# Water Quality along Selected Flowpaths in the Prairie du Chien-Jordan Aquifer, Southeastern Minnesota

By Shannon E. Smith and David A. Nemetz

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**U.S. DEPARTMENT OF THE INTERIOR**

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## Contents

# Illustrations

## Illustrations--Continued

## Tables

## Tables--Continued

## Conversion Factors

| Multiply | By | To Obtain |
|---|---|---|
| foot (ft) | 0.3048 | meter |
| mile (mi) | 1.609 | kilometer |
| foot per day (ft/d) | .3048 | meter per day |
| gallon per minute (gal/min) | .06308 | liter per second |
| degree Fahrenheit (°F) | 5/9 x (°F - 32) | degree Celsius (°C) |

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

# Water Quality along Selected Flow Paths in the Prairie du Chien-Jordan Aquifer, Southeastern Minnesota

By S.E. Smith and D.A. Nemetz

## Abstract

The Prairie du Chien-Jordan aquifer in southeastern Minnesota consists of the dolomitic Prairie du Chien Group and the underlying Jordan Sandstone. A study was conducted to characterize water-quality differences between the Prairie du Chien and Jordan parts of the aquifer, to identify the variables that appear to be responsible for these differences, and to describe the susceptibility of the Jordan part of the aquifer to contamination.

Differences in water quality between the Prairie du Chien and Jordan parts of the aquifer were investigated by sampling existing wells in six study areas in Hennepin, Dakota, Scott, and Olmsted Counties. On-site field measurements and samples for water-quality analysis were collected from 139 wells completed in the Prairie du Chien and Jordan parts of the aquifer and from overlying aquifers. Lithologic differences between the two parts of the Prairie du Chien-Jordan aquifer did not have a major effect on major-ion chemistry of water in the aquifer. Analysis of the distribution of indicator-constituent concentrations (nitrite-plus-nitrate nitrogen, chloride, and tritium) was useful in assessing the actual and potential extent of human-related contaminants in the aquifer.

In general, ground water from the Prairie du Chien part of the aquifer had higher indicator-constituent concentrations, a predominance of areas with oxidizing conditions, and shorter residence time compared to ground water from the Jordan part of the aquifer, which had ground water with lower indicator-constituent concentrations, a predominance of areas with reducing conditions, and longer residence time. Statistical analyses indicated a significant relation between the distribution of indicator-constituent concentrations and the following variables: well grouting, total depth of the well, and the presence of the overlying Decorah Shale. The thickness and composition of the overlying glacial drift was shown to be significantly related to nitrite-plus-nitrate nitrogen concentrations but not to chloride and tritium concentrations. Land use was not significantly related to the distribution of indicator-constituent concentrations in the Prairie du Chien-Jordan aquifer.

## Introduction

The Prairie du Chien-Jordan aquifer consists of the dolomitic Prairie du Chien Group and the underlying Jordan Sandstone. The aquifer extends throughout southeastern Minnesota and is the major water-supply aquifer for this region of the state (fig. 1). In the seven-county Minneapolis-St. Paul metropolitan area, 50 percent of the total water supply and 80 percent of the ground-water supply withdrawn for domestic, industrial, and municipal use comes from the Prairie du Chien-Jordan aquifer (Schoenberg, 1990). Throughout southeastern Minnesota, about 60 percent of total ground-water withdrawals are from this aquifer (Trotta, 1987).

Increased understanding of ground-water contamination has led to concern about water quality within the Prairie du Chien-Jordan aquifer. Evidence from previous studies suggests that water in the Prairie du Chien part of the aquifer may be more susceptible to contamination from human-related land-surface activity than is water in the deeper, Jordan part of the aquifer (Minnesota Pollution Control Agency, 1991; Wall and Regan, 1994; Setterholm and others, 1991). The extent of mixing between the two parts of the aquifer is not well documented. Water quality varies areally and with depth throughout the aquifer. Variables that control the concentrations of contaminants and naturally-occurring constituents in the aquifer are not well defined. Water-quality differences may result from variations in continuity and permeability of confining layers overlying the aquifer, thickness of the glacial drift, well grouting, ground-water residence time, and land use. An improved understanding of the variables that influence the concentrations of chemical constituents can allow for better management of the resource.

The U.S. Geological Survey (USGS), in cooperation with the Legislative Commission on Minnesota

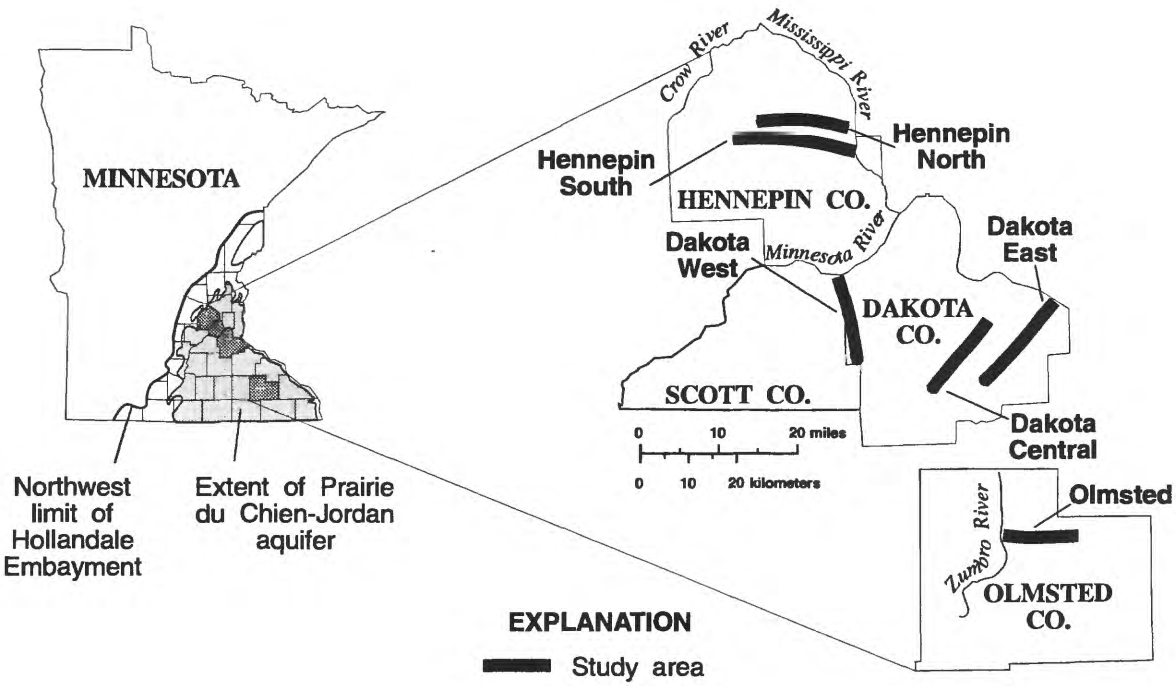


**Figure 1.--Location of study areas and the extent of the Prairie du Chien-Jordan aquifer, southeastern Minnesota.**

Resources (LCMR) and the Minnesota Department of Natural Resources (MNDNR) began a study in 1989 to investigate hydrogeology and water quality of the Prairie du Chien-Jordan aquifer at selected stites in southeastern Minnesota. The objectives of the study were to: (1) characterize differences in water quality between the Prairie du Chien and Jordan parts of the aquifer, (2) identify the variables that are responsible for these differences, and (3) describe the susceptibility of the Jordan part of the aquifer to contamination.

## Purpose and Scope

This report describes the distribution of water-quality constituents in the Prairie du Chien-Jordan aquifer in areas of Hennepin, Dakota, Scott, and Olmsted Counties, Minnesota. Differences in water quality between the Prairie du Chien and Jordan parts of the aquifer were determined by collecting water samples from 139 wells in six study areas within these counties. Distributions of selected water-quality constituents were statistically compared to hydrogeology, well grouting, and land use around the wells.

## Location and Description of Study Area

Six study areas were chosen within Hennepin, Dakota, Scott, and Olmsted Counties, Minnesota (fig. 1). The study areas were established along regional ground-water flow paths through the Prairie du Chien-Jordan aquifer. These study areas are called flowtubes later in the report. Regional ground-water flow in southeastern Minnesota was described by Delin and Woodward (1984) and in Minnesota Geological Survey (MGS) county studies (Balaban, 1988 and 1989; Balaban and Hobbs, 1990). The study areas were an average of 13 miles long and 2 miles wide. Two study areas, Hennepin North (HN) and Hennepin South (HS) were located in Hennepin County (fig.2). Three study areas, Dakota West (DW), Dakota Central (DC), and Dakota East (DE), were located in Dakota County (figs. 3 and 4). One study area, (OLM), was located in Olmsted County (fig. 5). Two flow paths along geologic section lines, Olmsted North (LN) and Olmsted South (LS), were included in the OLM study area because the number of wells sampled in this area was too great to include them on one geologic section.

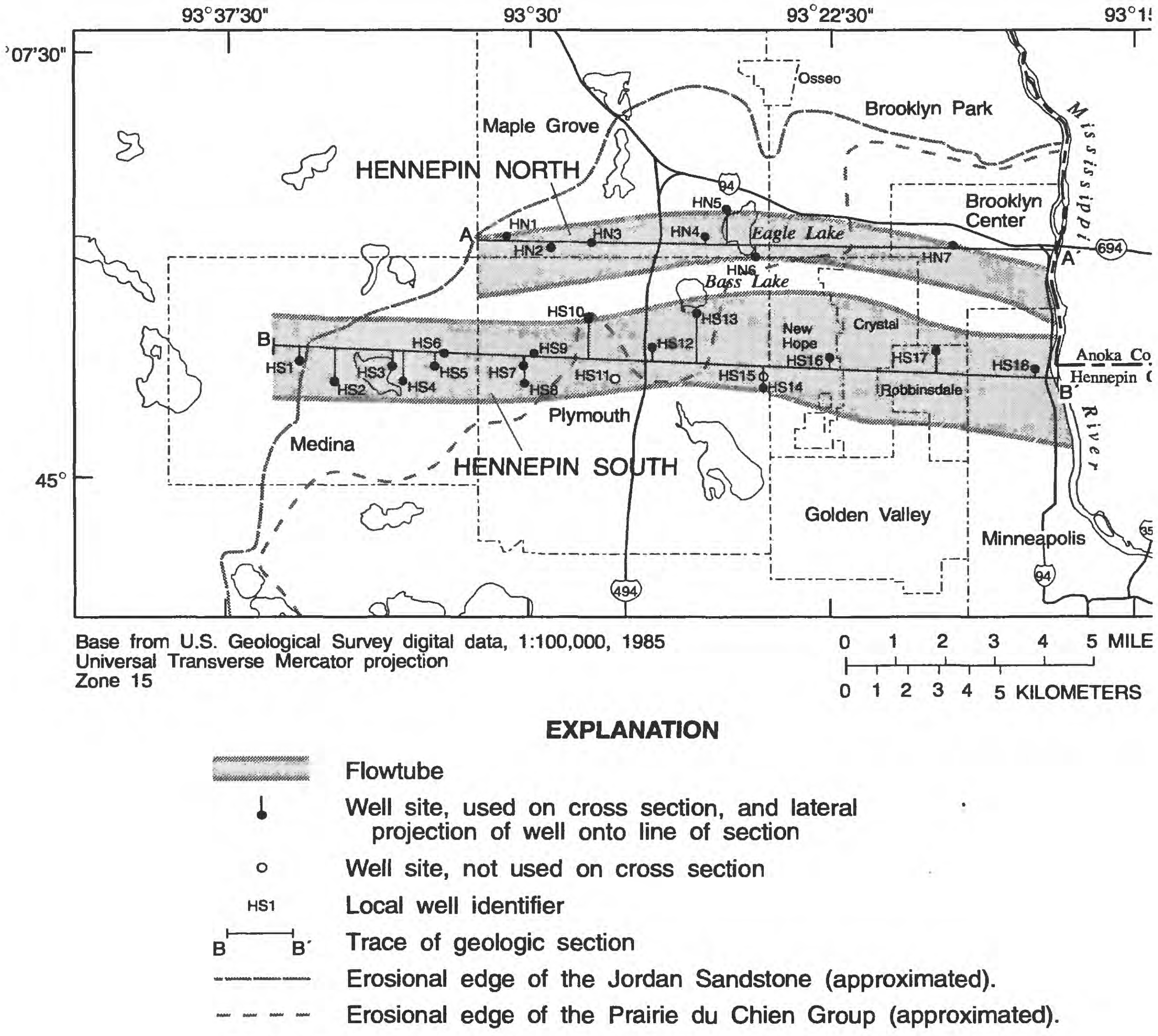
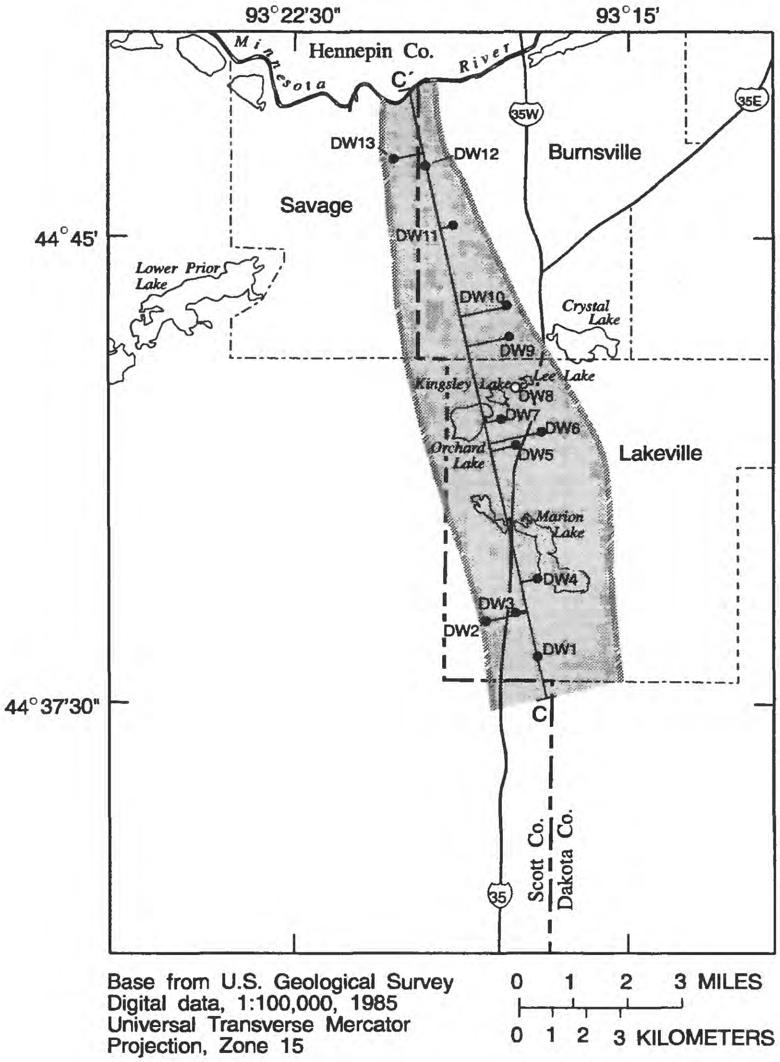


**Figure 2.--Hennepin County flowtubes, traces of geologic sections, and well sites (geology modified from Balaban (1989)).**

## Previous Investigations

Previous investigations of the Prairie du Chien-Jordan aquifer in southeastern Minnesota include studies of aquifer hydrogeology, water quality, and sensitivity to contamination. Hall and others (1911) discussed hydrogeologic characteristics and cation and anion analyses by county for glacial drift and bedrock geologic units, including the Prairie du Chien-Jordan aquifer. Thiel (1944) included data from the Hall (1911) report with updated information on stratigraphy, wells, and water-quality analyses. Ground-water hydrogeology, water-quality, and water-use information was presented for the Minneapolis-St. Paul metropolitan area by Prior and others (1953).

Maderak (1963, 1964, and 1965) focused on water quality of the Prairie du Chien-Jordan aquifer. His 1963 report included a compilation of water-quality data from 1955 to 1962 for the Prairie du Chien-Jordan aquifer. His 1964 paper presented water-quality data and interpretations for the Jordan Sandstone. His 1965 report discussed ground-water quality in the Twin Cities metropolitan area. Norvitch and others (1973)

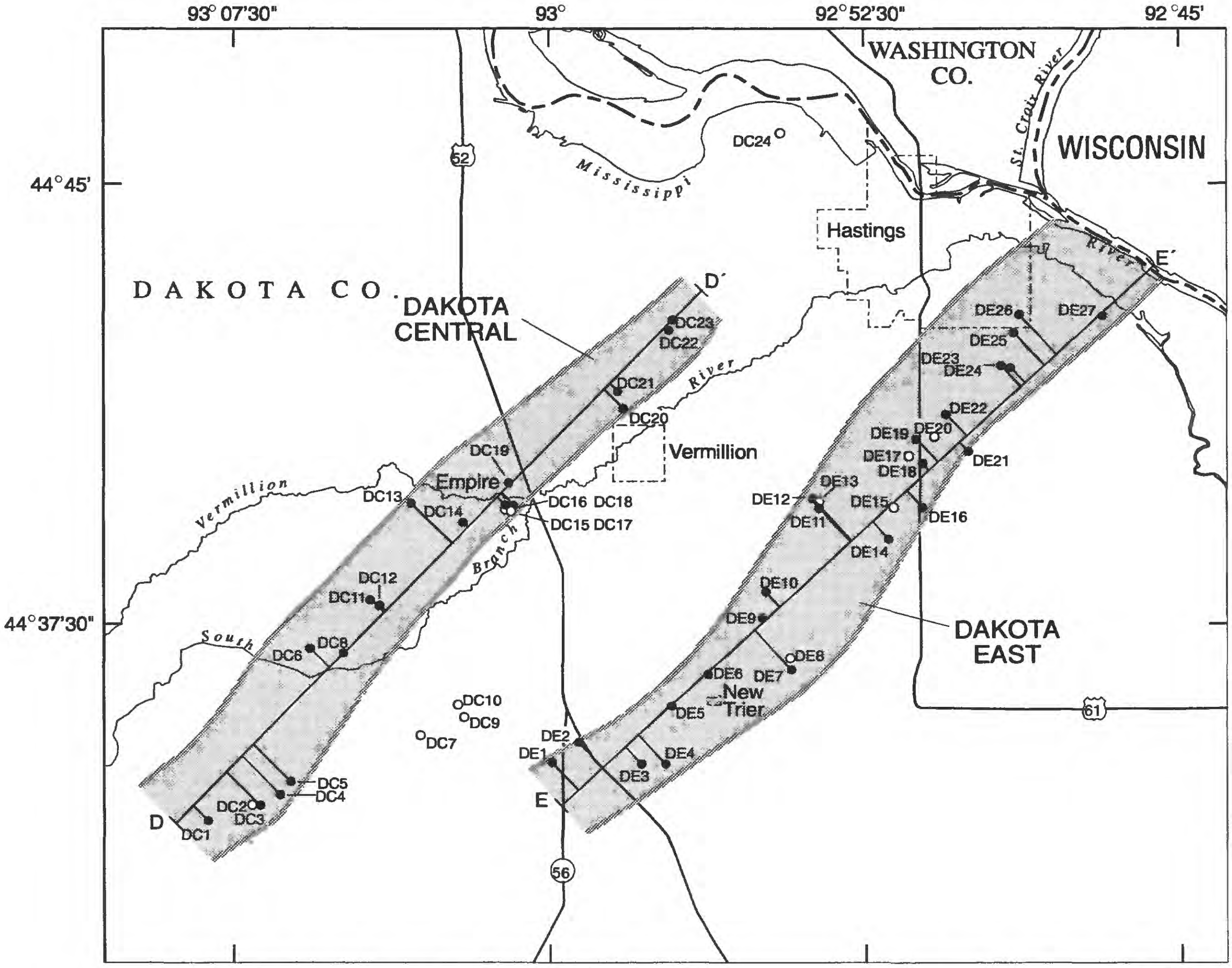


Base from U.S. Geological Survey
Digital data, 1:100,000, 1985
Universal Transverse Mercator
Projection, Zone 15

**EXPLANATION**

| | |
|---|---|
| ▨ | Flowtube |
| ● | Well site, used on cross section, and lateral projection of well onto line of section |
| ○ | Well site, not used on cross section |
| DW1 | Local well identifier |
| C——C' | Trace of geologic section |

**Figure 3.--Dakota West flowtube, trace of geologic section, and well sites.**



Base from U.S. Geological Survey digital data, 1:100,000, 1985
Universal Transverse Mercator projection
Zone 15

0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

**EXPLANATION**

▨ Flowtube

● Well site, used on cross section, and lateral projection of well onto line of section

○ Well site, not used on cross section

DC1 Local well identifier

D—D' Trace of geologic section

Figure 4.--Dakota Central and Dakota East flowtubes, traces of geologic sections, and well sites.

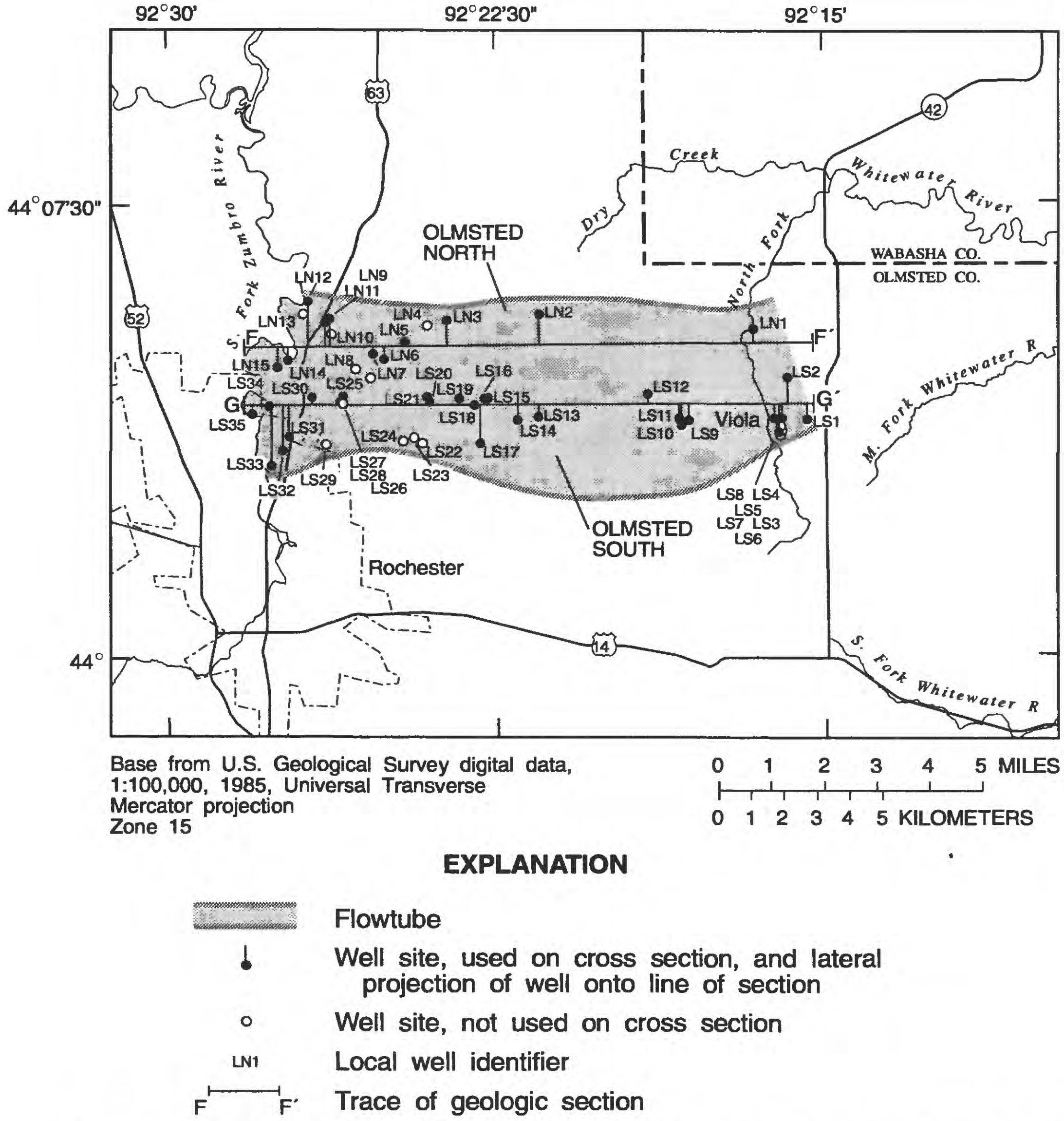


**Figure 5.--Olmsted flowtube, traces of geologic sections, and well sites.**

summarized the hydrogeologic system in the Twin Cities metropolitan area and compiled water-quality data from 1951 to 1970, with medians and ranges listed by aquifer. Guswa and others (1982) built upon the report by Norvitch and others (1973) and presented maps of lines of equal concentration of calcium, sodium, sulfate, and chloride for the glacial drift, Jordan, and Mt. Simon-Hinckley aquifers.

Regional hydrologic and water-quality atlases were completed for southeastern Minnesota during the 1970's and 1980's. Hydrogeologic and water-quality characteristics of the Prairie du Chien-Jordan aquifer was presented by Ruhl and others (1983). Delin and Woodward (1984) described the hydrogeologic setting and potentiometric surfaces of regional aquifers in southeastern Minnesota. Woodward (1986) described the hydraulic properties of regional aquifers in southeastern Minnesota. Mossler (1987) described the geology and nomenclature for Paleozoic units in southeastern Minnesota. Balaban (1988 and 1989) and Balaban and Hobbs (1990) provided a county based, detailed description of the geology, hydrogeology, sensitivity of the ground-water system to pollution, and water-well data base for Olmsted, Hennepin, and Dakota Counties, respectively.

Municipal water use and aquifer utilization were presented in a historical context by Woodward (1985). Setterholm and others (1991) discussed the hydrogeologic sensitivity of the Prairie du Chien-Jordan aquifer where it subcrops beneath the glacial drift in southeastern Minnesota.

### Well-Numbering System

Three systems of labeling wells are used for this investigation (Supplemental Information Section in the back of the report). The first system is a local identifier used in the text, figures, and tables of this report. The first two letters of the identifier refer to the study area that includes the well; the number following the letters identifies the relative position of the well on the geologic-section line. The well at the farthest upgradient position in the study area is number one; successive numbers are assigned to wells farther downgradient along the geologic-section line.

The second system of labeling wells is the Minnesota unique-well number. The unique number is a six digit number assigned by the Minnesota Department of Health for all wells in Minnesota that have been located, described, and entered into the State data base.

The third system of labeling wells is a location system based on the U.S. Bureau of Land Management's (BLM) system of land subdivision (township, range, and section) (fig. 6). In this system, the first numeral of a location number indicates the township; the second, the range; and the third, the section in which the well is located. Uppercase letters after the section number indicate the location within the section by successively smaller divisions into quarter tracts. Letters A, B, C, and D are assigned in a counterclockwise direction, beginning in the northeast corner of each tract. The first letter denotes the 160-acre tract; the second, the 40-acre tract; the third, the 10-acre tract; and the fourth, the 2.5 acre tract. The number of uppercase letters indicates the accuracy of the location number. If a point can be located within a 2.5-acre tract, four uppercase letters are shown in the location number. For example, the number 118N22W15ADCD indicates a well in the SE1/4 of the SW1/4 of the SE1/4 of the NE1/4 of section 15, township 118 north, range 22 west.

### Acknowledgments

The authors are grateful to staffs of the Minnesota Geological Survey, Minnesota Department of Natural Resources, Minnesota Pollution Control Agency, Hennepin County, and Olmsted County, who provided information and consultation on aquifer hydrogeology and related projects they were conducting concurrently with this investigation; to the Minnesota Geological Survey for assistance in assembling the large list of wells that were necessary to determine those wells to be sampled; and to the Metropolitan Council and Olmsted County who provided land-use designation data used in this investigation. A special thank you is offered to the well owners who allowed us to obtain water samples from their wells and include the data in this study.

## Methods of Investigation

### Flowtube Delineation

Study areas for this investigation (hereinafter referred to as flowtubes) were established along regional ground-water flow paths and average 13 miles long and 2 miles wide. A flowtube represents a three dimensional volume of the aquifer whose lateral boundaries are parallel to the direction of ground-water movement (fig. 7). The lateral boundaries of the flowtubes are formed by ground-water flowlines which are perpendicular to the Prairie du Chien-Jordan aquifer potentiometric contour lines (Freeze and Cherry, 1979). There is no ground-water flow through the sides of the flowtubes. The upgradient end of each flowtube was located near regional topographic highs and potentiometric-surface highs. The downgradient end of each flowtube was at a river discharge area for the Prairie du Chien-Jordan aquifer. The upper boundary of the flowtubes was open; ground-water recharge occurs over the areal extent of the flowtubes by infiltration of precipitation. The bottom boundary of the flowtubes was the underlying St. Lawrence Formation.

Potentiometric-surface maps were constructed using data from the MGS county atlases (Balaban, 1988 and 1989; Balaban and Hobbs, 1990), a 1989 synoptic water level measurement in the seven-county Minneapolis-St. Paul metropolitan area, water-level data from the Hennepin Conservation District, and results from previous USGS investigations in Olmsted County (Delin, 1991). These maps were used to delineate the flowtubes in areas where the lateral boundaries would be reasonably straight. Water levels were measured in 50 of the sampled wells during the 1990 field season, and in 70 additional wells located in and near the flowtubes during March and April of 1991. These water levels were used to refine the Prairie du Chien-Jordan aquifer potentiometric surface in the flowtubes.

Flowtube width was determined as an area which was wide enough to contain a sufficient number of wells available for sampling and narrow enough to draw two somewhat parallel flowlines. Flowtubes about 13 miles

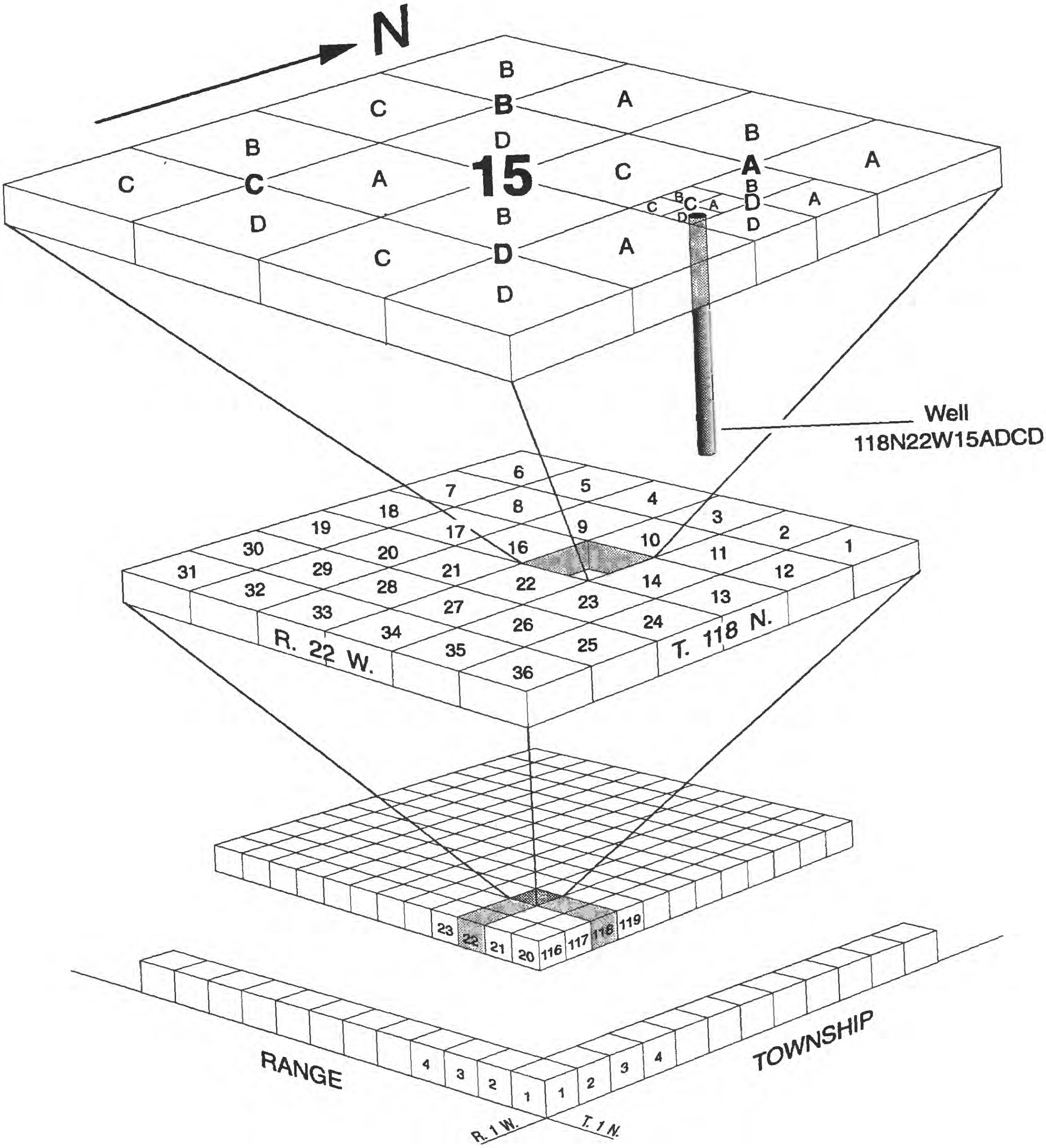


Figure 6.--Well numbering system.

