Presence, Distribution, and Potential Sources of Nitrate and Selected Pesticides in the Surficial Aquifer along the Straight River in North-Central Minnesota, 1992-93

By James F. Ruhl

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Contents

List of Illustrations

List of Illustrations--Continued

List of Tables

Conversion Factors, Abbreviations, Vertical Datum, Concentration Units, and Site Numbering and Location System

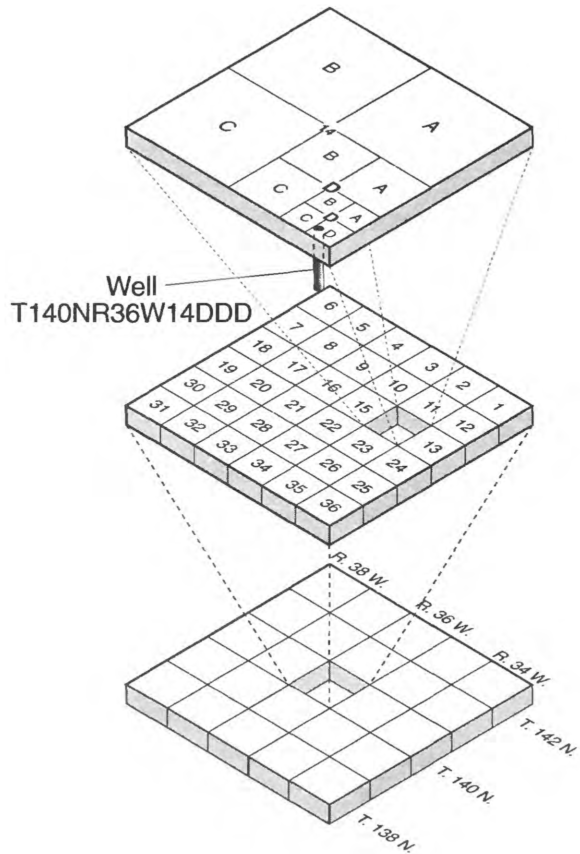
Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	25.4	millimeter
foot (ft)	.3048	meter
mile (mi)	1.609	kilometer
acre	4.047×10^{-3}	square kilometer
square mile (mi^2)	2.590	square kilometer
pound	.4536	kilogram
pound per acre	1.1208×10^{2}	kilogram per square kilometer

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

Chemical concentrations: Given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter.

Median concentration: The central concentration value, or 50th percentile, of a distribution of concentrations ranked in order of magnitude. For an odd number of concentrations, the median is the concentration with an equal number of higher and lower concentrations. For an even number of concentrations, the median is the average of the two central concentrations. When necessary median concentrations have been rounded off to the nearest even number for expression to the correct number of significant figures.

Site location and numbering system: The numbering system used to define the location of water-quality data collection sites is based on the Federal system of land subdivision (township, range, and section). The first number of a site location indicates the township (the N after the township number is an abbreviation for north); the second, the range (the W after the range number is an abbreviation for west); and the third, the section. Uppercase letters after the section number indicate location within the section; the first letter denotes the 160-acre tract, the second the 40-acre tract, and the third the 10-acre tract. Letters A, B, C, and D are assigned in a counterclockwise direction, beginning in the northeast corner of each tract. The number of uppercase letters indicates accuracy of the location number. For instance, if a point can be located within a 10-acre tract, three uppercase letters are shown in the location number. The number T140NR36W14DDD indicates the site is located in the SE 1/4 of the SE 1/4 of the SE 1/4, section 14, township 140 north, range 36 west.



Definition of Terms

Alkalinity: Capacity for neutralizing acid and commonly reported as an equivalent amount of calcium carbonate. This property is attributed mostly to dissolved species of carbon dioxide if the pH of the water is less than 9.5.

Aquifer: Geologic or stratigraphic unit that contains sufficient saturated, permeable material to yield usable quantities of water to wells or springs.

Confined aquifer: An aquifer bound above and below by confining units. Synonymous with a buried aquifer where hydraulic head rises above the top of the aquifer in a tightly cased well.

Confining unit: Layer of material with low vertical permeability that is in contact with the top or bottom of an aquifer.

Dissolved: The portion of a given constituent carried in solution that passes through a 0.45-micrometer membrane filter.

Dissolved solids: Total amount of mineral constituents dissolved in water and expressed in milligrams per liter.

Drift: All material (clay, silt, sand, gravel, pebbles, and boulders) transported and deposited by glacial ice or meltwater.

Evapotranspiration: Water discharge to the atmosphere by evaporation from water and land surfaces and by plant transpiration of soil moisture.

Ground water: Subsurface water that is in the saturated zone beneath the water table.

Horizontal hydraulic gradient: The change in hydraulic head per unit of horizontal distance in a given horizontal ground-water flow direction.

Isotopes: Atoms of a chemical element with the same number of protons but different number of neutrons.

Leachate: Water-soluble substance transported from near land surface to the water table by recharge.

Metabolite: Decomposition product of a compound, such as a pesticide, after it begins to degrade in the environment.

Outwash: Sorted and stratified sand and gravel deposited by flowing meltwater from glacial ice.

Permeability: Measure of the ease that water can flow through a given material.

Pesticides: A general term for agricultural chemicals used to kill crop pests; these chemicals include herbicides, insecticides, and fungicides.

pH: A measure of the acidity (or alkalinity) of a solution; the negative logarithm of the concentration of hydrogen ions in solution. A pH of 7.0 indicates a neutral solution. pH values less than 7.0 indicate an acid solution and pH values greater than 7.0 indicate an alkaline solution.

Recoverable: Refers to the fraction of a given constituent in a water sample that can be analytically determined after chemical digestion of the water sample. This fraction is less than the total amount of the given constituent in the dissolved or suspended phase.

Saturated zone: The part of an aquifer where all of the pore space is filled with water. In a surficial or unconfined aquifer the respective top and bottom of this zone are the water table and the top of the uppermost confining unit.

Specific conductance: The capacity of water to conduct an electrical current; generally proportional to the dissolved solids concentration in most dilute natural water.

Till: Unsorted and unstratified clay, silt, sand, gravel, pebbles, and boulders of glacial origin.

Unconfined aquifer: A water-bearing formation that is not completely saturated with water; an aquifer that has a water table. Also referred to as a surficial or water-table aquifer.

Unsaturated zone: Bounded above by land surface and below by the water table. Also called the vadose zone.

Water table: The level in the saturated zone where the water pressure is atmospheric; this level is the same as the top of the saturated zone in an unconfined aquifer.

Presence, Distribution, and Potential Sources of Nitrate and Selected Pesticides in the Surficial Aquifer Along the Straight River in North-Central Minnesota, 1992-1993

By James F. Ruhl

Abstract

The presence and distribution of nitrate and selected pesticides in ground water in the surficial aquifer along the Straight River in north-central Minnesota were studied. Local residents and public officials are concerned that these substances may pose a health hazard to humans and livestock. Nitrate and pesticides may move downward from cultivated croplands, livestock feedlots and manured fields, waste-water lagoons, and residential development to the ground water.

Ground water near the water table ranged in nitrate-nitrogen concentration (based on median values determined for sampled monitoring wells) from less than 5 to a little greater than 20 mg/L (milligrams per liter) except for one concentration of 50 mg/L downgradient from a feedlot and manured field. Increased nitrate-nitrogen concentrations generally were coincident with cultivated croplands. Decreased nitrate-nitrogen concentrations generally were coincident with forests. Trace amounts of atrazine were detected in 4 of 8 ground-water samples collected from 8 monitoring wells screened near the water table. Detections were more frequent in cultivated croplands (detections at 3 of 5 monitoring wells) than in forests (detections at 1 of 3 monitoring wells). Atrazine concentrations ranged from 0.01 to 0.11 μg/L (micrograms per liter), which are well below the MCL (Maximum Contaminant Level) of 3 μg/L established by the USEPA (U.S. Environmental Protection Agency). Trace amounts of metolachlor and alachlor were detected in one of the samples in which atrazine was detected. MCLs for metolachlor and alachlor have not been established by the USEPA.

