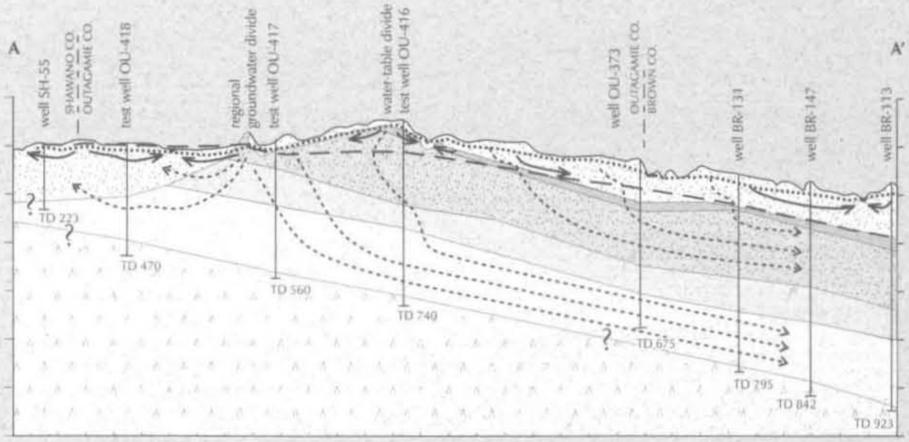
University of Wisconsin–Extension
Wisconsin Geological and Natural History Survey

REGIONAL GROUNDWATER FLOW SYSTEM BETWEEN THE WOLF AND FOX RIVERS NEAR GREEN BAY, WISCONSIN

William G. Batten and Kenneth R. Bradbury

Prepared in cooperation with the
U.S. Geological Survey and Brown County Planning Commission



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The mission of the Wisconsin Geological and Natural History Survey (WGNHS) is to conduct earth-science surveys, field studies, and research and to provide objective scientific information about the geology, mineral resources, soil, climate, water, and biology of Wisconsin. The WGNHS collects, interprets, disseminates, and archives natural resource information. As a part of the University of Wisconsin–Extension, the WGNHS publishes maps, reports, and educational materials and communicates results of research to the public. These activities support informed decision making by government, industry, business, and individual citizens of Wisconsin.

FIGURES

TABLES

REGIONAL GROUNDWATER FLOW SYSTEM BETWEEN THE WOLF AND FOX RIVERS NEAR GREEN BAY, WISCONSIN

William G. Batten[1] and Kenneth R. Bradbury[2]

ABSTRACT

The water used by many communities and industries in the Green Bay metropolitan area of east-central Wisconsin is pumped from wells open to deep carbonate and sandstone rocks. These rocks collectively form the Cambrian–Ordovician aquifer system, commonly called the sandstone aquifer. The objectives of this study were to determine the approximate location of a regional groundwater divide in this aquifer system and to collect new hydrogeologic information about the aquifer. Determining the location of the regional groundwater divide was necessary to verify one of the assumptions used in a groundwater-flow model of the area and for delineating the principal recharge area for the sandstone aquifer. In this report we describe regional groundwater flow in the sandstone aquifer in a 20- by 30-mi area west of Green Bay, Wisconsin. Much of the description is based on hydrogeologic and geochemical data collected from three test wells drilled in the fall of 1992 as part of a study conducted by the U.S. Geological Survey and the Wisconsin Geological and Natural History Survey in cooperation with the Brown County Planning Commission. The three wells are located along an east–west line about 15 to 25 mi west of Green Bay. The aquifer system consists of an upper unconfined unit (the water-table aquifer), a middle confined unit (the St. Peter aquifer), and a lower unit (the Elk Mound aquifer). Confining beds separate these aquifer units. Upper dolomite and sandstone units of the aquifer system gradually thin to the west and are absent in the western part of the study area.

Inflatable straddle packers were used to isolate specific hydrostratigraphic zones in each test well. The hydraulic head declined a total of 37 ft over a vertical distance of 516 ft in the easternmost test well and a total of about 15 ft over a vertical distance of 428 ft in the middle well. These downward gradients indicate that both wells are located in groundwater recharge areas. Hydraulic head in the westernmost test well increased about 0.5 ft over a vertical distance of 132 ft, indicating that this well is located in a discharge area. Groundwater flows southwest toward the Wolf River in the western part of the study area and east toward the Fox River in the eastern part of the study area.

A regional groundwater divide bisects the aquifer system within the study area and extends from north to south through the middle of Outagamie County. This divide is offset about 4 mi west of the shallow groundwater and surface-water divides between the Wolf and Fox River Basins. Oxygen-18 ($\delta^{18}O$) values of water in the test wells were consistent with hydraulic-head data. Tritium isotope concentrations indicated that water at all depths in the middle test well is younger than water in the other two wells, indicating a nearby source and shorter groundwater-flow path.

The horizontal hydraulic conductivity of specific units of the aquifer system ranged from 1.4 to about 23 ft/day. Horizontal hydraulic conductivity of the lower part of the aquifer system appears to increase toward the west. The Tunnel City Group, normally considered a confining unit in the Green Bay area, is less dolomitic in the western part of the study area than in the Green Bay area. The horizontal hydraulic conductivity of this unit near the three test wells ranged from about 3 to 12 ft/day.

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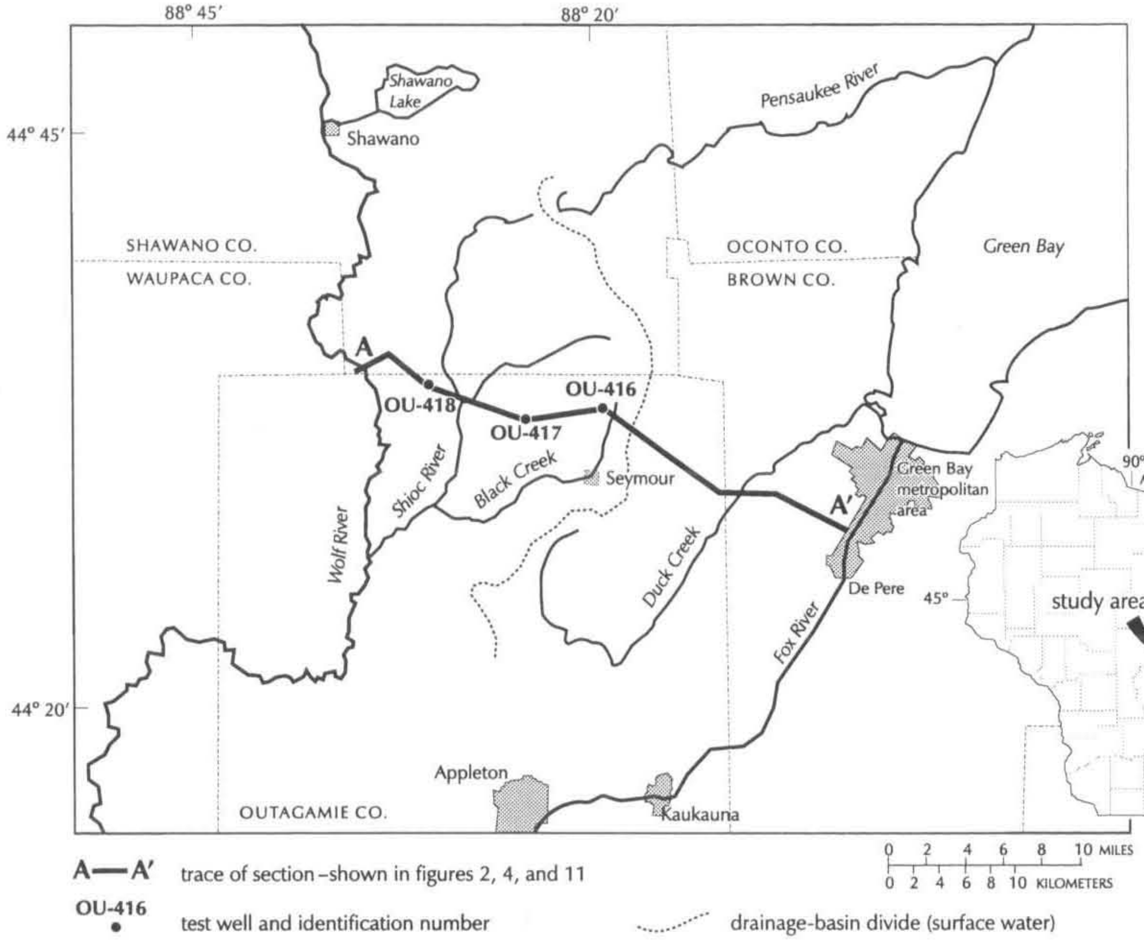

Figure 1. Location of study area and test wells in east-central Wisconsin.

INTRODUCTION

The water used by many communities and industries in the Green Bay metropolitan area of east-central Wisconsin (fig. 1) is pumped from wells open to deep carbonate and sandstone rocks. These rocks collectively form the Cambrian-Ordovician aquifer system, commonly called the "sandstone aquifer."

In 1957, Green Bay began using water piped from Lake Michigan because of declining groundwater levels in city wells completed in the sandstone aquifer. Groundwater levels in the sandstone aquifer quickly recovered, particularly near the center of the cone of depression, which in 1957 was located beneath Green Bay (Krohelski, 1986, p. 1). Following this recovery, groundwater levels in the sandstone aquifer again declined because of increased pumpage by surrounding communities and industries, causing concern over the continued availability of water from this aquifer.

Well constructor's reports and aquifer-test data from the many municipal and industrial wells provide an adequate description of the sandstone aquifer in the metropolitan area along the Fox River. However, there are few deep wells open to the aquifer west and northwest of the Green Bay metropolitan area. The general direction of groundwater flow has been reported as from the west and northwest toward the Fox River and pumping centers in the Green Bay metropolitan area (Drescher, 1953; Krohelski, 1986). However, base flows in the Wolf River, about 30 mi west of Green Bay (fig. 1), are high, and extensive wetlands lie just east of the Wolf River in west-central Outagamie County. This suggests that a substantial quantity of groundwater flows from the north and east and discharges into the Wolf River and the adjacent wetlands. The high base flow and extensive wetlands also suggest that a regional groundwater divide may separate groundwater flow between the Wolf River Basin to the west and the Fox River Basin to the east.

A regional groundwater divide between the two rivers was an important assumption of a numerical groundwater-flow model developed in the mid-1980s (Krohelski, 1986) to provide a basic understanding of the groundwater flow system and to simulate water levels in the sandstone aquifer in the Green Bay metropolitan area. This model was used again in 1992 to simulate future drawdowns as part of a comprehensive study of water-supply options for communities and industries in the Green Bay area (Consoer, Townsend, and Associates, Inc., 1992)

Purpose and scope

The objectives of this study were to determine the approximate location of a regional groundwater divide in the 20- by 30-mi area between the Wolf and Fox Rivers west of the city of Green Bay and to collect new hydrologic, geologic, and geochemical information on the sandstone aquifer in an area where little information was available in the past. Determining the location of the regional groundwater divide is necessary to verify one of the assumptions used in the groundwater-flow model and for delineating the principal recharge area for the sandstone aquifer in the Green Bay area. To meet these objectives, we collected geologic and hydrologic data from three test wells that we drilled in northern Outagamie County northwest of the city of Green Bay.

Description of study area

The entire study area encompasses about 600 mi^2 in east-central Wisconsin between the Wolf River in western Outagamie County and the Fox River at Green Bay (fig. 1). This area covers much of western Brown County, northern Outagamie County, and a small part of southeastern Shawano County (fig. 1). The three test-well sites were drilled in northern Outagamie County about 15 to 25 mi northwest of the city of Green Bay (fig. 1) along a line roughly parallel to the assumed west–east regional direction of groundwater flow in the sandstone aquifer. Data from the three sites and other selected well sites were used to construct a representative cross section (fig. 2) of the geologic setting and groundwater flow system between the Wolf and Fox Rivers.

Physical setting

The Wolf River flows south along the western edge of the study area; the Fox River flows northeast into Green Bay along the eastern edge of the area. A dolomite ridge extends from the northeast into the middle of the study area near Seymour, Wisconsin (fig. 1). The top of this ridge ranges from about 850 to 920 ft above sea level. The land surface slopes gently eastward to the Fox River valley, where the land surface generally ranges from about 600 to 650 ft above sea level. The mouth of the Fox River at Green Bay is about 580 ft above sea level. The land surface in the western part of the study area is generally flat and is dissected by the Wolf River, the Shioc River, and Black Creek. These streams all flow through or are adjacent to large wetland areas that range from about 790 to 820 ft above sea level.

Surface drainage in the western half of the study area is southward and westward toward the Wolf River by way of the Shioc River and Black Creek (fig. 1). Drainage in the eastern half of the study area is east and north toward the Fox River and Green Bay. The divide separating surface runoff between the Wolf and Fox River Basins is shown in figure 1.