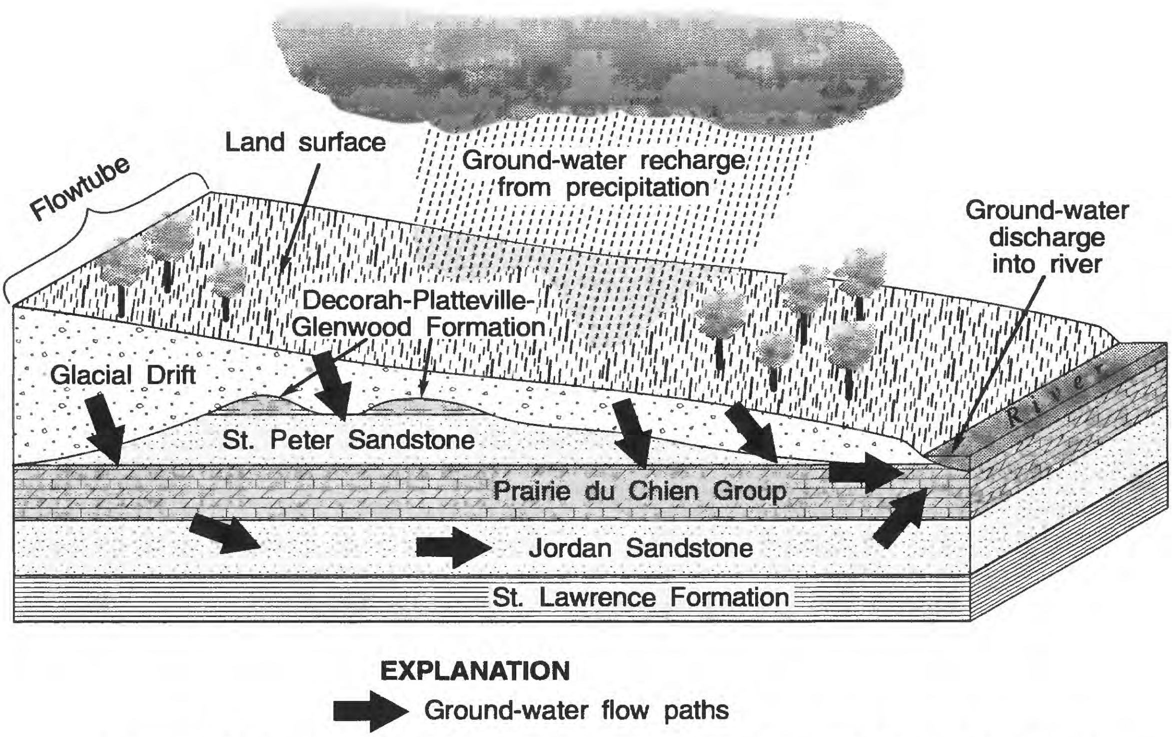


**Figure 7.--Conceptual diagram of a flowtube and ground-water flow paths.**

long and 2 miles wide provided study areas in which it was possible to investigate ground-water quality and flow on a regional scale along the flowtube and compare that to water quality and flow on a local scale directly surrounding a well.

The flowtubes were chosen in areas that represented (1) agricultural or residential land use (2) several combinations of overlying stratigraphy, and (3) highly karstic terrain in Olmsted County. An additional criterion was that the study areas had a wide distribution of wells completed in the Prairie du Chien-Jordan aquifer. An MGS data base of existing wells was used to locate areas with an adequate distribution of wells. Bedrock geology maps from the MGS county atlases were used to determine the subcrop geology patterns in these counties and to delineate flowtubes in areas with differing overlying stratigraphy. A flowtube in Olmsted County was chosen because of the presence of karstic features.

Geologic-section lines in the flowtubes were established to be generally parallel with the regionally predominant ground-water flow direction in the aquifer. Information about well location, well depth, and geology along the geologic sections was obtained from well logs and projected perpendicularly from the location of the wells onto the section lines. MGS county atlas maps showing depth to bedrock, bedrock geology, and quaternary geology were used to include additional information on the extent and location of features along the geologic sections.

## Land-Use Designation

The flowtubes were chosen to represent two major land-use types in southeastern Minnesota: agricultural and residential. These two broad categories were used to make a general comparison of the effects of land use on ground-water quality. The number and percent of wells in each land-use category, and the percent of the flowtube areas in each land-use category, are listed in table 1.

The agricultural and residential land-use categories used for this study are broad groupings of multiple land-use designations that the counties had generated for their own use. Digital land-use maps were obtained from regional and county planning offices, the location of the sampled wells and flowtube boundaries were added to the digital file, and land-use designations for each well and for the flowtube areas were computed.

Residential land use for this study included areas designated by the counties as single- and multiple-family housing, business, commercial, industrial, institutional, landfills, and open lands and park lands within an urban area. Agricultural land use for this study included areas designated by the counties as isolated farmsteads or homes, agricultural cultivated land, pasture, feedlots, agricultural business, golf courses, and public, semi-public, and vacant land in rural areas. The land-use categories assigned to the individual wells for this study were approximate because (1) the more detailed land-use designations provided by the counties overlapped when they were grouped into just two broad categories (for example, an area of single family housing in a largely agricultural land-use area, or open, park, and golf course lands in either agricultural or residential areas), and (2) the land-use category assigned to individual wells was based on the land use at the land surface, which assumes primarily vertical recharge to the well; however, the flow paths of recharge water from the land surface to the wells is undetermined.

The Hennepin County (HN and HS) and Dakota West (DW) flowtubes were selected to represent areas with a higher percent of residential land use than the other three flowtubes. These three flowtubes have large areas of residential land use, with low-density single-family housing present in many areas still classified as agricultural.

In the HN and HS flowtubes agricultural areas are present in the far western portion with increasing density to the east. Blocks of single-family homes predominate in the eastern halves of the flowtubes. Most of these homes have been converted to municipal water supplies; however, some homeowners have retained their wells in working order from which water samples could be obtained. Commercial and industrial areas are also present in the eastern halves of these flowtubes and water use is heavy due to municipal and industrial pumping.

Table 1.--Number of wells sampled and total land area by land use in the flowtubes

[--, not applicable]

| Flowtube | Land use | Number of wells sampled | Percent of well sites in flowtubes | Percent of total land area in flowtubes |
|---|---|---|---|---|
| Hennepin North and | agricultural | 5 | 20 | 44 |
| Hennepin South | residential | 20 | 80 | 50 |
| | roads, water | -- | -- | 6 |
| Dakota West | agricultural | 3 | 23 | 63 |
| | residential | 10 | 77 | 29 |
| | roads, water | -- | -- | 8 |
| Dakota Central | agricultural | 18 | 75 | 98 |
| | residential | 6 | 25 | 2 |
| | roads, water | -- | -- | 0 |
| Dakota East | agricultural | 18 | 67 | 96 |
| | residential | 9 | 33 | 3 |
| | roads, water | -- | -- | 1 |
| Olmsted | agricultural | 25 | 50 | 92 |
| | residential | 25 | 50 | 7 |
| | roads, water | -- | -- | 1 |

The DW flowtube has agricultural areas in the southern part of the flowtube, with housing density increasing from south to north. Heavy municipal pumping occurs in the northern one-half of the DW flowtube.

The Dakota Central (DC), Dakota East (DE), and Olmsted (OLM) flowtubes were selected to represent areas with a higher percent of agricultural land use and to assess the effect of farming on ground-water quality. The DC and DE flowtubes are in areas of primarily agricultural land use with scattered residential subdivisions and isolated homesteads. Land use in the eastern three-quarters of the OLM flowtube is predominantly agricultural with isolated areas of residential housing. The western one-quarter of the OLM flowtube changes to residential land use, including residential subdivisions, business, and commercial areas.

## Well Selection

Wells in the data base with lithologic logs describing the strata penetrated by the bore hole were evaluated for water sample collection. Selection of wells was limited to those that obtained water from only the Prairie du Chien part or the Jordan part of the aquifer (not to both), or to an aquifer overlying the Prairie du Chien-Jordan aquifer. Of the 139 wells selected for sampling, 58 were completed in the Prairie du Chien part of the aquifer and 60 were completed in the Jordan part of the aquifer. Where possible, pairs of nearby wells were selected -- one completed in the Prairie du Chien and the other completed in the Jordan. Eleven wells were completed in the overlying St. Peter aquifer, two in the Platteville Formation, and 8 in glacial drift aquifers.

Selected wells included 123 domestic wells, 6 irrigation wells used for agricultural, golf course, or institutional-grounds purposes, 6 commercial wells, and 4 municipal or community water-supply wells. All wells were cased through overlying formations and were either open or screened in the aquifer. According to well records, well casings were grouted in 95 wells; the other 44 wells either were not grouted or had no information about grouting listed on the well log.

## Water Sample Collection and Analysis

Water samples from 139 wells in the six flowtubes were collected for analysis during two field seasons. The first field season was from July through September 1990 in which 103 wells were sampled. The second field season 36 different wells were sampled from July through August 1991. In addition, 11 of the wells sampled in 1990 were resampled in 1991 to evaluate water-quality variations with time. Nineteen duplicate samples and two equipment blank samples were collected for quality control purposes.

Specific conductance, pH, oxidation-reduction potential (Eh), water temperature, dissolved oxygen, and alkalinity were measured at each well site. The Hydrolab[1] multi-parameter water monitoring system was used for all field measurements except alkalinity. The Hydrolab was calibrated for dissolved oxygen, pH, and specific conductance each day before sampling. Alkalinity was measured by incremental titration with a pH meter during both field seasons and also by colorimetric methods in 1991.

The standard practice for sampling the well water was as follows: A garden hose (dedicated to the project) was connected to an outside water spigot. The other end of the hose was either connected to a flow-through chamber on the Hydrolab that allowed water to pass by the probes, or water from the hose was allowed to fill a container in which the Hydrolab probes were submerged. Measurements were recorded every three minutes until the values stabilized for three consecutive measurements. Stabilization was defined as changes in measured values less than ± 0.1°C for temperature, 3 microsiemens per centimeter at 25 °C for specific conductance, 0.03 pH units, and 0.1 milligrams per liter (mg/L) dissolved oxygen. The time for stabilization averaged 20 minutes. This procedure assured that the well casing had been purged of standing water and sample water was being drawn directly from the aquifer. After the stabilized field values were recorded the hose was disconnected and water samples for laboratory analysis were collected at the spigot. Unfiltered samples were collected directly from the spigot. Filtered samples were forced through 0.45 micron filter paper by a peristaltic pump or water pressure in a short hose connected to the spigot.

Water samples were analyzed for major cations and anions, nutrients, trace elements, triazine and other selected herbicides, volatile-organic-carbon compounds, and tritium. Laboratory analyses for cations and anions, nutrients, and trace elements were performed at the USGS National Water-Quality Laboratory in Arvada, Colorado. The presence or absence of compounds in the triazine herbicide family was evaluated by enzyme-

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

linked immunosorbent assay (immunoassay) (Thurman and others, 1990). Immunosystems assay kits were used during the 1990 field season, and Ohmicron assay kits were used during the 1991 field season. Water samples that indicated detectable triazines using these kits were analyzed quantitatively for triazine herbicides and other selected herbicides by gas chromatography/mass spectroscopy (GC/MS) at the USGS National Water-Quality Laboratory (1990 and 1991 field seasons) or by Dr. Paul Capel at his laboratory (Department of Civil and Mineral Engineering, University of Minnesota, Minneapolis) (1991 field season). Volatile-organic-carbon compounds in water samples from the Hennepin County flowtubes were determined by GC at the USGS Laboratory in West Trenton, New Jersey. Tritium analyses using the enriched tritium technique were completed at either the USGS National Water-Quality Laboratory or the Environmental Isotope Laboratory, University of Waterloo, Waterloo, Ontario, Canada.

Eight wells completed in the Jordan part of the aquifer were sampled for analysis of carbon-14 and carbon-13 composition in 1990 by Dr. E. Calvin Alexander Jr., and Scott Alexander of the University of Minnesota Department of Geology and Geophysics, using methods described by Alexander and Alexander (1987). These samples were sent to Beta Analytic, Inc. Laboratory in Coral Gables, Florida for analysis.

## Water-Quality Indicator Constituent Selection

Concentrations of dissolved nitrite-plus-nitrate nitrogen ($NO_3$-N), chloride (Cl), and tritium were used in this study to compare water from different parts of the Prairie du Chien-Jordan aquifer, to understand how water moves in the aquifer, and to identify areas where the aquifer may be susceptible to contamination from the land surface. The susceptibility of an aquifer to contamination is determined in part by the travel time of recharge water from the land surface to its present location in the aquifer (residence time). Areas of the aquifer overlain by more permeable and thin geologic units are more susceptible to contamination than areas overlain by less permeable and thick geologic units (Minnesota Department of Natural Resources, Geologic Sensitivity Project Workgroup, 1991).

$NO_3$-N and Cl are commonly used as indicators of human activities that affect ground water. One or both of these constituents can be introduced into an aquifer by land-use practices such as agricultural and residential fertilizer applications, barnyard runoff, road deicing, septic drainfields, and industrial chemical spills. Cl is a conservative constituent in water and remains dissolved without precipitating, adsorbing to organic material, or undergoing change in oxidizing or reducing conditions. These characteristics make Cl an effective tracer of human-related water-quality effects in the aquifer. $NO_3$-N is less conservative than Cl because it is removed from ground water through reduction reactions. Based on data from this investigation $NO_3$-N concentrations less than or equal to 3 mg/L and Cl concentrations less than or equal to 5 mg/L represent background concentration levels in the Prairie du Chien-Jordan aquifer. Concentrations of $NO_3$-N or Cl greater than these concentrations indicate a human-related effect on ground-water chemistry.

Tritium concentration can be used as an indicator of ground-water susceptibility to contamination, because it provides an approximation of the residence time from when precipitation or surface water enters an aquifer in a recharge area, to when the ground water is discharged into a lake, river, or well. Tritium dissolves in precipitation in the atmosphere and is carried with recharge water into ground water. Tritium concentrations in ground water change only by radioactive decay and mixing.

Tritium ($^3H$) is a radioactive isotope of hydrogen found naturally in the atmosphere at low levels. The half-life of tritium is 12.43 years. Tritium concentrations are measured in tritium units (TU) or picoCuries per liter. A TU is equal to one atom of $^3H$ per $10^{18}$ atoms of $^1H$, or about 3.2 picoCuries per liter. Prior to 1954 the atmospheric tritium concentration was 3-10 TU. Ground water that entered the ground before 1954 would now have tritium concentrations less than 1 TU (1994) (Robertson and Cherry, 1989; Bradbury, 1991). Levels of tritium in the atmosphere increased by several orders of magnitude in 1954 when atmospheric testing of nuclear weapons began. Water that entered the ground between 1954 and the early 1970's, during periods of high atmospheric tritium concentrations, would now have tritium concentrations between 10 and several hundred TU. Atmospheric tritium concentrations have been 20-30 TU since 1982 (Bradbury, 1991). Water that has entered the ground since 1982 would now have a tritium concentration of at least 10 TU.

In this report, tritium concentrations in ground water were grouped into one of three general age classifications (Alexander and Alexander, 1989). Concentrations less than 0.8 TU indicate water that entered the ground water before 1954 (old). Concentrations greater than 15 TU indicate water that entered the ground water in 1954 or later (recent). Concentrations from 0.8 to 15 TU represent water that is a mixture of recent and old water (mixed).

## Statistical Analysis

Statistical tests were used to establish the significance of the relations between the concentrations of water-quality indicator constituents ($NO_3$-N, Cl, and tritium) and hydrogeologic, well-grouting, and land-use variables. These variables included: well grouting, total depth of the well, thickness and composition of overlying glacial drift, presence of the overlying Decorah Shale, and land use. The MGS ground-water pollution sensitivity index (Balaban, 1988 and 1989; Balaban and Hobbs, 1990) also was tested for its relation to the distribution of indicator constituents in the flowtubes. Univariate statistics were used to analyze the distribution of water-quality-constituent data. The chi-square ($\chi^2$) best-fit statistic and Kruskal-Wallis (K-W) median-comparison statistic were used to test the relations between the statistical distribution of indicator-constituent concentrations and the hydrogeologic, well-grouting, and land-use variables. The univariate, $\chi^2$, and K-W statistics were calculated using Statistical Analysis System software (SAS Institute Inc., 1989).

The $\chi^2$ best-fit statistic was used to compare the relations between indicator-constituent concentrations and tested variables by grouping the numerical concentration data into ranges of low, medium, and high. The $\chi^2$ statistic measures the extent to which an observed count of the distribution of observations in categories differs from the expected count (Ott, 1988). The null hypothesis ($H_o$) is that the observed and expected distributions are the same. If they are different, $H_o$ is rejected and the statistic indicates that a significant relation exists between the constituent and the variable being considered. The resultant $\chi^2$ statistic is compared to a critical value for a particular number of degrees of freedom. The statistic also provides an attained significance level (p-value) which can be used as a test for the rejection of $H_o$. The p-value is compared to a predetermined significance level, $\alpha$, for the test (Helsel and Hirsch, 1992). For the relations tested in this study, $\alpha = 0.05$; thus, 0.05 was the upper limit for the p-value in rejection of $H_o$. An $\alpha$ of 0.05 means that there was only a 95 percent chance of rejecting $H_o$ when $H_o$ was true. If the p-value was less than 0.05, $H_o$ was rejected; if the p-value was greater than 0.05, $H_o$ was not rejected.

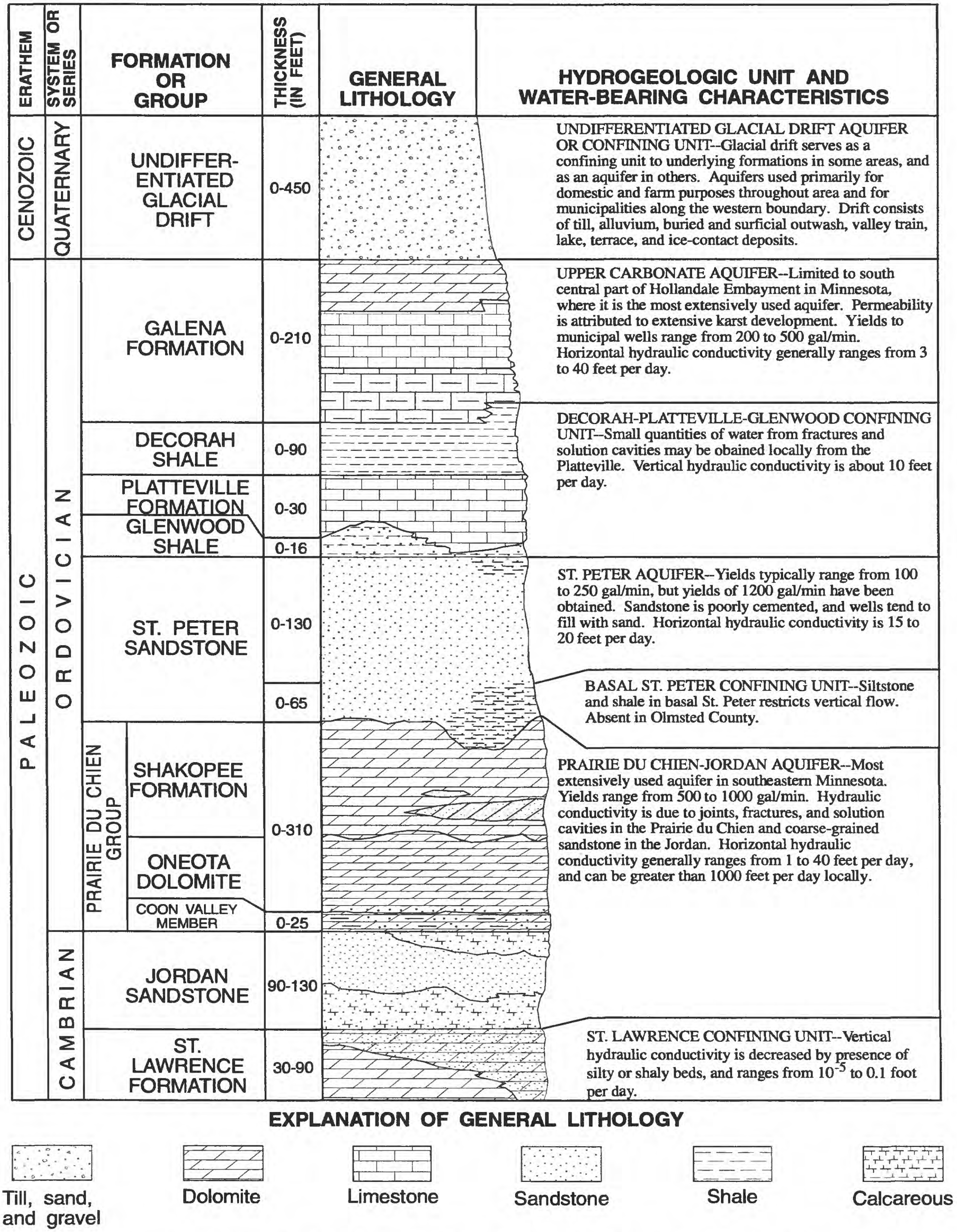
The K-W median-comparison statistic was used to compare the relations between numerical and categorized data where low, medium, and high ranges could not easily be assigned to some constituents on a scientific basis, and where there were not enough data to validly populate a $\chi^2$ table. The K-W statistic is comparable to a one-way analysis of variance test (ANOVA) for non-parametric data (Armour and Platts, 1983). K-W compares the medians of a constituent between differing categories of a particular variable and tests to see if the difference between the medians is significant. $H_o$ for the K-W statistic is that the concentration medians for the different categories of a variable are the same. Using SAS, the statistic provides a $\chi^2$ approximation and p-value, giving a fairly direct comparison with the $\chi^2$ statistic result.

# Hydrogeology

## Regional Hydrogeology

The Prairie du Chien Group and the Jordan Sandstone are part of a larger sequence of marine sedimentary bedrock units known as the Hollandale Embayment. This sequence was deposited during the Paleozoic Era in a shallow basin occupying southeastern Minnesota and southwestern Wisconsin, and extending southward into northern Illinois and Missouri (Mossler, 1987). The bedrock alternates vertically among sandstone, shale, and carbonate units which form a layered pattern of aquifers and confining units. A geologic column showing a part of this sequence of bedrock units that pertains to this study, and their lithology and waterbearing characteristics, is shown in figure 8. In some areas the bedrock was incised by glacial meltwater which carved out bedrock valleys, many of which were filled later with glacial drift. Some units in the upper half of the sequence are known to be highly eroded on their upper surface (for example the Prairie du Chien Group, St. Peter Sandstone, and Galena Formation) (Mossler, 1987). The layers of the Hollandale Embayment slope downward toward depressions in the embayment, with the result that different layers of the sequence subcrop areally over southeastern Minnesota. A concave depression in the sequence called the Twin Cities Basin underlies the seven-county Minneapolis-St. Paul metropolitan area. The following paragraphs describe the regional aquifers and confining units in order of increasing depth below land surface.

Glacial drift overlies the bedrock in most of southeastern Minnesota. The glacial drift is very heterogeneous, ranging from sand and gravel outwash to clayey till. The sand and gravel outwash deposits form surficial-drift aquifers. Areas or layers of clay-rich till are confining layers that limit vertical ground-water movement and form an upper confining unit for buried-drift and bedrock aquifers. The glacial drift is highly variable in its water-bearing characteristics over short



| ERATHEM | SYSTEM OR SERIES | FORMATION OR GROUP | | THICKNESS (IN FEET) | HYDROGEOLOGIC UNIT AND WATER-BEARING CHARACTERISTICS |
|---|---|---|---|---|---|
| CENOZOIC | QUATERNARY | UNDIFFERENTIATED GLACIAL DRIFT | | 0-450 | UNDIFFERENTIATED GLACIAL DRIFT AQUIFER OR CONFINING UNIT--Glacial drift serves as a confining unit to underlying formations in some areas, and as an aquifer in others. Aquifers used primarily for domestic and farm purposes throughout area and for municipalities along the western boundary. Drift consists of till, alluvium, buried and surficial outwash, valley train, lake, terrace, and ice-contact deposits. |
| PALEOZOIC | ORDOVICIAN | GALENA FORMATION | | 0-210 | UPPER CARBONATE AQUIFER--Limited to south central part of Hollandale Embayment in Minnesota, where it is the most extensively used aquifer. Permeability is attributed to extensive karst development. Yields to municipal wells range from 200 to 500 gal/min. Horizontal hydraulic conductivity generally ranges from 3 to 40 feet per day. |
| | | DECORAH SHALE | | 0-90 | DECORAH-PLATTEVILLE-GLENWOOD CONFINING UNIT--Small quantities of water from fractures and solution cavities may be obained locally from the Platteville. Vertical hydraulic conductivity is about 10 feet per day. |
| | | PLATTEVILLE FORMATION | | 0-30 | |
| | | GLENWOOD SHALE | | 0-16 | |
| | | ST. PETER SANDSTONE | | 0-130 | ST. PETER AQUIFER--Yields typically range from 100 to 250 gal/min, but yields of 1200 gal/min have been obtained. Sandstone is poorly cemented, and wells tend to fill with sand. Horizontal hydraulic conductivity is 15 to 20 feet per day. |
| | | | | 0-65 | BASAL ST. PETER CONFINING UNIT--Siltstone and shale in basal St. Peter restricts vertical flow. Absent in Olmsted County. |
| | | PRAIRIE DU CHIEN GROUP | SHAKOPEE FORMATION | 0-310 | PRAIRIE DU CHIEN-JORDAN AQUIFER--Most extensively used aquifer in southeastern Minnesota. Yields range from 500 to 1000 gal/min. Hydraulic conductivity is due to joints, fractures, and solution cavities in the Prairie du Chien and coarse-grained sandstone in the Jordan. Horizontal hydraulic conductivity generally ranges from 1 to 40 feet per day, and can be greater than 1000 feet per day locally. |
| | | | ONEOTA DOLOMITE | | |
| | | | COON VALLEY MEMBER | 0-25 | |
| | CAMBRIAN | JORDAN SANDSTONE | | 90-130 | |
| | | ST. LAWRENCE FORMATION | | 30-90 | ST. LAWRENCE CONFINING UNIT--Vertical hydraulic conductivity is decreased by presence of silty or shaly beds, and ranges from $10^{-5}$ to 0.1 foot per day. |

**Figure 8.--Generalized hydrogeologic column showing regional aquifers and confining units in the study areas in southeastern Minnesota (modified from Delin and Woodward, 1984; Delin, 1991; Mossler, 1987).**

horizontal and vertical distances. Other drift types include loess, alluvium, valley train, lake, terrace, and ice-contact deposits.

Glacial drift in the flowtubes is of various ages. The oldest reported drift deposits in the region are the pre-Wisconsin outwash and the pre-Illinoian till found in Olmsted County. Composition of the pre-Illinoian till ranges from clay to silt to sandy loam, and is not uniform in its confining characteristics (Balaban, 1988).

The Wisconsin glaciation advanced with two glacial lobes that covered parts of Hennepin and Dakota Counties. The Superior Lobe entered the area from the northeast and deposited a mix of clay, sand, gravel, and boulder drift. The Des Moines Lobe advanced over the Twin Cities region from the southwest, picking up Superior Lobe drift and ice as it advanced, and deposited a clay rich, heterogeneous till over part of Hennepin and Dakota Counties (Sims and Morey, 1972). The Superior Lobe drift is more permeable than the Des Moines Lobe drift (Lindgren, 1990; Schoenberg, 1990). In Hennepin and Dakota Counties Superior Lobe and Des Moines Lobe deposits are known to alternate with depth, resulting in a complex mix of permeability characteristics in the drift. The only drift units that can be assumed with relative certainty to permit higher ground-water recharge rates are the sand- and gravel-outwash and terrace-sand deposits.

The Upper Carbonate aquifer, which consists of the Galena Formation in the study areas, is present only in the Olmsted flowtube. In Dakota and Hennepin Counties, the formation has been almost completely eroded, with only scattered subcrop islands remaining. The formation consists of dolomite and limestone units containing varying amounts of interbedded shale and sand (Mossler, 1987). The formation has extensive karst features, especially where the overlying drift is less than 50 ft thick, including almost all of the Olmsted flowtube. The Upper Carbonate aquifer is susceptible to contamination from the land surface due to fractures, joints, and solution channels which allow quick downward movement of water (Woodward, 1986).

The Decorah-Platteville-Glenwood confining unit consists of shale, shaley dolomite and limestone, and dolomitic limestone. Where present, this unit is the greatest impediment to downward ground-water flow to the St. Peter aquifer and the Prairie du Chien-Jordan aquifer (Delin, 1991). The topmost unit is the Decorah Shale, which has the smallest vertical hydraulic conductivity of the three layers. The Platteville Formation is predominantly a dolomitic limestone with some thin shale partings (Mossler, 1987). Water can be extracted from the Platteville Formation in some places sufficient for domestic use. The Glenwood Shale is primarily a calcareous and sandy shale.

The Decorah-Platteville-Glenwood confining unit is continuous over a broad area only in the Olmsted flowtube. In the Dakota County flowtubes the Decorah Shale is missing from the unit, and isolated patches of the Platteville Formation and the Glenwood Shale are present. The unit is completely absent in the Hennepin County flowtubes.

The St. Peter aquifer is a fine- to medium-grained, well-sorted, poorly-cemented quartzose sandstone. The St. Peter aquifer is rarely fully saturated in the flowtubes. In Hennepin County and the western part of Dakota County the lower 40 to 65 ft of the St. Peter Sandstone is a confining layer consisting of shale and siltstone interbedded with fine-grained sandstone (Mossler, 1987). This basal confining unit separates the St. Peter aquifer from the Prairie du Chien-Jordan aquifer in the Minneapolis-St. Paul metropolitan area. In Olmsted County the basal confining unit is absent, and the St. Peter Sandstone is considered to be part of the St. Peter-Prairie du Chien-Jordan aquifer. Glacial meltwater channels have eroded much of the St. Peter Sandstone in the region surrounding the Hennepin and Dakota County flowtubes, often cutting into the underlying Prairie du Chien-Jordan aquifer.

The Prairie du Chien-Jordan aquifer is composed of the Prairie du Chien Group and the underlying Jordan Sandstone. Except where the units thin at their edges, the aquifer thickness ranges from 240 ft at its northern extent to more than 450 ft near the Iowa border (Woodward, 1986). The Jordan Sandstone is typically between 90 and 130 ft thick, but thickness of the Prairie du Chien Group varies, thickening toward the center of the embayment (Austin, 1972). The Prairie du Chien-Jordan aquifer is underlain by the St. Lawrence confining unit, which consists of siltstone and dolomite.

The Prairie du Chien part of the aquifer is a sandy dolomite with water flowing mainly through joints, fractures, and solution channels. These features give the unit a highly variable hydraulic conductivity (Delin, 1991; Schoenberg, 1990). Significant erosion at the top of the Prairie du Chien Group, especially at its northern extent, resulted in upper surface relief as much as 100 ft (Mossler, 1987). In other areas, including the Olmsted flowtube, there is almost no relief in the upper surface. In Hennepin and Dakota Counties the Prairie du Chien Group is generally the first or second bedrock unit encountered below land surface and it is heavily karstic (Balaban, 1989; Balaban and Hobbs, 1990). Olmsted County also has significant karst development in this unit, even where it is confined by the overlying

Decorah-Platteville-Glenwood Formation (Balaban, 1988).

The Jordan part of the aquifer is predominantly a variably cemented, quartzose sandstone with water flowing mainly through intergranular pore spaces. In more strongly cemented areas ground-water flow may occur through joint partings (Schoenberg, 1990).

The Prairie du Chien and Jordan parts of the aquifer have similar hydraulic heads and water-level fluctuations, and are considered to comprise one aquifer. Norvitch and others (1973) have documented this connection by showing a lowering of hydraulic head in both units when just one unit is pumped. Questions exist, however, on the continuity of the hydraulic connection between the two parts of the aquifer. Setterholm and others (1991) suggest that a transitional zone, the Coon Valley member, which consists of interbedded sandstone, sandy dolomite, siltstone, and shale serves as a confining unit between the Prairie du Chien and the Jordan where it is present. Maderak (1964 and 1965) indicated that the lower portion of the Prairie du Chien Group serves to partially restrict the downward movement of water into the Jordan part of the aquifer.

## Hennepin North and Hennepin South Flowtubes

The Hennepin North (HN) and Hennepin South (HS) flowtubes extend from west to east in the northwestern corner of the Minneapolis-St. Paul metropolitan area (fig. 2). The flowtubes are close to the northwest edge of the Hollandale Embayment. The erosional edges of the St. Peter Sandstone, the Prairie du Chien Group, and the Jordan Sandstone are present in both flowtubes; the Prairie du Chien Group is absent in the western two-thirds of the flowtubes (figs. 2, 9, 10). The bedrock in these flowtubes was deeply incised by glacial meltwaters, creating many bedrock valleys. Well logs from this area indicate that the St. Peter Sandstone is shale-rich. The presence of the shale and the different erosional edges made it difficult to locate the top and bottom of the different geologic units from information on driller's logs, and caused uncertainties in delineating edges and isolated patches of the St. Peter Sandstone, the Prairie du Chien Group, and the Jordan Sandstone. The locations of the geologic units shown on figures 9 and 10 were interpreted from logs of wells located within the flowtubes.