The median nitrate-nitrogen concentration determined from sampled monitoring wells along the direction of ground-water flow through five land-use settings: (1) increased from slightly greater than 0 to 50 mg/L near the water table at a feedlot and an adjacent manured field; animal waste was a nitrate source; (2) increased from 8.0 to 16 mg/L near the water table at cultivated croplands irrigated with municipal treated waste water; fertilizer probably was a nitrate source; (3) increased from slightly greater than 0 to 14 mg/L near the bottom of the aquifer at cultivated croplands irrigated with ground water; fertilizer probably was a nitrate source; (4) increased from 1.6 to 3.7 mg/L near the water table and from slightly greater than 0 to 2.8 mg/L near the bottom of the aquifer at a residential development; septic-system leachates, and possibly lawn fertilizer, may have been nitrate sources; and (5) decreased from 14 to 2.6 mg/L near the water table at three waste-water treatment lagoons; waste water was not a nitrate source.

Upgradient to downgradient mean or individual nitrogen isotope $\delta^{15}N$ values in ‰ (delta units in parts per thousand) determined for sampled monitoring wells along the direction of ground-water flow through the five land-use settings were: (1) 5.1 ‰ and 4.0 ‰ for the feedlot and adjacent manured field; (2) 1.1 ‰ and 0.9 ‰ for the cultivated croplands irrigated with waste water; (3) 3.8 ‰ and 2.7 ‰ for the cultivated croplands irrigated with ground water; (4) 3.4 ‰ and 4.9 ‰ for the residential development; and (5) 1.7 ‰ and 3.0 ‰ for the three waste-water lagoons. Nitrate from fertilizer appeared to have been present in ground water at the waste-water lagoons, cultivated croplands irrigated with waste water, and cultivated croplands irrigated with ground water. Nitrate from soil organic matter rather than from animal waste appeared to have been present in ground water at the feedlot and adjacent manured field.

Introduction

The presence of nitrate and pesticides in ground water at concentrations that may be hazardous to humans and livestock concerns citizens and government officials in Minnesota. These chemicals may readily move downward from near the land surface to ground water in surficial aquifers with shallow water tables. Agricultural, residential, and waste-water disposal land-use areas are potential nonpoint sources of these chemicals. Concern about nitrate and pesticides in ground water in surficial aquifers in north-central Minnesota was the impetus for this study. The USGS (U.S. Geological Survey) conducted this study in cooperation with the Hubbard and Becker County Soil and Water Conservation Districts and the Minnesota Pollution Control Agency.

Background

Nitrate and pesticides in drinking water may be hazardous at large concentrations to humans and livestock. The USEPA (U.S. Environmental Protection Agency) has established a drinking water MCL (Maximum Contaminant Level) of 10 mg/L nitrate nitrogen, which is equivalent to 44 mg/L of nitrate (U.S. Environmental Protection Agency, 1991). The USEPA has established a drinking water MCL for only a small number of pesticides. The MCL for atrazine, a widely used herbicide analyzed in this study, is 3 μg/L (U.S. Environmental Protection Agency, 1991).

The amounts of nitrate and pesticides that move downward from near land surface into the ground water depend on climate, hydrogeologic factors, land-management practices, and the mobility and persistence of the chemicals. The vulnerability of ground water to nitrate and pesticide contamination generally increases as: (1) the depth to the water table decreases; (2) the permeability of the unsaturated zone increases; (3) the time interval from chemical application to rainfall or irrigation decreases; and (4) the frequency and intensity of rainfall or irrigation increases.

In a study of near-surface aquifers (tops within 50 ft of land surface) in agricultural areas of the midcontinental United States, 6 percent of 599 ground-water samples collected from 303 wells during spring and summer of 1991 contained more than 10 mg/L of nitrate nitrogen (Kolpin and others, 1994). Potential nitrate sources in ground water in agricultural areas are: (1) soil organic matter; (2) nitrogen-based fertilizer; and (3) livestock animal waste (Heaton, 1986). Other potential nitrate sources in ground water include septic-system leachates.

Nitrogen (N) constituents may undergo the following chemical transformations: (1) ammonification, which is the conversion of organic nitrogen to ammonium (NH_4^+); (2) nitrification, which is the conversion of ammonium to nitrate (NO_3^-); (3) denitrification, which is the conversion of nitrate to nitrogen gas (N_2); and (4) dissimilatory nitrate reduction, which is the conversion of nitrate to ammonium. In shallow aquifer environments ammonification and nitrification generally occur in the unsaturated zone where oxygen is available, whereas denitrification and dissimilatory nitrate reduction generally occur in the saturated zone where dissolved oxygen may be present at small concentrations (less than 0.01 mg/L) (Freeze and Cherry, 1979).

Increased usage of pesticides in the midcontinental United States, where pesticide usage is nearly sixty percent of the total for the United States (Gianessi and Puffer, 1990), combined with increased capability to measure pesticides at small concentrations, has resulted in increased frequency of detection of these compounds. The study by Kolpin and others (1994) found that 24 percent of 579 ground-water samples (collected from 303 wells during spring and summer of 1991) contained at least one detectable herbicide or atrazine metabolite. These detections, however, were at concentrations below USEPA MCLs.

Purpose and Scope

The purpose of this report is to present the results of a ground-water quality study of the surficial aquifer in a 45 square-mile area along the Straight River in north-central Minnesota (fig. 1). The southern and northeastern boundaries of the study area coincide with the boundary of the Straight River watershed; the western and northwestern boundaries of the study area coincide with section lines. The report contains: (1) an areal appraisal of the presence and distribution of nitrate and selected pesticides in relation to land use; (2) a site-specific appraisal of the presence and distribution of nitrate at five land-use settings; and (3) an analysis of nitrogen isotopes to qualitatively estimate nitrate sources.

Data were collected from 1992 to 1993 and included: (1) water levels from 38 monitoring wells; (2) measurements of physical and chemical properties and concentrations of major ions in ground-water samples from 10 monitoring wells; (3) nitrate-nitrogen concentrations in ground-water samples from 34 monitoring wells; (4) isotopic composition of nitrate nitrogen in ground-water samples from 11 monitoring wells; (5) pesticide concentrations in ground-water samples from 8 monitoring wells; and (6) land use determined for 2.5-acre parcels throughout the study area.

Previous Investigations

The hydrogeology and water quality of surficial aquifers in and near the study area have been investigated by Lindholm (1970), Lindholm and others (1972), Reeder (1972), Helgesen (1977), Myette (1982), Myette (1984a), Myette (1984b), and Stark and others (1991). A report by Stark and others (1994) describes stream-aquifer interaction along the Straight River and contains comprehensive information about the hydrogeology of the watershed.

