GROUND-WATER-QUALITY APPRAISAL OF SAND-PLAIN AQUIFERS IN HUBBARD, MORRISON, OTTER TAIL, AND WADENA COUNTIES, MINNESOTA

By C. F. Myette

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CONVERSION FACTORS

For use of readers who prefer to use metric units, conversion factors for terms used in this report are listed below:

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/d)
square foot per day (ft^2/d)	0.09290	square meter per day (m^2/d)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
gallon (gal)	0.00378	cubic meter (m^3)
gallon per minute (gal/min)	0.0000630	cubic meter per second (m^3/s)
mile (mi)	1.609	kilometer (km)
acre	0.4047	hectare (ha)
pound per acre (lb/acre)	1.12	kilogram per hectare
micromho per centimeter at 25° Celsius (umho/cm at 25°C)	1.000	microsiemen per centimeter at 25° Celsius (uS/cm at 25°C)

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

$$°F = 1.8°C + 32$$

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ABSTRACT

Water samples were collected periodically from 124 wells completed in sand-plain aquifers in Hubbard, Morrison, Otter Tail, and Wadena Counties, Minnesota, to determine baseline water quality, provide data for evaluation of trends, and to investigate seasonal variations in concentrations of selected chemical constituents during a 3-year study that began in October 1979. Results of the study show that the water is predominantly a calcium bicarbonate type with low to moderate concentrations of dissolved solids (77 to 710 milligrams per liter), and that it generally is suitable chemically for most uses. Concentrations of most constituents are below limits for domestic consumption recommended by the Minnesota Pollution Control Agency and the U.S. Environmental Protection Agency. Concentrations of nitrite plus nitrate nitrogen, iron, and manganese in localized areas, however, exceed the recommended limits. Comparison of current data to historical data indicates that concentrations of nitrite plus nitrate nitrogen and chloride have increased in local agricultural areas.

Data indicate that concentrations of certain chemical constituents vary seasonally and annually with changes in ground-water levels. This relationship suggests that chemicals infiltrate the land surface and percolate to the water table during major recharge events.

Site-specific investigations at the Staples Irrigation Center near Staples, Minnesota, indicate that, in addition to seasonal variation, nitrite plus nitrate nitrogen and chloride concentrations decreased with depth while iron concentrations increased. Although no direct quantifiable relationship between concentration and depth was found, mean nitrite plus nitrate nitrogen and chloride concentrations were both 15 milligrams per liter near the top of the aquifer and were 0.1 and 3.5 milligrams per liter, respectively, near the bottom; mean concentrations of dissolved iron were 460 ug/L near the top of the aquifer and 3840 ug/L near the bottom. Data show that the stratification with depth of nitrite plus nitrate nitrogen, chloride, and iron exists at least several hundred feet from the source area throughout most of the year. Chemical stratification appears to be greatest during periods of little recharge.

INTRODUCTION

Sand-plain aquifers in west-central Minnesota are the principal source of freshwater for most domestic, industrial, and agricultural needs. In the past decade, population growth and rapid development of lands for irrigation have greatly increased the demand for water. In Otter Tail County, for example, irrigated acreage during 1970 to 1977 increased more than tenfold (4,328 to 45,878 acres). Similar increases have taken place in Hubbard, Morrison, and Wadena Counties. An increase in wastes (barn-yard and sewage effluents) and contaminants (agricultural and industrial chemicals) discharged to the ground-water system often accompanies this growth. Water recharging the aquifer from precipitation and irrigation return is the major factor in transporting chemicals to the water table. The sand-plain aquifer, which is highly permeable, is highly susceptible to contamination.

In 1979, a cooperative program between the Minnesota Pollution Control Agency and the U.S. Geological Survey led to the development of a network of wells to assess regional ground-water quality in the major aquifers of the State (Hult, 1979). The network, however, lacks detail in areas of rapid and intensive development of land and water supplies. As a result, personnel from the local Soil and Water Conservation Districts, the State Irrigators Association, and the Staples Irrigation Center requested technical assistance to establish a network for assessing the regional quality of ground water in the sand-plain aquifers in Hubbard, Morrison, Otter Tail, and Wadena Counties.

Purpose and Scope

The purpose of the 3-year study was to establish a network for monitoring ground-water quality in the four-county area that would be adequate to (1) assess the areal and seasonal variability in the quality of water in sand-plain aquifers, (2) determine historical trends in ground-water quality (by comparison of current and previous chemical analyses), and (3) determine the characteristics of movement of selected chemicals (solute transport) in the sand-plain aquifers.

The scope of this study was limited to a regional evaluation of nonpoint-source pollution and to evaluation of the transport of selected chemical constituents near an experimental agricultural field. Sampling of water regionally was from private wells completed in the sand-plain aquifer. At the Staples Irrigation Center near Staples, Minn., however, the U.S. Geological Survey installed nested wells to collect water samples upgradient and downgradient from the experimental field. All the regional data and some data from the Staples Irrigation Center were collected during previous investigations as referenced in the text.

This report is a regional assessment of ground-water quality of sand-plain aquifers within the study area. This, along with the accompanying basic-data report, provides baseline data for use in future assessments and for development of a monitoring network that will be used to determine future changes in ground-water quality.

Previous Investigations

The earliest account of the geology of the area was by Winchell and Upham (1888). A later study by Allison (1932) provided the first discussion of ground water and its relationship to the local geology. Leverett (1932) provided more detailed reports of the glacial geology. Recent regional hydrological studies were prepared as part of the statewide Hydrologic Investigations Atlas series by Winter and others (1969), Lindholm and others (1972), and Helgesen and others (1975). Comprehensive ground-water appraisals of the local sand-plain aquifers were made by Jones and others (1963), Lindholm (1970), Reeder (1972), Helgesen (1973; 1977), and McBride (1975). Hult (1979) included the four-county area in a water-quality-sampling network designed for the Minnesota Pollution Control Agency, which lead to systematic statewide annual sampling and publication of data (Minnesota Pollution Control Agency, 1978).

Study Area

The study area consists of sand plains in Hubbard, Morrison, Otter Tail, and Wadena Counties in west-central Minnesota (fig. 1). The combined areal extent of the sand plains is approximately 1,850 mi^2. Soils, generally quite thin (less than a foot thick), are classified as loamy sands or sandy loams. Major use of the land is farming, with corn, potatoes, and soybeans as the primary crops. At present, no large-scale urbanization has taken place. Recent major land development has been for irrigation.

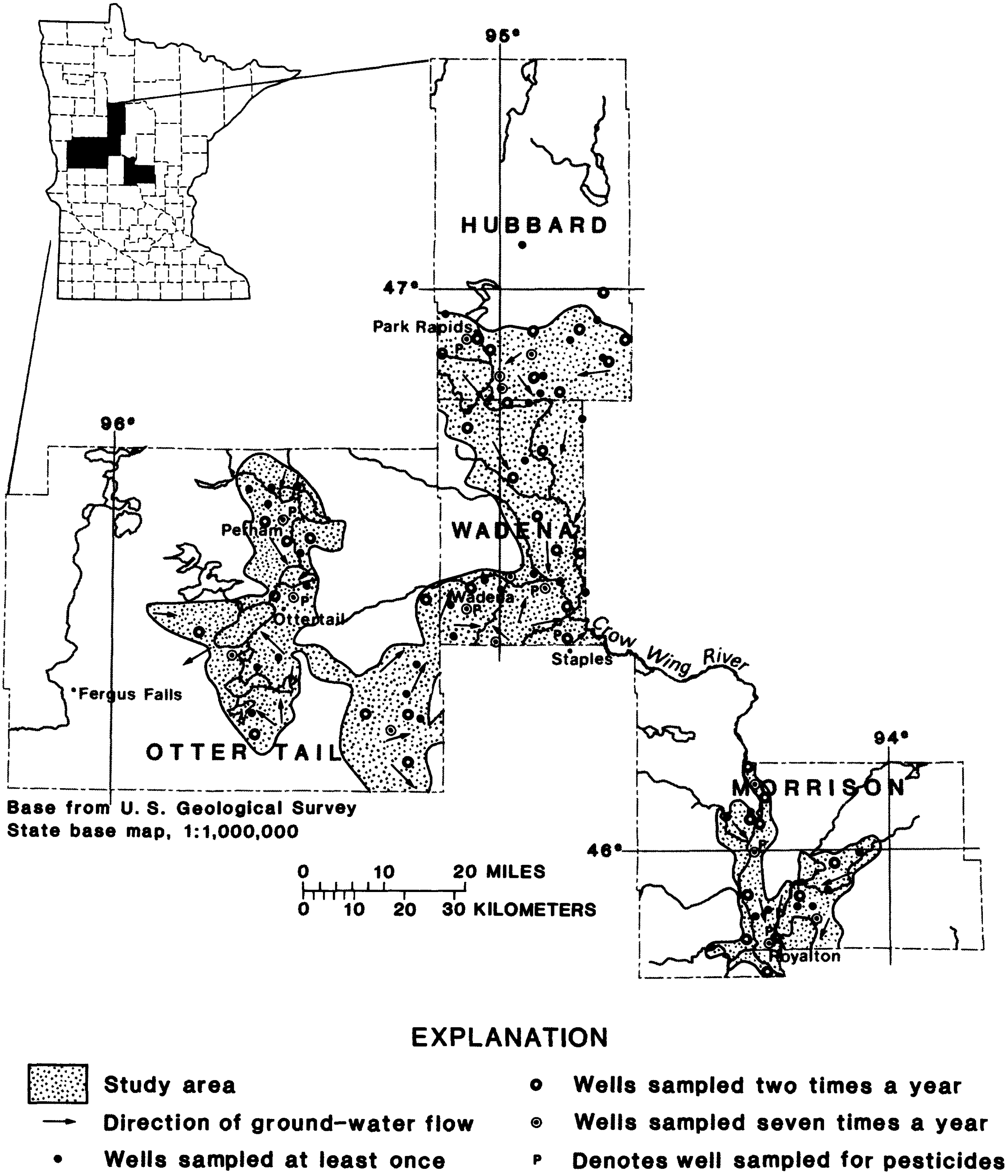
Mean annual precipitation is 26 inches, of which an average of 5 inches recharge the aquifer system (Helgesen, 1977, p. 2). Major watersheds in the study area are the Otter Tail, Crow Wing, and Mississippi-Sauk.

The solute-transport study was performed on an experimental field at the Staples Irrigation Center in southeast Wadena County. The soils are thin and are classified as loamy sand. The area is within the Crow Wing watershed.

WELL-NUMBERING SYSTEMS

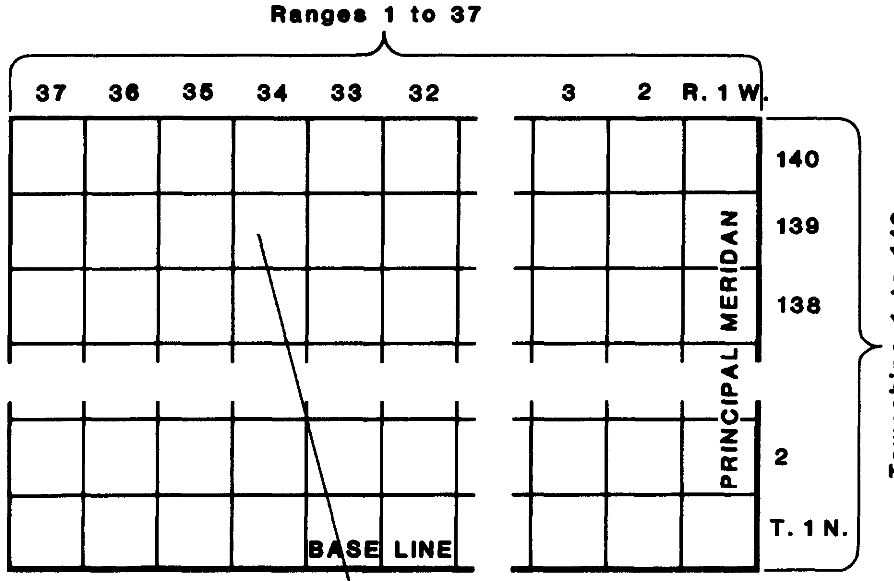
Wells used in this study are identified in three ways. The first system consists of a 15-digit station number. The first 13 digits are the latitude and longitude coordinates of the well. The last 2 digits are sequential numbers used to differentiate between closely spaced wells that for practical purposes have the same latitude and longitude. This system is used primarily to code well data for storage and retrieval in computer systems of the University of Minnesota, Environmental Protection Agency, and U.S. Geological Survey.

Wells also are identified by a local well-location number based on the township, range, and section system (fig. 2). Local well numbers consist of the township, range, and section numbers followed by uppercase letters, A, B, C, or D that locate the well within the section. The first letter following the section number denotes the quarter section, or 160-acre tract, the second denotes the quarter-quarter section, or 40-acre tract, and the third denotes the quarter-quarter-quarter section, or 10-acre tract. A sequential number at the end of the local well number distinguishes wells within the same 10-acre

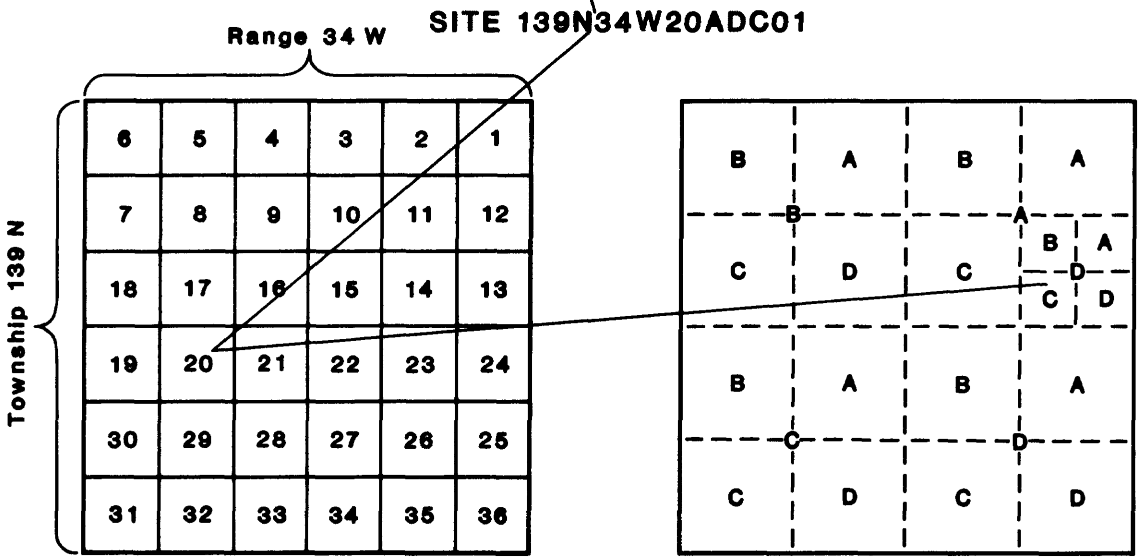


Base from U. S. Geological Survey
State base map, 1:1,000,000

Figure 1.--Areal extent of the sand plains and approximate location of the wells sampled in Hubbard, Morrison, Otter Tail, and Wadena Counties, Minnesota



(a) Representation of townships 1 to 140 and ranges 1 to 37



(b) Subdivision of a township into 36 sections

(c) Successive quartering of a section into 160, 40, and 10 acre parcels

Figure 2.--Well numbering system

tract. Figure 2 shows well 139N34W20ADC01 to be in the SW¼SE¼NE¼, sec. 20, T. 139 N., R. 34 W., and the sequential number shows it to be the first well. This identification system, which is familiar to most property owners, is the principal system used in this report.

The 18 wells drilled for this study at Staples Irrigation Center are identified locally by a third system. Each well is identified by a prefix letter "S" followed by a sequential number from 1 through 18 in the order in which the wells were drilled.

Acknowledgments

The U.S. Geological Survey would like to take this opportunity to thank all the property owners for their cooperation and use of their wells. We would also like to thank the Morrison County Soil Conservation Service for the use of their equipment, and Greg Cox of Morrison County for his work in collection and field testing of the samples. Appreciation is extended to Professor Alf Caldwell and Gregory Buzicky of the University of Minnesota, St. Paul, for cooperating in research at the Staples Irrigation Center. Appreciation is also extended to the Soil and Water Conservation Districts of Hubbard, Morrison, Otter Tail, and Wadena Counties and the Minnesota Department of Natural Resources for their support of this project.

HYDROGEOLOGY

Four-County Area

The predominant geologic formations are crystalline basement rocks of Proterozoic age, sedimentary rocks of Cretaceous age, and glacial drift of Quarternary age.

Crystalline basement rocks underlie the entire area. Depth to these rocks ranges from zero where metamorphic slate crops out in southern Wadena County (Allison, 1932, p. 231) to about 600 feet where granite underlies drift in Hubbard County (Helgesen, 1977, p. 2). These rocks are generally considered to be poor aquifers owing to their low porosity and permeability. Yields of wells in the crystalline rocks are greatest where the rocks are weathered and fractured; they rarely exceed 10 gal/min.

