EFFECTS OF AGRICULTURAL AND RESIDENTIAL LAND USE ON GROUND-WATER QUALITY, ANOKA SAND PLAIN AQUIFER, EAST-CENTRAL MINNESOTA

By Henry W. Anderson, Jr.

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CONVERSION FACTORS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.09290	meter squared per day
cubic foot (ft^3)	0.02832	cubic meter
gallons per minute (gal/min)	0.06308	liters per second
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
acre	4,047	square meters
million gallons per year (Mgal/yr)	3,785	cubic meter per year
degrees Fahrenheit (F)	5/9 x (F-32)	degrees Celsius

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929--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."

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ABSTRACT

Water quality in the 1,700-square-mile Anoka Sand Plain aquifer is affected by irrigated and nonirrigated agriculture and by residential land use. Concentrations of sulfate, chloride, nitrite plus nitrate nitrogen, and pesticides in ground water are related to human activities; nitrite plus nitrate nitrogen concentrations are affected more than concentrations of other chemical constituents. Of the water samples collected from 100 wells during this study, samples from 30 wells had concentrations of nitrite plus nitrate nitrogen greater than 10 mg/L (milligrams per liter), which is the limit recommended for drinking water by the Minnesota Pollution Control Agency. Analysis of 360 water samples indicated that the median concentrations of nitrite plus nitrate nitrogen for undeveloped, nonirrigated-cultivated, irrigated, and residential lands were 0.22, 2.0, 5.3, and 4.2 mg/L, respectively.

Differences in nitrite plus nitrate nitrogen concentrations at various depths below the water table were statistically significant. Median concentrations of nitrite plus nitrate nitrogen in ground-water samples less than 10 feet, 10 to 20 feet, and more than 20 feet below the water table were 5.1 mg/L, 2.7 mg/L, and less than 0.1 mg/L, respectively.

Seasonal fluctuations in nitrite plus nitrate nitrogen concentrations at many wells were as great or greater than long-term change; however, the springtime median concentration of nitrite plus nitrate nitrogen increased steadily from 1984 (4.8 mg/L) through 1987 (5.5 mg/L).

Triazine herbicides were detected in 11 of 18 samples analyzed for pesticides. Concentrations of atrazine were less than the 3 µg/L maximum contaminant level set for atrazine by the Minnesota Department of Health and by the U.S. Environmental Protection Agency.

INTRODUCTION

Degradation of ground-water quality by nonpoint-source contamination from various land uses is of concern to residents and to State and local agencies in Minnesota. One area of concern is the Anoka Sand Plain aquifer, with an areal extent of about 1,700 mi^2 in parts of 11 counties in east-central Minnesota (fig. 1).

The Anoka Sand Plain aquifer underlies and is coincident with the Anoka Sand Plain. The aquifer is used extensively for domestic water supplies, although the largest water use is for irrigation. This surficial-sand aquifer is particularly susceptible to contamination from human activity at the land surface. Potential sources of ground-water contamination in the Anoka Sand

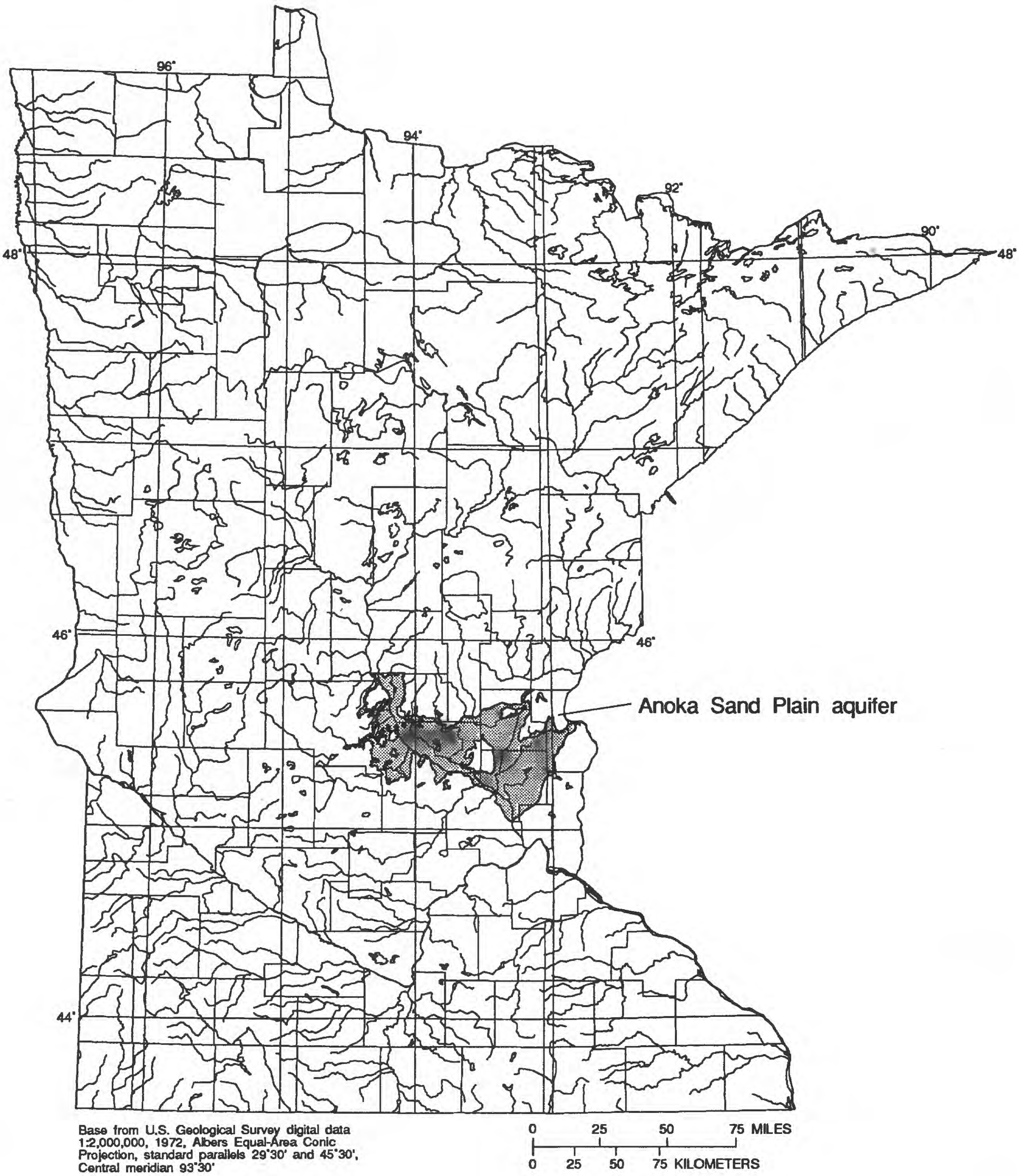

Figure 1.--Location of the Anoka Sand Plain aquifer.

Plain are agricultural chemicals (fertilizer, herbicides, and pesticides), manure produced in feedlots, lawn fertilizer, and septic-system effluent in residential areas.

Because of concern about the susceptibility of the Anoka Sand Plain aquifer to contamination, the U.S. Geological Survey studied the quality of water in the aquifer from 1983-87 in cooperation with the Minnesota Department of Natural Resources, Division of Waters, and the Soil and Water Conservation Districts of Anoka, Chisago, Isanti, Sherburne, and Stearns Counties. The study concentrated on Anoka, Chisago, Isanti, Sherburne, and Stearns Counties, which include about 80 percent of the Anoka Sand Plain (about 1,370 mi^2). The remaining area is distributed among Benton, Hennepin, Mille Lacs, Ramsey, Washington, and Wright Counties.

Purpose and Scope

This report describes the effects of land use on quality of water in the Anoka Sand Plain aquifer, particularly the effects of agricultural chemicals and residential development. Emphasis is placed on the distribution of sulfate, chloride, and nitrite plus nitrate nitrogen. Data also are presented from a reconnaissance survey of pesticides in ground water.

Water samples were collected from 100 wells in the five counties comprising most of the Anoka Sand Plain to determine areal differences in ground-water quality within the Anoka Sand Plain aquifer. Water-quality differences were compared among three areas (Eastern area, Elk River area, and Western area), and delineated on the basis of hydrogeologic and land-use characteristics. Land use at well-sampling locations is shown in figure 2. Vertical differences in water quality and possible mixing of chemical constituents from different depths within the aquifer were evaluated for 31 well clusters where samples could be collected near the water table and at different depths below the water table. Chemical concentrations from water samples collected at different depths were compared with respect to land use. Seasonal variations in ground-water quality were evaluated. Long-term (1965-87) changes in ground-water quality were examined for five wells.

Previous Studies

The planning and design of this study was based on results of ground-water appraisals including studies of the Bonanza Valley (Van Voast, 1971), the Viking basin (McBride, 1975), and four counties near St. Cloud, Minnesota (Lindholm, 1980). Myette (1984), in a study of sand-plain aquifers in central Minnesota, described historic trends and changes in concentrations of chloride and nitrite plus nitrate nitrogen in response to changes in water levels. Myette also described the movement of agricultural chemicals downgradient from an irrigated area and differences in water quality with depth in the aquifer at that site. Reconnaissance studies of water resources in the Anoka Sand Plain are summarized by Ericson and others (1974), Helgesen and others (1975), and Lindholm and others (1974). Anderson (1989) described baseline water quality in Douglas, Kandiyohi, Pope, and Stearns Counties.

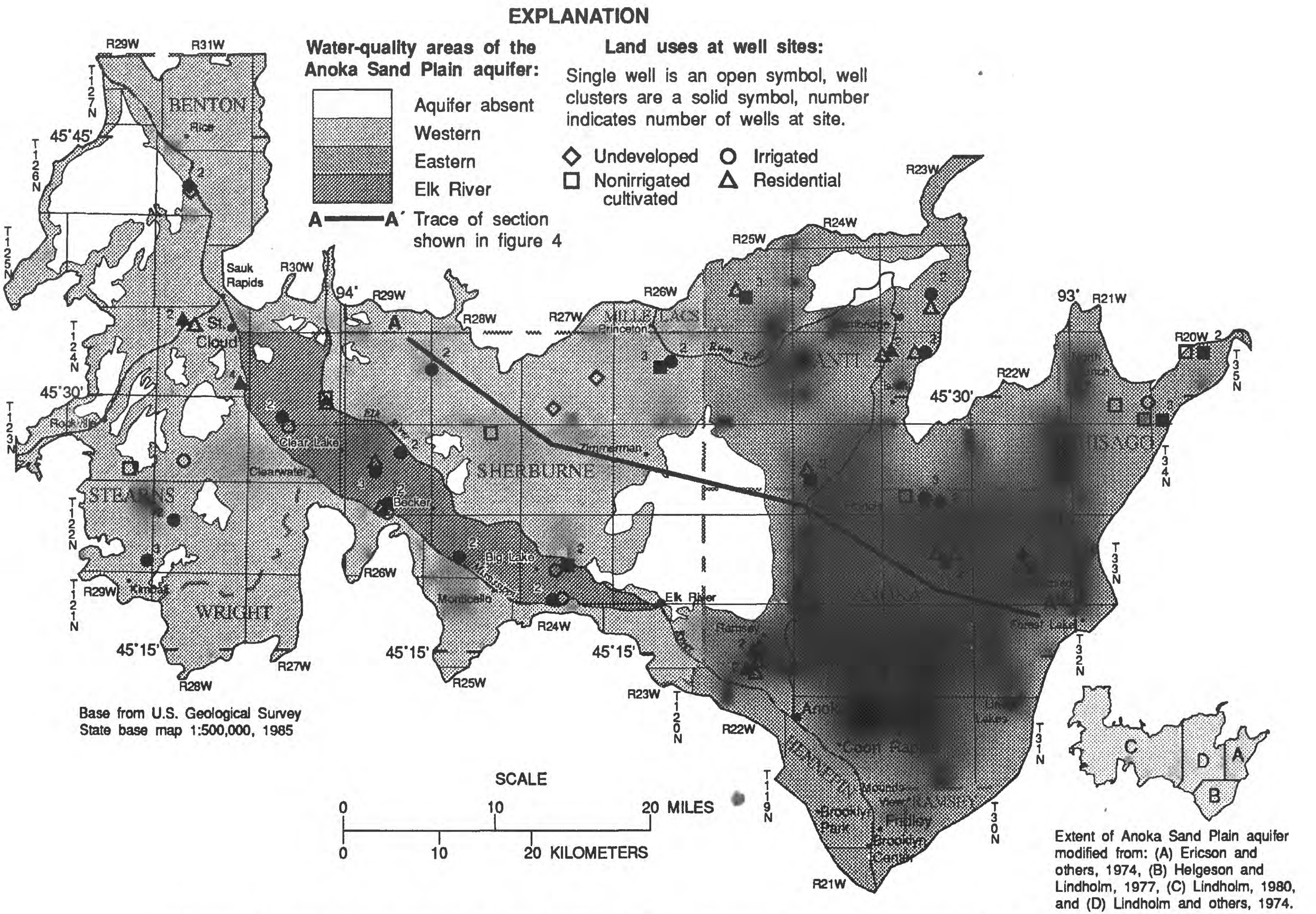

Figure 2.--Water-quality areas of the Anoka Sand Plain aquifer and land uses at well-sample locations.

Methods of Investigation

The effects of agricultural chemicals and residential septic systems on ground-water quality were evaluated on the basis of water samples from 100 wells located downgradient from areas that include the four predominant land uses in the study area (fig. 2): (1) undeveloped land showing minimal influence of human activities (11 wells), (2) nonirrigated-cultivated land (25 wells), (3) irrigated land (35 wells) and (4) residential land with septic systems (29 wells).

Fifty-one wells were installed for this study. The wells were constructed of 2-inch diameter[1] galvanized-steel pipe with 2- or 3-foot-long wire-wound sand-point well screens. Twenty of the wells were 1 1/4-inch diameter observation wells installed during a previous hydrologic study of this area (Lindholm, 1980). The remaining 29 wells sampled were domestic-supply wells.

Water samples were collected during May and June of 1984 to establish baseline water-quality conditions. Samples were analyzed for major inorganic ions, nutrients (nitrate, nitrite, ammonium, organic nitrogen, phosphate), iron, manganese, and dissolved organic carbon. Field measurements of water level, specific conductance, pH, temperature, and alkalinity were made each time a sample was collected. Samples were collected at most of these wells during November 1984 through January 1985, and again between March through June 1985. These samples were analyzed for the indicator constituents: nitrite plus nitrate nitrogen, sulfate, and chloride. Samples were collected at thirty-two wells during May and June 1986 and at 13 wells during June 1987 for indicator constituents and field parameters. Samples collected from 18 wells during August 1984 were analyzed for triazine herbicides. Samples collected from eight wells during September 1984 were analyzed for the insecticide aldicarb.

Samples were collected, filtered, and preserved. Field tests were conducted according to the National Handbook of Recommended Methods of Water-Data Acquisition (Office of Water Data Coordination, 1977). Water-quality analyses were done by the U.S. Geological Survey's National Water-Quality Laboratory using methods described in Fishman and Friedman (1989). Nitrogen data are reported as nitrite plus nitrate nitrogen ($NO_2 + NO_3$ as N). Aldicarb analyses were done by the Wisconsin State Laboratory of Hygiene in Madison, Wisconsin, using a gas chromatograph with a flame photometric detector. The analytical methods are from unpublished guidelines developed by Union Carbide Corp.[2], the manufacturer of the pesticide (David Degenhardt, Wisconsin State Laboratory of Hygiene, oral commun., 1985). All water-quality data were published in U.S. Geological Survey annual water-data reports for Minnesota (USGS, 1986-89).

Water-quality data were analyzed by using nonparametric statistical methods, which are more appropriate than parametric statistical methods for evaluating most hydrologic and water-quality data (Crawford and others 1983). Nonparametric (or distribution-free) methods were devised for evaluating data that do not conform to a specific (particularly the normal) probability distribution of

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[1] Diameters referred to in this report are nominal diameters of the inside pipe.

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

the population of values. Spearman correlation coefficients are a type of nonparametric statistical procedure (a form of a rank test) that uses a rank-correlation method (Spearman, 1904). Spearman correlation coefficients, computed from ranked data, were used to compare chemical constituents by area, by well depth below the water table, and by type of land use.

Nonparametric general linear models were used for multiple sample tests to compare specific conductance and concentrations of sulfate, chloride, and nitrite plus nitrate nitrogen at different depths below the water table and for different land uses. The general linear models used for this report provide a comparison of groups of data and indicate statistically significant differences among the groups. For example, nitrite plus nitrate nitrogen concentrations in water samples from undeveloped sites are compared with those from irrigated, nonirrigated-cultivated, and residential sites.

The water-quality data collected for the Anoka Sand Plain aquifer during 1984 can serve as a baseline or reference condition that may be used for comparison with data from later studies to evaluate temporal changes in water quality.

Well-Numbering System

The system of numbering wells used in this report is based on the U.S. Bureau of Land Management's system of land subdivision (township, range, and section). The first 4 characters of a well-location number indicate the township, the next three characters indicate the range, and the last 2 characters indicate the section in which the well is located. The upper-case letters A, B, C, and D locate the well within the section and are assigned in a counterclockwise direction, beginning in the northeast corner of each tract (fig. 3). The first letter following the section number denotes the quarter section (160-acre tract), the second denotes the quarter-quarter section (40-acre tract), and the third denotes the quarter-quarter-quarter section (10-acre tract). A sequential number at the end of the local well number distinguishes wells within the same 10-acre tract. In figure 3, for example, well 36N25W15ADC01 is in the SW1/4, SE1/4, NE1/4, Sec 15, T36N, R25W; the sequential number shows it to be the first well in the 10-acre tract.

Acknowledgments

Property owners are thanked for their cooperation and the use of their wells for collecting water samples. Appreciation also is extended to the Soil and Water Conservation Districts of Anoka, Chisago, Isanti, Sherburne, and Stearns Counties for providing the local Steering Committee that aided the progress of this study. Appreciation is extended to Jerry Wright, area Extension Irrigation Engineer with the Agricultural Extension Service, University of Minnesota, and Greg Larson of the Western Minnesota Resources Conservation and Development Commission Project Office for their advice on this study.

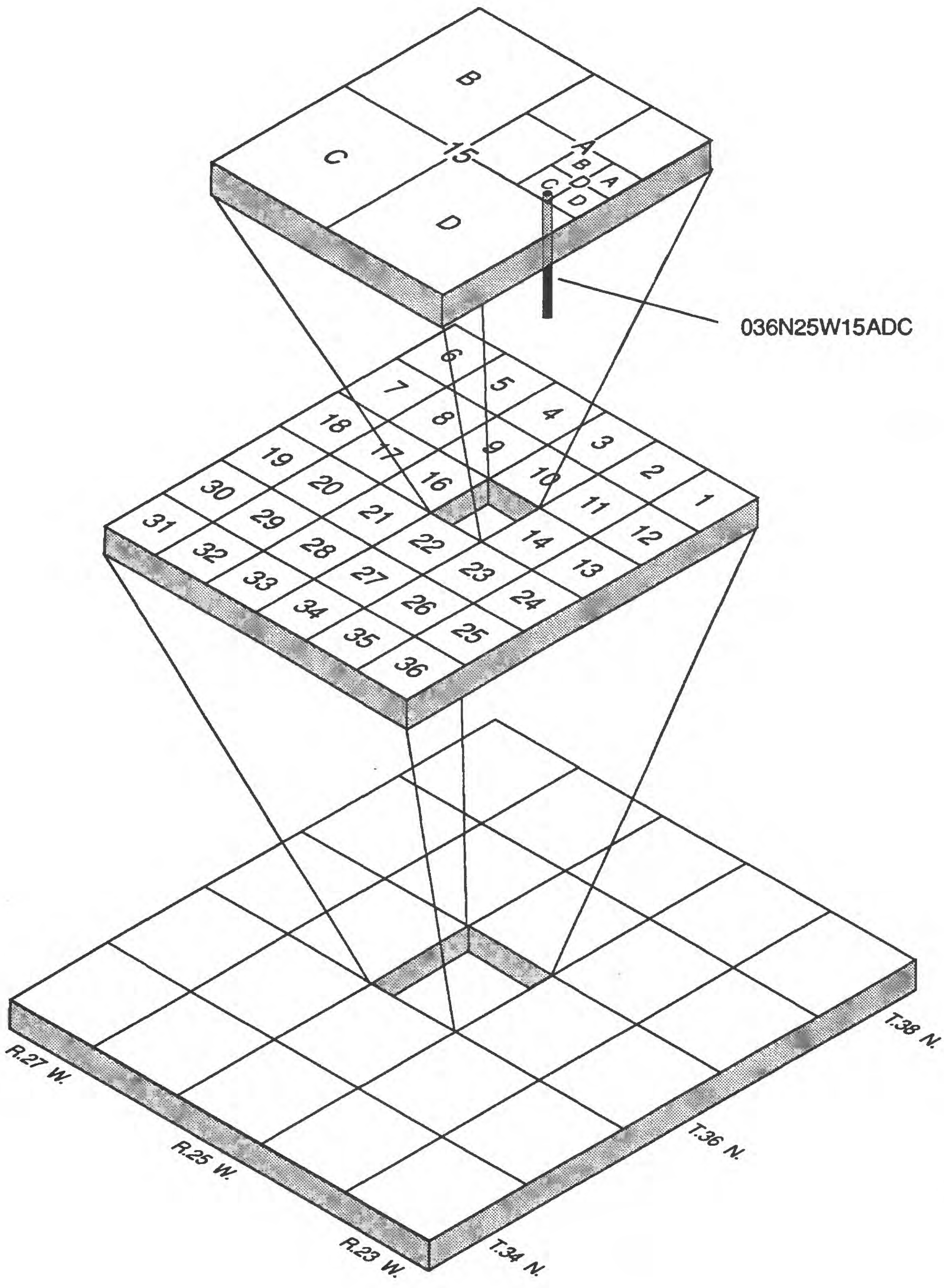

Figure 3.--Example of the well-numbering system.

DESCRIPTION OF THE STUDY AREA

Hydrogeologic Setting

The glacial deposits and geomorphic features of east-central Minnesota are the result of several ice advances during Pleistocene glaciation (Wright and Ruhe, 1965). The Anoka Sand Plain is primarily glaciofluvial in origin (Cooper, 1935). The Anoka Sand Plain comprises an area of about 1,700 mi^2 of surficial outwash. Areas where the aquifer is absent and till is exposed at land surface form topographic highs within the Sand Plain.

The Anoka Sand Plain aquifer consists of two outwash sand units (fig. 4). The stratigraphically lower outwash sand unit is the red sand of Superior lobe origin (hereinafter called red outwash). It is discontinuous in the eastern two-thirds of the study area and is not present in the western one-third of the study area. The red outwash ranges in thickness from 0 to 50 ft. The upper outwash unit is the gray sand of Grantsburg sublobe origin (hereinafter called gray outwash). The gray outwash ranges in thickness from about 0 to 60 ft.

The Anoka Sand Plain aquifer is underlain by red-brown sandy till and gray silty till. The red-brown sandy till from the Superior glacial lobe contains materials originating from igneous rock of the Lake Superior area and from iron-rich minerals of iron-ore deposits in northeastern Minnesota. The gray silty till from the Grantsburg sublobe of the Des Moines glacial lobe includes Cretaceous shale, Paleozoic limestone, and other rocks from the Red River Valley in western Minnesota. The geologic section (fig. 4) by Helgesen and Lindholm (1977, p. 8) shows the glacial deposits underlying the Anoka Sand Plain aquifer where the gray silty till overlies the red-brown sandy till.