Methods

Thirty-eight monitoring wells completed in the surficial aquifer were used for collection of either water-

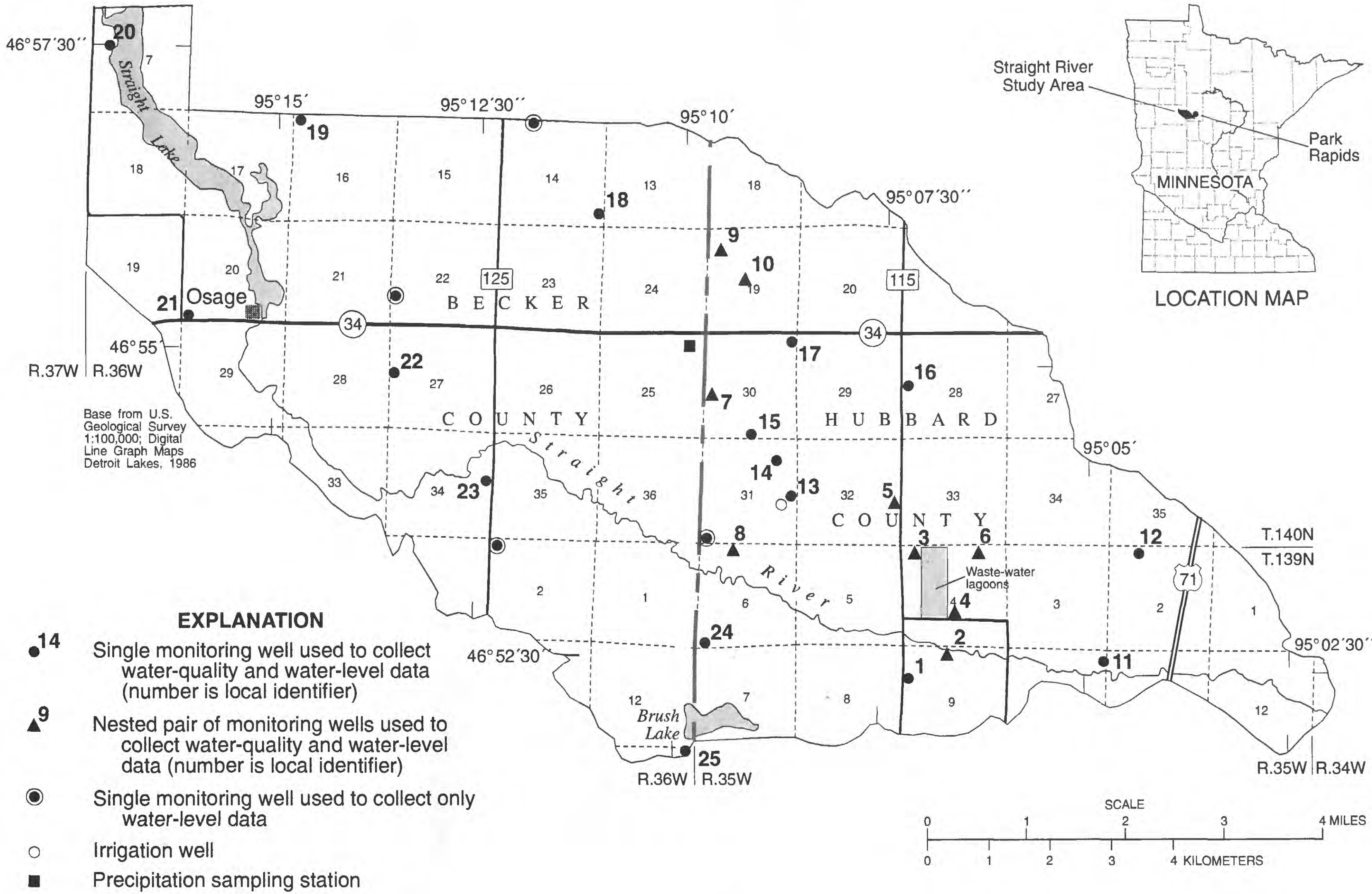


Figure 1. Locations of monitoring wells used to collect water-quality and water-level data and an irrigation well, a precipitation sampling station, and waste-water lagoons sampled for nitrogen constituents in the Straight River study area, north-central Minnesota.

level or water-quality data or both (fig. 1). Seventeen wells were installed during previous studies; these wells were constructed of 2-inch diameter galvanized-steel pipe with 3-foot-long wire-wound sand-point well screens. The other 21 wells were installed during the present study and were constructed of 2-inch diameter PVC (poly-vinyl chloride) pipe attached to 5-foot long PVC slotted well screens. Eighteen wells were installed as nested pairs; the other 20 wells were installed singly. The wells were screened near the water table except the deep wells of each nested pair, which were screened near the bottom of the aquifer.

Samples for water-quality analyses were collected from (1) 34 monitoring wells; (2) an irrigation well; (3) a precipitation sampling station; and (4) a municipal waste-water treatment lagoon (fig. 1). Procedures used to collect, treat, and store water samples are described by Fishman and Friedman (1989). Water was pumped from the wells for about 20 minutes and monitored to determine temperature, acidity (pH), and specific conductance. When these properties stabilized, the quality of water from the well was assumed to be representative of the quality of ground water in the aquifer and a sample was collected. Chemical analyses of water samples were done at the USGS NWQL (National Water Quality Laboratory) in Arvada, Colorado.

Acidity, alkalinity, specific conductance, and concentrations of dissolved calcium, magnesium, sodium, bicarbonate, chloride, sulfate, and minor ions were determined in ground-water samples collected from each of 10 randomly selected monitoring wells. Concentrations of nitrite nitrogen, nitrite plus nitrate nitrogen, ammonium nitrogen, and ammonium plus organic nitrogen, were determined in 1 to 5 ground-water samples collected from each of 34 monitoring wells. The isotopic composition of nitrate nitrogen was determined in 1 to 2 ground-water samples collected from each of 11 monitoring wells.

The laboratory analytical reporting limits were 0.001 mg/L for nitrite nitrogen, 0.002 mg/L for ammonium nitrogen, and 0.005 mg/L for nitrite plus nitrate nitrogen. (The analytical reporting limit is the minimum concentration of a chemical constituent that can be reliably cited.) Concentrations less than these limits were assumed to be equal to the limit for the purpose of statistical data analysis. The nitrite-nitrogen concentration generally was negligible; thus the nitrite-plus nitrate-nitrogen concentration was considered to be equivalent to the nitrate-nitrogen concentration. Nitrate-nitrogen concentrations equal to or greater than 3 mg/L were assumed to be increased above background conditions because of human activities (Anderson, 1993).

Concentrations of about 45 pesticides were determined by gas chromatography and mass spectroscopy in ground-water samples collected from eight randomly selected monitoring wells in the study area. These pesticides included triazine, acidimide, organophosphate, organochlorine, and carbamate pesticides. The laboratory analytical reporting limit for these pesticides generally was less than or equal to 0.02 μg/L but was as high as 0.08 μg/L.

Water levels were measured in monitoring wells at the time of sample collection. A synoptic measurement of water levels in 38 monitoring wells was made in May 1993. The water level in monitoring well 12 was measured weekly during spring and summer of 1993.

Quality Assurance

Blank-water and replicate samples were analyzed for nitrogen constituents and pesticides to verify analytical quality. Five field blanks were subjected to the same processing, handling, and equipment as sample water. Four of the field blanks consisted of inorganic-free water and were analyzed for the same nitrogen constituents as sample water. One field blank consisted of organic-free water and was analyzed for the same pesticides as sample water. Chemical analyses of the field blanks showed that concentrations of nitrogen constituents and pesticides did not exceed their respective analytical reporting limits. These results indicate that procedures used to clean field equipment did not result in cross contamination of water samples among sample sites. Replicate ground-water samples were collected at 10 monitoring wells and were chemically analyzed for nitrogen constituents at the USGS NWQL to evaluate the reproducibility and precision of the analytical results. These results were within 5 percent of each other.

Acknowledgments

Many people made valuable contributions to the success of this study. Bill Alden and Jeff Braaten of the Hubbard County Soil and Water Conservation District collected precipitation samples and water-level data, provided land-use data, and assisted in obtaining permission from local landowners to install monitoring wells. Dale Steevens of the R.D. Offutt Co. granted permission to install many of the monitoring wells used in this study and provided information about the agricultural and irrigation practices used on croplands managed by the R.D. Offutt Co. Dr. Carl Rosen of the University of Minnesota Soil Science Department

coordinated his study of best management practices for nitrogen fertilizer applications with this study, and provided useful background information about soils and agricultural practices in the study area.