Sedimentary rocks of Cretaceous age, present in parts of the area (Allison, 1932, p. 231), are composed of a conglomerate of marine deposits and are discontinuous, generally thin, and of low permeability. Yields from wells completed in the Cretaceous rocks are generally less than 10 gal/min.

Glacial deposits (drift) overlie the crystalline basement rocks and cover nearly all the area. These deposits are composed of till (unsorted silt, clay, sand, and boulders) and outwash (stratified sand and gravel). The drift ranges in thickness from 0 ft in southern Wadena County (Allison, 1932, p. 231) to more than 600 feet in parts of Hubbard County (Helgesen, 1977, p. 2). Generally, the outwash (particularly in the sand-plain areas) has the greatest potential for ground-water development. Figure 1 shows the areal extent of sand-plain deposits and the general direction of ground-water flow as modified from Jones and others (1963), Lindholm (1970), Reeder (1972), Helgesen (1973; 1977), and McBride (1975). Saturated thicknesses of the deposits range from 0 ft to more than 100 ft. Yields greater than 4,000 gal/min are available locally from wells completed in the sand-plain aquifers (Helgesen, 1977, p. 16). Recharge to the sand-plain aquifers varies regionally, but averages about 5 inches annually (Helgesen, 1977, p. 22). Because of the sandy topsoil, infiltration rates are high.

The chemical and hydraulic characteristics of the major sand-plain aquifers in each of the four counties have been studied previously by the U.S. Geological Survey. For additional hydrologic detail, the reader is referred to the reports listed in the "Previous Investigations" section.

Staples Irrigation Center

The Staples Irrigation Center, located about 5 miles northwest of Staples, is part of the Staples Area Vocational Technical Institute. The sand-plain aquifer at Staples Irrigation Center is comprised of glacial sand and gravel outwash overlain by Sverdrup loamy sand and underlain by gray sandy till. Average thickness of the sand-plain aquifer is 30 ft. Average depth to water is about 10 ft. Direction of ground-water flow is generally northeastward to the Crow Wing River, which is the discharge boundary. Table 1 shows a representative lithologic log describing the deposits at the Staples Irrigation Center. Table 2 lists the hydraulic characteristics derived from an aquifer test a quarter mile north of the experimental plot (Tom Scherer, University of Minnesota, written commun., 1980).

Table 1.--Representative lithologic log of the sand-plain aquifer at Staples Irrigation Center

[Land-surface altitude is 1290 feet above the National Geodetic Vertical Datum of 1929]

Depth (ft)	Lithologic description	Thickness (ft)
0-1	Topsoil (loamy sand)	1
1-12	Sand, fine to medium	11
12-22	Sand, fine to coarse, predominately medium	10
22-28	Sand, fine to coarse, slightly silty	6
28-30	Sand, fine to coarse, very silty	2
30-34	Till, sandy, gray	>4

Table 2.--Hydrologic properties of the sand-plain aquifer as determined by an aquifer test at Staples Irrigation Center

Hydrologic property	
Saturated thickness (ft)	30
Transmissivity (ft^2/d)	9800
Average hydraulic conductivity (ft/d)	325
Ratio of horizontal to vertical hydraulic conductivity	9.8:1
Storage coefficient	0.185
Horizontal hydraulic gradient, before pumping ft/ft	0.001083
Vertical hydraulic gradient, before pumping ft/ft	0.001428

DESIGN OF THE SAMPLING NETWORKS

Four networks were established for sampling regional water quality in the sand-plain aquifers as follows: (1) baseline, (2) biannual, (3) seasonal, and (4) pesticide. Results of the field and laboratory analyses of samples collected from wells in each network are found in the report by Myette (1982). Figure 1 shows the approximate location of the sampling sites.

A baseline network of 106 domestic wells was established to provide information on the regional distribution of selected common chemical constituents. It provides a data base to which future data can be compared to detect water-quality trends. One set of water-quality samples was collected from each well during late summer or early fall 1979. Criteria for selecting wells in the baseline network are outlined in table 3 and the number of wells selected per county is listed in table 4.

Prior to sampling, each well was pumped with a peristaltic pump until several well-bore volumes of water had been removed and field values of pH, specific conductance, and temperature had stabilized. Water samples were appropriately filtered and preserved, then shipped to the U. S. Geological Survey Central Laboratory in Doraville, Ga. Laboratory analyses were performed to measure specific conductance and pH, and to quantify total alkalinity, dissolved solids, and dissolved forms of calcium, magnesium, sodium, potassium, carbon dioxide, sulfate, chloride, fluoride, nitrite plus nitrate nitrogen, ammonia nitrogen, phosphorus, boron, iron, and manganese. Calculations were made for the sum of dissolved constituents, percent sodium, and sodium-adsorption ratios. Samples for physical properties and chemical constituents were collected and determined by the methods of Goerlitz and Brown (1972) and by Skougstad and others (1979).

Table 3.--Summary of criteria for selection of network wells

[X, criterion is important to network design]

Criteria	Sampling requirement of selected network wells			
	Baseline network	Biannual network	Seasonal network	Pesticide network
1. Wells were free of local contamination sources, such as feedlots and septic tanks.	X	X	X	X
2. Wells were selected in areas both upgradient and downgradient from present and potential (as dictated by present development and aquifer capabilities) pumping centers and from agriculturally developed and undeveloped areas.	X	X	—	—
3. Wells were selected within areas of present and potential development.	X	X	X	X
4. Preference was given to wells with credible historical water-quality data.	X	X	X	X
5. Wells were selected in areas not covered by the above criteria.	X	X	—	—

Table 4.--Number of wells sampled for each network by county

County	Number of wells for network			
	Baseline	Biannual	Seasonal	Pesticide
Hubbard	22	14	4	2
Morrison	29	14	4	2
Otter Tail	30	14	4	2
Wadena	25	14	4	2
Total	106	56	16	8

The network of wells to be sampled biannually was established to determine concentrations of selected chemical constituents at the beginning and end of the annual growing cycle, which usually correspond to periods of high and low ground-water recharge. The wells were sampled in May and September from 1979-81. The network, consisting of 56 wells, was selected from the 106 wells in the baseline network. Criteria for selecting the biannual network wells are outlined in table 3 and the number of wells selected by county is listed in table 4. Field measurements were made for specific conductance, pH, and temperature. Laboratory analyses determined the concentrations of dissolved forms of calcium, chloride, nitrite plus nitrate nitrogen, and iron. Methods of sample collection and techniques of physical and chemical analyses were the same as those used for the baseline network as outlined by Goerlitz and Brown (1972) and Skougstad and others (1979).

Seasonal changes in water quality were defined by sampling 16 of the biannual-network wells 7 times a year for 2 years. The sampling periods were February, May, June, July, August, September, and November, inclusive of 1980 and 1981. Techniques of analysis, methods of collection, and physical properties and chemical constituents analyzed for samples from the seasonal network were the same as those for the biannual network.

Eight of the 16 seasonally sampled wells were sampled for orthophosphate insecticides and triazine herbicides. Because of the cost of pesticide analyses, the wells were only sampled once during the study in November 1980. Methods of collection and laboratory analyses were those outlined in Goerlitz and Brown (1972). The November sampling period was chosen to allow several months after application for the chemicals to biodegrade and (or) enter the aquifer system. A single sample, however, represents only an instantaneous measurement of regional water quality. Chemical concentrations will change seasonally as well as annually.

The variation in concentrations of selected constituents within an aquifer was monitored by constructing a series of nested wells near a ¼-acre field to which irrigation water and fertilizers were applied. The field, located at the Staples Irrigation Center, was selected to (1) complement research being done at an experimental plot by personnel from the University of Minnesota, and (2) take advantage of results from previous studies by the University and by Lindholm (1970) in which the area was instrumented and the hydrogeology was documented.

Research conducted concurrently by the University at the experimental plot was headed by Professor Alf Caldwell and by Gregory Buzicky and involved the study of nitrogen distribution in soils and ground water under irrigated conditions. A nitrogen cycle for potato crops was developed that traced nitrogen concentrations from the soil surface to the water table. Fertilizer was applied at the equivalent rate of 300 lb/acre of ammonium chloride (NH_4Cl) and calcium nitrate [$Ca(NO_3)_2$]. Three equal allotments of 100 lb/acre were applied on April 30, May 27, and June 9, 1980. For further details of the University's research, the reader is referred to Gerwing and others (1979) and Buzicky (1982).

The observation-well network at the Staples Irrigation Center consisted of 18 wells in 6 groups of 3 wells each, called nests. The criteria for placement of the wells were:

1. Nests of wells to be placed both upgradient and downgradient from the experimental plot, and at least one group to be placed within the experimental plot.

2. Within each nest, one well to be screened near the top of the aquifer, one near the middle, and one near the bottom of the aquifer.

3. Distance between the farthest well groups (nests) downgradient of the experimental plot not to exceed the average annual distance of horizontal ground-water flow.

4. Alignment of wells to parallel the direction of ground-water flow.

Field and laboratory analyses included specific conductance, pH, temperature, and the dissolved forms of calcium, chloride and nitrite plus nitrate nitrogen. Samples were collected and analyzed by the methods of Skougstad and others (1979). Water levels were measured prior to pumping. Each well was sampled 12 times from May 1980 to May 1981. The sampling frequency was timed to collect samples during periods of different recharge rates. Samples for pesticides were collected in November 1980 from well S-15. Methods of collection and analysis were those of Goerlitz and Brown (1972). Sampling dates and field and laboratory results can be found in the report by Myette (1982) listed as S-1 through S-18 in Wadena County. Figure 3 is a diagram showing the layout of the experimental plot, approximate location of observation wells, and approximate direction of ground-water flow.

Figure 4 illustrates the arrangement of a representative well nest. S-1 is screened near the bottom of the aquifer, S-2 is screened near the middle of the aquifer, and S-3 is screened near the water table. Well construction is of 1¼-inch-diameter black steel pipe with a 2-ft-long (0.010-in. opening) sandpoint. Each group of wells was installed in a similar manner.

The maximum spacing between the experimental plot and the farthest downgradient well nests was determined by calculating the average ground-water velocity and multiplying by 365 days. From the equation found in Lohman (1979, p. 10) the average ground-water velocity can be approximated by:

$$\overline{V} = \frac{K\ dh/dl}{\theta}$$

where

$\overline{V}$ = average velocity in ft/d;

K = hydraulic conductivity in ft/d;

dh/dl = hydraulic gradient in ft/ft; and

θ = effective porosity, as a decimal fraction.

At the experimental plot at the Staples Irrigation Center, the average ground-water velocity was estimated to be 1.17 ft/d as follows:

$$\overline{V} = \frac{(325)(0.001083)}{0.3} = 1.17 \text{ ft/d}$$

and the maximum separation between the experimental plot and the farthest well nest should not exceed:

$$TS = 1.17 \times 365 = 428 \text{ feet}$$

Maximum separation between the experimental plot and the farthest well groups downgradient, therefore, was set at less than 400 feet so that changes occurring between them could be detected. Figure 5 is a geologic section of the aquifer system showing the approximate altitude of the observation well nests and the distances between nests.

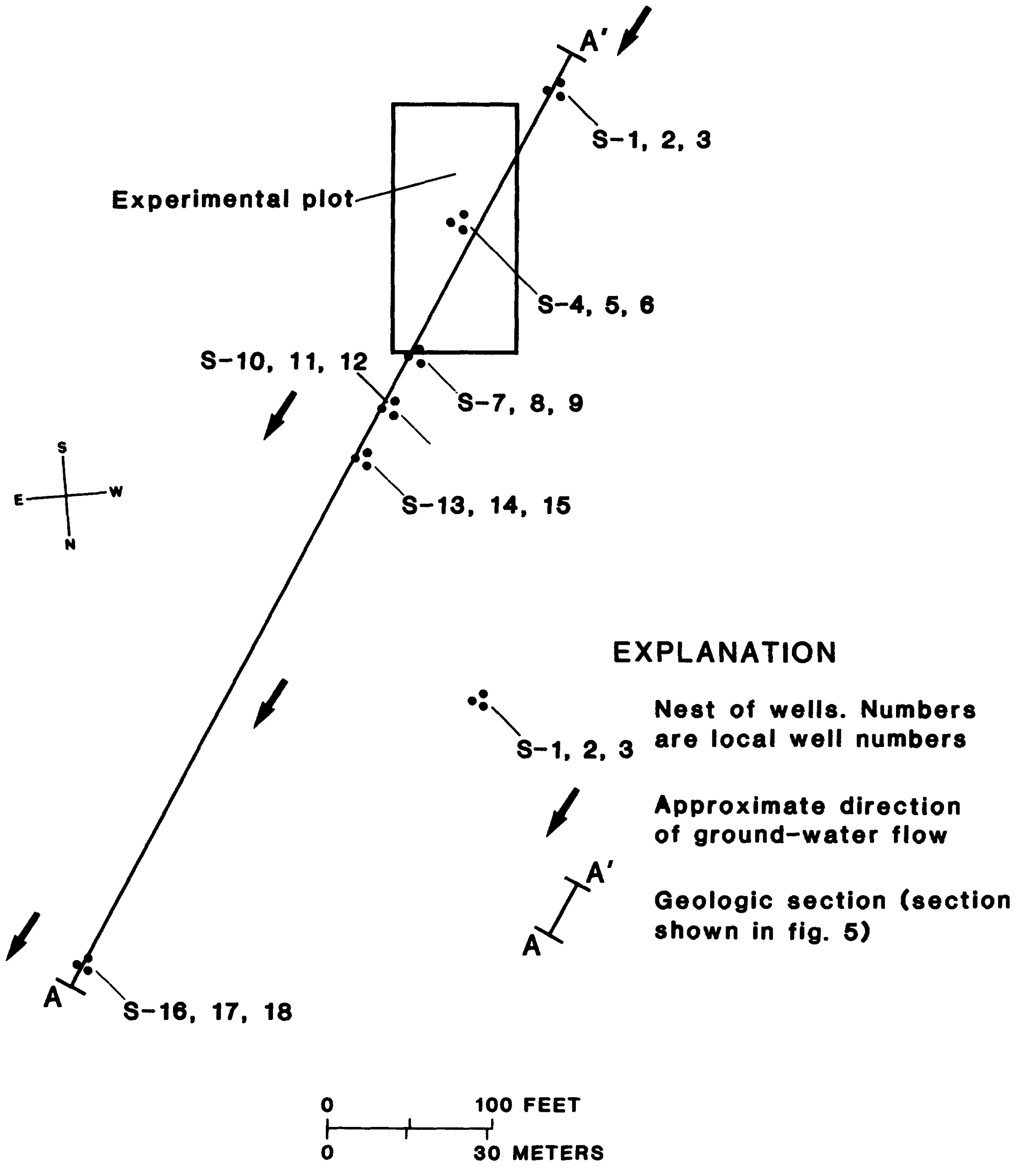


Figure 3.--Schematic of experimental plot at Staples Irrigation Center near Staples, Minnesota, and approximate location of observation wells