Recharge to the Anoka Sand Plain aquifer is primarily from rain and snowmelt that readily infiltrates the sandy topsoil and percolates through the unsaturated zone to the water table. Most recharge generally follows spring snowmelt and spring rains before active plant growth begins. A second period of recharge generally occurs in the fall when rain penetrates bare fields after frost halts active plant growth. The average annual precipitation is 27 in., about 8 in. of which is recharge to the aquifer (Lindholm, 1980). Water moves downgradient in the aquifer from areas where the water table is high toward areas where the water table is low and where water discharges to streams, lakes, and marshes. The water-table surface generally reflects, in a subdued way, the topography of the land surface, and the general direction of ground-water flow is from topographic highs toward major rivers, such as the Mississippi, Sauk, Elk, Rum, and Sunrise Rivers, where ground water discharges. The water table ranges from land surface to 35 ft below land surface. Ground water also discharges through evapotranspiration in areas where the water table is less than 10 ft below land surface.

Saturated thickness of the Anoka Sand Plain aquifer ranges from about 10 to 80 ft as mapped by Helgesen and Lindholm (1977) and Lindholm (1980). Hydraulic conductivity ranges from 50 to as much as 1,000 ft/d. About 20 percent of the Anoka Sand Plain is underlain by sand capable of yielding water to a well at a rate greater than 500 gal/min. Average annual fluctuation of the water table is about 2 ft, and the total range of fluctuation was 4 to 7 ft from 1975 through 1985. This magnitude of water-table fluctuation does not seriously limit the sustained yield of the aquifer in the part of the Anoka Sand Plain capable of yielding water at a rate of 500 gal/min.

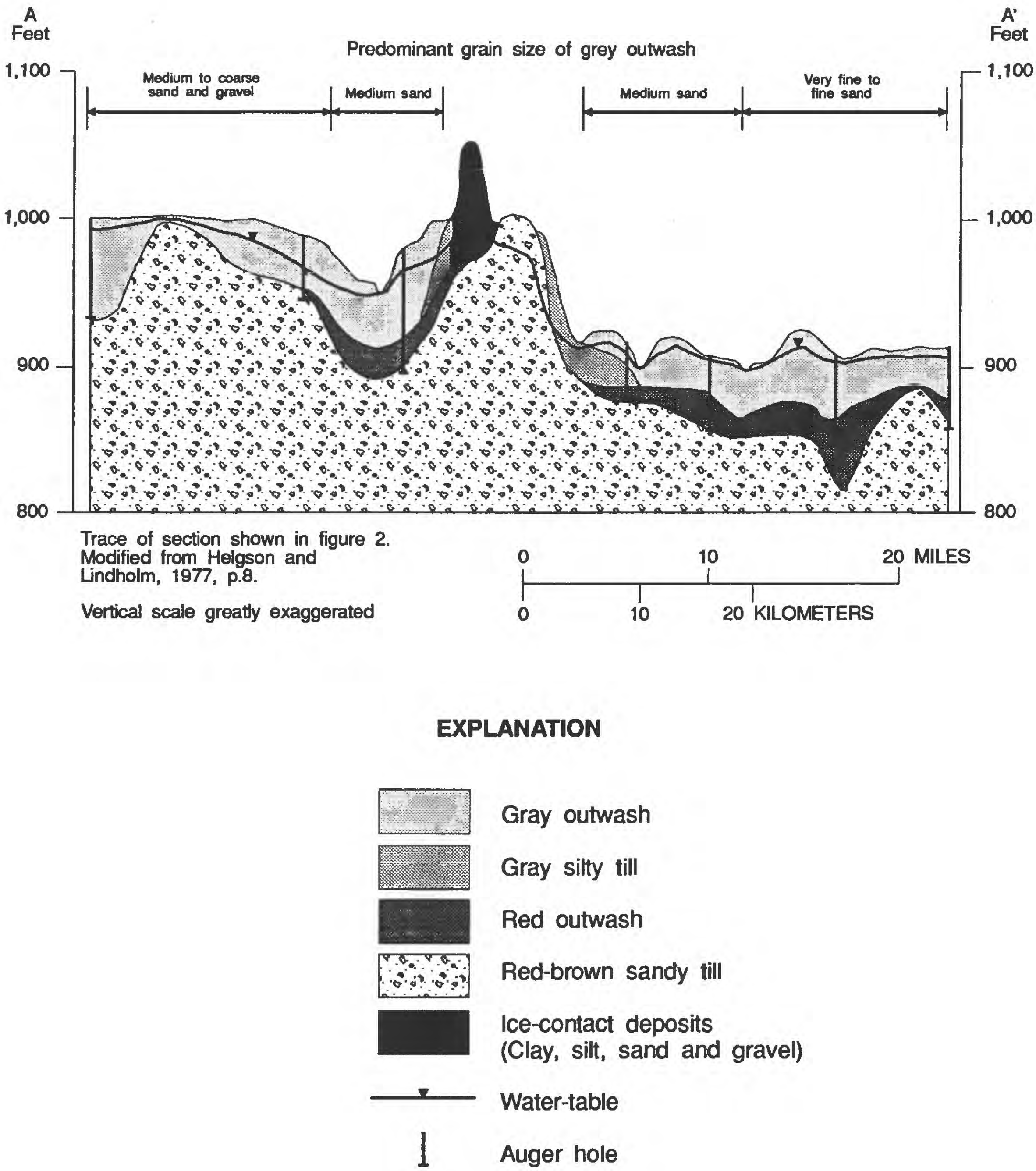

Figure 4.–Geologic section showing stratigraphic relations of the Anoka Sand Plain aquifer

Regional Ground-Water Quality

The types and concentrations of naturally occurring dissolved constituents in ground water depend on the composition and grain size of soil and geologic materials through which the water flows and on the length of time that water and materials are in contact. The relation of ground-water flow to chemistry starts where infiltrating precipitation comes in contact with soluble chemicals in the unsaturated zone of the soil column and transports them to the aquifer. Some of these chemicals, such as sulfate and chloride, are relatively stable and remain unchanged in solution as they are transported in ground water to areas of discharge from the aquifer. Other chemicals, such as nitrite plus nitrate nitrogen, are less stable and react with other chemicals or minerals as they are transported through the aquifer. For example, denitrification changes nitrite plus nitrate nitrogen to nitrogen gas in reducing environments, and pesticides decay into other compounds (metabolites) in oxidizing environments.

Water from the Anoka Sand Plain aquifer is used mainly for residential supply and irrigation. The most restrictive Minnesota water-quality standards are applied to water used for drinking (Minnesota Pollution Control Agency, 1988, p. 19) and food processing. The quality of water from wells sampled for this study generally met those standards (table 1) with the exception of nitrite plus nitrate nitrogen, iron, and manganese concentrations.

Table 1.--Minnesota standards for drinking water and number of samples and wells in which the recommended limit was exceeded
[Standards from Minnesota Pollution Control Agency, 1988.]

Constituent	Minnesota drinking-water standard (milligrams per liter)	Total number of samples from 100 wells	Number that exceed the standard: Number of samples	Number that exceed the standard: Number of wells
Dissolved solids, calculated, sum of constituents	500	100	0	0
Sulfate	250	299	0	0
Chloride	250	300	0	0
Fluoride	2	104	0	0
Nitrite plus nitrate nitrogen	10	358	88	30
Iron	.3	100	29	29
Manganese	.05	100	41	41

The quality of water from the 100-well network during May and June 1984 is summarized in table 2. Calcium, magnesium and bicarbonate are the predominant dissolved constituents in ground water at all sites. Water in the study area is predominantly of the calcium bicarbonate type and is suitable for most uses. Ranges of concentration of most constituents are about one order of magnitude; however, the ranges of chloride, nitrite plus nitrate nitrogen, iron, and manganese are two or more orders of magnitude. The large range in concentration of chloride and nitrite plus nitrate nitrogen seems to be related to human activities.

The greatest concentration of ammonia nitrogen (0.60 mg/L) in baseline samples was from a well at which the concentration of nitrite plus nitrate nitrogen was less than 0.1 mg/L. Ammonia and nitrite plus nitrate nitrogen concentrations generally are inversely related in the ground-water samples collected for this study. The high ammonium and low nitrite plus nitrate nitrogen concentrations indicate reducing conditions.

Table 2.--Statistical summary of baseline chemical analyses of water from 100 wells in the Anoka Sand Plain area in Anoka, Chisago, Isanti, Sherburne, and Stearns Counties, east-central Minnesota, May and June 1984

[Depth to water and well depth in feet below land surface; values are concentrations in milligrams per liter, except as noted; <, less than; --, not determined; Na, not applicable]

Constituent or property	Median	Minimum	Maximum	Reporting level	Number of samples less than reporting level
Depth to water, in feet (84 wells)	--	-0.33	40.00	Na	Na
Depth of well, in feet (100 wells)	--	4.2	250	Na	Na
Specific conductance (microsiemens per centimeter at 25 degrees Celsius)	440	95	1,020	1	0
pH (standard units)	7.6	5.9	8.8	.1	0
Temperature, water (degrees Celsius)	9.0	7.5	18.0	Na	Na
Hardness, as $CaCO_3$	210	16	400	1	0
Calcium, dissolved	57	3.80	120	.1	0
Magnesium, dissolved	17	1.50	32	.1	0
Sodium, dissolved	3.9	1.5	53	.1	0
Potassium, dissolved	1	<.1	3	.1	3
Bicarbonate, IT, Field, as HCO_3	219	13	451	1	0
Sulfate, dissolved	17	<.2	72	.2	2
Chloride, dissolved	12	.5	130	.1	0
Fluoride, dissolved	.1	<.1	.7	.1	79
Silica, dissolved	18	6.8	38	.1	0
Dissolved solids, calculated, sum of	240	57	480	1	0
Nitrite, dissolved as N	.01	<.01	.91	.01	61
Nitrite plus nitrate, dissolved as N	2.8	<.10	35	.10	74
Nitrogen, ammonia, dissolved as N	.04	<.01	.60	.01	73
Nitrogen, dissolved organic as N	.69	<.10	3.2	.10	1
Phosphorus, dissolved orthophosphate as P	.01	<.01	.22	.01	68
Boron, dissolved	.02	<.02	.75	.01	0
Iron, dissolved	.02	<.01	20	.01	31
Manganese, dissolved	.03	<.001	2.2	.01	33
Carbon, organic dissolved as C	1.4	<.01	17	.01	2

EFFECTS OF LAND USE ON GROUND-WATER QUALITY

The use of fertilizers and pesticides, and discharge from feedlots and septic systems can affect the quality of ground water in the Anoka Sand Plain aquifer because of the relatively high permeability of the sandy surficial materials and the shallow water table. Chemical constituents of particular concern relative to these sources of contamination include nitrite plus nitrate nitrogen, sulfate, chloride, and pesticides. Water from all of the wells used in this study meet the Minnesota drinking-water standards for sulfate, chloride, and fluoride; however, water samples from 30 of the 100 wells contained water with concentrations of nitrite plus nitrate nitrogen greater than the recommended limit. Elevated[3] concentrations of nitrite plus nitrate nitrogen can result from excessive applications of manure or commercial fertilizer, feedlot seepage, or seepage from septic systems. Infiltration of nitrates from decomposition of organic material in the soil of cultivated fields also is a potential source of nitrogen. Contamination of ground water by pesticides also is of interest because widely recognized standards for safe levels of pesticides in drinking water have not been established.

Land Use Related to Spatial Differences in Water Quality

The Anoka Sand Plain aquifer was subdivided, on the basis of hydrogeology and land use, into three general areas for a comparison of areal differences in water quality. The areas are referred to as the: Western area, Elk River area, and Eastern area (fig. 2). Ground-water samples also were analyzed with respect to three ranges of depths below the water-table: less than 10 ft, 10 to 20 ft, and more than 20 ft.

Areal Differences

The Western area, west of the area where the aquifer is absent and till is exposed at land surface consists mainly of northern Sherburne County and eastern Stearns County. Land use is agricultural in almost half of the area, and most of the other half is undeveloped. The Western area has more cultivated land than the Eastern area, but it is not irrigated as intensively as is the Elk River area. Large residential developments near St. Cloud use septic systems.

The Elk River area is located between the Elk and Mississippi Rivers in the southern part of Sherburne County. The two rivers form natural hydrologic boundaries to the north and south of the area. More than 34 percent of Sherburne County is cultivated, and much of that cultivation is in the Elk River area. The Elk River area is one of the most intensively irrigated areas of Minnesota. The Elk River area also includes a few small communities with residential septic systems and some undeveloped land.

The Eastern area, east of the area where the aquifer is absent and till is exposed at land surface and along the Anoka County-Sherburne County boundary, includes parts of Anoka, Chisago, and

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[3] In this study, concentrations less than 0.2 mg/L (milligrams per liter) of nitrite plus nitrate nitrogen are considered to represent background concentrations in oxygenated parts of the aquifer (Madison and Brunett, 1985); concentrations greater than 3 mg/L nitrite plus nitrate nitrogen are assumed to indicate elevated concentrations resulting from human activities.

Isanti Counties. This area consists of diverse, small-scale land uses including cultivated fields smaller than one square mile separated by natural marsh or woodland and small residential developments. More than one half of the area is undeveloped, in part, because of extensive marshes that are unsuitable for development. Only a small part of the cultivated land is irrigated. Much of the residential development in the Eastern area uses individual septic systems.

The descriptive statistics of ground-water quality in the three areas of the Anoka Sand Plain aquifer are summarized in Table 3. The areal comparison of ground-water quality is based on specific conductance and concentrations of major cations, (calcium, magnesium, sodium, and potassium), bicarbonate, sulfate, chloride, and nitrite plus nitrate nitrogen.

The specific conductances of samples from all wells in each area of the Anoka Sand Plain aquifer were compared with specific conductances in the 44 samples that represent undeveloped land (fig. 5). Specific conductance was determined for 360 water samples from 100 wells during this study. The box plot representing specific conductances in the Eastern area shows considerable overlap with the box plot representing undeveloped land (fig. 5). The distribution of specific conductances in the Western area also shows a large amount of overlap with the distribution of specific conductances in undeveloped land; however, the median value for the Western area exceeds all values for specific conductance in undeveloped land except the maximum value. Nearly all specific conductance measurements in the Elk River area exceed the maximum for undeveloped land. This probably is due to the increased dissolution of chemicals by percolating irrigation water.

The areal distribution of specific conductance in ground water less than 10 ft below the water table during May and June 1984 is shown in figure 6. The greatest values generally are in the Elk River area and lowest values generally are in the Eastern area. Local differences in specific conductance can be found (for example, in northern Anoka County in T34N, R23W; fig. 6).

The distribution of concentrations of the major cations (calcium, magnesium, sodium, and potassium) in undeveloped land and in the three areas of the Anoka Sand Plain aquifer (fig. 7) show a similar relation to that of specific conductance (fig. 5). The greatest median concentrations of major cations generally are in the Elk River area and the lowest generally are in the undeveloped sites. The relatively low specific conductance and low concentrations of calcium and magnesium in the Eastern area could be related to the larger number of marshes and less intensive development of agriculture in the Eastern area than in the Elk River and Western areas.

Concentrations of nitrite plus nitrate nitrogen are greater in the Elk River and the Eastern areas than in the Western area (fig. 8). Even in the Western area, however, the median nitrite plus nitrate nitrogen concentration is almost as great as the 75th-percentile concentration for undeveloped land.

The concentrations of sulfate and chloride in the Western and Eastern areas are similar, but are substantially greater than those for undeveloped land, and generally are less than those for the Elk River area (fig. 8).

Concentrations of bicarbonate in the Eastern area are similar to those for undeveloped land, as were specific conductances and concentrations of cations. Median bicarbonate concentrations in the Western and Elk River areas are greater than the 75th percentile for undeveloped land and in the Eastern area (fig. 8). Concentrations of nitrite plus nitrate nitrogen, sulfate, chloride, and bicarbonate

Table 3.--Descriptive statistics of ground-water quality in the three areas of the Anoka Sand Plain aquifer

[Values are concentrations in milligrams per liter unless otherwise noted; --, not determined; <, less than]

Constituent or property	Part of Sand Plain	Number of samples	Median	Minimum	Maximum
Depth of water below land surface (feet)	Western	88	6.10	0.10	20.00
	Elk River	70	13.00	3.40	18.60
	Eastern	163	9.80	-.33	40.00
Depth of well, total (feet)	Western	92	22	6.3	100
	Elk River	82	23	10	111
	Eastern	186	22	7.0	250
Specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Western	92	488	86	890
	Elk River	81	630	200	950
	Eastern	186	345	65	1170
pH (standard units)	Western	90	7.4	6.1	8.6
	Elk River	82	7.4	6.2	8.0
	Eastern	182	7.6	5.6	9.0
Temperature, water (degrees Celsius)	Western	92	9.5	4.0	18.0
	Elk River	81	9.5	7.0	14.0
	Eastern	186	9.0	6.0	15.5
Hardness, as $CaCO_3$	Western	30	240	16	340
	Elk River	22	300	180	380
	Eastern	49	150	34	400
Calcium, dissolved	Western	30	62	3.8	90
	Elk River	22	77	49	100
	Eastern	49	43	10	120
Magnesium, dissolved	Western	30	19	1.5	27
	Elk River	22	24	14	31
	Eastern	49	11	2.3	32
Sodium, dissolved	Western	30	3.5	1.5	33
	Elk River	22	3.6	1.8	53
	Eastern	49	4.0	1.6	35
Potassium, dissolved	Western	30	1	0.1	2
	Elk River	22	1	.4	3
	Eastern	49	0.8	.1	2
Bicarbonate, IT, field as HCO_3	Western	83	260	34	380
	Elk River	80	270	110	510
	Eastern	169	150	10	360
Sulfate, dissolved	Western	81	15	0.2	94
	Elk River	65	26	1.2	98
	Eastern	154	15	1.0	80
Chloride, dissolved	Western	81	6.5	.1	93
	Elk River	67	22	2.8	93
	Eastern	154	11	.5	180

Table 3.--Descriptive statistics of ground-water quality in the three areas of the Anoka Sand Plain aquifer--Continued

Constituent or property	Part of Sand Plain	Number of samples	Median	Minimum	Maximum
Fluoride, dissolved	Western	30	0.1	0.1	0.7
	Elk River	22	.1	.1	.6
	Eastern	50	.1	.1	.4
Silica, dissolved	Western	30	19	10	30
	Elk River	22	16	8.4	21
	Eastern	49	20	6.8	38
Dissolved solids, calculated, sum of constituents	Western	28	265	57	470
	Elk River	22	320	160	440
	Eastern	49	190	70	480
Nitrite, dissolved as N	Western	25	.01	<.01	.08
	Elk River	17	.01	<.01	.91
	Eastern	39	.01	<.01	.26
Nitrite plus nitrate, dissolved as N	Western	92	1.3	<.1	16
	Elk River	81	4.8	<.1	44
	Eastern	186	3.9	<.1	45
Nitrogen, ammonia, dissolved as N	Western	73	.05	<.01	2.0
	Elk River	67	.04	<.01	.38
	Eastern	146	.05	<.01	1.5
Nitrogen, dissolved organic as N	Western	28	.42	<.1	1.6
	Elk River	22	.39	<.1	2.5
	Eastern	49	1.2	.22	3.2
Phosphorus, dissolved orthophosphate as P	Western	28	0.01	<0.01	0.05
	Elk River	28	.01	<.01	.04
	Eastern	50	.02	<.01	.22
Boron, dissolved	Western	30	.02	.02	.34
	Elk River	22	.02	.02	.18
	Eastern	49	.02	.02	.75
Iron, dissolved	Western	28	.14	<.01	20
	Elk River	22	.02	<.01	7.5
	Eastern	49	.02	<.01	10
Manganese, dissolved	Western	28	.04	.001	2.2
	Elk River	22	.02	.001	.54
	Eastern	49	.03	.001	1.3
Carbon, organic, dissolved, as C	Western	28	1.4	.8	17
	Elk River	22	1.3	.9	2.7
	Eastern	46	1.3	.4	4.7

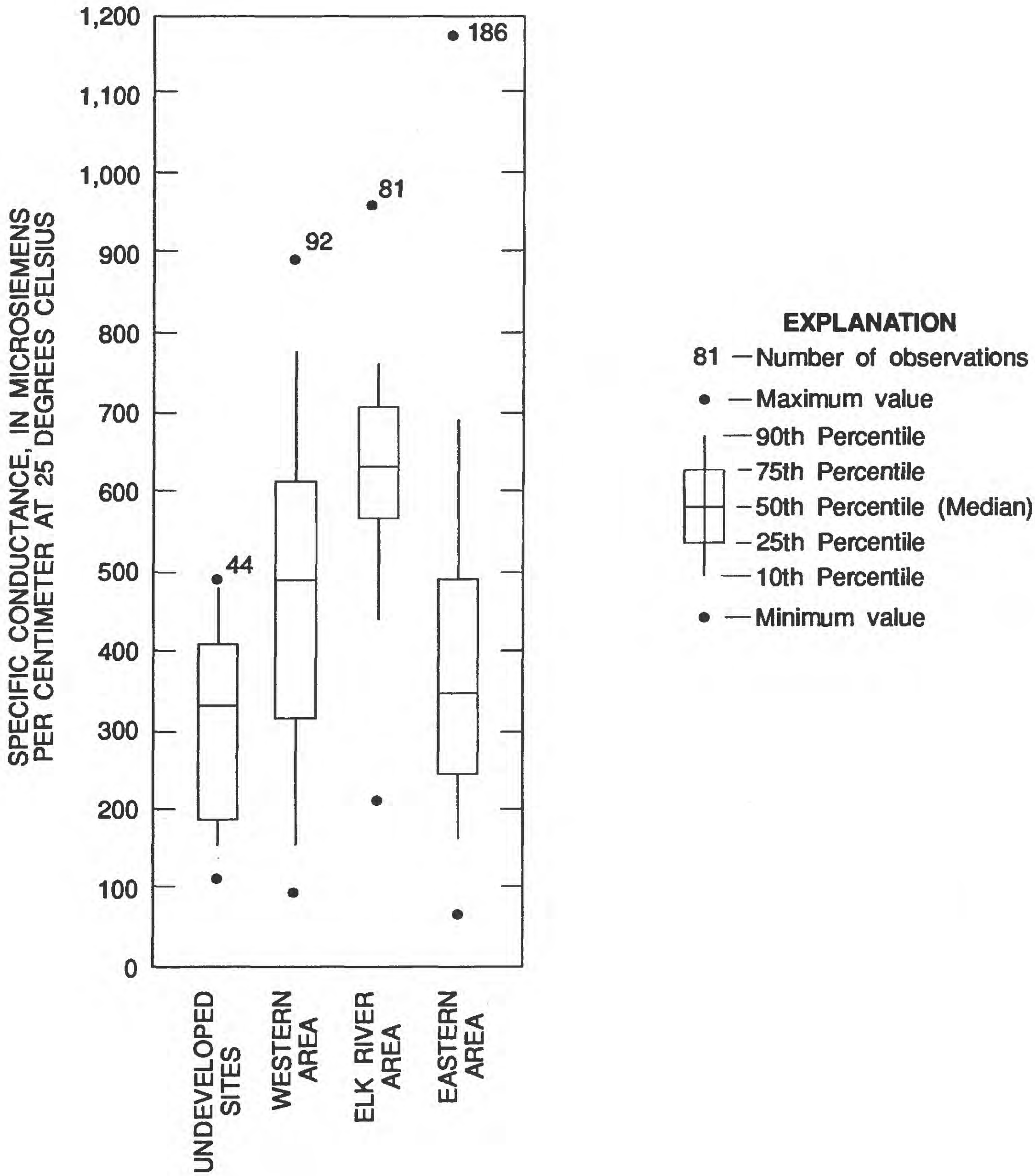


Figure 5.--Specific conductance of ground-water samples from undeveloped sites and areas of the Anoka Sand Plain aquifer.