The greatest amount of recharge to the Prairie du Chien-Jordan aquifer occurs where these units subcrop beneath the glacial drift (Norvitch and others, 1973). A layer of glacial drift, ranging from about 50 to more than 300 ft thick, overlies the bedrock in the HN and HS flowtubes. The drift is largely clay-rich till with lenses of outwash sand and gravel. The eastern edges of the flowtubes have terrace sand and gravel deposits from the glacial Mississippi River. The sand lenses and deposits may provide preferential flow paths for aquifer recharge where interconnected lenses are present through the thickness of the drift. The Prairie du Chien-Jordan aquifer is confined in the HN and HS flowtubes by both the clay-rich glacial till and the basal St. Peter confining unit.

The upgradient ends of the HN and HS flowtubes are characterized by rolling hills which have similar mean topographic altitudes. The upgradient end of the HN flowtube is located about three and one-half miles east of the topographic watershed divide. The upgradient end of the HS flowtube is located at the topographic watershed divide. Regional ground-water flow in the Prairie du Chien-Jordan aquifer begins at the eroded edge of the Jordan Sandstone and at the upgradient ends of the flowtubes. The water-level altitude (potentiometric surface) in the aquifer along the HN flowtube was generally within 50 ft of the land surface, sloping evenly from 910 ft above sea level in the west to 800 ft at the Mississippi River discharge area. The altitude of the potentiometric surface along the HS flowtube was at about 913 ft and decreased to 800 ft at the Mississippi River discharge area. The potentiometric surface rise near HS14 cannot be explained by data available from this investigation. Selected water-quality data for HN and HS flowtube wells, discussed in a later section of this report, are listed in tables 2 and 3.

## Dakota West Flowtube

The Dakota West (DW) flowtube extends from south to north along the western border of Dakota County and parts of northeastern Scott County (fig. 3). Hydrogeology in the area of the DW flowtube has been affected by glacial meltwater that eroded channels through the bedrock (fig. 11). These channels have eroded into the Prairie du Chien Group, leaving subcrops of St. Peter Sandstone which are, in some places, capped by the Platteville-Glenwood Formation. The St. Peter Sandstone includes the basal shale confining layer in this area; there are, however, so many eroded valleys that the Prairie du Chien-Jordan aquifer is not continuously confined by the St. Peter Sandstone.

Glacial drift composition varies greatly and has a correspondingly variable effect on vertical ground-water movement. Well logs indicate that the majority of the drift consists of clay or a clay and sand mix with layers of sand and gravel. Some bedrock valleys contain glacial till which retards vertical flow, while others contain glacial outwash sand and gravel and other coarse deposits that allow rapid ground-water recharge to the Prairie du Chien-Jordan aquifer.

The upgradient end of the DW flowtube is located in a hilly area that includes regional topographic high points within 0.5 to 1 miles of the end of the flowtube. Regional ground-water flow in the Prairie du Chien-Jordan aquifer is from a ground-water divide located in southwestern Dakota County northward to the Minnesota River. The end of the DW flowtube is about 3 to 4 miles downgradient of the ground-water divide (Balaban and Hobbs, 1990). The aquifer is confined by clay-rich glacial drift. The altitude of the potentiometric surface along this flowtube was from 940 ft to 695 ft at the Minnesota River discharge area. Selected water-quality data for DW flowtube wells, discussed in a later section of this report, are listed in table 4.

## Dakota Central Flowtube

The Dakota Central (DC) flowtube extends from southwest to northeast toward the Mississippi River in central Dakota County (fig. 4). The flowtube is on the border of the fault-bound Twin Cities Basin (Balaban and Hobbs, 1990); the presence of geologic faulting and warping of beds is shown on the geologic section for this flowtube (fig. 12). The faults may be significant pathways for recharge to, or ground-water flow in, the aquifer. Most of the St. Peter Sandstone has been eroded and the basal St. Peter confining unit is also absent. Buried bedrock valleys dominate the subsurface bedrock topography. The bedrock valley located beneath the town of Empire extends into the Jordan Sandstone. The glacial drift in the DC flowtube has a higher percent of outwash sand and gravel than all of the other study areas except the DE flowtube.

The upgradient end of the DC flowtube is at the edge of a hilly topographically high area. The high point near well DC5 is a hill near the location of that well only, and did not represent a regional watershed divide. Regional ground-water flow for the Prairie du Chien-Jordan aquifer begins at a ground-water divide in southwestern Dakota County. The upgradient end of the DC flowtube is about 9 miles northeast of the ground-water divide. Within the DC flowtube ground water moves northeastward and discharges to the Mississippi River. The flowtube does not extend to the discharge point due to a lack of wells close to the river. Unlike the HN, HS, and DW flowtubes, the Prairie du Chien-Jordan aquifer is not fully saturated through the length of the flowtube. The potentiometric surface was below the top of the Prairie du Chien part of the aquifer downgradient from the bedrock valley at Empire. The altitude of the potentiometric surface along this flowtube was from 925 ft to 745 ft. The potentiometric surface dropped to 687 ft at the Mississippi River discharge area. Selected water-quality data for DC flowtube wells, discussed in a later section of this report, are listed in table 5.

## Dakota East Flowtube

The Dakota East (DE) flowtube extends from southwest to northeast in east central Dakota County, roughly parallel to the DC flowtube (fig. 4). The bedrock in the flowtube has a complex subsurface structure. Hydrogeology in the area of the DE flowtube is affected by the faulted border of the Twin Cities Basin. Fault displacement and folding of the Jordan Sandstone are evident (fig. 13). Eroded bedrock valleys are present, two of which extend to the St. Lawrence Formation. Where the St. Peter Sandstone is present, well logs indicate that the basal confining unit is absent. The land surface topography of the DE flowtube shows much relief. The glacial drift has a high percent of outwash sand and gravel compared to the other study areas.

The upgradient end of the DE flowtube is in a topographically high area in south-central Dakota County. A regional ground-water divide for the Prairie du Chien-Jordan aquifer is within the DE flowtube, near DE4 (fig. 13). The water-level measurement from DE4 appeared anomalously high, but represents the location of the ground-water divide. Wells DE1-3 are part of another flow system flowing to the southwest. The altitude of the potentiometric surface along this flowtube was at about 930 ft at the ground-water divide near DE4, and decreased northeastward to 675 ft at the Mississippi River discharge area. In the northeastern one-half of the DE flowtube the Prairie du Chien-Jordan aquifer was not fully saturated, with as much as 100 ft of the Prairie du Chien Group above the potentiometric surface. Selected water-quality data for DE flowtube wells, discussed in a later section of this report, are listed in table 6.

## Olmsted Flowtube

The Olmsted (OLM) flowtube extends from the town of Viola westward to the south fork of the Zumbro River (fig. 5). The OLM flowtube differed from the other flowtubes because a bedrock confining layer is present above much of the middle portion of the flowtube (figs 14, 15). The effective thickness of the aquifer is greater in this area (about 500 ft thick) because the basal confining layer of the St. Peter

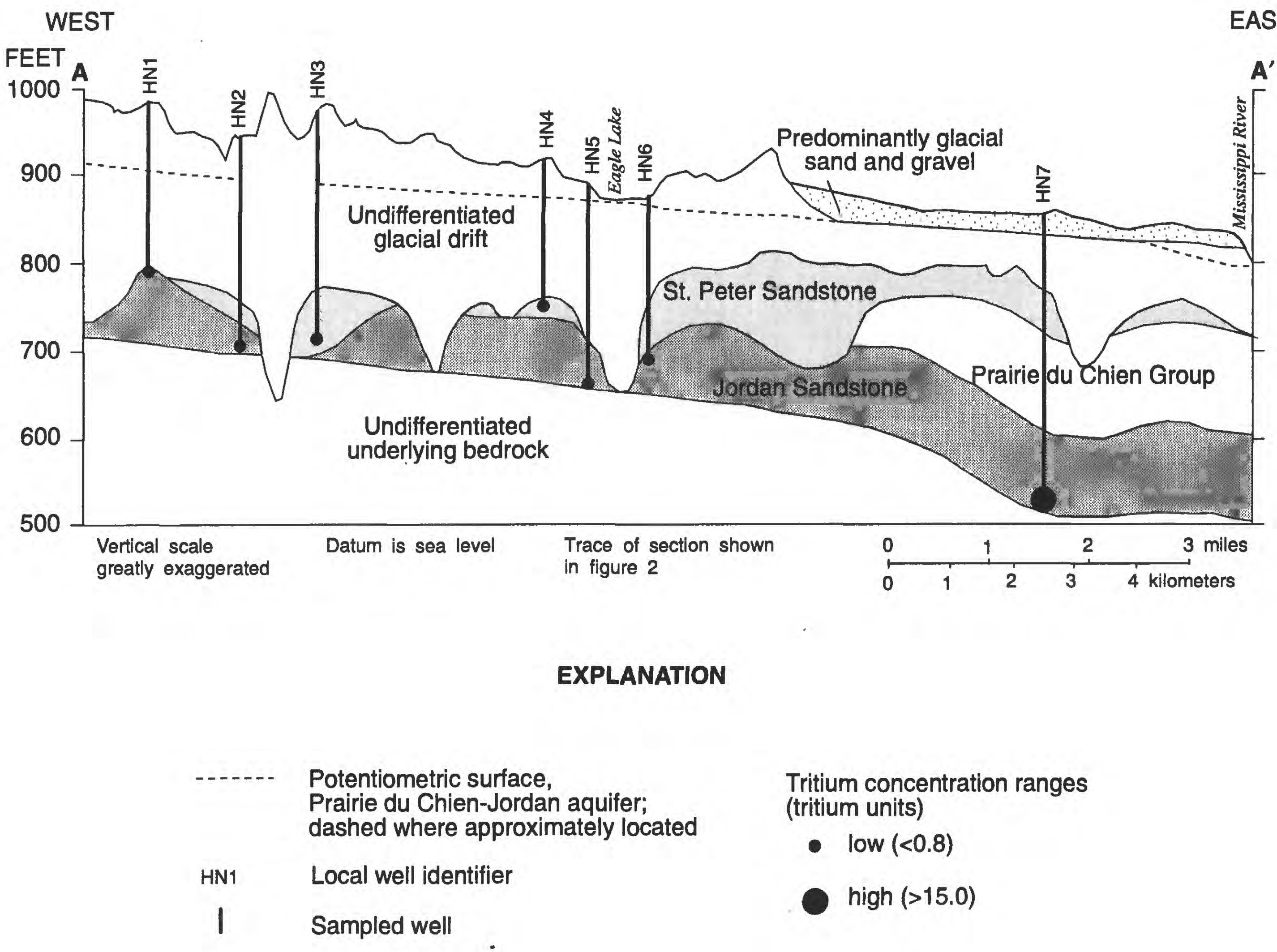


**Figure 9.--Geologic section A-A′ through the Hennepin North flowtube showing wells sampled and tritium concentration ranges (geology modified from driller's well logs and Balaban (1989)).**

### Table 2--Selected water-quality data for the Hennepin North flowtube

[HN, Hennepin North; Stp, St. Peter Sandstone; Jrd, Jordan Sandstone; mg/L, milligrams per liter; TU, tritium units; L, low; H, high; V, volts; µg/L, micrograms per liter; --, not available; <, less than; ≤, less than or equal to; >, greater than; ≥, greater than or equal to]

| Local identifier | HN1 | HN2 | HN3 | HN4 | HN5 | HN6 | HN7 |
|---|---|---|---|---|---|---|---|
| Geologic unit | Jrd | Jrd | Stp | Stp | Jrd | Jrd | Jrd |
| Nitrogen, nitrite plus nitrate, dissolved (mg/L as N) | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 |
| Chloride, dissolved (mg/L as Cl) | 2.9 | 2.9 | 2.7 | 3.5 | 1.6 | 3.4 | 12 |
| Tritium, total (TU) | <.8 | <.8 | <.8 | <.8 | <.8 | <.8 | 25 |
| Triazine herbicide compounds (µg/L) | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 |
| Nitrogen category[1] | L | L | L | L | L | L | L |
| Chloride category[2] | L | L | L | L | L | L | H |
| Tritium category[3] | L | L | L | L | L | L | H |
| Oxygen, dissolved (mg/L) | <.1 | .3 | .2 | .4 | <.1 | .3 | 3.2 |
| Oxidation-reduction potential (V) | -- | -- | -- | - | -.18 | -- | -- |
| Iron, dissolved (µg/L as Fe) | 2400 | 3900 | 230 | 500 | 3200 | 200 | 28 |
| Sulfate, dissolved (mg/L as $SO_4$) | 15 | 7 | 26 | <1 | <1 | 12 | 36 |

[1] Nitrogen concentration categories: low, ≤1.0; medium, >1.0 to ≤10; high, >10 mg/L

[2] Chloride concentration categories: low, ≤5.0; medium, >5.0 to ≤10; high, >10 mg/L

[3] Tritium concentration categories: low, <0.8; medium, ≥0.8 to ≤15; high, >15 TU

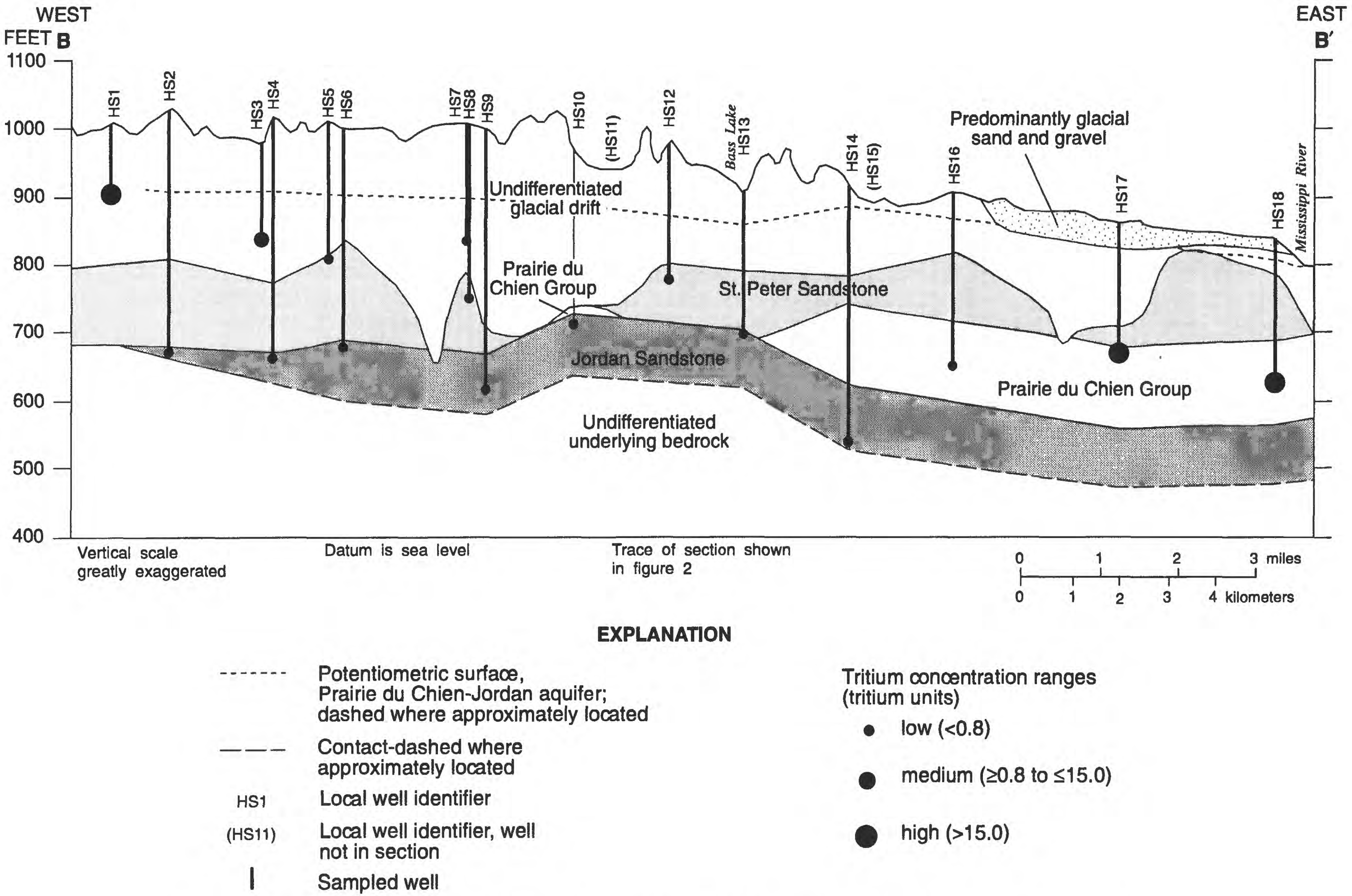


**Figure 10.--Geologic section B-B′ through the Hennepin South flowtube showing wells sampled and tritium concentration ranges (geology modified from driller's logs and Balaban (1989)).**

## Table 3.--Selected water-quality data for the Hennepin South flowtube

[HS, Hennepin South; Qua, glacial drift; Stp, St. Peter Sandstone; Pdc, Prairie du Chien Group; Jrd, Jordan Sandstone; mg/L, milligrams per liter; TU, tritium units; ND, not detected; L, low; M, medium; H, high; V, volts; µg/L, micrograms per liter; --, not available; <, less than; ≤, less than or equal to; >, greater than; ≥, greater than or equal to]

| Local identifier | HS1 | HS2 | HS3 | HS4 | HS5 | HS6 | HS7 | HS8 | HS9 | HS10 | [1]HS11 | HS12 | HS13 | HS14 | [1]HS15 | HS16 | HS17 | HS18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Geologic unit | Qua | Jrd | Qua | Jrd | Stp | Jrd | Qua | Stp | Jrd | Jrd | Pdc | Stp | Jrd | Jrd | Pdc | Pdc | Pdc | Pdc |
| Nitrogen, nitrite plus nitrate, dissolved (mg/L as N) | <0.1 | <0.1 | <0.1 | 0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 |
| Chloride, dissolved (mg.L as C1) | 23 | 2.8 | 4.4 | 2.7 | <.10 | 2.7 | 3.0 | 3.5 | 3.1 | 2.5 | 3.5 | 3.6 | 2.8 | 4.3 | 6.1 | <.10 | 51 | 35 |
| Tritium, total (TU) | 31 | <.8 | 5.0 | <.8 | <.8 | <.8 | <.8 | <.8 | <.8 | <.8 | .9 | <.8 | <.8 | <.8 | <.8 | <.8 | 58 | 32 |
| Triazine herbicide compounds (µg/L) | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 |
| Nitrogen category[2] | L | L | L | L | L | L | L | L | L | L | L | L | L | L | L | L | L | L |
| Chloride category[3] | H | L | L | L | L | L | L | L | L | L | L | L | L | L | M | L | H | H |
| Tritium category[4] | H | L | M | L | L | L | L | L | L | L | M | L | L | L | L | L | H | H |
| Oxygen, dissolved (mg/L) | .1 | <.1 | .2 | <.1 | <.1 | <.1 | <.1 | .1 | .2 | <.1 | <.1 | .3 | 2.5 | .4 | <.1 | .1 | <.1 | 4.5 |
| Oxidation reduction potential (V) | -.19 | -.15 | -.19 | -.19 | -.19 | -.18 | -.11 | -.13 | .02 | -.12 | -.10 | -- | -.18 | -- | -- | -.10 | -.22 | -- |
| Iron, dissolved (µg/L as Fe) | 8400 | 3100 | 8500 | 4900 | 1400 | 3600 | 430 | 2800 | 210 | 380 | 1200 | 710 | 3400 | 810 | 860 | 120 | 5000 | 580 |
| Sulfate, dissolved (mg/L as $SO_4$) | 7 | 13 | 15 | 3 | 2 | 3 | 5 | 8 | 12 | 2 | 32 | 13 | 3 | 3 | 8 | 3 | 24 | 150 |

[1] Well not on cross section.

[2] Nitrogen concentration categories: low, ≤1.0; medium, >1.0 to ≤10; high, >10 mg/L.

[3] Chloride concentration categories: low, ≤5.0; medium, >5.0 to ≤10; high, >10 mg/L.

[4] Tritium concentration categories: low, <0.8; medium, ≥0.8 to ≤15; high, >15 TU.

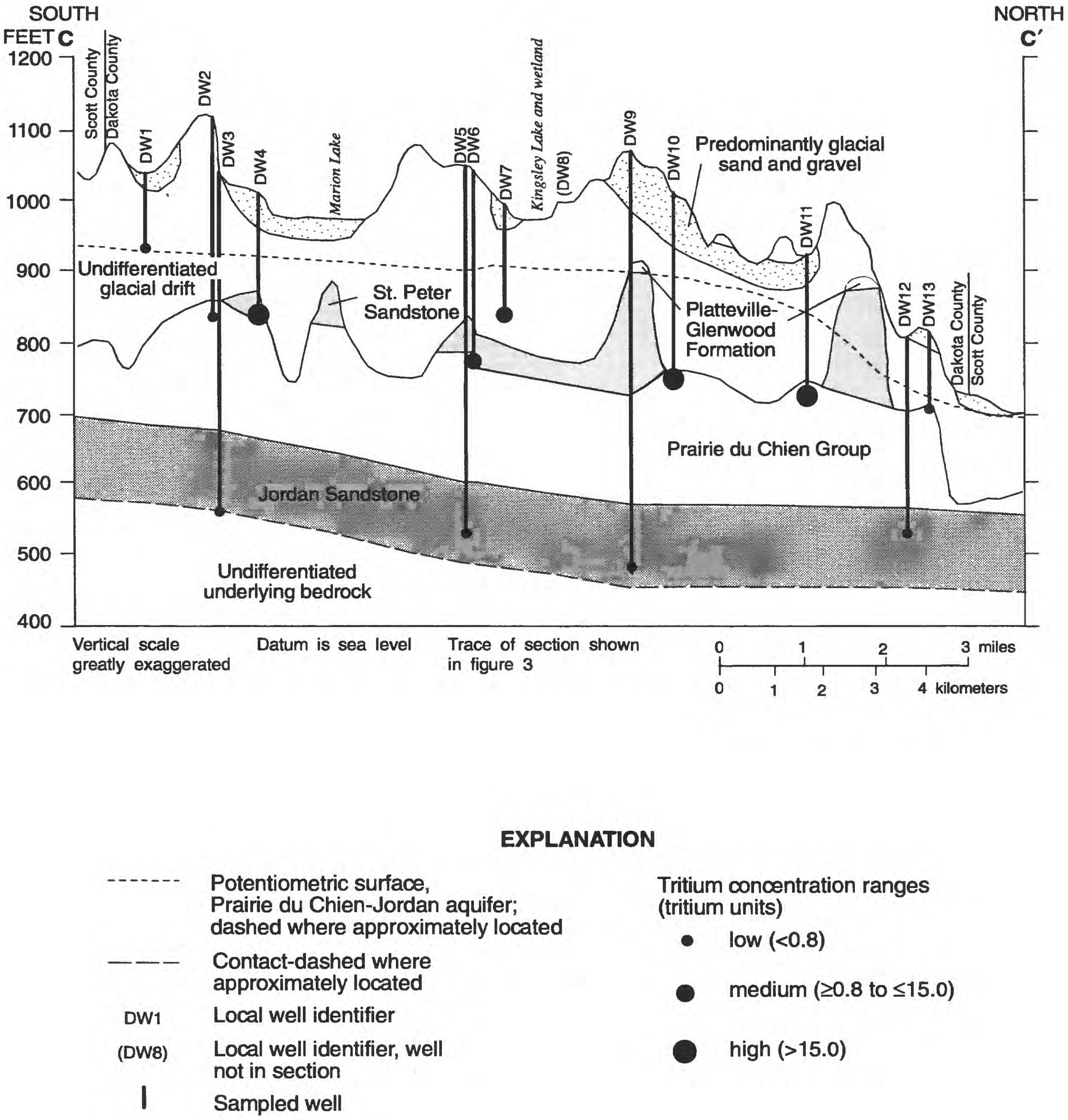


**Figure 11.**--Geologic section C-C′ through the Dakota West flowtube showing wells sampled and tritium concentration ranges (geology modified from driller's logs and Balaban and Hobbs (1990)).

## Table 4.--Selected water-quality data for the Dakota West flowtube

[DW, Dakota West; Qua, glacial drift; Stp, St. Peter Sandstone; Pdc, Prairie du Chien Group; Jrd, Jordan Sandstone; mg/L, milligrams per liter; TU, tritium units; L, low; M, medium; H, high; V, volts; mg/L, micrograms per liter; --, not available; <, less than; ≤, less than or equal to; >, greater than; ≥, greater than or equal to]

| Local identifier | DW1 | DW2 | DW3 | DW4 | DW5 | DW6 | DW7 | [1]DW8 | DW9 | DW10 | DW11 | DW12 | DW13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Geologic unit | Qua | Pdc | Jrd | Stp | Jrd | Stp | Qua | Pdc | Jrd | Pdc | Pdc | Jrd | Pdc |
| Nitrogen, nitrite plus nitrate, dissolved (mg/L as N) | <0.1 | <0.1 | <0.1 | 0.3 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 |
| Chloride, dissolved (mg/L as Cl) | 3.0 | 2.1 | 2.5 | 14 | 7.9 | 2.6 | 3.1 | 51 | 2.6 | 13 | 11 | 3.4 | 4.5 |
| Tritium, total (TU) | <.8 | <.8 | <.8 | 17 | <.8 | 8.0 | 2.7 | 29 | <.8 | 20 | 23 | <.8 | <.8 |
| Triazine herbicide compounds (µg/L) | <10 | <10 | <10 | <10 | <10 | <.10 | <10 | <10 | <.10 | <10 | .3 | <10 | <10 |
| | | | | | | | | | | | | | |
| Nitrogen category[2] | L | L | L | L | L | L | L | L | L | L | L | L | L |
| Chloride category[3] | L | L | L | H | M | L | L | H | L | H | H | L | L |
| Tritium category[4] | L | L | L | H | L | M | M | H | L | H | H | L | L |
| | | | | | | | | | | | | | |
| Oxygen, dissolved (mg/L) | <.1 | <.1 | 2.1 | .3 | 7.8 | <.1 | 7.1 | .3 | 4.1 | <.1 | <.1 | .6 | .1 |
| Oxidation-reduction potential (V) | -- | -- | -- | -- | -- | -.16 | -- | -- | .02 | -.13 | -.14 | -.01 | -.08 |
| Iron, dissolved (µg/L as Fe) | 1400 | 1900 | 890 | 460 | <10 | 1400 | 1000 | 8700 | 50 | 1200 | 910 | 50 | 170 |
| Sulfate, dissolved (mg/L as $SO_4$) | 6 | 14 | 20 | 49 | 2 | 1 | 19 | 32 | 1 | 34 | 39 | 2 | 22 |

[1] Well not on cross section.

[2] Nitrogen concentration categories: low, ≤1.0; medium, >1.0 to ≤10; high, >10 mg/L.

[3] Chloride concentration categories: low, ≤5.0; medium, >5.0 to ≤10; high, >10 mg/L.

[4] Tritium concentration categories: low, <0.8; medium, ≥0.8 to ≤15; high, >15 TU.

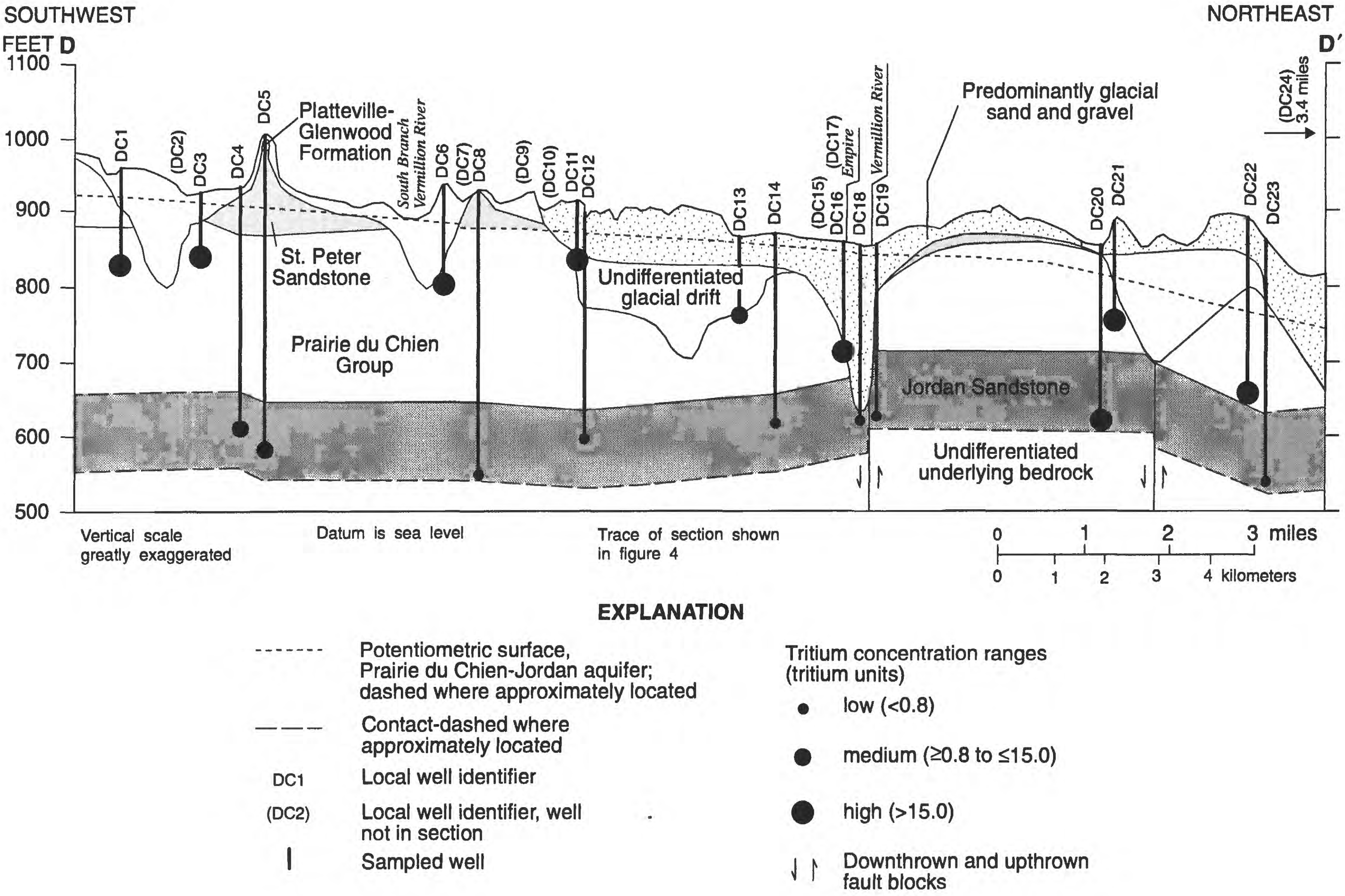


Figure 12.--Geologic section D-D′ through the Dakota Central flowtube showing wells sampled and tritium concentration ranges (geology modified from driller's well logs and Balaban and Hobbs (1990)).

## Table 5.--Selected water-quality data for the Dakota Central flowtube

[DC, Dakota Central; Pdc, Prairie du Chien Group; Jrd, Jordan Sandstone; mg/L, milligrams per liter; TU, tritium units; L, low; M, medium; H, high; V, volts; µg/L, micrograms per liter; --, not available; <, less than; ≤, less than or equal to; >, greater than; ≥, greater than or equal to]

| Local identifier | DC1 | [1]DC2 | DC3 | DC4 | DC5 | DC6 | [1]DC7 | DC8 | [1]DC9 | [1]DC10 | DC11 | DC12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Geologic unit | Pdc | Pdc | Pdc | Jrd | Jrd | Pdc | Jrd | Jrd | Pdc | Pdc | Pdc | Jrd |
| Nitrogen, nitrite plus nitrate, dissolved (mg/L as N) | 4.2 | 7.2 | 8.0 | <0.1 | <0.1 | 6.8 | <0.1 | <0.1 | 4.0 | 0.12 | 11.0 | <0.1 |
| Chloride, dissolved (mg/L as Cl) | 8.8 | 14 | 21 | 4.5 | .9 | 9.1 | 2.0 | 2.3 | 5.6 | .6 | 11 | 4.1 |
| Tritium, total (TU) | 17 | 34 | 34 | 13 | 1.9 | 18 | <.8 | <.8 | 17 | 9.9 | 50 | <.8 |
| Triazine herbicide compounds (µg/L) | <.1 | .5 | .3 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 |
| Nitrogen category[2] | M | M | M | L | L | M | L | L | M | L | H | L |
| Chloride category[3] | M | H | H | L | L | M | L | L | M | L | H | L |
| Tritium category[4] | H | H | H | M | M | H | L | L | H | M | H | L |
| Oxygen, dissolved (mg/L) | 6.9 | 6.5 | 6.2 | <.1 | <.1 | 4.6 | <.1 | .1 | 5.5 | .1 | 6.9 | <.1 |
| Oxidation-reduction potential (V) | -- | .15 | -- | -- | -.17 | .12 | -- | -.14 | -- | -.04 | .11 | -.15 |
| Iron, dissolved (µg/L as Fe) | 10 | 10 | 8 | 710 | 1700 | 5 | 1400 | 2100 | 6 | 120 | 5 | 1500 |
| Sulfate, dissolved (mg/L as $SO_4$) | 12 | 32 | 30 | 63 | 44 | 26 | 16 | 18 | 30 | 36 | 19 | 28 |

Table 5.--Selected water-quality data for the Dakota Central flowtube--Continued

| Local identifier | DC13 | DC14 | [1]DC15 | DC16 | [1]DC17 | DC18 | DC19 | DC20 | DC21 | DC22 | DC23 | [1]DC24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Geologic unit | Pdc | Jrd | Pdc | Pdc | Pdc | Jrd | Jrd | Jrd | Pdc | Pdc | Jrd | Jrd |
| Nitrogen, nitrite plus nitrate, dissolved (mg/L as N) | <0.1 | <0.1 | 14.0 | 14.0 | 11.0 | <0.1 | 0.1 | 5.2 | 4.9 | 6.2 | <0.1 | <0.1 |
| Chloride, dissolved (mg/L as Cl) | 1.4 | .1 | 15 | 14 | 13 | .9 | 2.1 | 6.0 | 10 | 8.3 | 1.8 | 2.1 |
| Tritium, total (TU) | 1.0 | <.8 | 18 | 20 | 17 | <.8 | <.8 | 21 | 38 | 15 | <.8 | <.8 |
| Triazine herbicide compounds (μg/L) | <.1 | <.1 | 1.0 | .4 | .1 | <.1 | <.1 | .3 | <.1 | <.1 | <.1 | <.1 |
| Nitrogen category[2] | L | L | H | H | H | L | L | M | M | M | L | L |
| Chloride category[3] | L | L | H | H | H | L | L | M | M | M | L | L |
| Tritium category[4] | M | L | H | H | H | L | L | H | H | H | L | L |
| Oxygen, dissolved (mg/L) | <.1 | <.1 | 4.6 | 4.6 | 4.7 | <.1 | <.1 | -- | 8.8 | 6.6 | <.1 | .7 |
| Oxidation-reduction potential (V) | -.14 | -.13 | .15 | .11 | .15 | -.15 | -.16 | .09 | -- | .18 | -.16 | -- |
| Iron, dissolved (μg/L as Fe) | 670 | 1300 | 9 | 4 | 3 | 1300 | 1300 | 14 | 9 | 4 | 1800 | 200 |
| Sulfate, dissolved (mg/L as $SO_4$) | 15 | 21 | 27 | 21 | 28 | 17 | 21 | 11 | 29 | 23 | 16 | 17 |

[1] Well not on cross section.