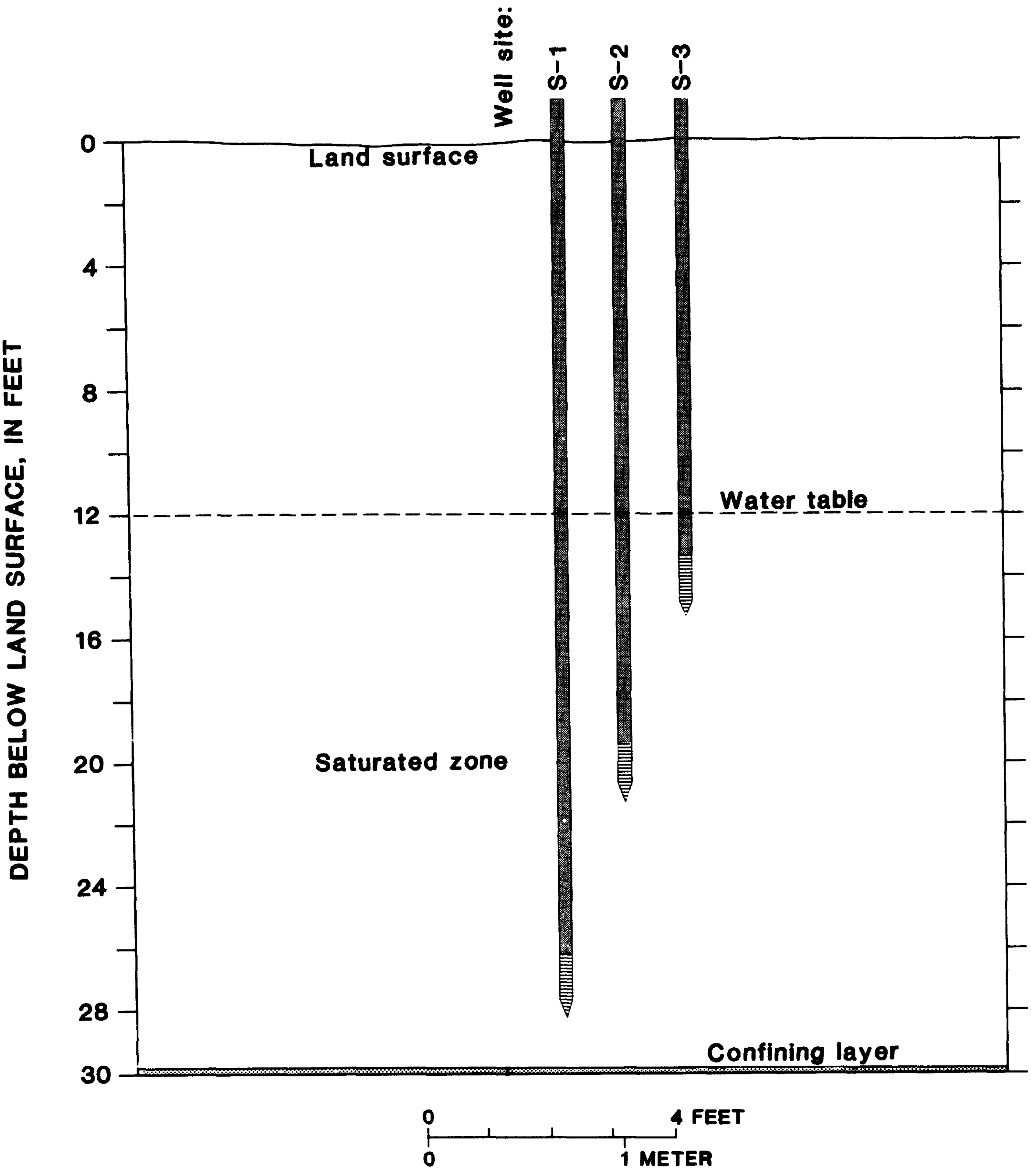


Figure 4.--Representative arrangement of well-nest at Staples Irrigation Center

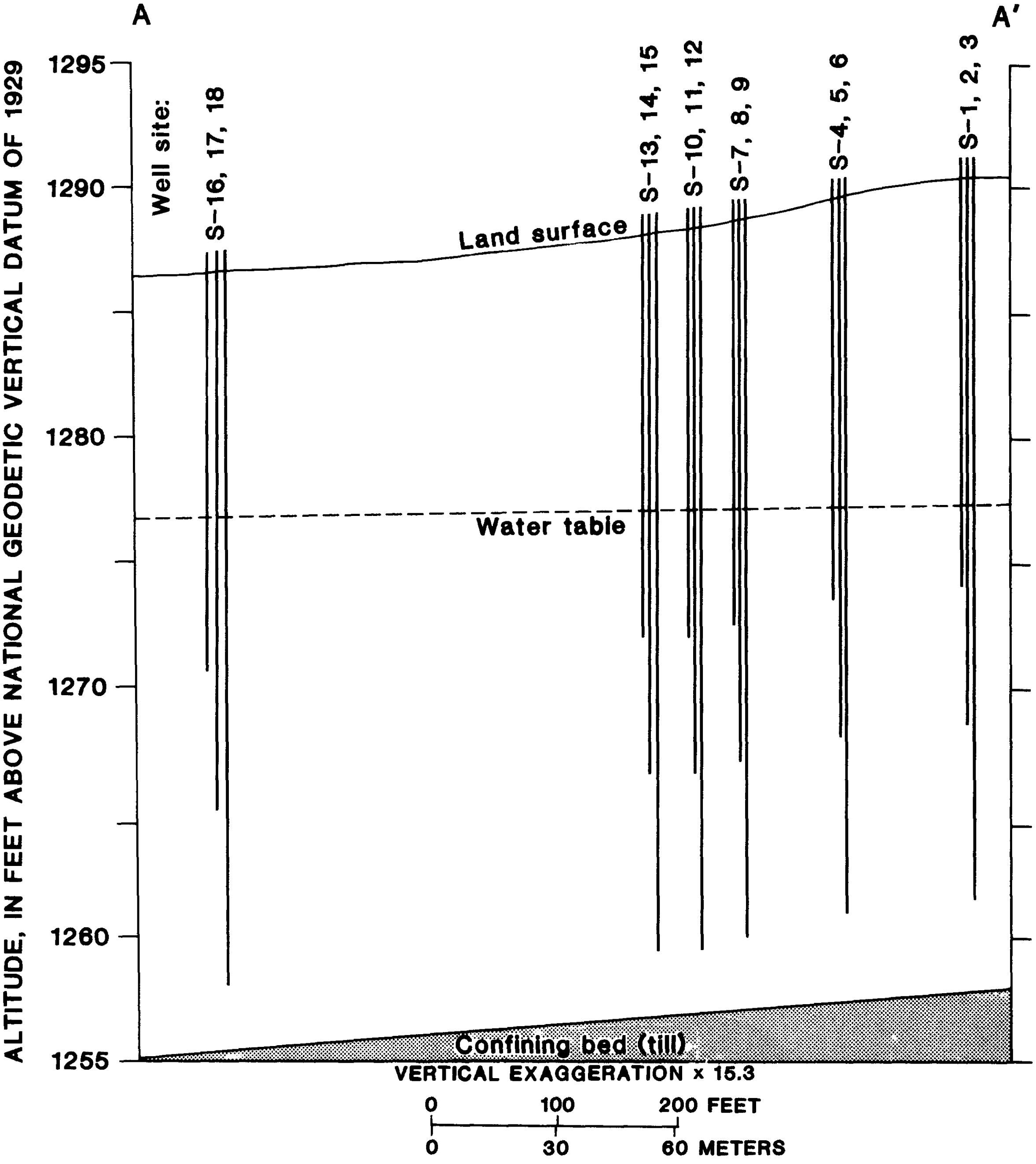


Figure 5. Hydrologic section of experimental plot at Staples Irrigation Center

WATER QUALITY

The chemical composition of water in the sand-plain aquifer is influenced by the material through which it moves. The degree of influence depends largely on residence time and chemical composition of the aquifer material. In sand-plain areas, because of high infiltration rates of the sands, chemical and petroleum spills, excessive application of fertilizers and pesticides, and discharge of wastes to the ground can readily alter the quality of ground water.

The chemical composition, of water primarily determines its suitability for an intended use. In Minnesota, the most stringent quality standards are applied to water used for domestic consumption and food processing. Limits for selected chemical constituents in water used for domestic consumption are discussed in the discussion of results section of the text. Standards for other water uses such as fisheries, recreation, and agriculture are available from the Minnesota Pollution Control Agency. The water in the sand-plain aquifers is a calcium bicarbonate type that is suitable for most uses.

Baseline Network

Table 5 is a statistical summary of results of analyses for selected chemical constituents for the first sampling period of each well in the four-county area. Statistical analyses were based on the concentration of each of the constituents, except as noted.

Chloride, an element essential to both plants and animals, can be toxic in excessive concentrations (Gough and others, 1979, p. 17). Fertilizers, road-deicing salts, and sewage effluent can contribute chloride to the environment. The limit recommended by the Minnesota Pollution Control Agency (1978, p. 12) for domestic consumption is 250 mg/L. Chloride concentrations of all samples ranged from 0.3 to 180 mg/L. The mean and median concentrations were 14 mg/L and 9.1 mg/L, respectively, indicating that variation exists in the sample group but that most of the concentrations are fairly low.

Dissolved solids can incrust well screens, depending on the concentrations and types of dissolved solids. The Minnesota Pollution Control Agency's (1978, p. 12) recommended limit of dissolved solids for domestic consumption is 500 mg/L. Concentrations of dissolved solids ranged from 77 to 710 mg/L and exceeded the recommended limits in several locations. The mean and median concentrations were 280 mg/L, indicating that the sample group is normally distributed and, therefore, is fairly representative of dissolved-solids concentrations throughout the study area. Within the study area, the dissolved-solids concentrations exhibit an increasing trend from east to west similar to that observed by Henry Anderson (U.S. Geological Survey, written commun., 1983) in water from the underlying Cretaceous and Precambrian aquifers. Locally, the water may need to be treated for domestic or industrial use.

Table 5.--Statistical summary of the 106 baseline-network results of selected chemical constituents for Hubbard, Morrison, Otter Tail, and Wadena Counties, Minnesota, 1979

	Depth of well, total (ft)	Specific conductance (umho)[1]	pH[2]	Temperature (deg C)	Hardness, (mg/L as (CaCO$_3$)	Hardness, noncarbonate (mg/L CaCO$_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Percent sodium
Standard deviation...	26	169	1.3	1.8	127	41	24	7.0	7.5	5.2
Mean..................	40	450	7.5	9.7	180	34	62	16	6.9	3.1
Median...............	30	450	7.5	9.5	210	25	62	17	4.4	2.0
Maximum..............	108	1050	8.3	19	480	240	130	38	50	49
Minimum..............	10	140	6.8	6.5	52	0	16	3.0	1.1	0.1

	Sodium adsorption ratio	Sodium + potassium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Alkalinity, (mg/L as CaCO$_3$)	Sulfate, dissolved (mg/L as SO$_4$)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO$_2$)	Dissolved solids, residue at 180°C (mg/L)
Standard deviation...	0.2	8.0	7.5	94	10	23	0.03	8.8	113
Mean..................	.2	7.9	3.8	180	4.2	14	.1	12	280
Median...............	.1	5.4	1.5	200	0.1	9.1	.1	14	280
Maximum..............	2.1	54	38	360	89	180	.2	33	710
Minimum..............	0.0	2.2	0.3	64	0.1	0.3	.03	0.1	77

	Dissolved solids, sum of constituents (mg/L)	Dissolved solids (ton/acre/ft)	Nitrogen, NO$_2$ + NO$_3$ dissolved (mg/L as N)	Nitrogen, ammonia + organic, dissolved (mg/L as N)	Phosphorus, dissolved (mg/L as P)	Boron, dissolved (ug/L as B)	Iron, dissolved (ug/L as Fe)	Manganese, dissolved (ug/L as Mn)
Standard deviation...	146	0.20	7.3	0.6	0.17	15	1460	200
Mean..................	210	.40	4.2	.3	.04	6.2	520	120
Median...............	220	.40	0.4	.2	.02	0	20	10
Maximum..............	622	.96	40	5.0	1.70	140	8300	960
Minimum..............	75	.13	0.01	0.01	0.00	0	0	1

[1] Micromho per centimeter at 25°C (umho/cm).
[2] Statistics calculated on the hydrogen ion concentration.

The effect of salinity on crops varies considerably with soil type and tolerance of each crop National Academy of Science, 1973, p. 324). The U.S. Salinity Laboratory (1954), however, developed a technique for classifying the salinity hazard of water for irrigation based on specific conductance. Figure 6 illustrates the technique used. Salinity hazards within the four-county area range from low to high. However, water in the high-hazard range may not be a problem because of the high permeability of the sandy soils, which inhibits accumulation of dissolved solids in the soils.

The U.S. Salinity Laboratory (1954) also developed a technique for classifying the sodium hazard of water for irrigation based on the sodium-adsorption ratio (SAR). Figure 6 shows the suitability of water based on the sodium hazard. Results indicate that all SAR ratios are in the low sodium-hazard class. Overall, the water is classified as C2-S1 (medium salinity hazard and low sodium hazard; fig. 6) and is suited for most types of the area's irrigation practices without treatment.

Fluoride in concentrations much greater than 1 to 2 mg/L can cause mottled teeth and bone deformities. In low concentrations, flouride has been shown to reduce the incidence of dental caries (Gough and others, 1979, p. 27). The Minnesota Pollution Control Agency's recommended limit for domestic consumption is 1.5 mg/L (Minnesota Pollution Control Agency, 1978, p. 12). Analyses showed that concentrations of fluoride ranged from 0.03 to 0.2 mg/L. The mean and median concentrations of both were 0.1 mg/L. The concentrations are well below recommended standards.

Iron is an element that is essential to plant and animal metabolism. In excessive concentration, however, it can render water undesirable for domestic consumption without treatment because of staining and chemical reactions (National Academy of Science, 1973, p. 69). The Minnesota Pollution Control Agency recommended limit for domestic consumption of dissolved iron (MPCA, 1978, p. 12) is 300 ug/L (micrograms per liter). Dissolved iron concentrations of many of the wells exceed the recommended limits for domestic consumption. Two possible sources are redeposited iron minerals transported by glaciers from nearby iron-ore deposits as oxide coatings on the outwash sand grains which then can be hydrolized into solution (Wilke and Coffin, 1973, p. 19) and dissolution of iron from well casings (Hem, 1970, p. 124). Dissolved-iron concentrations ranged from 0 to 8,300 ug/L and exceeded the recommended limit of 300 mg/L (Minnesota Pollution Control Agency, 1978, p. 12) in domestic wells at several locations. The median concentration of 20 ug/L shows that more than half of the sample concentrations were well below recommended limits and that the mean value of 520 ug/L was greatly influenced by several locally high concentrations of iron. Treatment to reduce iron concentrations will be beneficial locally for certain uses of the water.

Manganese is an essential trace element for both plants and animals, but may become toxic in excessive concentrations (Gough and others, 1979, p. 34). Manganese in high concentrations may react with other elements to produce objectionable taste, stains, and odors (Hem, 1970, p. 129). Accumulation of manganese in ground water may occur with long-term application of fertilizers (Gough and others, 1979, p. 32). The Minnesota Pollution Control Agency recommended limit for domestic consumption is 50 ug/L (Minnesota Pollution Control

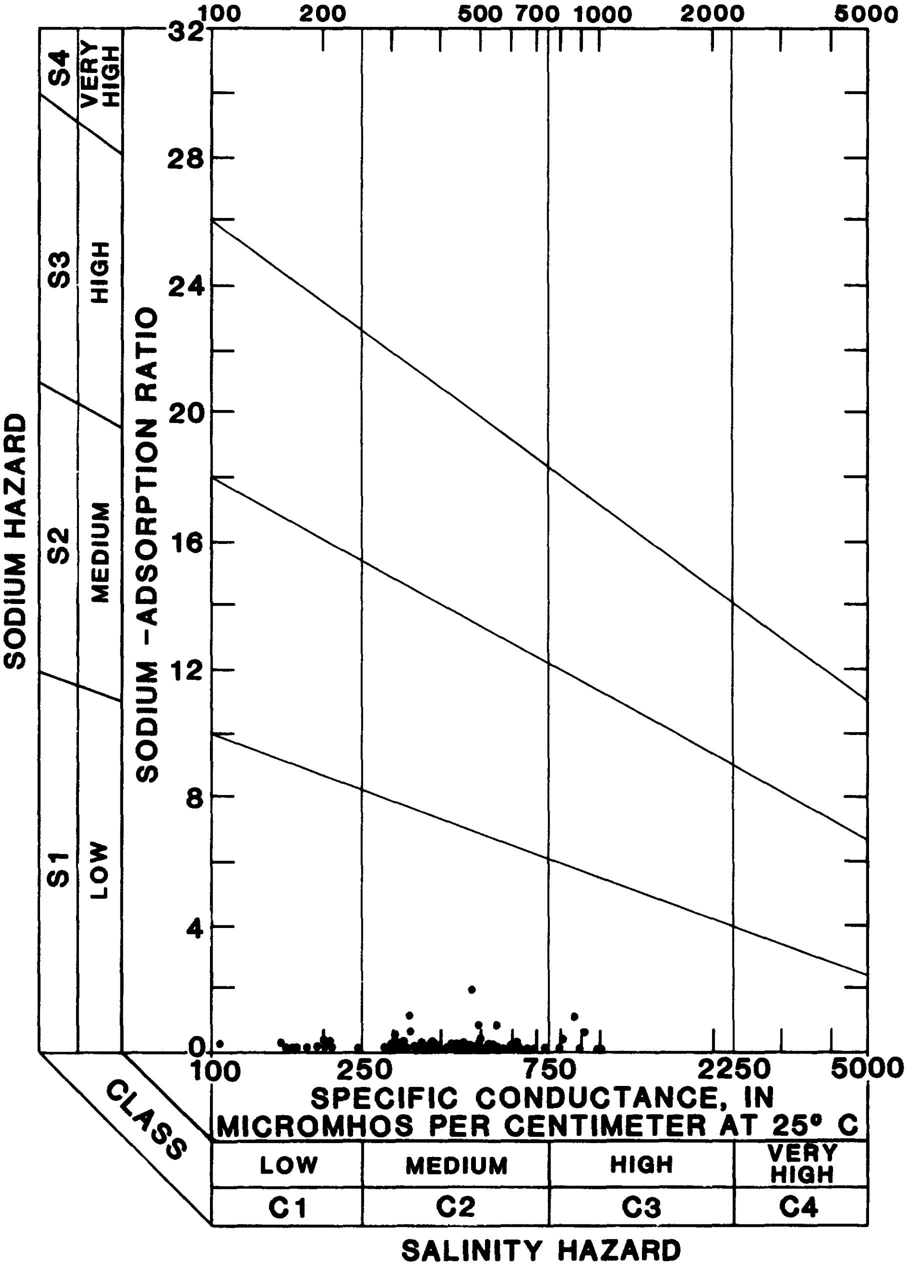


Figure 6.--Sodium and salinity hazards for the 106 baseline network wells

Agency, 1978, p. 12). Dissolved manganese concentrations ranged from 1 to 960 ug/L. The mean concentration is 120 ug/L and the median value is 10 ug/L. The primary source is probably from oxidation of manganese deposits (Hem, 1970, p. 126). Other sources such as fertilizers, and dissolution of the well casing (Pitt and others, 1975, p. 50) may also be the cause of locally high concentrations.