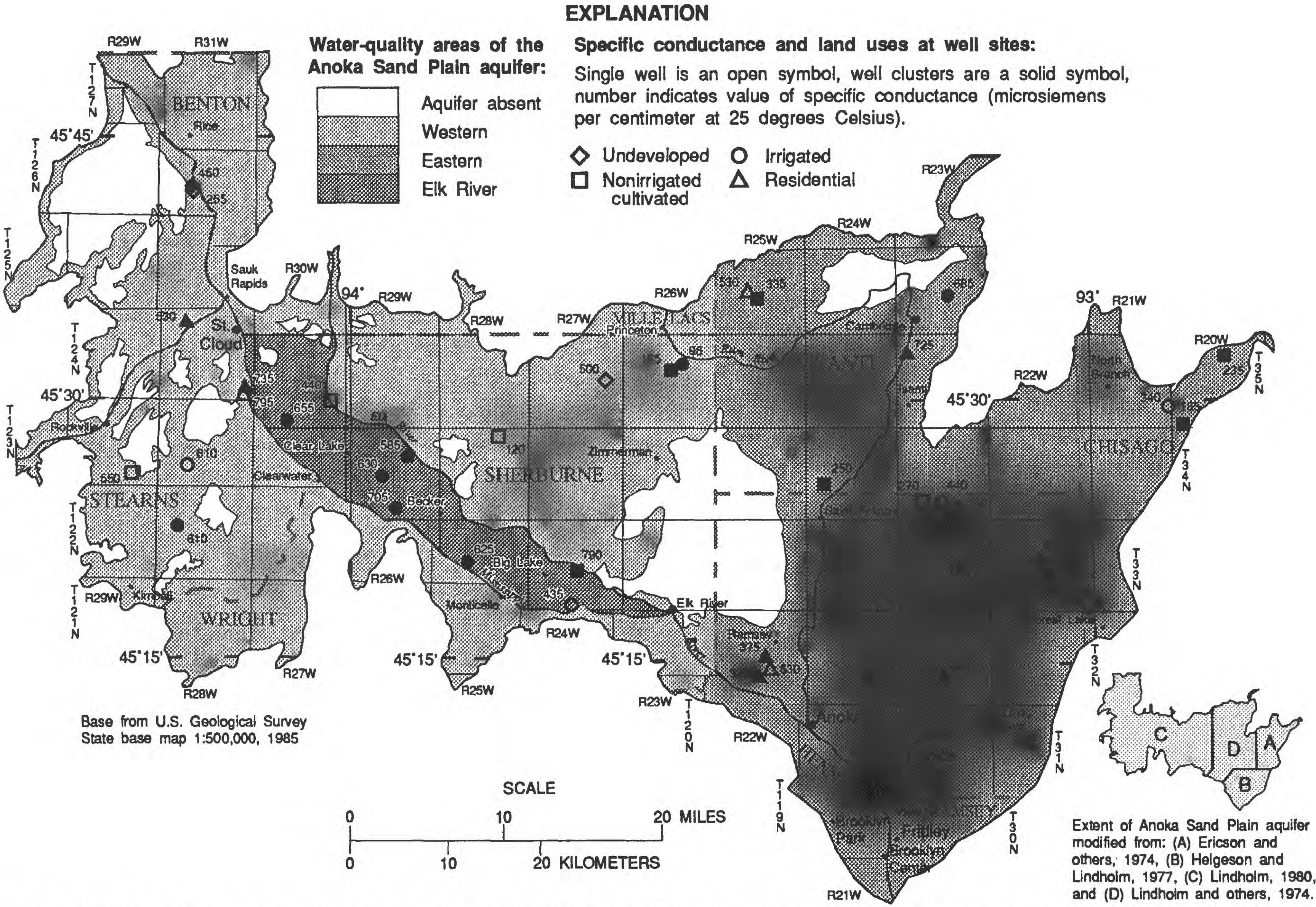


Figure 6.--Water-quality areas of the Anoka Sand Plain aquifer and specific conductance in ground-water samples collected during May and June 1984 from less than 10 feet below the water table.

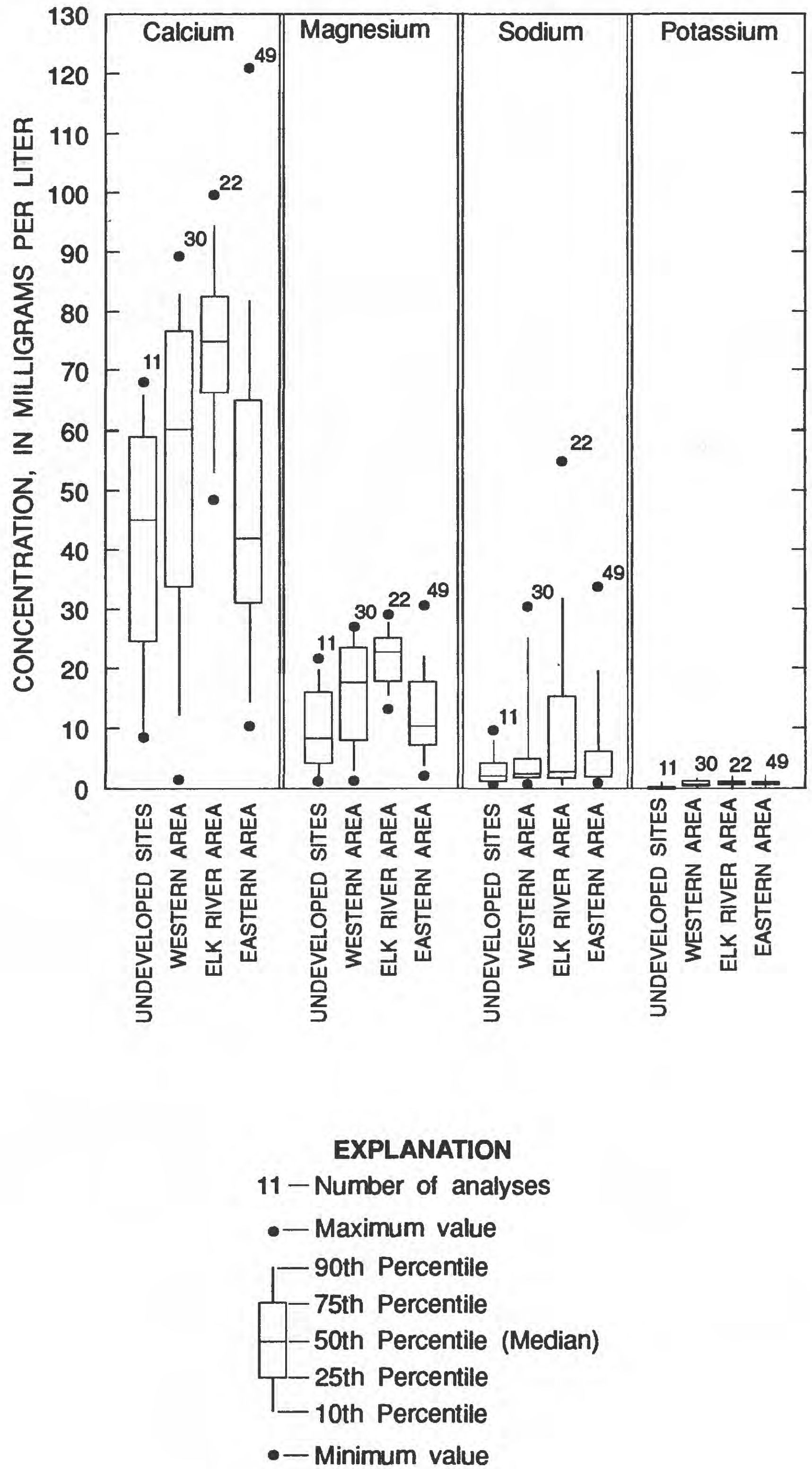


Figure 7.–Concentration of major cations in ground-water samples from the undeveloped sites and areas of the Anoka Sand Plain aquifer.

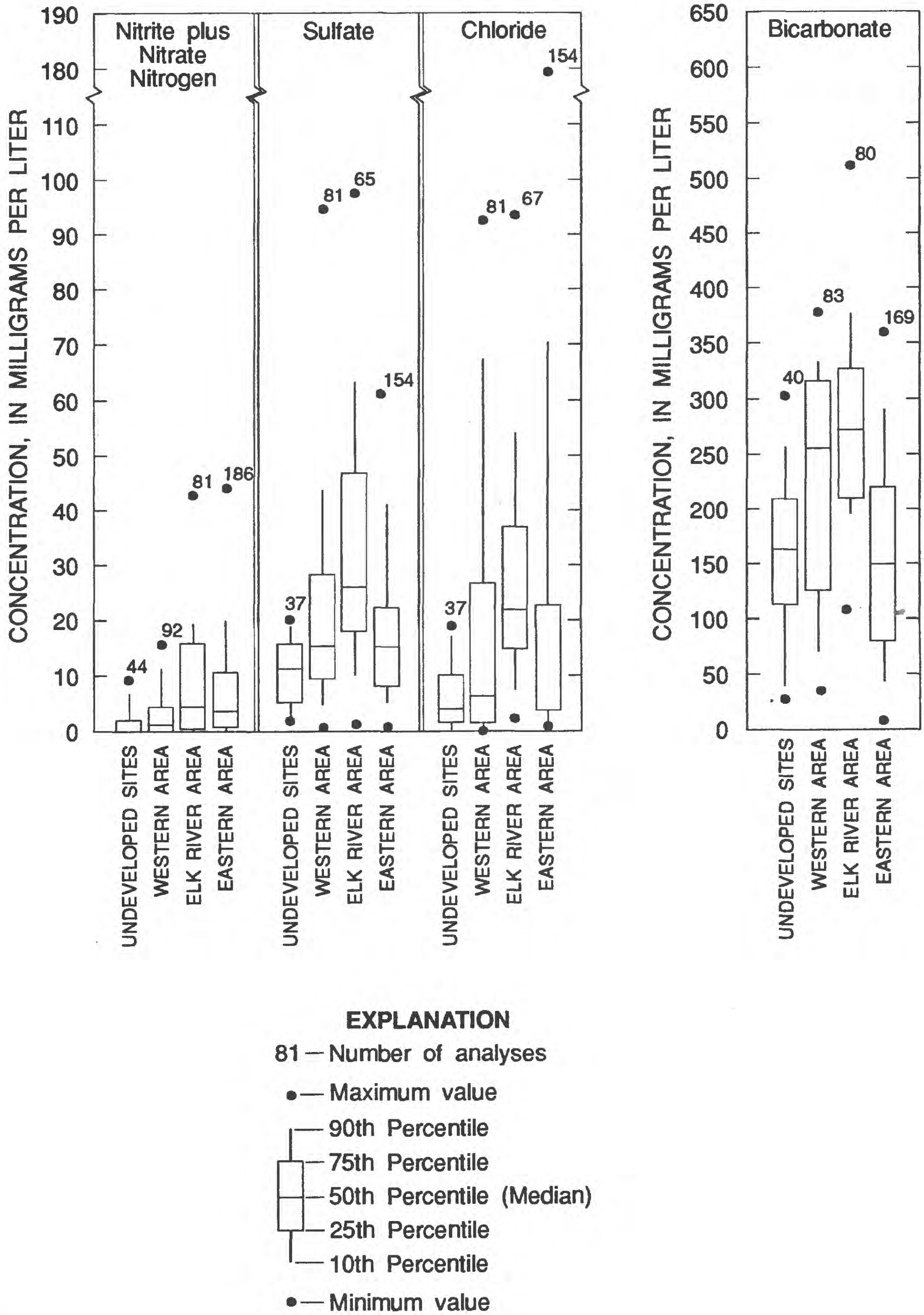


Figure 8.--Concentration of nitrite plus nitrate nitrogen, sulfate, chloride, and bicarbonate in ground-water samples from undeveloped sites and areas of the Anoka Sand Plain aquifer.

are greatest in the Elk River area, which could be related to the large amount of irrigation in the Elk River area where many of the irrigators use manure to fertilize their fields. Elevated concentrations of sulfate, chloride, and nitrite plus nitrate nitrogen are frequently associated with seepage from manure (Anderson, 1989). Elevated concentrations of bicarbonate could result from an increased volume of water percolating through the soil and unsaturated zone of irrigated land.

The areal distribution of concentrations of sulfate in ground water from less than 10 ft below the water table during May and June 1984 shows little local difference compared to chloride concentrations, which show large local differences (fig. 9-10). Elevated sulfate concentrations commonly are associated with manure or septic-system discharge. The areal distribution of concentrations of chloride shows a difference of an order of magnitude (1.4 to 19 mg/L) among a group of four wells in a small area in northern Anoka County in T34N, R23W (fig. 10). Three different land uses are represented by these four samples. The chloride concentrations of the water samples were 1.9 mg/L at an undeveloped site, 1.4 mg/L at a nonirrigated-cultivated site and 19 mg/L from both wells at irrigated sites. None of these wells are located where they could be affected by road salt. Manure used on the irrigated crops could have contributed to the elevated chloride concentrations.

Areal distribution of concentrations of nitrite plus nitrate nitrogen in ground water from less than 10 ft below the water table during May and June 1984 also shows local differences that probably are related to differences in land use (fig. 11). The areal distribution of nitrite plus nitrate nitrogen concentrations in ground water from 10 to 20 ft below the water table also shows local differences that probably are related to land use but could also be related to redox (oxidation-reduction) conditions in the aquifer (fig. 12).

The concentrations of iron and manganese are greatest in the Western area of the Anoka Sand Plain aquifer and are similar in the Elk River and Eastern areas (fig. 13). The median concentrations of iron and manganese in all areas are less than the median concentrations for undeveloped land. The greatest concentrations in areas of undeveloped land could be related to the proximity of some of the sampled wells to marshes, or buried peat deposits, where iron could be preferentially concentrated and where the redox potential is low.

The areal distribution of concentrations of iron (fig. 14) in water from less than 10 ft below the water table during May and June 1984 shows larger concentrations of iron in the Western area than in the rest of the Anoka Sand Plain aquifer. The same relation is shown by the box plots of concentrations of iron and manganese (fig. 13). Large local differences in iron concentrations were found in several townships in Anoka County, and in each case, the greatest iron concentration was from a well close to a marsh.

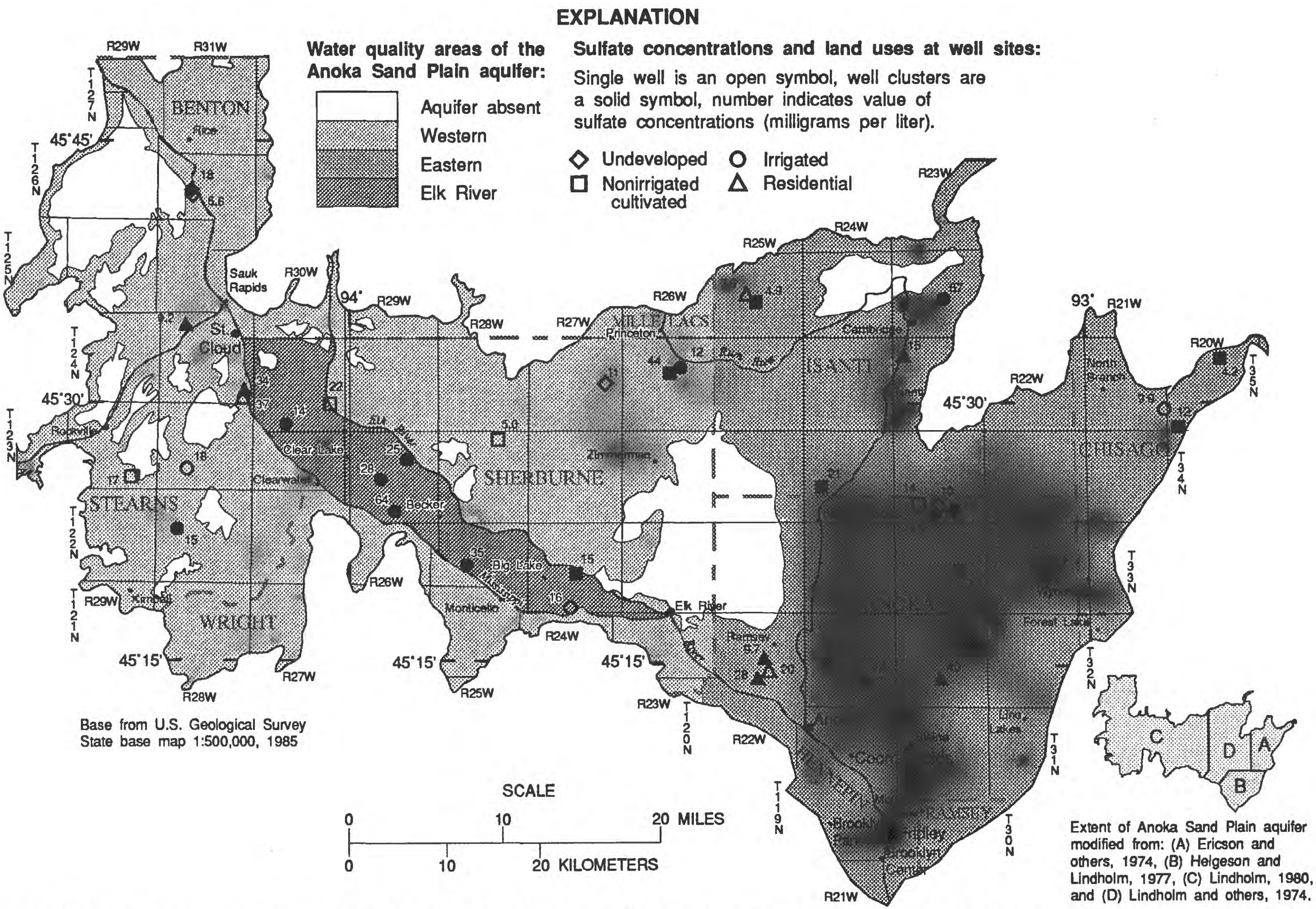


Figure 9.–Water-quality areas of the Anoka Sand Plain aquifer and sulfate concentrations in ground-water samples collected during May and June 1984 from less than 10 feet below the water table.

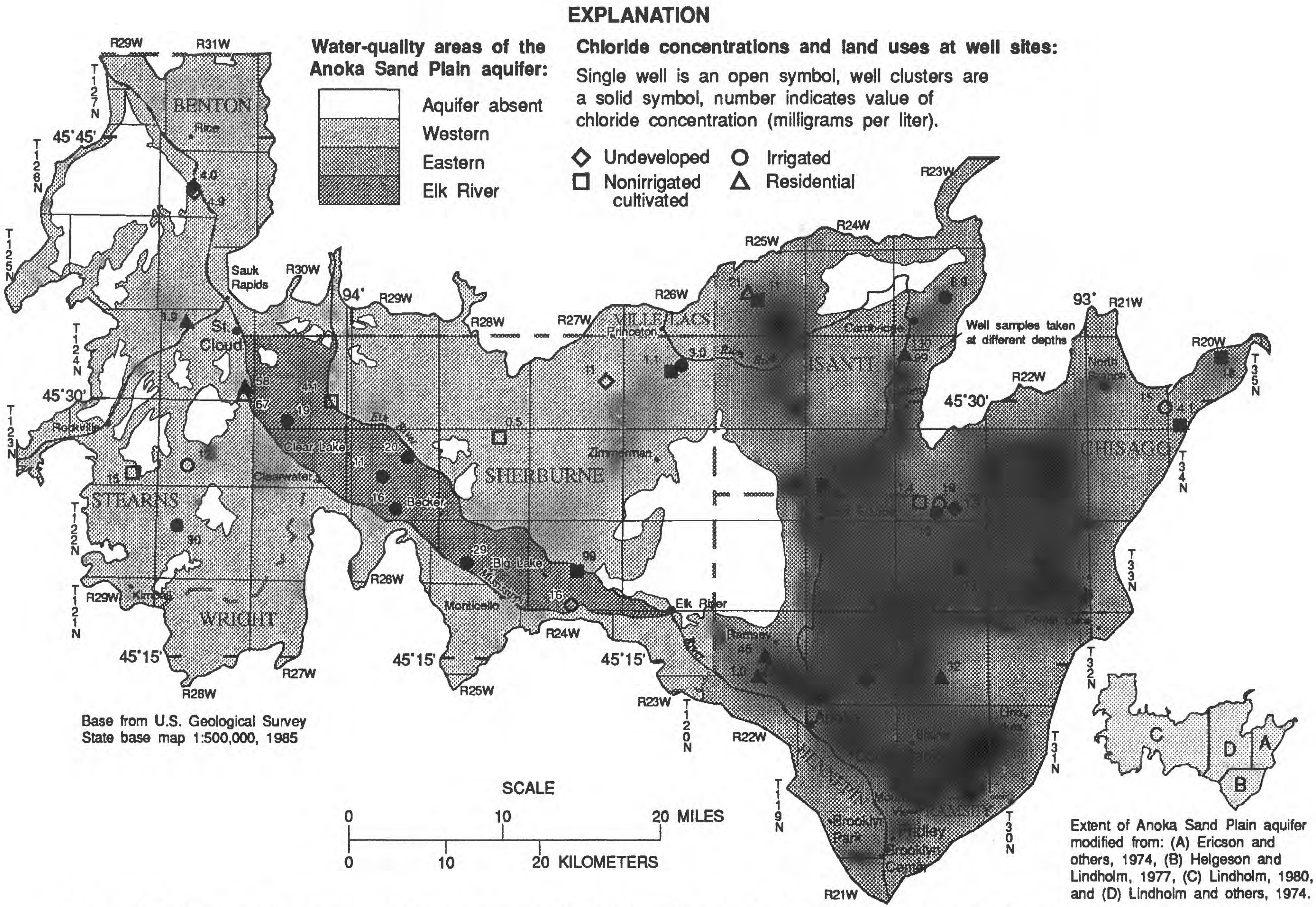


Figure 10.--Water-quality areas of the Anoka Sand Plain aquifer and chloride concentrations in ground-water samples collected during May and June 1984 from less than 10 feet below the water table.

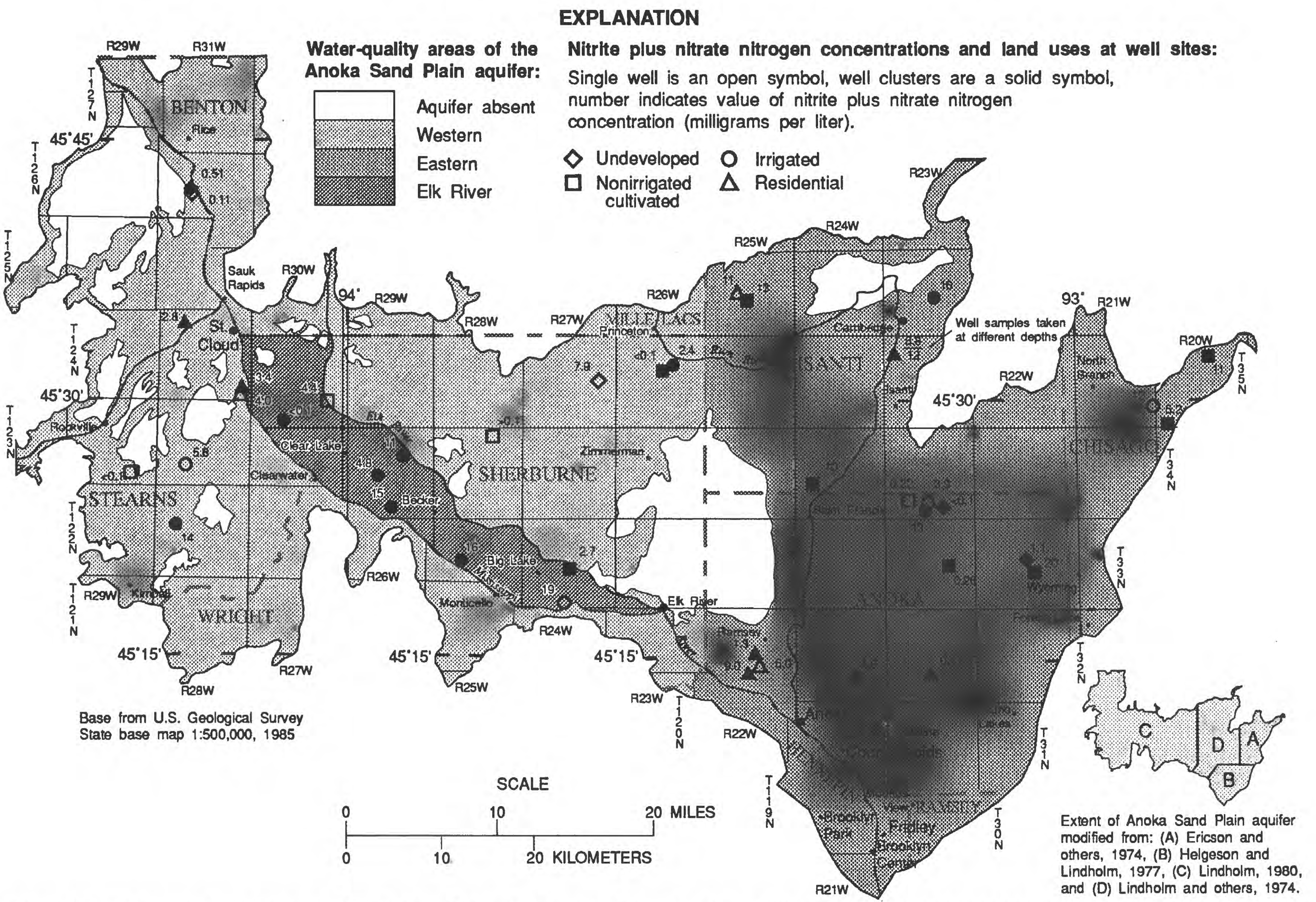


Figure 11.–Water-quality areas of the Anoka Sand Plain aquifer and nitrite plus nitrate nitrogen concentrations (NO_2 + NO_3, as N) in ground-water samples collected during May and June 1984 from less than 10 feet below the water table.