Environmental Setting

Cultivated croplands extend over about one-half and forests extend over slightly more than one-third of the study area. Other land uses include livestock production, pasture, residential development, wetlands, and municipal waste-water treatment. Land use surrounding the study area is primarily agriculture but includes tourism and outdoor recreation associated with local lakes and forests.

Potatoes, corn, beans, and to a lesser extent small grains, are grown on the cultivated croplands. Typical application rates of nitrogen fertilizer (as total pounds of N per acre) on these crops are 235 for potatoes, 140 for corn, and 100-120 for beans (Bill Alden, Hubbard County Soil and Water Conservation District, written commun., 1995). Irrigation in the region of the study area has increased significantly during the past 25 years. A total of 5 irrigation wells were being used throughout the Straight River watershed in 1974, but by 1988 the number had increased to 48 (Stark and others, 1994).

Continental glaciation resulted in deposition of drift as much as 500 ft thick over crystalline bedrock (Lindholm and others, 1972). The drift was deposited primarily as outwash, till, and lake sediments. At land surface the drift is mostly outwash that forms flat plains and to a lesser extent till that forms hilly moraines. The lake sediments underlie the outwash and till (Stark and others, 1994). Post-glacial peat deposits accumulated in poorly drained, scattered depressions and formed a small number of wetlands.

Aquifers in the study area consist of surficial and buried glacial outwash deposits of sand and gravel. The surficial aquifer is unconfined and, therefore, under water-table conditions. The buried outwash aquifers are confined by overlying lake sediments and till. The surficial aquifer, which is part of the Pineland Sands (Helgesen, 1977), extends over most of the study area. The buried outwash aquifers, commonly referred to as confined-drift aquifers, are not mapped. The first buried outwash aquifer encountered below land surface is the uppermost confined-drift aquifer. The surficial and uppermost confined-drift aquifer are the major aquifers in the study area (Stark and others, 1994). The bedrock is not used as a source of supply; however, usable quantities of water may be available from fractures and weathered zones in the upper part of the bedrock.

The saturated zone of the surficial aquifer ranged in thickness from 0 to as much as 60 ft but generally ranged from 15 to 40 ft. The depth below land surface to the water table, which represents the thickness of the unsaturated zone of the surficial aquifer, ranged from 0 at the shoreline of lakes, ponds, streams, and wetlands to as much as 50 ft in upland areas, but generally ranged from 20 to 30 ft.

Precipitation and probably some irrigation return flow recharges the surficial aquifer (Stark and others, 1994). Most of the precipitation is rain that falls during May through September. Normal precipitation in the study area averages 24-26 in. per year (Baker and Kuehnast, 1978). During this study precipitation was below normal in 1992 (20.36 in.), and above normal in 1993 (27.73 in.) (National Oceanic and Atmospheric Administration, 1992 and 1993). Recharge to the surficial aquifer is rapid because of the highly permeable unsaturated zone. A 2.25 in. rainstorm measured on April 24, 1993 in Park Rapids (a town just east of the study area) probably initiated the steady rise of the water level in monitoring well 12 that began during the first half of May 1993 (fig. 2). The water level in monitoring well 12 continued to rise throughout the summer in response to precipitation that followed this storm.

Precipitation does not directly recharge the uppermost confined-drift aquifer because of the overlying confining unit. Recharge to this aquifer is leakage that slowly penetrates confining units in contact with the aquifer. Sources of this leakage are the overlying surficial aquifer and underlying confined-drift aquifers (Stark and others, 1994).

The water table sloped to the east along the northeastern side of the study area and to the southeast in the central part of the study area at an average horizontal hydraulic gradient of about 6-10 ft per mile (fig. 3). The regional ground-water flow paths defined by these gradients were generally in easterly and southeasterly directions, but local ground-water flow paths into ponds and wetlands probably were in many directions. The ground-water flow probably was much greater laterally than vertically because ground water that moves several hundreds of feet laterally typically moves only a few feet vertically in flat-terrain surficial aquifers (Anderson and Stoner, 1989). Ground-water discharge from the surficial aquifer was mainly into the Straight River.

Calcium and bicarbonate, and to a lesser extent magnesium, were the predominant chemical constituents in ground-water samples collected from ten monitoring wells (fig. 4). The samples ranged in pH

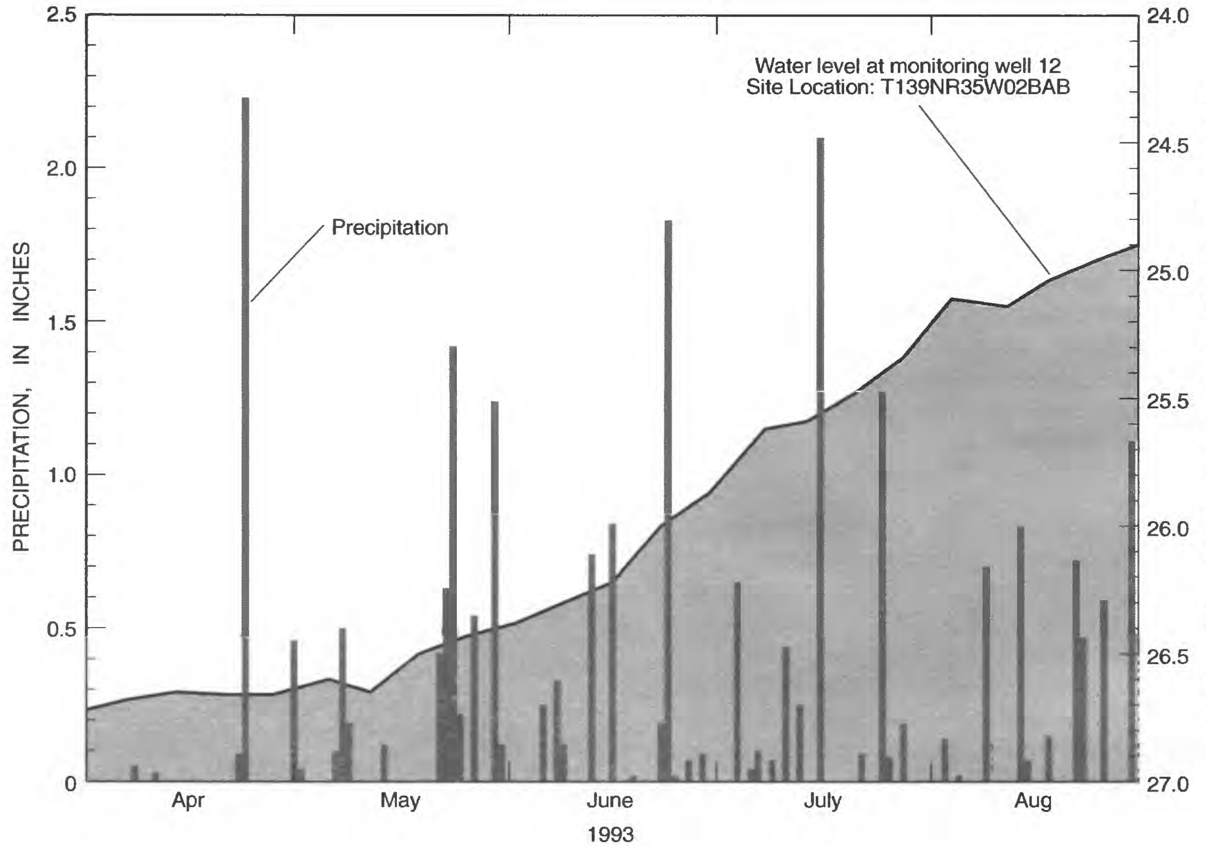


Figure 2. Water-level depth at monitoring well 12 in the Straight River study area and daily precipitation at Park Rapids, north-central Minnesota, April through August 1993.

from 7.6 to 8.6 and ranged in alkalinity from 165 to 312 mg/L as $CaCO_3$ (calcium carbonate) (table 1). The samples ranged in dissolved solids from 188 to 360 mg/L, which did not exceed the USEPA Secondary Maximum Contaminant Level of 500 mg/L for drinking water (U.S. Environmental Protection Agency, 1991).