Nitrates, although essential to plants and animals, may cause serious ana occasionally fatal poisoning of infants where present in excessive concentrations (National Academy of Science, 1973, p. 73). High nitrate concentrations usually can be attributed to fertilizers or barnyard and sewage effluents (Hem, 1970, p. 182). The U.S. Environmental Protection Agency (1977, p. 107) recommended limit of nitrite plus nitrate as nitrogen in drinking water is 10 mg/L. Concentrations of dissolved nitrite plus nitrate nitrogen ranged from 0.01 to 40 mg/L. The mean concentration was 4.2 mg/L and the median value was 0.4 mg/L. Locally, use of the water by infants should be avoided.

High sulfate concentrations can have a cathartic effect on occasional users (National Academy of Science, 1973, p. 89). In outwash areas, higher than normal levels of sulfate generally result from sewage effluents (Katz and others, 1978, p. 29). High concentrations of sulfate can also result from fertilizers. The Minnesota Pollution Control Agency's (Minnesota Pollution Control Agency, 1978, p. 12) recommended limit for sulfate in drinking water is 250 mg/L. Sulfate concentrations ranged from 0.1 to 89 mg/L, which are below the recommended limit. The mean concentration was 4.2 mg/L and the median value was 0.1 mg/L.

Data from table 5 indicate that the quality of water throughout the four-county area is similar with only slight variations.

Data from the baseline and biannual networks generally indicate that the quality of water in most areas has undergone little change. Several wells near Perham, in Otter Tail County, and near Royalton, in Morrison County, however, exhibit significant long-term increases in nitrite plus nitrate nitrogen concentrations (Figs. 7 and 8). In each of the four examples, historical (pre-1979) concentrations of nitrite plus nitrate nitrogen are significantly lower than present (post-1979) levels. Most development of water supplies for irrigation occurred after the 1976-77 drought. Because of the limited number of wells sampled regionally, changes in regional water quality cannot be directly attributed to agricultural practices or sewage effluent. Some of the fluctuations observed can be attributed to seasonal variations, but localized, significant water-quality changes have been observed within and downgradient of major agricultural areas.

Concentrations of certain chemical constituents locally exhibit large deviations from the mean. Nitrite plus nitrate nitrogen and chloride concentrations, for example, range from 0.01 to 40 mg/L and 0.3 to 180 mg/L, respectively, and iron and manganese concentrations range from 0 to 8,300 ug/L and 1 to 960 ug/L, respectively. The median values for nitrite plus nitrate nitrogen and chloride are 0.4 and 9.1 mg/L, and the mean values are 4.2 and 14 mg/L, respectively. The median values for iron and manganese are 20 and 10 ug/L and the mean values are 520 and 120 ug/L, respectively. Such variations indicate

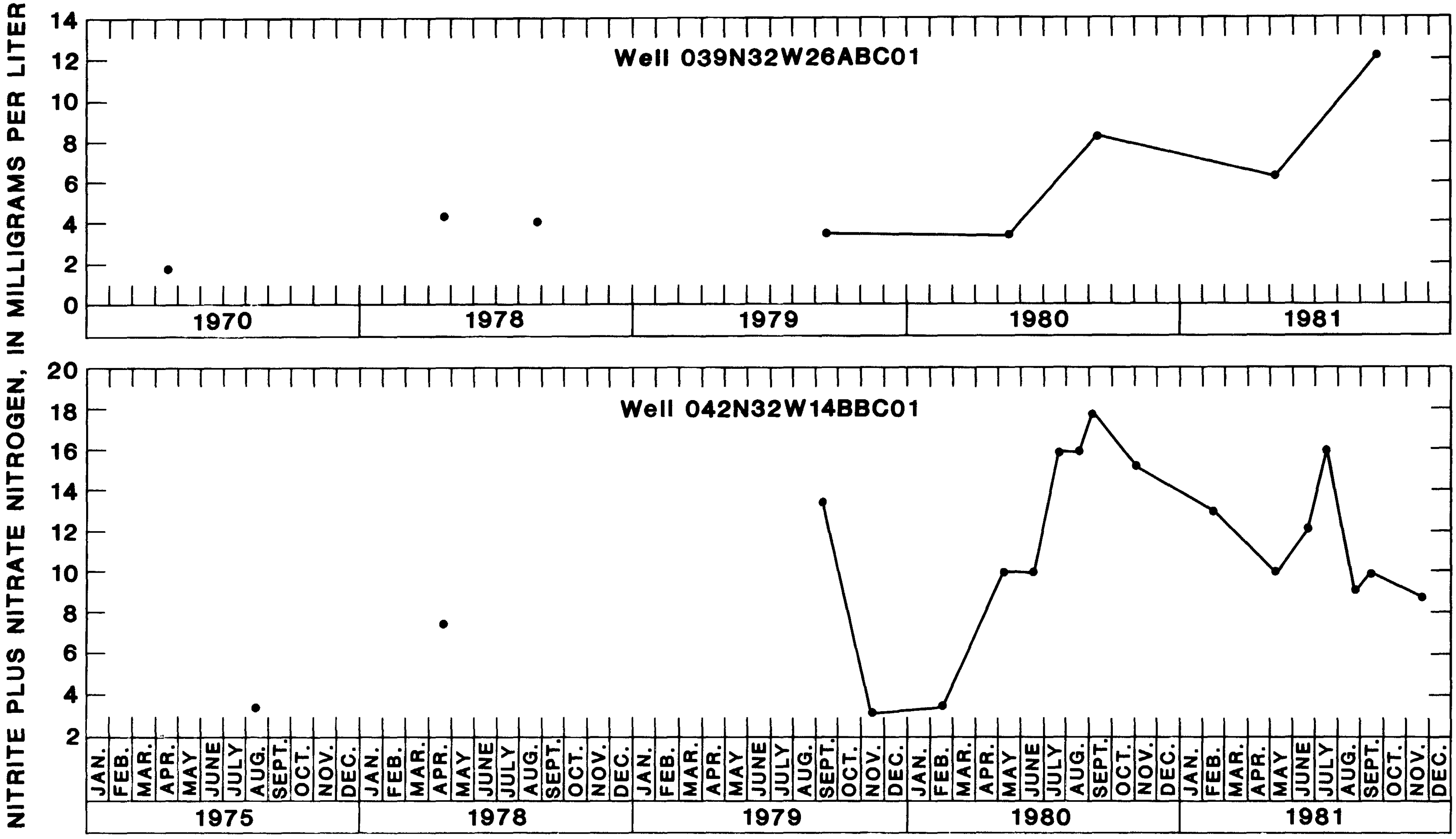


Figure 7.--Nitrite plus nitrate nitrogen concentrations at representative wells in Morrison County

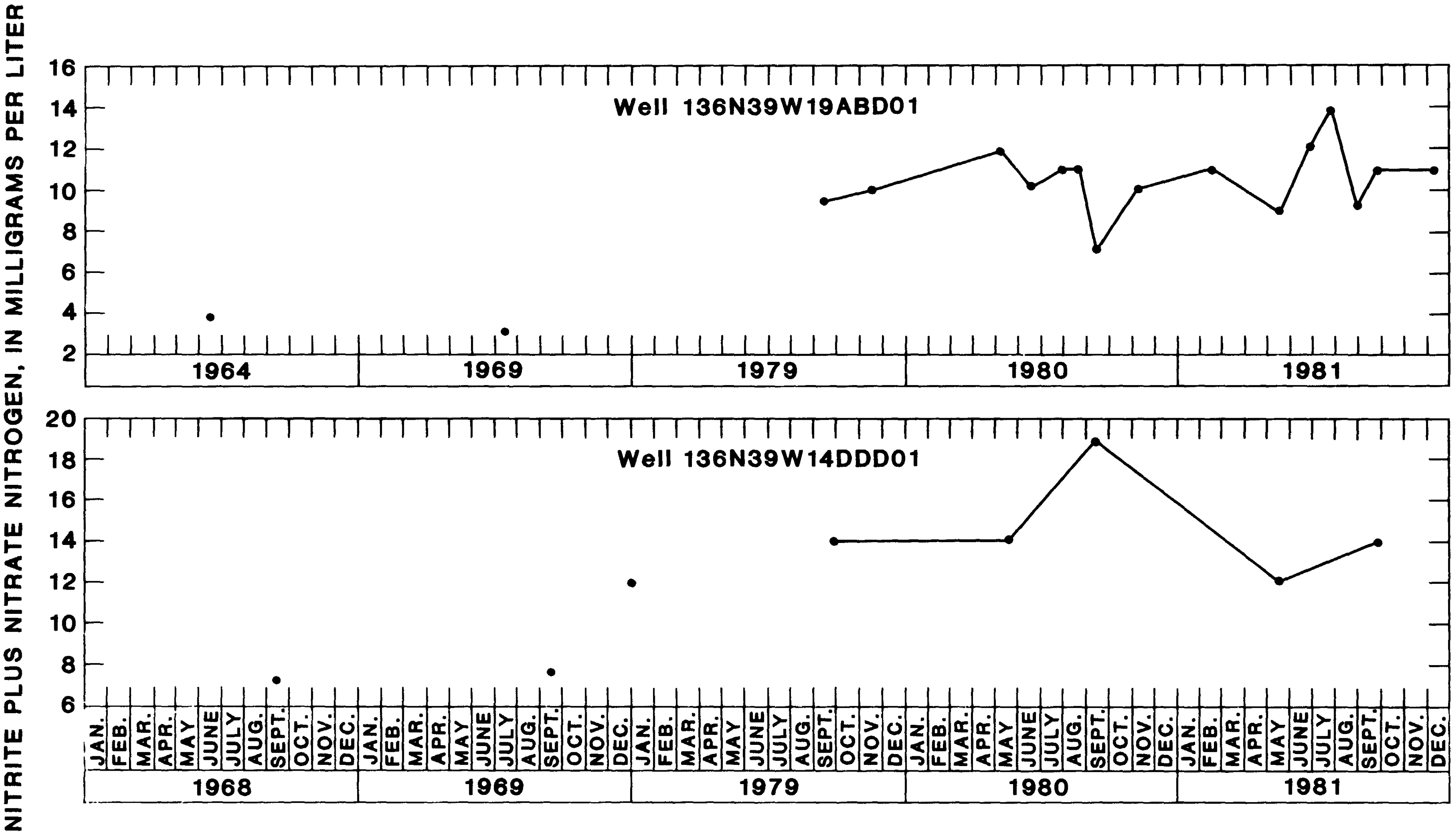


Figure 8.--Nitrite plus nitrate nitrogen concentrations at representative well sites in Otter Tail County

that several extremely high values produce a skewed data set, so the median is more significant as an average concentration than the mean. Table 6 is a statistical summary of results of analyses for selected chemical constituents listed by county. Although there is some areal variation in chemical concentrations, the quality of water generally is similar throughout the four counties. The large variations in concentrations of nitrite plus nitrate nitrogen, chloride, iron, and manganese suggest that these are local rather than areal occurances.

Results of chemical analyses indicate that nitrogen and chloride concentrations vary seasonally in response to changes in ground-water levels. Figure 9 shows the comparison of changes in concentration of nitrite plus nitrate nitrogen with changes in ground-water levels of representative wells in Morrison and Wadena Counties.[1] Graphic results indicate that variations in chemical concentrations follow annual cycles and respond to annual recharge. Chemical concentrations generally peak in spring or early summer and are lowest during winter. However, the data also suggest that nitrite plus nitrate nitrogen is introduced during major recharge events, that can occur anytime during the year.

Although no quantitative relationship was determined between amount of recharge and concentration of chemical constituents, nitrite plus nitrate nitrogen and chloride, in particular, exhibited significant seasonal variation. Figure 10 illustrates seasonal variations in dissolved nitrite plus nitrate nitrogen concentrations from 1979 to 1981 in samples from representative wells in each of the four counties. Figure 11 illustrates seasonal variations in dissolved chloride concentrations from 1979 to 1981 for samples from the same wells. Variability at a particular site probably is due to land use and infiltration characteristics of the soil. Areal variability is perhaps more complicated by relationships between soil and aquifer-hydraulic characteristics, areal precipitation, land-use practices, and proximity of the well to sources of chemicals.

Table 7 statistically compares regional concentrations of nitrite plus nitrate nitrogen for data from the baseline network in areas upgradient and downgradient of major developed areas (agriculture and irrigation) in each of the four counties. The data indicate that concentrations in each county increase significantly downgradient from the major developed areas, which indicates that agricultural practices may be a local contributing factor in degradation of ground-water quality by nitrogen compounds.

[1] When water level cannot be measured in the well being sampled, comparison is made to water levels in nearby observation wells completed in similar deposits at similar depths.

Table 6.—County statistical summary of baseline-network results for selected chemical constituents for Hubbard, Morrison, Otter Tail, and Wadena Counties, Minnesota, 1979

	Depth of well, total (ft)	Specific conductance (umho)[1]	pH[2]	Temperature (°C)	Hardness, (mg/L as ($CaCO_3$)	Hardness, noncarbonate (mg/L $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Percent sodium
				HUBBARD COUNTY						
Standard deviation...	27	130	0.5	2.4	61	42	20	4.0	4.4	2.2
Mean.................	50	470	7.5	9.9	234	27	68	16	4.6	3.7
Median...............	42	434	7.5	9.7	220	15	63	16	14	3.0
Maximum..............	101	900	7.9	19	410	170	130	23	23	11.0
Minimum..............	16	320	6.9	7.0	160	0	38	9.1	1.7	1.0
				MORRISON COUNTY						
Standard deviation...	24	190	0.8	1.2	82	51	22	7.0	10	4.9
Mean.................	33	350	7.5	9.6	160	45	44	12	7.3	7.5
Median...............	25	310	7.7	9.0	150	29	41	11	3.6	6.0
Maximum..............	108	1040	8.3	13	430	240	110	37	47	25
Minimum..............	12	140	6.5	7.5	52	0	16	3.0	2.3	3.0
				OTTER TAIL COUNTY						
Standard deviation...	27	124	0.4	1.3	57	39	16	5.2	1.8	1.5
Mean.................	47	540	7.4	9.6	280	45	76	22	3.2	2.5
Median...............	40	500	7.4	9.5	270	33	74	21	2.8	2.0
Maximum..............	90	1050	7.7	14	480	180	130	38	8.5	8.0
Minimum..............	16	380	6.9	8.0	200	0	54	14	1.1	1.0
				WADENA COUNTY						
Standard deviation...	24	168	0.4	2.1	85	29	24	6.9	10	9.6
Mean.................	34	450	7.6	9.8	220	23	62	15	7.2	6.8
Median...............	24	460	7.5	9.5	220	11	61	16	3.4	4.0
Maximum..............	87	867	8.3	17	400	120	110	31	50	49
Minimum..............	10	163	7.3	6.5	80	0	25	3.5	1.6	2.0

[1] Micromho per centimeter at 25°C (umho/cm).

[2] Statistics calculated on the hydrogen ion concentration.