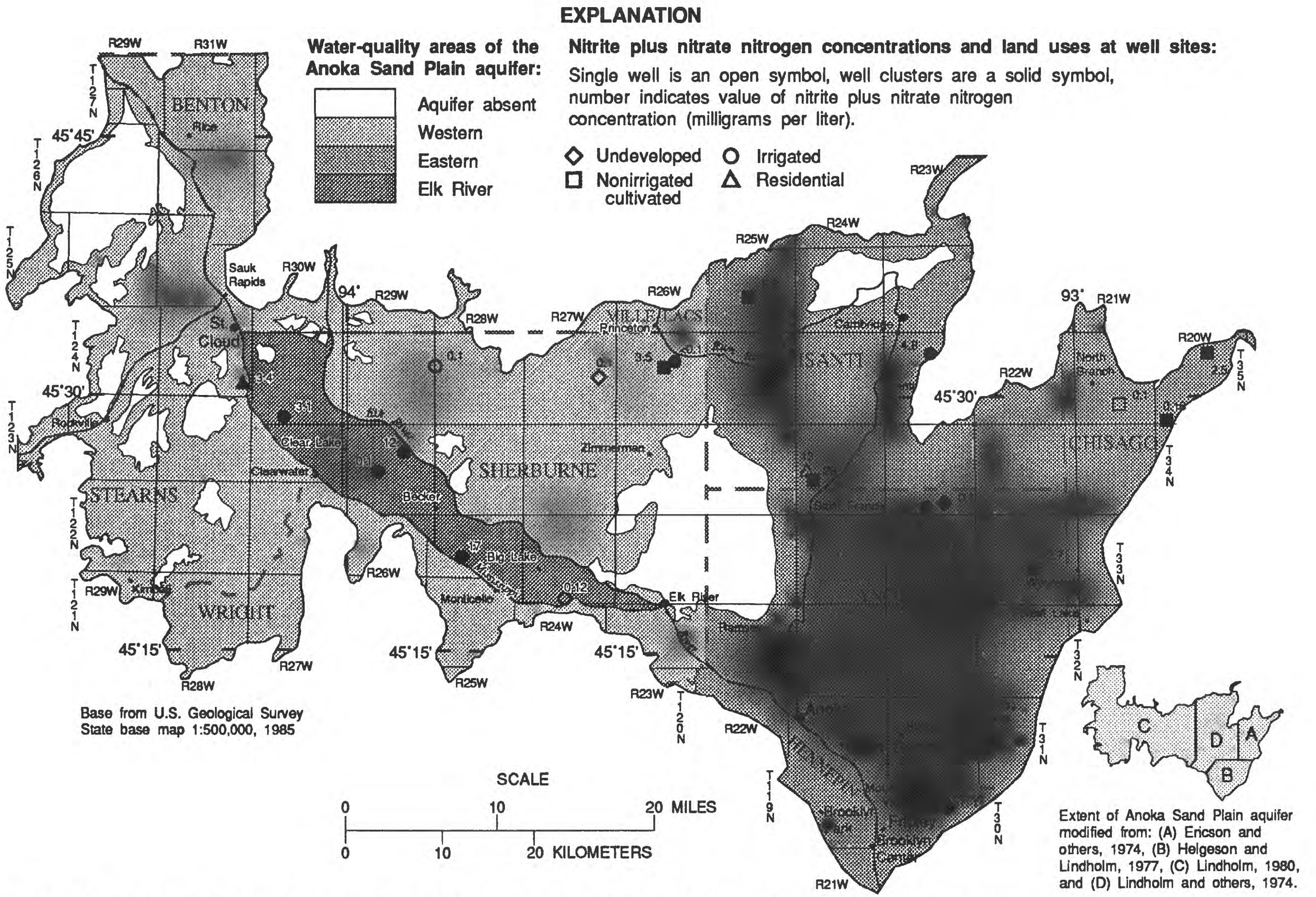


Figure 12.--Water-quality areas of the Anoka Sand Plain aquifer and nitrite plus nitrate nitrogen concentrations (NO_2 + NO_3, as N) in ground-water samples collected during May and June 1984 from 10 to 20 feet below the water table.

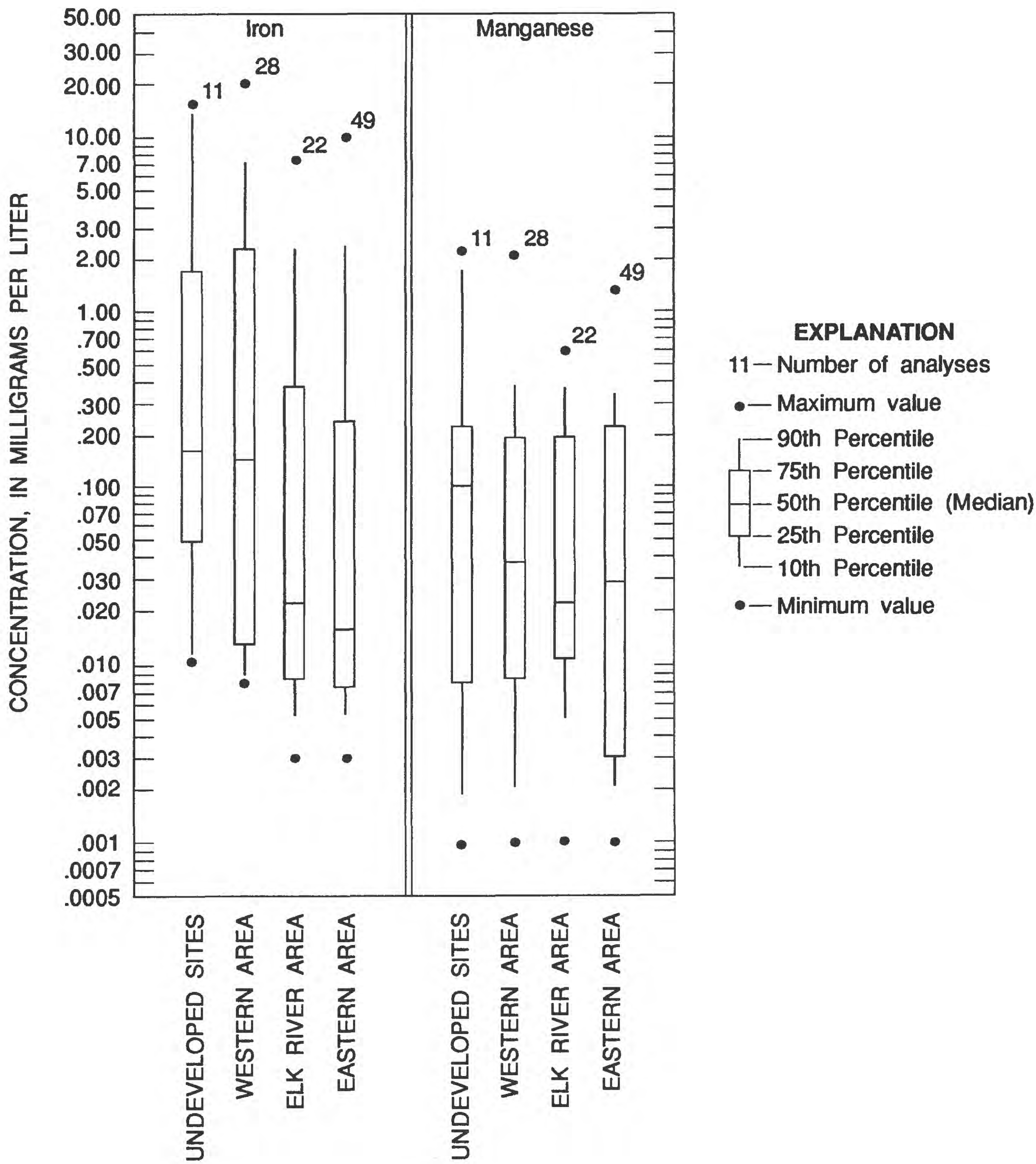


Figure 13.--Concentrations of iron and manganese in ground-water samples from the undeveloped sites and areas of the Anoka Sand Plain aquifer.

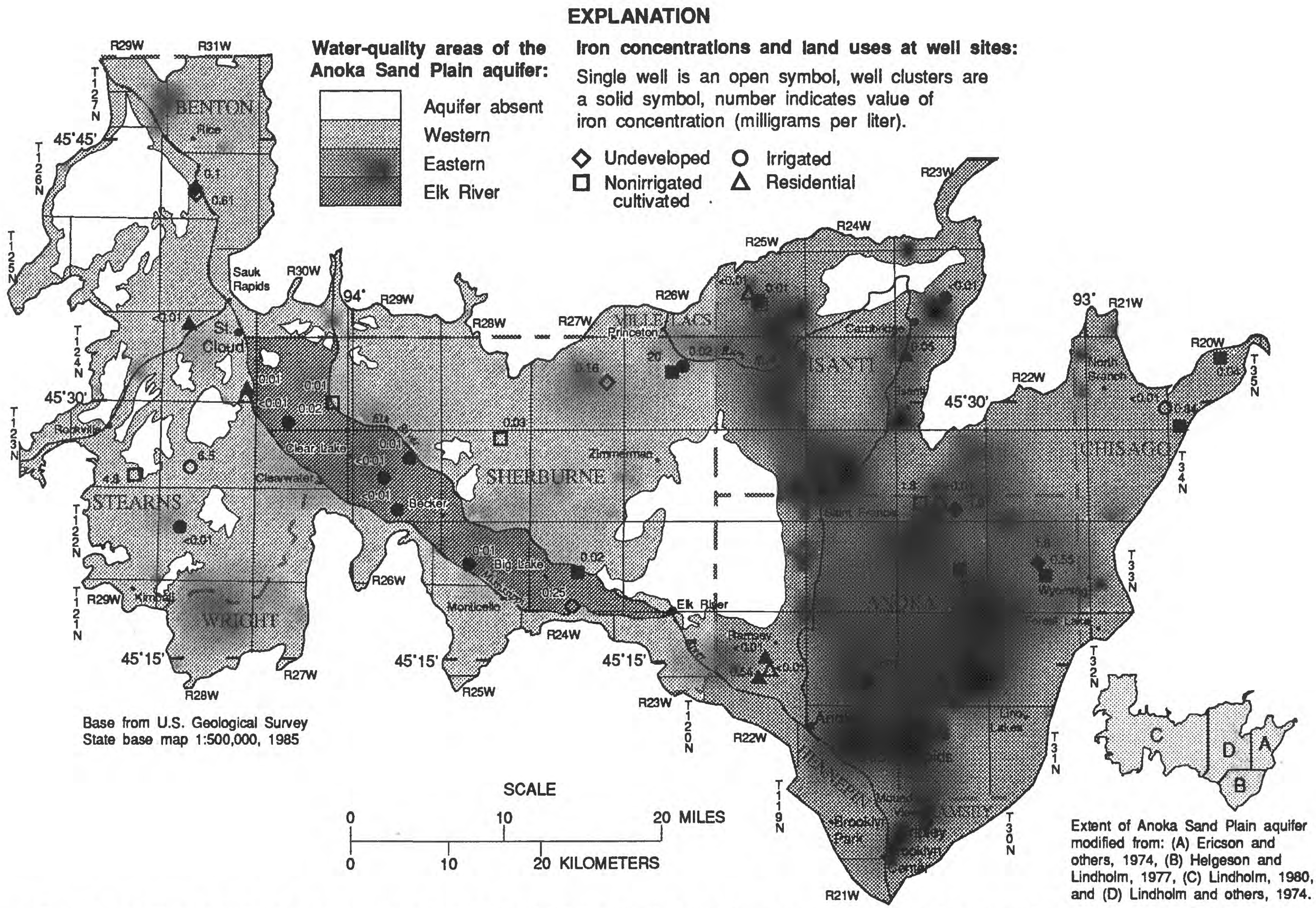


Figure 14.--Water-quality areas of the Anoka Sand Plain aquifer and iron concentrations in ground-water samples collected during May and June 1984 from less than 10 feet below the water table.

Vertical Differences

Throughout most of the Anoka Sand Plain aquifer, horizontal movement of water is much more significant than vertical movement. On the basis of ground-water modeling of an adjacent sand-plain area (Anderson and Stoner, 1989), water recharging a sand-plain aquifer under typical hydraulic conditions in relatively flat terrain can be expected to move several hundred feet laterally and only a few feet downward. Therefore, differences in water quality with depth are related to differing conditions in the recharge areas. Ground-water quality data for 91 wells screened at different depths in the Anoka Sand Plain aquifer are presented in table 4. Data from eight wells screened in the underlying confined-drift aquifer also are presented to provide a comparison of water quality between unconfined- and confined-drift aquifers in the area. The deepest parts of the aquifer, more than 20 ft below the water table, are generally anoxic and have low redox potential. Water samples from this reducing environment generally will have no nitrite plus nitrate nitrogen and have elevated concentrations of iron.

Table 4.--Water quality at various depths below the water table in the Anoka Sand Plain aquifer and in the underlying confined-drift aquifer

[Total depth of well and depth to water in feet below land surface (negative values are above land surface); confined, confined-drift aquifer; values are concentrations in milligrams per liter, except as noted; --, not determined; <, less than; >, greater than]

Constituent or property	Depth below water table (feet)	Number of samples	Median	Minimum	Maximum
Depth to water (in feet)	<10	170	10.35	-0.33	40.00
	10-20	129	9.90	-.22	22.10
	>20	20	5.95	2.88	20.00
	Confined	1	34.00		
Total depth of well (in feet)	<10	171	15	6.3	50
	10-20	140	28	15	41
	>20	32	60	30	111
	Confined	16	152	80	250
Specific conductance (microsiemens per centimeter at 25 degrees Celsius)	<10	171	420	65	1140
	10-20	140	510	140	1170
	>20	32	467	305	870
	Confined	16	350	225	620

Table 4.--Water quality at various depths below the water table in the Anoka Sand Plain aquifer and in the underlying confined-drift aquifer--Continued

Constituent or property	Depth below water table (feet)	Number of samples	Median	Minimum	Maximum
pH (standard units)	<10	170	7.3	5.6	8.5
	10-20	138	7.6	6.2	9.0
	>20	30	7.5	6.7	7.9
	Confined	16	4.5	7.2	8.9
Temperature, water (degrees Celsius)	<10	171	9.0	4.0	18.0
	10-20	139	9.5	7.0	14.0
	>20	32	9.5	7.5	11.0
	Confined	16	9.5	8.5	11.0
Hardness as $CaCO_3$	<10	44	200	16	340
	10-20	38	230	64	400
	>20	11	240	150	320
	Confined	8	170	48	300
Calcium, dissolved	<10	44	55	3.8	100
	10-20	38	62	16	120
	>20	11	63	44	88
	Confined	8	44	14	82
Magnesium, dissolved	<10	44	14	1.5	32
	10-20	38	18	3.5	31
	>20	11	23	10	27
	Confined	8	15	3.1	22
Sodium, dissolved	<10	44	3.4	1.6	53
	10-20	38	3.9	1.6	38
	>20	11	4.0	1.5	33
	Confined	8	5.4	2.9	35
Potassium, dissolved	<10	44	.8	.1	2
	10-20	38	1	.4	2
	>20	11	2	.8	3
	Confined	8	1	.7	2

Table 4.--Water quality at various depths below the water table in the Anoka Sand Plain aquifer and in the underlying confined-drift aquifer--Continued

Constituent or property	Depth below water table (feet)	Number of samples	Median	Minimum	Maximum
Bicarbonate, IT field, as HCO^{3}	<10	159	170	10	410
	10-20	129	210	15	510
	>20	28	260	130	330
	Confined	16	200	25	280
Sulfate, dissolved	<10	142	14	.2	80
	10-20	116	19	.2	98
	>20	27	20	1	72
	Confined	15	3.7	2	57
Chloride, dissolved	<10	143	13	.1	180
	10-20	117	17	.7	180
	>20	27	5.4	.9	93
	Confined	15	1.3	.8	30
Fluoride, dissolved	<10	45	.1	<.1	.3
	10-20	38	.1	<.1	.6
	>20	11	.1	<.1	.2
	Confined	8	.1	<.1	.7
Silica, dissolved	<10	44	19	8.4	38
	10-20	38	18	6.8	30
	>20	11	19	15	25
	Confined	8	16	11	25
Dissolved solids, calculated, sum of constituents	<10	42	225	57	430
	10-20	38	240	91	480
	>20	11	280	190	470
	Confined	8	200	140	320
Nitrite, dissolved, as N	<10	36	<.01	<.01	.08
	10-20	30	<.01	<.01	.91
	>20	9	<.01	<.01	.05
	Confined	6	<.01	<.01	.01

Table 4.--Water quality at various depths below the water table in the Anoka Sand Plain aquifer and in the underlying confined-drift aquifer--Continued

Constituent or property	Depth below water table (feet)	Number of samples	Median	Minimum	Maximum
Nitrite plus nitrate, dissolved, as N	<10	171	5.1	<.10	44
	10-20	140	2.7	<.10	45
	>20	32	<.10	<.10	13
	Confined	16	<.10	<.10	22
Nitrogen, ammonia, dissolved, as N	<10	136	.04	<.01	2.0
	10-20	108	.04	<.01	.80
	>20	26	.06	<.01	.18
	Confined	16	.12	<.01	.49
Nitrogen, dissolved organic, as N	<10	43	.69	<.10	2.5
	10-20	37	.73	<.10	3.2
	>20	11	.33	.13	2.1
	Confined	8	1.4	.11	2.7
Phosphorus, dissolved orthophosphate, as P	<10	47	<.01	<.01	.22
	10-20	40	<.01	<.01	.14
	>20	11	<.01	<.01	.08
	Confined	8	.05	<.01	.09
Boron, dissolved	<10	44	<.02	<.02	.75
	10-20	38	<.02	<.02	.12
	>20	11	<.02	<.02	.05
	Confined	8	<.02	<.02	.34
Iron, dissolved	<10	43	.02	<.01	20
	10-20	37	.02	<.01	16
	>20	11	.31	<.01	2.4
	Confined	8	.23	<.01	2.8
Manganese, dissolved	<10	43	.013	<.001	.86
	10-20	37	.04	<.001	2.2
	>20	11	.19	<.001	.54
	Confined	8	.086	<.001	.28
Carbon, organic dissolved, as C	<10	41	1.4	.7	17
	10-20	36	1.4	.8	4.7
	>20	11	1.4	1	2.3
	Confined	8	1.2	.4	1.5

The stratigraphy of the Anoka Sand Plain aquifer contributes to differences in water quality with depth. The upper part of the aquifer is gray outwash (fig. 4) deposited by the Grantsburg sublobe of the Des Moines glacial lobe. These sediments, mainly quartz sand, contain calcium-magnesium carbonate (limestone) and some sulfate evaporites (Anderson and Ruhl, 1984; Woodward and Anderson, 1986). The lower part of the Anoka Sand Plain aquifer is red outwash (fig. 4) deposited by the Superior glacial lobe. These sediments are predominantly quartz sand that include iron minerals in substantial quantities. Red brown sandy till deposited by the Superior lobe underlies the Anoka Sand Plain aquifer. Locally the red outwash is under confined conditions where it is overlain by gray silty till.

Specific conductance in the Anoka Sand Plain aquifer is less in water from less than 10 ft below the water table than in water from 10 ft or more below the water table (fig. 15). The water from 10 ft or more below the water table generally has moved farther in the gray sand outwash than has the shallower water. Consequently, it has had more time to dissolve calcareous minerals. The concentrations of cations such as calcium, magnesium, sodium, and potassium increased with depth below the water table in the Anoka Sand Plain aquifer (fig. 16). This increase is due to increased residence time of the water in the aquifer and is related to the increase in concentrations of dissolved solids and in specific conductance (fig. 15). Water samples from more than 20 ft below the water table, which show little additional increase in calcium concentration and a reduction in specific conductance (fig. 16), may indicate the influence of the virtually insoluble quartz in the red sand near the bottom of the aquifer. The lesser specific conductance in water samples from the underlying confined-drift aquifer may result from the less soluable quartz sand aquifer material.

Concentrations of anions such as nitrite plus nitrate nitrogen, sulfate, chloride, and bicarbonate are more variable with depth below the water table than are concentrations of cations in the Anoka Sand Plain aquifer (fig. 17). Median concentrations of sulfate increase with depth in the Anoka Sand Plain aquifer. The concentration of chloride increases from the water table to 20 ft below the water table but then decreases in the lower part of the Anoka Sand Plain aquifer and in the confined aquifer. Elevated concentrations of chloride in the upper 20 ft of the surficial aquifer probably result from chloride in some fertilizers and in manure and from the use of chloride as a road de-icer. The water from more than 20 ft below the water table represents sources of recharge more distant than the sources of shallower ground water, or water that has been in the aquifer for a longer period of time.

The concentrations of nitrite plus nitrate nitrogen generally are greatest near the water table and decrease with depth below the water table (fig. 17). This decrease indicates a local source of nitrite plus nitrate nitrogen at land surface, or it could also indicate denitrification at depth in the aquifer. Denitrification occurs as the decay of organic matter in the aquifer removes oxygen and creates reducing conditions, which results in the reduction of nitrite plus nitrate nitrogen to nitrous oxide or nitrogen gas. Nitrite plus nitrate nitrogen in ground water near agricultural areas can be related to the use of fertilizer and to seepage from feedlots and septic systems. In residential areas, nitrite plus nitrate nitrogen concentration is related to use of lawn fertilizer and seepage from septic systems. The median concentration of nitrite plus nitrate nitrogen is 5.1 mg/L near the water table and is below the detection limit of 0.1 mg/L for depths of more than 20 ft below the water table (fig. 17).