Presence, Distribution, and Potential Sources of Nitrate and Selected Pesticides

Cultivated croplands, a feedlot and adjacent manured field, residential development, and waste-water treatment lagoons, were land uses investigated as potential source areas of nitrate in ground water in the surficial aquifer. These land uses were analyzed on an areal and site-specific basis. Soil organic matter was considered to be a small but undefined nitrate source that was constant across the study area. Precipitation and irrigation return flow were assumed to be insignificant sources of nitrate. Pesticides applied to croplands were considered to be the only potentially significant source of these chemicals in ground water in the surficial aquifer.

Areal Appraisal of Nitrate in Relation to Land Use

Nitrate sources in the study area appeared to be nonpoint. Ground water near the water table ranged in nitrate-nitrogen concentration (based on median values determined for sampled monitoring wells) from 5 to a little greater than 20 mg/L in the central and east-central parts of the study area (fig. 5). These areas generally were coincident with cultivated croplands. The concentrations generally were less than 5 mg/L in the western part and along the northern and southern sides of the study area. Land use in this portion of the study area was mostly forest. The median concentration at a location (local identifier 2) in the southeastern part of the study area was 50 mg/L (table 2). This location was downgradient from a feedlot and an adjacent manured field.

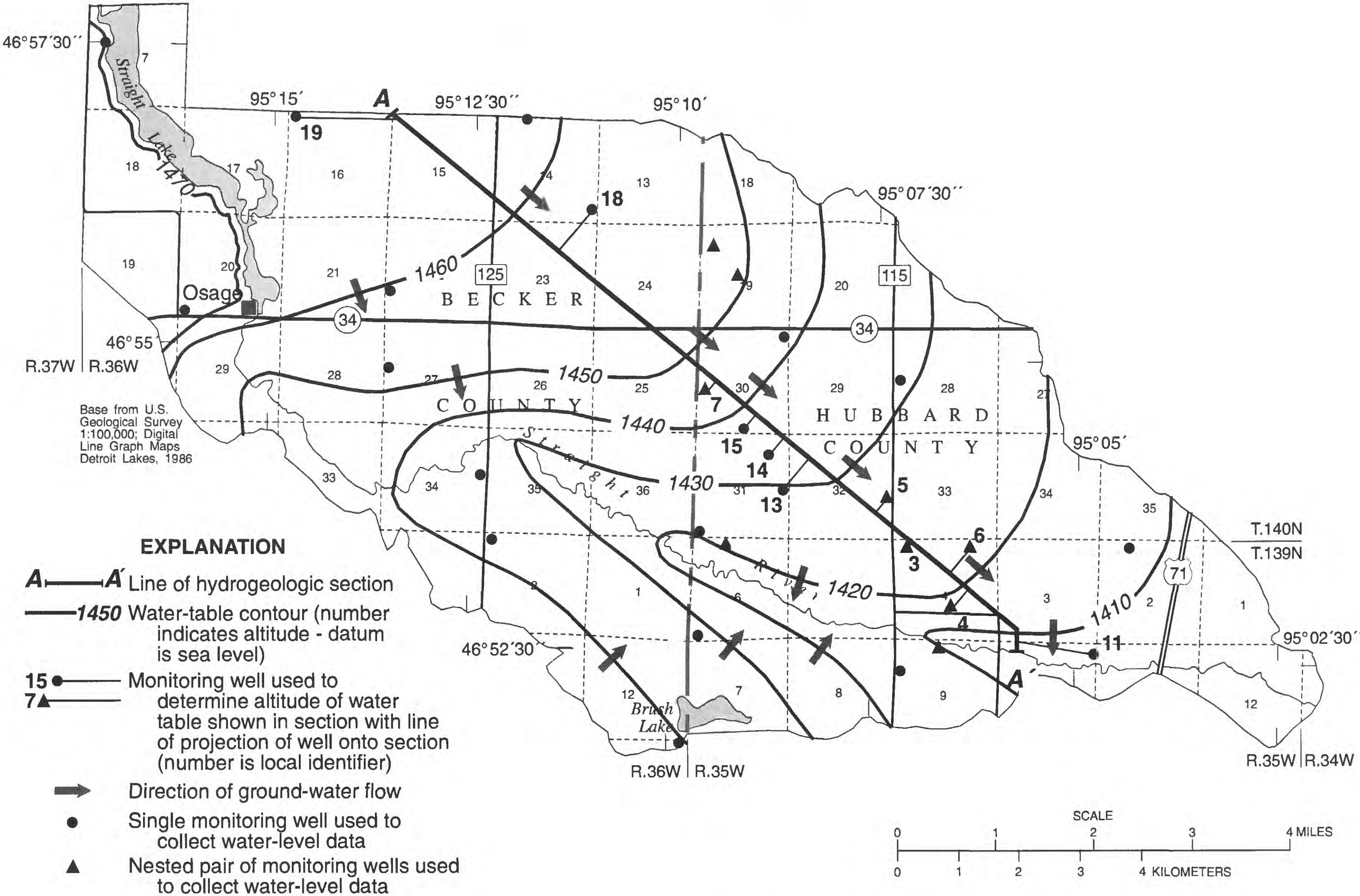
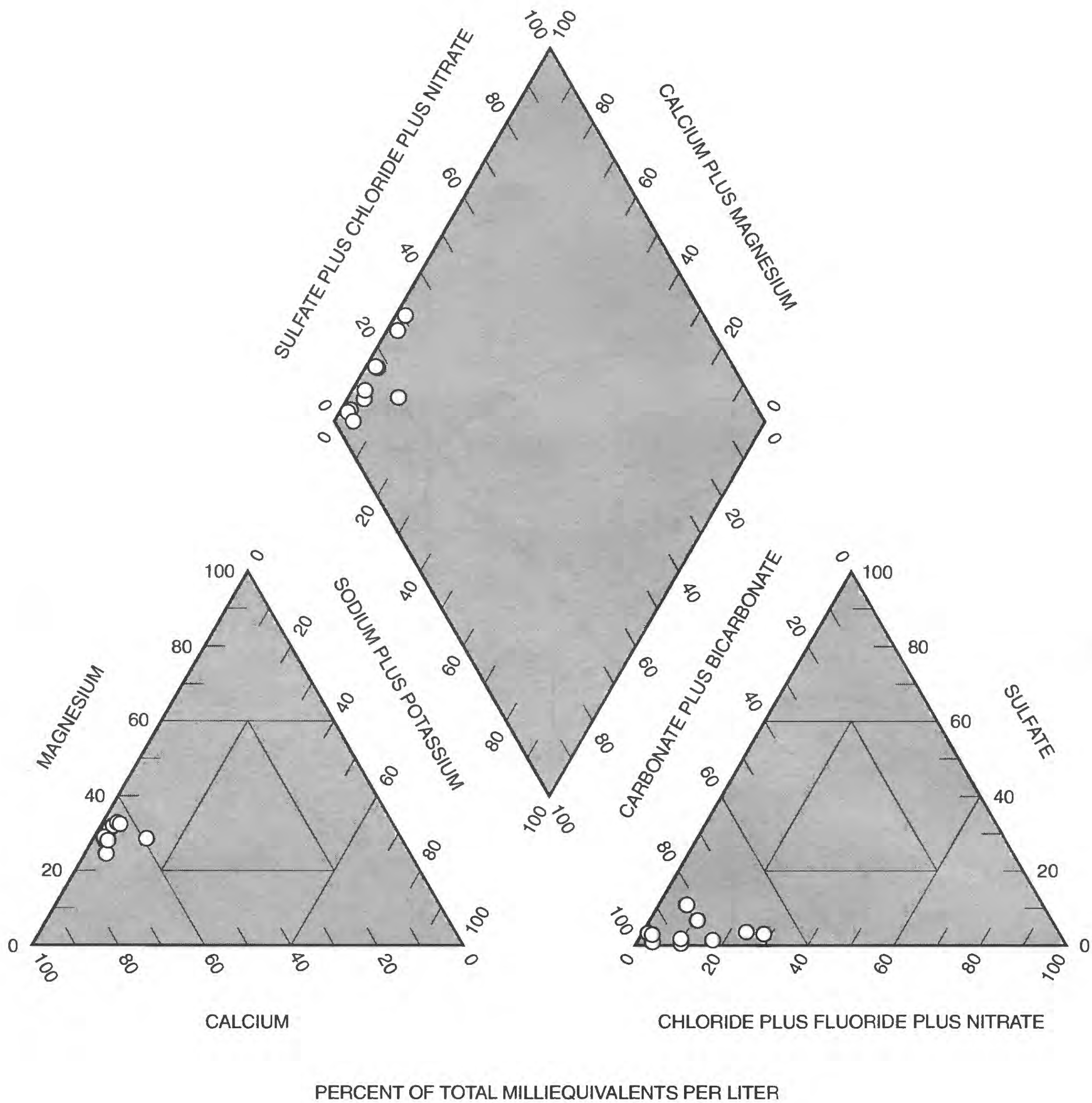