[2] Nitrogen concentration categories: low, ≤1.0; medium, >1.0 to ≤10; high, >10 mg/L.

[3] Chloride concentration categories: low, ≤5.0; medium, >5.0 to ≤10; high, >10 mg/L.

[4] Tritium concentration categories: low, <0.8; medium, ≥0.8 to ≤15; high, >15 TU.

Sandstone is absent and the St. Peter aquifer is hydraulically connected to the Prairie du Chien-Jordan aquifer. In addition, the OLM flowtube is closer to the center of the Hollandale Embayment where the Prairie du Chien Group is thicker. The Galena Formation and the Prairie du Chien Group both have karstic features in this flowtube. The Platteville Formation can yield enough water for domestic use in some places. Two of the wells in this flowtube, LS2 and LS10, obtain water from this unit. Glacial drift in the OLM flowtube is thin to absent and consists mostly of pre-Illinoian till, loess, and alluvium deposits.

The topographic surface-water divide for the OLM flowtube is in the central part of the flowtube. The upgradient end of the flowtube is at a regional ground-water divide for the Prairie du Chien-Jordan aquifer. Where the Decorah-Platteville-Glenwood confining unit is present vertical ground-water flow from the land surface to the Prairie du Chien-Jordan aquifer is retarded (Delin, 1991). The buried and surficial bedrock valleys in the OLM flowtube are pathways for water recharging the aquifer. The altitude of the potentiometric surface was at about 1,080 ft at the ground-water divide on the eastern end of the flowtube and decreased to about 950 ft at the Zumbro River discharge area. The Prairie du Chien-Jordan aquifer was not fully saturated throughout the length of the flowtube in places where the St. Peter aquifer is considered as part of the Prairie du Chien-Jordan aquifer. Selected water-quality data for the LN and LS parts of the flowtube wells, discussed in a later section of this report, are listed in tables 7 and 8.

## Water Quality

### Regional and Historical Water Quality

Water within the Prairie du Chien-Jordan aquifer was calcium-magnesium-bicarbonate type regardless of depth. Piper diagrams showing the major-ion characteristics of water from the Prairie du Chien and the Jordan parts of the aquifer in the DC and OLM flowtubes illustrate the similarity of water from the two parts of the aquifer (fig. 16). The principal difference between the two parts of the aquifer was that the cations and anions plotted in a tighter cluster for water from the Jordan than for water from the Prairie du Chien. Outliers from the groups of data points on the anion part of the Piper diagrams were related to greater than average $NO_3$-N, Cl, or sulfate ($SO_4$) concentrations. There was no discernible change in major-ion water chemistry from the upgradient to the downgradient end of the flowtubes. The chemical characteristics of water from the Prairie du Chien and Jordan parts of the aquifer for all of the flowtubes was similar to that shown in figure 16.

Table 9 lists median constituent concentrations in the Prairie du Chien and Jordan parts of the aquifer as reported by Maderak (1963, 1965), Norvitch and others (1973), and this investigation. The historical comparison of median water chemistry concentrations revealed similar constituent concentrations in the two parts of the aquifer. Several changes were apparent over time. Median concentrations of $NO_3$-N increased from less than 1.0 to 3.6 mg/L in the Prairie du Chien, but no change was observed in the Jordan. Median Cl concentrations increased in the Prairie du Chien from 1.2 to 11 mg/L and in the Jordan from 0.20 to 3.0 mg/L. Median $SO_4$ concentrations increased in the Jordan from 7.5 to 17 mg/L. Median iron (Fe) concentrations decreased in the Prairie du Chien from 330 to 20 micrograms per liter (µg/L), and median manganese (Mn) concentrations decreased in the Prairie du Chien from 90 to 10 µg/L. Median Fe concentrations increased in the Jordan from 260 to 670 µg/L. Median phosphorus concentrations decreased over time in both the Prairie du Chien and Jordan from about 0.20 to 0.01 mg/L. The changes listed above may have been influenced by the different wells from which water was sampled in the four studies that are summarized in table 9, or by localized constituent concentration variations; however some of the changes are strong enough to suggest a trend over time (for example the changes in Cl and Fe concentrations).

Table 10 lists median constituent concentrations from this study by flowtube and part of the aquifer. Compared to the Prairie du Chien part of the aquifer, water from the Jordan part of the aquifer generally had lower or similar median values of sulfate, chloride, and nitrate; slightly lower or similar median values of silica, calcium, total dissolved solids, and specific conductance. Bicarbonate, magnesium, fluoride, and pH had similar median values in the two parts of the aquifer. These relative concentrations also were present in the historical data set (table 9). No consistent trends in water chemistry were apparent along the project flowtubes: there was no general increase in total dissolved solids or Cl concentrations, or in the ratio of magnesium to calcium, with increasing distance along the flowtubes as has been identified in other flow path studies (Hem, 1985; Siegel, 1989). The short length of the flowtubes on a regional scale, and the infiltration of precipitation along the length of the flowtubes, could be reasons for the absence of water-chemistry trends along the flowtubes.

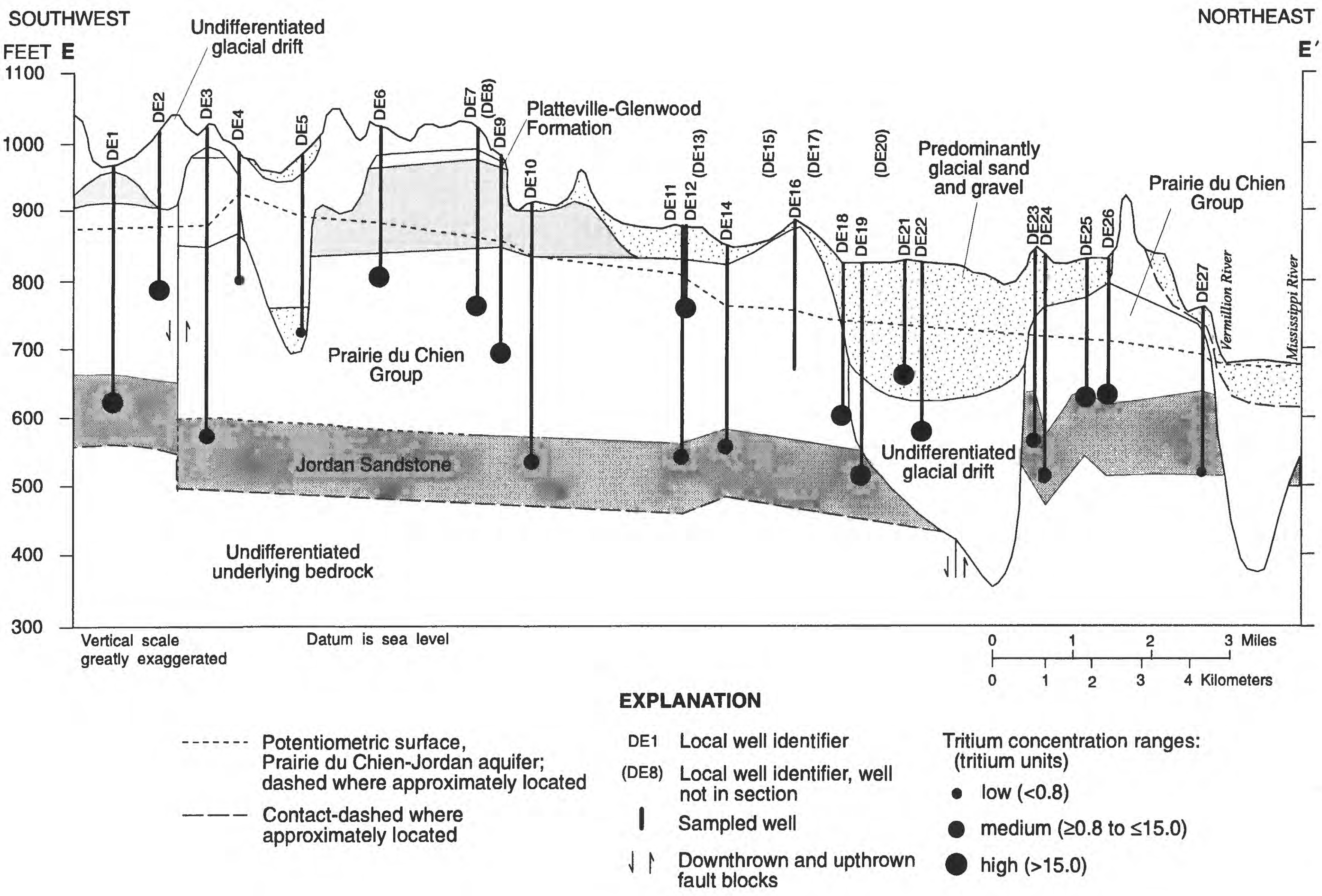


**Figure 13.--Geologic section E-E′ through the Dakota East flowtube showing wells sampled and tritium concentration ranges (geology modified from driller's logs and Balaban and Hobbs (1990)).**

## Table 6.--Selected water-quality data for the Dakota East flowtube

[DE, Dakota East; Qua, glacial drift; Pdc, Prairie du Chien Group; Jrd, Jordan Sandstone; mg/L, milligrams per liter; TU, tritium units; L, low; M, medium; H, high; V, volts; µg/L, micrograms per liter; --, not available; <, less than; ≤, less than or equal to; >, greater than; ≥, greater than or equal to]

| Local identifier | DE1 | DE2 | DE3 | DE4 | DE5 | DE6 | DE7 | [1]DE8 | DE9 | DE10 | DE11 | DE12 | [1]DE13 | DE14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Geologic unit | Jrd | Pdc | Jrd | Pdc | Qua | Pdc | Pdc | Pdc | Pdc | Jrd | Jrd | Pdc | Pdc | Jrd |
| Nitrogen, nitrite plus nitrate, dissolved (mg/L as N) | 8.1 | 3.7 | <0.1 | <0.1 | <0.1 | 5.6 | 3.4 | 1.0 | 1.4 | <0.1 | 4.3 | 24.0 | 40.0 | 2.7 |
| Chloride, dissolved (mg/L as Cl) | 13 | 15 | 4.0 | 1.9 | 1.9 | 10 | 16 | 56 | 10 | 2.0 | 7.9 | 47 | 160 | 5.3 |
| Tritium, total (TU) | 53 | 26 | 2.1 | <.8 | <.8 | 17 | 25 | <.8 | 42 | 1.7 | 1.0 | 30 | 31 | 3.0 |
| Triazine herbicide compounds (µg/L) | .3 | .2 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 | .2 | .3 | <.1 |
| Nitrogen category[2] | M | M | L | L | L | M | M | M | M | L | M | H | H | M |
| Chloride category[3] | H | H | L | L | L | M | H | H | M | L | M | H | H | M |
| Tritium category[4] | H | H | M | L | L | H | H | L | H | M | M | H | H | M |
| Oxygen, dissolved (mg/L) | 7.0 | 1.7 | .2 | .2 | <.1 | 7.8 | 5.1 | .4 | <.1 | 1.0 | 2.4 | 7.7 | 11.0 | .8 |
| Oxidation-reduction potential (V) | .14 | .08 | -.12 | -.10 | -.16 | .19 | -- | .02 | .03 | -.15 | .10 | .14 | .24 | .08 |
| Iron, dissolved (µg/L as Fe) | 7 | 11 | 180 | 260 | 750 | 110 | <15 | 15 | 40 | 2000 | 7 | 11 | 11 | 8 |
| Sulfate, dissolved (mg/L as $SO_4$) | 23 | 61 | 30 | 9 | 20 | 14 | 56 | 22 | 88 | 24 | 21 | 34 | 34 | 18 |

### Table 6.--Selected water-quality data for the Dakota East flowtube--Continued

| Local identifier | [1]DE15 | DE16 | [1]DE17 | DE18 | DE19 | [1]DE20 | DE21 | DE22 | DE23 | DE24 | DE25 | DE26 | DE27 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Geologic unit | Jrd | Pdc | Jrd | Pdc | Jrd | Jrd | Qua | Qua | Jrd | Jrd | Jrd | Pdc | Jrd |
| Nitrogen, nitrite plus nitrate, dissolved (mg/L as N) | 4.0 | 0.4 | 2.8 | 10.0 | 6.0 | 5.7 | 15.0 | 15.0 | 4.4 | <0.1 | 5.5 | 6.6 | <0.1 |
| Chloride, dissolved (mg/L as Cl) | 15 | 4.3 | 13 | 6.0 | 14 | 16 | 18 | 20 | 3.0 | 4.0 | 14 | 15 | 1.4 |
| Tritium, total (TU) | 28 | -- | 23 | 19 | 17 | 30 | 44 | 35 | 2.0 | 1.4 | 49 | 50 | .8 |
| Triazine herbicide compounds (µg/L) | <.1 | <.1 | .3 | <.1 | .2 | <.1 | .2 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 |
| Nitrogen category[2] | M | L | M | M | M | M | H | H | M | L | M | M | L |
| Chloride category[3] | H | L | H | M | H | H | H | H | L | L | H | H | L |
| Tritium category[4] | H | -- | H | H | H | H | H | H | M | M | H | H | L |
| Oxygen, dissolved (mg/L) | -- | <.1 | 8.1 | -- | 8.8 | 9.8 | 7.8 | -- | 5.6 | <.1 | 9.5 | 9.4 | .1 |
| Oxidation-reduction potential (V) | -- | -.17 | .28 | -- | .20 | .15 | .08 | -- | -- | -.14 | .14 | .08 | -.12 |
| Iron, dissolved (µg/L as Fe) | 4 | 910 | 5 | 25 | 7 | 3 | 12 | <3 | <3 | 900 | 4 | 20 | 620 |
| Sulfate, dissolved (mg/L as $SO_4$) | 66 | 24 | 23 | 17 | 57 | 13 | 20 | 17 | 15 | 40 | 16 | 17 | 17 |

[1] Well not on cross section.

[2] Nitrogen concentration categories: low, ≤1.0; medium, >1.0 to ≤10; high, >10 mg/L.

[3] Chloride concentration categories: low, ≤5.0; medium, >5.0 to ≤10; high, >10 mg/L.

[4] Tritium concentration categories: low, <0.8; medium, ≥0.8 to ≤15; high, >15 TU.

The indicator-constituent concentrations were grouped into ranges of low, medium, and high for purposes of statistical testing. The $NO_3$-N concentration ranges were: low (less than or equal to 1.0 mg/l), medium (greater than 1.0 to less than or equal to 10 mg/l), and high (greater than 10 mg/l). The Cl concentration ranges were: low (less than or equal to 5.0 mg/l), medium (greater than 5 to less than or equal to 10 mg/l), and high (greater than 10 mg/l). The tritium concentration ranges were: low (less than 0.8 TU), medium (greater than or equal to 0.8 to less than or equal to 15 TU), and high (greater than 15 TU). The distribution of tritium concentrations and the number of samples in each concentration range are shown on figure 17, by geologic or hydrogeologic unit. The detection limit for the tritium analysis (0.8 TU) was used as the break between low (old water) and medium (mixed water) tritium concentrations. A tritium concentration of 15 TU was used as the break between medium and high (recent water) tritium concentrations.

Triazine herbicide compound concentrations were below the immunoassay detection limit of 0.10 µg/L for 112 of the 139 wells. Results of the triazine herbicide immunoassay analysis were used to label the wells as having either a detect or no detect for triazine family herbicides. Thirteen percent of the samples from the Jordan part of the aquifer (8 of 60 samples) and 28 percent of samples from the Prairie du Chien part of the aquifer (16 of 58 samples) had detectable triazine herbicides.

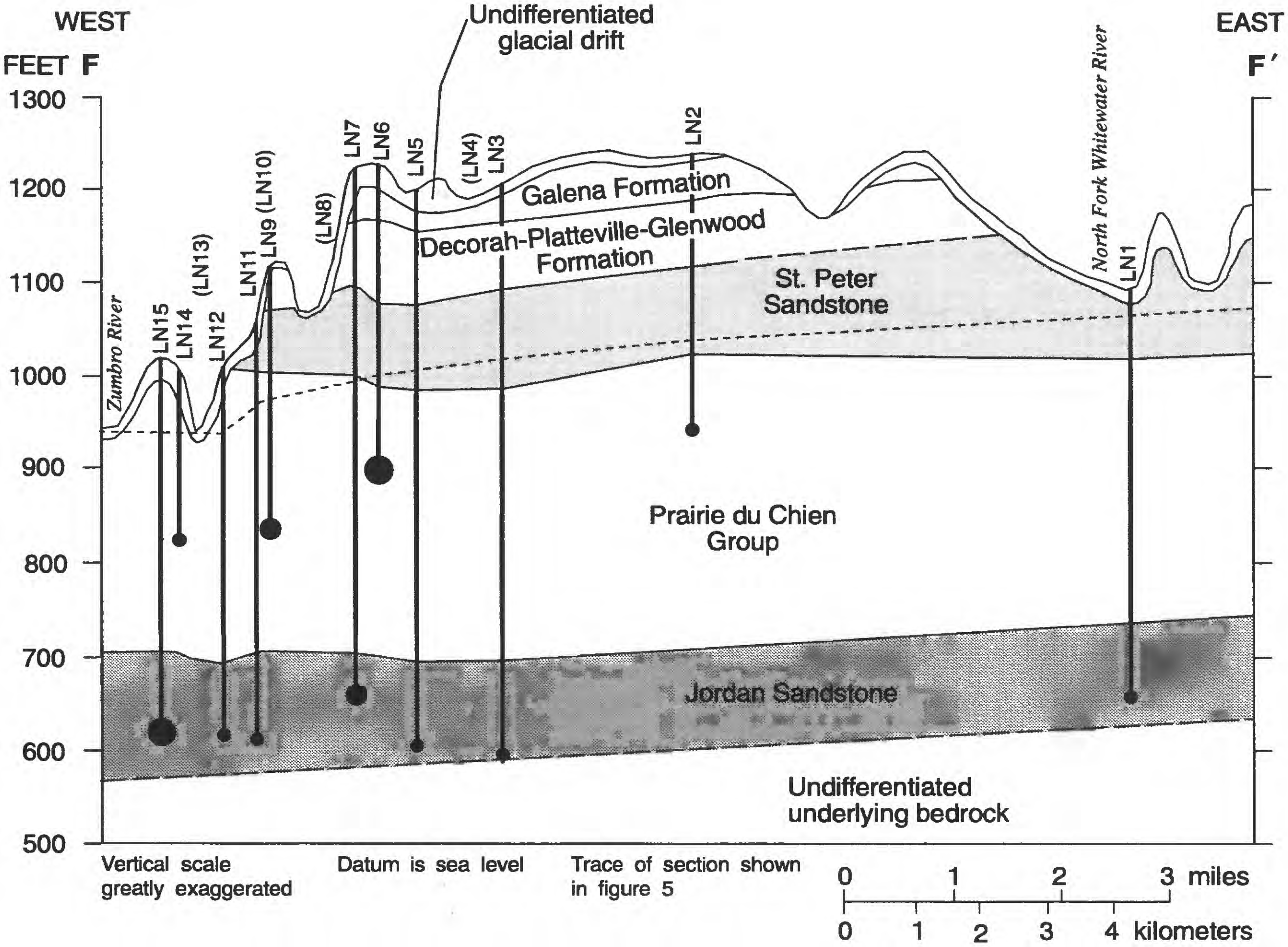
$NO_3$-N, Cl, and tritium concentrations by flowtube and part of the aquifer are shown in figure 18. The median and range of $NO_3$-N, Cl, and tritium concentrations were greater in the Prairie du Chien part of the aquifer than they were in the Jordan part of the aquifer. Tritium concentrations at the open intervals of the sampled wells are shown on the flowtube geologic sections by circles representing the concentration ranges (figs. 9-15). Two-thirds of the Jordan samples (40 of 60 samples) had undetectable tritium, indicating that most of the water entered the ground-water system before 1954 (fig. 17). About two-thirds of the Prairie du Chien samples (35 of 56 samples) had tritium concentrations representative of recent water which would have entered the ground-water system in 1954 or later. The greater median and range of indicator-constituent concentrations in water from the Prairie du Chien indicates a greater variability in the age and mixing of these waters, a shorter ground-water residence time to the Prairie du Chien part of the aquifer, and a greater susceptibility to contamination, compared to water from the Jordan part of the aquifer.

WATEQF, a water chemical-equilibrium calculation program (Truesdell and Jones, 1974; Plummer and others, 1976), was used to calculate mineral saturation indices (SI) for all samples. The SI of calcite, dolomite, quartz, sepiolite, gypsum, and goethite are listed in tables 15 to 17 in the Supplemental Information Section. These minerals were chosen because they represent possible source or sink minerals for major dissolved cations and anions. Figure 19 shows the average SI for these minerals by Prairie du Chien or Jordan part of the aquifer in the DE flowtube. Results from the WATEQF analysis for all of the flowtubes were similar to these and indicated that: (1) water from the Prairie du Chien and Jordan parts of the aquifer was geochemically similar, (2) water from both parts of the aquifer in all of the flowtubes was near saturation for calcite, dolomite, and quartz; undersaturated for sepiolite and gypsum; and oversaturated for goethite, and (3) there was little apparent difference between water samples collected at the upgradient and the downgradient ends of the flowtubes.

Oxidation-reduction (redox) conditions in the Prairie du Chien-Jordan aquifer were analyzed to assess their relation to the distribution of indicator-constituent concentrations. Constituents indicative of redox condition and used in the analysis were: redox potential as determined by platinum electrode measurements (Eh), $NO_3$-N, dissolved oxygen (DO), Fe, and ammonium ($NH_4$) concentrations. Data from tables 2-8 in conjunction with figures 9-15 indicate the distribution of Eh, $NO_3$-N, DO, and Fe along the geologic sections. Eh is an approximate measurement of ground-water redox condition. Negative Eh indicates reducing conditions in the aquifer; positive Eh indicates oxidizing conditions (Postma and others, 1991). Areas of the aquifer with negative Eh had very low DO, low to undetectable $NO_3$-N, and higher Fe and $NH_4$ concentrations, compared to areas of the aquifer with positive Eh.

## Hennepin North and Hennepin South Flowtube

Indicator-constituent concentrations were primarily in the low range throughout the Jordan part of the aquifer in the HN and HS flowtubes (tables 2, 3). The only sample from the Jordan part of the aquifer having high Cl and tritium concentrations was from well HN7, which is near the discharge area for the HN flowtube (fig. 9). Indicator-constituent concentrations varied more widely in the Prairie du Chien part of the aquifer in the HS flowtube. Samples from Prairie du Chien wells HS11, 15, and 16 had primarily low indicator-constituent concentrations, but samples from



**EXPLANATION**

| | |
|---|---|
| - - - - - - - | Potentiometric surface, Prairie du Chien-Jordan aquifer; dashed where approximately located |
| — — — | Contact-dashed where approximately located |
| LN15 | Local well identifier |
| (LN10) | Local well identifier, well not in section |
| \| | Sampled well |

Tritium concentration ranges (tritium units)

| | |
|---|---|
| • | low (<0.8) |
| ● | medium (≥0.8 to ≤15.0) |
| ⬤ | high (>15.0) |

Figure 14.--Geologic section F-F′ through the northern part of the Olmsted flowtube showing wells sampled and tritium concentration ranges (geology modified from driller's logs and Balaban (1988)).

## Table 7.--Selected water-quality data for the northern part of the Olmsted flowtube

[LN, northern part of the Olmsted; Pdc, Prairie du Chien Group; Jrd, Jordan Sandstone; mg/L, milligrams per liter; TU, tritium units; L, low; M, medium; H, high; V, volts; μg/L, micrograms per liter; --, not available; <, less than; ≤, less than or equal to; >, greater than; ≥, greater than or equal to]

| Local identifier | LN15 | LN14 | [1]LN13 | LN12 | LN11 | [1]LN10 | LN9 |
|---|---|---|---|---|---|---|---|
| Geologic unit | Jrd | Pdc | Jrd | Jrd | Jrd | Pdc | Pdc |
| Nitrogen, nitrite plus nitrate, dissolved (mg/L as N) | 1.9 | <0.1 | <0.1 | <0.1 | <0.1 | 3.0 | <0.1 |
| Chloride, dissolved (mg/L as Cl) | 9.1 | 10.0 | .8 | 3.3 | 1.8 | 7.5 | 2.4 |
| Tritium, total (TU) | 21 | .8 | <.8 | <.8 | <.8 | 13 | <.8 |
| Triazine herbicide compounds (μg/L) | .1 | <.1 | <.1 | <.1 | <.1 | <.1 | .2 |
| Nitrogen category[2] | M | L | L | L | L | L | M |
| Chloride category[3] | M | M | L | L | L | L | M |
| Tritium category[4] | H | L | L | L | L | L | M |
| Oxygen, dissolved (mg/L) | 6.3 | 1.9 | 7.3 | 7.6 | .1 | 10.7 | 2.4 |
| Oxidation-reduction potential (V) | .14 | -- | .14 | -.02 | -- | -- | .23 |
| Iron, dissolved (μg/L as Fe) | <3 | 190 | 79 | 390 | 35 | 10 | 80 |
| Sulfate, dissolved (mg/L as $SO_4$) | 21 | 22 | 19 | 27 | 17 | 24 | 23 |

## Table 7.--Selected water-quality data for the northern part of the Olmsted flowtube--Continued

| Local identifier | [1]LN8 | LN7 | LN6 | LN5 | [1]LN4 | LN3 | LN2 | LN1 |
|---|---|---|---|---|---|---|---|---|
| Geologic unit | Pdc | Jrd | Pdc | Jrd | Pdc | Jrd | Pdc | Jrd |
| Nitrogen, nitrite plus nitrate, dissolved (mg/L as N) | <0.1 | 0.3 | 1.3 | <0.1 | 1.0 | <0.1 | 0.1 | <0.1 |
| Chloride, dissolved (mg/L as Cl) | 2.6 | 2.4 | 5.3 | 2.1 | 3.8 | 1.3 | <.1 | 2.1 |
| Tritium, total (TU) | 3.3 | 2.0 | 16 | <.8 | 8.7 | <.8 | <.8 | <.8 |
| Triazine herbicide compounds (μg/L) | <.1 | <.1 | <.1 | <.1 | <.1 | .3 | <.1 | <.1 |
| Nitrogen category[2] | L | L | M | L | M | L | L | L |
| Chloride category[3] | L | L | M | L | L | L | L | L |
| Tritium category[4] | M | M | H | L | M | L | L | L |
| Oxygen, dissolved (mg/L) | 6.4 | 4.9 | 9.1 | .3 | 2.1 | <.1 | .1 | .3 |
| Oxidation-reduction potential (V) | -- | .06 | .13 | -- | .12 | -.18 | -.10 | -- |
| Iron, dissolved (μg/L as Fe) | 75 | 23 | <3 | 2700 | 12 | 5500 | 2700 | 2100 |
| Sulfate, dissolved (mg/L as $SO_4$) | 29 | 24 | 24 | 30 | 22 | 14 | 16 | 15 |

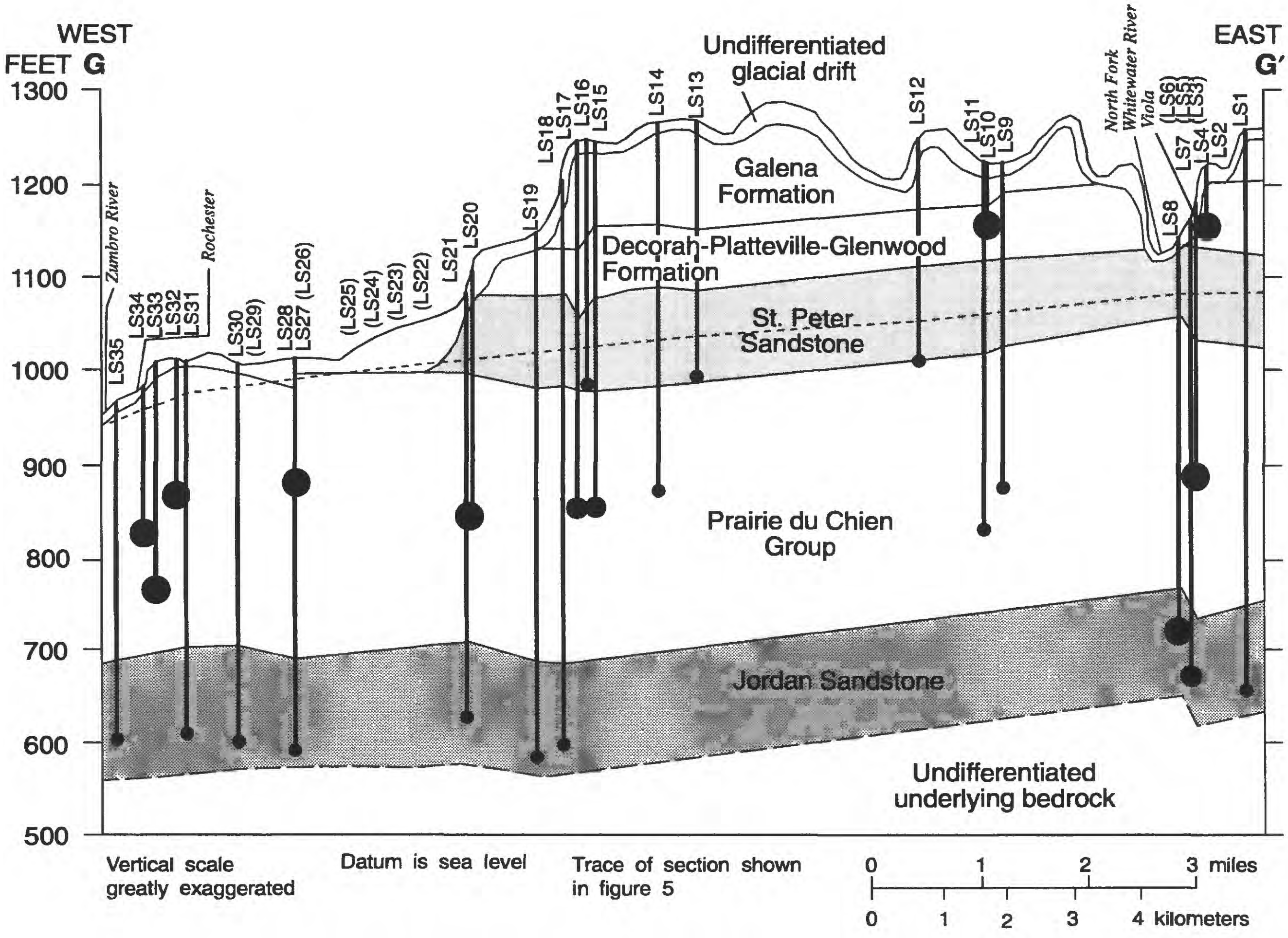
---

[1] Well not on cross section.

[2] Nitrogen concentration categories: low, ≤1.0; medium, >1.0 to ≤10; high, >10 mg/L.

[3] Chloride concentration categories: low, ≤5.0; medium, >5.0 to ≤10; high, >10 mg/L.

[4] Tritium concentration categories: low, <0.8; medium, ≥0.8 to ≤15; high, >15 TU.



**EXPLANATION**

| | |
|---|---|
| - - - - - - - | Potentiometric surface, Prairie du Chien-Jordan aquifer; dashed where approximately located |
| ——– – | Contact-dashed where approximately located |
| LS35 | Local well identifier |
| (LS29) | Local well identifier, well not in section |
| \| | Sampled well |

Tritium concentration ranges (tritium units)

| | |
|---|---|
| • | low (<0.8) |
| ● | medium (≥0.8 to ≤15.0) |
| ⬤ | high (>15.0) |

Figure 15.--Geologic section G-G′ through the southern part of the Olmsted flowtube showing wells sampled and tritium concentration ranges (geology modified from driller's logs and Balaban (1988)).