General linear models were used to evaluate the statistical significance of the ranked analysis of variance for vertical differences in water quality in the Anoka Sand Plain aquifer. The differences in concentration of nitrite plus nitrate nitrogen among the three depth categories were statistically significant at the 99-percent level of probability. By use of Duncan's Multiple Range Test, nitrite plus nitrate nitrogen concentrations among the three depth categories were found to be significantly

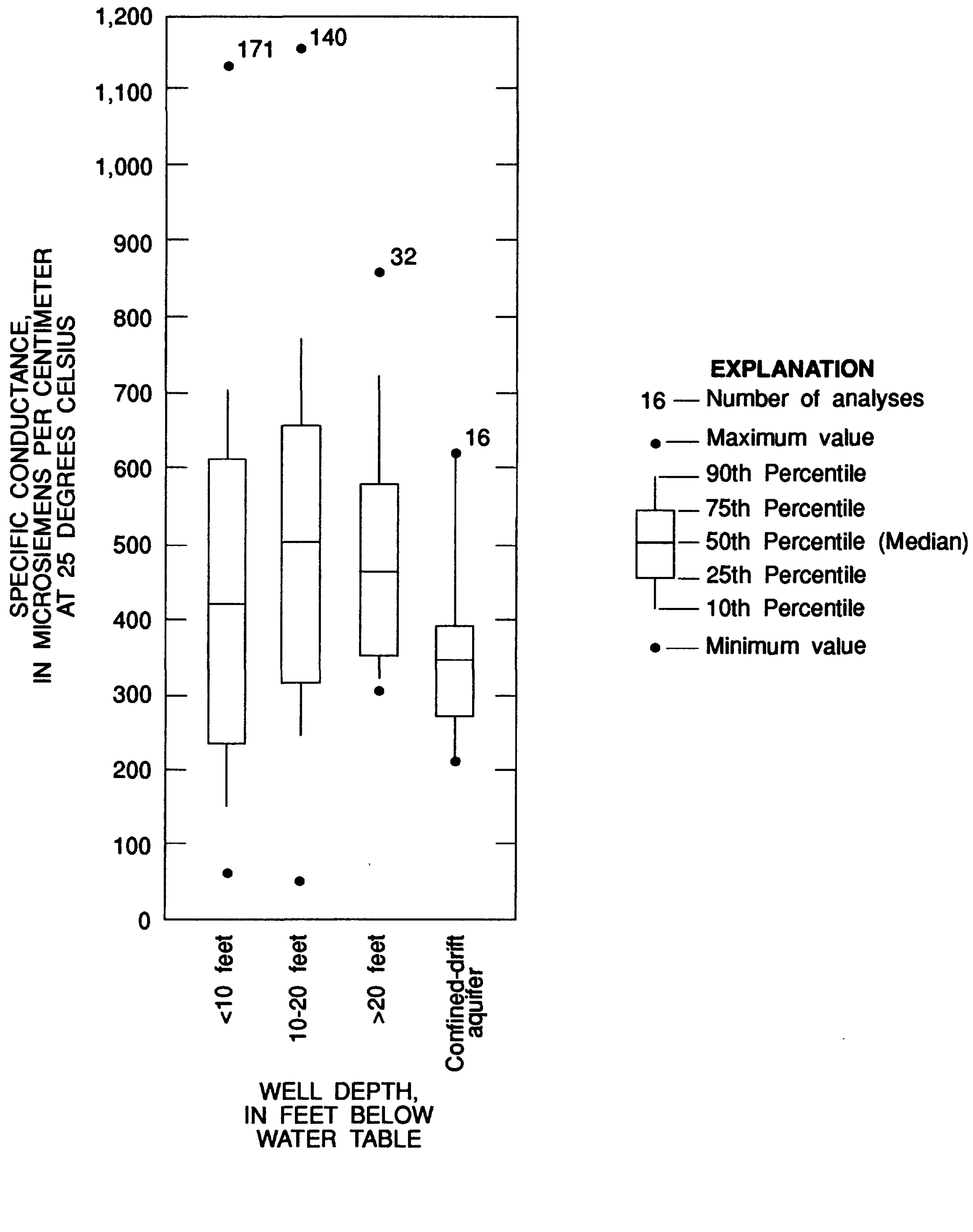


Figure 15.--Specific conductance of ground-water samples from different depths below the water table in the Anoka Sand Plain aquifer and from the underlying confined-drift aquifer.

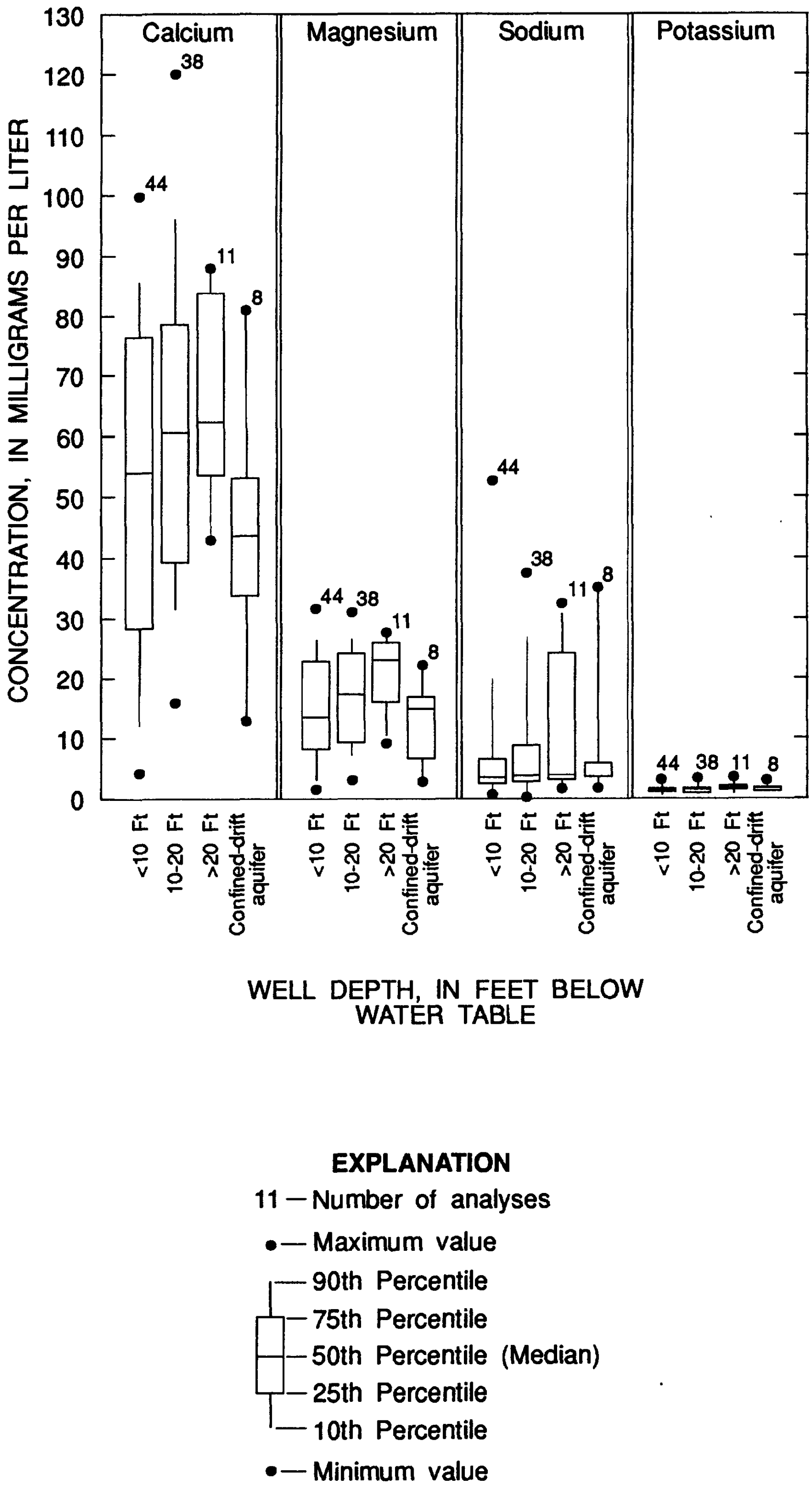


Figure 16.--Concentration of major cations in ground-water samples from different depths below the water table in the Anoka Sand Plain aquifer and from the underlying confined-drift aquifer.

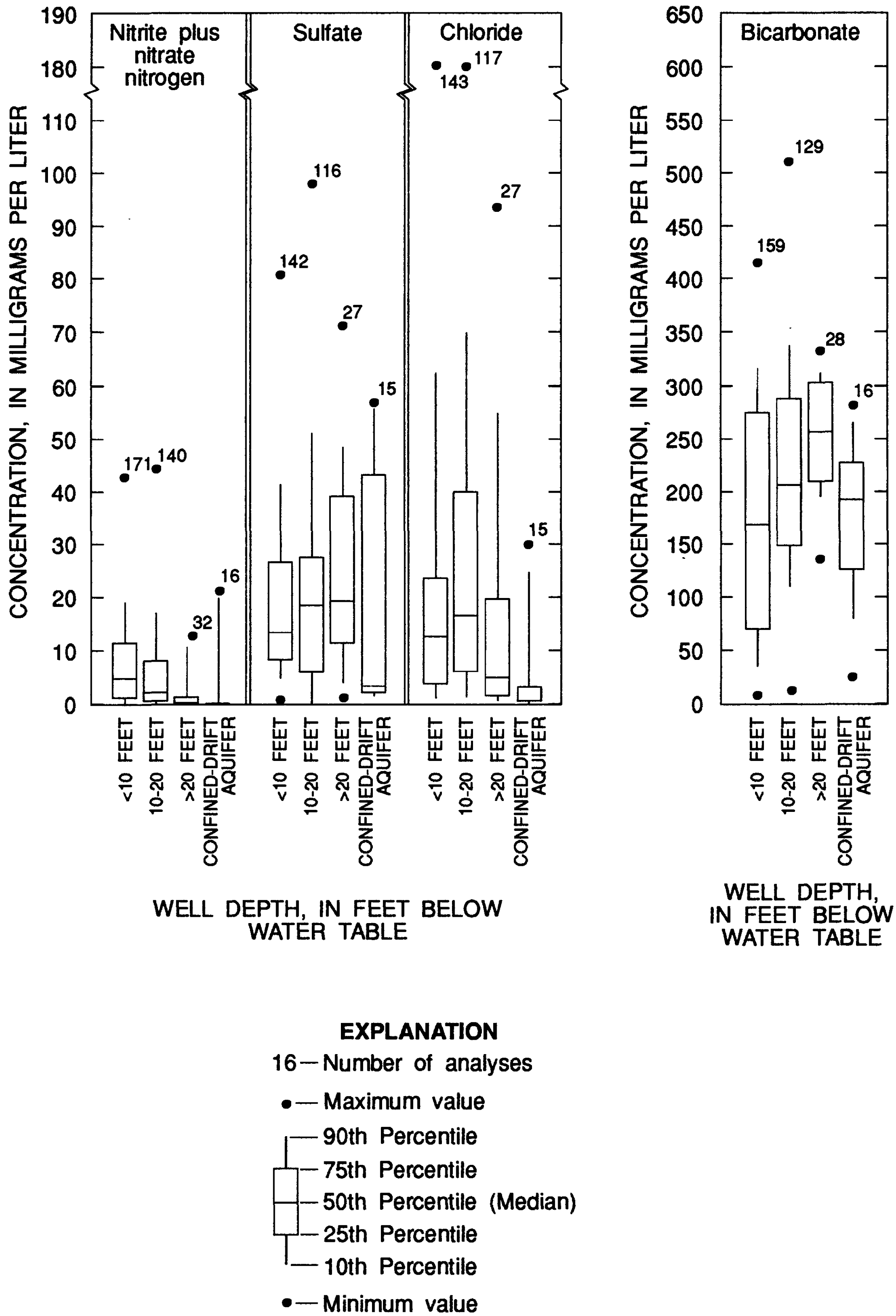


Figure 17.–Concentration of nitrite plus nitrate nitrogen, sulfate, chloride, and bicarbonate on ground-water samples from different depths below the water table in the Anoka Sand Plain aquifer and from the underlying confined-drift aquifer.

different from each other. Results of Tukey's Studentized Range Test indicated a significant difference between nitrite plus nitrate nitrogen concentrations in water sampled from less than 20 ft and water sampled from 20 ft or more below the water table.

Water quality was evaluated at 29 well clusters for nitrite plus nitrate nitrogen concentrations. Large vertical differences in nitrite plus nitrate nitrogen concentrations were found at 23 of the 29 well clusters. At 15 of these 23 well clusters, nitrite plus nitrate nitrogen concentrations were greater near the water table than deeper in the aquifer (table 5). At the other eight well clusters, nitrite plus nitrate nitrogen concentrations were less near the water table than deeper in the aquifer. The most common situation throughout most of the sand-plain aquifers in Minnesota is represented by the 15 well clusters at which nitrite plus nitrate nitrogen concentrations were greater near the water table than at depth.

Table 5.--Differences in concentrations of nitrite plus nitrate nitrogen at different depths in the Anoka Sand Plain aquifer
[mg/L, milligrams per liter; <, less than; ≥, greater than or equal to]

	Well depth below water table (feet)	Number of well clusters	Number of samples	Median nitrate nitrogen (mg/L)
Well clusters with greater nitrite plus nitrate-nitrogen concentrations near the water table	< 10	15	66	4.7
	≥ 10	15	66	1.0
Well clusters with lesser nitrite plus nitrate-nitrogen concentrations near the water table	< 10	8	36	1.8
	≥ 10	8	36	4.8
Well clusters with little vertical difference	< 10	6	23	12
	≥ 10	6	23	12

In most areas of the Anoka Sand Plain aquifer, concentrations of nitrite plus nitrate nitrogen are greatest at shallow depth and decrease with depth. Edmunds (1973) attributes this trend in nitrite plus nitrate nitrogen concentrations to the biochemical process of denitrification. J.A. Cherry (University of Waterloo, Waterloo, Ontario, Canada, oral commun., 1986) has documented denitrification in surficial sand-plain aquifers. This process requires denitrifying bacteria, organic material, other nutrients necessary for growth of bacteria, and a moderate to low redox potential of the ground water. In their discussion of redox processes, Freeze and Cherry (1979, p. 114-118) list reactions in which nitrite plus nitrate nitrogen is converted to the gases nitrogen or nitrous oxide or to the ions nitrite or ammonium. The denitrification process also forms bicarbonate, hydrogen ions, and water. Where the environmental conditions are favorable, this process accounts for some of the vertical differences in nitrite plus nitrate nitrogen concentrations in the Anoka Sand Plain aquifer.

The eight well clusters at which nitrite plus nitrate nitrogen concentrations were low near the water table than at depth (table 5) represent exceptions to the common condition. Of these eight well clusters, five are near ephemeral ponds or highway-drainage ditches that collect water during heavy precipitation. This pond precipitation generally is low in concentrations of nitrite plus nitrate nitrogen and dissolved solids. Samples collected from two such ponds in an adjoining county had nitrite plus nitrate nitrogen concentrations less than 1 mg/L (Anderson, 1989). Water in the ponds drains rapidly downward through the permeable sandy soils. The dilute, focused recharge from the ponds can displace water with elevated nitrite plus nitrate nitrogen concentrations from near the water table to deeper in the aquifer. This results in reduced nitrite plus nitrate nitrogen concentrations near the water table and increased concentrations at depth. Another example of conditions resulting in greater nitrite plus nitrate nitrogen concentrations at depth than near the water table is at an undeveloped site near the Mississippi River. Hydraulic-head measurements at wells in this area indicate ground water flows upward toward the water table where it mixes with dilute recharge from the surface and discharges to the river. This example of greater nitrite plus nitrate nitrogen at depth than near the water table could be typical in areas of ground-water discharge.

In the Anoka Sand Plain aquifer, six of the well clusters (table 5) showed little vertical difference in concentration of nitrite plus nitrate nitrogen with depth. Two of these clusters had nitrite plus nitrate nitrogen concentrations less than 1 mg/L, indicating no influence from human activities. The other four clusters had nitrite plus nitrate nitrogen concentrations that ranged from 2.7 to 24 mg/L. These four clusters were all in areas of heavy pumping from the aquifer either for irrigation or residential supplies. This pumping caused more mixing of water in the aquifer in these areas than elsewhere. In the one residential area where little vertical difference in nitrite plus nitrate nitrogen was measured, a relatively steep water-table gradient (1 ft per 100 ft locally) also could contribute to mixing of the water in the aquifer.

Somewhat greater concentrations of iron and manganese are present in ground water from more than 20 ft below the water table than in shallower ground water (fig. 18). This reflects the high iron and manganese content of the red outwash of Superior lobe origin. The greater iron and manganese concentrations also reflect reducing conditions in the lower part of the Anoka Sand Plain aquifer.

Land Use Related to Temporal Changes in Water Quality

Seasonal Changes

Data on water levels and quality of water from wells screened in the Anoka Sand Plain aquifer are compiled by season in table 6. In a nearby sand-plain area, concentrations of chloride and nitrite plus nitrate nitrogen fluctuate in a pattern similar to that of water-level fluctuations (Myette, 1984). Myette reported greatest nitrite plus nitrate nitrogen concentrations after spring recharge, lowest concentrations in summer, increased concentrations in fall and decreased concentrations again in winter. Maximum water levels usually occur in the spring after snowmelt and spring rains recharge the surficial aquifer. Minimum water levels usually occur in the summer when evapotranspiration limits recharge and increased pumping stresses the system. Water levels begin to increase in the fall after frost stops most plant growth and reduces evapotranspiration. Water levels generally decline during winter when frozen ground prevents ground-water recharge. Water levels in well 032N23W04AAD02 (fig. 19) show these trends.

Fluctuations in nitrite plus nitrate nitrogen concentrations are due to the interrelation of many factors affecting the presence of nitrite plus nitrate nitrogen in ground water. These factors include (1) the rate of flow of recharge through the unsaturated zone, (2) the volume of recharge, (3) the timing of fertilizer applications either before, during, or after periods of recharge, and (4) denitrification. Changes in nitrite plus nitrate nitrogen concentrations over time are compared at four well-cluster sites in figures 20 through 23.

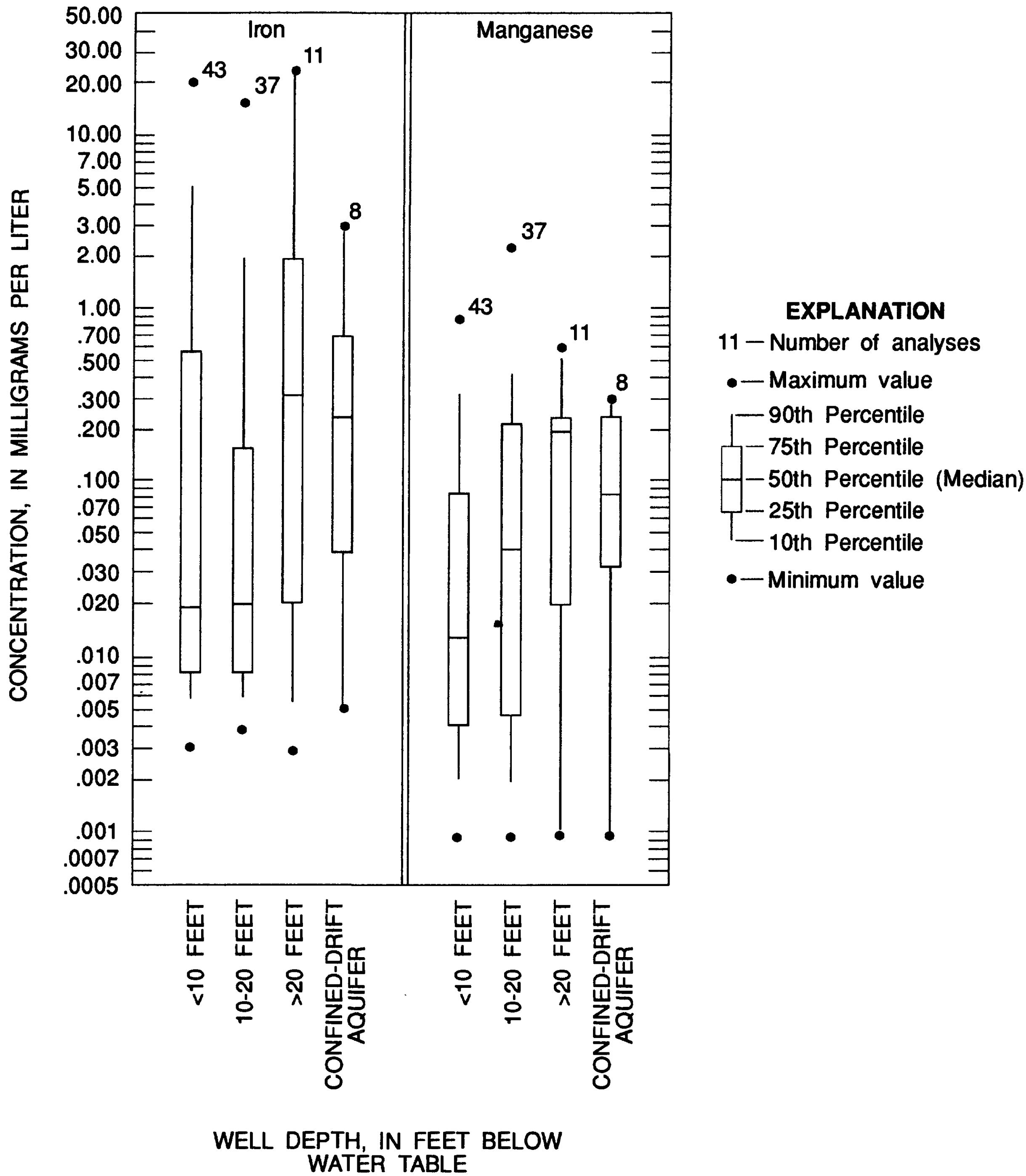


Figure 18.--Concentrations of iron and manganese in ground-water samples from different depths below the water table in the Anoka Sand Plain aquifer and the underlying confined-drift aquifer.

Table 6.--Fluctuations in water quality in the Anoka Sand Plain aquifer
[Depth to water below land surface is in feet (negative values are above land surface). Values are concentrations in milligrams per liter, except as noted. Season designations: Spring 1984, May-June; Winter 1985, December 1984-February 1985; Spring, 1985, June; Spring 1986, June; Spring 1987, May; --, not determined; <, less than]

Constituent or property	Season	Number of samples	Median	Minimum	Maximum
Depth to water (in feet)	Spring 1984	31	8.70	1.70	18.00
	Winter 1985	30	10.25	1.70	18.50
	Spring 1985	31	10.30	1.10	18.30
	Spring 1986	31	10.40	-.33	17.43
	Spring 1987	13	9.25	2.26	15.04
Specific Conductance (microsiemens per centimeter at 25 degrees Celsius)	Spring 1984	31	435	175	1015
	Winter 1985	31	510	116	880
	Spring 1985	31	460	155	850
	Spring 1986	31	435	65	960
	Spring 1987	13	350	140	1170
pH (standard units)	Spring 1984	33	7.6	5.9	8.6
	Winter 1985	33	7.2	5.6	9.0
	Spring 1985	33	7.5	6.2	8.4
	Spring 1986	33	7.6	6.0	8.5
	Spring 1987	13	7.8	6.2	8.5
Temperature, water (degrees Celsius)	Spring 1984	31	9.0	7.5	10.5
	Winter 1985	31	9.5	6.0	11.0
	Spring 1985	31	9.0	8.0	14.5
	Spring 1986	31	9.0	7.5	12.0
	Spring 1987	13	8.5	7.0	10.0
Bicarbonate, IT, field, as HCO_3	Spring 1984	31	200	13	342
	Winter 1985	31	189	11	376
	Spring 1985	31	183	10	366
	Spring 1986	31	183	17	366
	Spring 1987	13	129	32	293

Table 6.--Fluctuations in water quality in the Anoka Sand Plain aquifer--Continued

Constituent or property	Season	Number of samples	Median	Minimum	Maximum
Sulfate, dissolved	Spring 1984	31	19	4.2	66
	Winter 1985	30	18	4.1	66
	Spring 1985	31	16	5.1	64
	Spring 1986	31	18	3.6	98
	Spring 1987	13	17	3.8	27
Chloride, dissolved	Spring 1984	31	17	1.0	130
	Winter 1985	31	19	.7	100
	Spring 1985	31	24	.8	93
	Spring 1986	31	19	.7	140
	Spring 1987	13	11	.7	180
Nitrate, dissolved, as N	Spring 1984	31	4.8	<.1	29
	Winter 1985	31	4.7	<.1	41
	Spring 1985	31	5.1	.2	38
	Spring 1986	31	5.5	<.1	45
	Spring 1987	13	5.5	<.8	35

Water levels and nitrite plus nitrate nitrogen concentrations in a shallow well 033N22W09ADB01 at an undeveloped site downgradient from a wooded area and nitrite plus nitrate nitrogen concentrations in deep well 033N22W09ADB02 at this site in Anoka County are shown in figure 20. Water-level fluctuations in the shallow well are similar to other shallow wells at other sites. Concentration of nitrite plus nitrate nitrogen in water samples from the wells at this undeveloped site reached a maximum of only 1.6 mg/L. Water in the deeper well is anoxic most of the time, and the water samples collected generally did not contain nitrite plus nitrate nitrogen.