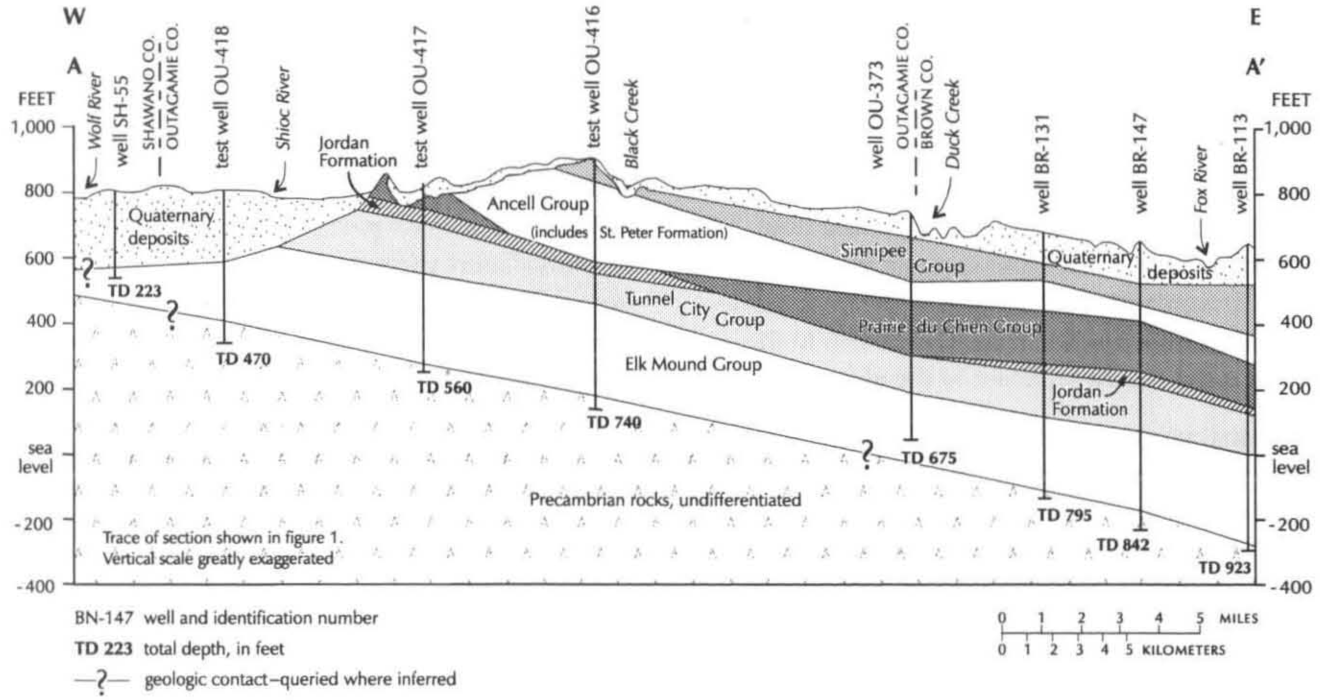

Figure 2. *Geologic section from the Wolf River to the Fox River in east-central Wisconsin.*

Geologic framework

The entire study area is underlain by layered sedimentary rocks of Cambrian and Ordovician age that rest on rocks of Precambrian age (Krohelski, 1986, p. 4). Unlithified glacial deposits of Quaternary age overlie these bedrock units. A geologic section extending from the Wolf River to the Fox River (fig. 2) shows the relative thicknesses and stratigraphic positions of the rock units. (The stratigraphic nomenclature used in fig. 2 and the rest of this report is that of Mudrey and others, 1982.) The surfaces of the sedimentary and the Precambrian rocks generally slope to the east at about 30 to 40 ft/mi. The Precambrian rock is apparently granite, according to drillers' descriptions of drill cuttings from a small number of relatively deep wells that typically penetrate a few feet into the Precambrian rocks.

The Elk Mound Group of Cambrian age is the oldest sedimentary rock group underlying the study area. This group has a uniform thickness of 250 to 300 ft (fig. 2), except in the western part of the area (LeRoux, 1957). The lower part of the Elk Mound Group is a poorly cemented, fine-grained sandstone, and the upper part is medium- to coarse-grained sandstone (Krohelski, 1986, p. 4).

The Tunnel City Group of Cambrian age overlies the Elk Mound Group and is typically about 100 to 150 ft thick. The Tunnel City Group and overlying rocks have been completely removed in the far western part of the study area (fig. 2) by erosion. The lithology of this group ranges from medium-grained sandstone to dolomitic siltstone to sandy dolomite.

The St. Lawrence Formation lies above the Tunnel City Group (Krohelski, 1986, p. 4). However, the St. Lawrence Formation was not reported in the well constructor's reports of the wells shown in figure 2; it is present in other parts of the study area and consists of silty, shaly dolomite. The Jordan Formation overlies the St. Lawrence Formation or the Tunnel City Group where the St. Lawrence Formation is absent. The Jordan Formation is found only in the eastern and west-central part of the study area, according to well constructor's reports of the wells shown in figure

2. The Jordan Formation is about 20 to 50 ft thick where present and consists of fine- to coarse-grained sandstone.

The Prairie du Chien Group overlies the Tunnel City Group and the Jordan Formation and is a massive dolomite with minor layers of limestone, sandstone, shaly sandstone, and dolomitic sandstone. The Prairie du Chien Group is absent in some areas (fig. 2; Krohelski, 1986, p. 4) but can be as much as 150 ft thick.

The Ancell Group overlies the Prairie du Chien Group and comprises the St. Peter Formation and the thin Glenwood Formation (not shown in fig. 2). The St. Peter Formation is, for the most part, a poorly cemented, fine- to medium-grained sandstone, but contains sandy shale and chert layers at the base (Krohelski, 1986, p. 4). The St. Peter Formation varies from less than 50 ft in areas where the Prairie du Chien Group is thickest to about 250 ft in areas where the underlying Prairie du Chien Group has been completely eroded (fig. 2; Krohelski, 1986, p. 4). The Glenwood Formation, at the top of the Ancell Group, is a silty sandstone. The combined thickness of the Ancell and Prairie du Chien Groups is a fairly uniform 220 to 250 ft in the study area (Kathleen Massie-Ferch, Wisconsin Geological and Natural History Survey, verbal communication, 1992).

The Sinnipee Group is the uppermost bedrock unit in the study area. It comprises the Platteville Formation (dolomite) and the Galena Formation (undifferentiated in fig. 2), which are separated in many localities by the Decorah Formation, a fairly thin (less than 25 ft) shale (Krohelski, 1986, p. 4). The Sinnipee Group forms the dolomite ridge near middle of the study area (fig. 2) and ranges from about 100 to 200 ft thick throughout the eastern half of the area.

Unlithified glacial deposits of Quaternary age overlie the entire study area and are predominantly fine-grained till, a mixture of silty or sandy clay and some gravel. Wind-blown sediment was deposited in some areas near the Wolf River, and buried sand and gravel deposits of small areal extent are present throughout much of the study area (Krohelski, 1986, p. 5). Lacustrine silt and clay (deposited at the bottom of glacial meltwater lakes) also are common at or near land surface in lowland areas. In the eastern half of the study area, glacial deposits range from about 50 to 100 ft in thickness. A veneer of glacial deposits overlies much of the upland in the middle of the study area where dolomite of the Sinnipee and Prairie du Chien Groups and St. Peter Formation crops out in numerous locations. Glacial deposits are thickest in the western part of the study area, where they exceed 200 ft (fig. 2).

PREVIOUS INVESTIGATIONS

Concern over the continued availability of groundwater from the sandstone aquifer in the Green Bay area began in the early 1950s. Drescher (1953) first summarized the groundwater sources in the Green Bay area. His report emphasized the hydraulic properties of the sandstone aquifer and presented hydrographs showing water-level declines from the 1890s through 1950 in the intensively pumped areas within the city of Green Bay. LeRoux (1957) provided additional hydrogeologic information about the sandstone aquifer in Outagamie County. Knowles and others (1964) summarized the occurrence, availability, and use of groundwater and surface water in the Green Bay area. Knowles (1964) presented more detailed information about the sandstone aquifer in the Green Bay area based on water-level recovery data in municipal wells after the city of Green Bay switched to Lake Michigan for its water supply in 1957.

Krohelski (1986) compiled all geologic and aquifer-test data for the Green Bay area and designated rock units as either aquifers or confining

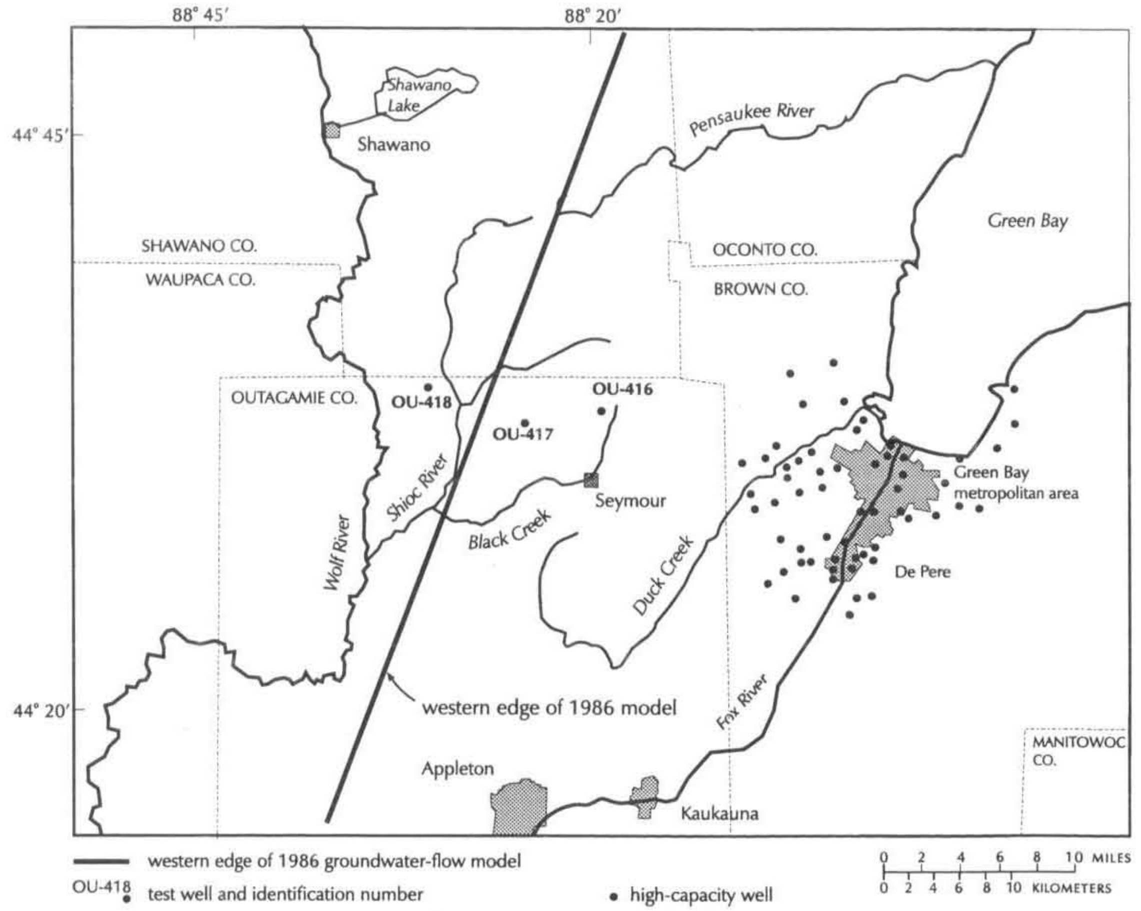

Figure 3. *Location of western edge of 1986 groundwater-flow model (Krohelski, 1986) and high-capacity wells completed in sandstone-aquifer system in the Green Bay metropolitan area, Wisconsin.*

units in developing a computer model to simulate groundwater flow and water-level (hydraulic-head) changes in the sandstone aquifer in the Green Bay area from predevelopment through 1980. That part of our study area simulated in the 1986 groundwater-flow model is shown in figure 3, along with the locations of municipal and industrial wells in the Green Bay area completed in the sandstone aquifer. Notice the lack of wells in the western part of the study area. The computer model provided a measurement of the effects of historical pumpage on the natural groundwater flow system; this model was subsequently used to predict future drawdowns in the sandstone aquifer on the basis of population and water-use projections for the Green Bay metropolitan area through the year 2010 (Consoer, Townsend, and Associates, Inc., 1992).

Methods of study

Geologic, aquifer-test, hydraulic-head, and geochemical data were collected during September and October 1992 from three test wells drilled in northern Outagamie County. Rock type (lithology) was determined from drill cuttings and geophysical logs at each test well. Inflatable packers were lowered into each test well to isolate specific zones of aquifers and confining units for testing. The length of the tested zones ranged from about 60 to 130 ft. Specific-capacity tests were performed on each isolated zone with a submersible pump discharging at constant rates ranging from about 20 to 60 gal/min for periods of 1 to 2 hours. Drawdown in each pumped zone was measured with a pressure transducer, and data were analyzed to determine the horizontal hydraulic conductivity of each zone. Pressure transducers also were used to make static hydraulic-head measurements in each zone to determine the vertical distribution of hydraulic head at each test-well site.

Water levels from the test wells and selected municipal, industrial, and domestic wells were combined with water levels calculated in groundwater-flow model simulation (Consoer, Townsend, and Associates, Inc., 1992; J.T. Krohelski, U.S. Geological Survey, verbal communication, 1992) to develop a potentiometric-surface map of the sandstone aquifer. Some historical water levels from domestic wells in the western part of the study area were used in developing this map; we assumed that water levels in these wells are not affected by pumpage in the Green Bay metropolitan area. Geologic data were compiled and presented in a geohydrologic section that extends through the study area from the Wolf River to the Fox River (fig. 2). The section is representative of the study area and, combined with the potentiometric map, presents a complete description of the regional groundwater flow system between the Wolf and Fox Rivers west of the Green Bay area.