Table 6.—County statistical summary of baseline-network results for selected chemical constituents for Hubbard, Morrison, Otter Tail, and Wadena Counties, Minnesota, 1979—Continued

	Sodium adsorption ratio	Sodium + potassium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Alkalinity, (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Dissolved solids, residue at 180°C (mg/L)
HUBBARD COUNTY									
Standard deviation...	0.09	6.2	4.4	47	4.2	9.7	0.00	3.7	113
Mean.................	.1	7.2	2.6	210	6.6	7.4	.1	13	288
Median...............	.1	5.3	1.2	200	5.7	4.3	.1	13	250
Maximum..............	.5	24	20	360	15	42	.1	26	684
Minimum..............	.0	2.2	.4	150	1.4	.5	.1	6.7	160
MORRISON COUNTY									
Standard deviation...	0.2	14	6.9	62	15	40	0.03	3.9	127
Mean.................	.2	9.7	2.4	116	15	18	.11	16	230
Median...............	.1	4.2	.9	110	13	7.7	.10	16	210
Maximum..............	1.2	48	38	260	89	180	.20	27	710
Minimum..............	.1	2.8	.3	36	1.6	.5	.10	9.8	98
OTTER TAIL COUNTY									
Standard deviation...	0.06	2.4	0.7	47	11	10	0.03	3.8	77
Mean.................	.09	5.0	1.7	240	16	9.2	.11	22	340
Median...............	.10	4.0	1.5	230	14	5.0	.10	22	330
Maximum..............	.30	11	3.6	350	51	52	.20	33	650
Minimum..............	.00	2.6	.7	160	.7	.9	.10	14	240
WADENA COUNTY									
Standard deviation...	0.4	14	5.8	70	11	10	0.00	3.4	100
Mean.................	.3	12	3.1	190	14	7.9	.1	15	260
Median...............	.1	5.8	1.2	200	10	4.3	.1	15	280
Maximum..............	2.1	54	28	300	39	41	.1	23	520
Minimum..............	.1	2.2	.3	64	2.1	.3	.1	8.7	98

Table 6.—County statistical summary of baseline-network results for selected chemical constituents for Hubbard, Morrison, Otter Tail, and Wadena Counties, Minnesota, 1979—Continued

	Dissolved solids, sum of constituents (mg/L)	Dissolved solids (ton/acre/ft)	Nitrogen, $NO_2 + NO_3$ dissolved (mg/L as N)	Nitrogen, ammonia + organic, dissolved (mg/L as N)	Phosphorus, dissolved (mg/L as P)	Boron, dissolved (ug/L as B)	Iron, dissolved (ug/L as Fe)	Manganese, dissolved (ug/L as Mn)
				HUBBARD COUNTY				
Standard deviation...	92	0.15	10	0.3	0.02	2.1	1340	101
Mean.................	273	.4	6.4	.3	.02	.5	670	50
Median...............	244	.3	2.6	.2	.01	.0	10	10
Maximum..............	567	.9	40	1.1	.08	10	4900	430
Minimum..............	161	.2	.02	.05	.00	.0	10	1
				MORRISON COUNTY				
Standard deviation...	111	0.17	6.1	0.2	0.03	0	1100	104
Mean.................	210	.31	5.5	.2	.03	0	380	77
Median...............	190	.28	3.3	.1	.03	0	10	8.0
Maximum..............	590	.96	25	.8	.17	0	5200	320
Minimum..............	87	.13	.01	.1	.01	0	10	1.0
				OTTER TAIL COUNTY				
Standard deviation...	75	0.10	8.1	0.4	0.03	1.8	2380	255
Mean.................	320	.46	7.0	.3	.02	.3	1180	170
Median...............	310	.45	5.2	.1	.01	.0	20	20
Maximum..............	622	.88	33	1.8	.10	10	8300	960
Minimum..............	233	.33	.01	.01	.01	.0	0	1
				WADENA COUNTY				
Standard deviation...	100	0.13	5.3	1.0	0.34	30	1430	444
Mean.................	260	.36	3.3	.5	.09	6.4	850	280
Median...............	270	.38	.34	.2	.02	.0	130	100
Maximum..............	520	.71	23	5.0	1.70	14	5500	2000
Minimum..............	90	.13	.02	.01	.01	.0	0	3

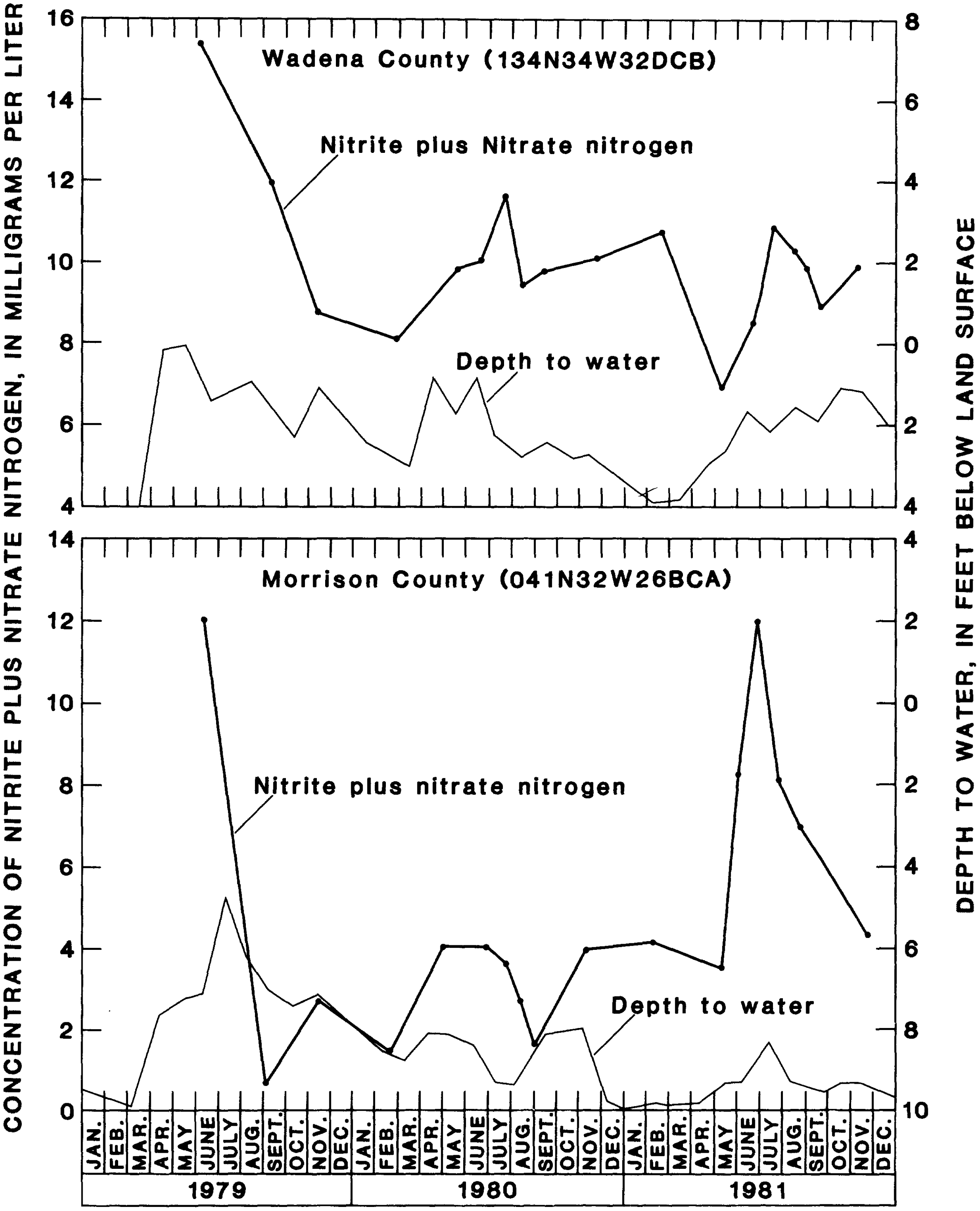


Figure 9.--Comparison of seasonal changes in concentration of nitrite plus nitrate nitrogen to water-level fluctuations

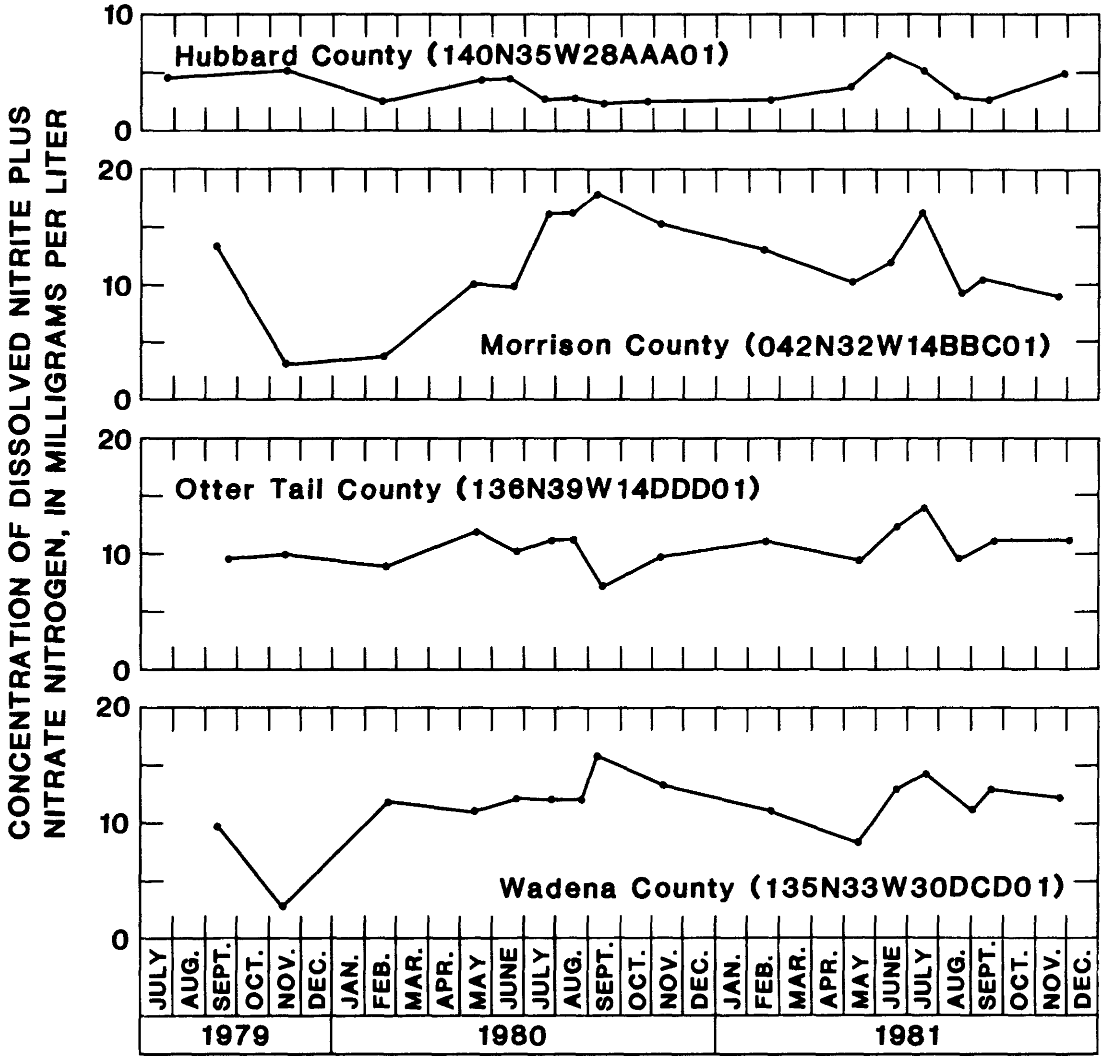


Figure 10.--Seasonal variation of dissolved nitrite plus nitrate nitrogen from representative wells

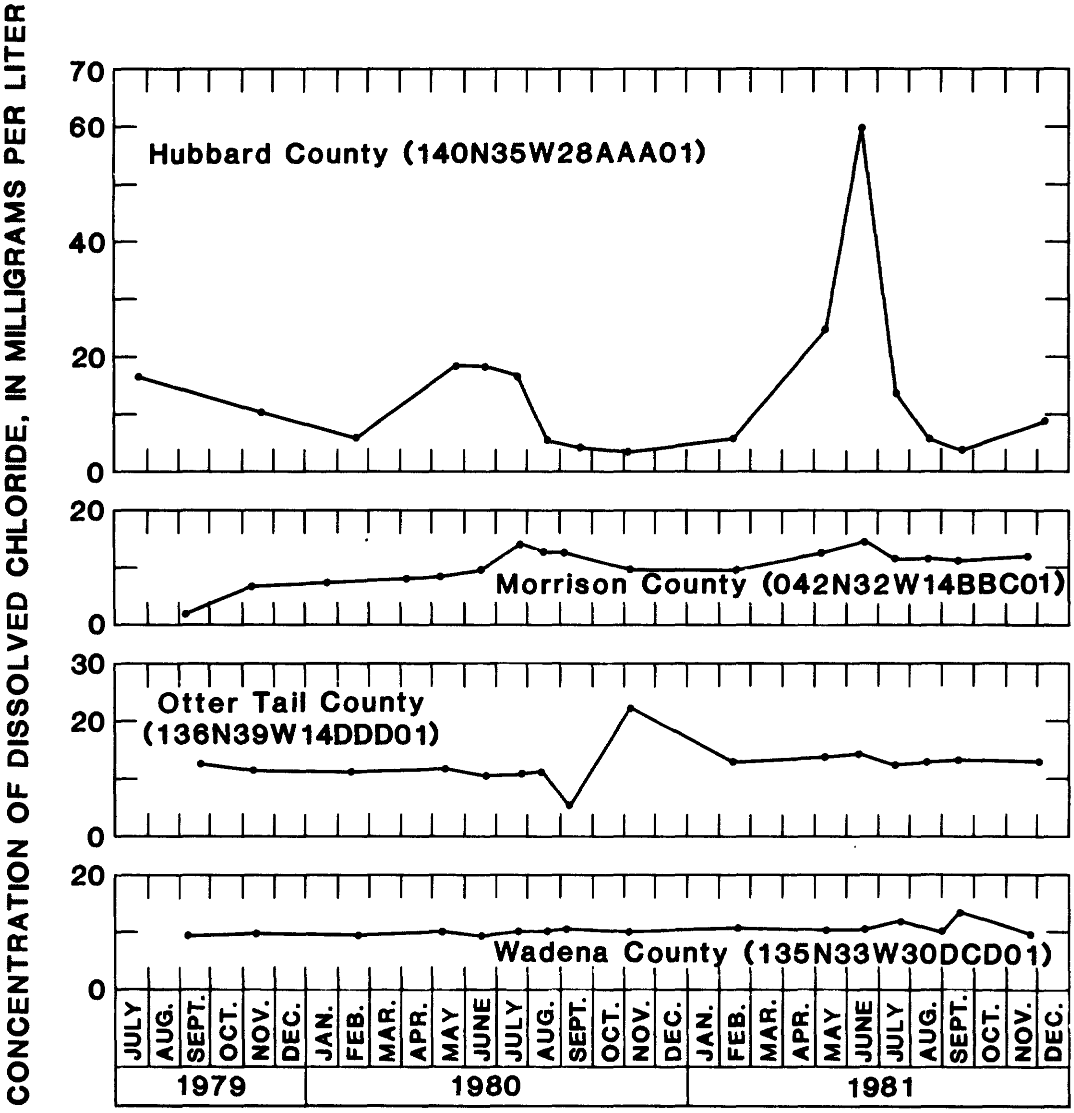


Figure 11.--Seasonal variation of dissolved chloride from representative wells

Table 7.--Statistical comparison of nitrite plus nitrate nitrogen concentrations up and down gradient from major developed areas

County	Upgradient samples			Downgradient samples		
	Number of wells sampled	Nitrite plus nitrate nitrogen (mg/L)		Number of wells sampled	Nitrite plus nitrate nitrogen (mg/L)	
		Mean	Median		Mean	Median
Hubbard..........	13	1.6	0.2	7	11.6	8.2
Morrison.........	15	2.7	.7	13	7.9	6.6
Otter Tail.......	14	1.5	.2	16	11.6	9.5
Wadena...........	15	0.8	.1	10	7.3	6.0

Eight of the 16 wells in the seasonal network were sampled during November 1980 for pesticides. The samples generally showed no residuals from the orthophosphate group of insecticides or from the triazine group of herbicides. The absence of residuals may be due to low application rates, to adherance of the organic compounds to soil particles, or to rapid degradation of the compounds in the environment. Some pesticide sampling during November 1980 at Staples Irrigation Center showed residuals of atrazine and simazine. The simazine had been applied to within 50 feet of the upgradient sampling well during the previous year (1979). Atrazine was applied to the experimental plot at Staples during the summer of 1980. Detection of pesticides at one location and not another may be due to the proximity of the sampling wells to the point of application. As shown earlier, ground water moves only a few feet per day. The network wells were established as a regional guide for persistent pesticides and were, therefore, placed some distance downgradient from major developed areas.

Staples Irrigation Center

The transport of selected chemical constituents in the sand-plain aquifers was studied by sampling 18 nested wells at the Staples Irrigation Center 12 times between May 1980 and May 1981. Table 8 is a statistical summary of the results of analyses for samples collected from each well on May 8 and 9, 1980. Chemical concentrations at the Staples Irrigation Center are slightly higher than regional averages, but, with the exception of nitrogen, do not differ significantly.

Interpretation of results from the repetitive sampling indicates that variations in chemical concentrations of selected constituents are dependent on recharge to the system and seasonal applications of fertilizers. Figure 12 is a comparison of annual variation of nitrite plus nitrate nitrogen concentrations to water-level fluctuations in a well screened at the water-table (S-6). In general, high concentrations of nitrite plus nitrate nitrogen occur shortly after recharge. An exception occurs during July, August, and September when increased concentrations may be caused by recharge from irrigation. Perhaps 15 percent (G. Lindholm, U.S. Geological Survey, oral commun., 1983) of the water applied to crops infiltrates to the water table, leaching nutrients from the soil column and increasing the concentration of chemicals in the ground water. The September peak may have been enhanced by harvest of the crop and disturbance of the soil by farm machinery, which may have allowed greater infiltration. The increases in nitrite plus nitrate nitrogen concentrations during May-June 1980 and February-May 1981 may not be linear as depicted by the dashed line on the graph. The concentrations probably rise sharply just prior to the end of June 1980 and the beginning of May 1981, respectively, as does recharge.

Concentrations of chloride, and, to a lesser degree, calcium, also vary seasonally and temporarily coincide with ground-water-level fluctuations. Figures 13-15, 16- 18, and 19-21, illustrate seasonal variations in nitrite plus nitrate nitrogen, chloride, and calcium concentrations, respectively, from May 1980 to May 1981.