The fluctuations of the water levels and concentrations of nitrite plus nitrate nitrogen in shallow and deep wells at a nonirrigated-cultivated site (fig. 21) are similar to fluctuations in the wells shown in figure 20. Although the water levels declined only 0.1 ft from May to June 1984, the nitrite plus nitrate nitrogen concentrations in the shallow well decreased from 20 mg/L to 2.7 mg/L. Infiltration of heavy precipitation containing low nitrite plus nitrate nitrogen from the fall of 1983 through the spring of 1984 and the growth of crops during the previous growing season probably resulted in depletion of solublenitrite plus nitrite plus nitrate nitrogen in the soil and reduced the nitrite plus nitrate nitrogen available for recharge to the aquifer. The nitrite plus nitrate nitrogen concentrations in samples from the deep well at the nonirrigated-cultivated site (fig. 21) are similar to those from the shallow well at the undeveloped site (fig. 20). This similarity could indicate that the recharge area for water reaching the deep well is in undeveloped land or that any nitrite plus nitrate nitrogen previously present had been removed by denitrification.

Water-level and nitrite plus nitrate nitrogen fluctuations at an irrigated site are shown in figure 22. Concentrations of nitrite plus nitrate nitrogen in water samples from the shallow well increased from 15 to 22 mg/L during irrigation from June through August 1984. Above-normal precipitation slowly leached nitrite plus nitrate nitrogen from the soil to the aquifer throughout the winter and maintained the concentration of nitrite plus nitrate nitrogen at 22 mg/L. Infiltration of spring snowmelt and spring rains containing little nitrite plus nitrate nitrogen either diluted the ground water or displaced the high nitrite plus nitrate nitrogen water to below the shallow well screen. Nitrite plus nitrate nitrogen concentrations in the deep well, which were less than in the shallow well, decreased from 3.9 mg/L in June 1984 to 0.50 mg/L in July 1986. Nitrite plus nitrate nitrogen concentrations generally decreased in both wells from 1984 through 1986, probably from dilution and denitrification.

Fluctuations of water levels and nitrite plus nitrate nitrogen concentrations in a shallow and a deep well at a residential site are shown in figure 23. Water from the shallow well at this site had fairly constant lesser nitrite plus nitrate nitrogen concentrations during the study. Nitrite plus nitrate nitrogen concentrations in samples from the deep well rose from 0.60 mg/L in September 1983 to 8.6 mg/L by June 1985. At least 50 homes on quarter-acre lots with septic systems are immediately upgradient from this well site. In addition, the slope of the valley continues downward beyond the well site. The steep hydraulic gradient results in possible mixing of the ground water and brings elevated concentrations of nitrite plus nitrate nitrogen to greater depth than if the area had a flatter hydraulic gradient. Another influence on nitrite plus nitrate nitrogen concentrations is a roadside drainage ditch, which flows within 40 feet of the well cluster and could provide a source of recharge with diluted concentrations of nitrite plus nitrate nitrogen; the dilute recharge could displace elevated concentrations of nitrite plus nitrate nitrogen to greater depth below the water table.

From the fall of 1986 through the spring of 1987 precipitation was insufficient to cause recharge to the aquifer in most of the Anoka Sand Plain. Forty lysimeters on the Rosholt Research Farm, located in a sand plain about forty-five miles west of the Anoka Sand Plain, indicated that no measurable recharge reached a depth of 4 ft in the unsaturated zone from the fall of 1986 through 1987. This drought is reflected in figure 23 by a decline in water levels and nitrite plus nitrate nitrogen concentrations in both wells.

Long-term Changes

Five wells in the Anoka Sand Plain aquifer that had been sampled for nitrite plus nitrate nitrogen in 1965 through 1978 were resampled to determine long-term changes in water quality. Water from these wells showed little change in nitrite plus nitrate nitrogen concentrations, unlike water from wells in other parts of the State (Anderson, 1989). Concentrations of nitrite plus nitrate nitrogen shown in figure 23 for the deep well fluctuated from 0.6 mg/L in September 1983 to 8.6 mg/L in June 1985 and to 3.4 mg/L in May 1987. Although a general decline was observed from 1985 through 1987, the concentration of nitrite plus nitrate nitrogen in 1987 was still above that in 1983. This could indicate a long-term increase in nitrite plus nitrate nitrogen; however, short-term fluctuations are greater than the possible long-term increase.

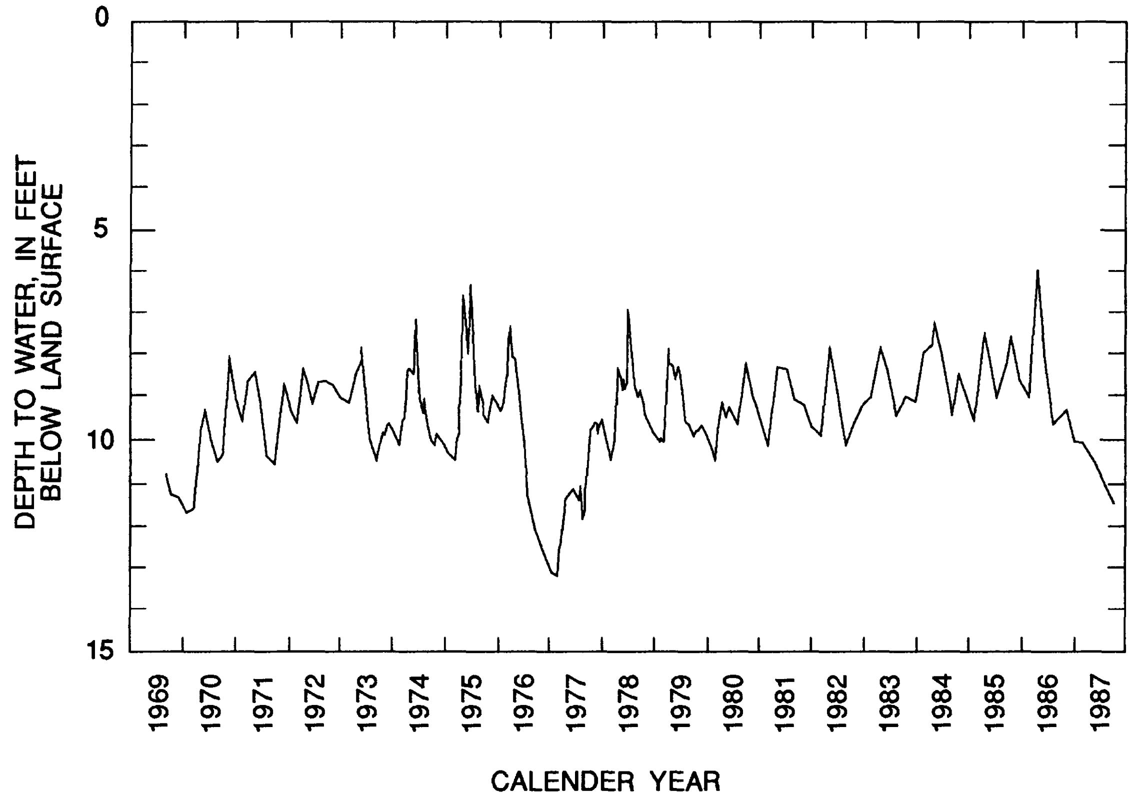
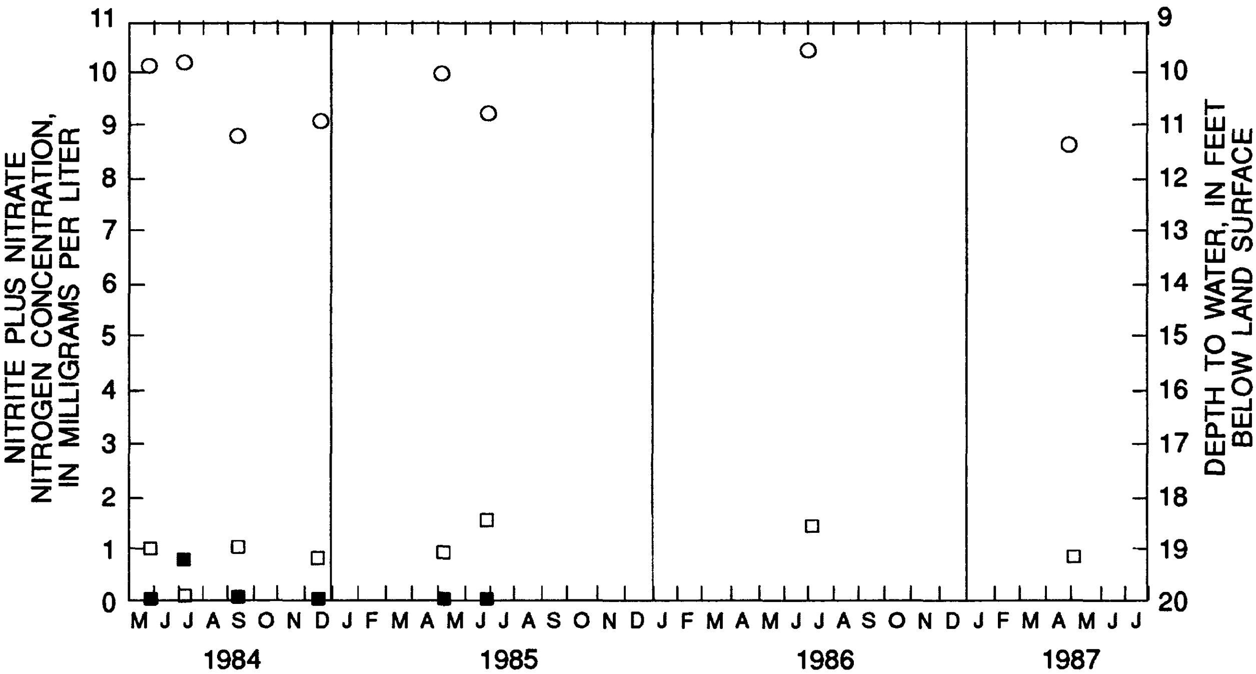


Figure 19.--Water levels from 1969 through 1987 at observation well 032N23W04AAD02 in the Anoka Sand Plain aquifer.



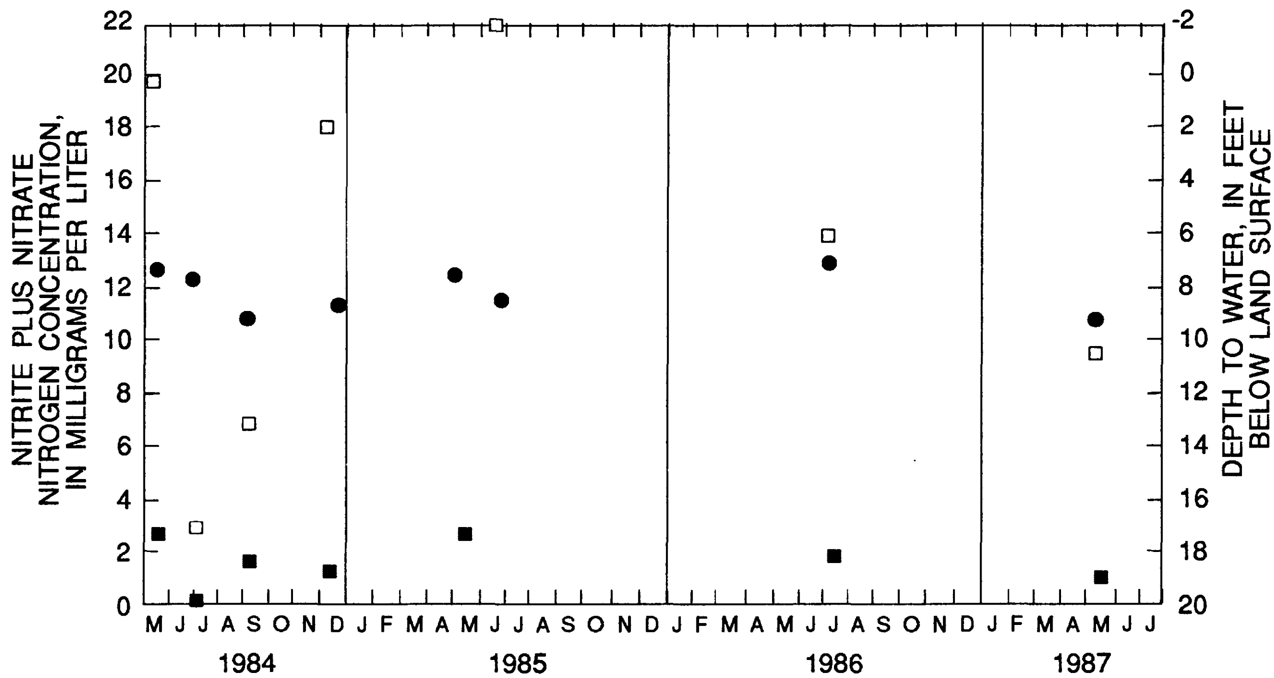
EXPLANATION

○ Water level-shallow well 033N22W09ADB01 (15 feet deep)

□ Nitrite plus nitrate nitrogen-shallow well

■ Nitrite plus nitrate nitrogen-deep well 033N22W09ADB02 (87 feet deep)

Figure 20.--Water levels and concentrations of nitrite plus nitrate nitrogen (NO_2 + NO_3, as N) in ground water at a well cluster at an undeveloped site in the Anoka Sand Plain aquifer.



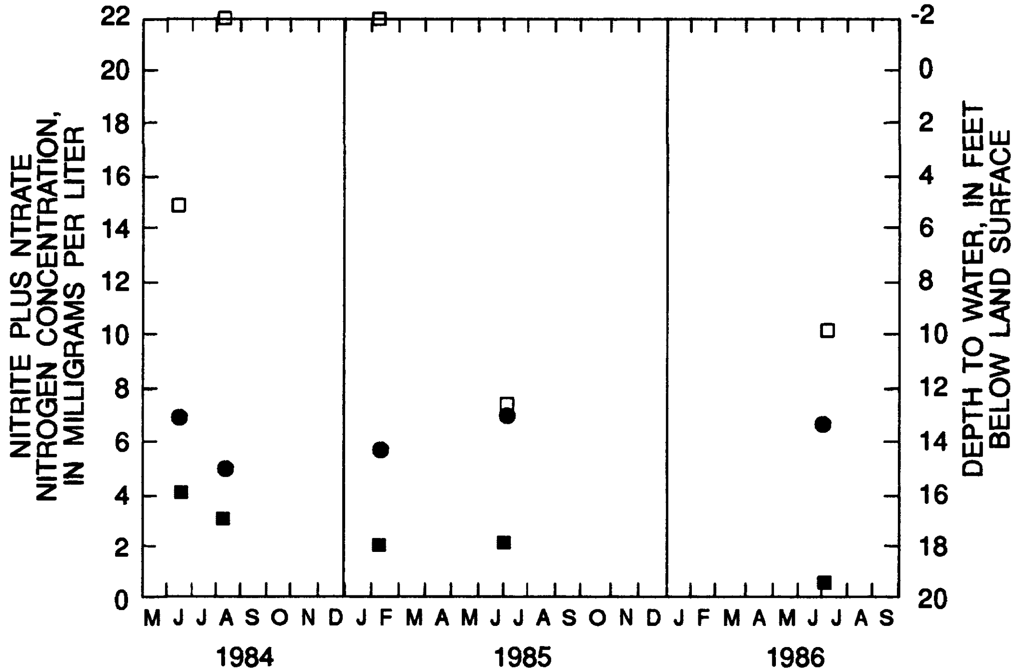
EXPLANATION

○ Water level-shallow well 033N22W10CCB01 (13 feet deep) and deep well 033N22W10CCB02 (28 feet deep)

□ Nitrite plus nitrate nitrogen-shallow well

■ Nitrite plus nitrate nitrogen-deep well

Figure 21.--Water levels and concentrations of nitrite plus nitrate nitrogen (NO_2 + NO_3, as N) in ground water at a well cluster at a nonirrigated-cultivated site in the Anoka Sand Plain aquifer.



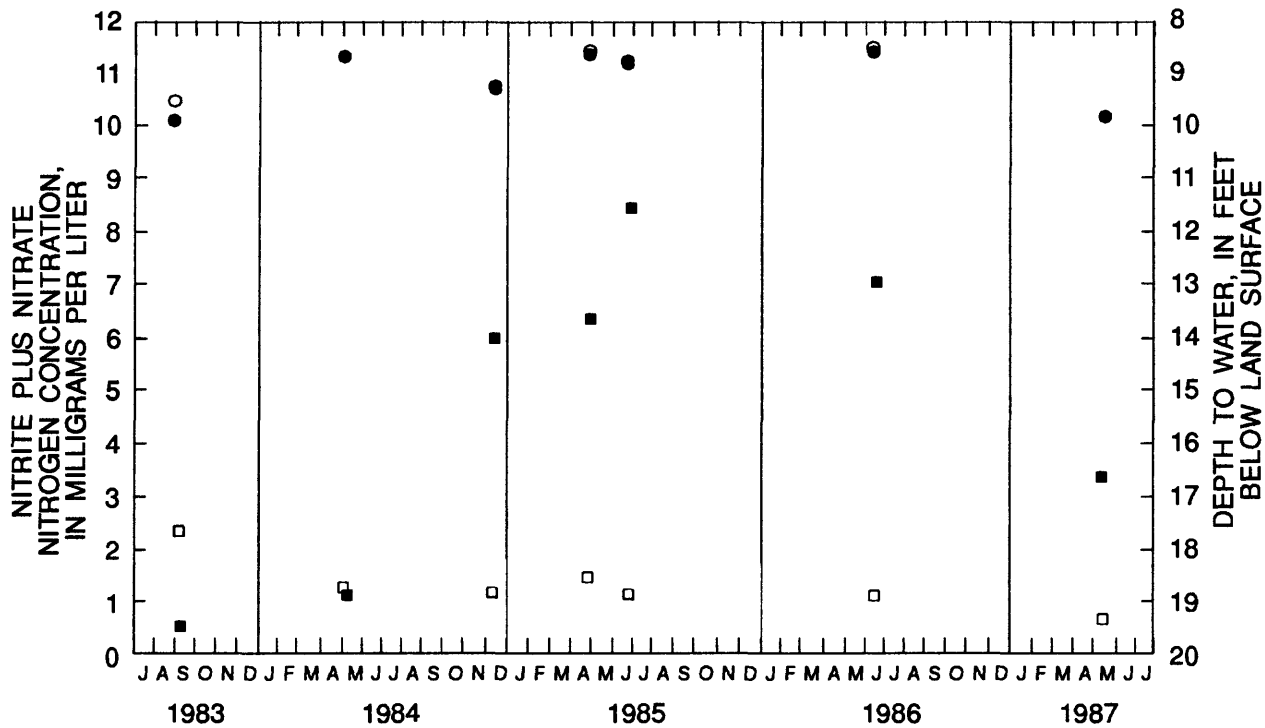
EXPLANATION

● Water level-shallow well 033N29W04BBA01 (20 feet deep) and deep well 033N29W04BBA02 (35 feet deep)

□ Nitrite plus nitrate nitrogen-shallow well

■ Nitrite plus nitrate nitrogen-deep well

Figure 22.--Water levels and concentrations of nitrite plus nitrate nitrogen (NO_2 + NO_3, as N) in ground water at a well cluster at an irrigated site in the Anoka Sand Plain aquifer.



EXPLANATION

- ● Water level-shallow well 032N25W15CAC01 (14feet deep)
- ○ Water level-deep well 032N25W15CAC02 (29 feet deep)
- □ Nitrite plus nitrate nitrogen-shallow well
- ■ Nitrite plus nitrate nitrogen-deep well

Figure 23.--Water levels and concentrations of nitrite plus nitrate nitrogen (NO_2 + NO_3, as N) in ground water at residential site in the Anoka Sand Plain aquifer.

Ground-Water Quality Characterized by Land-Use

Data from 11 wells at undeveloped sites, 25 wells at nonirrigated-cultivated sites, 35 wells at irrigated sites, and 29 wells at residential sites were statistically analyzed to compare the water-quality effects of agricultural and residential land uses by type of use. Well locations were selected to represent the maximum influence of a particular land use and to minimize the influence of other land uses. The quality of water from wells at undeveloped sites provides a basis of comparison with water quality in areas affected by human activities (table 7).

Well sites selected to represent cultivated land, either with or without irrigation, were chosen to avoid the influence of septic systems, and feedlots. The most apparent source of nitrates at these sites is fertilizer applied to fields upgradient from the well site. Commonly used fertilizers (Shearer and others, 1974, p. 313) include: anhydrous ammonia (NH_3), ammonium hydroxide (NH_4OH), ammonium phosphate ($(NH_4)_2HPO_4$), ammonium sulfate ($(NH_4)_2SO_4$), ammonium nitrate (NH_4NO_3), sodium nitrate ($NaNO_3$), potassium nitrate (KNO_3), urea (an organic compound), potassium chloride (KCl), and animal manure, which contains nitrogen, chloride, sulfates, and many other constituents.

