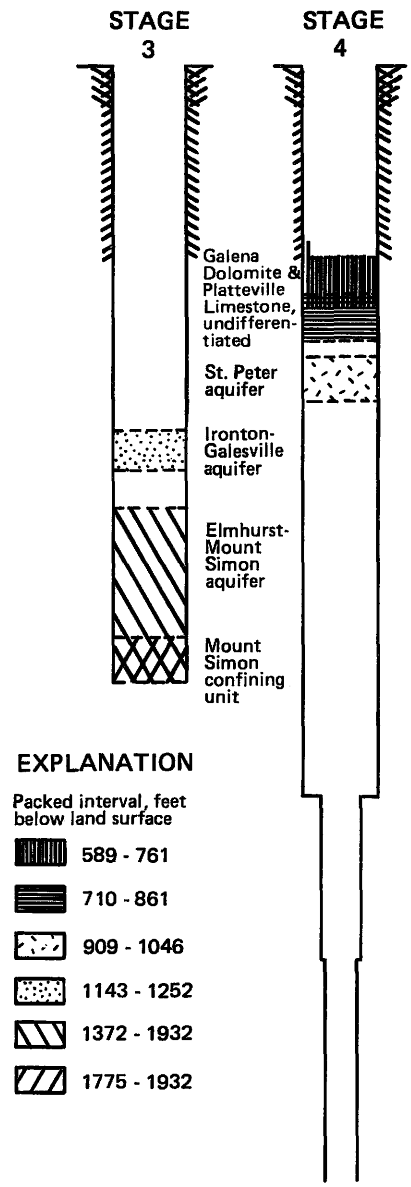


Figure 6.1–2 Location of packed intervals.

HYDRAULIC CONDUCTIVITY HIGHEST IN THE IRONTON–GALESVILLE AQUIFER

The hydraulic conductivity of the Ironton-Galesville aquifer is about six times greater than that of the St. Peter or Elmhurst-Mount Simon aquifers.

Analysis of aquifer-test data shows that the hydraulic conductivity of hydrogeologic units varies from 1.3 to 10 ft/d (table 6.2–1). The hydraulic conductivity (*K*) of the Ironton–Galesville aquifer is 10 ft/d, compared to 1.8 ft/d for the St. Peter aquifer and 1.5 ft/d for the Elmhurst–Mount Simon aquifer. The hydraulic conductivity of the Mount Simon confining bed in the interval tested is 1.3 ft/d. Figure 6.2–1 shows the location of the packed intervals.

Attempts were made to test two intervals of the Galena–Platteville unit, but the packed zones did not yield 15 gal/min, the minimum capacity of the pump. Similar results have been obtained during packer tests by the Northern Midwest RASA where the Galena–Platteville is overlain by the Maquoketa Shale in northwestern Indiana and southeastern Wisconsin.

Potentiometric head was measured several times during pumping at a constant rate and during the subsequent recovery for use in determining transmissivity and hydraulic conductivity of the rock strata between the packers. These characteristics define the water-yielding ability of the aquifer and are essential input data to the digital-computer model.

Forms of the Jacob (1950) modified nonequilibrium formula,

$$T=\frac{264Q}{\Delta s}, \quad (1)$$

and the related Theis (1935) recovery formula,

$$T=\frac{264Q}{\Delta s'}, \quad (2)$$

where

T = transmissivity, in gallons per day per foot,
Q = rate of discharge of the pumped well, in gallons per minute, and
Δs and $\Delta s'$ = change in drawdown and recovery, respectively, over one log cycle of time, in feet,

are used to determine transmissivity from a semi-log plot of time-drawdown data from a pumped well when no observation wells are available. These formulas are based on the assumptions that:

1) aquifer is homogenous and isotropic,
2) aquifer has infinite areal extent,
3) pumped well penetrates and receives water from the entire thickness of the aquifer,
4) well has an infinitesimal diameter (not significant after a few minutes of pumping),
5) water removed from storage is discharged instantaneously with decline in head, and
6) time of pumping or recovery is large enough such that

$$u=\frac{1.87\, r^2S}{Tt} \leq 0.01,$$

where

u = variable of integration of the Theis (1935) nonequilibrium formula,
r = radius of the pumping well or distance to an observation well, in feet,
S = storage coefficient, and
t = time since pumping or recovery began, in days.

All the assumptions are met in this case of using time-drawdown data from pumping a single confined aquifer unit isolated with packers. *S* and *r* are small; *S* is always small for a confined aquifer and *r* is the well radius, because no observation well is used. Therefore, *u* is small for all times in this situation.

The transmissivity (*T*) of the packed interval is determined by plotting drawdown (*s*) or recovery (*s'*) of potentiometric head against the logarithm of time in minutes (fig. 6.2–2). A straight line is fitted through the data and the change in head (Δs or $\Delta s'$) over one log cycle of time (*t*) is determined. The change in head over one log cycle and the pumping rate are used in equation 1 or 2 to calculate transmissivity. Because $T=Kb$, where *b* is the thickness of saturated aquifer, in feet, hydraulic conductivity can be determined from the transmissivity derived from the packer tests by using the thickness of aquifer between the packers for *b*. Transmissivity or hydraulic conductivity in the gallon-foot-day units are converted to consistent foot-day units by multiplying by 0.1337.

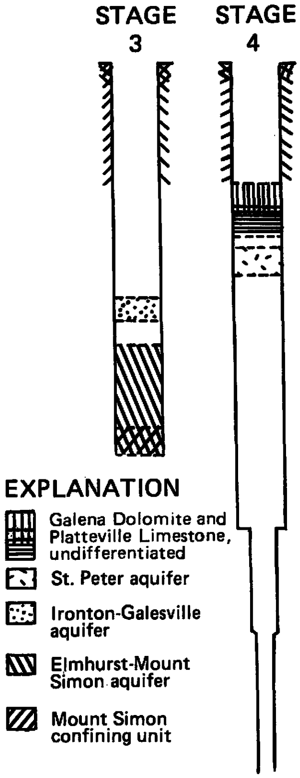


Figure 6.2–1 Location of packed intervals.