## Table 8.--Selected water-quality data for the southern part of the Olmsted flowtube

[LS, southern part of the Olmsted; Plv, Platteville Formation; Stp, St. Peter Sandstone; Pdc, Prairie Du Chien Group; Jrd, Jordan Sandstone; mg/L, milligrams per liter; TU, tritium units; L, low; M, medium; H, high; V, volts; µg/L, micrograms per liter; --, not available; <, less than; ≤, Less than or equal to; >, greater than; ≥, greater than or equal to]

| Local identifier | LS35 | LS34 | LS33 | LS32 | LS31 | LS30 | [1]LS29 | LS28 |
|---|---|---|---|---|---|---|---|---|
| Geologic unit | Jrd | Pdc | Pdc | Pdc | Jrd | Jrd | Pdc | Jrd |
| Nitrogen, nitrite plus nitrate, dissolved (mg/L as N) | <0.1 | 4.1 | 3.5 | 5.9 | <0.1 | <0.1 | 1.8 | <0.1 |
| Chloride, dissolved (mg/L as Cl) | 2.3 | 8.4 | 14 | 8.4 | 2.1 | 2.1 | 7.2 | 2.2 |
| Tritium, total (TU) | <.8 | 16 | 23 | 31 | <.8 | <.8 | 21 | <.8 |
| Triazine herbicide compounds (µg/L) | <.1 | .1 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 |
| Nitrogen category[2] | L | M | M | M | L | L | M | L |
| Chloride category[3] | L | M | H | M | L | L | M | L |
| Tritium category[4] | L | H | H | H | L | L | H | L |
| Oxygen, dissolved (mg/L) | 5.2 | 7.2 | 7.9 | 8.3 | <.1 | .7 | 7.7 | 1.9 |
| Oxidation-reduction potential (V) | -- | .23 | .39 | .11 | -.19 | -.11 | .15 | -.13 |
| Iron, dissolved (µg/L as Fe) | 280 | 11 | 14 | <3 | 1400 | 520 | <3 | 1500 |
| Sulfate, dissolved (mg/L as $SO_4$) | 22 | 20 | 54 | 19 | 17 | 22 | 26 | 34 |

## Table 8.--Selected water-quality data for the southern part of the Olmsted flowtube--Continued

| Local identifier | LS27 | [1]LS26 | [1]LS25 | [1]LS24 | [1]LS23 | [1]LS22 | LS21 | LS20 | LS19 |
|---|---|---|---|---|---|---|---|---|---|
| Geologic unit | Pdc | Pdc | Pdc | Stp | Pdc | Jrd | Jrd | Pdc | Jrd |
| Nitrogen, nitrite plus nitrate, dissolved (mg/L as N) | 7.5 | 6.5 | 5.2 | 10.0 | <0.1 | <0.1 | <0.1 | 3.6 | <0.1 |
| Chloride, dissolved (mg/L as Cl) | 16 | 13 | 30 | 31 | 4.4 | 2.2 | 2.6 | 13 | .7 |
| Tritium, total (TU) | 29 | -- | 20 | 15 | <.8 | <.8 | <.8 | 30 | <.8 |
| Triazine herbicide compounds (µg/L) | .1 | 1.0 | .1 | .3 | <.1 | <.1 | <.1 | <.1 | <.1 |
| Nitrogen category[2] | M | M | M | M | L | L | L | M | L |
| Chloride category[3] | H | H | H | H | L | L | L | H | L |
| Tritium category[4] | H | -- | H | H | L | L | L | H | L |
| Oxygen, dissolved (mg/L) | 10.5 | 9.5 | 9.5 | 10.3 | <.1 | .8 | .8 | -- | .3 |
| Oxidation-reduction potential (V) | .1 | .33 | .29 | .21 | .73 | -- | -- | -- | -.15 |
| Iron, dissolved (µg/L as Fe) | <3 | -- | 3 | 10 | 5 | 340 | 590 | 8 | 4100 |
| Sulfate, dissolved (mg/L as $SO_4$) | 17 | -- | 32 | 38 | 48 | 51 | 32 | 17 | 13 |

Table 8.--Selected water-quality data for the southern part of the Olmsted flowtube--Continued

| Local identifier | LS18 | LS17 | LS16 | LS15 | LS14 | LS13 | LS12 | LS11 | LS10 |
|---|---|---|---|---|---|---|---|---|---|
| Geologic unit | Jrd | Pdc | Stp | Pdc | Pdc | Stp | Stp | Pdc | Plv |
| Nitrogen, nitrite plus nitrate, dissolved (mg/L as N) | <0.1 | <0.1 | 0.2 | <0.1 | <0.1 | <0.1 | 0.8 | <0.1 | 5.5 |
| Chloride, dissolved (mg/L as Cl) | 1.0 | .6 | 2.2 | 1.9 | 1.0 | 3.1 | 2.9 | .1 | 10 |
| Tritium, total (TU) | <.8 | .8 | <.8 | 1.0 | <.8 | <.8 | <.8 | <.8 | 19 |
| Triazine herbicide compounds (µg/L) | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 | <.1 | .2 |
| Nitrogen category[2] | L | L | L | L | L | L | L | L | M |
| Chloride category[3] | L | L | L | L | L | L | L | L | M |
| Tritium category[4] | L | M | L | M | L | L | L | L | H |
| Oxygen, dissolved (mg/L) | 1.3 | <.1 | 1.6 | <.1 | <.1 | .5 | 6.2 | -- | 7.3 |
| Oxidation-reduction potential (V) | -.08 | -.12 | -- | -- | -.13 | -.07 | -- | -- | -- |
| Iron, dissolved (µg/L as Fe) | 380 | 2000 | 210 | 900 | 2900 | 1200 | 6 | 1700 | <3 |
| Sulfate, dissolved (mg/L as $SO_4$) | 17 | 22 | 76 | 39 | 25 | 50 | 27 | 10 | 22 |

Table 8.--Selected water-quality data for the southern part of the Olmsted flowtube--Continued

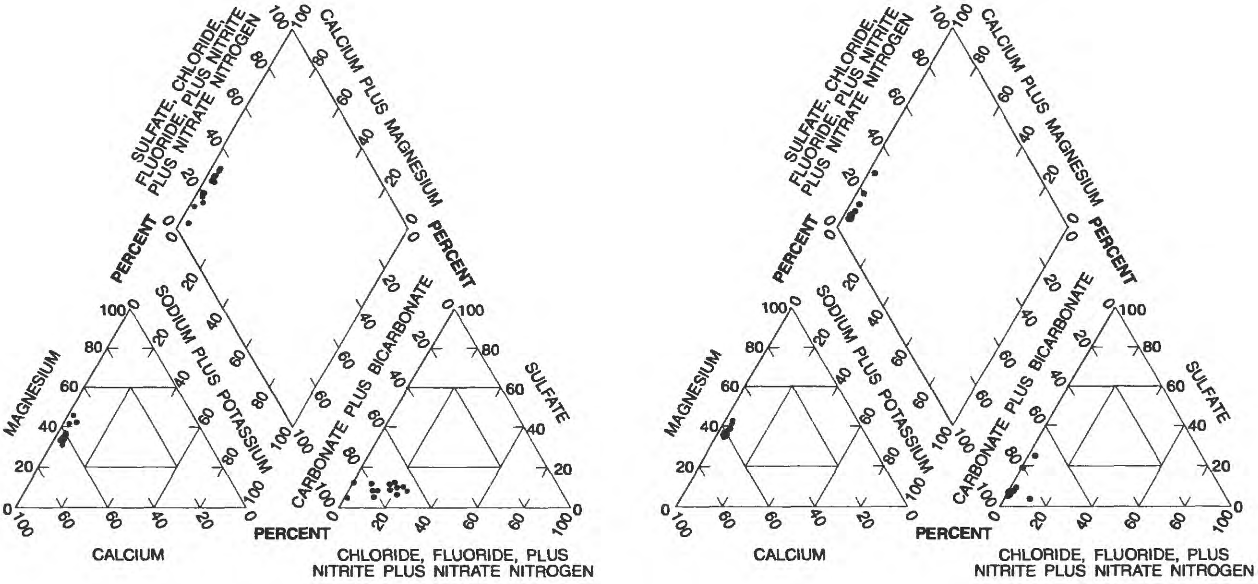
| Local identifier | LS9 | LS8 | LS7 | [1]LS6 | [1]LS5 | LS4 | [1]LS3 | LS2 | LS1 |
|---|---|---|---|---|---|---|---|---|---|
| Geologic unit | Pdc | Jrd | Jrd | Pdc | Pdc | Pdc | Jrd | Plv | Jrd |
| Nitrogen, nitrite plus nitrate, dissolved (mg/L as N) | <0.1 | 3.0 | <0.1 | 2.2 | 5.9 | 6.6 | <0.1 | 9.3 | <0.1 |
| Chloride, dissolved (mg/L as Cl) | 1.0 | 15 | 8.9 | 12 | 41 | 19 | 6.2 | 25 | <.1 |
| Tritium, total (TU) | <.8 | 24 | 8.4 | 19 | 26 | 22 | <.8 | 27 | <.8 |
| Triazine herbicide compounds (µg/L) | <.1 | <.1 | .1 | <.1 | .2 | .3 | .1 | <.1 | <.1 |
| Nitrogen category[2] | L | M | L | M | M | M | L | M | L |
| Chloride category[3] | L | H | M | H | H | H | M | H | L |
| Tritium category[4] | L | H | M | H | H | H | L | H | L |
| Oxygen, dissolved (mg/L) | 7.8 | 3.3 | 3.1 | 6.9 | 8.4 | 7.3 | <.1 | 1.0 | 4.5 |
| Oxidation-reduction potential (V) | .11 | .08 | -.12 | -- | .16 | -- | -.13 | -- | -.10 |
| Iron, dissolved (µg/L as Fe) | 220 | 6 | 510 | 9 | 9 | 28 | 2700 | <3 | 600 |
| Sulfate, dissolved (mg/L as $SO_4$) | 16 | 43 | 64 | 35 | 35 | 22 | 44 | 110 | 18 |

[1] Well not on cross section.

[2] Nitrogen concentration categories: low,≤1.0; mediun,>1.0 to <to≤10; high, >10 mg/L.

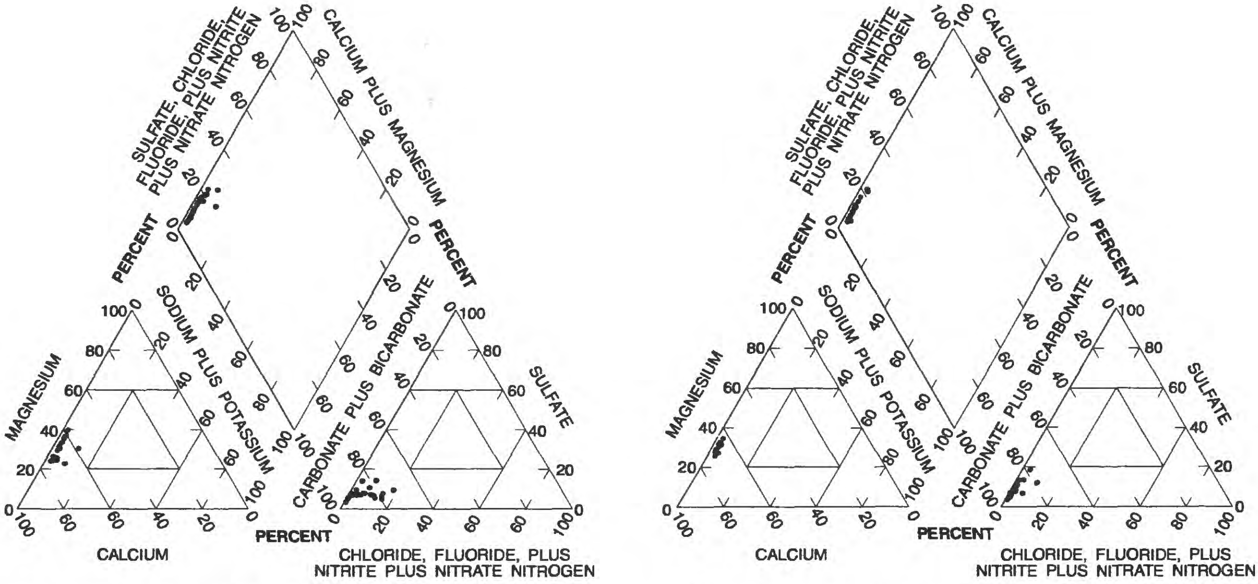
[3] Chloride concentration categories: low, ≤5.0; medium, >5.0 to ≤10; high, 10 mg/L.

[4] Tritium concentration categories: low, <0.8; medium, ≥0.8 to ≤15; high, > 15 TU.



Water from wells in the Prairie du Chien part of the aquifer in the Dakota Central flowtube (13 samples)

Water from wells in the Jordan part of the aquifer in the Dakota Central flowtube (11 samples)



Water from wells in the Prairie du Chien part of the aquifer in the Olmsted flowtube (24 samples)

Water from wells in the Jordan part of the aquifer wells in the Olmsted flowtube (20 samples)

**Figure 16.--Chemical characteristics of water from the Prairie du Chien and Jordan parts of the Prairie du Chien-Jordan aquifer in the Dakota Central and Olmsted flowtubes.**

Table 9.--Historical comparison of median constituent concentrations in the Prairie du Chien and Jordan parts of the Prairie du Chien-Jordan aquifer in the Minneapolis-St. Paul metropolitan area

[Pdc, Prairie du Chien part of the aquifer; Jrd, Jordan part of the aquifer; mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; --, not available; *, sodium and potassium together; <, less than]

| | Source of chemical analyses | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Chemical constituent or other information | Maderak 1965 | Maderak 1963 | Norvitch and others 1973 | This study[1] | Maderak 1965 | Maderak 1963 | Norvitch and others 1973 | This study[1] |
| Hydrogeologic unit | Pdc | Pdc | Pdc | Pdc | Jrd | Jrd | Jrd | Jrd |
| Sample date (years) | 1899-1963 | 1955-1962 | 1951-1970 | 1990-1991 | 1899-1963 | 1955-1962 | 1951-1970 | 1990-1991 |
| Number of samples | 7 | 9 | 14 | 34 | 29 | 30 | 97 | 40 |
| Specific conductance (µS/cm) | -- | 542 | 495 | 533 | -- | 476 | 456 | 510 |
| pH (standard units) | -- | 7.8 | 7.6 | 7.5 | -- | 7.8 | 7.6 | 7.5 |
| Hardness (mg/L as $CaCO_3$) | 290 | 270 | 270 | 310 | 240 | 260 | 250 | 290 |
| Calcium (mg/L as Ca) | 67 | 72 | 70 | 72 | 57 | 62 | 64 | 69 |
| Magnesium (mg/L as Mg) | 29 | 27 | 23 | 27 | 23 | 23 | 27 | 27 |
| Sodium (mg/L as Na) | 8.0* | 5.3 | 5.4 | 4.4 | 6.1* | 4.0 | 4.5 | 4.2 |
| Potassium (mg/L as K) | * | 1.7 | 1.4 | 1.3 | * | 1.8 | 1.8 | 1.5 |
| Bicarbonate (mg/L as $HCO_3$) | 330 | 300 | 280 | 290 | 290 | 300 | 310 | 310 |
| Sulfate (mg/L as $S0_4$) | 31 | 18 | 8.9 | 27 | 11 | 7.7 | 7.5 | 17 |
| Chloride (mg/L as C1) | 1.2 | 2.1 | 2.0 | 11 | .5 | .2 | 1.6 | 3.0 |
| Fluoride (mg/L as F) | .2 | .2 | .2 | .2 | .2 | .2 | .2 | |
| Silica (mg/L as $SiO_2$) | 20 | 18 | 19 | 15 | 15 | 15 | 15 | 14 |
| Total dissolved solids (mg/L) | 343 | 343 | 305 | 328 | 272 | 273 | 275 | 300 |
| Nitrite plus nitrate nitrogen ($NO_3$) | .2 | .5 | <1.0 | 3.6 | <1.0 | .02 | <1.0 | <.1 |
| Phosphorus (mg/L as P) | .18 | .18 | .02 | .01 | .20 | .19 | .06 | .01 |
| Boron (mg/L as B) | .04 | .02 | .03 | -- | .02 | .02 | .02 | -- |
| Iron (µg/L as Fe) | 150 | 150 | 330 | 20 | 300 | 260 | 290 | 670 |
| Manganese (µg/L as Mn) | 90 | 50 | 40 | 10 | 50 | 60 | 30 | 50 |

[1] Only wells from Hennepin and Dakota Counties are included for appropriate comparison with previous studies.

Table 10.--Median constituent concentrations in the Prairie du Chien and Jordan parts of the Prairie du Chien-Jordan aquifer, by flowtube
[HN, Hennepin North; HS, Hennepin South; DW, Dakota West; DC, Dakota Central; DE, Dakota East; LN, northern part of the Olmsted; LS, southern part of the Olmsted; Pdc, Prairie du Chien part of the aquifer; Jrd, Jordan; mg/L, milligrams per liter; µg/L, micrograms per liter; TU, tritium units; V, volts; µS/cm, microsiemens per centimeter at 25 degrees Celsius;
<, less than]

| Flowtube | HN | HS | HS | DW | DW | DC | DC | DE | DE | LN | LN | LS | LS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hydrogeologic unit | Jrd | Pdc | Jrd | Pdc | Jrd | Pdc | Jrd | Pdc | Jrd | Pdc | Jrd | Pdc | Jrd |
| Number of samples | 5 | 5 | 7 | 5 | 4 | 13 | 11 | 11 | 13 | 7 | 8 | 16 | 12 |
| Specific conductance (µS/cm) | 629 | 700 | 697 | 556 | 520 | 496 | 489 | 484 | 436 | 534 | 514 | 572 | 479 |
| pH (standard units) | 7.5 | 7.3 | 7.1 | 7.5 | 7.5 | 7.5 | 7.5 | 7.5 | 7.6 | 7.1 | 7.3 | 7.2 | 7.1 |
| Oxidation-reduction potential (V) | -.18 | -.1 | -1.8 | -.13 | .01 | .12 | -.15 | .08 | .09 | .13 | .06 | .14 | -.12 |
| Dissolved oxygen (mg/L) | .2 | <.1 | <.1 | <.1 | 3.1 | 5.5 | <.1 | 1.8 | 2.4 | 2.4 | 2.6 | 7.7 | 1.1 |
| | | | | | | | | | | | | | |
| Calcium (mg/L as Ca) | 80 | 92 | 89 | 79 | 78 | 68 | 64 | 60 | 57 | 76 | 76 | 92 | 76 |
| Magnesium (mg/L as Mg) | 36 | 41 | 37 | 30 | 28 | 25 | 25 | 25 | 22 | 27 | 23 | 22 | 21 |
| Sodium (mg/L as Na) | 5.9 | 6.5 | 5.6 | 4.5 | 4.9 | 4.4 | 3.3 | 4.1 | 3.2 | 2.3 | 2.5 | 2.9 | 2.6 |
| Potassium (mg/L as K) | 2.5 | 2.4 | 2.9 | 3.0 | 2.1 | 1.1 | 1.3 | .9 | .9 | 1.1 | 1.2 | 1.4 | 1.1 |
| Bicarbonate mg/L as $SO_3$) | 420 | 440 | 460 | 370 | 380 | 230 | 290 | 260 | 240 | 340 | 330 | 340 | 330 |
| Sulfate (mg/L as $SO_4$) | 12 | 24 | 2.9 | 32 | 2.0 | 27 | 18 | 24 | 23 | 23 | 20 | 24 | 27 |
| Chloride (mg/L as C1) | 2.9 | 6.1 | 2.8 | 11 | 3.0 | 10 | 2.1 | 15 | 7.9 | 3.8 | 2.1 | 8.4 | 2.2 |
| | | | | | | | | | | | | | |
| Fluoride (mg/L as F) | .2 | .1 | .3 | .2 | .5 | .2 | .2 | .1 | .1 | .2 | .2 | .2 | .2 |
| Silica (mg/L as $SiO_2$) | 20 | 22 | 21 | 26 | 15 | 14 | 13 | 14 | 12 | 11 | 12 | 12 | |
| Total dissolved solids (mg/L) | 362 | 419 | 368 | 340 | 314 | 309 | 282 | 298 | 255 | 297 | 276 | 337 | 286 |
| Nitrite plus nitrate nitrogen (mg/L as N) | <.1 | <.1 | <.1 | <.1 | <.1 | 6.8 | <.1 | 3.7 | 4.0 | <.1 | <.1 | 2.9 | <.1 |
| Phosphorus (mg/L as P) | <.01 | .02 | .03 | .02 | .02 | <.01 | <.01 | <.01 | <.01 | <.01 | <.01 | <.01 | <.01 |
| Iron (µg/L as Fe) | 2400 | 860 | 3100 | 1200 | 50 | 10 | 1300 | 20 | 10 | 80 | 240 | 10 | 560 |
| Manganese (µg/L as Mn) | 280 | 200 | 560 | 230 | 33 | <1 | 45 | 2 | 6 | 8 | 29 | <1 | 25 |
| Tritium (TU) | <.8 | .9 | <.8 | 20 | <.8 | 18 | <.8 | 26 | 3.0 | 3.3 | <.8 | 20 | <.8 |
| Total dissolved solids (mg/L) | 362 | 419 | 368 | 340 | 314 | 309 | 282 | 298 | 255 | 297 | 276 | 337 | 286 |

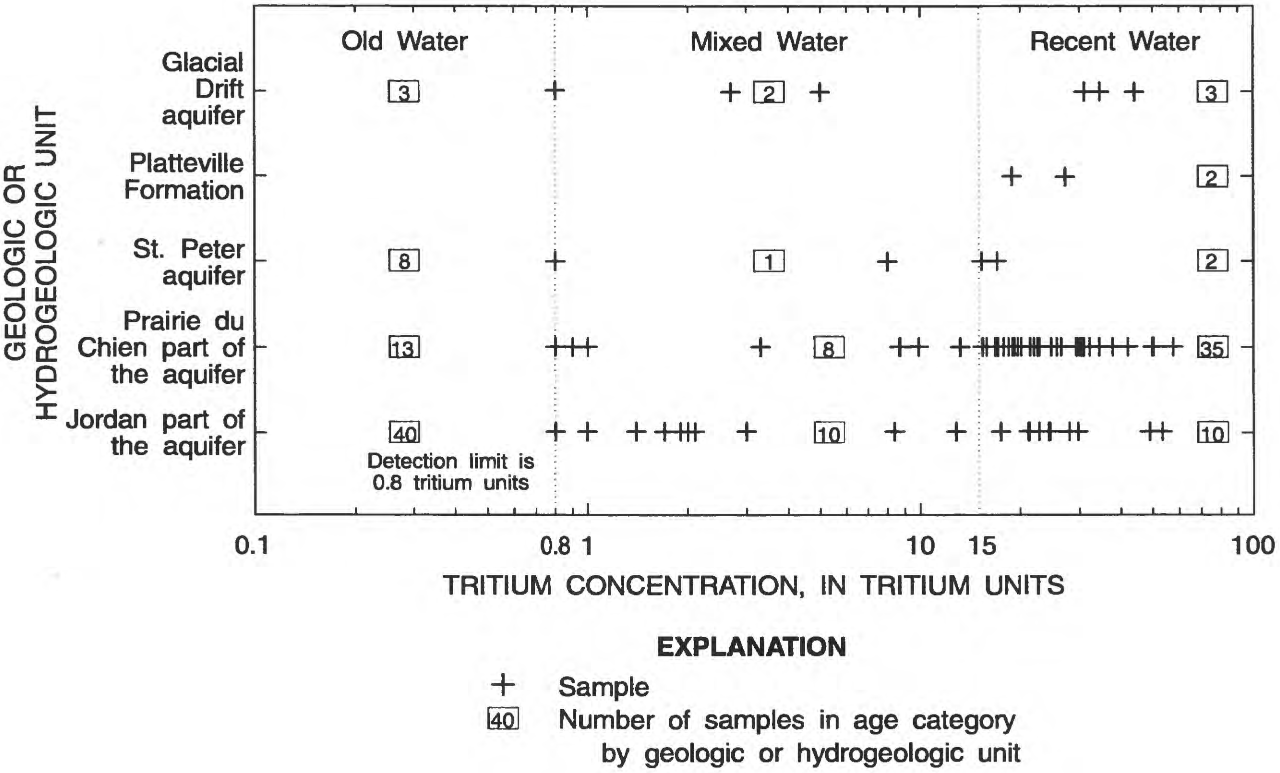


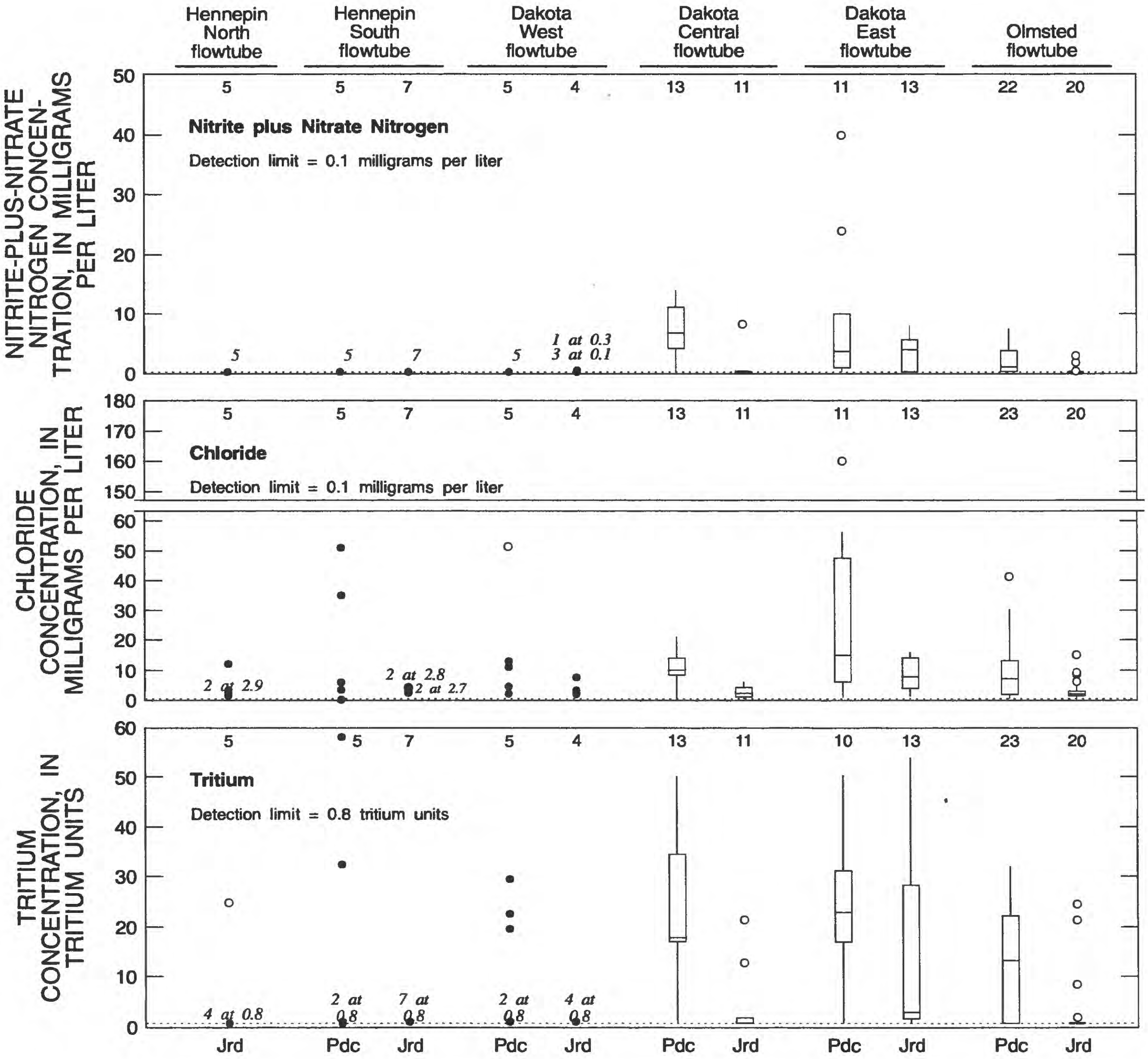
**Figure 17.--Tritium concentration distribution by age and geologic or hydrogeologic unit.**

wells HS17 and HS18, near the discharge area in the HS flowtube (fig. 10), had high Cl and tritium concentrations. The sample from glacial drift aquifer well HS1 had high Cl and tritium concentrations. $SO_4$ concentrations were elevated in samples from wells HS11, 17, and 18. No volatile organic carbons or triazine herbicides were detected in samples from wells in Hennepin County.

Most of the Prairie du Chien and Jordan parts of the aquifer had low DO concentrations, high Fe concentrations, and negative Eh readings, indicating reducing conditions in much of the aquifer. Samples from wells HS18 and HN7, however, had relatively large DO concentrations and low Fe concentrations, indicating oxidizing conditions at the downgradient ends of the flowtubes.

The difference in water chemistry in the Jordan part of the aquifer between areas where the overlying Prairie du Chien Group was absent and where it was present was minimal (figs. 9, 10; tables 2, 3). The ratio of magnesium to calcium (concentrations in milliequivalents per liter) increased slightly, from about 0.7 to 0.8, in the Jordan part of the aquifer from areas where the overlying Prairie du Chien Group was absent to areas where it was present. This increase may indicate the occurrence of de-dolomitization along the flowtube. Samples from Jordan wells from the western one-quarter of the HN and HS flowtubes had higher concentrations of sodium (mean = 11 mg/L) than samples from Jordan wells from the eastern three-quarters of the flowtubes (mean = 5.2 mg/L).

Boxplots of Cl and tritium concentrations by part of the aquifer show that the median concentrations and interquartile range (IQR) were less in the Jordan part of the aquifer than they were in the Prairie du Chien part of the aquifer (fig. 18). The median concentration was at the detection level for all three indicator constituents in the Jordan and at the detection limit for $NO_3$-N in the Prairie du Chien.



## EXPLANATION

| | |
|---|---|
| 5 | Number of analyses |
| ○ | Concentration greater than 1.5 x IQR from 75th percentile |
| ...................... | Detection limit--the minimum analytical detection limit with method used |
| Pdc | Prairie du Chien part of the aquifer |
| Jrd | Jordan part of the aquifer |
| IQR | Interquartile range--the range of data from the 25th to 75th percentile |
| Percentile | Percentage of analyses having concentrations equal to or less than indicated values |

—1.5 x IQR
IQR —75th percentile
—50th percentile
—25th percentile
—1.5 x IQR

- ● Sites with fewer than 10 data values, number indicates multiple values at a given concentration.

**Figure 18.--Concentrations of nitrite plus nitrate nitrogen, chloride, and tritium by hydrogeologic unit and flowtube.**

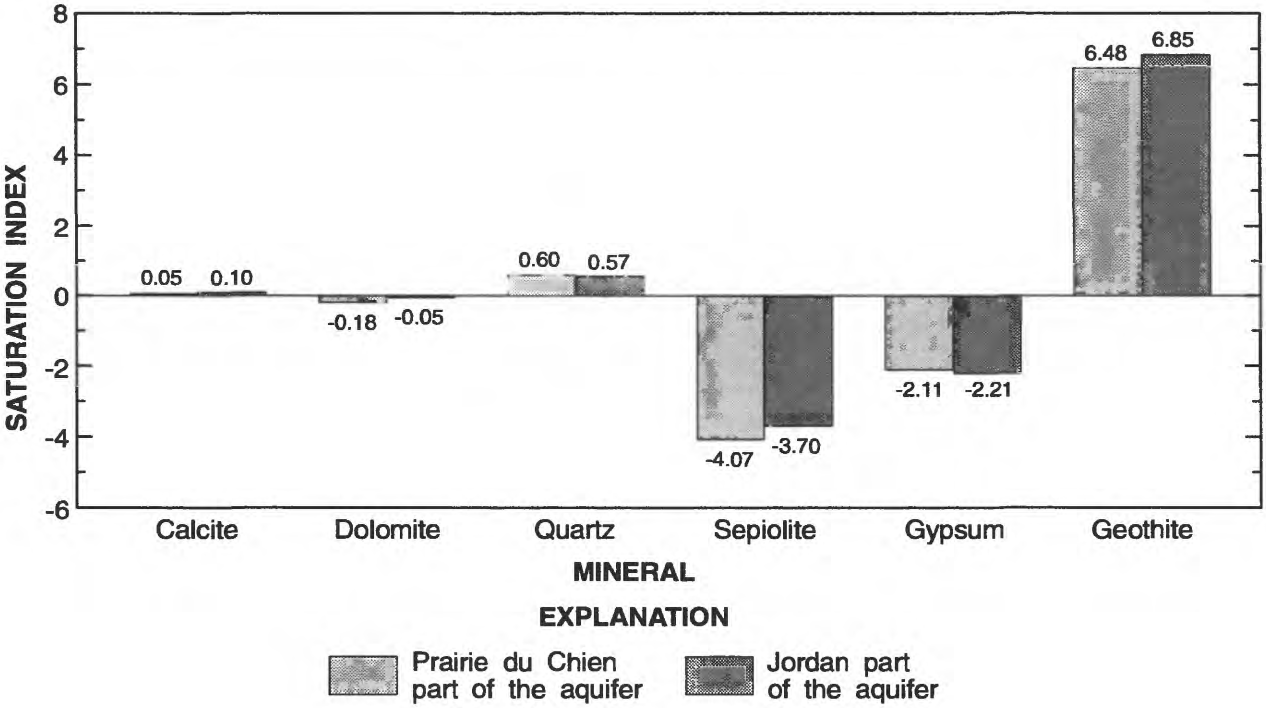


**Figure 19.--Mineral saturation index averages by hydrogeologic unit for the Dakota East flowtube as determined by the WATEQF Program (Truesdell and Jones, 1974; Plummer and other, 1976).**

## Dakota West Flowtube

Indicator-constituent concentrations were primarily in the low range in the Jordan part of the aquifer in the DW flowtube (table 4). Indicator-constituent concentrations varied more widely in the Prairie du Chien part of the aquifer. Samples from Prairie du Chien wells DW8, 10, and 11 had high Cl, tritium, and $SO_4$ concentrations. These wells all were completed near the top of the Prairie du Chien (fig. 11). The sample from DW4, a St. Peter aquifer well, also had high Cl, tritium, and $SO_4$ concentrations. The sample from another St. Peter well, DW6, had low $NO_3$-N and Cl concentrations, and medium range tritium concentrations. Triazine herbicides were detected only in the sample from well DW11.