Groundwater samples from each isolated zone were collected at the end of the specific-capacity tests using the submersible pump contained within the packer assembly. Each pumping period represented at least 25 well volumes and was considered sufficient to ensure that ambient groundwater was being drawn through the packer equipment to the sample point. Samples for analysis of major ions and trace elements were filtered on site through a 0.45-micrometer membrane filter and acidified with concentrated high-purity nitric acid. Samples for bicarbonate and nitrate were filtered but not acidified. Samples for isotopes were neither filtered nor acidified. All samples were kept chilled in a portable cooler during transport to the laboratory.

Specific conductance, pH, water temperature, and dissolved oxygen were measured on site immediately after sample collection. Major ions and trace elements were analyzed by inductively coupled plasma emission (ICP) spectroscopy at the University of Wisconsin–Extension Soil and Plant Analysis Laboratory in Madison, Wisconsin. Bicarbonate, chloride, and nitrate as nitrogen were analyzed by wet chemical methods at the same laboratory.

As a check on analytical precision for major ions, an equivalents per million (EPM) charge balance was calculated for each analysis (Freeze and Cherry, 1979). For electrical neutrality of the solution, the sum of the electrical equivalents of cations (for example, Ca^{+2}, Mg^{+}) should be equal and opposite of the sum of the equivalents of the cations (for example, Cl^{-}, HCO_3-) in a given sample. Samples having an EPM error of greater than 10 percent were rejected. Mineral saturation indices were calculated for all samples using the pH-redox-equilibrium-equations (PHREEQE) computer code (Parkhurst and others, 1980). The PHREEQE program was also used to calculate sulfate concentrations from total sulfur analyses.

Isotopes of tritium (^3H), oxygen-18 ($\delta^{18}O$), and deuterium (δ^2H) in each water sample were analyzed by the Isotope Laboratory at the University of Waterloo in Waterloo, Ontario, Canada. The samples were tested for ^3H content by liquid scintillation counting following ^3H enrichment. Results are expressed in tritium units (TU), where 1.0 TU corresponds to one tritium atom in 10^{18} hydrogen atoms. This method has a detection limit of approximately 0.8 TU and an analytical precision of about ±0.3 TU. Samples were tested for $\delta^{18}O$ and δ^2H by mass spectrometry. These

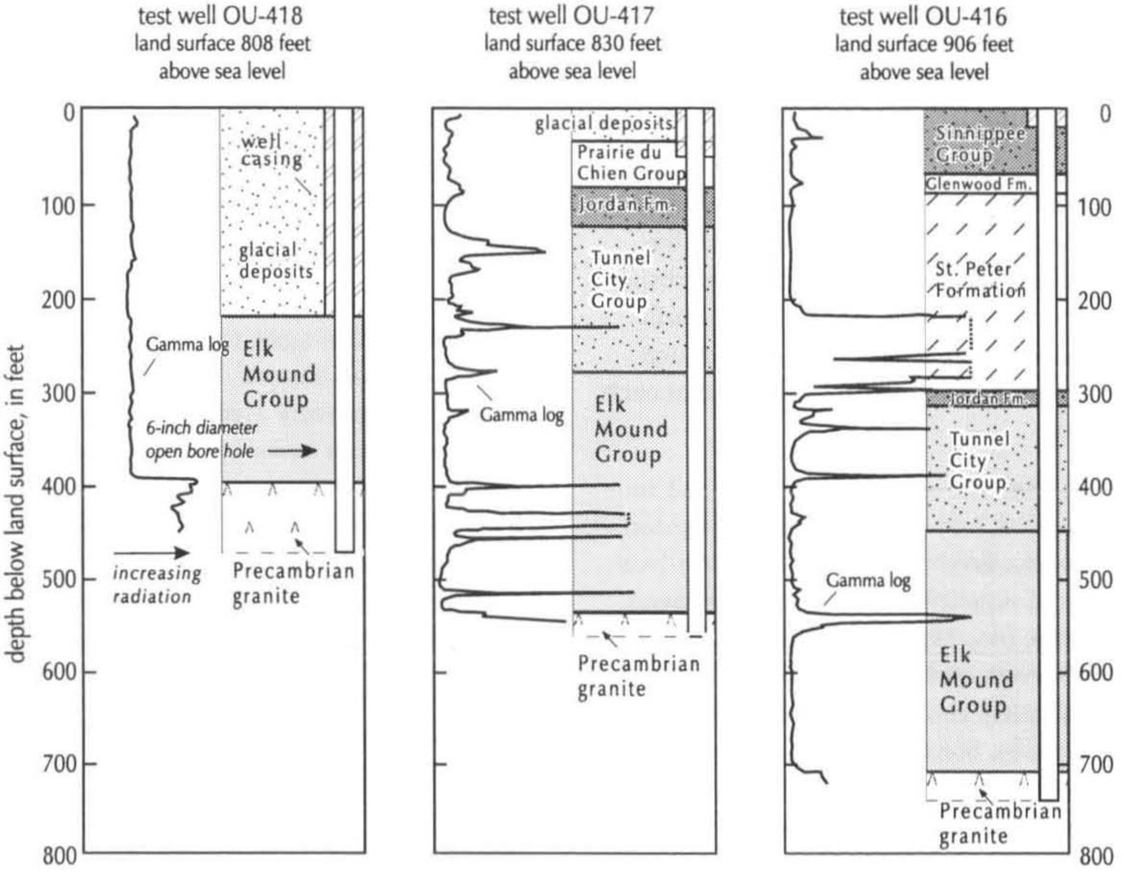

Figure 4. *Geology, gamma logs, and information from well constructor's reports for test wells OU-418, OU-417, and OU-416 in east-central Wisconsin. (Wells are arranged from west [OU-418] to east [OU-416].)*

analyses are expressed in the conventional (delta) notation as per mil differences from standard mean ocean water (SMOW), with an analytical precision of ±0.2 per mil for $\delta^{18}O$ and ±1.0 per mil for $\delta^{2}H$.

Total arsenic was analyzed by the Wisconsin State Laboratory of Hygiene in Madison, Wisconsin. Arsenic was determined in filtered, acidified samples using atomic absorption, with a detection limit of 10 µg/L (micrograms per liter).

Acknowledgments

The authors thank the land owners who provided access to their property for drilling the test wells necessary for this study and Kenneth Jaworski, Senior Planner at the Brown County Planning Commission, for his efforts and interest in making this study a success. The authors also acknowledge Mark T. Duigon, Maryland Geological Survey, and Timothy T. Eaton, Wisconsin Geological and Natural History Survey, for their critical reviews of the manuscript.

TEST-WELL DATA COLLECTED IN 1992

The three test wells were drilled in September 1992 to collect information about the geology and hydraulic characteristics of the aquifers and confining units and to confirm the location of the groundwater divide (fig. 1), hypothesized by Krohelski (1986) to be near the village of Seymour in Outagamie County. Prior to drilling these wells, little information was available in this area, particularly for deep parts of the sandstone aquifer. Detailed water-level, aquifer-test, and geochemical data from these test wells were analyzed to improve the general understanding of the groundwater flow system between the Wolf and Fox Rivers.

Test-well locations and construction

The three test wells are located north and west of the village of Seymour (fig. 1), on a line approximately parallel to the assumed direction of regional groundwater flow toward the Green Bay area. The middle well (OU-417) is slightly offset from a line between the westernmost well (OU-418) and the easternmost well (OU-416).

The site of test well OU-416 is at the top of the topographic high near the middle of the study area, close to the surface-water drainage-basin divide between the Wolf and Fox Rivers (fig. 1). The land surface at this location is 906 ft above sea level. Test well OU-417 is located about 4 mi southwest of test well OU-416 on a hillside about 0.33 mi east of a small stream and wetland (not shown). The land surface at test well OU-417 is about 50 ft higher than the wetland area. The westernmost test well, OU-418, is located about 5 mi northwest of test well OU-417 and is adjacent to a broad wetland area (not shown) on the east side of the Wolf River.

Each well was drilled with a rotary hammer drilling rig using air to remove drill cuttings. Each well was constructed by drilling a 10-in.-diameter borehole to the top of the first bedrock unit. Six-inch-diameter steel well casing was installed, and the annular space grouted with concrete to seal off overlying unconsolidated glacial deposits. After casing installation, a 6-in.-diameter borehole was drilled to the base of the Elk Mound Group. The three boreholes ended at depths ranging from about 20 to 70 ft into the underlying Precambrian granite.

Test well OU-416 is 740 ft deep (fig. 4) and is cased to 18 ft below land surface. The top of the Sinnipee Group is only 2 ft below land surface at this site. Test well OU-417 is 560 ft deep and is cased from land surface to a depth of 48 ft. The top of the first bedrock unit, the Prairie du Chien Group, is 42 ft below land surface. Test well OU-418 is 470 ft deep and is cased from land surface to 219 ft below land surface. The top of the Elk Mound Group is at a depth of about 200 ft below land surface at this site.

Aquifer and confining-unit lithology

The stratigraphic units penetrated by each test well and natural gamma logs of the wells are shown in figure 4. Formation contacts were determined from drill cuttings collected and analyzed at 5-ft intervals and from geophysical logs. Geophysical logs included caliper, resistivity, fluid temperature, fluid conductivity, and natural gamma logs. The natural gamma log is the most useful of these for qualitative hydrogeologic interpretation. Shale or silty sandstone layers show as right deflections in the natural gamma log because of relatively high natural radioactivity, which is typically associated with fine-grained clay or shale layers. Sandstone and dolomite have relatively low natural radioactivity and show as left deflections.

Test well OU-416 penetrates almost all bedrock units from the uppermost Sinnipee Group down to the Precambrian granite (figs. 2 and 4). Only the upper part of the St. Lawrence–Tunnel City confining unit and the Prairie du Chien Group are absent at this site. At the site of test well OU-417, the Sinnipee Group and Ancell Group, which includes the St. Peter Formation, are completely absent (figs. 2 and 4). At test well OU-418, only sandstone of the Elk Mound Group is present. All overlying bedrock units have been eroded or were never deposited at this site (figs. 2 and 4).

Hydraulic characteristics

Static water-level measurements were taken in each isolated zone to determine the vertical distribution of hydraulic head and hydraulic gradient

Table 1. Summary of hydraulic-head measurements and vertical hydraulic gradients in test wells

Test well OU-416 (composite open-hole hydraulic head = 800.0 ft)			Test well OU-417 (composite open-hole hydraulic head = 792.0 ft)			Test well OU-418 (composite open-hole hydraulic head = 793.0 ft)		
Geologic unit and isolated interval (ft)	**Hydraulic head (ft)**	**Vertical hydraulic gradient**	**Geologic unit and isolated interval (ft)**	**Hydraulic head (ft)**	**Vertical hydraulic gradient**	**Geologic unit and isolated interval (ft)**	**Hydraulic head (ft)**	**Vertical hydraulic gradient**
Upper St. Peter Formation (80–211)	807.0	+0.011	—	—	—	—	—	—
Lower St. Peter Formation (238–301)	808.4	-0.371	—	—	—	—	—	—
—	—	—	Prairie du Chien Group and Jordan Formation (48–116)	803.4	-0.059	—	—	—
Jordan Formation and upper Tunnel City Group (303–366)	784.3	-0.055	Lower Jordan Formation and upper Tunnel City Group (114–172)	799.8	-0.081	—	—	—
—	—	—	Lower Tunnel City Group (219–277)	791.3	-0.021	—	—	—
Upper Elk Mound Group (443–506)	776.6	—	Upper Elk Mound Group (289–347)	789.8	-0.002	Upper Elk Mound Group (220–286)	792.4	+0.003
Middle Elk Mound Group (513–576)	—	-0.014	Middle Elk Mound Group (344–402)	789.7	-0.012	Middle Elk Mound Group (289–336)	792.6	+0.004
Lower Elk Mound Group (608–671)	774.2	-0.072	Middle and lower Elk Mound Group (409–560)	788.5	+0.023	Lower Elk Mound Group (334–391)	792.8	+0.013
Lower Elk Mound Group and Precambrian rock (608–740)	771.7	—	Lower Elk Mound Group and Precambrian rock (479–560)	789.5	—	Lower Elk Mound Group and Precambrian rock (369–416)	793.2	0.000
—	—	—	—	—	—	Precambrian rock (401–470)	793.2	—

All isolated-interval values are in feet below land surface; all hydraulic-head values reported in feet above sea level; vertical hydraulic gradient represents the change (in feet) of hydraulic head per foot of vertical distance from the midpoint of the isolated interval to the midpoint of the immediate underlying isolated interval; positive (+) value of vertical hydraulic gradient represents upward groundwater flow; negative (-) gradient represents downward flow; —, not determined

in each of the three test wells. Specific-capacity data from each isolated zone were used to estimate the horizontal hydraulic conductivity of the rock units open to each isolated zone during testing.