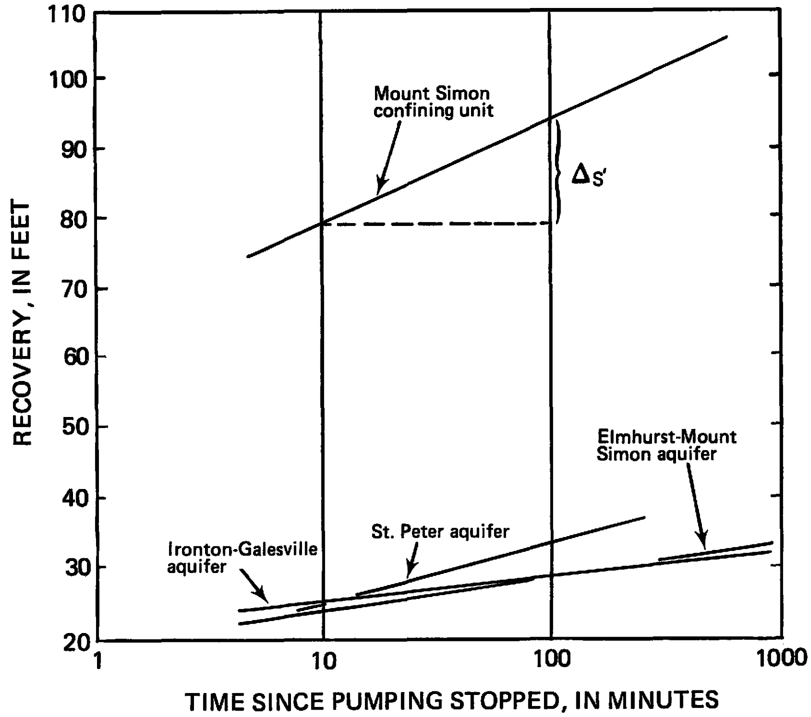


Figure 6.2–2 Straight-line (Jacob) solution of transmissivity of packer intervals.

Table 6.2–1 Summary of data from packer tests

Hydrogeologic unit	Packed interval (ft below land surface)	Discharge (gal/min)	Drawdown (ft)	Time of pumping (min)	Time of recovery (min)	Transmissivity (ft²/d)	Hydraulic conductivity (ft/d)
Galena Dolomite and Platteville Limestone, un-differentiated	589–761, 710–861	[1]	>256	20	—	—	—
St. Peter aquifer	909–1,046	60	36.5	170	187	250	1.8
Ironton–Galesville aquifer	1,143–1,252	104	31.1	305	705	1,100	10
Elmhurst–Mount Simon aquifer	1,372–1,932	106	30.8	310	853	840	1.5
Mount Simon confining unit	1,775–1,932	92	102.8	300	664	200	1.3

[1] Neither interval yielded 15 gallons per minute.

WATER LEVEL LOWEST IN IRONTON-GALESVILLE AQUIFER

The Ironton-Galesville aquifer has the lowest water level and the Lower Mount Simon aquifer has the highest water level. Water levels fluctuate in the confined aquifers in response to regional ground-water use.

Water levels measured in the piezometers installed in the test well (fig. 6.3–1) show that the Ironton–Galesville aquifer has the lowest potentiometric head in the Cambrian–Ordovician aquifer system (fig. 6.3–2). Ground water from units above and below moves slowly to the Ironton–Galesville aquifer. Regional pumpage and the unit's higher transmissivity combine to lower the potentiometric head in this aquifer. Table 6.3–1 shows the altitude of water levels in each aquifer. Heads in the St. Peter and Elmhurst–Mount Simon aquifers are only 3 to 7 ft higher than the head in the Ironton–Galesville aquifer. However, the head in the Lower Mount Simon aquifer is about 57 ft higher than the head in the Ironton–Galesville aquifer. Heads in each aquifer are hundreds of feet above the bottom of their respective overlying confining beds.

Observed water levels in the newly installed piezometers recorded the adjustment from the composite water level in the open hole to the potentiometric head in each respective aquifer. Water levels in the piezometers took 4 to 5 months to recover and then began to respond to regional pumpage (fig. 6.3–3). Water levels declined in all four aquifers during the summer period of heavy ground-water use. After October, water levels recovered in response to reduced ground-water withdrawal.

Table 6.3–1 Altitude of water levels in four aquifers, in feet above sea level

	1981			1982					
Date	**Dec. 9**	**Dec. 10**	**Dec. 29**	**Feb. 5**	**Mar. 8**	**Apr. 18**	**Aug. 8**	**Oct. 22**	**Nov. 16**
St. Peter aquifer	373.38	372.98	372.46	371.37	370.84	370.88	369.66	368.06	368.14
Ironton–Galesville aquifer	369.03	368.73	368.15	367.50	366.86	367.59	365.90	364.54	364.69
Elmhurst–Mount Simon aquifer	376.39	375.55	374.32	373.77	373.81	374.11	373.10	371.37	371.51
Lower Mount Simon aquifer	424.09	423.29	424.02	425.04	425.41	425.15	424.27	422.25	422.58

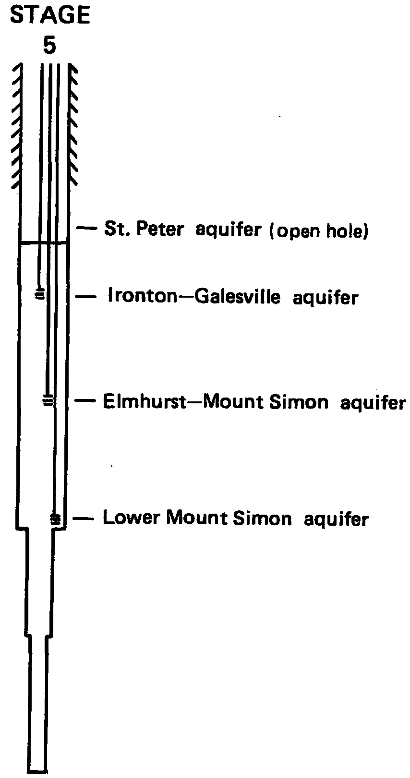


Figure 6.3-1 Location of three piezometers and open-hole section in the test well. (See fig. 4.0-1).