Figure 3. Water-table surface and ground-water flow directions in the surficial aquifer of the Straight River study area, north-central Minnesota, May 1993.



EXPLANATION

○ water sample

Figure 4. Percentage distribution of major ions in 10 ground-water samples from the surficial aquifer of the Straight River study area, north-central Minnesota.

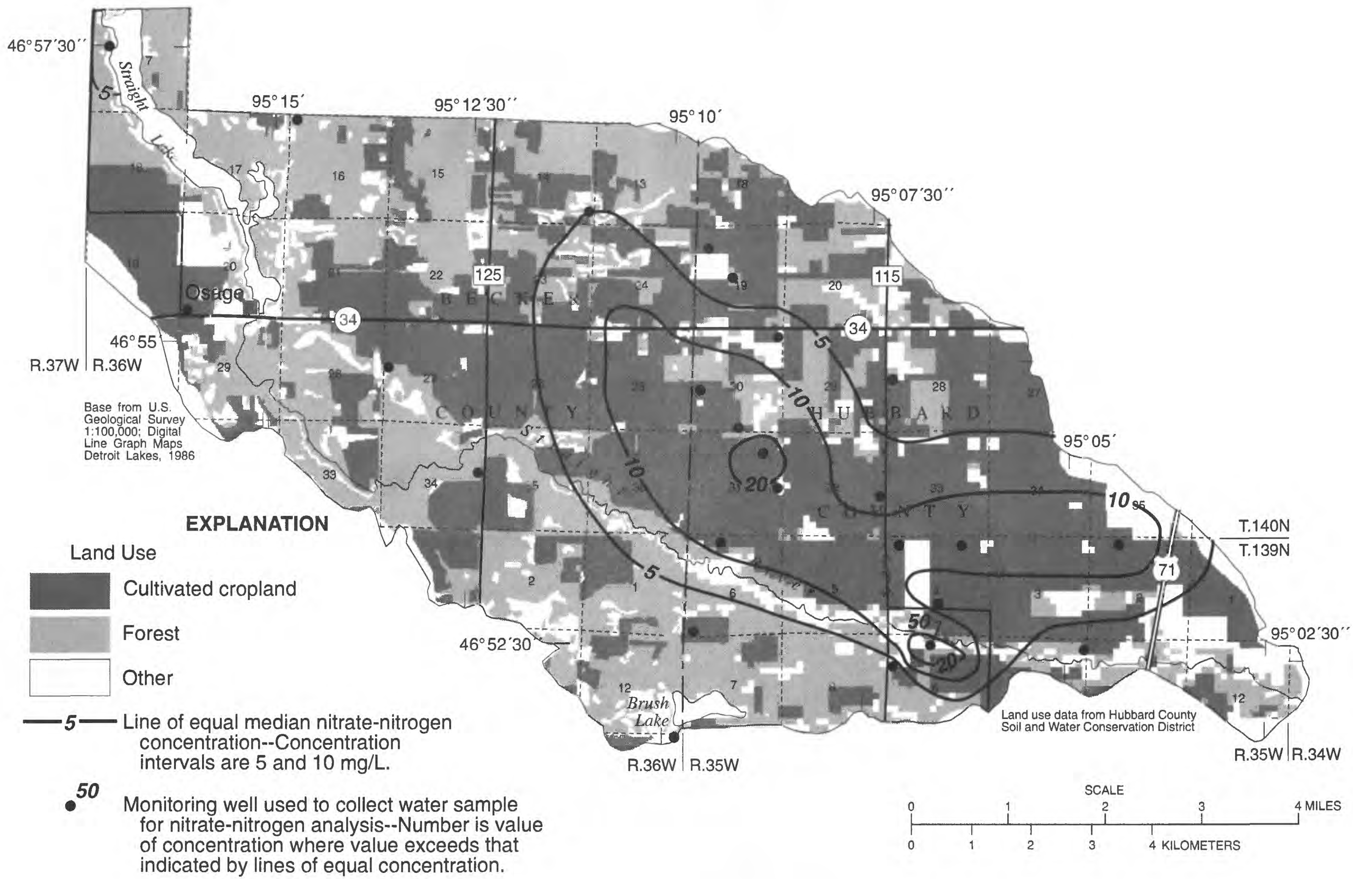


Figure 5. Median nitrate-nitrogen concentration near the water table in the surficial aquifer of the Straight River study area, north-central Minnesota, 1992-93.

Table 1.--Physical and chemical properties and chemical constituents in ground-water samples from monitoring wells completed in the surficial aquifer of the Straight River study area, north-central Minnesota.

[mg/L, milligrams per liter; °C, degrees Celsius; µS/cm, microsiemens per centimeter; <, less than]

Site location	Local identifiers, shown on figure 1	Date	Depth to water below land surface (feet)	Specific conduct-ance, lab (µS/cm)	pH, lab (standard units)	Alkalinity, total, field (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Fluoride, dissolved (mg/L as F)	Dissolved solids, residue at 180 °C, (mg/L)
T139NR35W02BAB	12	08/05/92	26.1	458	7.8	165	64	16	2.5	0.7	16	11	0.1	266
T140NR35W28CBB	16	08/04/92	17.4	361	7.8	185	52	13	1.9	.5	1.3	1.9	<.1	210
T140NR35W30AAA	17	08/06/92	15.7	504	7.7	193	70	18	3.4	.5	11	12	.1	330
T140NR36W14DDD	18	08/04/92	19.4	416	8.6	199	57	17	2.3	.8	11	11	.1	250
T140NR36W16BBB	19	08/04/92	42.4	465	8.4	238	66	19	2.1	.6	.9	7.3	.1	258
T140NR36W20CCC	21	08/03/92	16.6	534	8.5	238	64	19	14	1.7	34	2.7	.1	288
T140NR36W27BCB	22	08/06/92	20.2	391	7.9	191	56	14	3.1	.8	6.5	5.6	.1	216
T140NR36W34ADD	23	08/04/92	28.7	505	8.6	235	67	21	2.9	1.7	13	31	.2	306
T139NR35W06CCC	24	08/05/92	21.2	351	7.9	180	53	11	4.0	.8	1.9	2.9	.1	188
T139NR36W13AAA	25	08/06/92	18.0	619	7.6	312	84	26	6.1	.6	24	2.4	.2	360

Table 2.--Nitrogen constituents and nitrate-nitrogen $\delta^{15}N$ values in water from monitoring wells completed in the surficial aquifer, an irrigation well completed in the uppermost confined-drift aquifer, a precipitation sampling station, and a waste-water lagoon, in the Straight River study area, north-central Minnesota.