The distribution of hydraulic head in the aquifers and confining units determines the direction of groundwater flow. The horizontal component of the direction of groundwater flow can be determined by comparing the hydraulic-head values between test wells. The vertical component of flow can be determined by comparing the vertical change in hydraulic head with depth in a single well. The hydraulic conductivity of an aquifer or confining unit is a measure of the ability of that rock unit to transmit water and is defined as the volume of water that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

Hydraulic-head measurements

Hydraulic heads were measured in each isolated zone in all three test wells (table 1), using procedures outlined in the *Methods of study* section of this report. Sea level is used as the datum for hydraulic head. Hydraulic-head data were used to calculate vertical hydraulic gradients between adjacent isolated zones in each test well. Vertical hydraulic gradients shown in table 1 represent the change (in feet) in hydraulic head per foot of vertical distance from the midpoint of one isolated interval to the midpoint of the immediate underlying interval. Positive values of vertical hydraulic gradient indicate upward groundwater flow and negative values indicate downward flow.

Hydraulic-head values declined with depth in test wells OU-416 and OU-417. The total decline in test well OU-416 was about 37 ft from a high of

808.4 ft in the lower part of the St. Peter Formation (table 1) to 771.7 ft at the base of the Elk Mound Group, an overall downward gradient of 0.091. The downward gradient was relatively large (0.371) in the upper part of the borehole material from the lower part of the St. Peter Formation to the top of the Tunnel City Group (table 1). Hydraulic head also declined with depth in the Elk Mound Group from about 443 ft below land surface to the bottom of the borehole, but at a much slower rate. The composite hydraulic head in the Elk Mound Group is about 775 ft.

Hydraulic head also declined with depth in test well OU-417 from about 803 ft in the Prairie du Chien Group (table 1) near land surface to about 790 ft in the lower part of the Elk Mound Group at the bottom of the borehole. As in test well OU-416, the largest declines in hydraulic head, with resulting downward gradients, were in the upper part of the borehole, particularly below the Prairie du Chien Group and the lower Jordan Formation above the 219 ft depth (table 1). The hydraulic head in the Elk Mound Group (lower 350 ft of the borehole) in test well OU-417 is relatively uniform at about 789 ft.

All measured hydraulic heads in test well OU-418 are near 793 ft (table 1) but show a slight upward vertical gradient in the Elk Mound Group, the only Paleozoic bedrock unit at this site. The altitude of the water surface in the Wolf River and wetlands immediately west of test well OU-418 is about 775 to 780 ft above sea level. Therefore, the hydraulic head in the Elk Mound Group was about 15 ft higher than the Wolf River and nearby wetlands at the time of this study.

Hydraulic-conductivity measurements

Horizontal hydraulic conductivities of the bedrock units were determined from specific-capacity tests performed in a total of 16 zones in the three test wells (table 2). Fifteen of the tests were performed on various rock units that make up the sandstone aquifer and one was done in the Precambrian granite in test well OU-418. (The test methods are described in the *Methods of study* section of this report.) During the test of the Precambrian granite, pump discharge rapidly decreased to zero in less than 1 minute so that no analysis was possible. The specific-capacity data for each isolated zone were analyzed using an iterative computer procedure (Bradbury and Rothschild, 1985) based on the Theis (1963) method for estimating the transmissivity from specific-capacity data, but also including corrections for well loss and partial penetration.

Horizontal hydraulic conductivity ranged from slightly more than 1 to about 23 ft/day (ft/d) for all tested bedrock units (table 2). Horizontal hydraulic conductivity of rock units at test well OU-416 ranged from just more than 1 ft/d in lower parts of the Elk Mound Group to about 16 ft/d in the upper part of the St. Peter Formation. The difference in values between the upper and lower parts of the St. Peter Formation in test well OU-416 probably is due to the large amount of fine-grained shaly and silty material in the lower part of the unit (shown by the strong right deflection in the natural gamma log from 220 to 300 ft below land surface; fig. 4).

At test well OU-417, horizontal hydraulic conductivities ranged from 2 ft/d in the upper Elk Mound and Prairie du Chien Groups to about 12 ft/d in the Tunnel City Group. Values were fairly uniform in the Elk Mound Group, only ranging from 2.0 to 6.6 ft/d in the three tested intervals. At test well OU-418, there was a sharp contrast in the horizontal hydraulic conductivity between the middle and lower parts of the Elk Mound Group, the only rock unit present at this site. The horizontal hydraulic conductivity of 23.2 ft/d of the lower part is the largest for all intervals tested.

Table 2. Horizontal hydraulic-conductivity values calculated from specific-capacity tests in three test wells, October 1992

Test well OU-416			Test well OU-417			Test well OU-418		
Geologic unit and isolated interval (ft)	**Specific capacity [(gal/min)/ft]**	**Hydraulic conductivity (ft/d)**	**Geologic unit and isolated interval (ft)**	**Specific capacity [(gal/min)/ft]**	**Hydraulic conductivity (ft/d)**	**Geologic unit and isolated interval (ft)**	**Specific capacity [(gal/min)/ft]**	**Hydraulic conductivity (ft/d)**
Upper St. Peter Formation (80–211)	16.3	16.3	—	—	—	—	—	—
Lower St. Peter Formation (238–301)	8.2	1.9	—	—	—	—	—	—
—	—	—	Prairie du Chien Group and Jordan Formation (48–116)	0.8	2.7	—	—	—
Jordan Formation and upper Tunnel City Group (303-366)	0.9	3.1	Lower Jordan Formation and upper Tunnel City Group (114–172)	2.4	9.5	—	—	—
—	—	—	Lower Tunnel City Group (219–277)	2.9	11.7	—	—	—
Upper Elk Mound Group (443–506)	2.4	8.8	Upper Elk Mound Group (344–402)	0.5	2.0	Upper Elk Mound Group (220–286)	0.6	2.0
Middle Elk Mound Group (513–576)	0.4	1.5	Middle and lower Elk Mound Group (409–560)	3.7	6.6	Middle Elk Mound Group (289–336)	0.9	4.0
Lower Elk Mound Group and Precambrian rock (608–740)	0.7	1.4	Lower Elk Mound Group and Precambrian rock (479–560)	1.4	4.7	Lower Elk Mound Group and Precambrian rock (369–416)	5.2	23.2

—, absent or not determined

Table 3. Qualitative interpretations of tritium concentrations in groundwater (from Hendry, 1988)

Tritium concentration (tritium units)	Interpretation
>100	Groundwater likely recharged during thermonuclear testing between 1960 and 1965.
10–100	Groundwater less than 35 years old.
2–10	Groundwater at least 20 years old.
<2.0	Groundwater older than 30 years.
<0.2	Groundwater older than 50 years.

Geochemical analyses

Isotopes naturally present in groundwater, often referred to as "environmental isotopes," can be important in aiding interpretation of groundwater ages, flow paths, and source areas. Water from the three test wells was analyzed for ^{3}H, δ^{18}O, and δ^{2}H isotopes to test hypotheses about the origins and flow paths of groundwater in the sandstone aquifer in northern Outagamie County. All three isotopes are useful groundwater tracers because these isotopes travel as part of the water molecule rather than as a dissolved constituent in the water. The following is a brief summary of the theory of the use of these isotopes in groundwater studies. Hendry (1988) gave a more extensive overview of the theory.

Tritium is a radioactive isotope of hydrogen produced in increased quantities in the Earth's atmosphere during the testing of thermonuclear weapons in the 1960s. Because the history of ^{3}H concentrations in the Earth's atmosphere is well known, ^{3}H is an excellent indicator of approximate groundwater age. Approximate groundwater age can be estimated according to ^{3}H concentrations shown in table 3.

Latitude and temperature are the two dominant factors that affect the composition of δ^{18}O and δ^{2}H in groundwater systems (Freeze and Cherry, 1979). In general, for continental hydrologic systems, the more northerly the recharge area of the groundwater, the isotopically lighter it becomes with respect to oxygen and hydrogen. Therefore, variations in the δ^{18}O content of groundwater can

Table 4. *Isotopic composition in water collected from three test wells, September and October 1992*

Test well	Date sampled	Depth to midpoint of packed interval (feet below land surface)	Tritium (TU)	Tritium error (TU)	Ground-water age (years)	Oxygen-18 (per mil SMOW, ±0.1)	Deuterium (per mil SMOW, 0.00)
OU-416	9/22/92	146	<0.8	±0.3	>30	-10	-68
	9/22/92	270	<0.8	±0.3	>30	-9.9	-68
	9/23/92	334	<0.8	±0.3	>30	-10	-69
	9/23/92	474	<0.8	±0.2	>30	-10.1	-68
	9/24/92	544	<0.8	±0.3	>30	-10	-68
	9/24/92	640	<0.8	±0.3	>30	-10.1	-67
	9/24/92	674	<0.8	±0.3	>30	-9.9	-68
		Mean	<0.8	—	—	-10	-68
		Standard deviation	0	—	—	0.07	0.6
OU-417	9/29/92	82	4.8	±0.5	>20	-9.5	-67
	9/29/92	143	<0.8	±0.3	>30	-9.3	-66
	9/30/92	248	1	±0.3	>30	-9.4	-64
	9/30/92	373	1.3	±0.3	>30	-9.3	-67
	10/01/92	474	1.4	±0.3	>30	-9.6	-67
	10/01/92	520	<0.8	±0.3	>30	-9.6	-67
		Mean	1.42	—	—	-9.4	-66
		Standard deviation	1.68	—	—	0.13	1.32
OU-418	10/07/92	253	<0.8	±0.3	>30	-10	-70
	10/07/92	312	<0.8	±0.3	>30	-10.2	-68
	10/08/92	392	<0.8	±0.3	>30	-10	-71
		Mean	<0.8	—	—	-10.1	-70
		Standard deviation	0	—	—	0.11	1.2

SMOW, standard mean ocean water; —, not determined

suggest variations in the latitude of the recharge area of the groundwater. However, $\delta^{18}O$ in precipitation can fluctuate seasonally and even within specific storms, which can cause short-term fluctuations of $\delta^{18}O$ concentrations in groundwater, particularly in areas of rapid recharge.

Saturation indices with respect to various mineral phases also are used as indicators of groundwater source areas and flow paths, particularly in geochemical environments dominated by carbonate rocks (Freeze and Cherry, 1979). Saturation indices are a measure of the ability of water to dissolve or precipitate various minerals, such as calcite or dolomite. For example, groundwater with a calcite saturation index less than zero is undersaturated with respect to calcite and has the capacity to dissolve additional calcite. Groundwater with a calcite saturation index greater than zero is oversaturated with respect to calcite and has the potential to precipitate calcite. Groundwater having a calcite saturation index of zero is in thermodynamic equilibrium with calcite. Mineral saturation is affected by many different factors, including temperature, pressure, aquifer lithology, and the concentrations and species of all ions present in solution. Differences in saturation indices with depth or geographic location in an aquifer often are used as evidence either for different source areas or for geochemical evolution of the water along groundwater-flow paths.

Environmental isotopes

The ^3H concentrations in groundwater sampled in the three test wells ranged from less than 0.8 to 4.8 TU (table 4). On the basis of qualitative age relations (table 3), groundwater sampled from all isolated intervals in wells OU-416 and OU-418 was at least 30 years old. Groundwater sampled in well OU-417 was at least 20 years old 82 ft below land surface and at least 30 years old below that depth.

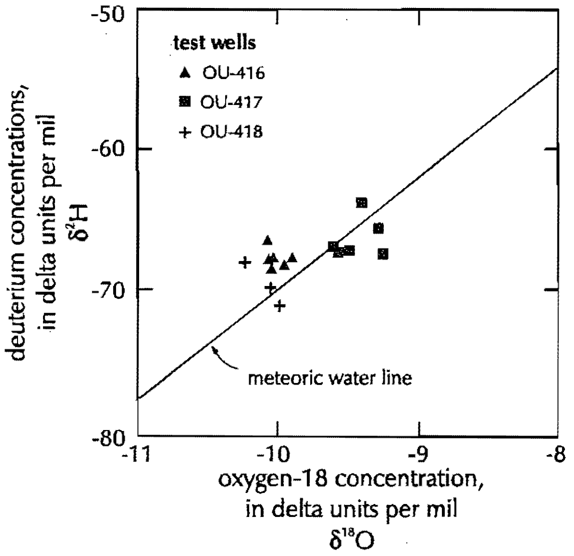

Figure 5. *Relationship of oxygen-18 to deuterium concentrations in water from three test wells, September and October 1992.*

Oxygen-18 in water from the three test wells ranged from -9.30 to -10.24 per mil, which is similar to the composition of precipitation falling on the study area. The $\delta^{18}O$ values showed no apparent trend with depth in any of the three test wells. The relationship of $\delta^{18}O$ to δ^2H (fig. 5) shows that the groundwater samples from Outagamie County fall (within analytical error) along the global meteoric water line. Differences in the mean $\delta^{18}O$ content of water between wells probably resulted from differences in the source area of water in each well. Secondary geochemical processes, such as evaporation of recharge or high-temperature rock–water interactions, have apparently not occurred in the study area.

A small but significant difference was found between the groundwater yielded by the middle well (OU-417) and groundwater sampled in the other two wells. The mean $\delta^{18}O$ concentration in water from well OU-417 was -9.4 per mil (table 4); water samples from wells OU-416 and OU-418 had mean concentrations of $\delta^{18}O$ of -10.0 and -10.1 per mil, respectively. The mean difference of about -0.6 per mil is significant as shown by the small standard deviations, but the cause of this difference is unclear.

Mineral saturation indices

Mineral saturation indices calculated from chemical analyses of water from the test wells mainly reflect the lithology of the geologic units in each isolated interval. Saturation indices for calcite and dolomite and partial pressures of carbon dioxide were calculated with the computer code PHREEQE (Parkhurst and others, 1980). Groundwater at each test site was in equilibrium with respect to calcite and dolomite (fig. 6). The relatively consistent saturation indices with depth and between wells suggest that water from various stratigraphic intervals at each site has undergone similar geochemical reactions along flow paths to the well.