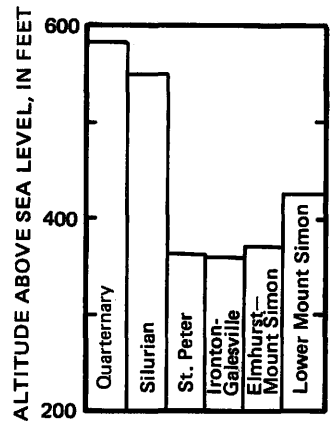


Figure 6.3-2 Potentiometric head in six hydrogeologic units at the test well. Quaternary and Silurian measurements during drilling, 1980; other measurements in the spring of 1982.

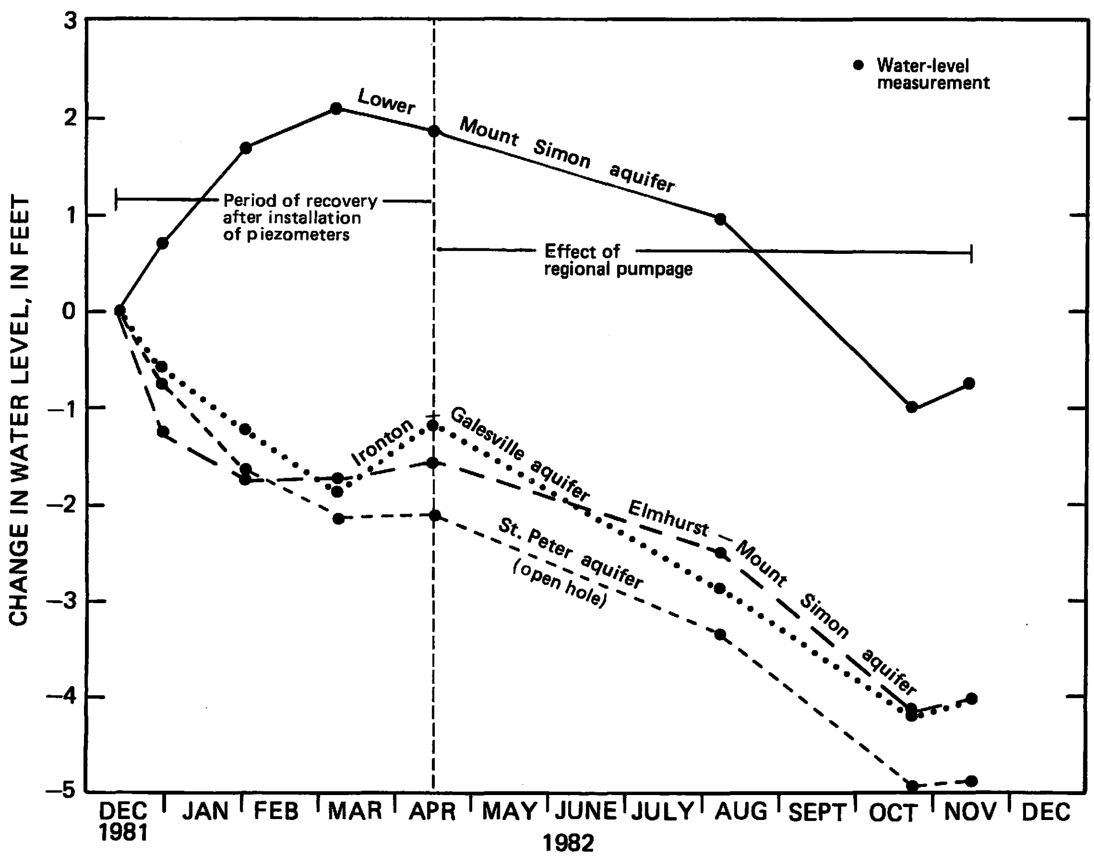


Figure 6.3-3 Change in water levels after final installation of three piezometers, Dec. 9, 1981 to Nov. 16, 1982.

SPECIFIC CONDUCTANCE, TEMPERATURE, AND CHLORIDE CONCENTRATION GENERALLY INCREASE WITH DEPTH

Samples of fluid collected during drilling show an increase in specific conductance and chloride concentration with depth. After the drilling, fluid conductivity and temperature logs show that water moved into the Ironton-Galesville aquifer from the other aquifers.

Drilling fluid composed of polymer foam and Lake Michigan water was circulated down through the drill stem and up the well. The fluid discharged at the land surface also contained ground water. Field measurements of specific conductance and chloride concentration of samples of the discharged fluid indicate relative changes of these constituents with depth (fig. 7.1–1).

Specific conductance and chloride concentration of drilling fluid generally increased with depth below the Eau Claire confining unit. The increases were greatest in the Lower Mount Simon aquifer; specific conductance increased from 4,000 to 23,000 μmho/cm at 25°C and chloride concentration increased from 1,000 to 10,000 mg/L from 2,950 to 3,250 ft below land surface. During drilling in the Eau Claire and Mount Simon confining units, these parameters increased only slightly; in the St. Peter and Ironton–Galesville aquifers, they decreased slightly.

Below the Eau Claire confining unit, specific conductance and chloride concentration increase with depth because water at greater depths has had more time to dissolve minerals—it is in a slower-moving flow system. In addition, there is evidence that chloride ions tend to be preferentially concentrated as ground water moves through shale (Hem, 1970).

Relative changes in specific conductance and chloride concentration with depth during drilling are related to hydraulic characteristics of hydrogeologic units. Fine-grained confining units contribute less water to drilling fluid because they have lower transmissivity than aquifers. Thus, specific conductance and chloride concentration of the borehole fluid changed very little while drilling through confining units. In contrast, water flowed relatively freely out of aquifers into the well during drilling, which caused specific conductance and chloride to change markedly.