[mg/L, milligrams per liter; --, not determined; <, less than; NA, not applicable; sw, shallow well; dw, deep well; ‰, delta units in parts per thousand]

Site location	Local well identifiers shown on figure 1 and site type	Date	Well depth (feet)	Depth below land surface to water level (feet)	Depth below water level to top of screen (feet)	Nitrogen, ammonium, dissolved (mg/L as N)	Nitrogen, nitrite, dissolved (mg/L as N)	Nitrogen, ammonium + organic, dissolved (mg/L as N)	Nitrogen, nitrite + nitrate, dissolved (mg/L as N)	$\delta^{15}N$ for nitrate nitrogen (delta units as ‰)
T139NR35W09BCB	1	08/26/92	38	30.2	2.8	0.122	<0.001	<0.2	0.18	--
		10/27/92	38	30.1	2.9	.076	.010	<.2	.16	--
		05/14/93	38	30.3	2.7	.070	<.001	<.2	.18	7.7
		09/01/93	38	28.6	4.4	.027	<.001	<.2	.18	2.4
T139NR35W09BBA	2 (sw)	08/26/92	28	25.8	[1]-2.8	.033	<.001	.4	50	--
		10/27/92	28	25.8	-2.8	.013	.003	.3	60	--
		05/14/93	28	26	-3.0	<.002	<.001	.5	51	3.8
		09/01/93	28	22.7	.3	<.002	<.001	.3	42	4.2
T139NR35W09BBA	2 (dw)	08/26/92	45	26.0	14.0	.143	.023	.3	18	--
		10/27/92	45	26.0	14.0	.019	.00	.2	18	--
		05/14/93	45	26.0	14.0	<.002	.016	.3	7.7	--
		09/01/93	45	24.1	15.9	.006	.024	.2	23	--
T139NR35W04BBA	3 (sw)	08/27/92	30	24.5	.5	.019	<.001	.2	11	--
		10/27/92	30	24.0	1.0	.008	.002	<.2	9.1	
		05/12/93	30	24.2	.8	.003	<.001	<.2	18	1.7
		09/01/93	30	22.7	2.3	<.002	<.001	<.2	17	--
		10/14/93	30	--	--	--	--	--	--	1.6
T139NR35W04BBA	3 (dw)	08/27/92	42	25.5	11.5	.024	.001	<.2	7.5	--
		10/27/92	42	25.0	12.0	.006	.003	<.2	6.0	--
		05/12/93	42	25.1	11.9	<.002	<.001	<.2	7.6	--
		09/01/93	42	23.7	13.3	<.002	<.001	<.2	6.4	--
T139NR35W04DBC	4 (sw)	08/26/92	33	28.5	-.5	.031	<.001	<.2	.75	--
		10/27/92	33	28.6	-.6	.011	.012	<.2	4.2	--
		05/13/93	33	28.5	-.5	<.002	<.001	.2	6.5	3.0
		09/02/93	33	26.1	1.9	<.002	<.001	<.2	1.0	--
		10/14/93	33	--	--	--	--	--	--	3.0
T139NR35W04DBC	4 (dw)	08/26/92	39	28.6	5.4	.035	<.001	<.2	9.5	--
		10/27/92	39	28.5	5.5	.010	.004	<.2	8.4	--
		05/13/93	39	28.5	5.5	<.002	<.001	<.2	9.6	--
		09/02/93	39	26.1	7.9	<.002	<.001	<.2	11	--
T140NR35W32DAA	5 (sw)	08/27/92	25	22.7	-2.7	.034	<.001	<.2	8.3	--
		10/27/92	25	22.9	-2.9	.007	.004	<.2	8.8	--
		05/13/93	25	22.9	-2.9	<.002	<.001	<.2	7.8	.4
		09/08/93	25	20.9	-.9	<.002	<.001	.3	7.3	1.8

Table 2.--Nitrogen constituents and nitrate-nitrogen $\delta^{15}N$ values in water samples from monitoring wells completed in the surficial aquifer, an irrigation well completed in the uppermost confined-drift aquifer, a precipitation sampling station, and a waste-water lagoon, in the Straight River study area, north-central Minnesota.--Continued

Site location	Local well identifiers shown on figure 1 and site type	Date	Well depth (feet)	Depth below land surface to water level (feet)	Depth below water level to top of screen (feet)	Nitrogen, ammonium, dissolved (mg/L as N)	Nitrogen, nitrite, dissolved (mg/L as N)	Nitrogen, ammonium + organic, dissolved (mg/L as N)	Nitrogen, nitrite + nitrate, dissolved (mg/L as N)	$\delta^{15}N$ for nitrate nitrogen (delta units as ‰)
T140NR35W32DAA	5 (dw)	08/27/92	45	23.1	16.9	0.025	0.006	<0.2	4.2	--
		10/27/92	45	22.9	17.1	.007	.003	<.2	3.8	--
		05/13/93	45	23.1	16.9	<.002	<.001	<.2	4.0	--
		09/08/93	45	21.2	18.8	<.002	<.001	<.2	4.0	--
T139NR35W04ABA	6 (sw)	08/27/92	30	25.0	.0	.010	<.001	<.2	12	--
		10/27/92	30	24.4	.6	.026	.003	<.2	11	--
		05/13/93	30	24.5	.5	<.002	<.001	<.2	21	<0
		09/08/93	30	22.9	2.1	<.002	<.001	.2	21	1.7
T139NR35W04ABA	6 (dw)	08/27/92	49	25.4	18.6	.019	<.001	<.2	7.5	--
		10/27/92	49	24.7	19.3	.010	.003	<.2	4.2	--
		05/13/93	49	24.8	19.2	<.002	<.001	<.2	6.9	--
		09/08/93	49	23.2	20.8	<.002	<.001	<.2	6.4	--
T140NR35W30CBB	7 (sw)	08/26/92	22	20.9	-3.9	.026	<.001	.2	18	--
		10/28/92	22	20.2	-3.2	.006	.002	<.2	17	--
		05/13/93	22	20.5	-3.5	.009	<.001	<.2	11	5.1
		09/08/93	22	18.3	-1.3	<.002	<.001	<.2	17	2.4
T140NR35W30CBB	7 (dw)	08/26/92	53	21.1	26.9	.083	<.001	<.2	<.005	--
		10/28/92	53	20.9	27.1	.052	<.001	<.2	.01	--
		05/13/93	53	20.6	27.4	.052	<.001	<.2	<.005	--
		09/08/93	53	18.5	29.5	.062	.002	.3	<.005	--
T139NR35W06BAA	8 (sw)	08/25/92	37	35.7	-1.7	.047	<.001	.2	18	--
		10/28/92	37	35.6	-1.6	.009	.004	.2	17	--
		05/13/93	37	35.5	-1.5	<.002	<.001	.3	18	2.4
		08/30/93	37	32.5	1.5	.004	<.001	<.2	15	--
		09/01/93	37	--	--	<.002	<.001	<.2	12	3.0
T139NR35W06BAA	8 (dw)	08/25/92	42	36.1	.9	.036	<.001	<.2	14	--
		10/28/92	42	35.9	1.1	.006	.004	<.2	9.2	--
		05/13/93	42	35.8	1.2	.005	<.001	<.2	15	--
		08/30/93	42	33.6	3.4	.006	<.001	<.2	18	--
T140NR35W19BCB	9 (sw)	08/26/92	25	23.3	-3.3	.015	<.001	<.2	1.0	--
		11/03/92	25	23.7	-3.7	.118	.014	<.2	2.1	--
		05/12/93	25	23.6	-3.6	<.002	<.001	<.2	1.1	3.4
		08/31/93	25	21.4	-1.4	.006	<.001	<.2	4.4	--
T140NR35W19BCB	9 (dw)	08/26/92	36	23.4	7.6	.131	<.001	<.2	.02	--
		11/03/92	36	23.4	7.6	.067	.010	<.2	1.0	--
		05/12/93	36	23.5	7.5	.085	.002	<.2	<.005	--
		08/31/93	36	20.7	10.3	.074	<.001	<.2	.01	--