Oxidizing conditions were indicated in samples from Jordan wells DW3, 5, and 9 by relatively high DO concentrations and low Fe concentrations. Reducing conditions were indicated in samples from Jordan well DW12, Prairie du Chien wells DW2, 8, 10, 11, and 13, St. Peter well DW6, and glacial drift well DW1, by low DO concentrations, higher Fe concentrations, and negative Eh readings. The samples from Jordan well DW12 and Prairie du Chien well DW13 had lower DO concentrations and negative Eh readings, but also had low Fe concentrations, which indicated that iron reduction had not begun in these areas of the aquifer.

Boxplots of the indicator-constituent concentrations show that median Cl and tritium concentrations were higher in samples from the Prairie du Chien part of the aquifer than in samples from the Jordan part of the aquifer (fig. 18). Median $NO_3$-N concentrations were at the detection limit in both the Prairie du Chien and Jordan parts of the aquifer.

## Dakota Central Flowtube

Indicator-constituent concentrations were primarily in the low range in the Jordan part of the aquifer in the DC flowtube (table 5). Samples from Jordan wells DC4 and DC5 had medium range tritium concentrations and high $SO_4$ concentrations. The sample from DC20 had medium $NO_3$-N and Cl concentrations, a high tritium concentration, and a detection of triazine herbicides. Samples from the other Jordan wells had no triazine herbicide detections. Indicator-constituent concentrations in the Prairie du Chien part of the aquifer were primarily in the medium and high ranges, and samples from 5 of the 13 wells had a detection of triazine herbicides.

### Table 11.--Results of statistical tests on relations between selected variables and water-quality indicator constituents

[--, not applicable; <, less than]

| | | | Attained significance level (p-value) with relation to: | | | |
|---|---|---|---|---|---|---|
| Tested variable | Samples used | Statistical test | Nitrite-plus-nitrate nitrogen concentration | Chloride concentration | Tritium concentration | Triazine herbicide concentration |
| Chloride concentration | All | Chi-square | <0.001 | -- | <0.001 | <0.001 |
| Tritium concentration | All | Chi-square | <.001 | <0.001 | -- | <.001 |
| Triazine concentration | All | Chi-square | <.001 | <.001 | <.001 | -- |
| Dissolved oxygen concentration | All | Kruskal-Wallis | .0001 | .0001 | .0001 | .0001 |
| Iron concentration | All | Kruskal-Wallis | .0001 | .0001 | .0001 | .0001 |
| Grouting of well concentration | All | Chi-square | .021 | <.001 | <.001 | .043 |
| Depth of well below land surface | All | Chi-square | <.001 | <.001 | <.001 | <.001 |
| Thickness of glacial drift (all samples) | Prairie du Chien and overlying aquifers | Chi-square | .001 | .113 | .662 | .196 |
| Thickness of glacial drift (by flowtube) | Prairie du Chien and overlying aquifers | Chi-square | .041 | .431 | .378 | .819 |
| Composition of glacial drift | Prairie du Chien and overlying aquifers | Kruskal-Wallis | .013 | .890 | .814 | .345 |
| Land use | Prairie du Chien and overlying aquifers | Kruskal-Wallis | .116 | .064 | .632 | .550 |
| Overlying Decorah Shale confining unit | Olmsted County | Kruskal-Wallis | .026 | .002 | .013 | .021 |
| Minnesota Geological Survey sensitivity index | All | Chi-square | <.001 | .016 | .001 | .013 |

Oxidizing conditions were indicated in samples from 11 of the 13 Prairie du Chien wells and in samples from Jordan wells DC20 and DC24 (table 5). Reducing conditions were indicated in samples from 9 of the 11 Jordan wells and in the samples from Prairie du Chien wells DC10 and DC13.

Boxplots of the indicator-constituent concentrations show that $NO_3$-N, Cl, and tritium concentrations were higher in the Prairie du Chien part of the aquifer than in the Jordan part of the aquifer (fig. 18). The median $NO_3$-N concentration was higher in the Prairie du Chien for the DC flowtube than in the other flowtubes (table 10).

### Dakota East Flowtube

Indicator-constituent concentrations varied from low to high ranges in both the Prairie du Chien and the Jordan parts of the aquifer in the DE flowtube (table 6). Only samples from Jordan wells DE3, 10, 24, and 27, Prairie du Chien wells DE4 and DE16, and glacial drift well DE5 had primarily low indicator-constituent concentrations and reducing conditions. Samples from the other 17 wells in the flowtube had primarily medium to high indicator-constituent concentrations and oxidizing conditions. Samples from nine of these wells (4 Jordan, 4 Prairie du Chien, and 1 glacial drift) had detectable triazine herbicides. Median $NO_3$-N, Cl, and tritium concentrations in the Jordan, and median Cl and tritium concentrations in the Prairie du Chien, were higher in the DE flowtube than they were in the other flowtubes (fig. 18, table 10). Indicator-constituent concentrations were substantially higher in the downgradient one-half of the flowtube compared to the upgradient one-half of the flowtube.

Areas of reducing conditions were evident in the DE flowtube, but they were not present in the Jordan part of the aquifer as consistently as in other flowtubes. Reducing conditions were evident in three localized areas: from DE4 and DE5 and downward to DE3 and DE10; at DE16; and in the lower part of the Jordan near DE24 and DE27 (table 6).

### Olmsted Flowtube

Indicator-constituent concentrations in the Jordan part of the aquifer were in the low range throughout most of the flowtube, and in medium and high ranges in two distinct zones of the Jordan in the OLM flowtube (figs. 14, 15; tables 7, 8). Primarily low range indicator-constituent concentrations were found in the downgradient one-half of the Jordan part of the aquifer in samples from wells LS18, 19, 21, 22, 28, 30, 31, and 35, and in the area between LN1, 3, 5, 11, 12, and 13. Medium-and-high-range indicator-constituent concentrations were found at the upgradient and downgradient ends of the flowtube including samples from Jordan wells LS8 and LN15. Samples from four Jordan wells, LS3, LS7, LN3, and LN15, had detectable triazine herbicides.

Indicator-constituent concentrations in the Prairie du Chien part of the aquifer had a similar distribution pattern as the Jordan wells. Primarily low-range indicator-constituent concentrations were found through the central part of the flowtube including samples from Prairie du Chien wells LS9, 11, 14, and 17, and LN2, 8, 10, 14. Medium- and high-range indicator-constituent concentrations were found at the upgradient and downgradient ends of the flowtube including samples from Prairie du Chien wells LS4-6, LS20, in the area between wells LS25-27, 29, 32-34, and wells LN4, 6, and 9. Samples from seven of the Prairie du Chien wells, all with medium- and high-range indicator-constituent concentrations, had detectable triazine herbicides. These wells were LS4, 5, 25, 26, 27, and 34 and LN9.

Reducing conditions were only found in samples from Prairie du Chien and Jordan wells with generally low-range indicator-constituent concentrations (tables 7, 8). Oxidizing conditions were found in samples from several wells with low-range indicator-constituent concentrations and in all of the wells with medium- and high-range indicator-constituent concentrations.

Boxplots of the indicator-constituent concentrations show that the median and IQR of $NO_3$-N, Cl, and tritium were higher in the Prairie du Chien part of the aquifer than in the Jordan part of the aquifer (fig. 18).

## Relations Between Water-Quality Constituent Concentrations and Selected Variables

The distributions of indicator-constituent concentrations in the Prairie du Chien-Jordan aquifer were used to assess ground-water residence time. Redox conditions in the aquifer were compared to indicator-constituent concentrations. Statistical analyses were used to test the relation between indicator-constituent concentrations and selected variables. Ground-water residence time, redox condition, and indicator-constituent concentrations in the aquifer were used to assess susceptibility to contamination from the land surface to various parts of the aquifer.

Univariate, $\chi^2$ (chi-square), and K-W (Kruskal-Wallis) statistics were used to compare water-quality constituent data with selected variables to determine the statistical significance of relations between the variables and water-quality. These variables were: well grouting, total depth of the well, thickness and composition of overlying glacial drift, presence of the overlying Decorah Shale in Olmsted County, and land use. The MGS ground-water pollution sensitivity index was also tested for its relation to the distribution of indicator constituents in the flowtubes. For all of the variables, the statistical comparison between constituent concentrations and selected variables assumed predominantly vertical recharge to the aquifer. For some of the variables, statistical tests included results of all 139 of the samples analyzed. For other variables, only the 79 samples from the Prairie du Chien part of the aquifer and the overlying St. Peter aquifer, Platteville Formation, and glacial drift aquifer were included. The smaller data set was used to ensure that the large number of Jordan wells that indicated no human-related effects did not distort the statistical significance of some of the tested variables. The significance level ($\alpha$) applied to the $\chi^2$ and K-W tests was 0.05. The results of these statistical tests are presented in table 11 and discussed in the following sections.

## Ground-Water Residence Time

Ground-water flow within the Prairie du Chien-Jordan aquifer has characteristics of the regional and intermediate flow systems described by Toth (1963). From Toth's definition, regional ground-water flow is from topographically high recharge areas near the ground-water divide to topographically low discharge areas along major rivers. Intermediate ground-water flow is between recharge and discharge areas that are not the highest or the lowest points in the basin, and they may have topographic high and low points located between them. A local ground-water-flow system has recharge and discharge areas at adjacent topographic high and low points. For this investigation, regional ground-water flow was characterized as lateral flow through the deeper part of the Prairie du Chien-Jordan aquifer, especially the Jordan part of the aquifer, having a longer ground-water residence time. Intermediate ground-water flow was characterized as having vertical and lateral flow components in the upper part of the aquifer, and having a shorter ground-water residence time. Local ground-water flow was not defined for the Prairie du Chien-Jordan aquifer in this investigation.

Depth below land surface, permeability of geologic or hydrogeologic units, and length of ground-water flow paths are some of the physical controls over ground-water residence time in the Prairie du Chien-Jordan aquifer. The distribution of indicator-constituent concentrations in the Prairie du Chien-Jordan aquifer was used to determine the relative residence times of ground water from the land surface to parts of the aquifer. Ground-water from the Prairie du Chien part of the aquifer had medium- and high-range $NO_3$-N, Cl, and tritium concentrations and appeared to be part of an intermediate flow system (figs. 9-15; tables 2-8). This is illustrated in samples from wells completed in the Prairie du Chien part of the aquifer: DC1, 2, 3, 6, 9, 11, 15-17, 21, and 22; DE2, 6-9, 12, 13, 18, and 26; LN4, 6, and 9; LS4-6, 20, 25-27, 29, and 32-34. Some areas of the Prairie du Chien part of the aquifer had predominantly low-range indicator-constituent concentrations and appeared to be part of a regional flow system. This is illustrated in samples from wells completed in the Prairie du Chien part of the aquifer: HS15 and HS16; DW13; LN2 and LN10; LS9, 11, 14, 15, and 17. Ground water from the Jordan part of the aquifer had low-range indicator-constituent concentrations and appeared to be part of a regional flow system. This is illustrated in samples from wells completed in the Jordan part of the aquifer: HN1-6; HS2, 4, 6, 9, 10, 13; DW3, 9, and 12; DC7, 8, 12, 14, 18, and 19; LN1, 3, 5, 11, 12, and 13; LS18, 19, 21, 22, 28, 30, 31, and 35. Some areas of the Jordan part of the aquifer had medium to high range indicator-constituent concentrations and appeared to be part of an intermediate flow system. This is illustrated in wells completed in the Jordan part of the aquifer: HN7; DC4, 5, and 20; DE11, 14, 15, 17, 19, 20, and 25; LN15; LS8.

The Prairie du Chien-Jordan aquifer in the HS and HN flowtubes appeared to have longer ground-water residence time and a stronger regional component to the flow system than the other flowtubes. At the discharge ends of the HS and HN flowtubes, however, a shorter ground-water residence time and intermediate flow system was evident. The Prairie du Chien part of the aquifer in the DC flowtube, and both the Prairie du Chien and Jordan parts of the aquifer in the DE flowtube, had many areas with shorter ground-water residence times. At both the upgradient and downgradient ends of the LN and LS parts of the OLM flowtube, areas with shorter ground-water residence times were evident.

## Oxidation-Reduction Conditions

Plots of $NO_3$-N, DO, Fe, $NH_4$, Cl, and tritium concentrations versus redox potential (Eh) are shown in figure 20. Negative Eh indicates reducing conditions and positive Eh indicates oxidizing conditions. These plots suggest that the redox potential had a substantial affect on $NO_3$-N, Fe, DO, and $NH_4$ concentrations in the aquifer. Detectable to high concentrations of $NO_3$-N

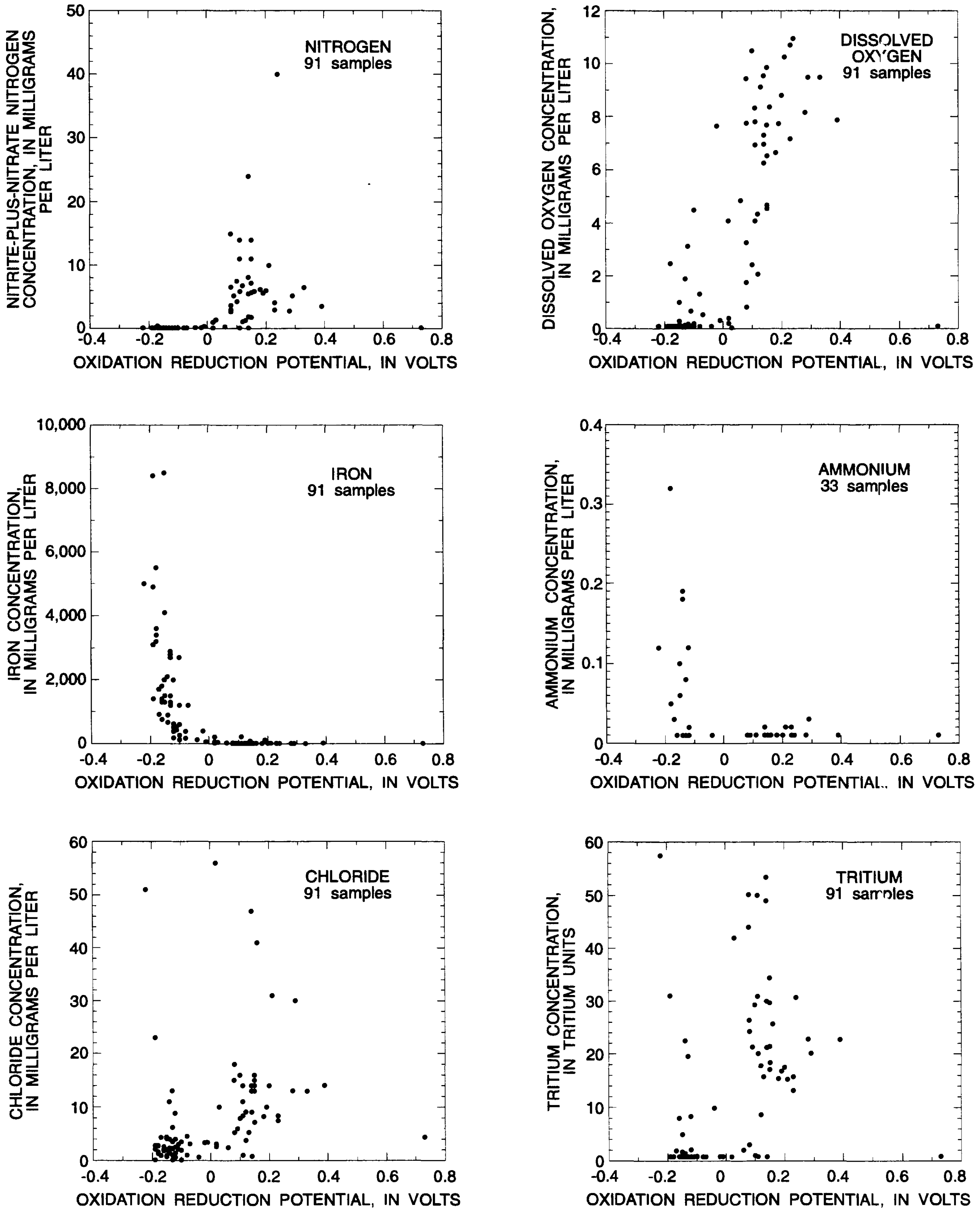


**Figure 20.--Relation of water-quality-constituent concentrations to oxidation-reduction potential.**

were associated with oxidizing conditions, and very low to nondetectable concentrations were associated with reducing conditions. The inverse was true for soluble Fe and $NH_4$ concentrations. DO concentrations decreased with decreasing Eh. These patterns are consistent with the expected effect of oxidizing and reducing conditions in an aquifer (Postma and others, 1991). DO concentrations above 0.5 mg/L corresponding to negative Eh were anomalous. These values could have resulted from aeration of the sampled water during the pumping and sampling process.

The plots of Cl and tritium versus Eh indicated a weak tendency for lower concentrations to be associated with reducing conditions. Cl and tritium are non-reactive in reducing conditions; the tendency of the majority of negative Eh samples to also have low Cl and tritium concentrations suggests that areas of the aquifer with reducing conditions tend to have longer ground-water residence times. Low concentrations of tritium in areas with reducing conditions indicates that ground-water residence time to these areas is greater than 40 years. Carbon-14 age dating analyses from eight wells completed in the Jordan part of the aquifer showed that water from one well, LS28, was approximately 1,100 years old (table 12). Some water with medium- and high-range Cl and tritium concentrations was reaching areas with reducing conditions, however. This indicates that these parts of the aquifer can be susceptible to contamination from human-related constituents not affected by reduction reactions.

Redox conditions in the flowtubes were discussed by individual flowtube in the Water-Quality Section. In general, oxidizing conditions were present in the Prairie du Chien part of the aquifer and were associated with medium and high indicator-constituent concentrations. Reducing conditions were present in the Jordan part of the aquifer and were associated with low indicator-constituent concentrations. Within each flowtube, however, there were exceptions to this generalization. In the DW flowtube the occurrence of oxidizing and reducing conditions was not consistently associated with high and low ranges of indicator-constituent concentrations (table 4). Samples from the four Jordan wells in the DW flowtube had low indicator-constituent concentrations and oxidizing conditions. Samples from the four Prairie du Chien wells had low to high indicator-constituent concentrations and reducing conditions. The four Jordan wells in the DW flowtube were all large municipal or institutional water-supply wells, so the oxidizing conditions could have been caused by aeration in the large diameter well casings or concentrations and oxidizing conditions in the Jordan holding tanks. In the DE flowtube there was a higher occurrence of medium and high indicator-constituent concentrations and oxidizing conditions in the Jordan part of the aquifer than in the other flowtubes, indicating that an intermediate flow system was more predominant in the Jordan part of the aquifer in the DE flowtube compared to the other flowtubes.

Table 12.--Approximate age of ground water from selected wells using carbon-14, carbon-13, and tritium analyses

[<, less than; >, greater than; yrs, years; modern, water entered the ground since the mid-1950's; mixed, water is a mix of water > 40 years and water < 40 years old]

| Local identifier | Carbon-14 (percent modern) | Carbon-13 (per milliliter) | Estimated age from carbon-isotope results[1] | Tritium, total (tritium units) | Approximate age[2] |
|---|---|---|---|---|---|
| LN1 | 62.7 ± 0.5 | -9.2 | modern | <0.8 | >40 yrs |
| LN5 | 58.9 ± .5 | -7.8 | modern | <.8 | >40 yrs |
| LN8 | 65.1 ± .6 | -9.5 | modern | 3.3 | mixed |
| LS18 | 62.9 ± .6 | -9.8 | modern | <.8 | >40 yrs |
| LS28 | 43.9 ± .5 | -10.7 | 1,100 yrs | <.8 | 1,100 yrs |
| DE3 | 59.8 ± .5 | -6.3 | modern | 2.1 | mixed |
| DE10 | 60.1 ± .5 | -7.8 | mixed | 1.7 | mixed |
| DE14 | 58.6 ± .5 | -8.0 | modern | 3.0 | mixed |

[1] Carbon-isotope analyses were interpreted by C.E. Alexander and S.C. Alexander as described in their paper (1987).

[2] Approximate age is determined from combining carbon-isotope and tritium age-dating analyses for an estimate of ground water residence time.

Areas of oxidizing and reducing conditions within the Prairie du Chien-Jordan aquifer were not at the same depth in all of the flowtubes. It is unknown if the locations of areas of oxidizing and reducing conditions in the aquifer are stable over time or if they vary. The stability of the redox conditions in an area of the aquifer has an impact on the susceptibility of the lower parts of the aquifer to $NO_3$-N contamination.

### Relations Between Indicator-Constituent Concentrations

The attained significance levels (p-values) resulting from a statistical test comparing concentrations of the three indicator constituents with each other, consistently indicated the highest association of all the tested variables (p-values less than 0.001) (table 11). High concentrations of each indicator constituent were directly related to high concentrations of the other indicator constituents. The same direct relation between the constituents was found for low concentrations. The direct relations between indicator constituents also is illustrated by the boxplots (fig. 18).

Other constituents also were statistically compared to indicator-constitutent concentrations. Triazine detection had significant direct relations to high $NO_3$-N, Cl, tritium, and DO concentrations (p-values less than 0.001). DO was also shown to have significant direct relation to $NO_3$-N, Cl, and tritium concentrations (p-values = 0.0001). Fe concentrations were shown to have significant inverse relation to $NO_3$-N, Cl, and tritium concentrations, and to triazine herbicide detection (p-values = 0.0001). These results indicate that consistent patterns are present for indicator-constituent and redox-constituent distribution in the Prairie du Chien-Jordan aquifer.

### Well Grouting

Well grouting was tested for its relation to indicator-constituent concentrations by a $\chi^2$ analysis. Well logs for project wells indicated that 95 wells were grouted when they were installed and 44 wells either were not grouted or had no record of grouting on the log. Since 1974, Minnesota State Law has required that all wells be grouted upon installation or reconstruction to isolate the aquifer from other aquifers and from contamination from the land surface. The $\chi^2$ analysis indicated that well grouting was significantly related to $NO_3$-N, Cl, and tritium concentrations (p-value = 0.021, less than 0.001, less than 0.001, respectively) (table 11). Samples from grouted wells had lower indicator-constituent concentrations than samples from ungrouted wells. This indicates the possibility of substantial water movement down the annulus of ungrouted wells, which provides a pathway for ground-water contamination.

Well grouting also was significantly related to well depth (p-value = less than 0.001) and to aquifer of completion (p-value = 0.033). About one-third of the ungrouted wells (15 of 44) were less than 150 ft deep, and one-half (22 of 44) were completed in the Prairie du Chien part of the aquifer. About two-thirds of grouted wells (64 of 95) were greater than 250 ft deep and about one-half (48 of 95) were completed in the Jordan part of the aquifer. Well depth and the part of the aquifer the well is completed in may have an effect on the statistical significance of the relation between well grouting and indicator-constituent concentrations.

### Well Depth

The depth of the well below land surface was shown to be significantly related to $NO_3$-N, Cl, and tritium concentrations by a $\chi^2$ analysis. The p-value was less than 0.001 for each of these three indicators (table 11). Samples from deep wells (greater than 250 ft) had lower indicator-constituent concentrations than samples from shallow wells (less than 150 ft). This result reinforces what was observed earlier: that wells in the deeper, Jordan part of the aquifer had primarily low indicator-constituent concentrations and reducing conditions, indicating that ground-water in the Jordan has a strong component of regional ground-water flow. Wells in the Prairie du Chien part of the aquifer had primarily medium to high indicator-constituent concentrations and oxidizing conditions, indicating that ground-water flow in the Prairie du Chien has a strong component of intermediate ground-water flow.

### Thickness of Overlying Glacial Drift

Thickness of the overlying glacial drift was tested for its relation to indicator-constituent concentrations by a $\chi^2$ analysis, using two different groupings of wells. For the first set of tests the drift was categorized into three ranges (shallow = 0-49 ft, medium = 50-99 ft, and thick = greater than 100 ft). The results showed that thickness was significantly related to $NO_3$-N concentrations (p-value = 0.001), but not to Cl and tritium concentrations (p-values = 0.113 and 0.662, respectively) (table 11). Samples from wells with thin glacial drift overlying the Prairie du Chien-Jordan aquifer had higher $NO_3$-N concentrations than samples from wells with thick glacial drift overlying the aquifer. Areas with thin glacial drift did not have a statistically significant relation to higher Cl and tritium concentrations compared to areas with thick glacial drift, however.

To more closely relate the thick, medium, and shallow ranges of glacial drift with the thickness of the glacial drift in the individual flowtubes, the thickness data were grouped by ranges that applied more closely to the drift thickness in the individual flowtubes. These thickness ranges are shown in tables 15-17, Supplemental Information Section. The p-values from this test also indicated a significant relation with $NO_3$-N concentrations (p-value = 0.041) but not with Cl and tritium concentrations (table 11). Again, samples from wells with thin glacial drift overlying the Prairie du Chien-Jordan aquifer had higher $NO_3$-N concentrations than samples from wells with thick glacial drift overlying the aquifer.

From analysis of the flowtube geologic sections (figs. 9-15) with respect to the thickness of the glacial drift and indicator constituent distribution, it appears that areas with thicker glacial drift have lower indicator-constituent concentrations than areas with thinner glacial drift. This is shown in the upgradient parts of the HS and HN flowtubes where there is thicker glacial drift and low indicator-constituent concentrations, compared to the DC and DE flowtubes where there is thin glacial drift and higher indicator-constituent concentrations. The lack of statistical significance from the tests between glacial drift thickness and Cl and tritium concentrations, however, suggests that glacial drift thickness is not a major factor of the susceptibility in Prairie du Chien-Jordan aquifer to contamination. The inability to hold constant other variables that may be affecting this relation (for example, the composition of the glacial drift or presence of confining units) could be affecting the results of this test.

## Composition of Overlying Glacial Drift

The composition of the overlying glacial drift was tested for its relation to indicator-constituent concentrations by a K-W analysis. From the well logs, three general categories of drift type were defined and assigned to the wells: (1) sand, gravel; (2) sand and clay, gravel and clay; and (3) clay, till. These glacial drift types and their presence by flowtube are listed in table 13.

The K-W analysis indicated that drift composition was significantly related to $NO_3$-N concentrations (p-value = 0.013) (table 11). Samples from wells with predominantly sand and gravel glacial drift overlying the Prairie du Chien-Jordan aquifer had higher $NO_3$-N concentrations, and samples from wells with predominantly clay and till overlying the aquifer had lower $NO_3$-N concentrations. Statistical significance

Table 13.--Composition of glacial drift in flowtubes

| Flowtube | Predominant composition of glacial drift | Number of sampled wells | Percent of sampled wells |
|---|---|---|---|
| Hennepin North and Hennepin South | sand, gravel | 0 | 0 |
| | sand and clay, gravel and clay | 14 | 56 |
| | clay; till | 11 | 44 |
| Dakota West | sand, gravel | 0 | 0 |
| | sand and clay, gravel and clay | 4 | 31 |
| | clay; till | 9 | 69 |
| Dakota Central | sand, gravel | 12 | 50 |
| | sand and clay, gravel and clay | 5 | 21 |
| | clay; till | 7 | 29 |
| Dakota East | sand, gravel | 14 | 52 |
| | sand and clay, gravel and clay | 5 | 18 |
| | clay, till | 8 | 30 |
| Olmsted | sand, gravel | 10 | 20 |
| | sand and clay, gravel and clay | 6 | 12 |
| | clay, till | 34 | 68 |

was not indicated between drift composition and Cl or tritium concentrations. Boxplots of the relation between drift composition and indicator-constituent concentrations indicated little relation between the two (fig. 21).

The lack of a significant relation between drift composition and concentrations of all three indicator constituents was surprising, because it was expected that the vertical permeability of the overlying glacial drift would have a clear effect on indicator-constituent concentrations. Clay-rich glacial drift would retard vertical recharge from the land surface to the Prairie du Chien-Jordan aquifer while more permeable sand and gravel would allow more direct vertical recharge to the aquifer. This appears to be the case in the HS and HN flowtubes, where indicator-constituent concentrations are low in the upgradient three-quarters of the aquifer where there is more clay and till in the glacial drift, compared to the downgradient one-quarter of the flowtubes where there is more sand and gravel in the glacial drift and higher indicator-constituent concentrations. Another example of this is in the DE flowtube, where the buried valley in the southwestern part of the DE flowtube, near DE5, consists primarily of clay-rich glacial tills and samples from well DE5 have low indicator-constituent concentrations. The buried valley in the northeastern half of the flowtube, near DE17-22, however, consists of outwash sand and gravel in the upper one-half of the valley. Samples from these wells all have medium to high indicator-constituent concentrations. The analysis of the relation between glacial-drift composition and indicator-constituent distribution could have indicated minimal statistical significance because of limitations in being able to correctly describe the dominant glacial drift type and the ground-water recharge pathways, based upon available information.

## Bedrock Permeability

The permeability of bedrock units overlying the Prairie du Chien-Jordan aquifer, and of the Prairie du Chien Group and the Jordan Sandstone themselves, will have an effect on the susceptibility of the aquifer to contamination. The effect of the permeability of bedrock units on indicator-constituent concentrations was evaluated using a K-W analysis and spatial relations illustrated the geologic sections (figs. 9-15).

Bedrock units that serve as overlying confining units for the Prairie du Chien-Jordan aquifer are the Decorah Shale and the basal part of the St. Peter Sandstone. The OLM flowtube is the only one of the six flowtubes that has a continuous section of Decorah Shale overlying the aquifer (figs. 14, 15). The Decorah Shale has been shown to be an effective confining unit for the aquifer in Olmsted County (Delin, 1991). Ground-water above the Decorah Shale was determined to move laterally to the edge of the shale, then move downward into the underlying aquifer. Indicator-constituent concentrations in the Prairie du Chien part of the aquifer are lower beneath the Decorah Shale than they are where the Decorah Shale is absent in the LS and LN parts of the OLM flowtube (tables 7, 8). The basal St. Peter Sandstone is present as a continuous section only in the HS and HN flowtubes. Indicator-constituent concentrations are low throughout these two flowtubes, so it is uncertain what effect the basal St. Peter Sandstone is having on aquifer water quality.

The effect of the presence or absence of the Decorah Shale on indicator-constituent concentrations was tested for samples from the Prairie du Chien part of the aquifer and the Platteville Formation in the OLM flowtube. Boxplots of the indicator-constituent concentrations illustrate higher median concentrations and IQP of $NO_3$-N, Cl, and tritium where the Decorah Shale was absent compared to where it was present (fig. 22). Tritium concentration ranges plotted on the geologic sections for this flowtube (figs. 14, 15) also indicated high values where the Decorah Shale is absent. The K-W analysis indicated that the presence of the Decorah Shale was significantly related to $NO_3$-N, Cl, and tritium concentrations (p-values = 0.026, 0.002, and 0.013, respectively) (table 11). Samples from wells with overlying Decorah Shale had lower indicator-constituent concentrations than samples from wells without overlying Decorah Shale.

Ground-water flow in the Prairie du Chien part of the aquifer is through fractures and solution channels in the limestone. Where these features are extensive, and in karstic areas of the Prairie du Chien-Jordan aquifer, contaminated ground-water can readily travel into deeper areas of the aquifer. Ground-water that appears to be affected by this process was found in the DC, DE, and OLM flowtubes. In the DC and DE flowtubes, fault lines and folding are present through both the Prairie du Chien Group and the Jordan Sandstone, and the Prairie du Chien Group is also highly fractured (figs. 12, 13). Samples from Jordan wells DC20 and DE1, 11, 14, 15, 17, 19, 20, and 25 have medium- and high-range indicator-constituent concentrations that may be reaching these parts of the aquifer through fractures in the bedrock. At the upgradient end of the LS part of the OLM flowtube, in the area of wells LS2-8, ground water with medium- and high-range indicator-constituent concentrations was present down into the Jordan part of the aquifer.