After drilling was completed, logs were made of fluid conductivity and temperature (fig. 7.1–1). These logs record the properties of the water in the well, which may or may not be related to the properties of the water in the adjacent rocks. Fluid conductivity is measured in micromhos per centimeter and can be converted to specific conductance (micromhos per centimeter at 25°C) using figure 7.1–2. Changing the fluid conductivity log to a specific conductance log would not alter its general shape.

Fluid conductivity and temperature logs can be used to determine flow patterns in the well and zones that contributed water to the well before piezometers were installed. Measurements of hydraulic head aid in this interpretation. Prior to installation of piezometers, the Ironton–Galesville aquifer was being recharged by downward movement of water from the Galena Dolomite, Platteville Limestone, and St. Peter aquifer, and by upward movement of water from the Elmhurst–Mount Simon and Lower Mount Simon aquifers. Nearly vertical segments of the temperature log in the Eau Claire and Mount Simon confining units indicate that these confining units contributed little water to the well. Increases in temperature with depth in the upper parts of the Elmhurst–Mount Simon and Lower Mount Simon aquifers indicate the flow of warmer water into the well from these zones. Lower temperatures and fluid conductivities in the St. Peter aquifer and the lower part of the Platteville Limestone indicate that these units also contributed water to the well. Lower temperature and fluid conductivity above the Franconia Formation indicate that water from the Lower Mount Simon aquifer did not move up past the Ironton–Galesville aquifer (see flow arrows on fig. 7.1–1).

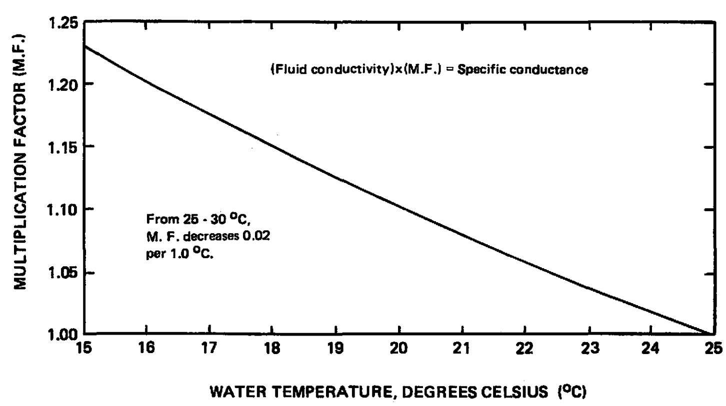


Figure 7.1-2 Graph to convert fluid conductivity to specific conductance.

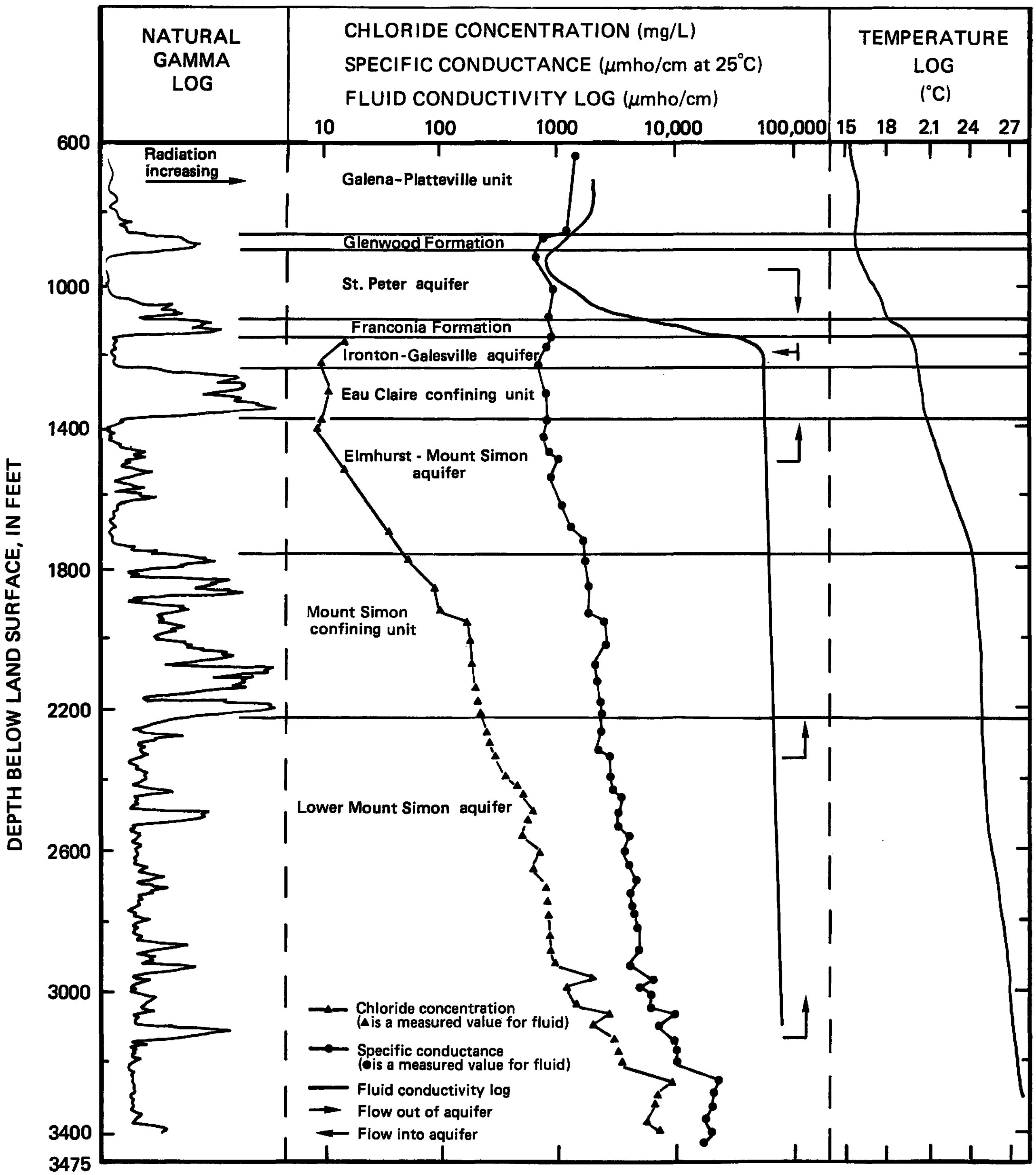


Figure 7.1-1 Relation of quality of water to hydrogeologic units and intrawell flow of ground water. (Altitude of land surface is 586 feet above sea level).