REGIONAL GROUNDWATER FLOW SYSTEM

The test wells provided data about groundwater flow, and about the thickness, extent, and hydraulic properties of aquifers and confining units in the western part of the study area. Available information on these flow-system components in the Green Bay metropolitan area was presented by Krohelski (1986). The information from these two sources is combined in the following sections to provide a comprehensive description of the regional groundwater flow system between the Wolf and Fox Rivers.

Aquifers and confining units

Krohelski (1986) identified three aquifers and three confining units in the conceptual design of the groundwater-flow model for the Green Bay area (fig. 7). The upper (water-table) aquifer is unconfined. The middle (St. Peter) and lower (Elk Mound) aquifers are confined. The Sinnipee confining unit separates the upper from the middle aquifer, and the St. Lawrence–Tunnel City confining unit separates the middle from the lower aquifer. The Precambrian confining unit forms a lower boundary to the system. The St. Peter and

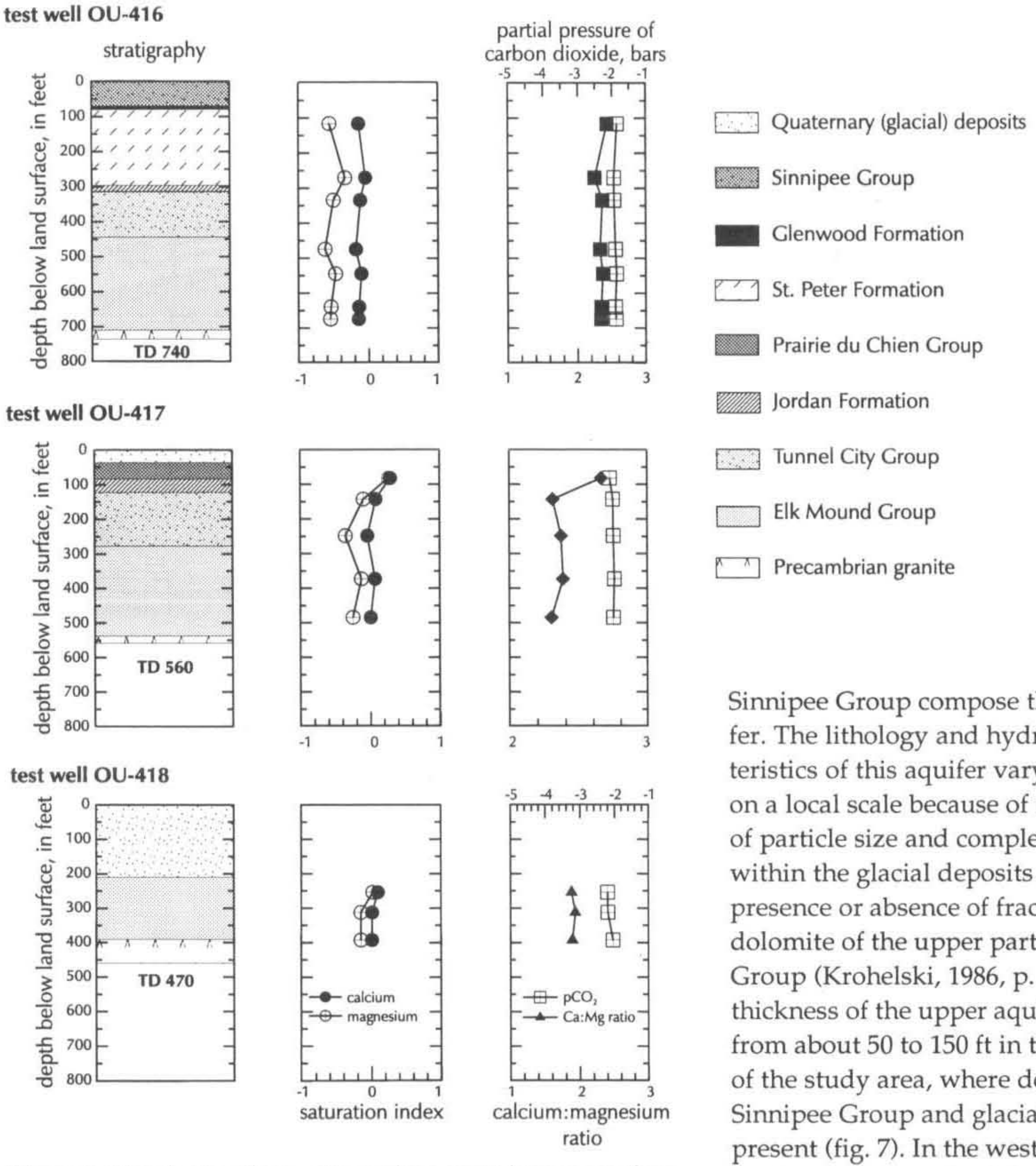

Figure 6. Distribution of saturation indices, partial pressures of carbon dioxide, and calcium:magnesium ratios with depth in three test wells, September and October 1992.

Elk Mound aquifers, separated by the St. Lawrence–Tunnel City confining unit, constitute what is commonly referred to as the sandstone aquifer.

Lithology and areal distribution

Undifferentiated glacial deposits and weathered or fractured dolomite in the upper part of the Sinnipee Group compose the upper aquifer. The lithology and hydrologic characteristics of this aquifer vary considerably on a local scale because of the wide range of particle size and complex layering within the glacial deposits as well as the presence or absence of fracturing in the dolomite of the upper part of the Sinnipee Group (Krohelski, 1986, p. 11). The overall thickness of the upper aquifer ranges from about 50 to 150 ft in the eastern half of the study area, where dolomite of the Sinnipee Group and glacial deposits are present (fig. 7). In the western part of the study area where the dolomite is absent, glacial deposits exceed 200 ft in thickness and constitute the entire upper aquifer. In the middle of the study area, near test wells OU-416 and OU-417 (fig. 7), the Sinnipee Group dolomite is absent and only a thin mantle of glacial deposits overlies the lower (older) bedrock units. Here, the upper aquifer is generally less than 50 ft thick. In the upland west of test well OU-416, the St. Peter Formation or Prairie du Chien Group crops out or is within 20 ft of land surface. In this area, the water table (top of

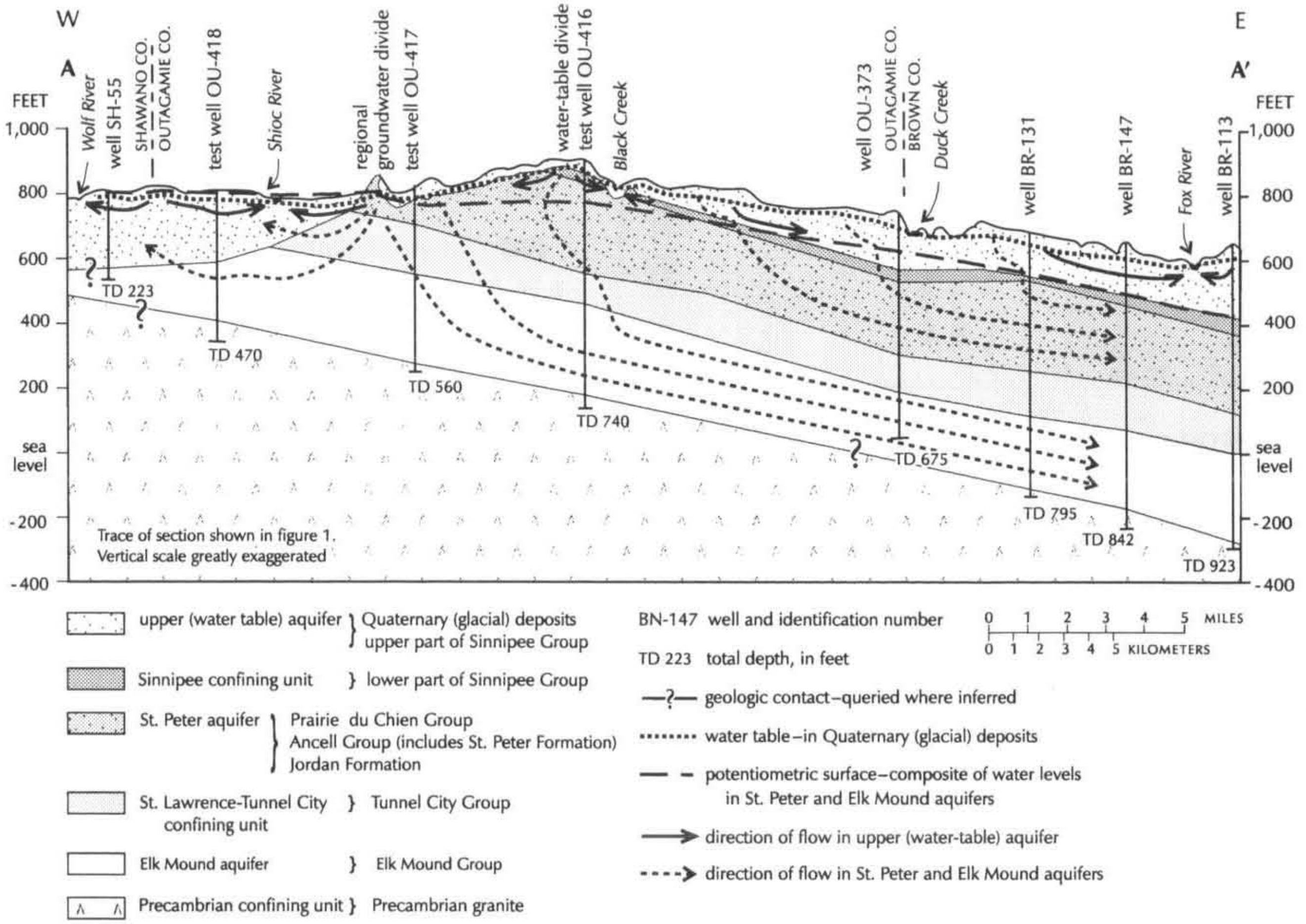

***Figure 7.** Hydrogeologic section from the Wolf River to the Fox River in east-central Wisconsin, based on test-well data collected in 1992.*

the upper aquifer) probably lies in these bedrock units.

The lower part of the Sinnipee Group is a confining unit in the eastern half of the study area (fig. 7), and Krohelski (1986) simulated it as such in his 1986 groundwater-flow model. The interpretation as a confining unit was based on lack of weathering and fractures in exposed quarry walls in the Brown County area, the presence of the Decorah Formation (not shown), which is a thin (less than 20 ft), shaly layer in the middle of the Sinnipee Group, and the results of aquifer tests (Krohelski, 1986, p. 11). The thickness of this unit varies from about 50 to 75 ft and is somewhat arbitrarily assumed to be half the total thickness of the Sinnipee Group (J.T. Krohelski, U.S. Geological Survey, verbal communication, 1993). Clayey and silty layers (not shown) within the thick sequence of glacial deposits very likely form an effective confining unit in the western half of the study area, and restrict the hydraulic connection between any shallow sand and gravel layers (not shown) and the underlying Elk Mound aquifer.

The St. Peter aquifer consists of the Ancell Group, the Prairie du Chien Group, and the Jordan Formation (fig. 7; Krohelski, 1986). This aquifer lies below the Sinnipee confining unit and above the St. Lawrence–Tunnel City confining unit. The Ancell Group (which includes the St. Peter Formation) and the Jordan Formation are primarily sandstones, and the Prairie du Chien Group is mostly weathered dolomite. The thickness of the St. Peter aquifer ranges from about 200 to 250 ft throughout the area where it is present. However, thicknesses of specific units can vary greatly over short distances. The St. Peter thins near the middle of the area and is absent in the western part of the study area, as shown by test wells OU-417 and OU-418 (figs. 2 and 7). In the upland area between test wells OU-416 and OU-417, where the Ancell and Prairie du Chien Groups are very near land surface (fig. 7), the St. Peter aquifer is not confined.

The second confining unit, designated by Krohelski (1986) as the St. Lawrence–Tunnel City confining unit, consists of the St. Lawrence Formation and the Tunnel City Group (fig. 7). Together, these units are about 150 ft thick and are mostly silty, shaly dolomite. This confining-unit designation is based primarily on lithologic descriptions from well constructor's reports in the Green Bay area because no aquifer-test data specifically for this unit are available. Krohelski (1986) estimated that, because of the relatively fine-grained texture of the rocks in this unit, the horizontal hydraulic conductivity of the unit as a whole is probably an order of magnitude lower than the overlying St. Peter aquifer and the underlying Elk Mound aquifer in the Green Bay area.

The St. Lawrence Formation was not present in any of the three test wells (fig. 4). The Tunnel City Group, however, was present at test wells OU-416 and OU-417. The Tunnel City Group, as seen in drill cuttings at these two sites, is a silty sandstone and is not shaly or dolomitic as it is in the Green Bay area.

The third aquifer specified by Krohelski (1986) is the Elk Mound aquifer (fig. 7). It consists of undifferentiated sandstone units of variable grain sizes, and it has a fairly uniform thickness of about 200 to 300 ft over most of the study area (fig. 7). However, its thickness diminishes to about 100 ft along the extreme western edge of the section shown in figure 7, and it is completely absent in some areas (not shown) in the southwestern part of the study area (LeRoux, 1957). In these areas, glacial deposits directly overlie Precambrian granite.