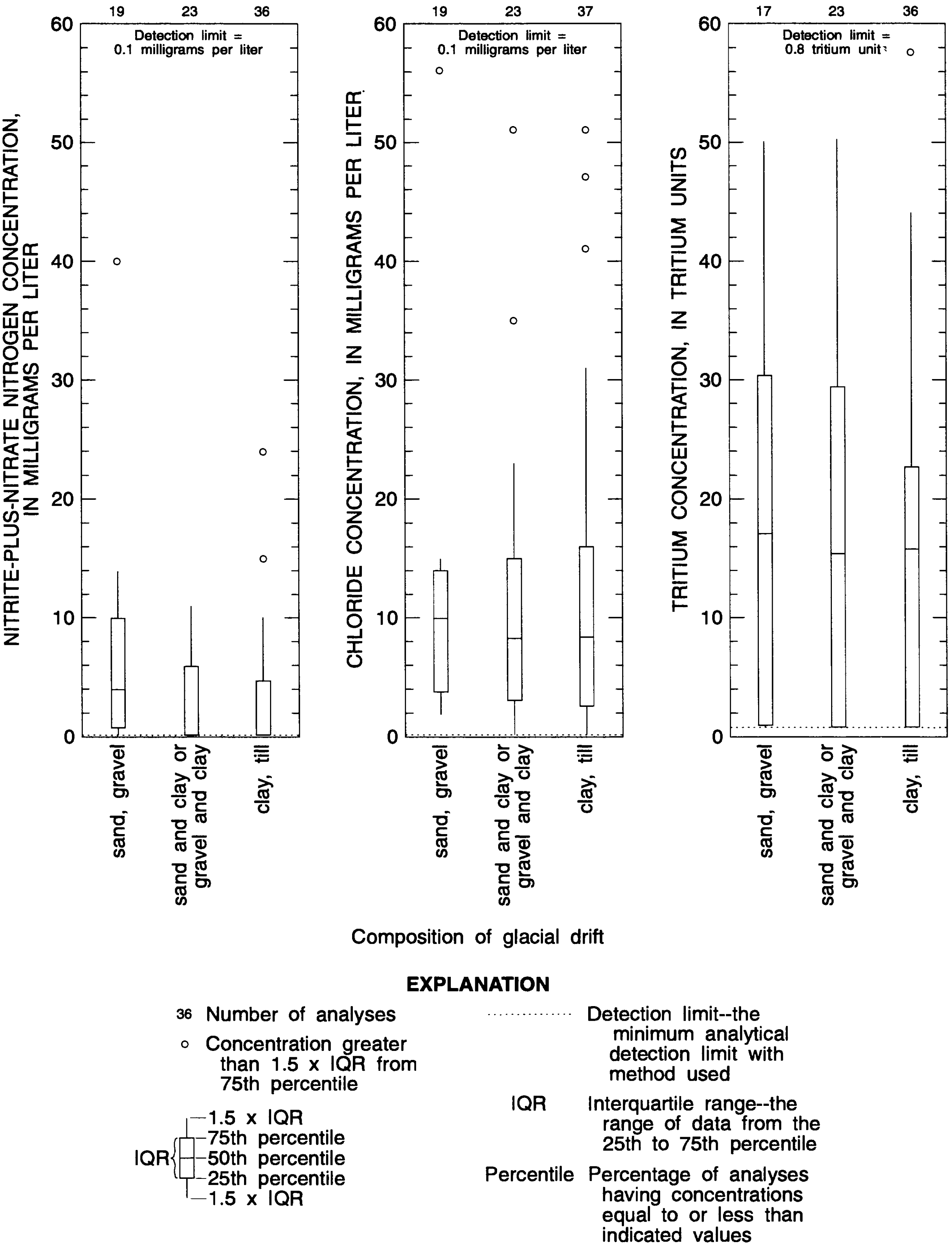


**Figure 21.--Relation of water-quality-constituent distribution to composition of the glacial drift as exhibited in the Prairie du Chien part of the aquifer and overlying aquifers.**

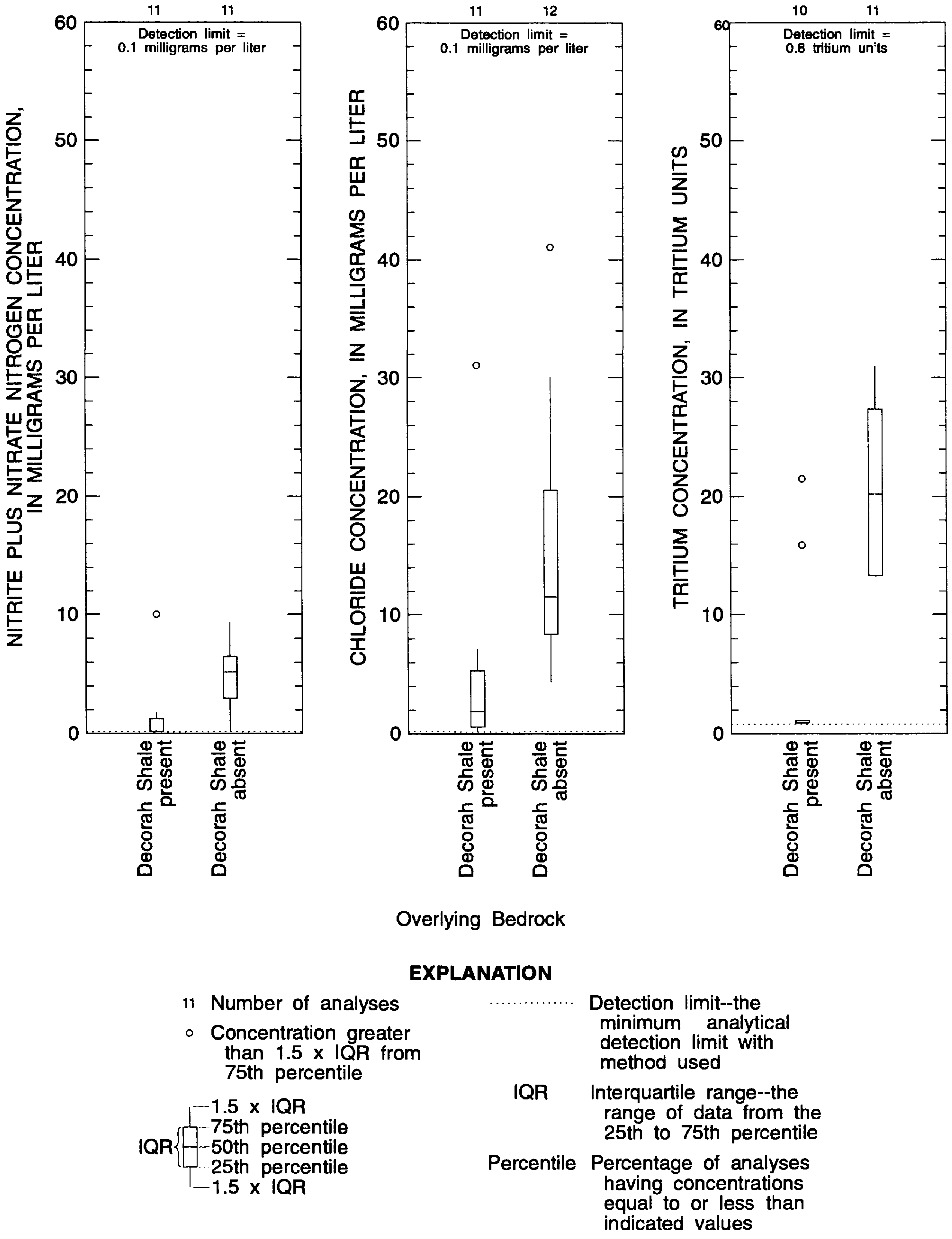


**Figure 22.--Relation of water-quality-constituent distribution to presence of overlying Decorah Shale as exhibited in the Prairie du Chien part of the aquifer and overlying aquifers.**

## Land Use

The presence of agricultural versus residential land use was tested for its relation to indicator-constituent concentrations. Table 14 lists the numbers and percent of wells in each land-use area by indicator-constituent concentration range. A greater percent of samples had low $NO_3$-N concentrations in residential compared to agricultural areas, a greater percent of samples had medium $NO_3$-N concentrations in agricultural compared to residential areas, and about the same percent of samples had high $NO_3$-N concentrations in agricultural and residential areas. A greater percent of samples had low Cl concentrations in agricultural compared to residential areas, about the same percent of samples had medium Cl concentrations in agricultural and residential areas, and a greater percent of samples had high Cl concentrations in residential compared to agricultural areas. About the same percent of samples had low, medium, and high tritium concentrations in both agricultural and residential areas. The K-W analysis indicated that land use was not significantly related to indicator-constituent concentrations (table 11).

The percent distribution of low, medium, and high indicator constituent concentrations by land use, and the K-W analysis of this relation, both suggest that land use is not a conclusive variable in determining the susceptibility of the Prairie du Chien-Jordan aquifer to contamination. Tritium concentrations likely would not be affected appreciably by land use, which is verified by these results. Sources of $NO_3$-N and Cl inputs to the environment are present in both agricultural and residential areas. The inconclusive determination of the effect of land use on $NO_3$-N and Cl distribution in the aquifer may reflect these widespread sources.

Detections of arsenic were present in the areas of greatest residential land use. Arsenic was detected in the HN, HS, and DW flowtubes. Dissolved arsenic in the HN, HS, and DW flowtubes ranged from less than 1 to 15 µg/L. All of the detections of triazine herbicides were in the areas of greatest agricultural land use: the DC, DE, and OLM flowtubes.

## MGS Sensitivity Index

The sensitivity of the Prairie du Chien-Jordan aquifer to contamination was mapped and published by MGS within their County Atlas series (Balaban, 1988, 1989; Balaban and Hobbs, 1990). The MGS pollution sensitivity index has seven categories ranging from very high to low based on: composition of the drift (4 types), thickness of the drift (3 types), and the type of bedrock confining layer (4 types). The MGS indices were grouped into three categories for this project, high, medium, and low, and a statistical analysis was made with indicator-constituent concentrations. The sensitivity index was shown to be significantly related to $NO_3$-N, Cl, tritium, and herbicide concentrations by the $\chi^2$ analysis (p-values = less than 0.001, 0.016, 0.001, and 0.013, respectively) (table 11). Samples from wells with a high sensitivity index had higher

Table 14.--Relation of water-quality constituent distribution to land use category
[mg/L, milligrams per liter; TU, tritium units; <, less than; ≤, less than or equal to; >, greater than; ≥, greater than or equal to]

| Water-quality constituent | Concentration range | Number of wells in agricultural areas | Percent of wells with agricultural land use | Number of wells in residential areas | Percent of wells with residential land use |
|---|---|---|---|---|---|
| Nitrite-plus-nitrate nitrogen (mg/L as N) | low, ≤ 1.0 | 41 | 58 | 46 | 69 |
| | medium, >1.0 to ≤ 10 | 26 | 37 | 17 | 25 |
| | high, >10 | 4 | 5 | 4 | 6 |
| Chloride (mg/L as Cl) | low, ≤ 5.0 | 43 | 61 | 34 | 50 |
| | medium, >5.0 to ≤ 10 | 13 | 18 | 10 | 15 |
| | high, >10 | 15 | 21 | 24 | 35 |
| Tritium (TU) | low, <.8 | 32 | 45 | 32 | 49 |
| | medium, ≥ .8 to ≤ 15 | 13 | 18 | 8 | 12 |
| | high, >15 | 26 | 37 | 26 | 39 |
| Triazine herbicide | not detected | 57 | 80 | 58 | 85 |
| | detected | 14 | 20 | 10 | 15 |

indicator-constituent concentrations than samples from wells with a low sensitivity index.

The MGS sensitivity index was compared with indicator-constituent concentrations to determine how well a sensitivity index could predict actual water-quality distribution. The significant relation found in this analysis indicates that a sensitivity index can be a useful planning tool for water-resource management.

## Summary and Conclusions

The Prairie du Chien-Jordan aquifer in southeastern Minnesota consists of the dolomitic Prairie du Chien Group and the underlying Jordan Sandstone. The aquifer varies in thickness from 240 ft in the Minneapolis-St. Paul area to 450 ft near the Iowa border, and is the major water-supply aquifer for southeastern Minnesota. A study was conducted to characterize water-quality differences between the Prairie du Chien and Jordan parts of the aquifer, to identify the variables that appear to be responsible for these differences, and to describe the susceptibility of the Jordan part of the aquifer to contamination.

Six study areas were chosen within Hennepin, Dakota, Scott, and Olmsted Counties, Minnesota. The study areas, called flowtubes, represented a three dimensional volume of the aquifer whose lateral boundaries were parallel to the direction of ground-water movement. The flowtubes were an average of 13 miles long and 2 miles wide. On-site field measurements and samples for water-quality analysis were collected from 139 wells completed in the Prairie du Chien and Jordan parts of the aquifer and in overlying aquifers.

Lithologic differences between the two parts of the Prairie du Chien-Jordan aquifer were shown not to have a major effect on the major-ion chemistry of water in the aquifer. No systematic patterns in major-ion chemistry were observed along the flowtubes.

Differences in water chemistry between the two parts of the aquifer were evident through analysis of the distribution of indicator-constituent concentrations ($NO_3$-N, Cl, and tritium). Indicator-constituent distribution was used to compare water from different parts of the Prairie du Chien-Jordan aquifer, to understand how water moves in the aquifer, and to identify areas where the aquifer may be susceptible to contamination from the land surface. The susceptibility of an aquifer to contamination is determined in part by the travel time of recharge water from the land surface to its present location in the aquifer (residence time). The indicator-constituent concentrations were grouped into ranges of low, medium, and high for purposes of statistical testing and to more easily detect patterns in the distribution of the constituent concentrations.

Consistent patterns in the distribution of indicator constituents and redox constituents were present in the Prairie du Chien-Jordan aquifer. The relative concentrations of indicator-constituents in the aquifer were directly correlated with each other. High concentrations of each indicator constituent were directly related to high concentrations of the other indicator constituents. Triazine herbicide detection was directly related to high concentrations of $NO_3$-N, Cl, tritium, and DO; DO concentrations were directly related to $NO_3$-N, Cl, and tritium concentrations; and Fe concentrations were inversely related to $NO_3$-N, Cl, tritium, and herbicide concentrations.

Univariate statistics showed that the median and range of indicator-constituent concentrations were greater in the Prairie du Chien part of the aquifer than they were in the Jordan part of the aquifer. The greater median and range of indicator-constituent concentrations in water from the Prairie du Chien indicated a greater variability in the age and mixing of these waters and a greater susceptibility to contamination, compared to water from the Jordan part of the aquifer.

Ground-water residence time from the land surface to areas of the Prairie du Chien-Jordan aquifer was analyzed using indicator-constituent distributions. Ground-water from the Prairie du Chien part of the aquifer had predominantly medium- and high-range $NO_3$-N, Cl, and tritium concentrations and appeared to be part of an intermediate flow system. Ground water from the Jordan part of the aquifer had predominantly low-range indicator-constituent concentrations and appeared to be part of a regional flow system. In most cases where the Prairie du Chien-Jordan aquifer was overlain by continuous bedrock or glacial-drift confining units, indicator-constituent concentrations were low and these parts of the aquifer appeared to be part of a regional flow system. Some areas of the Jordan part of the aquifer had medium- to high-range indicator-constituent concentrations suggesting that these areas were receiving recharge water more rapidly from the land surface than most areas of the Jordan, and had a component of intermediate ground-water flow.

Indicator-constituent concentrations within the Prairie du Chien-Jordan aquifer were associated with oxidation-reduction (redox) conditions in the aquifer. In general, $NO_3$-N and DO concentrations were high in areas of oxidizing conditions in the aquifer and low in areas with reducing conditions. High Fe, Mn, and $NH_4$ concentrations were not common in areas with oxidizing conditions and common in areas with reducing conditions in the aquifer. Cl and tritium concentrations tended to be lower in areas with reducing conditions compared to areas with oxidizing conditions. This tendency indicated that most recharge water from the land surface was not reaching areas of the aquifer characterized by reducing conditions in less than 40 years. Samples from some wells in areas of reducing conditions did have medium- and high-range Cl and tritium concentrations, however.

In general, oxidizing conditions were present in the Prairie du Chien part of the aquifer and were associated with medium- and high-range indicator-constituent concentrations, and reducing conditions were present in the Jordan part of the aquifer and were associated with low-range indicator-constituent concentrations. Areas with reducing conditions are less susceptible to $NO_3$-N contamination. Human-related constituents not affected by reduction reactions may still be able to reach deeper areas of the aquifer over time. It is not known whether the locations of areas of oxidizing and reducing conditions in the aquifer are stable over time.

Statistical analysis of relations between indicator-constituent concentrations and hydrogeology, well grouting, and land use variables indicated that several variables had a significant relation to water-quality characteristics of the Prairie du Chien-Jordan aquifer. The statistical comparison between constituent concentrations and selected variables assumed predominantly vertical recharge to the wells. Variables shown to be significantly related to the distribution of indicator-constituent concentrations in the aquifer were well grouting, total depth of the well, and, in Olmsted County, the presence of the overlying Decorah Shale. Variables shown to be significantly related to $NO_3$-N concentration distribution were the thickness and composition of the overlying glacial drift. Land use was shown not to be significantly related to the distribution of indicator-constituent concentrations in the aquifer. The MGS sensitivity index was significantly related to the distribution of indicator constituents in the aquifer.

Well grouting is important to the distribution of indicator-constituent concentrations because grouted wells isolate the Prairie du Chien-Jordan aquifer from contamination from the land surface or from flow exchange with other aquifers through the annulus of the well. Well depth is strongly related to indicator-constituent distribution because deeper wells generally have a longer ground-water residence time. The presence of the overlying Decorah Shale is important to indicator-constituent distribution because it retards ground-water recharge to the aquifer. The effect of the thickness and composition of the overlying glacial drift on indicator constituent distribution in the Prairie du Chien-Jordan aquifer could be better described if more information were available on the composition and permeability of the glacial drift. The varying concentrations of the indicator constituents at the upper part of the aquifer indicate that there are areas of relatively rapid and slow percolation of recharge water from the land surface to the aquifer. Further studies designed to better define recharge pathways to the Prairie du Chien-Jordan aquifer and to sample specific oxidized and reduced water-quality constituents would help to better describe variables affecting water-quality distribution in the Prairie du Chien-Jordan aquifer.

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# SUPPLEMENTAL INFORMATION

## Table 15--Categorical data and saturation indices for project wellls, Hennepin North, Hennepin South & Dakota West flowtubes

(HN, Hennepin North; HS, Hennepin South; DW, Dakota West; Qua, glacial drift; Stp, St. Peter Sandstone; Pdc Prairie du Chien Group; Jrd, Jordan Sandstone; A, agricultural; R, residential; L, low; M, medium; H, high; G, grouted; N, not grouted or not known; na, not applicable; S, shallow, M, medium; D, deep; 1, clay, till; 2, sand, gravel; 3, sand and clay or gravel and clay; --, no data; <, less than; >, greater than; ≤, less than or equal to; ≥, greater than or equal to]

| Local Identifier | Geologic unit | Well grouting | Categorical well depth label[1] | Thickness of glacial drift at well (feet) | Categorical glacial drift label, all project wells together[2] | Categorical glacial drift label, by flowtube[3] | Categorical composition of glacial drift label | Overyling bedrock confining unit |
|---|---|---|---|---|---|---|---|---|
| HN1 | Jrd | G | M | 190 | D | M | 1 | na |
| HN2 | Jrd | G | M | 193 | D | D | 1 | na |
| HN3 | Stp | G | D | 215 | D | D | 1 | na |
| HN4 | Stp | N | M | 158 | D | M | 3 | na |
| HN5 | Jrd | G | M | 180 | D | M | 1 | na |
| HN6 | Jrd | N | M | 127 | D | M | 3 | na |
| HN7 | Jrd | G | D | 92 | M | S | 1 | na |
| HS1 | Qua | N | S | 114 | D | M | 3 | na |
| HS2 | Jrd | N | D | 219 | D | D | 3 | na |
| HS3 | Qua | G | M | 152 | D | M | 3 | na |
| HS4 | Jrd | G | D | 245 | D | D | 1 | na |
| HS5 | Stp | G | M | 192 | D | D | 3 | na |
| HS6 | Jrd | G | D | 164 | D | M | 1 | na |
| HS7 | Qua | G | M | 179 | D | M | 3 | na |
| HS8 | Stp | N | D | 238 | D | D | 3 | na |
| HS9 | Jrd | N | D | 298 | D | D | 1 | na |
| HS10 | Jrd | N | D | 245 | D | D | 3 | na |
| HS11 | Pdc | G | D | 227 | D | D | 3 | na |
| HS12 | Stp | G | M | 188 | D | M | 3 | na |
| HS13 | Jrd | N | M | 116 | D | M | 3 | na |
| HS14 | Jrd | N | D | 140 | D | M | 1 | na |
| HS15 | Pdc | N | D | 194 | D | D | 1 | na |
| HS16 | Pdc | N | D | 93 | M | S | 3 | na |

Table 15--Categorical data and saturation indices for project wellls, Hennepin North, Hennepin South & Dakota West flowtubes--Continued

| Local Identifier | Geologic unit | Well grouting | Categorical well depth label[1] | Thickness of glacial drift at well (feet) | Categorical glacial drift label, all project wells together[2] | Categorical glacial drift label, by flowtube[3] | Categorical composition of glacial drift label | Overyling bedrock confining unit |
|---|---|---|---|---|---|---|---|---|
| HS17 | Pdc | N | M | 147 | D | M | 1 | na |
| HS18 | Pdc | N | M | 47 | S | S | 3 | na |
| | | | | | | | | |
| DW1 | Qua | G | S | 113 | D | M | 1 | na |
| DW2 | Pdc | G | D | 253 | D | D | 1 | na |
| DW3 | Jrd | G | D | 180 | D | M | 1 | na |
| DW4 | Stp | N | M | 140 | D | M | 3 | na |
| DW5 | Jrd | N | D | 214 | D | D | 1 | na |
| | | | | | | | | |
| DW6 | Stp | G | D | 235 | D | D | 3 | na |
| DW7 | Qua | N | M | 158 | D | M | 3 | na |
| DW8 | Pdc | N | M | 138 | D | M | 3 | na |
| DW9 | Jrd | G | D | 154 | D | M | 1 | na |
| DW10 | Pdc | N | D | 253 | D | D | 1 | na |
| | | | | | | | | |
| DW11 | Pdc | N | M | 172 | D | M | 1 | na |
| DW12 | Jrd | G | D | 100 | M | S | 1 | na |
| DW13 | Pdc | N | S | 100 | M | S | 1 | na |

Table 15--Categorical data and saturation indices for project wellls, Hennepin North, Hennepin South & Dakota West flowtubes--Continued

| Local Identifier | Land use | Modified Minnesota Geological Survey sensitivity index[4] | Calcite saturation index | Dolomite saturation index | Quartz saturation index | Sepiolite saturation index | Gypsum saturation index | Goethite saturation index |
|---|---|---|---|---|---|---|---|---|
| HN1 | R | L | 0.41 | 0.65 | 0.77 | -3.40 | -2.35 | 8.10 |
| HN2 | A | L | .29 | .31 | .78 | -3.98 | -2.65 | 8.66 |
| HN3 | A | L | .23 | .22 | .83 | -4.06 | -2.07 | 6.68 |
| HN4 | R | M | -.01 | -.23 | .71 | -4.74 | -3.84 | 7.61 |
| HN5 | R | M | .52 | .84 | .62 | -2.89 | -3.86 | 8.80 |
| HN6 | R | M | .31 | .41 | .88 | -3.08 | -2.45 | 7.70 |
| HN7 | R | M | -.21 | -.66 | .73 | -5.13 | -2.00 | 6.36 |
| HS1 | R | H | .15 | -.11 | 1.05 | -4.46 | -2.58 | 7.81 |
| HS2 | R | L | .05 | -.18 | .87 | -5.11 | -2.33 | 7.20 |
| HS3 | R | H | .06 | -.32 | 1.02 | -5.07 | -2.21 | 7.53 |
| HS4 | A | L | .01 | -.25 | .80 | -4.99 | -3.06 | 7.65 |
| HS5 | A | L | .30 | .27 | .75 | -4.31 | -3.19 | 7.55 |
| HS6 | R | L | .06 | -.14 | .77 | -4.92 | -3.00 | 7.60 |
| HS7 | R | L | -.19 | -.71 | .89 | -5.49 | -2.76 | 6.26 |
| HS8 | R | L | .19 | .08 | .93 | -4.17 | -2.58 | 7.59 |
| HS9 | A | L | .18 | .03 | .82 | -3.91 | -2.43 | 7.45 |
| HS10 | R | L | .03 | -.23 | .73 | -4.89 | -3.13 | 6.75 |
| HS11 | R | L | -.18 | -.56 | .88 | -5.67 | -1.98 | 6.46 |
| HS12 | R | L | .41 | .60 | .97 | -3.07 | -2.37 | 8.02 |
| HS13 | R | M | -.05 | -.25 | .60 | -4.82 | -3.13 | 8.79 |
| HS14 | R | L | -.01 | -.26 | .87 | -4.72 | -3.03 | 7.51 |
| HS15 | R | L | .58 | .93 | .93 | -2.26 | -2.58 | [illegible] |
| HS16 | R | M | -.04 | -.26 | .79 | -4.75 | -3.13 | 6.16 |

Table 15--Categorical data and saturation indices for project wellls, Hennepin North, Hennepin South & Dakota West flowtubes--Continued

| Local Identifier | Land use | Modified Minnesota Geological Survey sensitivity index[4] | Calcite saturation index | Dolomite saturation index | Quartz saturation index | Sepiolite saturation index | Gypsum saturation index | Goethite saturation index |
|---|---|---|---|---|---|---|---|---|
| HS17 | R | M | 0.51 | 1.01 | 0.62 | -1.76 | -2.24 | 9.50 |
| HS18 | R | M | .12 | -.01 | .77 | -4.03 | -1.30 | 8.02 |
| DW1 | A | M | .28 | .15 | -- | -- | -2.74 | 7.92 |
| DW2 | R | M | .34 | .24 | .67 | -3.95 | -2.37 | 8.18 |
| DW3 | A | L | .33 | .31 | .61 | -3.94 | -2.21 | 8.63 |
| DW4 | R | M | .22 | .11 | .74 | -3.58 | -1.82 | 8.11 |
| DW5 | R | M | .21 | .12 | .65 | -4.17 | -3.28 | 6.40 |
| DW6 | R | M | .13 | -.17 | .76 | -4.92 | -3.44 | 7.33 |
| DW7 | R | M | .33 | .40 | .79 | -3.08 | -2.25 | 8.88 |
| DW8 | R | M | .06 | -.14 | .86 | -4.52 | -1.95 | 8.60 |
| DW9 | A | M | .33 | .42 | -.89 | -8.16 | -3.53 | 7.56 |
| DW10 | R | M | .27 | .24 | .91 | -3.03 | -1.99 | 8.40 |
| DW11 | R | M | .31 | .30 | .87 | -2.89 | -1.92 | 7.99 |
| DW12 | R | H | .14 | .00 | .68 | -4.33 | -3.19 | 7.00 |
| DW13 | R | H | .21 | .16 | -.55 | -7.49 | -2.30 | 10.55 |

[1] S, 0 to 150 feet; M, 151 to 249 feet; D, > 250 feet.

[2] S, 0 to 50 feet; M, 51 to 100 feet; D, > 100 feet.

[3] Thickness of glacial drift (feet), by flowtube Hennepin North (HN): S, 0 to 100 ft; M, 101 to 190 ft; D, 191 to 215 ft.
Hennepin South (HS): S, 0 to 100 ft; M, 101 to 190 ft; D, 191 to 298 ft.
Dakota West (DW): S, 0 to 100 ft; M, 101 to 200 ft; D, 201 to 235 ft.

[4] Modified Minnesota Geological Survey sensitivity index: L, very low, low;
M, low medium, medium, high medium;
H, high, very high.

## Table 16.--Categorical data and saturation indices for project wells, Dakota Central and Dakota East flowtubes

[DC, Dakotal Central; DE, Dakota East; Qua, glacial drift; Pdc, Prairie du Chien Group; Jrd, Jordan Sandstone; A, agricultural; R, residential; L, low; M, medium; H, high; G, grouted; N, not grouted or not known; na, not applicable; S, shallow, D, deep; 1, clay, drift; 2, sand, gravel; 3, sand and clay or gravel and clay; --, no data; <, less than; >, greater than; ≤, less than or equal to; ≥, greater than or equal to]

| Local identifier | Geologic unit | Well grouting | Categorical well depth label[1] | Thickness of glacial drift at well (feet) | Categorical glacial drift label, all project wells together[2] | Categorical glacial drift label, by flowtube[3] | Categorical composition of glacial drift label | Overyling bedrock confining unit |
|---|---|---|---|---|---|---|---|---|
| DC1 | Pdc | G | S | 60 | M | M | 1 | na |
| DC2 | Pdc | N | S | 40 | S | S | 2 | na |
| DC3 | Pdc | N | S | 40 | S | S | 3 | na |
| DC4 | Jrd | G | D | 5 | S | S | 1 | na |
| DC5 | Jrd | G | D | 5 | S | S | 1 | na |
| DC6 | Pdc | G | S | 107 | D | M | 3 | na |
| DC7 | Jrd | G | D | 0 | S | S | 2 | na |
| DC8 | Jrd | G | D | 0 | S | S | 2 | na |
| DC9 | Pdc | G | S | 0 | S | S | 2 | na |
| DC10 | Pdc | G | M | 5 | S | S | 1 | na |
| DC11 | Pdc | N | S | 68 | M | M | 2 | na |
| DC12 | Jrd | G | D | 125 | D | D | 1 | na |
| DC13 | Pdc | G | S | 104 | D | M | 1 | na |
| DC14 | Jrd | G | D | 54 | M | M | 2 | na |
| DC15 | Pdc | G | S | 105 | D | M | 2 | na |
| DC16 | Pdc | N | S | 130 | D | D | 2 | na |
| DC17 | Pdc | N | S | 144 | D | D | 3 | na |
| DC18 | Jrd | G | M | 225 | D | D | 2 | na |
| DC19 | Jrd | G | M | 52 | M | M | 2 | na |
| DC20 | Jrd | G | M | 5 | S | S | 1 | na |
| DC21 | Pdc | N | S | 102 | D | M | 2 | na |
| DC22 | Pdc | G | M | 87 | M | M | 3 | na |
| DC23 | Jrd | G | D | 85 | M | M | 2 | na |
| DC24 | Jrd | N | D | 5 | S | S | 3 | na |

## Table 16.--Categorical data and saturation indices for project wells, Dakota Central and Dakota East flowtubes--Continued

| Local identifier | Geologic unit | Well grouting | Categorical well depth label[1] | Thickness of glacial drift at well (feet) | Categorical glacial drift label, all project wells together[2] | Categorical glacial drift label, by flowtube[3] | Categorical composition of glacial drift label | Overlying bedrock confining unit |
|---|---|---|---|---|---|---|---|---|
| DE1 | Jrd | G | D | 6 | S | S | 1 | na |
| DE2 | Pdc | G | M | 120 | D | D | 3 | na |
| DE3 | Jrd | G | D | 37 | S | M | 1 | na |
| DE4 | Pdc | G | M | 26 | S | S | 3 | na |
| DE5 | Qua | N | D | 262 | D | D | 2 | na |
| DE6 | Pdc | G | M | 42 | S | M | 2 | na |
| DE7 | Pdc | N | D | 36 | S | M | 3 | na |
| DE8 | Pdc | G | D | 27 | S | S | 2 | na |
| DE9 | Pdc | G | D | 12 | S | S | 1 | na |
| DE10 | Jrd | G | D | 15 | S | S | 2 | na |
| DE11 | Jrd | G | D | 42 | S | M | 2 | na |
| DE12 | Pdc | N | S | 38 | S | M | 1 | na |
| DE13 | Pdc | N | S | 38 | S | M | 2 | na |
| DE14 | Jrd | G | D | 26 | S | S | 2 | na |
| DE15 | Jrd | G | D | 20 | S | S | 3 | na |
| DE16 | Pdc | G | M | 8 | S | S | 2 | na |
| DE17 | Jrd | N | M | 145 | D | D | 2 | na |
| DE18 | Pdc | G | M | 75 | M | M | 2 | na |
| DE19 | Jrd | N | D | 279 | D | D | 1 | na |
| DE20 | Jrd | N | M | 120 | D | D | 1 | na |

## Table 16.--Categorical data and saturation indices for project wells, Dakota Central and Dakota East flowtubes--Continued

| Local Identifier | Land use | Modified Minnesota Geological Survey sensitivity index[4] | Calcite saturation index | Dolomite saturation index | Quartz saturation index | Sepiolite saturation index | Gypsum saturation index | Goethite saturation index |
|---|---|---|---|---|---|---|---|---|
| DE21 | Qua | G | M | 174 | D | D | 1 | na |
| DE22 | Qua | N | D | 256 | D | D | 1 | na |
| DE23 | Jrd | G | D | 105 | D | D | 2 | na |
| DE24 | Jrd | G | D | 75 | M | M | 2 | na |
| DE25 | Jrd | G | M | 58 | M | M | 2 | na |
| DE26 | Pdc | N | M | 30 | S | S | 3 | na |
| DE27 | Jrd | G | M | 30 | S | S | 2 | na |
| DC1 | A | M | -0.47 | -1.12 | 0.51 | -6.04 | -2.55 | 5.95 |
| DC2 | A | H | .11 | -.04 | .55 | -3.68 | -2.05 | 7.05 |
| DC3 | A | H | -.07 | -.51 | .61 | -4.61 | -2.05 | 6.42 |
| DC4 | A | H | .08 | -.17 | .43 | -4.36 | -1.77 | 7.89 |
| DC5 | A | H | .20 | .20 | .43 | -3.40 | -1.97 | 8.80 |
| DC6 | A | H | .12 | -.16 | .72 | -3.31 | -2.16 | 6.70 |
| DC7 | A | H | .07 | -.14 | .50 | -4.11 | -2.43 | 8.24 |
| DC8 | A | H | .22 | .14 | .56 | -4.18 | -2.27 | 8.17 |
| DC9 | A | H | -.41 | -1.04 | .55 | -5.94 | -2.09 | 5.66 |
| DC10 | A | H | .06 | -.02 | .50 | -4.46 | -2.03 | 7.24 |
| DC11 | R | H | -.13 | -.57 | .17 | -5.61 | -2.29 | 6.39 |
| DC12 | A | H | .21 | .09 | .60 | -4.09 | -2.08 | 8.02 |
| DC13 | A | H | .26 | .18 | .78 | -3.36 | -2.36 | 7.80 |