WATER TYPES ARE CALCIUM BICARBONATE, SODIUM SULFATE, AND SODIUM CHLORIDE

Water types change from calcium bicarbonate in the St. Peter aquifer to sodium sulfate in the Mount Simon confining unit and to sodium chloride in the Lower Mount Simon aquifer.

Water samples were collected that are representative of the ground water within three zones open to the well. These samples are from packer tests in the St. Peter aquifer and Mount Simon confining bed and from a point sample in the lower Mount Simon aquifer. Other water samples collected during the packer tests and as point samples contained mixtures of water caused by intrawell flow and therefore are not representative of a specific hydrogeologic unit (fig. 7.2–1). The full suite of analyses for the three representative samples is presented in section 10.

Water types are different in each of the sampled hydrogeologic units. Water in the St. Peter aquifer is the calcium bicarbonate type (fig. 7.2–2). Sodium sulfate water occurs in the Mount Simon confining unit from 1,772 to 1,932 ft below land surface. Dissolved solids increase from 507 mg/L in the St. Peter aquifer to 2,800 mg/L in the Mount Simon confining unit. Representative water samples could not be obtained from the Ironton–Galesville and Elmhurst–Mount Simon aquifers because of water mixing from intrawell flow. However, data from other deep wells in Lake County (Woller and Gibb, 1976) show that the Ironton–Galesville and Elmhurst–Mount Simon aquifers are characterized by calcium bicarbonate water of relatively low dissolved-solids concentration (less than 600 mg/L). Water in the Lower Mount Simon aquifer is a sodium chloride type. The water is very high in dissolved solids; a concentration of 55,800 mg/L was measured in water collected at 3,120 ft below land surface.

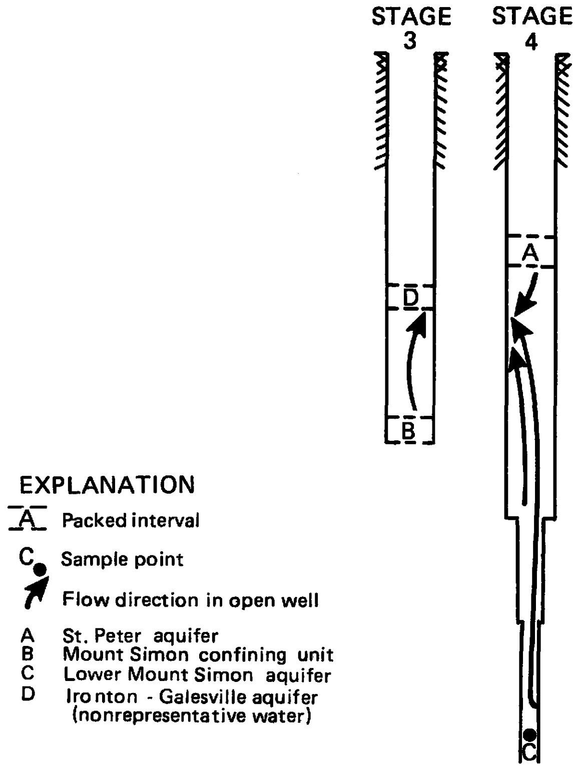


Figure 7.2–1 Intrawell direction of flow and location of representative water samples in stages 3 and 4.

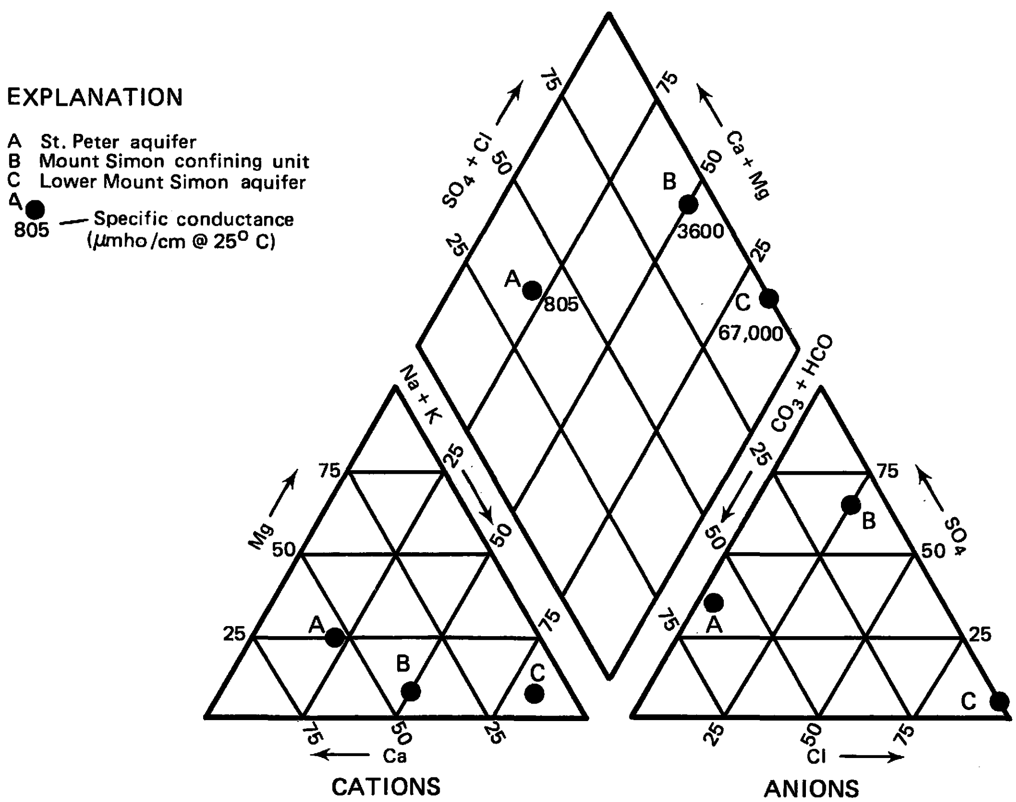


Figure 7.2–2 Trilinear diagram of percent equivalents of major cations and anions in representative water samples.