Hydraulic characteristics

Values of hydraulic conductivity and transmissivity of the aquifers and confining units used in the groundwater-flow model (Krohelski, 1986) are shown in table 5. These values are based on geologic and aquifer-test data from wells in the Green Bay metropolitan area and on results of the calibration process used in developing the groundwater-flow model (Krohelski, 1986). Two important facts should be noted from table 5: (1) the vertical hydraulic conductivity of the two confining units is generally three to five orders of magnitude less than the average horizontal hydraulic conductivity of the three aquifers, and (2) the minimum thickness of each aquifer and confining unit is zero (that is, the unit is absent) in some places.

Horizontal hydraulic conductivity of the St. Peter and Elk Mound aquifers determined from pumping the test wells (table 2) is fairly similar to that used for the Green Bay area in the groundwater-flow model (table 5), with some minor exceptions. The horizontal hydraulic conductivity value of 16.3 ft/d calculated for the upper part of the St. Peter aquifer in test well OU-416 is about 8 to 10 times higher than values used in the groundwater-flow model. However, the tested interval only includes the St. Peter Formation; the model simulation also includes Prairie du Chien dolomite, in which the lower horizontal hydraulic conductivity is less than that of the St. Peter Formation. The lower part of the St. Peter Formation has a horizontal hydraulic conductivity of only 1.9 ft/d, as

Table 5. Hydraulic characteristics of aquifers and confining units in Green Bay metropolitan area, Wisconsin

Hydrologic unit	Thickness (ft)	Horizontal hydraulic conductivity (ft/d)	Vertical hydraulic conductivity (ft/d)	Transmissivity (ft^2/d)	Remarks
Upper aquifer	0–150	3.0–8.0	—	0–1,200	None
Sinnipee confining unit	0–100	—	0.003–0.00007	—	None
St. Peter aquifer	0–300	1.6–2.4	—	0–720	Greatest horizontal hydraulic conductivity in areas where St. Peter Formation predominates.
St. Lawrence-Tunnel City confining unit	0–300	—	0.003–0.00004	—	Greatest vertical hydraulic conductivity where unit subcrops.
Elk Mound aquifer	0–500	2.4	—	1,200	None

—, not determined
Source: Krohelski (1986).

estimated from pumping test on test well OU-416. This interval contains some fine-grained silty and shaly layers that typically have lower hydraulic conductivities than sandstone. The horizontal hydraulic conductivities of the lower part of the Elk Mound aquifer estimated by pumping test wells OU-416 and OU-417 are about 1.4 ft/d and 4.7 ft/d, respectively (table 2), and are similar to the model simulation value of 2.4 ft/d (table 5). The horizontal hydraulic conductivity of the Elk Mound aquifer apparently increases toward the west in the study area (from 4.7 ft/d in OU-417 to 23.2 ft/d in OU-418).

Possibly the most important finding of the specific-capacity testing is the high (3.1 to 12 ft/d) horizontal hydraulic conductivity of the Tunnel City Group, considered a confining unit in the Green Bay area (Krohelski, 1986). These values are as large or even larger than values of some parts of the St. Peter and Elk Mound aquifers that were tested (table 2), and probably occur because the Tunnel City Group, a silty or shaly dolomite in the Green Bay area (Krohelski, 1986), is a silty sandstone at the sites of test wells OU-416 and OU-417. This means that the Tunnel City Group is an aquifer and increases the overall thickness of the sandstone aquifer in the central and western parts of the study area.

Groundwater flow

Water-level (hydraulic-head) data from several sources were interpreted to show, in map view, the potentiometric surface of the sandstone aquifer and the general direction of groundwater flow between the Wolf and Fox Rivers (fig. 8). The vertical and horizontal flow of groundwater through aquifers and confining units of the sandstone-aquifer system is shown in cross-sectional view in figure 7. The location of a regional divide (fig. 8) separating groundwater flow between the Wolf and Fox Rivers was also determined from the hydraulic-head distribution. The divide represents the western boundary of groundwater flow in the sandstone aquifer toward the Green Bay metropolitan area.

Composite hydraulic-head measurements in the three test wells were combined with composite hydraulic heads measured in 1990 in selected high-capacity wells in the Green Bay metropolitan area (J. T. Krohelski, written communication, 1992) and with historic reported water levels from selected wells in the western part of the study area to develop the map of the potentiometric surface (fig. 8). For purposes of discussion, it is assumed that all these measurements reasonably approximate water-level conditions in 1992. The altitude of the potentiometric surface ranges

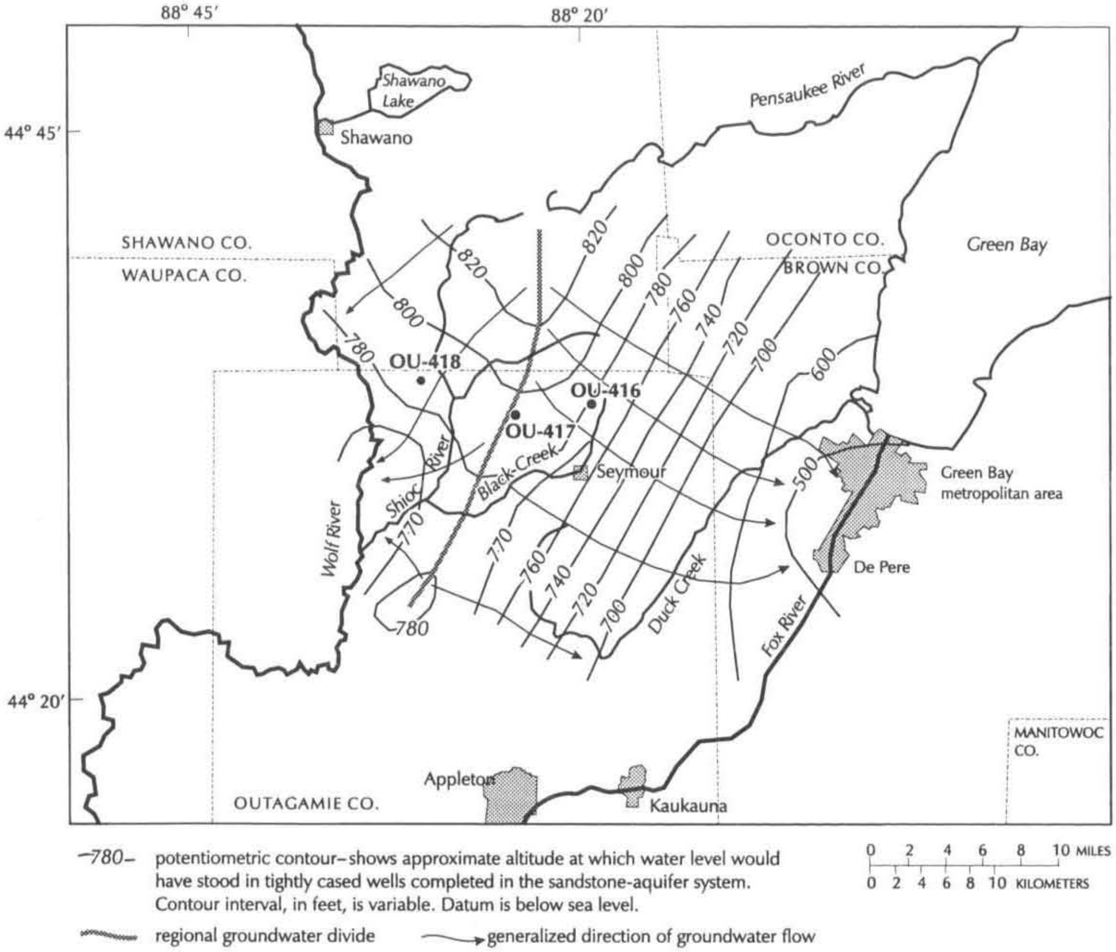

Figure 8. *Potentiometric surface of the sandstone-aquifer system, east-central Wisconsin, 1992.*

from more than 820 ft above sea level in Shawano County (fig. 8) to less than 500 ft in the Green Bay metropolitan area. West of the divide, the altitude of the potentiometric surface ranges from more than 820 ft to just less than 770 ft above sea level along the Wolf River. Much of the total decline of more than 300 ft east of the divide (as compared to slightly more than 50 ft west of the divide) is related to the cone of depression developed from pumpage in the Green Bay metropolitan area. The general direction of flow east of the groundwater divide is east–southeast toward the Green Bay area (fig. 8). The general direction of flow west of the divide is southwest toward the Wolf River and adjacent wetlands. However, a fairly large north–south component of groundwater flow is indicated near the divide north of Black Creek; south of Black Creek is a potentiometric high, providing some flow to the northwest.

Environmental-isotope data from test-well water samples were consistent with the above interpretations and with water-level conditions in the sandstone aquifer in the Green Bay metropolitan area simulated with the 1986 groundwater-flow model (Krohelski, 1986). The isotopic composition of water from the three test wells is consistent with the presence of a groundwater divide at the location shown in figure 8. Groundwater reaching test well OU-417 from the region of the divide is younger than water reaching the other two test wells because of the shorter distance it travels. Tritium data also showed that water in all three test wells has been in the subsurface for at least 30 years, which supports the location of a recharge area located north of the three test wells. The relatively recent recharge (as determined from $\delta^{18}O$) is evidence against a distant recharge area west of the Wolf River. Furthermore, $\delta^{18}O$ and $\delta^{2}H$ data (table 4; fig. 5) suggest a different recharge area for water sampled from test well OU-417 than for the other two wells. The hydraulic-head distribution shown in figure 8 indicates a more southern area of recharge for test well OU-417.

Arrows on figure 8 depict the general horizontal direction of groundwater flow in the St. Peter and Elk Mound aquifers, which make up the sandstone aquifer. Water recharging the upper aquifer flows along relatively short flow paths and discharges to lowlands and streams such as Black Creek (fig. 7). However, some water leaks vertically from the upper aquifer through the Sinnipee confining unit to the underlying St. Peter aquifer (fig. 7), through which it moves laterally toward the Fox River and well fields in the Green Bay area. Vertical flow through the Sinnipee confining unit is driven by the difference in hydraulic head between the water table in the upper aquifer and the potentiometric surface in the St. Peter aquifer. In the eastern part of the study area, where the water table is higher than the potentiometric surface in the St. Peter and Elk Mound aquifers (fig. 7), vertical flow is downward to the St. Peter aquifer. Water reaching the St. Peter aquifer through the Sinnipee confining unit flows along paths of intermediate length (fig. 7) toward the Green Bay area. Groundwater-flow model results (Krohelski, 1986) indicate hydraulic heads in the St. Peter aquifer are higher than hydraulic heads in the Elk Mound aquifer in the immediate Green Bay area, where some water in the St. Peter aquifer probably flows downward through the St. Lawrence–Tunnel City confining unit to the Elk Mound aquifer. However, no water-level data are available from the Green Bay area to confirm this.

Most groundwater flow in the Elk Mound aquifer is along relatively long flow paths that originate near the middle of the study area just east of the regional groundwater divide (fig. 7) in the vicinity of test wells OU-416 and OU-417. The Sinnipee confining unit is absent in this area and test-well data indicated that the St. Lawrence–Tunnel City Group, previously considered to be a confining unit, is actually an aquifer. Therefore, flow paths in the St. Peter aquifer and all underlying units are not strongly refracted across the aquifer boundaries, and vertical and horizontal flow takes place in the St. Lawrence–Tunnel City aquifer.

In the western part of the study area, the potentiometric surface in the Elk Mound aquifer is slightly higher than the water table (fig. 7). In this area, water recharges the upper aquifer in upland areas and moves downward to the St. Peter and Elk Mound aquifers and moves westward and southward, discharging to the Wolf River and adjacent wetlands.

The regional groundwater divide (fig. 8) is the western edge of the principal recharge area for the sandstone aquifer in the Green Bay area. The Sinnipee confining unit (fig 7), where present, limits vertical flow of groundwater to the underlying St. Peter and Elk Mound aquifers in the eastern part of the study area. Where the Sinnipee confining unit is absent (fig. 7), a relatively larger volume of water flows vertically and reaches the St. Peter aquifer. Therefore, the area west of the edge of the Sinnipee confining unit and east of the regional groundwater divide (fig. 9; the subcrop of the St. Peter aquifer beneath the glacial deposits) represents the principal recharge area for the sandstone aquifer in the Green Bay area. Water recharges the sandstone aquifer within this area, and moves eastward toward Green Bay.