Table 7.--Water quality in the Anoka Sand Plain aquifer by type of land use
[Total depth of well and depth to water in feet below land surface (negative values are above land surface). --, not determined. Values are in milligrams per liter, except as note. Nonirrigated land use refers to nonirrigated-cultivated land]

Constituent or property	Land use	Number of samples	Median	Minimum	Maximum
Depth to water (in feet)	Undeveloped	39	9.80	1.50	17.60
	Nonirrigated	92	8.50	2.20	40.00
	Irrigated	120	12.80	.10	24.00
	Residential	70	10.25	-.33	34.00
Total depth of well (in feet)	Undeveloped	44	20.0	7.0	87.0
	Nonirrigated	97	20.0	9.0	232.0
	Irrigated	129	24.0	6.3	111.0
	Residential	89	22.0	7.0	250.0
Specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Undeveloped	44	330	115	500
	Nonirrigated	97	300	65	1020
	Irrigated	129	580	92	950
	Residential	89	560	65	1170
pH (standard units)	Undeveloped	42	7.5	5.9	8.2
	Nonirrigated	96	7.4	5.6	9.0
	Irrigated	129	7.5	6.2	8.8
	Residential	87	7.5	6.3	8.4

Table 7.--Water quality in the Anoka Sand Plain aquifer by type of land use--Continued

Constituent or property	Land use	Number of samples	Median	Minimum	Maximum
Temperature, water (degrees Celsius)	Undeveloped	44	9.0	6.0	14.0
	Nonirrigated	97	9.0	7.0	14.0
	Irrigated	129	9.5	4.0	18.0
	Residential	88	9.5	6.0	15.5
Hardness, as $CaCO_3$	Undeveloped	11	150	34	240
	Nonirrigated	26	120	16	300
	Irrigated	36	280	35	380
	Residential	28	280	120	400
Calcium, dissolved	Undeveloped	11	46	10	68
	Nonirrigated	26	34	3.8	83
	Irrigated	36	76	10	100
	Residential	28	72	32	120
Magnesium, dissolved	Undeveloped	11	9.6	2.3	23
	Nonirrigated	26	8.5	1.5	22
	Irrigated	36	23	2.5	32
	Residential	28	21	7.6	29
Sodium, dissolved	Undeveloped	11	3.5	1.9	11
	Nonirrigated	26	3.7	1.6	53
	Irrigated	36	3.2	1.5	38
	Residential	28	13	2.1	33
Potassium, dissolved	Undeveloped	11	.7	.1	1.7
	Nonirrigated	26	.9	.3	2.3
	Irrigated	36	1.0	.3	2.7
	Residential	28	1.3	.1	2.4
Bicarbonate IT, field as HCO_3	Undeveloped	40	160	27	310
	Nonirrigated	88	120	10	360
	Irrigated	117	260	34	510
	Residential	87	270	61	380
Sulfate, dissolved	Undeveloped	37	11	1.0	47
	Nonirrigated	82	12	2.0	94
	Irrigated	100	22	.2	98
	Residential	81	20	2.6	57

Table 7.--Water quality in the Anoka Sand Plain aquifer by type of land use--Continued

Constituent or property	Land use	Number of samples	Median	Minimum	Maximum
Chloride, dissolved	Undeveloped	37	3.5	0.7	30
	Nonirrigated	82	5.3	.5	100
	Irrigated	102	19	.0	92
	Residential	81	26	.7	180
Fluoride, dissolved	Undeveloped	11	.1	<.1	.2
	Nonirrigated	27	.1	<.1	.4
	Irrigated	36	.1	<.1	.6
	Residential	28	.1	<.1	.7
Silica, dissolved	Undeveloped	11	23	17	38
	Nonirrigated	26	19	11	26
	Irrigated	36	18	8.4	30
	Residential	28	18	6.8	27
Dissolved solids, calculated, sum of constituents	Undeveloped	10	190	96	270
	Nonirrigated	26	150	70	410
	Irrigated	35	290	57	440
	Residential	28	320	170	480
Nitrite, dissolved, as N	Undeveloped	11	.01	<.01	.07
	Nonirrigated	14	.01	<.01	.08
	Irrigated	28	.01	<.01	.91
	Residential	28	.01	<.01	.05
Nitrite plus nitrate, dissolved, as N	Undeveloped	44	.22	<.1	9.5
	Nonirrigated	97	2.0	<.1	45
	Irrigated	129	5.3	<.1	44
	Residential	89	4.2	<.1	35
Nitrogen, ammonia, dissolved, as N	Undeveloped	37	.07	<.01	.39
	Nonirrigated	74	.04	<.01	1.5
	Irrigated	95	.04	<.01	2.0
	Residential	80	.04	<.01	.49
Nitrogen, dissolved organic, as N	Undeveloped	11	1.1	<.1	2.1
	Nonirrigated	25	1.1	<.1	2.5
	Irrigated	35	.5	<.1	2.4
	Residential	28	.8	<.1	3.2

Table 7.--Water quality in the Anoka Sand Plain aquifer by type of land use--Continued

Constituent or property	Land use	Number of samples	Median	Minimum	Maximum
Phosphorus, dissolved, orthophosphate as P	Undeveloped	11	0.01	<0.01	0.08
	Nonirrigated	27	.01	<.01	.16
	Irrigated	40	.01	<.01	.14
	Residential	28	.01	<.01	.22
Boron, dissolved	Undeveloped	11	.02	.02	.06
	Nonirrigated	26	.02	.02	.75
	Irrigated	36	.02	.02	.18
Iron, dissolved	Undeveloped	11	.16	<.01	16
	Nonirrigated	25	.05	<.00	20
	Irrigated	35	.02	<.01	7
	Residential	28	.01	<.00	10.5
Manganese, dissolved	Undeveloped	11	.097	<.001	2.2
	Nonirrigated	25	.044	<.001	1.3
	Irrigated	35	.020	<.001	.60
	Residential	28	.007	<.001	.86
Carbon, organic, dissolved, as C	Undeveloped	9	1.8	1.0	2.4
	Nonirrigated	24	1.4	.7	3.9
	Irrigated	35	1.4	.8	17
	Residential	28	1.2	.4	4.7

The most widely used pesticides in the study area are the triazine group and related herbicides. The five herbicides used in the greatest quantities are alachlor, atrazine, cyprazine, metribuzin, and trifluralin (Minnesota Agricultural Statistics Service, 1982). The carbamate insecticide aldicarb, used in Minnesota sand plains mainly on potatoes, also is of concern because it is not readily degraded in ground water and has been detected in ground water in several states including Wisconsin, New York, and Florida. Other insecticides and fungicides, as well as other herbicides, are used locally. Ground-water samples were analyzed for only those pesticides most likely to be present. Samples were analyzed for the triazine herbicide group by a test that identifies alachlor, ametryn, atratone, atrazine, cyanazine, cyprazine, metribuzin, prometone, prometryne, propazine, simazine, simeton, simetryne, and trifluralin. Separate analyses also were done for aldicarb.

The Minnesota Department of Health set a limit of 3 μg/L. This concentration is the same as the maximum contaminant level of 3 μg/L for concentrations of atrazine in drinking water proposed by United States Environmental Protection Agency. Atrazine is the pesticide most commonly found in ground water in agricultural areas of Minnesota (Anderson, 1989).

The concentrations of herbicides detected in this study (less than 0.1 to 1.7 μg/L) are less than the recommended limit for drinking water (Minnesota Department of Agriculture, 1988). Although alachlor was the most heavily used herbicide from 1976 through 1981 (Minnesota Department of Agriculture, written commun., 1977; Minnesota Agricultural Statistics Service, 1982), it was detected in only 3 of the 18 samples analyzed for this study. All 18 samples analyzed for pesticides were collected at cultivated sites, 5 at nonirrigated-cultivated sites and 13 at irrigated sites. None of the samples analyzed for pesticides were collected at undeveloped or residential sites. The herbicides detected are listed in table 8.

Table 8.--Herbicides detected in the Anoka Sand Plain aquifer
[--, levels not established]

Herbicide	Number detected from 18 wells	Greatest concentration (micrograms per liter)	U.S. Environmental Protection Agency Primary Drinking-Water Regulation[1] MCLG[2] (micrograms per liter)	MCL[3] (micrograms per liter)
Atrazine	8	1.7	3	3
Cyanazine	6	.2	--	--
Alachlor	3	.2	0	2
Simazine	2	.4	1	1
Metribuzin	2	.2	--	--
Cyprazine	1	.1	--	--

[1] U.S. Environmental Protection Agency, 1986.
[2] MCLG = Maximum Contaminant Level Goal:
A non-enforceable concentration of a drinking water contaminant that is protective of adverse human health effects and allows an adequate margin of safety (U.S. Environmental Protection Agency, 1986).
[3] MCL = Maximum Contaminant Level:
Maximum permissible level of a contaminant in water which is delivered to any user of a public water system (U.S. Environmental Protection Agency, 1986).

Undeveloped Sites

Ground water at undeveloped sites generally had low specific conductance (table 7). The median specific conductance in ground-water samples collected at undeveloped sites is 330 μS/cm (microsiemens per centimeter at 25 degrees Celsius) (table 7).

The median concentrations of sulfate, chloride, and nitrite plus nitrate nitrogen among undeveloped sites are 11, 3.5, and 0.22 mg/L, respectively (table 7). The median concentration of 0.22 mg/L nitrite plus nitrate nitrogen in the water samples from undeveloped sites indicates a minimal effect from human activities; however, water from 4 of the 11 wells at undeveloped sites had nitrite plus nitrate-nitrogen concentrations greater than 3.0 mg/L, indicating human influence even at these apparently natural sites. The elevated nitrite plus nitrate-nitrogen concentrations could result from: (1) land uses upgradient from the undeveloped sites, (2) windblown spray from chemigation in upwind areas, or (3) abandoned farms or former cattle yards (although none are apparent at these sites).

Nonirrigated-Cultivated Sites

The median specific conductance of water samples from nonirrigated- cultivated sites, 300 μS/cm (table 7), is about the same as the median specific conductance for water from undeveloped sites. Median sulfate and chloride concentrations at nonirrigated-cultivated sites are 12 and 5.3 mg/L, respectively. The median concentration of nitrite plus nitrate nitrogen at nonirrigated-cultivated sites, 2.0 mg/L, indicates possible effects of human activities (Madison and Brunett, 1985). Furthermore, 37 percent of 97 samples had concentrations of nitrite plus nitrate nitrogen greater than 3.0 mg/L, and the maximum concentration among the nonirrigated-cultivated sites was 45 mg/L.

Triazine herbicides were present in three of the five samples collected during August 1984 from cultivated-nonirrigated sites (table 9). The sample containing the greatest concentration of pesticide detected during this investigation, 1.7 μg/L of atrazine, came from a nonirrigated-cultivated site.

Table 9.--Concentrations of herbicides in 11 of the 18 water samples collected during August 1984 at cultivated sites

Type of site	Date sample collected	Herbicide and concentration in micrograms per liter
Nonirrigated	08/01/1984	Alachlor, 0.2; atrazine, 0.1; cyanazine, 0.1
	08/29/1984	Cyanazine, 0.1
	08/30/1984	Atrazine, 1.7
Irrigated	08/01/1984	Atrazine, 0.1; cyanazine, <0.1; metribuzin, 0.2
	08/01/1984	Alachlor, 0.1; cyanazine, <0.1; simazine, 0.2
	08/01/1984	Atrazine, 0.1, cyanazine, <0.1; metribuzin, <0.1
	08/01/1984	Atrazine, 0.4
	08/01/1984	Alachlor, 0.1; cyanazine, 0.1; cyprazine, 0.1, simazine, 0.4
	08/29/1984	Atrazine, 0.1
	08/28/1984	Atrazine, 0.5
	08/28/1984	Atrazine, 0.3

Irrigated Sites

Ground-water samples from irrigated sites had a median specific conductance of 580 μS/cm (table 7). The median concentrations of sulfate, chloride, and nitrite plus nitrate nitrogen were 22, 19, and 5.3 mg/L, respectively. These medians all represent significantly greater specific conductances and concentrations than those in water samples from undeveloped sites at the 99-percent confidence level, as determined by analysis of variance and general linear models. Sixty-four percent of 129 samples from irrigated sites had nitrite plus nitrate-nitrogen concentrations greater than 3 mg/L. Triazine herbicides were detected in 8 of the 13 water samples collected from irrigated sites during August 1984. The concentrations detected are reported in table 9.

Residential Sites

Ground-water samples collected at residential sites had a median specific conductance of 560 µS/cm (table 7). The median concentrations of sulfate, chloride, and nitrite plus nitrate nitrogen at residential sites were 20, 26, and 4.2 mg/L, respectively. Although these concentrations are all significantly greater than those found at undeveloped or even cultivated-nonirrigated sites, the only chemical constituent that generally exceeds Minnesota drinking-water standards is nitrite plus nitrate nitrogen. The median sodium and chloride concentrations at residential sites (table 7) are several times greater than those for the other land-use categories. Sodium chloride is the main source of chloride in septic-system effluent and in road salt, both of which affect ground-water quality beneath residential land.

The concentration of nitrite plus nitrate nitrogen in ground-water samples from residential sites exceeded 3.0 mg/L in 56 of 89 samples (63 percent). The possible sources of this nitrite plus nitrate nitrogen are septic systems and lawn fertilizer. Much of the nitrite plus nitrate nitrogen in septic systems is converted by denitrification to nitrous oxide or nitrogen gas and is discharged to the atmosphere. Some nitrogen leaves the septic systems as ammonium ion and is later nitrified or oxidized to nitrite plus nitrate nitrogen in the ground water; thus, some nitrite plus nitrate nitrogen enters the aquifer from septic systems.

The fluctuations of nitrite plus nitrate-nitrogen concentrations at shallow well 032N25W21DAC01 (figure 24) indicate that nitrates come from a source that may not be constant over time. This well is screened from 5 to 7 ft below land surface, and the water table generally is about 2 ft below land surface. The most likely source of nitrite plus nitrate nitrogen is lawn fertilizer, in which the supply of nitrogen fluctuates with times when fertilizer is available for dissolution by precipitation.

The nitrite plus nitrate-nitrogen concentrations in water samples from the deep well shown in figure 24, 032N25W21DAC02, reflect a relatively constant source of nitrite plus nitrate nitrogen and probably represent combined effects of many septic systems and fertilized lawns, effects that are not discernible deeper in the aquifer at this site. The sample from the deep well represents water that probably traveled a substantially greater distance than did water from the shallow well.

Differences Among Land-Use Categories

Correlation coefficients were used to compare data from the undeveloped sites and data from sites where human activities were apparent from land use (agricultural and residential). A correlation coefficient in ground-water-quality analyses can be used to indicate the probability that different water samples or groups of samples have the same source or are related to the same environmental processes. Spearman correlation coefficients for water samples from the Anoka Sand Plain aquifer indicate that specific conductance does not correlate with concentrations of sulfate, chloride, and nitrite plus nitrate nitrogen nor do these constituents correlate with each other among the undeveloped sites. Spearman correlation coefficients at sites where agricultural and residential activities are evident indicate that sulfate, chloride, and nitrite plus nitrate nitrogen have the same source at a 95-percent confidence level. A relation between the concentration of these constituents and human activities is probable. The median concentrations of sulfate, chloride and nitrite plus nitrate nitrogen among undeveloped sites are 11, 3.5, and 0.22 mg/L respectively (table 7).

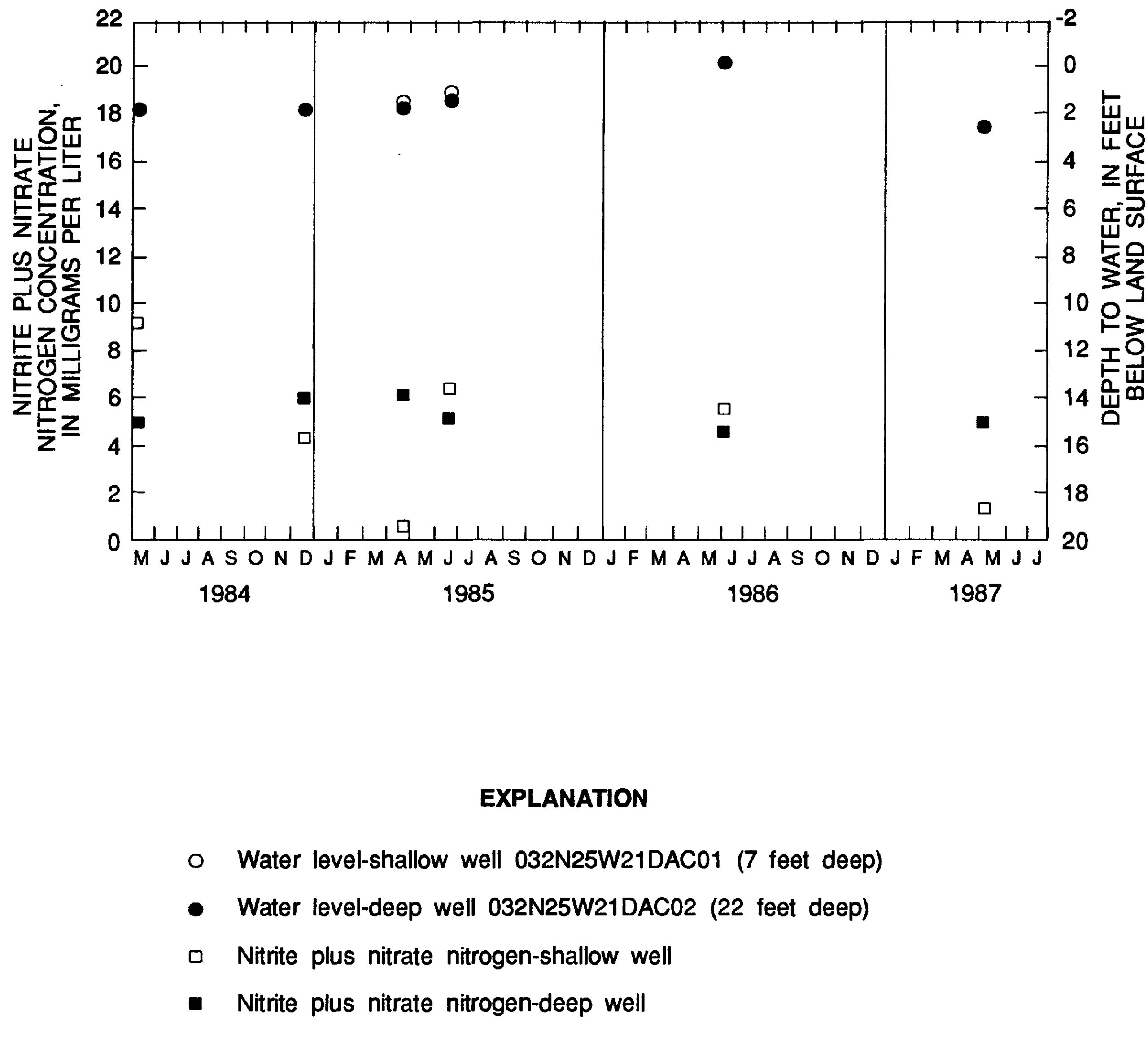


Figure 24.--Water levels and concentrations of nitrite plus nitrate nitrogen (NO_2 + NO_3, as N) in ground water at a well cluster at a residential site in the Anoka Sand Plain aquifer.

The specific conductance of water samples from undeveloped sites (median, 330 µS/cm) and nonirrigated-cultivated sites (median, 300 µS/cm) were not significantly different from each other, nor was specific conductance significantly different between water samples from irrigated sites (median, 580 µS/cm) and residential sites (median, 560 µS/cm); however, specific conductance of samples from undeveloped and nonirrigated-cultivated sites were significantly different from samples from irrigated and residential sites at the 99-percent confidence level.

The differences in water quality among the different land-use categories are illustrated with box plots in figures 25 through 28. The high specific conductances in ground water from irrigated and residential sites result primarily from larger amounts of calcium, magnesium, and bicarbonate in solution. This is caused by an increased amount of water infiltrating to the water table. Infiltration from irrigation and lawn watering combine with precipitation to increase the recharge in irrigated and residential sites. This can increase carbonate dissolution and leaching of fertilizer components. The concentrations of calcium, magnesium, sodium, and potassium (fig. 26) correlate closely with specific conductance (fig. 25) and their distribution among land-use categories is similar to that of specific conductance.

Irrigated sites were expected to show greater concentrations of nitrite plus nitrate nitrogen than other land-use categories but lesser concentrations of sulfate than residential sites near many septic systems. The concentrations of sulfate were greater than other land-use categories at irrigated sites (fig. 27). The reason for greater concentrations of sulfate at irrigated sites may be a result of the type of fertilizer used. Many of the irrigated sites were dairy farms where manure was used in addition to inorganic fertilizer. The manure may be the source for elevated concentrations of sulfate and chloride, as well as excess nitrite plus nitrate nitrogen. Manure was used at fewer nonirrigated sites than irrigated sites. In addition, lesser concentrations of nitrite plus nitrate nitrogen and sulfate at nonirrigated-cultivated sites could result from less water moving downward to transport these constituents to the water table.

General linear models indicated a significant difference in concentrations of chloride between each of the four land-use categories (fig. 27). Interpretation of differences in chloride concentrations is complicated by the number of potential sources. Chloride concentrations are elevated in septic-system discharge and manure; however, chloride also comes from potash fertilizer (potassium chloride) at cultivated sites and from road salt at residential sites. The median concentration of chloride generally increases progressively from undeveloped sites to nonirrigated-cultivated, irrigated, and residential sites (fig. 27).

Low nitrite plus nitrate-nitrogen concentrations (<0.2 mg/L) at undeveloped sites indicate that nitrite plus nitrate-nitrogen concentrations are not elevated regionally throughout the entire Anoka Sand Plain aquifer. Nitrite plus nitrate-nitrogen concentrations at nonirrigated-cultivated sites were significantly greater than concentrations at undeveloped sites, indicating that crop residue could contribute measurable quantities of nitrite plus nitrate nitrogen to ground water. The median concentration of nitrite plus nitrate nitrogen for nonirrigated-cultivated sites is only 2.0 mg/L. These elevated nitrite plus nitrate-nitrogen concentrations indicate that more nitrogen fertilizer is being applied to fields than is being used by the crops. Elevated concentrations of nitrite plus nitrate nitrogen were measured more often from wells on dairy farms where manure is applied to the fields than from wells on farms where commercial fertilizers are mainly used. Water samples collected from wells at dairy farms had concentrations of sulfate, chloride, and nitrite plus nitrate nitrogen that were all substantially above concentrations at undeveloped sites, especially near the water table.

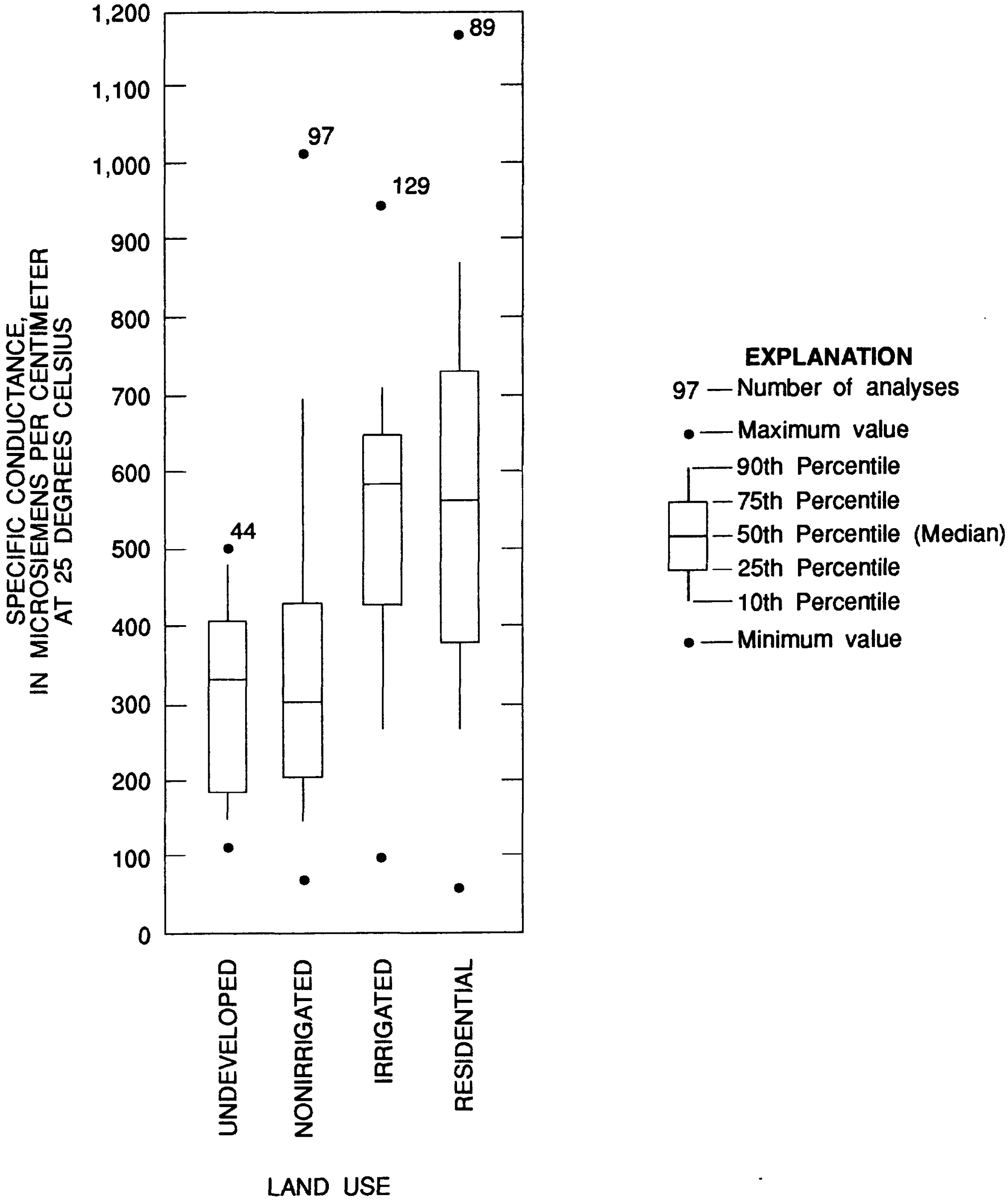


Figure 25.--Specific conductance of ground water at land-use sites in the Anoka Sand Plain.