TEST-WELL DATA AIDS CALIBRATION OF COMPUTER MODEL OF GROUND-WATER FLOW IN THE CHICAGO-MILWAUKEE AREA

A computer model of three-dimensional ground-water flow in the Chicago-Milwaukee area will help predict effects of large withdrawals of water from the Cambrian-Ordovician aquifer system. Data collected from each aquifer at the test well will be used to help calibrate this model.

A detailed study of the Cambrian–Ordovician aquifer system in the Chicago–Milwaukee area is included in the Northern Midwest RASA. The area is being intensively studied because past and projected future withdrawals are very large, resulting in significant water-level declines. The test well is located about midway between ground-water pumping centers near these two cities. A computer model is being developed to simulate three-dimensional ground-water flow in the Cambrian–Ordovician aquifer system in this area. The aquifer system is represented as three aquifer layers, each bounded above and below by confining beds (fig. 8.1–1). The model will be calibrated by simulating (1) predevelopment potentiometric head and (2) measured historical changes in potentiometric head due to ground-water pumpage. Hydraulic-conductivity data, potentiometric-head data, and water-density data obtained from the test well will be used to help calibrate the model.

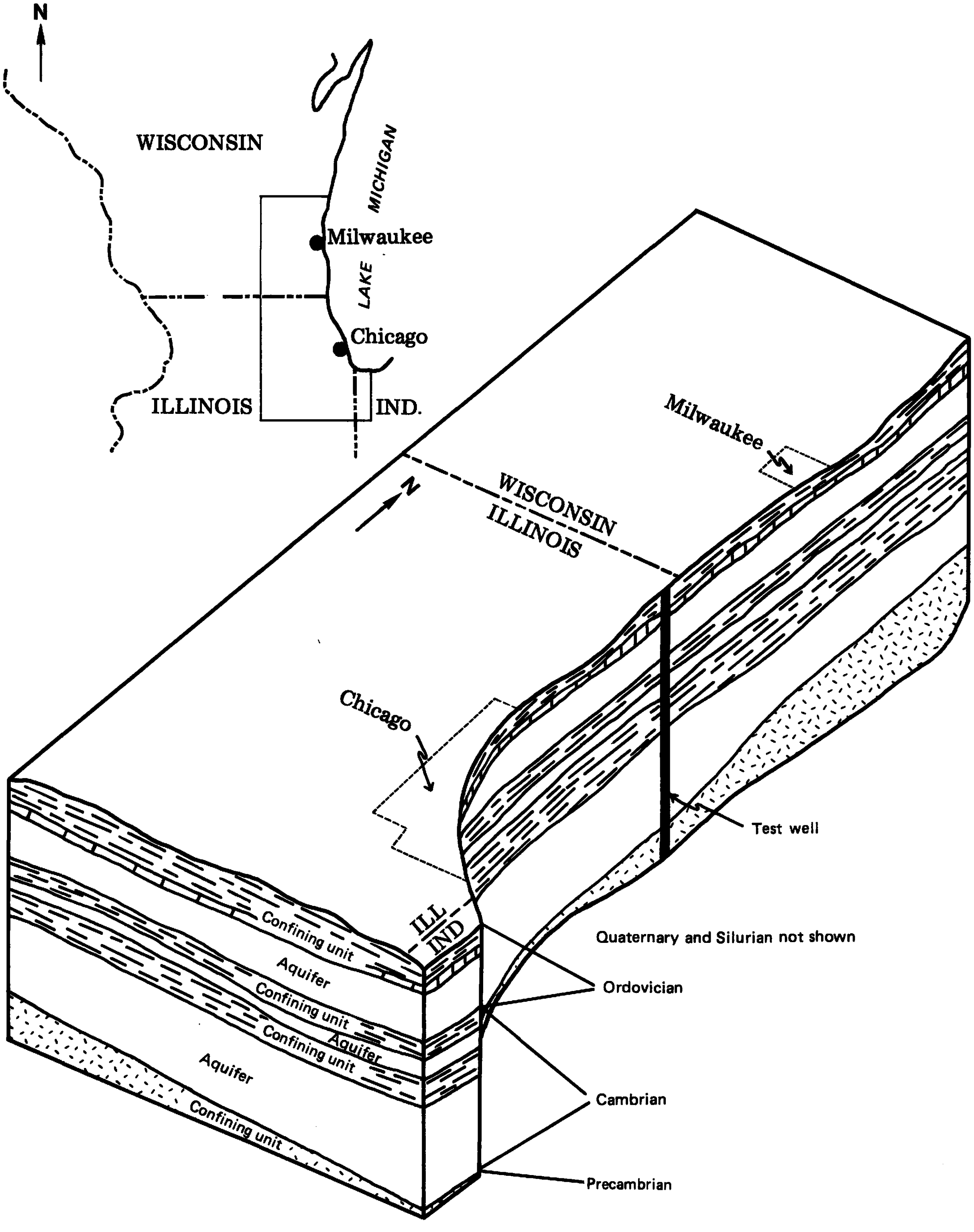


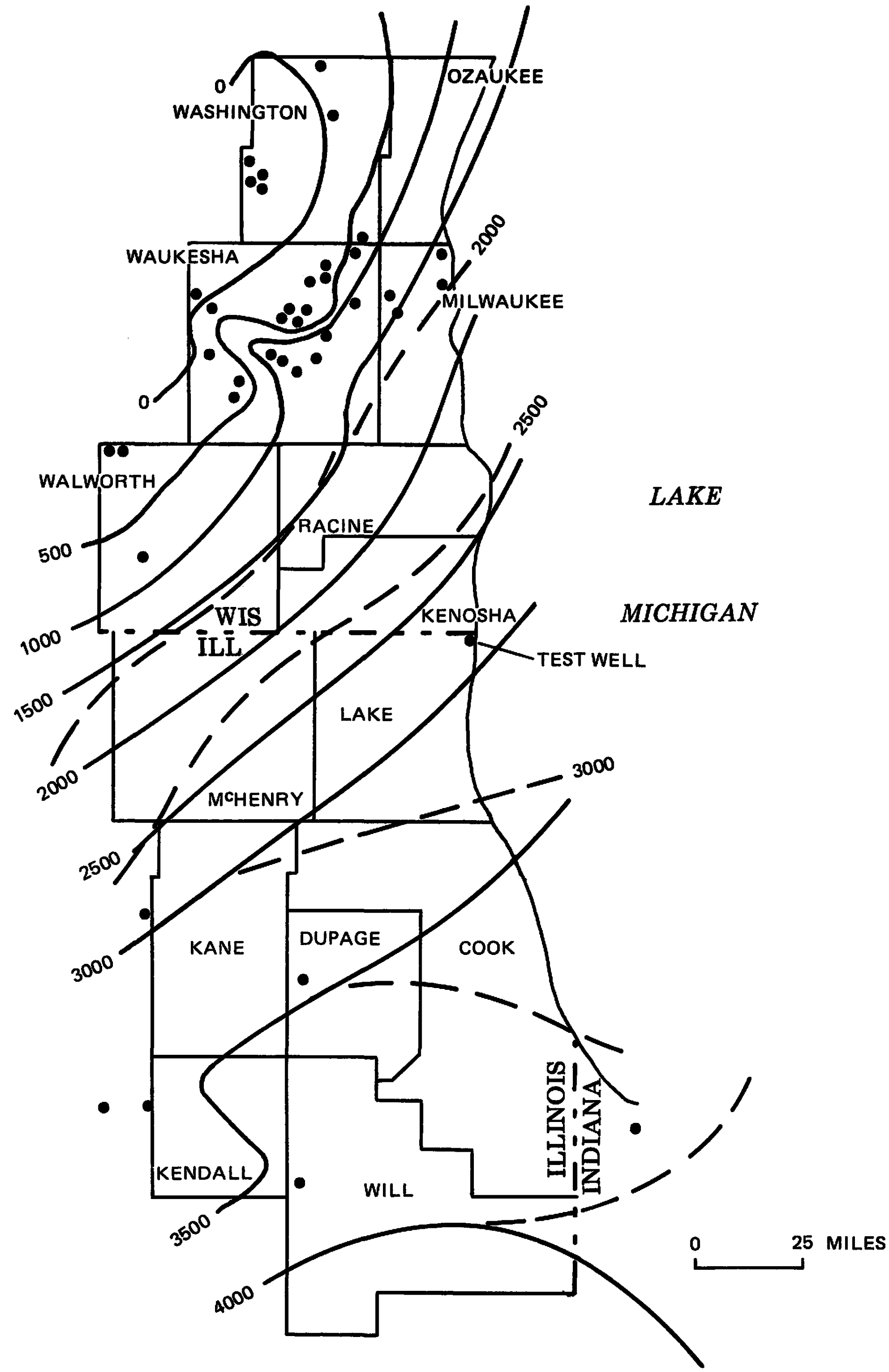
Figure 8.1-1 Generalized block diagram of the Cambrian-Ordovician aquifer system in the area of Chicago-Milwaukee ground-water model.

TEST WELL PROVIDES DATA ON PRECAMBRIAN ROCK

The test well is in a key location where depth to Precambrian rock was not known.

The test well ends in the top of the Precambrian basement rock and thus penetrates all of the Cambrian–Ordovician aquifer system. The nearest wells that reach Precambrian rock are about 40 to 50 mi to the northwest and southwest in Waukesha and Walworth Counties, Wisconsin, and in DuPage County, Illinois (fig. 8.2–1). Thus, this well has provided a unique opportunity to determine the geologic and hydrologic characteristics of the lower part of the aquifer system (see sections 3.1, 6.0, and 7.0) and the altitude and nature of the Precambrian rock.