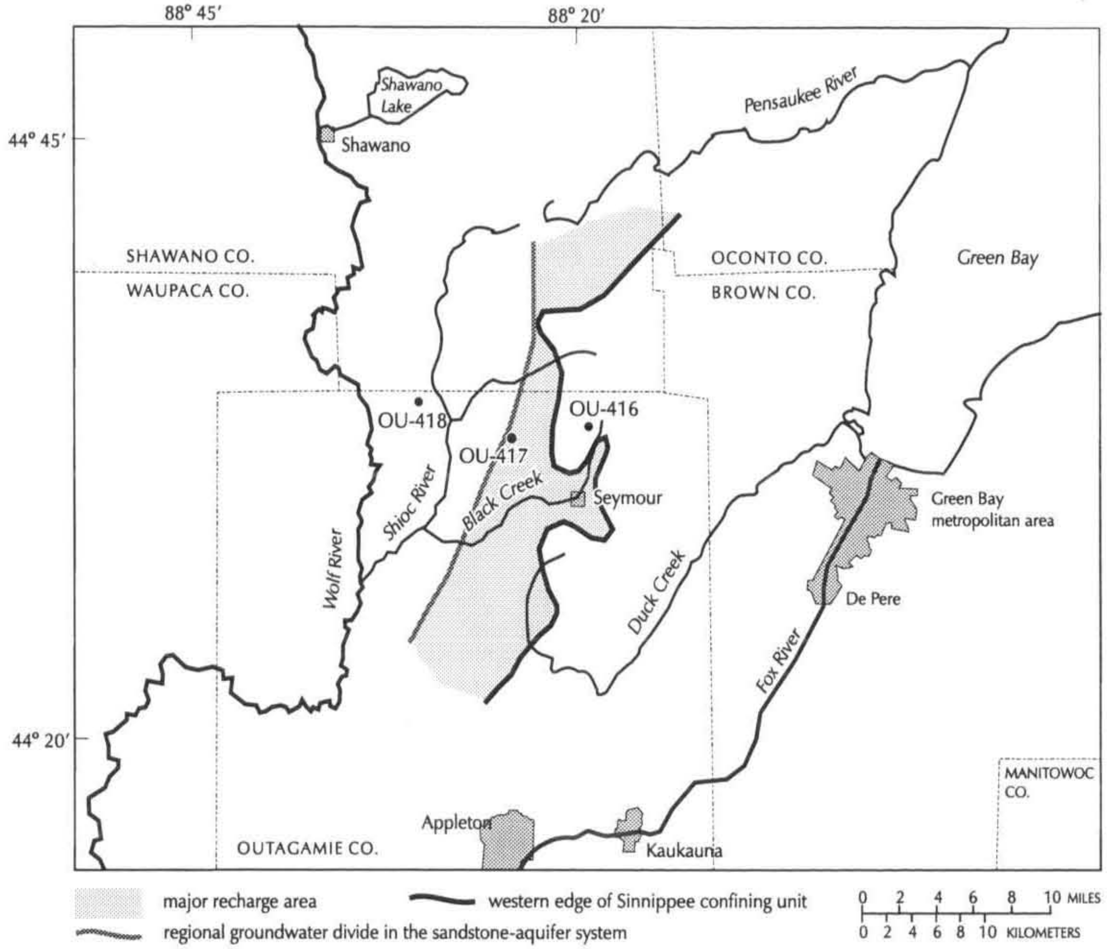

Figure 9. Major recharge area for the sandstone-aquifer system in the Green Bay metropolitan area, Wisconsin.

GENERAL GROUNDWATER QUALITY

Water samples from the isolated zones in each well were analyzed to determine concentrations of common ions, arsenic, and several trace metals. Common ions, including chloride and nitrate, provide useful information about the general quality of groundwater in the sandstone aquifer in the western part of the study area. Concentrations of arsenic and trace metals were determined to address potential health-risk concerns. Arsenic is of particular concern because the test wells are located in an area where arsenic is commonly found in groundwater.

Major ions

The chemical composition of groundwater at each test-well site is suitable for most domestic, agricultural, and industrial uses. Calcium, magnesium, and bicarbonate are the major ions in water from all three test wells. The three test wells were sampled in September and October, 1992 (appendixes 2 and 3); the results are summarized in table 6. Groundwater in each of the three wells is a calcium–magnesium bicarbonate type, as would be expected in a geologic terrain dominated by dolomite, limestone, and sandstone. Concentrations of most constituents varied only slightly with depth in the wells tested (fig. 10), and groundwater appears to be well mixed vertically. Sodium, potassium, and sulfate were present only in very small concentrations. The total hardness as $CaCO_3$ of water from all water samples was greater than 200 mg/L; such water

Table 6. Statistical summary of the chemistry of water sampled from various depth increments in three test wells, September and October 1992

	Test well OU-416 (n=7)		**Test well OU-417** (n=6)		**Test well OU-418** (n=3)	
	Mean	**Standard deviation**	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**
Specific conductance, µS/cm at 25°C	716	8.0	786	40.4	676	58
pH	7.3	0.03	7.4	0.06	7.5	0.05
Temperature (°C)	9.5	0	9.5	0.5	9.5	0
Dissolved oxygen (mg/L)	1.9	0.5	1.4	1	—	—
Hardness as $CaCO_3$ (mg/L)	266	3.2	280	17.8	246	1.6
Dissolved solids as $CaCO_3$ (mg/L)	402	13.8	430	27.5	406	22.7
Calcium (mg/L)	63	1.3	66	5.8	53	0
Magnesium (mg/L)	27	0	28	0.8	28	1
Sodium (mg/L)	<0.6	—	1.4	0.3	7.0	0.2
Potassium (mg/L)	<0.6	—	<0.6	—	<0.6	—
Sulfate (mg/L)	5.8	2.3	6.0	4.3	9.5	0
Chloride (mg/L)	0.9	0.3	1.5	0.9	5.3	0.2
Nitrate as nitrogen (mg/L)	0.4	0.3	<0.5	0	0.2	0.2
Arsenic (µg/L)	13	12	<10	8	<10	0
Iron (µg/L)	31	54	399	248	613	307
Manganese (µg/L)	0.003	0.002	0.005	0.003	0.011	0.004
Bicarbonate (mg/L)	306	13.2	327	20.7	303	22.4

is commonly classified as "very hard" (Hem, 1985, p. 159).

Chloride and nitrate concentrations in all water samples were very small (table 6; appendix 2). Chloride and nitrate are common mobile constituents found in human and animal wastes, fertilizers, and road salt (chloride). The three test wells are in an agricultural region where sources of chloride and nitrate are expected to be present at the land surface. However, the small concentrations of these two chemical constituents in groundwater indicate that near-surface sources are not contributing water to the deeper aquifers at each site.

Arsenic and trace metals

Small concentrations of arsenic, less than 10 to 34 µg/L, were measured in water samples from two of the three wells sampled (wells OU-416 and OU-417). Arsenic was detected at depths ranging from 100 to 700 ft below the land surface (fig. 11). No samples exceeded the drinking-water standard for arsenic of 50 µg/L in Wisconsin, although seven samples exceeded the preventive action limit (PAL) of 5 µg/L in Wisconsin. Arsenic in water from these wells does not appear to be associated with any particular depth or geologic formation.

Arsenic has been detected in water from many wells in northeastern Wisconsin; Mudrey and Bradbury (1993) showed a region of arsenic detections extending northeast from Winnebago and Outagamie Counties along the western side of Green Bay toward the Upper Peninsula of Michigan (fig. 12). Although the origin of the arsenic is unclear, its widespread occurrence and its association with isotopically old groundwater (discussed earlier) and with small concentrations

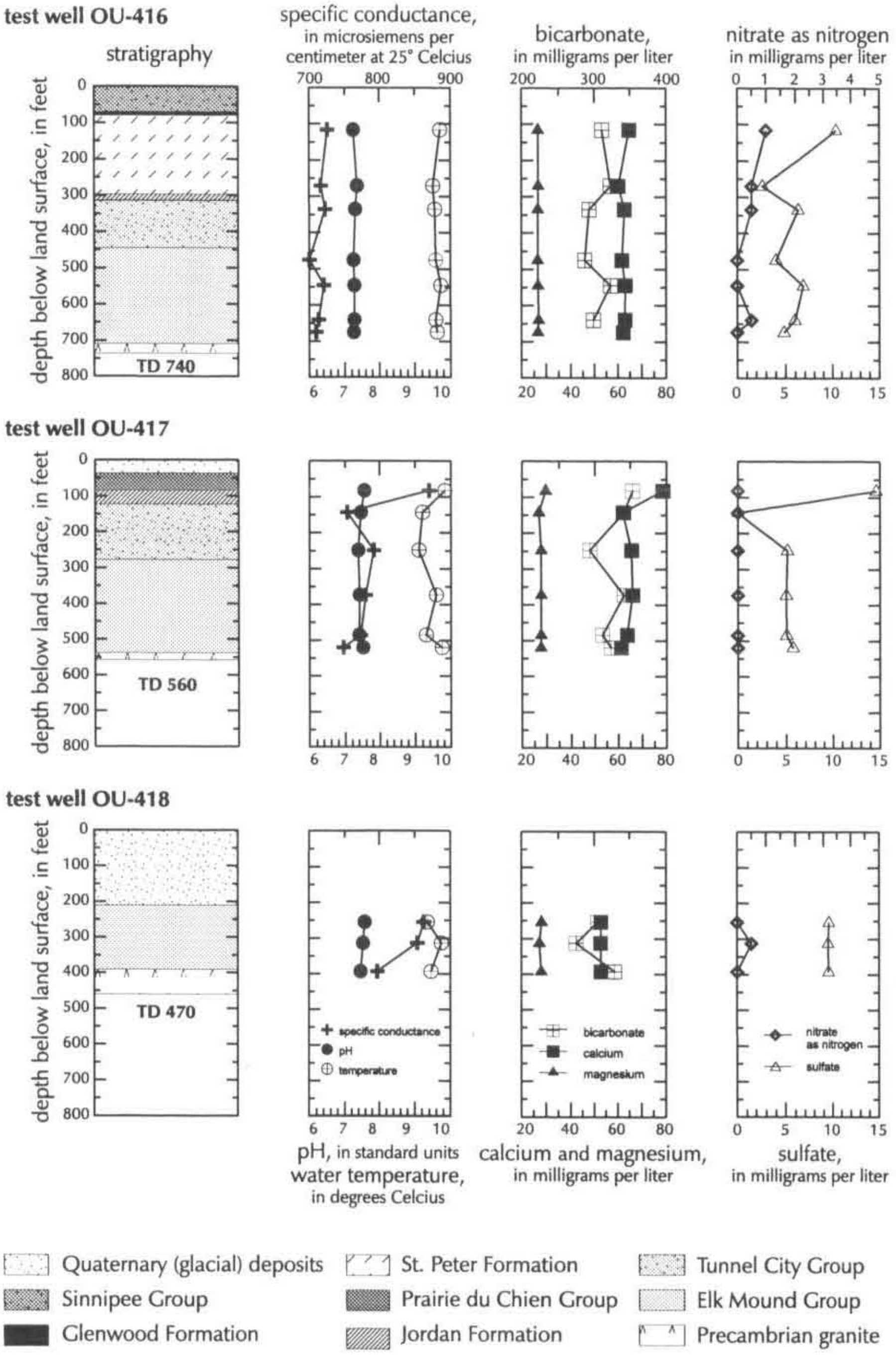

Figure 10. Comparisons of major chemical constituent concentrations in groundwater and stratigraphy in three test wells, September and October 1992.

of other constituents suggest that the arsenic is a natural component in the sandstone-aquifer system.

With the exception of arsenic, groundwater produced by the three test wells does not contain measurable quantities of the trace elements selected for analysis (aluminum, boron, cadmium, chromium, copper, lead, lithium, phosphorus, selenium, and zinc). Laboratory detection limits

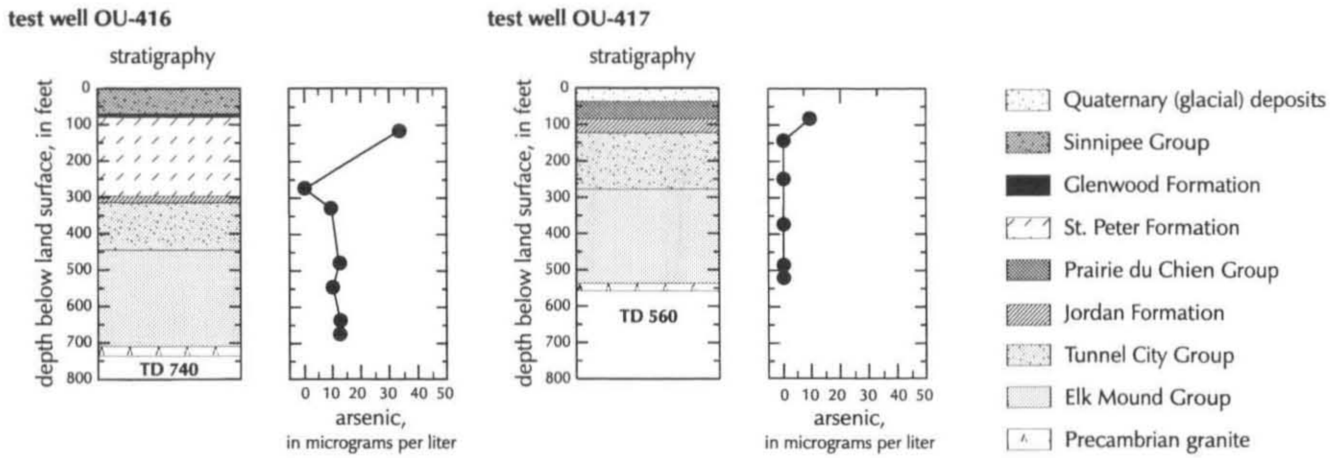

Figure 11. *Distribution of dissolved arsenic in relation to depth and stratigraphy in test wells OU-416 and OU-417, September and October 1992.*

and drinking-water standards are summarized in table 7.

SUMMARY

Hydrogeologic data collected from three test wells in northern Outagamie County, Wisconsin, during September and October 1992 indicated the location of a regional groundwater divide in the sandstone aquifer between the Wolf and Fox Rivers west of the Green Bay, Wisconsin, metropolitan area. This finding, along with measurements of hydraulic head and horizontal hydraulic conductivity in isolated intervals of the test-well boreholes, permitted a description of groundwater flow in the sandstone-aquifer system.