Table 8.—Statistical summary of selected chemical constituents from wells at Staples Irrigation Center, May 1980

	Depth of well, total (ft)	Specific conductance (umho)[1]	pH[2]	Temperature (deg C)	Hardness, (mg/L as (CaCO$_3$)	Hardness, noncarbonate (mg/L CaCO$_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Percent sodium
Standard deviation...	7	68	0.3	0.7	30	41	8.0	2.9	0.9	0.8
Mean..................	21	610	7.1	8.3	300	48	80	24	3.2	2.3
Median................	21	600	7.1	8.0	300	41	80	23	3.0	2.0
Maximum..............	28	730	7.3	9.5	350	120	93	28	6.4	5.0
Minimum..............	14	450	6.6	7.5	240	0	63	19	2.2	2.0

	Sodium adsorption ratio	Sodium + potassium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Alkalinity, (mg/L as CaCO$_3$)	Sulfate, dissolved (mg/L as SO$_4$)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO$_2$)	Dissolved solids residue at 180°C (mg/L)
Standard deviation...	0.02	0.95	0.2	34	5.5	7.3	0.0	2.8	57
Mean..................	.10	4.2	1.0	250	11	15	.1	11	360
Median................	.10	3.9	1.0	250	13	14	.1	12	340
Maximum..............	.20	7.7	1.5	300	18	36	.1	15	470
Minimum..............	.10	3.3	.6	200	1.6	4.6	.1	6.6	280

	Dissolved solids, sum of constituents (mg/L)	Dissolved solids (ton/acre/ft)	Nitrogen, NO$_2$ + NO$_3$ dissolved (mg/L as N)	Nitrogen, ammonia + organic, dissolved (mg/L as N)	Phosphorus, dissolved (mg/L as P)	Boron, dissolved (ug/L as B)	Iron, dissolved (ug/L as Fe)	Manganese, dissolved (ug/L as Mn)
Standard deviation...	41	0.07	8.3	0.44	0.019	3.2	2210	440
Mean..................	320	.48	5.1	.46	.007	1.1	1840	520
Median................	320	.46	0.6	.26	.00	.0	880	520
Maximum..............	430	.64	27	1.50	.08	10	6200	1500
Minimum..............	260	.38	.04	.06	.00	.0	10	30

[1] Micromho per centimeter at 25°C (umho/cm).

[2] Statistics calculated on the hydrogen ion concentration.

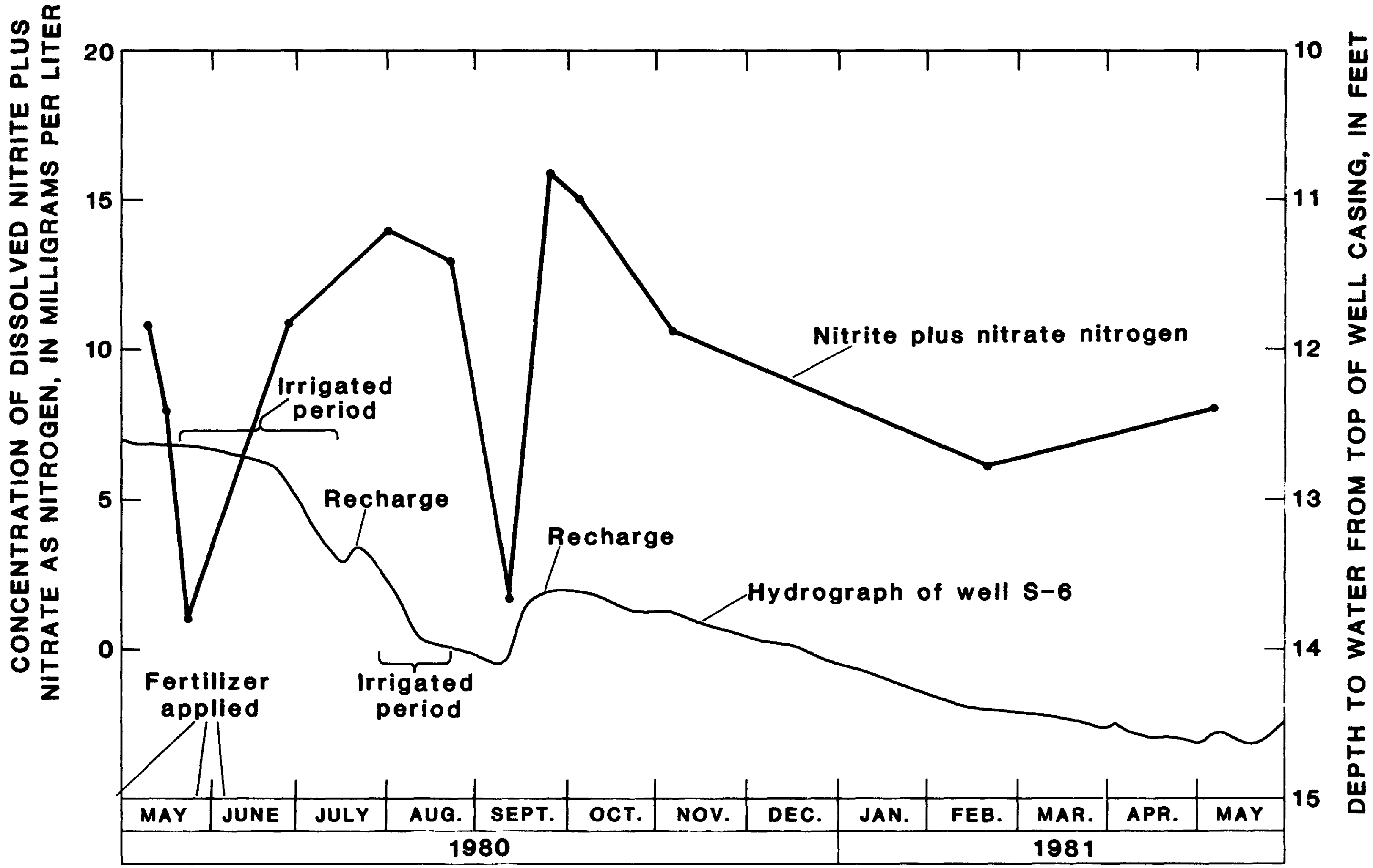


Figure 12.--Comparison of dissolved nitrite plus nitrate nitrogen concentrations to water-level fluctutions at Staples Irrigation Center from May 1980 to May 1981

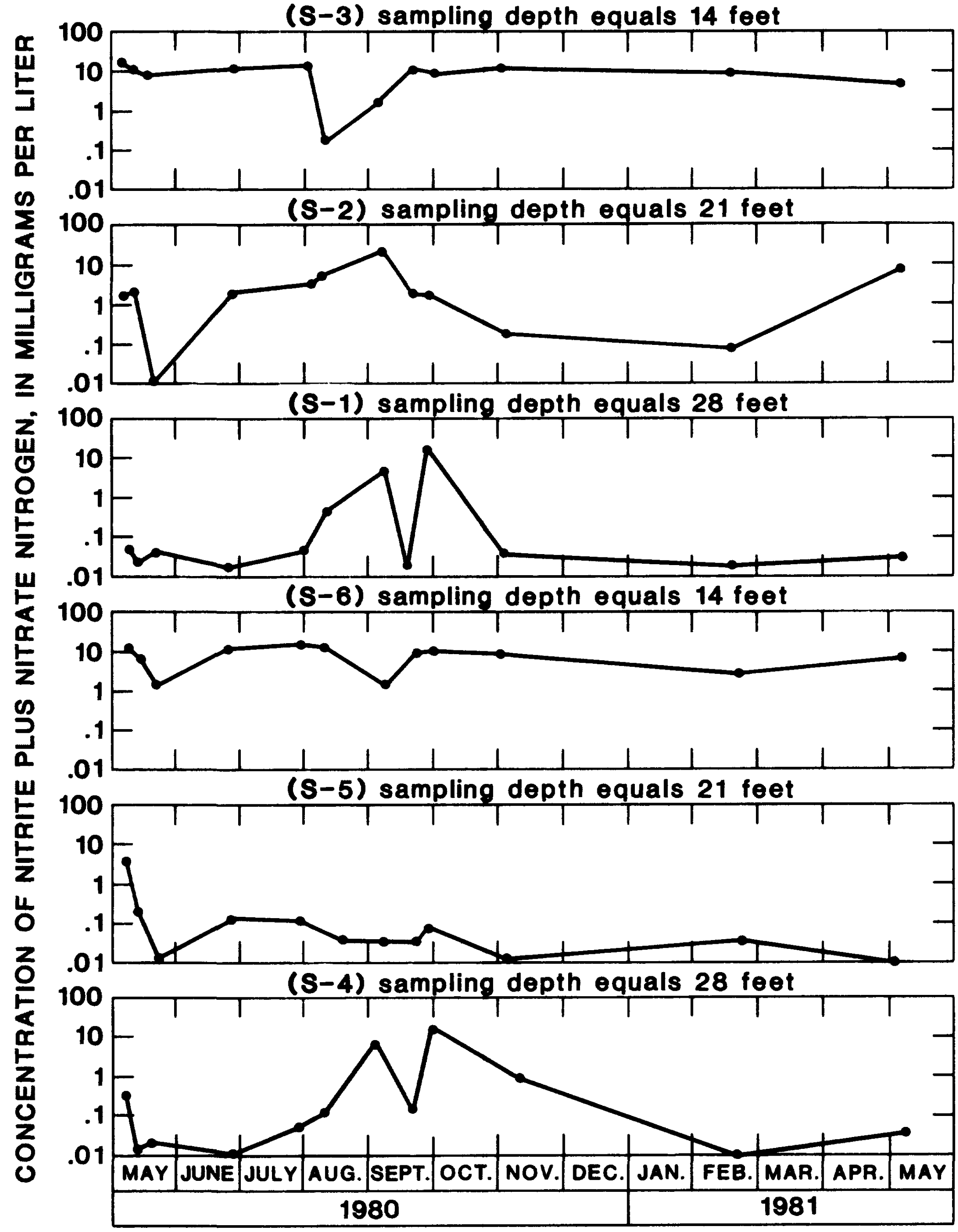


Figure 13.--Seasonal variation of nitrite plus nitrate nitrogen concentrations at Staples Irrigation Center for wells S-1 to S-6

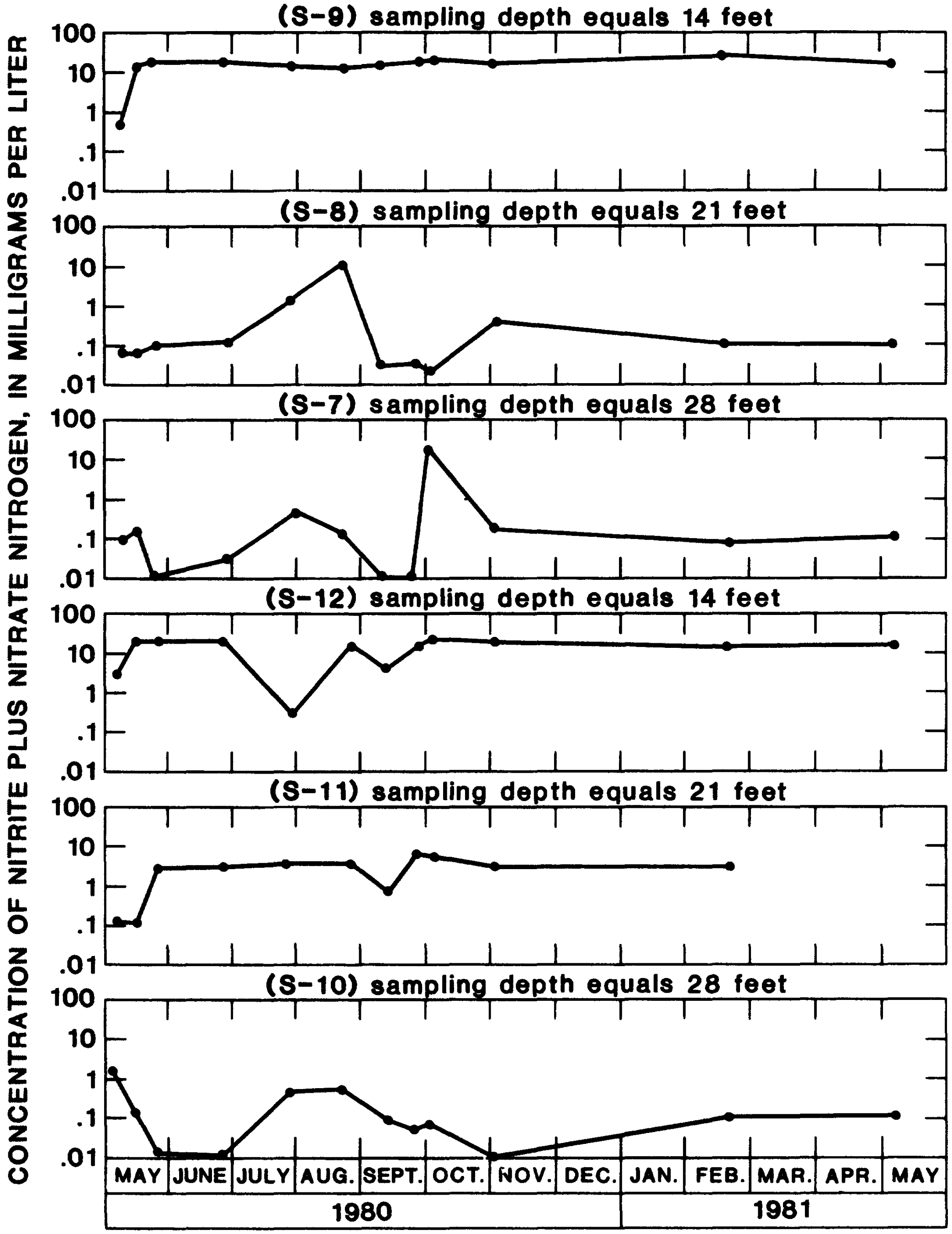


Figure 14.--Seasonal variation of nitrite plus nitrate nitrogen concentrations at Staples Irrigation Center for wells S-7 to S-12

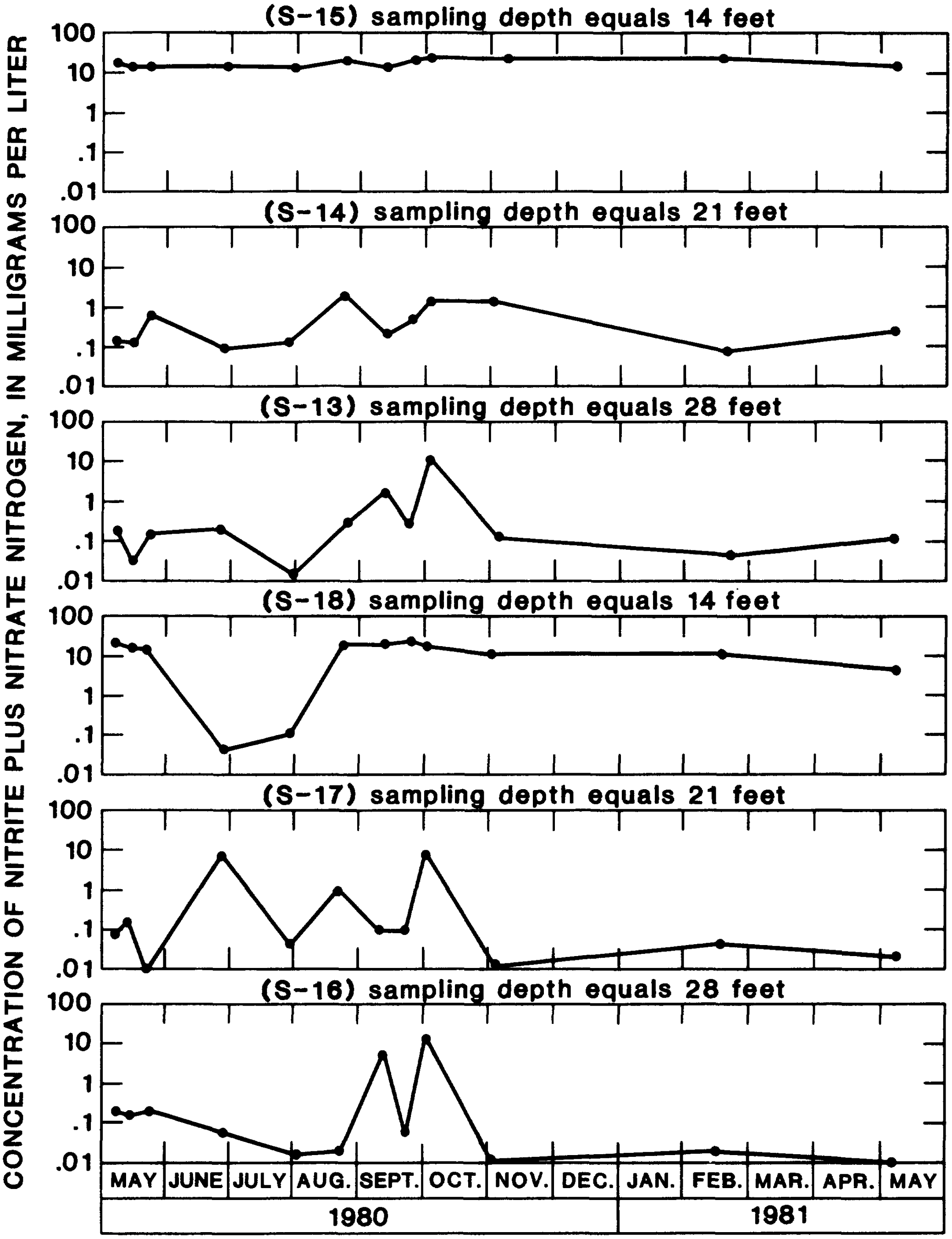


Figure 15.--Seasonal variation of nitrite plus nitrate nitrogen concentrations at Staples Irrigation Center for wells S-13 to S-18