Precambrian rock is 2,849 ft below sea level in the test well and is a granite with signs of weathering in the upper few feet. Drill cuttings contain about 70 percent feldspar, which is primarily albite and exhibits zoning and very fine twinning. Mafic minerals total 5 to 10 percent, of which 80 to 90 percent is biotite, and the remaining 10 to 20 percent is hornblende. Quartz and a few trace minerals compose the remaining part. The quartz is mostly glossy and colorless with few inclusions (Michael L. Sargent, Illinois State Geological Survey, written commun., 1982).



EXPLANATION

STRUCTURE CONTOUR - Shows altitude of top of Precambrian basement rock. Interval 500 feet. Datum is sea level

— — 2500 Original

—— 2500 Revised

● Well penetrating Precambrian basement

Figure 8.2-1 Altitude of top of Precambrian basement, revised based on data from test well.

9.0 SELECTED REFERENCES

Beaver, D. W., 1974, Cost of importing deep sandstone water to eliminate groundwater deficits in northeastern Illinois: Illinois State Water Survey Circular 120, 17 p.

Fetter, C. W., Jr.,1978, Analysis of the impact of deep well pumpage in the Chicago region on the water resources of southeastern Wisconsin: Memorandum to Attorney General, State of Wisconsin, 67 p.

Gilkeson, R. H., Perry, E. C., Jr., and Cartwright, Keros, 1981, Isotopic and geologic studies to identify the sources of sulfate in groundwater containing high barium concentrations: Illinois State Geological Survey Contract/Grant Report 1981–4, 39 p.

Hem, J. D., 1970, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 1473, 363 p.

Illinois Division of Water Resources, 1977, In the matter of Lake Michigan water allocation: Illinois Department of Transportation Opinion and Order LMO 77–1, March 24, 1977.

______1980, In the matter of allocation of water from Lake Michigan: Illinois Department of Transportation Opinion and Order LMO 80–4, December 15, 1980.

Jacob, C. E., 1950, Flow of groundwater *in* Rouse, H., ed., Engineering hydraulics: New York, John Wiley & Sons, p. 321–386.