## Table 16.--Categorical data and saturation indices for project wells, Dakota Central and Dakota East flowtubes--Continued

| Local Identifier | Land use | Modified Minnesota Geological Survey sensitivity index[4] | Calcite saturation index | Dolomite saturation index | Quartz saturation index | Sepiolite saturation index | Gypsum saturation index | Goethite saturation index |
|---|---|---|---|---|---|---|---|---|
| DC14 | A | H | .07 | -.21 | .56 | -4.59 | -2.21 | 7.76 |
| DC15 | R | H | .12 | -.02 | .59 | -4.11 | -2.09 | 6.63 |
| DC16 | R | H | .07 | -.16 | .63 | -4.26 | -2.19 | 6.13 |
| DC17 | R | H | .12 | -.04 | .60 | -4.15 | -2.08 | 6.13 |
| DC18 | R | H | .04 | -.22 | .56 | -4.44 | -2.33 | 7.91 |
| DC19 | A | H | .05 | -.20 | .54 | -4.80 | -2.23 | 7.70 |
| DC20 | A | H | .21 | .16 | .62 | -3.44 | -2.54 | -- |
| DC21 | A | H | .16 | -.06 | .75 | -3.97 | -2.04 | 6.56 |
| DC22 | A | H | .14 | -.04 | .65 | -3.78 | -2.18 | 6.46 |
| DC23 | R | H | .32 | .47 | .50 | -3.55 | -2.38 | 8.45 |
| DC24 | A | H | .11 | .43 | .60 | -4.70 | -2.38 | 7.53 |
| DE1 | A | H | .21 | .20 | .48 | -2.92 | -2.28 | 7.25 |
| DE2 | A | M | .13 | .01 | .49 | -3.14 | -1.84 | 7.25 |
| DE3 | A | M | .02 | -.18 | .50 | -3.81 | -2.19 | 8.02 |
| DE4 | A | M | -.20 | -.69 | .59 | -4.11 | -2.74 | 8.05 |
| DE5 | A | M | -.10 | -.63 | .67 | -4.06 | -2.35 | 7.96 |
| DE6 | R | M | 0 | -.27 | .76 | -2.89 | -2.53 | 8.21 |
| DE7 | R | H | .17 | .08 | .57 | -3.67 | -1.81 | 7.12 |
| DE8 | R | M | -.02 | -.33 | .65 | -4.51 | -2.22 | 6.36 |
| DE9 | A | M | .08 | -.12 | .46 | -4.95 | -1.57 | 6.13 |

Table 16.--Categorical data and saturation indices for project wells, Dakota Central and Dakota East flowtubes--Continued

| Local Identifier | Land use | Modified Minnesota Geological Survey sensitivity index[4] | Calcite saturation index | Dolomite saturation index | Quartz saturation index | Sepiolite saturation index | Gypsum saturation index | Goethite saturation index |
|---|---|---|---|---|---|---|---|---|
| DE10 | A | M | .20 | .16 | .55 | -3.45 | -2.24 | 9.30 |
| DE11 | A | H | .17 | .12 | .58 | -3.14 | -2.30 | 7.01 |
| DE12 | A | H | .02 | -.26 | .64 | -4.66 | -1.93 | 6.34 |
| DE13 | A | H | .24 | .15 | .68 | -4.26 | -1.88 | 6.44 |
| DE14 | A | H | -.01 | -.30 | .60 | -4.24 | -2.34 | 6.43 |
| DE15 | R | H | .04 | -.13 | .53 | -4.06 | -1.77 | na |
| DE16 | R | H | .09 | -.08 | .60 | -3.86 | -2.23 | 8.00 |
| DE17 | A | H | .10 | -.01 | .61 | -3.73 | -2.19 | 6.54 |
| DE18 | A | H | .05 | -.16 | .60 | -4.03 | -2.35 | -- |
| DE19 | A | H | .28 | .31 | .50 | -3.34 | -1.81 | 7.00 |
| DE20 | A | H | -.08 | -.42 | .66 | -4.47 | -2.43 | 5.99 |
| DE21 | A | H | -.03 | -.26 | .66 | -4.33 | -2.22 | 6.56 |
| DE22 | A | H | .23 | .17 | .64 | -2.87 | -2.33 | -- |
| DE23 | A | H | .22 | .14 | .67 | -2.96 | -2.44 | 6.23 |
| DE24 | A | H | .11 | -.03 | .55 | -3.74 | -2.00 | 8.11 |
| DE25 | R | H | -.14 | -.55 | .67 | -4.65 | -2.37 | 6.06 |
| DE26 | R | H | -0.02 | -0.27 | 0.59 | -4.07 | -2.36 | 7.11 |
| DE27 | A | H | .06 | -.15 | .60 | -3.91 | -2.38 | 7.82 |

[1] S, 0 to 150 feet; M, 151 to 249 feet; D, > 250 feet.

[2] S, 0 to 50 feet; M, 51 to 100 feet; D, > 100 feet.

[3] Thickness of glacial drift (ft), by flowtube Dakota Central (DC): S, 0 to 50 ft; M, 51 to 110 ft; D, 111 to 225 ft.
Dakota East (DE): S, 0 to 30 ft; M, 31 to 100 ft; D, 101 to 279 ft.

[4] Modified Minnesota Geological Survey sensitivity index: L, very low, low; M, low medium, medium, high medium; H, high, very high.

## Table 17.--Categorical data and saturation indices for project wells, Olmsted North and Olmsted South flowtubes

[LN, Olmsted North; LS, Olmsted South; Plv, Platteville Formation; Stp, St. Peter Sandstone; Pdc, Prairie du Chien Group; Jrd, Jordan Sandstone; A, agricultural; R, residential; G, grouted; N, not grouted or not known; Dc, Decorah Shale; G, Glenwood Shale; U, unconfined; S, shallow, D, deep; 1, clay, drift; 2, sand, gravel; 3, sand and clay or gravel and clay; DT, herbicide detected; ND, no herbicide detected; --, no data; <, less than; >, greater than; ≤, less than or equal to; ≥, greater than or equal to]

| Local Identifier | Geologic unit | Well grouting | Categorical well depth label[1] | Thickness of glacial drift at well (feet) | Categorical glacial drift label, all project wells together[2] | Categorical glacial drift label, by flowtube[3] | Categorical composition of glacial drift label | Overyling bedrock confining unit |
|---|---|---|---|---|---|---|---|---|
| LN1 | Jrd | G | D | 20 | S | M | 1 | U |
| LN2 | Pdc | G | D | 4 | S | S | 1 | Dc |
| LN3 | Jrd | G | D | 7 | S | S | 1 | Dc |
| LN4 | Pdc | G | M | 0 | S | S | 2 | G |
| LN5 | Jrd | G | D | 24 | S | D | 1 | Dc |
| LN6 | Pdc | G | D | 20 | S | M | 1 | Dc |
| LN7 | Jrd | G | D | 20 | S | M | 1 | Dc |
| LN8 | Pdc | G | D | 6 | S | S | 1 | G |
| LN9 | Pdc | G | D | 0 | S | S | 2 | U |
| LN10 | Pdc | G | D | 17 | S | M | 1 | G |
| LN11 | Jrd | G | D | 57 | M | D | 3 | U |
| LN12 | Jrd | G | D | 7 | S | S | 3 | U |
| LN13 | Jrd | N | D | 12 | S | M | 1 | U |
| LN14 | Pdc | G | M | 10 | S | S | 1 | U |
| LN15 | Jrd | G | D | 30 | S | D | 1 | U |
| LS1 | Jrd | G | D | 12 | S | M | 1 | Dc |
| LS2 | Plv | N | S | 20 | S | M | 1 | U |
| LS3 | Jrd | G | D | 5 | S | S | 1 | Dc |
| LS4 | Pdc | G | D | 14 | S | M | 1 | G |
| LS5 | Pdc | N | M | 42 | S | D | 1 | U |
| LS6 | Pdc | G | D | 10 | S | S | 1 | G |
| LS7 | Jrd | G | D | 12 | S | M | 1 | G |
| LS8 | Jrd | G | D | 20 | S | M | 2 | U |

Table 17.--Categorical data and saturation indices for project wells, Olmsted North and Olmsted South flowtubes--Continued

| Local Identifier | Geologic unit | Well grouting | Categorical well depth label[1] | Thickness of glacial drift at well (feet) | Categorical glacial drift label, all project wells together[2] | Categorical glacial drift label, by flowtube[3] | Categorical composition of glacial drift label | Overyling bedrock confining unit |
|---|---|---|---|---|---|---|---|---|
| LS9 | Pdc | G | D | 10 | S | S | 1 | Dc |
| LS10 | Plv | N | S | 10 | S | S | 1 | U |
| LS11 | Pdc | G | D | 19 | S | M | 1 | Dc |
| LS12 | Stp | N | M | 0 | S | S | 2 | G |
| LS13 | Stp | G | D | 6 | S | S | 1 | Dc |
| LS14 | Pdc | G | D | 8 | S | S | 1 | Dc |
| LS15 | Pdc | G | D | 0 | S | S | 2 | Dc |
| LS16 | Stp | G | D | 0 | S | S | 2 | Dc |
| LS17 | Pdc | G | D | 5 | S | S | 1 | Dc |
| LS18 | Jrd | G | D | 4 | S | S | 1 | Dc |
| LS19 | Jrd | G | D | 15 | S | M | 1 | Dc |
| LS20 | Pdc | G | D | 0 | S | S | 2 | G |
| LS21 | Jrd | G | D | 86 | M | D | 2 | U |
| LS22 | Jrd | G | D | 37 | S | D | 3 | G |
| LS23 | Pdc | G | D | 7 | S | S | 1 | U |
| LS24 | Stp | G | M | 10 | S | S | 1 | Dc |
| LS25 | Pdc | N | S | 10 | S | S | 1 | U |
| LS26 | Pdc | N | S | 20 | S | M | 2 | U |
| LS27 | Pdc | N | S | 20 | S | M | 1 | U |
| LS28 | Jrd | G | D | 38 | S | D | 3 | U |
| LS29 | Pdc | G | D | 9 | S | S | 1 | Dc |
| LS30 | Jrd | G | D | 0 | S | S | 2 | U |
| LS31 | Jrd | G | D | 50 | M | D | 3 | U |
| LS32 | Pdc | G | M | 9 | S | S | 3 | U |

Table 17.--Categorical data and saturation indices for project wells, Olmsted North and Olmsted South flowtubes--Continued

| Local Identifier | Geologic unit | Well grouting | Categorical well depth label[1] | Thickness of glacial drift at well (feet) | Categorical glacial drift label, all project wells together[2] | Categorical glacial drift label, by flowtube[3] | Categorical composition of glacial drift label | Overyling bedrock confining unit |
|---|---|---|---|---|---|---|---|---|
| LS33 | Pdc | G | D | 10 | S | S | 1 | U |
| LS34 | Pdc | G | M | 5 | S | S | 1 | U |
| LS35 | Jrd | G | D | 10 | S | S | 1 | U |

## Table 17.--Categorical data and saturation indices for project wells, Olmsted North and Olmsted South flowtubes--Continued

| Local Identifier | Land use | Modified Minnesota Geological Survey sensitivity index[4] | Calcite saturation index | Dolomite saturation index | Quartz saturation index | Sepiolite saturation index | Gypsum saturation index | Goethite saturation index |
|---|---|---|---|---|---|---|---|---|
| LN1 | A | H | 0.15 | -0.06 | 0.51 | -4.53 | -2.35 | 8.76 |
| LN2 | A | M | -.21 | -.79 | .54 | -6.15 | -2.31 | 7.88 |
| LN3 | A | M | .23 | .13 | .49 | -4.36 | -2.40 | 8.68 |
| LN4 | A | M | -.31 | -.93 | .62 | -6.22 | -2.18 | 5.62 |
| LN5 | A | M | -.05 | -.49 | .50 | -5.57 | -2.04 | 8.35 |
| LN6 | A | H | -.08 | -.56 | .61 | -5.63 | -2.11 | 5.05 |
| LN7 | R | H | -.02 | -.41 | .49 | -5.43 | -2.13 | 6.64 |
| LN8 | R | M | -.25 | -.72 | .48 | -6.03 | -2.08 | 6.81 |
| LN9 | R | M | .07 | -15 | .54 | -4.82 | -2.14 | 6.53 |
| LN10 | R | M | -.06 | -.43 | .51 | -5.48 | -2.17 | 7.01 |
| LN11 | R | M | -.41 | -1.21 | .49 | -7.15 | -2.29 | 5.61 |
| LN12 | R | H | -.31 | -.99 | .48 | -6.65 | -2.09 | 7.36 |
| LN13 | R | H | -.01 | -.39 | .48 | -5.40 | -2.24 | 7.29 |
| LN14 | R | H | -.18 | -.68 | .50 | -6.00 | -2.18 | 7.10 |
| LN15 | R | H | -.11 | -.63 | .64 | -5.62 | -2.16 | 5.00 |
| LS1 | A | H | -.06 | -.60 | .64 | -5.33 | -2.24 | 7.97 |
| LS2 | A | M | -.05 | -.51 | .53 | -6.37 | -1.35 | 4.39 |
| LS3 | R | M | .20 | -.02 | .52 | -4.59 | -1.83 | 8.29 |
| LS4 | R | M | -.40 | -1.32 | .67 | -7.03 | -2.08 | 5.76 |
| LS5 | R | M | .20 | -.12 | .67 | -4.83 | -1.85 | 6.30 |
| LS6 | R | M | .02 | -.49 | .63 | -5.39 | -1.90 | 6.17 |
| LS7 | R | M | .13 | -.28 | .61 | -5.03 | -1.65 | 8.00 |
| LS8 | R | H | -.06 | -.60 | .66 | -5.57 | -1.80 | 5.70 |

## Table 17.--Categorical data and saturation indices for project wells, Olmsted North and Olmsted South flowtubes--Continued

| Local Identifier | Land use | Modified Minnesota Geological Survey sensitivity index[4] | Calcite saturation index | Dolomite saturation index | Quartz saturation index | Sepiolite saturation index | Gypsum saturation index | Goethite saturation index |
|---|---|---|---|---|---|---|---|---|
| LS9 | A | H | -0.15 | -0.06 | 0.51 | -4.53 | -2.35 | 8.76 |
| LS10 | A | M | -0.52 | -1.57 | .78 | -7.01 | -2.11 | 4.20 |
| LS11 | A | M | -.08 | -.47 | .44 | -5.57 | -2.54 | -- |
| LS12 | A | M | -.11 | -.63 | .63 | -5.74 | -2.05 | 5.73 |
| LS13 | A | H | -.51 | -1.48 | .54 | -7.29 | -1.78 | 7.18 |
| LS14 | A | H | -.03 | -.50 | .45 | -6.08 | -2.10 | 7.62 |
| LS15 | A | H | -.40 | -1.21 | .45 | -7.29 | -1.88 | 6.46 |
| LS16 | A | H | -.30 | -1.01 | .44 | -6.95 | -1.62 | 6.84 |
| LS17 | A | H | -.14 | -.67 | .44 | -6.95 | -1.62 | 6.84 |
| LS18 | R | M | -.19 | -.77 | .51 | -6.00 | -2.29 | 7.48 |
| LS19 | A | M | .22 | .06 | .44 | -4.60 | -2.42 | 9.13 |
| LS20 | A | H | -.23 | -.99 | .54 | -6.49 | -2.22 | NA |
| LS21 | A | H | -.42 | -1.20 | .55 | -6.73 | -2.02 | 7.19 |
| LS22 | R | M | -.12 | -.58 | .43 | -6.24 | -1.81 | 7.35 |
| LS23 | A | M | .03 | -.27 | .48 | -5.39 | -1.80 | 5.05 |
| LS24 | A | H | .13 | -.51 | .58 | -5.88 | -1.80 | 6.24 |
| LS25 | A | H | -.01 | -.36 | .74 | -5.12 | -1.96 | 5.50 |
| LS26 | R | H | -- | -- | -- | -- | -- | -- |
| LS27 | R | H | -.15 | -.85 | .54 | -6.38 | -2.20 | 4.90 |
| LS28 | R | H | -.16 | -.73 | .50 | -6.17 | -1.96 | 7.98 |
| LS29 | R | M | -.17 | -.81 | .59 | -6.17 | -2.03 | 4.87 |
| LS30 | A | H | -.17 | -.74 | .50 | -5.94 | -2.17 | 7.56 |
| LS31 | R | H | -.01 | -.35 | .47 | -5.12 | -2.30 | 7.79 |
| LS32 | R | H | .00 | -.59 | .53 | -5.70 | -2.16 | 5.24 |

Table 17.--Categorical data and saturation indices for project wells, Olmsted North and Olmsted South flowtubes--Continued

| Local Identifier | Land use | Modified Minnesota Geological Survey sensitivity index[4] | Calcite saturation index | Dolomite saturation index | Quartz saturation index | Sepiolite saturation index | Gypsum saturation index | Goethite saturation index |
|---|---|---|---|---|---|---|---|---|
| LS33 | R | H | 0.10 | -0.28 | 0.54 | -5.45 | -1.69 | 6.41 |
| LS34 | A | H | 0.01 | -0.26 | 0.52 | -4.78 | -2.25 | 9.58 |
| LS35 | R | H | -.31 | -.98 | .50 | -6.24 | -2.20 | 7.42 |

[1] S, 0 to 150 feet; M, 151 to 249 feet; D, > 250 feet.

[2] S, 0 to 50 feet; M, 51 to 100 feet; D, > 100 feet.

[3] Thickness of glacial drift (ft), by flowtube Olmsted (OLM): S, 0 to 10 ft; M, 11 to 20 ft; D, 21 to 86 ft.

[4] Modified Minnesota Geological Survey sensitivity index: L, very low low; M, low medium, medium, high medium; H, high, very high.

Table 18.--Well identification and numbering system.
[HN, Hennepin North; HS, Hennepin South; DW, Dakota West; DC, Dakota Central; DE, Dakota East; LN, Olmsted North; LS, Olmsted South; --, no data]

| Local identifier | Township, range & section | Minnesota unique number | Station number | Date | Total depth of well below land surface (feet) |
|---|---|---|---|---|---|
| Hennepin County | | | | | |
| HN1 | 119N22W31DBBD | 166097 | 450418093303801 | 08-29-90 | 204 |
| HN2 | 119N22W32CDAA | 104701 | 450406093293001 | 08-31-90 | 247 |
| HN3 | 119N22W33CACD | 128030 | 450411093283101 | 08-30-90 | 280 |
| HN4 | 119N22W35DBBA | 204836 | 450419093254401 | 09-06-90 | 169 |
| HN5 | 119N22W36BBBA | 143957 | 450447093250401 | 08-13-91 | 232 |
| HN6 | 119N22W36DCCA | 204844 | 450359093242901 | 09-06-90 | 192 |
| HN7 | 119N21W34DCAB | 203317 | 450407093193301 | 08-31-90 | 340 |
| HS1 | 118N23W16BAAA | 157819 | 450210093353801 | 08-07-90 | 114 |
| HS2 | 118N23W15BCDC | 118855 | 450148093344801 | 08-08-90 | 360 |
| HS3 | 118N23W14BACA | 405084 | 450201093332201 | 08-07-90 | 152 |
| HS4 | 118N23W14ACCC | 104727 | 450145093330501 | 08-08-90 | 363 |
| HS5 | 118N22W09BABD | 163895 | 450205093321601 | 08-09-90 | 204 |
| HS6 | 118N23W12CDDB | 145406 | 450216093320401 | 08-08-90 | 319 |
| HS7 | 118N22W18AADA | 405052 | 450202093301001 | 08-10-90 | 179 |
| HS8 | 118N22W18ADDD | 164534 | 450147093300801 | 08-08-90 | 263 |
| HS9 | 118N22W08CCDA | 204208 | 450214093294701 | 09-10-90 | 392 |
| HS10 | 118N22W09BABD | 135325 | 450257093282901 | 08-09-90 | 275 |
| HS11 | 118N22W16ADCA | 136095 | 450150093275201 | 08-10-90 | 292 |
| HS12 | 118N22W10DBCD | 146122 | 450224093263501 | 08-30-90 | 215 |
| HS13 | 118N22W11BAAA | 204222 | 450301093255301 | 08-10-90 | 215 |
| HS14 | 118N22W13DADA | 204272 | 450408093192901 | 09-06-90 | 390 |
| HS15 | 118N22W13DABD | 204271 | 450147093244301 | 08-21-90 | 256 |
| HS16 | 118N21W08CCDA | 114311 | 450218093223201 | 08-09-90 | 260 |
| HS17 | 118N21W10CDAA | 203574 | 450224093194801 | 08-28-91 | 195 |
| HS18 | 29N24W04AABD | 203577 | 450208093173401 | 08-30-90 | 225 |
| Dakota County | | | | | |
| DW1 | 114N21W36ACDD | 178536 | 443819093170101 | 08-28-90 | 113 |
| DW2 | 114N21W26DBDA | 127124 | 443900093181501 | 08-28-90 | 277 |
| DW3 | 114N21W25CBAA | 161439 | 443905093173801 | 08-28-90 | 479 |
| DW4 | 114N21W25ABDA | 216487 | 443926093165901 | 08-28-90 | 180 |
| DW5 | 114N21W12CACA | 207768 | 444135093172901 | 08-07-90 | 517 |
| DW6 | 114N21W12ADCC | 427499 | 444145093165601 | 08-06-90 | 280 |
| DW7 | 114N21W12BBCC | 212390 | 444158093175001 | 08-08-90 | 158 |
| DW8 | 114N21W01CABB | 207752 | 444234093173101 | 09-04-90 | 167 |
| DW9 | 115N21W36CBAC | 207887 | 444322093173901 | 08-03-90 | 593 |
| DW10 | 115N21W36BBBA | 207861 | 444354093174301 | 08-02-90 | 273 |
| DW11 | 115N21W23BCDC | 206037 | 444513093185401 | 08-13-91 | 193 |
| DW12 | 115N21W15ACDC | 205839 | 444606093193101 | 08-02-90 | 274 |
| Scott County | | | | | |
| DW13 | 115N21W15BCCB | 208817 | 444609093201801 | 08-03-90 | 112 |

Table 18.--Well identification and numbering system--Continued

| Local identifier | Township, range & section | Minnesota unique number | Station number | Date | Total depth of well below land surface (feet) |
|---|---|---|---|---|---|
| | | Dakota County | | | |
| DC1 | 113N19W29BCAC | 101098 | 443404093075901 | 08-29-90 | 127 |
| DC2 | 113N19W21CCCD | 207503 | 443422093064901 | 08-01-91 | 90 |
| DC3 | 113N19W21CCDC | 207502 | 443422093064701 | 08-29-90 | 90 |
| DC4 | 113N19W21DCBA | 506626 | 443419093062001 | 08-24-90 | 320 |
| DC5 | 113N19W21ADCC | 207699 | 443449093060401 | 08-01-91 | 420 |
| DC6 | 113N19W03CCDC | 101031 | 443700093053301 | 07-31-90 | 138 |
| DC7 | 113N19W13CABB | 136520 | 443536093025901 | 08-22-90 | 380 |
| DC8 | 113N19W10AABB | 156918 | 443655093044901 | 07-31-90 | 379 |
| DC9 | 113N18W18BBCA | 435246 | 443555093015901 | 09-04-90 | 120 |
| DC10 | 113N18W18BBBB | 104113 | 443603093020301 | 08-02-91 | 190 |
| DC11 | 114N19W35CDCC | 104342 | 443750093041201 | 08-06-90 | 80 |
| DC12 | 113N19W02BAAA | 418684 | 443748093035901 | 07-30-90 | 300 |
| DC13 | 114N19W25BBBB | 198342 | 443932093031601 | 08-05-91 | 110 |
| DC14 | 114N18W30BCCC | 196606 | 443909093020401 | 08-05-91 | 257 |
| DC15 | 114N18W30AADB | 101038 | 443924093010001 | 08-09-91 | 128 |
| DC16 | 114N18W30AADB | 216439 | 443926093010001 | 08-01-90 | 137 |
| DC17 | 114N18W30AAAC | 236603 | 443927093010101 | 08-09-91 | 147 |
| DC18 | 114N18W29BBBA | 194283 | 443930093004801 | 08-14-91 | 234 |
| DC19 | 114N18W20CBBC | 185940 | 443952093005501 | 08-01-90 | 230 |
| DC20 | 114N18W15BBDB | 121076 | 444109092581701 | 08-14-91 | 235 |
| DC21 | 114N18W10CCBB | 124308 | 444127092582501 | 08-22-90 | 135 |
| DC22 | 114N18W02CBBC | 136495 | 444230092571101 | 08-06-91 | 234 |
| DC23 | 114N18W02BCDA | 170875 | 444240092565701 | 08-06-91 | 320 |
| DC24 | 115N17W18CACD | 207631 | 444551092542601 | 08-24-90 | 400 |
| DE1 | 113N18W20AAAA | 426961 | 443511092594201 | 08-09-91 | 350 |
| DE2 | 113N18W16CADD | 179135 | 443528092590701 | 08-09-91 | 240 |
| DE3 | 113N18W22ABAB | 426396 | 443510092574101 | 08-01-90 | 480 |
| DE4 | 113N18W23BBBA | 416201 | 44351102570901 | 08-01-90 | 185 |
| DE5 | 113N18W11CCDD | 412476 | 443606092565801 | 07-25-90 | 262 |
| DE6 | 113N18W11ADAD | 104172 | 443638092560401 | 07-26-90 | 230 |
| DE7 | 113N17W07AABC | 207654 | 443652092535101 | 08-27-90 | 275 |
| DE8 | 113N17W06DCDC | 145876 | 443658092540501 | 07-25-90 | 250 |
| DE9 | 113N18W01AADB | 145912 | 443737092545401 | 07-24-90 | 295 |
| DE10 | 114N17W31CBCB | 412491 | 443804092544701 | 07-24-90 | 380 |
| DE11 | 114N17W20CCCC | 435233 | 443933092533501 | 08-01-90 | 340 |
| DE12 | 114N17W19DDAD | 207656 | 443939092533801 | 07-27-90 | 125 |
| DE13 | 114N17W20CCCB | 240142 | 443936092533701 | 08-07-91 | 125 |
| DE14 | 114N17W28CAAD | 104248 | 443901092515101 | 07-23-90 | 292 |
| DE15 | 114N17W21DCCB | 104343 | 443936092514401 | 07-23-90 | 275 |
| DE16 | 114N17W22CCCD | 145889 | 443932092510401 | 07-27-90 | 220 |
| DE17 | 114N17W16DDDC | 145881 | 444026092511701 | 07-30-91 | 185 |
| DE18 | 114N17W22BBBC | 145915 | 444017092510901 | 07-23-90 | 234 |
| DE19 | 114N17W14DADD | 104125 | 444038092511401 | 08-14-91 | 318 |
| DE20 | 114N17W15CABB | 110545 | 444046092505101 | 07-17-90 | 202 |
| DE21 | 114N17W15DDCD | 170898 | 444025092501201 | 07-20-90 | 174 |
| DE22 | 114N17W15ABCB | 159526 | 444107092503401 | 08-08-90 | 254 |
| DE23 | 114N17W11ABDB | 426905 | 444159092490901 | 08-22-90 | 280 |
| DE24 | 114N17W11AACC | 425300 | 444156092490201 | 07-30-91 | 330 |
| DE25 | 114N17W02ADCD | 145852 | 444236092485701 | 07-17-90 | 195 |
| DE26 | 114N17W02AADA | 207641 | 444251092484701 | 07-23-90 | 200 |
| DE27 | 114N16W06ABCB | 194085 | 444252092465401 | 08-07-91 | 240 |

Table 18.--Well identification and numbering system--Continued

| Local identifier | Township, range & section | Minnesota unique number | Station number | Date | Total depth of well below land surface (feet) |
|---|---|---|---|---|---|
| Olmsted County | | | | | |
| LN1 | 107N12W09BBDC | 235540 | 440523092163201 | 08-21-90 | 440 |
| LN2 | 107N13W02CCCC | 105493 | 440536092212901 | 08-15-90 | 295 |
| LN3 | 107N13W09BABB | 421071 | 440535092233501 | 08-20-91 | 620 |
| LN4 | 107N13W08AAAC | 220766 | 440531092240101 | 08-15-90 | 230 |
| LN5 | 107N13W08BDDD | 150209 | 440512092243401 | 08-22-90 | 598 |
| LN6 | 107N13W08CCBA | 228653 | 440454092250101 | 08-13-90 | 335 |
| LN7 | 107N13W07DACD | 101263 | 440459092251901 | 08-14-90 | 570 |
| LN8 | 107N13W18ABBA | 228651 | 440443092253601 | 08-22-90 | 470 |
| LN9 | 107N13W07BCBB | 228652 | 440524092261701 | 08-22-90 | 321 |
| LN10 | 107N13W07BBBB | 228650 | 440534092261701 | 08-21-91 | 290 |
| LN11 | 107N14W12AAAD | 156970 | 440532092261901 | 09-05-90 | 455 |
| LN12 | 107N14W01DBCA | 101297 | 440554092264901 | 08-16-90 | 395 |
| LN13 | 107N14W01DCCA | 228620 | 440545092264801 | 08-21-91 | 384 |
| LN14 | 107N14W12CCAD | 228559 | 440451092271501 | 08-21-90 | 186 |
| LN15 | 107N14W12CCCC | 220810 | 440448092272601 | 08-13-90 | 413 |
| LS1 | 107N12W15CCDC | 119824 | 440353092152001 | 08-15-90 | 600 |
| LS2 | 107N12W16AACC | W00248 | 440435092155901 | 08-23-90 | 70 |
| LS3 | 107N12W21ABAC | 220755 | 440346092155501 | 08-20-91 | 506 |
| LS4 | 107N12W16DCDC | 220754 | 440352092155701 | 09-05-90 | 295 |
| LS5 | 107N12W21ABAB | 227474 | 440350092155801 | 08-19-91 | 191 |
| LS6 | 107N12W21ABBD | 227472 | 440345092160201 | 08-23-90 | 256 |
| LS7 | 107N12W21ABCA | 101409 | 440343092160001 | 08-19-91 | 500 |
| LS8 | 107N12W16DCCD | 148332 | 440352092160301 | 08-15-90 | 435 |
| LS9 | 107N12W18DDDC | 105012 | 440354092180301 | 08-20-91 | 350 |
| LS10 | 107N12W19ABAD | W00254 | 440347092181801 | 08-23-90 | 70 |
| LS11 | 107N12W18DCDC | 150319 | 440352092182001 | 08-17-90 | 398 |
| LS12 | 107N12W18BCCD | 227475 | 440418092190201 | 08-21-90 | 240 |
| LS13 | 107N13W15DDDA | 105498 | 440355092213201 | 08-15-90 | 280 |
| LS14 | 107N13W15DCCD | 401607 | 440353092220101 | 08-13-90 | 402 |
| LS15 | 107N13W15CBBB | 105470 | 440415092223801 | 08-22-90 | 395 |
| LS16 | 107N13W16DAAA | 220769 | 440416092224501 | 08-21-90 | 265 |
| LS17 | 197N13W21ADCA | 105490 | 440330092225201 | 08-21-91 | 395 |
| LS18 | 107N13W16DACB | 220771 | 440410092225801 | 08-13-90 | 623 |
| LS19 | 107N13W16CAAA | 139145 | 440415092231901 | 08-21-91 | 560 |
| LS20 | 107N13W17DAAD | 220773 | 440412092235701 | 08-22-90 | 285 |
| LS21 | 107N13W17DABD | 220774 | 440416092240901 | 08-21-90 | 460 |
| LS22 | 107N13W20ADCB | 150296 | 440333092240701 | 08-23-90 | 560 |
| LS23 | 107N13W20ACAC | 105455 | 440336092241801 | 08-22-91 | 292 |
| LS24 | 107N13W20BDAD | -- | 440335092243401 | 08-22-91 | 220 |
| LS25 | 107N13W18AACC | W01319 | 440433092252301 | 08-23-91 | 60 |
| LS26 | 107N13W18CABD | W00359 | 440411092255801 | 08-23-91 | 100 |
| LS27 | 107N13W18CABB | 228616 | 440417092255701 | 08-14-90 | 140 |
| LS28 | 107N13W18CABC | 180557 | 440414092255801 | 08-14-90 | 420 |
| LS29 | 107N14W24ADAD | 228649 | 440334092262001 | 08-15-90 | 332 |
| LS30 | 107N14W13DBAA | 228548 | 440417092263701 | 08-14-90 | 404 |
| LS31 | 107N14W24BCAD | 150277 | 440335092271501 | 08-14-90 | 400 |
| LS32 | 107N14W24CBAB | 228586 | 440326092271801 | 08-14-90 | 151 |
| LS33 | 107N14W23DDDC | 120037 | 440305092273901 | 08-22-91 | 250 |
| LS34 | 107N14W14DADA | 228549 | 440412092273201 | 08-21-91 | 156 |
| LS35 | 107N14W14DCBD | 220812 | 440402092280101 | 08-23-90 | 364 |