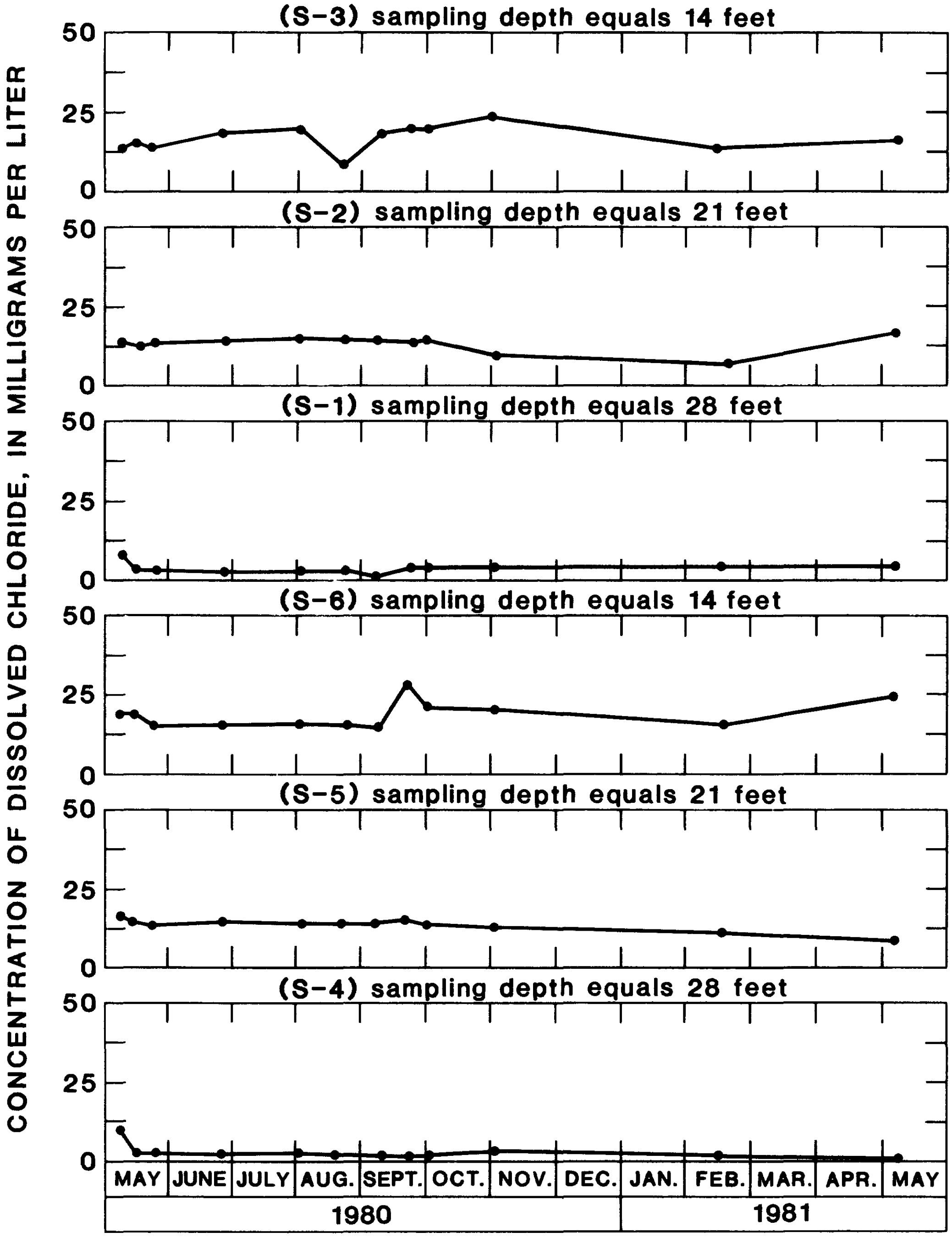


Figure 16.--Seasonal variation of dissolved chloride concentrations at Staples Irrigation Center for wells S-1 to S-6

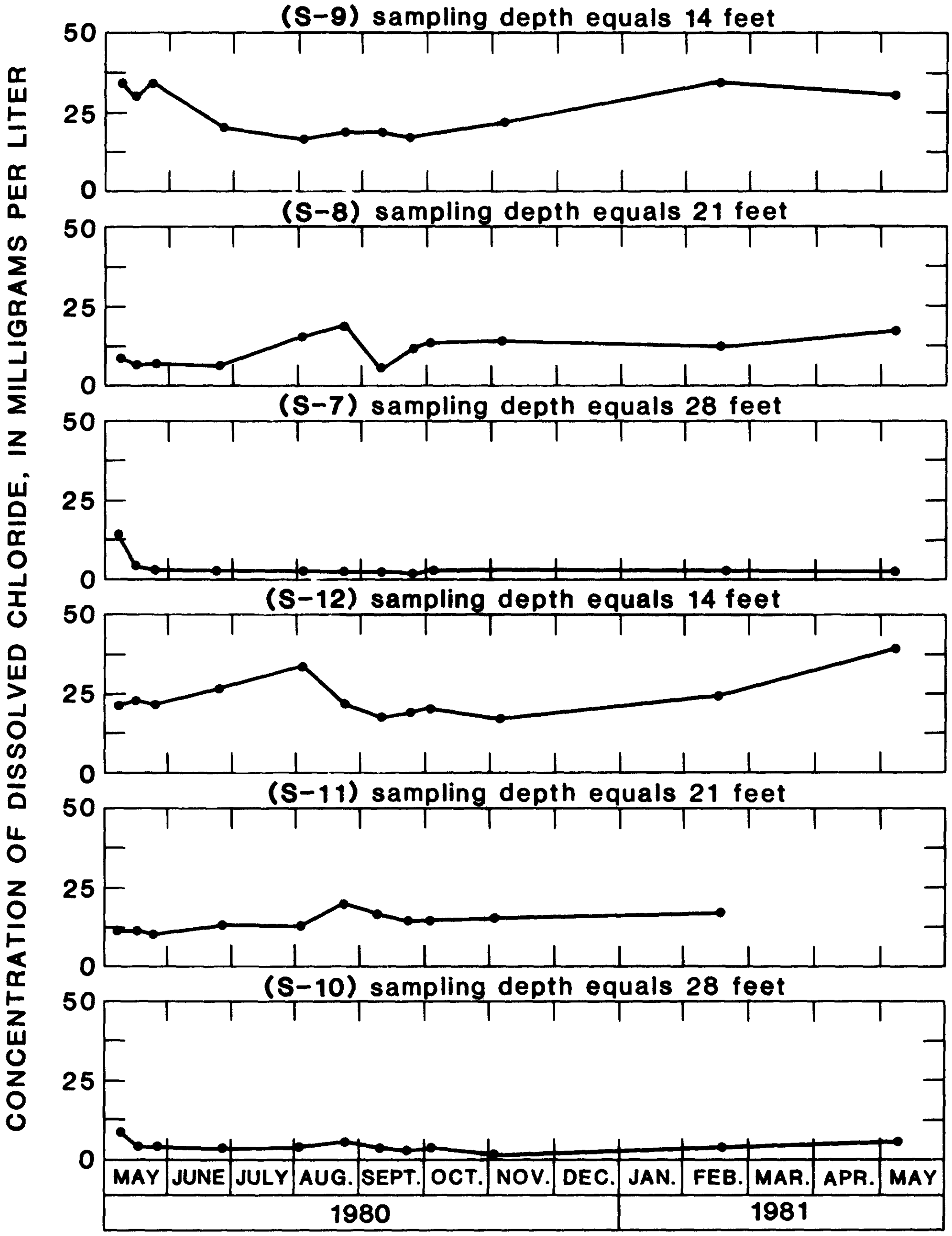


Figure 17.--Seasonal variation of dissolved chloride concentrations at Staples Irrigation Center for wells S-7 to S-12

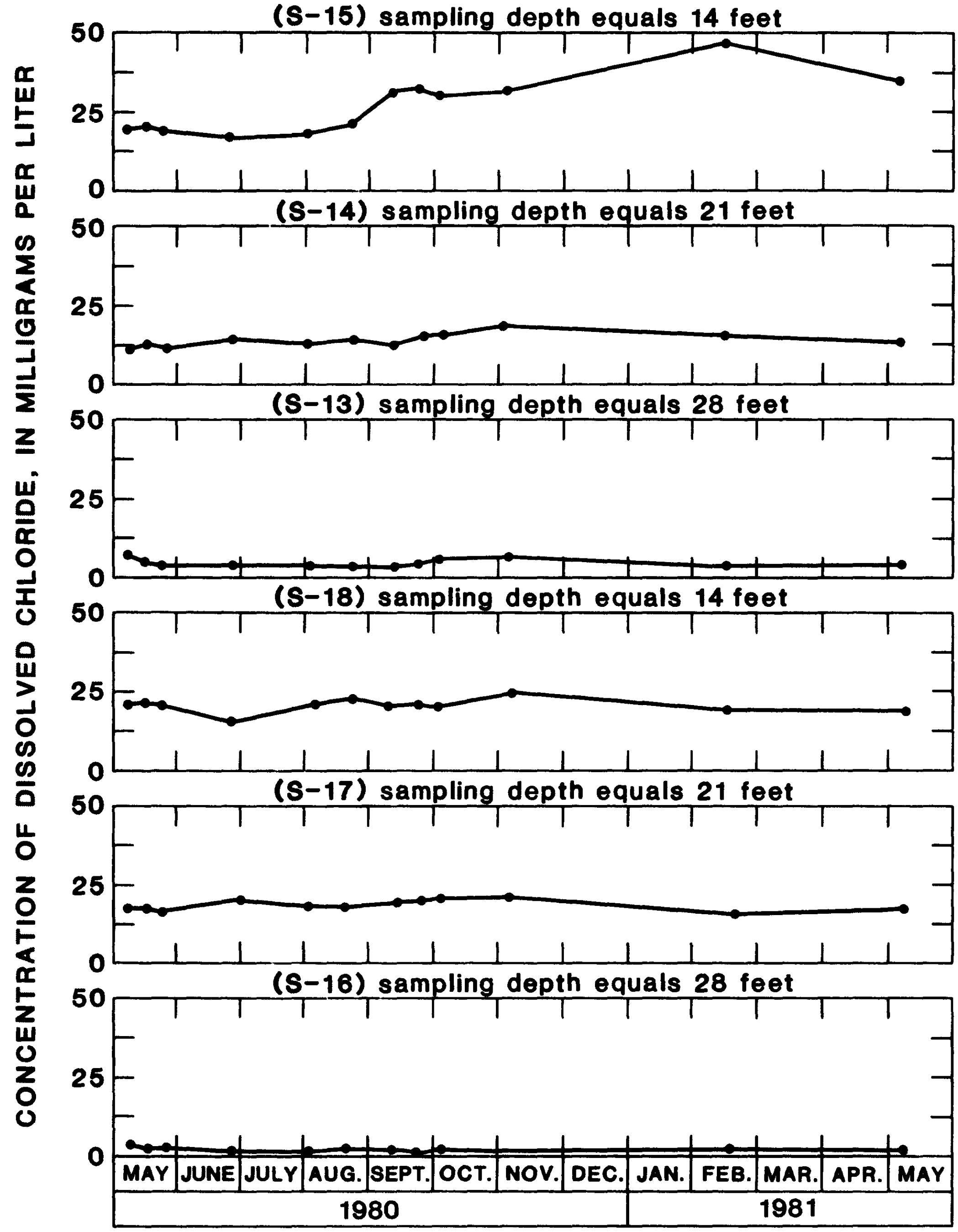


Figure 18.-Seasonal variation of dissolved chloride concentrations at Staples Irrigation Center for wells S-13 to S-18

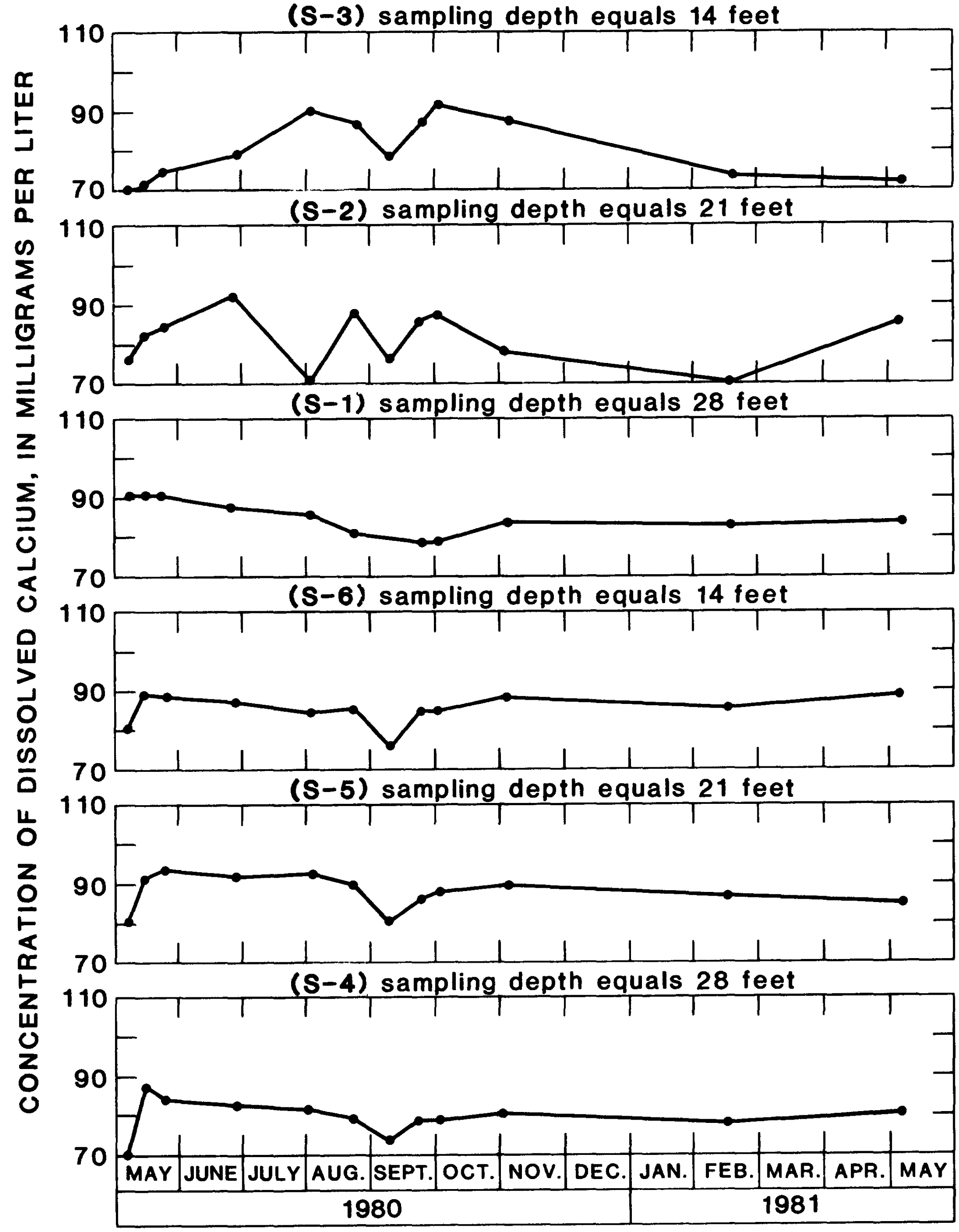


Figure 19.--Seasonal variation of dissolved calcium concentrations at Staples Irrigation Center for wells S-1 to S-6