Geologic logs from the three test wells showed that the sandstone-aquifer system has a fairly uniform thickness of about 550 to 650 ft in the eastern two-thirds of the 20- by 30-mi study area. Upper bedrock units thin and become absent in the western third of the study area near the Wolf River, where only the Elk Mound aquifer (the lowest unit of the sandstone-aquifer system) is present and has a thickness of about 200 ft. The Sinnipee confining unit, which overlies the sandstone-aquifer system in the eastern two-thirds of the study area, is absent in the western third.

Table 7. *Trace elements analyzed for but not detected in water samples from three test wells, September and October 1992*

Element	Detection limit ($\mu g/L$)	Drinking-water standard	Source of drinking standard ($\mu g/L$)
Aluminum	352	50	Hem, 1985
Boron	29	100	Hem, 1985
Cadmium	10	10	Chapter NR 140, Wisconsin Administrative Code
Chromium	17	50	Chapter NR 140, Wisconsin Administrative Code
Copper	25	1,000	Hem, 1985
Lead	111	50	Chapter NR 140, Wisconsin Administrative Code
Lithium	25	—	no standard
Phosphorus	217	—	no standard
Selenium	190	10	Chapter NR 140, Wisconsin Administrative Code
Zinc	10	5,000	Hem, 1985

Downward groundwater gradients, typical of recharge areas, were observed in two of the test wells located in upland areas. Hydraulic head declined a total of 37 ft from the top to the bottom of the borehole in one test well and about 15 ft in the other. There was a slight upward hydraulic gradient in the sandstone-aquifer system observed in test well OU-418, located nearest the Wolf River, which is typical of conditions in a groundwater discharge area. Groundwater flow is nearly horizontal in the lower part of the sand-

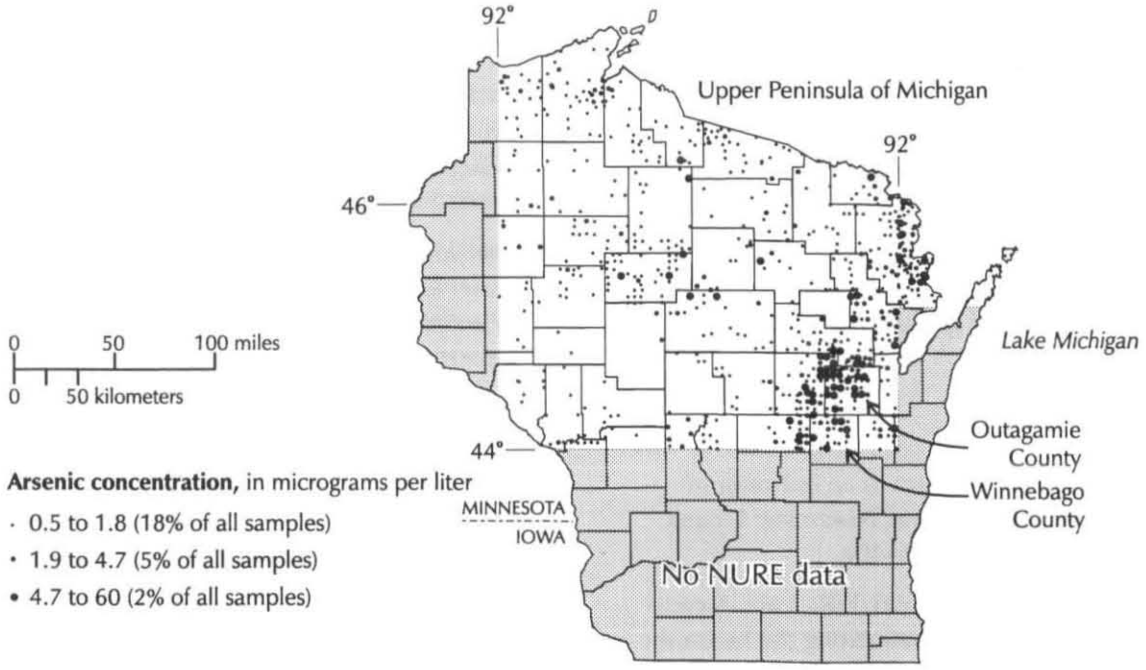

Figure 12. Distribution of dissolved arsenic in groundwater in Wisconsin based on data collected by the National Uranium Resources Evaluation (NURE) project in mid-1970s (modified from Mudrey and Bradbury, 1993).

stone-aquifer system; most of the hydraulic-head decline in the two eastern test wells was in the upper part of the core from the borehole. Composite hydraulic-head measurements from the three test wells combined with water-level measurements from available wells were intrepreted to indicate that groundwater flows eastward from the groundwater divide toward the Green Bay area in the eastern two-thirds of the study area and flows westward from the groundwater divide toward the Wolf River in the western third of the study area. Isotopes of oxygen and hydrogen, used to determine the age and direction of groundwater flow, further support this pattern of groundwater flow in the sandstone-aquifer system.

The horizontal hydraulic conductivity of specific units in the sandstone-aquifer system ranged from 1.4 to about 23 ft/d, as determined from specific-capacity tests. These values are similar to those determined from historical aquifer tests in the Green Bay area; however, two differences are apparent. The horizontal hydraulic conductivity of the Elk Mound aquifer, in the lower part of the sandstone-aquifer system, increased from 1.4 ft/d in the eastern test well (OU-416) to about 23 ft/d in the western test well (OU-419). Also, three horizontal hydraulic-conductivity values determined for the Tunnel City Group ranged from about 3 to 12 ft/d—within the range of values for aquifers rather than for confining units (which the Tunnel City was previously considered to be). Therefore, it appears that the Tunnel City Group is an aquifer in the western part of the study area, not a confining unit that restricts vertical groundwater flow between the overlying St. Peter and underlying Elk Mound aquifers.

The principal recharge area for the sandstone-aquifer system in the Green Bay area is 2- to 4-mi wide and extends from north to south through the middle of Outagamie County. The western edge of the recharge area is the groundwater divide. Groundwater recharging the sandstone-aquifer system east of this divide flows toward Green Bay. The eastern limit of the recharge area coincides with the western extent of the Sinnipee confining unit. Where present in the eastern part of the study area, the Sinnipee confining unit restricts vertical flow of groundwater to the underlying St. Peter aquifer.

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APPENDIXES

Appendix 1. Geochemical indicator constituents in water samples collected from three test wells in Outagamie County, Wisconsin, September and October 1992

Test well (fig. 1)	Date sampled	Depth to top packer (ft)	Depth to bottom packer (ft)	Depth to midpoint of packed interval (ft)	Specific conductance (μS/cm at field temperature)	Specific conductance (μS/cm at 25°C)	pH	Temperature (°C)	Dissolved oxygen (mg/L)
OU-416	9/22/92	80	211	145.5	504	726	7.2	9.5	2.4
	9/22/92	238	301	269.5	495	716	7.4	9.5	2.2
	9/23/92	303	366	334.5	500	723	7.3	9.5	1.6
	9/23/92	443	506	474.5	485	701	7.3	9.5	1.4
	9/24/92	513	576	544.5	501	721	7.3	9.5	—
	9/24/92	608	671	639.5	494	714	7.3	9.5	2.6
	9/24/92	608	740	674	492	710	7.3	9.5	1.2
OU-417	9/29/92	48	116	82	606	870	7.6	10.0	—
	9/29/92	114	172	143	516	753	7.4	9.0	1.0
	9/30/92	219	277	248	541	792	7.4	9.0	1.0
	9/30/92	344	402	373	540	780	7.4	9.5	0.5
	10/01/92	409	544	476.5	531	793	7.4	9.5	3.1
	10/01/92	479	560	519.5	520	748	7.5	9.5	—
OU-418	10/07/92	220	286	253	499	725	7.6	9.5	—
	10/07/92	289	336	312.5	492	708	7.3	9.5	—
	10/08/92	369	416	392.5	410	594	7.5	9.5	1.6

—, no measured value

Appendix 2. Major ion concentrations in water samples collected from three test wells in Outagamie County, Wisconsin, September and October 1992

Test well (fig. 1)	Date sampled	Depth to midpoint of packed interval (ft)	Dissolved calcium (mg/L)	Dissolved magnesium (mg/L)	Dissolved sodium (mg/L)	Dissolved potassium (mg/L)	Dissolved sulfate (mg/L)	Dissolved chloride (mg/L)	Dissolved nitrate as nitrogen (mg/L)	Total phosphorus (mg/L)	Dissolved iron (μg/L)	Dissolved manganese (μg/L)	Bicarbonate (mg/L)
OU-416													
	9/22/92	145.5	65	27	<0.6	<0.6	10	<0.5	1.0	<0.2	0.06	<0.003	311
	9/22/92	269.5	60	27	<0.6	<0.6	2.6	1.0	0.5	<0.2	0.15	<0.003	323
	9/23/92	334.5	63	27	<0.6	<0.6	6.3	1.0	0.5	<0.2	<0.01	<0.003	293
	9/23/92	474.5	62	27	<0.6	<0.6	4.0	1.0	<0.5	<0.2	<0.01	<0.003	286
	9/24/92	544.5	63	27	<0.6	<0.6	6.8	1.0	<0.5	<0.2	<0.01	<0.003	323
	9/24/92	639.5	63	27	<0.6	<0.6	6.0	1.0	0.5	<0.2	<0.01	<0.003	299
	9/24/92	674	62	27	<0.6	<0.6	4.9	1.0	<0.5	<0.2	<0.01	<0.003	305
OU-417													
	9/29/92	82	79	30	0.9	<0.6	15	3.0	<0.5	<0.2	0.64	0 .01	354
	9/29/92	143	62	27	1.6	<0.6	<0.10	<0.5	<0.5	<0.2	0.83	<0.003	341
	9/30/92	248	66	28	1.3	<0.6	5.1	1.5	<0.5	<0.2	0.22	<0.003	293
	9/30/92	373	66	28	1.5	<0.6	5.0	1.5	<0.5	<0.2	0.31	<0.003	341
	10/01/92	476.5	64	28	1.9	<0.6	5.1	1.5	<0.5	<0.2	0.15	0.01	323
OU-418													
	10/07/92	253	53	28	7.0	<0.6	9.6	5.5	<0.5	<0.2	1.1	0.01	305
	10/07/92	312.5	53	27	7.3	<0.6	9.5	5.0	0.5	<0.2	0.40	01	274
	10/08/92	392.5	53	28	6.8	<0.6	9.5	5.5	<0.5	<0.2	0.40	01	329

***Appendix* 3.** *Concentrations of trace elements and saturation indices in water samples collected from three test wells in Outagamie County, Wisconsin, September and October 1992*

Test well (fig. 1)	**Date sampled**	**Depth to midpoint of packed interval (ft)**	**Arsenic (µg/L)**	**Cobalt (µg/L)**	**Nickel (µg/L)**	**Zinc (µg/L)**	**pCO_2 (bars)**	**Calcite saturation index**	**Dolomite saturation index**	**Gypsum saturation index**	**Calcium: magnesium ratio**	**Radon-222 pCi/L**
OU-416	9/22/92	145.5	0.03	0.21	0.35	<0.01	-1.85	-0.15	-0.56	-2.46	2.43	—
	9/22/92	269.5	<0.01	<0.02	<0.04	<0.01	-1.94	-0.05	-0.34	-3.08	2.25	—
	9/23/92	334.5	0.01	0.09	0.15	<0.01	-1.94	-0.12	-0.51	-2.69	2.36	—
	9/23/92	474.5	0.01	0.05	0.08	<0.01	-1.89	-0.19	-0.63	-2.89	2.33	—
	9/24/92	544.5	0.01	0.09	0.17	<0.01	-1.86	-0.11	-0.48	-2.66	2.37	—
	9/24/92	639.5	0.01	0.06	0.11	<0.01	-1.90	-0.14	-0.54	-2.71	2.34	—
	9/24/92	674	0.01	0.06	0.11	<0.01	-1.88	-0.15	-0.55	-2.81	2.34	—
OU-417	9/29/92	82	0.01	0.02	<0.04	<0.01	-2.11	0.28	0.26	-2.26	2.66	—
	9/29/92	143	<0.01	<0.02	<0.04	<0.01	-2.02	0.08	-0.10	—	2.31	—
	9/30/92	248	<0.01	<0.02	<0.04	<0.01	-2.01	-0.04	-0.36	-2.76	2.37	—
	9/30/92	373	<0.01	<0.02	<0.04	<0.01	-1.98	0.07	-0.13	-2.78	2.38	—
	10/01/92	476.5	<0.01	<0.02	<0.04	<0.01	-2.01	0	-0.25	-2.78	2.30	—
	10/01/92	519.5	<0.01	<0.02	<0.04	<0.01	-2.10	0.12	0	-2.75	2.22	—
OU-418	10/07/92	253	<0.01	<0.02	<0.04	<0.01	-2.20	0.09	0.02	-2.59	1.88	430
	10/07/92	312.5	<0.01	<0.02	<0.04	<0.01	-2.19	0.01	-0.16	-2.58	1.93	290
	10/08/92	392.5	<0.01	<0.02	<0.04	<0.01	-2.05	0.01	-0.15	-2.59	1.89	740

—, not determined