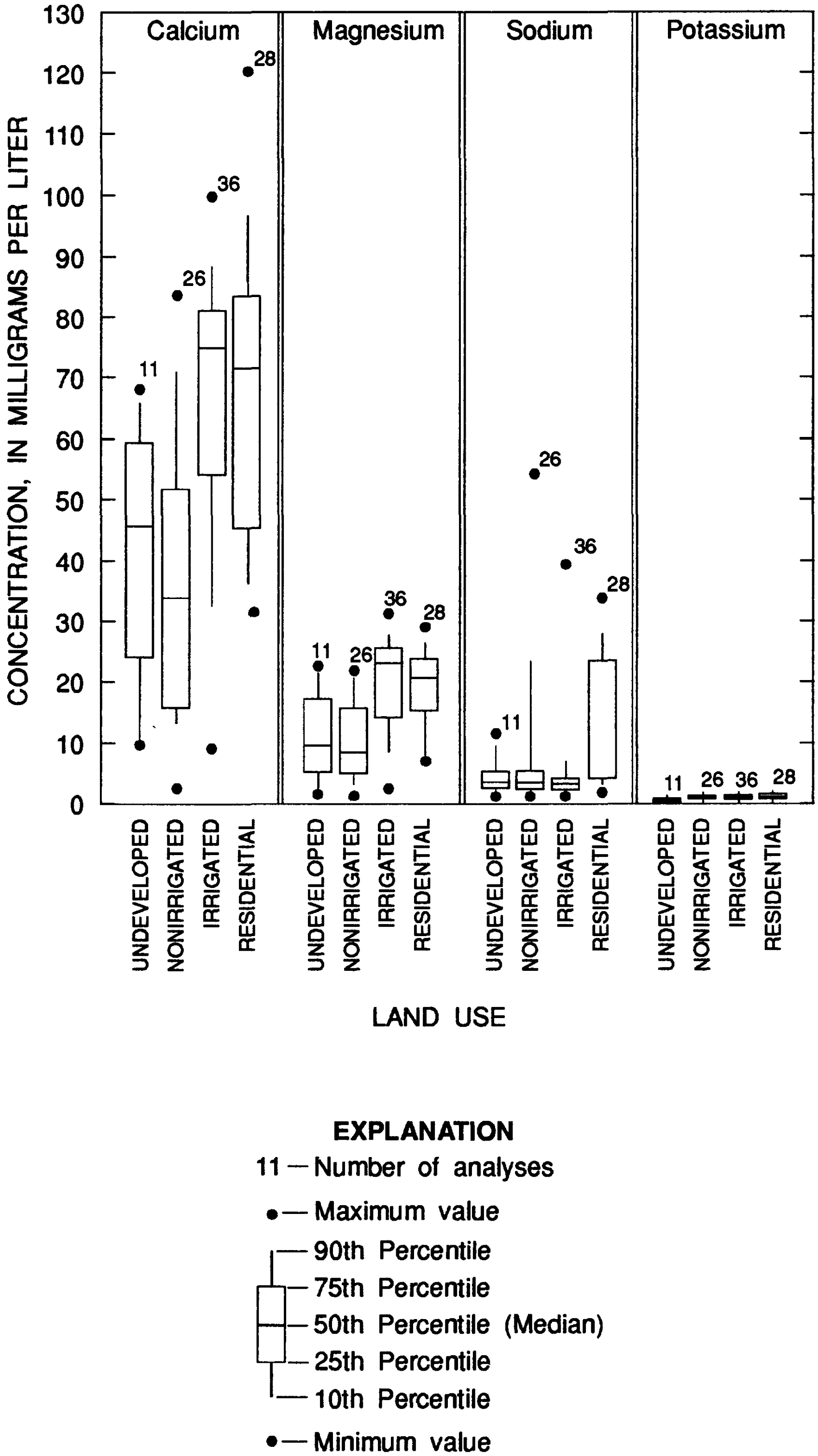


Figure 26.--Concentration of major cations in ground water at land-use sites in the Anoka Sand Plain aquifer.

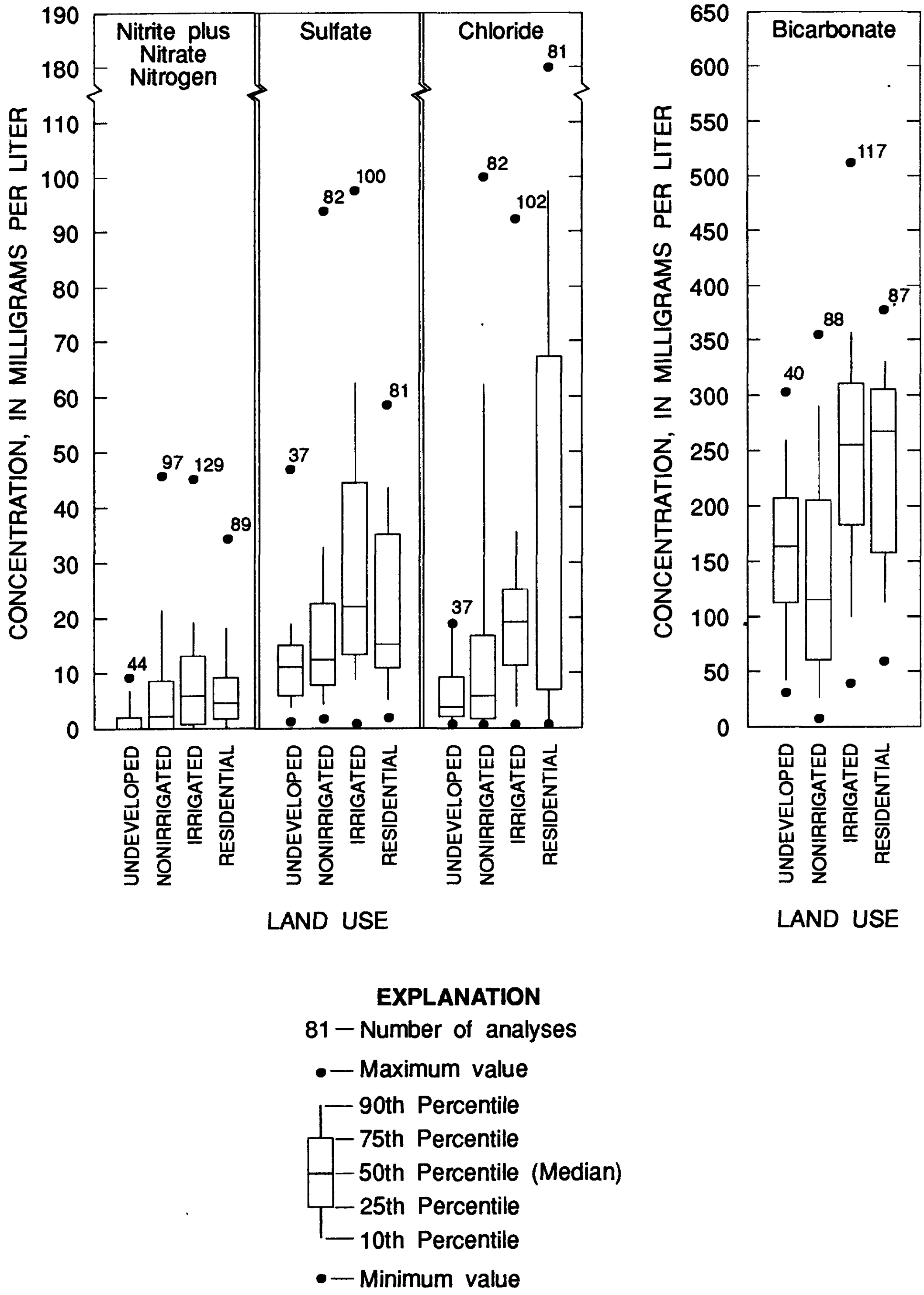


Figure 27.--Concentration of nitrite plus nitrate nitrogen, sulfate, chloride, and bicarbonate in ground water at land-use sites in the Anoka Sand Plain aquifer.

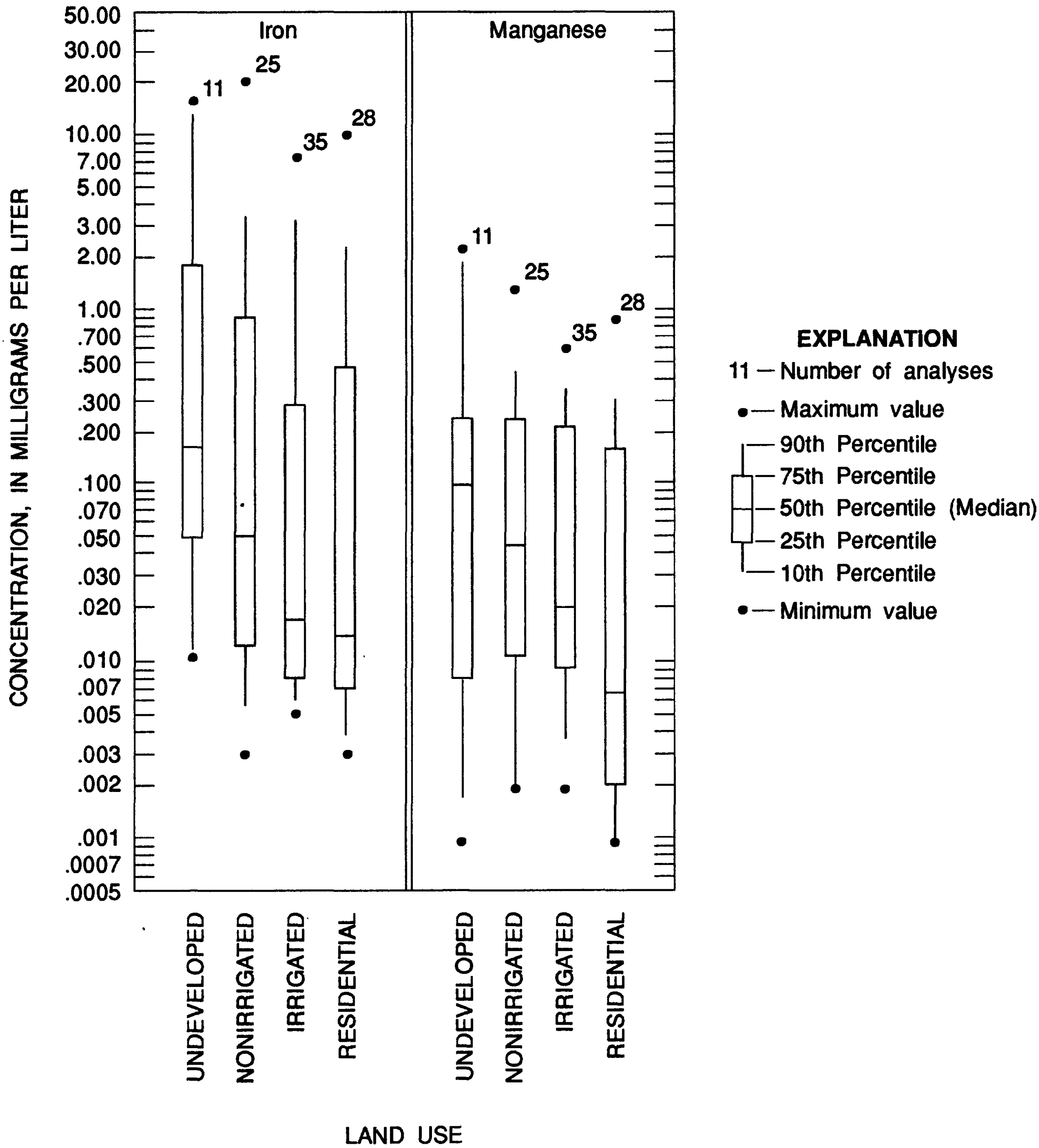


Figure 28.--Concentrations of iron and manganese in ground water at land-use sites in the Anoka Sand Plain aquifer.

The median concentration of nitrite plus nitrate nitrogen at irrigated sites is greater than at nonirrigated-cultivated sites. Ground water at both nonirrigated-cultivated and irrigated sites can be high or low in nitrite plus nitrate-nitrogen concentrations most likely because of differences in the amount and timing of nitrogen applied to the fields upgradient from the well site. The well depth and redox potential in the aquifer also are relevant factors.

The relation of iron and manganese concentrations at the different land-use sites is opposite to the relations of sulfate, chloride, and nitrite plus nitrite plus nitrate nitrogen concentrations (figs. 27 and 28). The lowest concentrations of iron and manganese were found at residential sites, and progressively greater concentrations were found at irrigated sites and nonirrigated-cultivated. The greater iron and manganese concentrations in the study area were found at undeveloped sites. This probably is related to the redox potential of the ground water. A decreased redox potential increases the ability of the ground water to dissolve additional iron and manganese from the sediments that make up the aquifer. Many of the wells representing undeveloped sites were near or downgradient from marshy areas conducive to redox conditions. This proximity to marshes could account for the predominance of redox conditions in the aquifer at undeveloped sites.

SUMMARY AND CONCLUSIONS

Ranges in concentrations of sulfate, chloride, and nitrite plus nitrate nitrogen were large in water from the Anoka Sand Plain aquifer, but differences in the concentrations of most other chemical constituents were small. Elevated concentrations of iron and manganese were detected most commonly at undeveloped sites and appear to be related to differences in redox potential and alkalinity of the ground water.

Differences in specific conductance and in concentrations of sulfate, chloride, and nitrite plus nitrate nitrogen with depth below the water table were measured at 31 well-cluster sites. Concentrations generally were greater near the water table than 10 ft or more below the water table. These vertical differences in water quality within the aquifer indicate no vertical mixing of water is occurring in some areas. In other areas, deep wells had greater nitrite plus nitrate-nitrogen concentrations than did shallow wells. Vertical differences in concentrations of nitrite plus nitrate nitrogen generally were smaller than those of other constituents. These smaller differences indicate vertical mixing of ground water and localized recharge to the aquifer of water low in nitrite plus nitrate nitrogen from ephemeral ponds and drainage ditches. Water from several of the well clusters had elevated nitrite plus nitrate-nitrogen concentrations and showed no difference in concentration of nitrite plus nitrate nitrogen with depth. These well clusters were in areas where periods of pumping and non-pumping from the aquifer causes drawdown and recovery of the water level and results in the mixing of ground water. Relatively steep water-table gradients, which contributed to the mixing of the ground water, also were noted at two of these sites.

Fluctuations in water quality with time are related to the rate and timing of recharge and fertilizer applications in agricultural and residential land. Recharge from snowmelt and spring rains in March and April 1984 was large and resulted in several record-high water levels in the study area. This unusually large amount of recharge flushed soluble nitrates from the soil quickly. The recharge water diluted the concentrations of nitrite plus nitrate nitrogen in ground water at some wells to the lowest nitrite plus nitrate-nitrogen concentrations measured during the study. This recharge of March and April was followed in May and June 1984 by a slug of recharge carrying nitrite plus nitrate nitrogen to the water table from recently applied fertilizer; as a result, nitrite plus nitrate-nitrogen concentrations in the ground water increased.

Sulfate and chloride concentrations fluctuated with time in some individual wells, but median concentrations of sulfate and chloride did not show substantial fluctuations. Concentrations of sulfate, chloride, and nitrite plus nitrate nitrogen are correlated with each other at the 95-percent confidence level beneath areas represented by residential and agricultural land use. This correlation indicates a relation between concentrations of these constituents and human activities. Concentrations of sulfate and chloride consistently are below the Minnesota drinking-water standard of 250 mg/L.

Short-term fluctuations in nitrite plus nitrate-nitrogen concentrations in some wells were as great or greater than the apparent long-term change. These results indicate that seasonal or short-term fluctuations in concentrations of nitrite plus nitrate nitrogen could account, in part, for the apparent long-term increase in nitrite plus nitrate nitrogen. However, median concentrations of nitrite plus nitrate nitrogen in spring 1984, 1985, 1986, and 1987 indicated a general increase in concentration during this study.

Nitrite plus nitrate-nitrogen concentrations at irrigated sites were significantly greater than at nonirrigated-cultivated sites at the 99-percent confidence level. According to these results, irrigated crop production has a significant effect on the concentration of nitrite plus nitrate nitrogen in ground water. The median concentration of nitrite plus nitrate nitrogen was 2.0 mg/L at nonirrigated-cultivated sites and 5.3 mg/L at irrigated sites. Median concentrations of nitrite plus nitrate nitrogen at residential sites with septic systems was 4.2 mg/L. On the basis of large short-term decreases in concentrations of nitrite plus nitrate nitrogen in several wells, it appears that nitrite plus nitrate-nitrogen concentrations can respond rapidly to changes in factors affecting nitrite plus nitrate nitrogen. The relation of elevated nitrite plus nitrate-nitrogen concentrations in the aquifer to the amount of irrigation water and precipitation emphasizes the significance of coordinating the timing of fertilizer application and irrigation.

Triazine herbicides were detected in water from 11 of 18 wells sampled; however, concentrations of herbicides were well below commonly recognized safe levels for drinking water. Further investigation of the presence, distribution, and change in concentration of pesticides is needed to evaluate the seriousness of ground-water contamination by these organic compounds in the Anoka Sand Plain aquifer.

REFERENCES CITED

Anderson, H.W., Jr., 1989, Effects of agriculture on quality of water in surficial sand-plain aquifers in Douglas, Kandiyohi, Pope, and Stearns Counties, Minnesota: U.S. Geological Survey Water-Resources Investigations Report 87-4040, 45 p.

Anderson, H.W., Jr., and Ruhl, J.F., 1984, Geohydrology and hydrochemistry of aquifers in Cretaceous rocks, Minnesota, *in* Jorgensen, D.G., and Signor, D.R., eds., Geohydrology of the Dakota aquifer--Proceedings of the first C.V. Theis Conferences of geohydrology, Lincoln, Nebraska, 1982: National Water Well Association, p. 27-37.

Anderson, H.W., Jr., and Stoner, J.D., 1989, Effects of controlled agricultural practices on water quality in a Minnesota sand-plain aquifer: U.S. Geological Survey Open-File Report 89-267, 2 p.

Cooper, W.S., 1935, The history of the upper Mississippi River in late Wisconsin and post-glacial time: Minnesota Geological Survey Bulletin 26, 116 p.

Crawford, C.G., Slack, J.R., and Hirsch, R.M., 1983, Nonparametric tests for trends in water-quality data using the Statistical Analysis System: U.S. Geological Survey Open-File Report 83-550, 102 p.

Edmunds, W.M., 1973, Trace element variations across an oxidation-reduction barrier in a limestone aquifer, *in* Symposium on Hydrogeochemistry and Biochemistry, Tokyo, 1970, Proceedings: Washington, D.C., The Clarke Company, p. 500-526.

Ericson, D.W., Lindholm, G.F., and Helgesen, J.O., 1974, Water resources of the Rum River watershed, central Minnesota: U.S. Geological Survey Hydrologic Investigations Atlas HA-509, 3 sheets.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice-Hall, 556 p.

Fishman, M.J., and Friedman, L.C., eds., 1989, Methods for the determination of inorganic substances in water and fluvial sediments (3rd ed.): U.S. Geological Survey Techniques of Water-Resources Investigations, Book 5, Chap. A1, 545 p.

Helgesen, J.O., Ericson, D.W., and Lindholm, G.F., 1975, Water resources of the Mississippi and Sauk Rivers watershed, central Minnesota: U.S. Geological Survey Hydrologic Investigations Atlas HA-534, 3 sheets.

Helgesen, J.O., and Lindholm, G.F., 1977, Geology and water-supply potential of the Anoka Sand Plain aquifer, Minnesota: Minnesota Department of Natural Resources, Division of Waters Technical Paper 6, 17 p.

Lindholm, G.F., 1980, Ground-water appraisal of sand plains in Benton, Sherburne, Stearns, and Wright Counties, central Minnesota: U.S. Geological Survey Water-Resources Investigations 80-1285, 103 p., 4 pl.

Lindholm, G.F., Farrell, D.F., and Helgesen, J.O., 1974, Water resources of the Crow River watershed, south-central Minnesota: U.S. Geological Survey Hydrologic Investigations Atlas HA-528, 3 sheets.

Madison, R.J., and Brunett, J.O., 1985, Overview of the occurrence of nitrate in ground water of the United States, *in* U.S. Geological Survey, National Water Summary 1984: U.S. Geological Survey Water-Supply Paper 2275, p. 93-105.

McBride, M.S., 1975, Ground water for irrigation in the Viking Basin, west-central Minnesota: U.S. Geological Survey Water-Resources Investigations 75-23, 48 p.

Minnesota Agricultural Statistics Service, 1982, Pesticides used on Minnesota farms in 1981: Minnesota Agricultural Statistics Service pamphlet, 1 p.

REFERENCES--Continued

Minnesota Department of Health and Minnesota Department of Agriculture, 1988, Pesticides and groundwater: Survey of selected Minnesota wells: Report prepared for the Legislative Commission on Minnesota Resources, February 1988, 55 p.

Minnesota Department of Health, 1991, Health risk assessment: Minnesota Department of Health, vol. 3, p. 19.

Minnesota Pollution Control Agency, 1988, Standards for the protection of the quality and purity of the waters of the State: Minnesota Rules Chapter 7050, 58 p.

Myette, C.F., 1984, Ground-water-quality appraisal of sand-plain aquifers in Hubbard, Morrison, Otter Tail, and Wadena Counties, Minnesota: U.S. Geological Survey Water-Resources Investigations 84-4080, 49 p.

Office of Water Data Coordination, 1977, National handbook of recommended methods for water-data acquisition: U.S. Geological Survey, unpaged.

Shearer, G.B., Kohl, D.H., and Commoner, B., 1974, The precision of determinations of the natural abundance of nitrogen-15 in soils, fertilizers, and shelf chemicals: Soil Science, v. 118, no. 5, p. 308-316.

Spearman, C., 1904, The proof and measurement of association between two things: American Journal of Psychology, v. 15, p. 72-101.

U.S. Environmental Protection Agency, 1986, Quality criteria for water 1986: U.S. Environmental Protection Agency, 440/5-86-001, 402 p.

U.S. Geological Survey, 1986-89, Water resources data for Minnesota-- Volume 2, Upper Mississippi and Missouri River Basins: U.S. Geological Survey Water-Data Reports MN-84-2 to MN-87-2, published annually.

Van Voast, W.A., 1971, Ground water for irrigation in the Brooten-Belgrade area, west-central Minnesota: U.S. Geological Survey Water-Supply Paper1899-E, 24 p.

Woodward, D.G., and Anderson, H.W., Jr., 1986, Hydrogeologic and water-quality characteristics of the Cretaceous aquifer, southwestern Minnesota: U.S. Geological Survey Water-Resources Investigations Report 84-4153, 2 pl.

Wright, H.E., Jr., Ruhe, R.V., 1965, Glaciation of Minnesota and Iowa *in* Wright, H.E., Jr., and Frey, D.G., eds., The Quaternary of the United States: Princeton, N.J., Princeton University Press, p. 29-41.

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