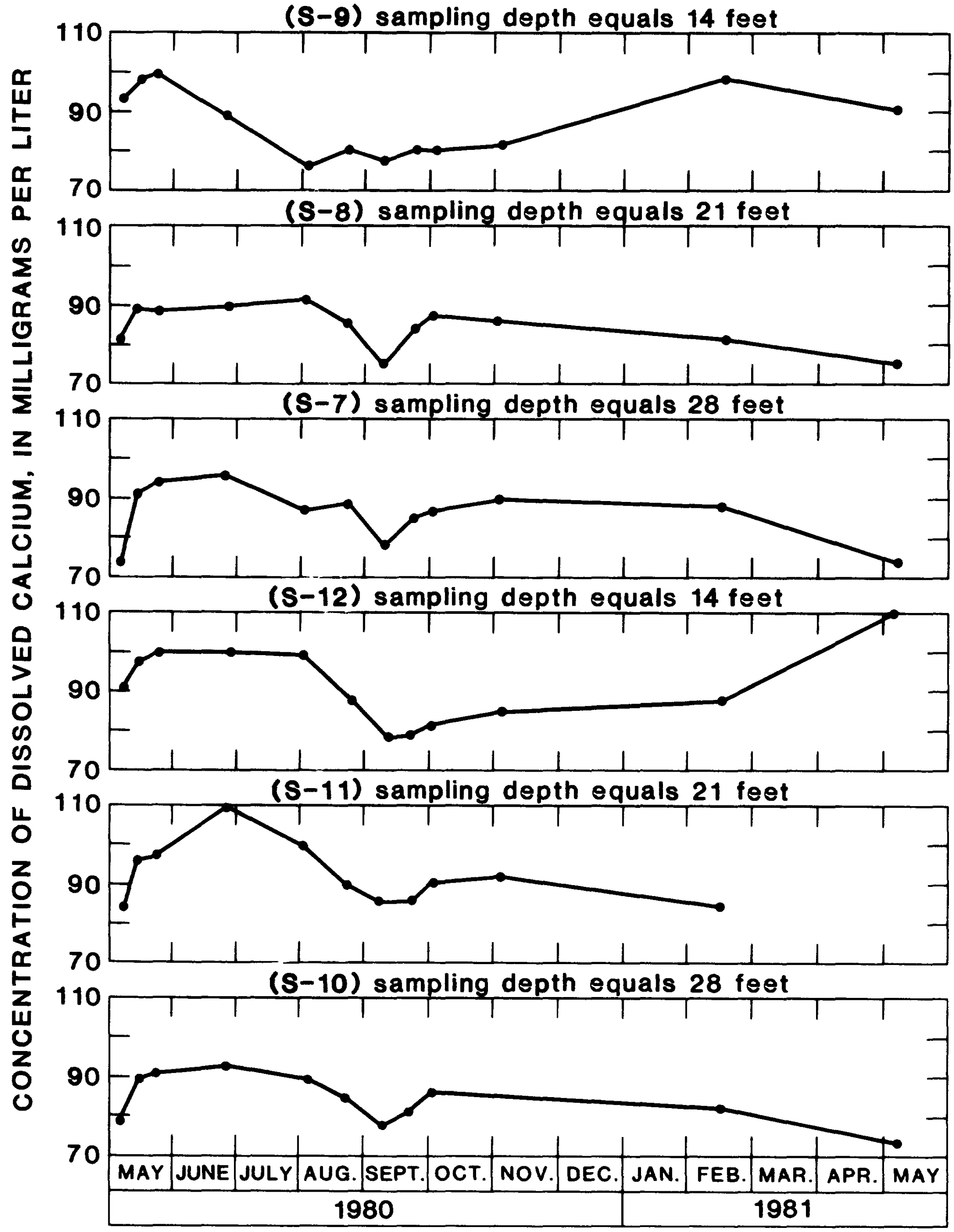


Figure 20.--Seasonal variation of dissolved calcium concentrations at Staples Irrigation Center for wells S-7 to S-12

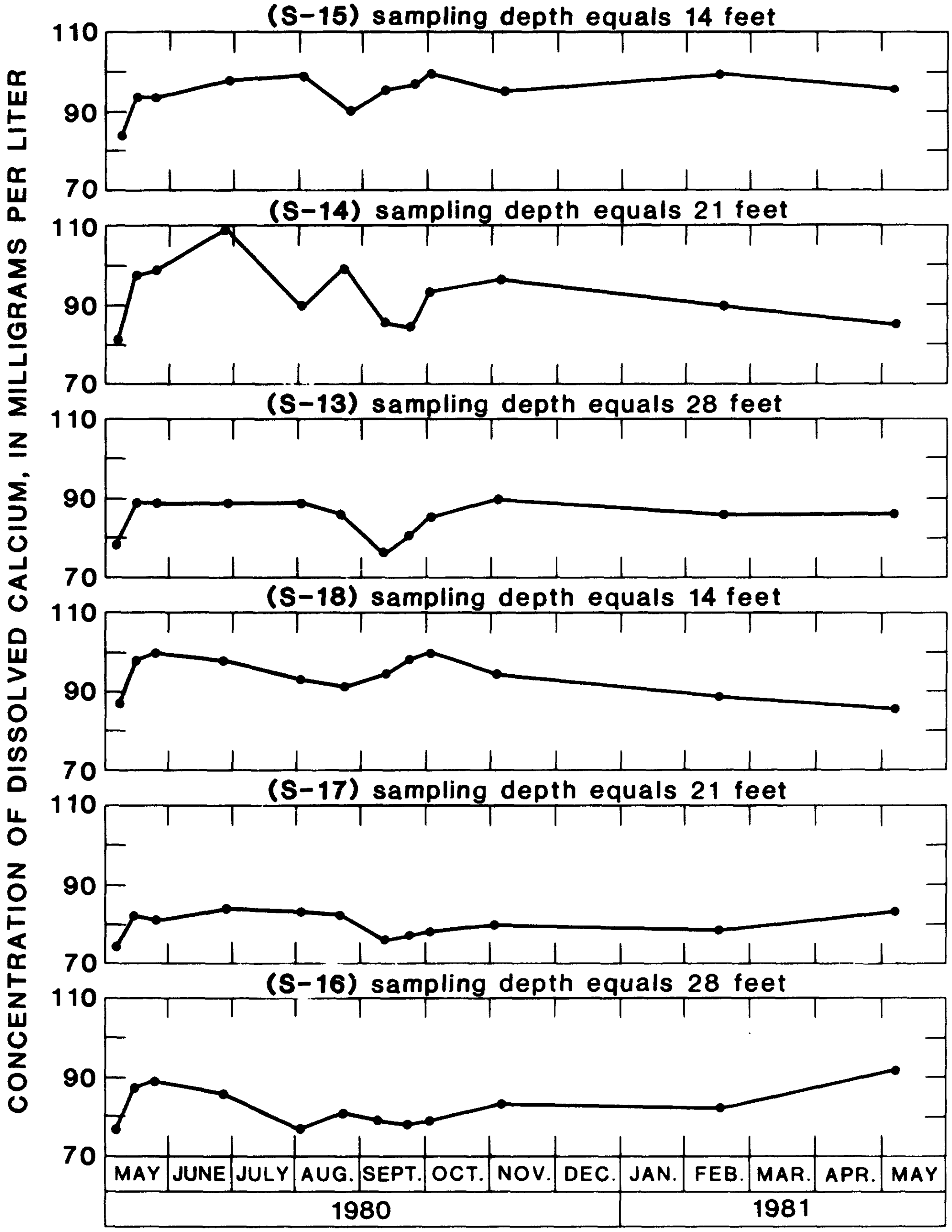


Figure 21.--Seasonal variations of dissolved calcium concentrations at Staples Irrigation Center for wells S-13 to S-18

Horizontal and vertical movement of chemicals within the aquifer at Staples Irrigation Center was determined by sampling nested wells upgradient and downgradient from the experimental plot. Table 9 is a statistical summary of water-quality data, by depth of well. Results indicate that concentrations of dissolved nitrite plus nitrate nitrogen, chloride, and iron vary significantly with depth. Mean concentrations of nitrogen and chloride at Staples Irrigation Center are generally greatest in samples from the shallowest wells (15 mg/L for both constituents) and 0.1 and 3.5 mg/L, respectively, in samples from near the deepest wells. These results indicate that water containing elevated levels of nitrite plus nitrate nitrogen and chloride moves vertically to the water table and then laterally with only a minor amount of mixing within the saturated part of the aquifer. Mean concentrations of iron, however, are greatest (3,840 ug/L) near the bottom of the aquifer and least (460 ug/L) near the top, suggesting: (1) that iron is not leached by recharge but may be diluted by recharge, and (2) dissolved-oxygen concentrations may control the dissolution of iron and result in increased concentrations with depth. Maximum concentrations of each of the constituents, however, can be present at various depths during pumping, probably owing to changes in vertical flow components caused by the pumping.

Figure 22 shows concentrations of nitrite plus nitrate nitrogen in the shallowest wells to be similar in May 1980. Figures 13-21 generally show that the highest concentrations were observed in wells near the source, whereas lowest concentrations were observed in the well farthest downgradient from the field. In February, concentrations are clearly separated (fig. 22), with the lowest concentrations found near the source and the highest concentrations found in the well farthest downgradient from the source (figs. 13-21). Figure 22 also indicates a strong chemical stratification with the highest concentrations of nitrite plus nitrate nitrogen near the water table and decreasing in concentration with depth in February.

Figure 22 illustrates the relationship of nitrite plus nitrate nitrogen concentrations at various depths with time. Concentrations generally decrease with depth. Similar conclusions were made by Pitt and others (1975) in shallow unconfined aquifers in Dade County, Fla. The graph (fig. 22) indicates that little mixing generally occurs with depth for each nest of wells throughout the annual cycle, suggesting ground-water flow is largely laterally laminar. The slope of the two 80th percentile lines (especially for the deep wells) indicates that concentrations decreased slightly from May 1980 to May 1981. Peaks generally occur during spring, depending on recharge, and lows occur during late winter. Interpretation of figures 13-21 and 22 indicates that most mixing occurs during the summer months from July through September. At Staples and other local areas, at least two major factors are probably involved with mixing. First, the introduction of chemicals with recharge (either precipitation or irrigation recharge) may create local downward-flow components, thus increasing the chemical concentrations below the source. Secondly, mixing may result from large-scale withdrawals of ground water that also change local vertical-flow patterns and cause water with higher concentrations to flow to the lower part of the aquifer towards pumping wells. The areal extent of the mixing area and degree of mixing depends on land use and development of water supplies. In heavily developed areas, the effect may be regional in scope.

Table 9.--Statistical summary of selected chemical constituents by depth at Staples Irrigation Center

	Number of wells	Depth of well below water table (ft)	Specific conductance (umho)[1]	pH[2]	Temperature (deg C)	Calcium, dissolved (mg/L as Ca)	Chloride, dissolved (mg/L as Cl)	Nitrogen, $NO_2 + NO_3$ dissolved (mg/L as N)	Iron dissolved (ug/L as Fe)
Wells screened near top of aquifer........	6								
Standard deviation......		1.2	69	6.0	1.4	8.9	1.9	7.8	460
Mean....................		4.2	620	7.2	9.8	89	15	15	460
Median..................		4.3	630	7.2	10	89	15	15	370
Maximum.................		6.0	750	7.8	13.5	110	18	30	2300
Minimum.................		2.7	450	6.2	7.5	67	13	0.06	10
Wells screened near middle of aquifer.....	6								
Standard deviation......		1.1	58	5.9	1.1	8.3	4.5	6.0	2270
Mean....................		7.8	600	7.2	9.8	87	12	2.6	2970
Median..................		7.9	600	7.2	10	86	13	0.4	2450
Maximum.................		9.5	780	7.7	14	110	17	46	9300
Minimum.................		6.7	400	6.3	8.0	69	3.5	0	0
Wells screened near bottom of aquifer.....	6								
Standard deviation......		1.4	39	5.7	0.9	8.5	3.4	6.5	3830
Mean....................		15.0	560	7.1	9.8	83	4.6	2.3	3840
Median..................		15.5	560	7.0	9.5	85	3.5	0.1	3700
Maximum.................		17.0	640	7.6	13	96	9.0	32	17000
Minimum.................		13.7	450	6.3	8.0	32	1.6	0	0

[1] Micromho per centimeter at 25°C (umho/cm).

[2] Statistics calculated on the hydrogen ion concentration.

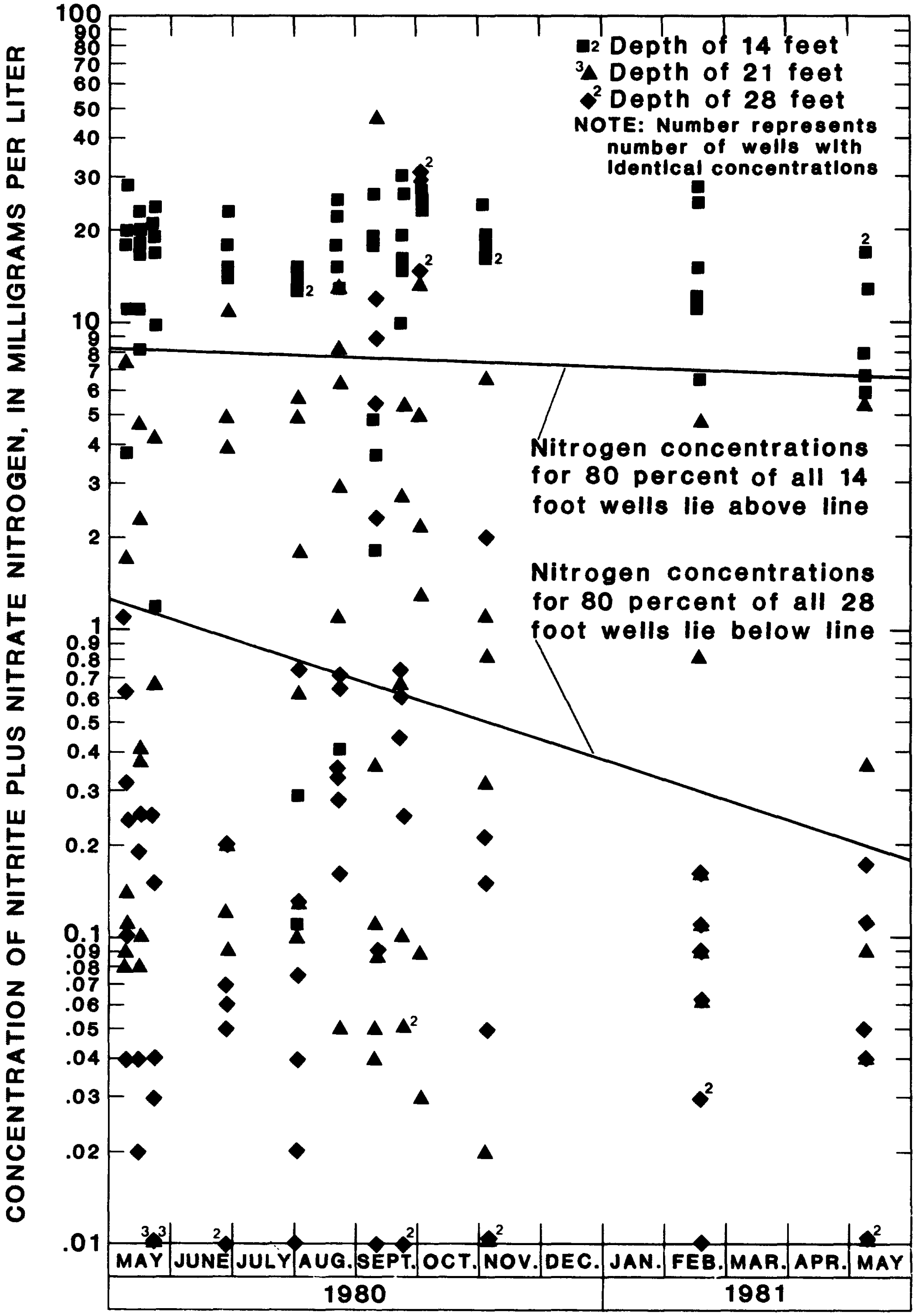


Figure 22.--Nitrite plus nitrate nitrogen concentrations at Staples Irrigation Center from May 1980 to May 1981

When interpreting long-term trends based on scant or incomplete historical data or from data collected over too short a time, it is important to observe the magnitude of the constituents and the frequency of the sampling. Slight variations observed may be those of unique climatological or agricultural events and not truly representative of long-term trends toward improvement or degradation of an aquifer system.

SUMMARY

Water samples were collected periodically from 124 wells completed in sand-plain aquifers during a 3-year period to: (1) establish baseline water quality, (2) evaluate trends in chemical concentrations, including seasonal variations, and (3) investigate the movement of selected chemical constituents through the aquifers. Ground water in the sand-plain aquifers is predominately a calcium bicarbonate type with low to moderate concentrations of dissolved solids (77 to 710 mg/L). Concentrations of nitrite plus nitrate nitrogen, iron, and manganese locally exceed limits recommended by the U.S. Environmental Protection Agency and the Minnesota Pollution Control Agency for drinking water. Generally, the ground water is chemically suitable for most uses. However, comparison of historical data to current data indicate that some localized degradation of quality from increasing concentrations of nitrite plus nitrate nitrogen is occurring downgradient from major agricultural areas in each of the four counties.

Concentrations of chloride and nitrite plus nitrate nitrogen vary seasonally as well as annually. The variations probably are related to the intermittent introduction of chemicals to the ground water during recharge. No quantitative relationship could be established between chemical concentrations and amount of recharge, but trends in concentration generally coincide seasonally with water-level fluctuations.

Samples from 18 wells at the Staples Irrigation Center showed a strong relation between sampling depth and the chemical concentration of nitrite plus nitrate nitrogen, chloride, and iron. Although no apparent quantitative relation exists between concentration and depth, mean concentrations of nitrite plus nitrate nitrogen, chloride, and calcium were greatest near the top of the aquifer and lowest near the bottom of the aquifer. Concentrations of iron were greatest at depth. Little mixing of nitrite plus nitrate nitrogen and chloride occurs in the aquifer to a distance of at least several hundred feet downgradient from source areas. Slight mixing during the year can be accounted for by introduction of the chemicals during recharge and local ground-water mixing caused by the effects of pumping.

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