Keys, W. S., and MacCary, L. M., 1971, Application of borehole geophysics to water-resources investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 2, Chapter E1, 126 p.

Moench, A. F., and Visocky, A. P., 1971, A preliminary "least cost" study of future groundwater development in northeastern Illinois: Illinois State Water Survey Circular 102, 19 p.

Montgomery, C. W., and Perry, E. C., Jr., 1982, Isotopic methods in hydrologic studies—an introduction *in* Montgomery, C. W., and Perry, E. C., Jr., eds., Isotope studies of hydrologic processes: Dekalb, Illinois, Northern Illinois University Press, p. 1–7.

Prickett, T. A., and Lonnquist, C. G., 1971, Selected digital computer techniques for groundwater resource evaluation: Illinois State Water Survey Bulletin 55, 62 p.

Sasman, R. T., Benson, C. R., Ludwigs, R. S., and Williams, T. L., 1982, Water-level trends, pumpage, and chemical quality in the Cambrian–Ordovician aquifer in Illinois, 1971–1980: Illinois State Water Survey Circular 154, 64 p.

Schicht, R. J., Adams, J. R., and Stall, J. B., 1976, Water resources availability, quality, and cost in northeastern Illinois: Illinois State Water Survey Report of Investigation 83, 90 p.

Schicht, R. J., and Moench, A. F., 1971, Projected groundwater deficiencies in northeastern Illinois, 1980–2020: Illinois State Water Survey Circular 101, 22 p.

Steinhilber, W. L., and Young, H. L., 1979, Plan of study for the Northern Midwest Regional Aquifer-System Analysis: U.S. Geological Survey Water-Resources Investigations Report 79–44, 20 p.

Suter, Max, and others, 1959, Preliminary report on ground-water resources of the Chicago region, Illinois: Illinois State Geological Survey and Illinois State Water Survey Cooperative Report 1, 89 p.

Theis, C. V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage: American Geophysical Union Transactions, v. 16, p. 519–524.

Visocky, A. P., 1982, Impact of Lake Michigan allocations on the Cambrian-Ordovician aquifer system: Illinois State Water Survey Contract Report 292, 36 p.

Woller, D. M., and Gibb, J. P., 1976, Public ground water supplies in Lake County: Illinois State Water Survey Bulletin 60–20, 91 p.

Young, H. L., 1976, Digital-computer model of the sandstone aquifer in southeastern Wisconsin: Southeastern Wisconsin Regional Planning Commission Technical Report 16, 42 p.

10.0 APPENDIX

Results of Laboratory Analysis of Water Samples from Test Well

Constituent	Unit	Hydrogeologic unit		
		St. Peter aquifer	Mount Simon confining unit	Lower Mount Simon aquifer
Date sampled		9-1-81	12-10-80	1-14-81
Packed interval or sampling depth	Depth below land surface, in feet	909–1,046	1,775–1,932	3,120
pH, field	Standard units	7.2	7.2	—
Temperature	°C	15.3	16.8	—
Density	gm/mL at 20°C	.999	—	1.044
Hardness (as $CaCO_3$)	mg/L	340	950	6,400
Hardness, noncarbonate (as $CaCO_3$)	mg/L	79	840	6,300
Calcium (Ca)	mg/L	94	311	1,000
Magnesium (Mg)	mg/L	23	39	930
Sodium (Na)	mg/L	41	440	15,000
Potassium (K)	mg/L	11	16	270
Alkalinity, total (as $CaCO_3$)	mg/L	260	110	120
Sulfide, total (as S)	mg/L	<.1	.0	.0
Sulfate (SO_4)	mg/L	150	1,300	1,400
Chloride (Cl)	mg/L	13	370	37,000
Fluoride (F)	mg/L	1.4	1.0	.3
Bromide (Br)	mg/L	.1	1.4	.2

10.0 APPENDIX—Continued

Results of Laboratory Analysis of Water Samples from Test Well—Continued

Constituent	Unit	Hydrogeologic unit		
		St. Peter aquifer	Mount Simon confining unit	Lower Mount Simon aquifer
Silica (SiO_2)	mg/L	8.0	7.5	4.4
Dissolved solids, residue at 180 °C	mg/L	519	2,800	58,300
Dissolved solids, calculated sum of constituents	mg/L	507	2,570	55,800
Barium (Ba)	µg/L	2	10	50
Beryllium (Be)	µg/L	1	< .7	<1
Boron (B)	µg/L	290	1,000	11,000
Cadmium (Cd)	µg/L	1	5	10
Cobalt (Co)	µg/L	3	6	<3
Copper (Cu)	µg/L	10	<10	36
Iron, total recoverable (Fe)	µg/L	760	2,500	15,000
Iron, suspended (Fe)	µg/L	110	0	6,500
Iron dissolved (Fe)	µg/L	650	2,700	8,500
Lead (Pb)	µg/L	<10	17	170
Lithium (Li)	µg/L	24	180	2,100
Magnesium (Mn)	µg/L	14	190	9,800
Molybdenum (Mo)	µg/L	<10	<10	<10
Selenium (Se)	µg/L	<1	0	0
Strontium (Sr)	µg/L	8,300	13,000	100,000
Vanadium (V)	µg/L	6	<6	<6
Zinc (Zn)	µg/L	40	38	6
Potassium-40 (K)	pCi/L	8.2	12	200
Radium-226, Planchet count (Ra)	pCi/L	6.0	6.9	99
Uranium, dissolved (U)	µg/L	.7	<.6	28.9
δ^2H, hydrogen stable isotope ratio in water, $^2H/^1H$[1]	permil	−68.5	−63.0	−57.5
$\delta^{18}O$, oxygen stable isotope ratio in water, $^{18}O/^{16}O$[1]	permil	−9.6	−9.3	−9.0
$\delta^{34}S$, sulfur stable isotope ratio in sulfate, $^{34}S/^{32}S$[1]	permil	15.5	8.7	—

[1] Standard expression of the ratio of the concentration of the less abundant, heavier isotope to the concentration of the more abundant, lighter isotope referenced to a specified standard (Montgomery and Perry, 1982).

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