Table 2.--Nitrogen constituents and nitrate-nitrogen $\delta^{15}N$ values in water samples from monitoring wells completed in the surficial aquifer, an irrigation well completed in the uppermost confined-drift aquifer, a precipitation sampling station, and a waste-water lagoon, in the Straight River study area, north-central Minnesota.--Continued

Site location	Local well identifiers shown on figure 1 and site type	Date	Well depth (feet)	Depth below land surface to water level (feet)	Depth below water level to top of screen (feet)	Nitrogen, ammonium, dissolved (mg/L as N)	Nitrogen, nitrite, dissolved (mg/L as N)	Nitrogen, ammonium + organic, dissolved (mg/L as N)	Nitrogen, nitrite + nitrate, dissolved (mg/L as N)	$\delta^{15}N$ for nitrate nitrogen (delta units as ‰)
T140NR35W19CAA	10 (sw)	08/26/92	16	15.3	-4.3	0.014	0.008	<0.2	4.3	--
		11/03/92	16	15.4	-4.4	.176	.011	<.2	<.005	--
		05/12/93	16	14.7	-3.7	.021	<.001	.4	3.5	4.9
		08/31/93	16	12.6	-1.6	<.002	<.001	<.2	3.9	--
T140NR35W19CAA	10 (dw)	08/26/92	50	15.3	29.7	.019	<.001	<.2	5.8	--
		11/03/92	50	15.4	29.6	.024	.006	<.2	1.0	--
		05/12/93	50	15.4	29.6	<.002	<.001	<.2	2.7	--
		08/31/93	50	13.4	31.6	.002	<.001	<.2	2.9	--
T139NR35W10AAD	11	08/27/92	27.5	18.2	6.3	.039	.018	<.2	4.0	--
		10/26/92	27.5	18.0	6.5	.016	.005	<.2	3.7	--
		05/11/93	27.5	18.0	6.5	<.002	.012	<.2	4.8	--
		09/01/93	27.5	16.9	7.6	<.002	.009	<.2	4.4	--
T139NR35W02BAB	12	08/05/92	31	26.1	1.9	.004	.001	<.2	12	--
		10/26/92	31	26.4	1.6	.008	.003	<.2	10	--
		05/11/93	31	26.5	1.5	<.002	<.001	<.2	11	--
		09/08/93	31	24.9	3.1	<.002	.001	<.2	12	--
T140NR35W31DAA	13	05/12/93	29.5	23.4	3.1	<.002	<.001	.3	24	--
		09/02/93	29.5	21.9	4.6	<.002	.001	<.2	9.6	--
T140NR35W31ADB	14	05/12/93	28.5	25.5	-2.0	<.002	<.001	<.2	20	1.2
		06/29/93	28.5	24.7	-1.2	.009	<.001	<.2	23	--
		07/15/93	28.5	--	--	<.002	<.001	<.2	21	--
		08/18/93	28.5	23.7	-.2	<.002	.002	.3	25	--
		09/02/93	28.5	23.5	0.0	<.002	<.001	<.2	24	2.5
T140NR35W30CDD	15	09/08/93	28	22.5	.5	<.002	.001	.2	15	--
T140NR35W28CBB	16	08/04/92	20	17.4	1.1	.011	.002	<.2	2.0	--
		11/04/92	20	17.3	1.2	.037	.004	<.2	2.3	--
		05/10/93	20	16.9	1.6	<.002	<.001	<.2	2.2	--
		08/30/93	20	15.3	3.2	<.002	<.001	<.2	1.6	--
T140NR35W30AAA	17	08/06/92	20.5	15.7	2.3	.010	.003	<.2	13	--
		11/03/92	20.5	16.5	1.5	.014	.006	<.2	1.0	--
		05.10/93	20.5	16.3	1.7	<.002	<.001	.3	14	--
		08/30/93	20.5	14.2	3.8	<.002	.003	<.2	3.6	--
T140NR36W14DDD	18	08/04/92	23	19.4	1.1	.010	.002	<.2	4.4	--
		11/04/92	23	20.7	-.2	.014	.004	<.2	4.9	--
		05/11/93	23	20.4	.1	<.002	<.001	<.2	5.4	--
		08/31/93	23	19.0	1.5	.005	<.001	<2	5.7	--

Table 2.--Nitrogen constituents and nitrate-nitrogen $\delta^{15}N$ values in water samples from monitoring wells completed in the surficial aquifer, an irrigation well completed in the uppermost confined-drift aquifer, a precipitation sampling station, and a waste-water lagoon, in the Straight River study area, north-central Minnesota.--Continued

Site location	Local well identifiers shown on figure 1 and site type	Date	Well depth (feet)	Depth below land surface to water level (feet)	Depth below water level to top of screen (feet)	Nitrogen, ammonium, dissolved (mg/L as N)	Nitrogen, nitrite, dissolved (mg/L as N)	Nitrogen, ammonium + organic, dissolved (mg/L as N)	Nitrogen, nitrite + nitrate, dissolved (mg/L as N)	$\delta^{15}N$ for nitrate nitrogen (delta units as ‰)
T140NR36W16BBB	19	08/04/92	46.5	42.4	1.1	0.008	0.002	<0.2	.96	--
		01/13/93	46.5	43.6	-.1	.017	.001	<.2	.74	--
		08/31/93	46.5	41.8	1.7	<.002	<.001	<.2	.79	--
T140NR36W07BCD	20	05/11/93	16	12.2	-1.2	<.002	<.001	<.2	12	--
		08/31/93	16	11.8	-.8	<.002	<.001	<.2	7.2	--
T140NR36W20CCC	21	08/03/92	19.5	16.6	-.1	.008	.001	<.2	1.1	--
		05/11/93	19.5	15.6	.9	.003	<.001	<.2	.98	--
		08/31/93	19.5	13.5	3.0	.005	<.001	<.2	.87	--
T140NR36W27BCB	22	08/06/92	27	20.2	3.8	.010	.002	<.2	3.1	--
		11/04/92	27	20.1	3.9	.176	.003	<.2	.01	--
		05/10/93	27	20.7	3.3	.003	<.001	<.2	2.7	--
		08/31/93	27	17.8	6.2	<.002	.001	<.2	3.0	--
T140NR36W34ADD	23	08/04/92	36	28.7	4.3	.260	.003	.4	.01	--
		10/28/92	36	28.8	4.2	.410	.001	.4	<.005	--
		05/10/93	36	28.8	4.2	.193	<.001	.3	<.005	--
		08/31/93	36	27.5	5.5	.174	<.001	.3	<.005	--
T139NR35W06CCC	24	08/05/92	28	21.2	3.8	.006	.002	<.2	1.1	--
		10/28/92	28	21.5	3.5	.003	.003	<.2	.55	--
		05/11/93	28	20.8	4.2	<.002	<.001	<.2	.89	--
		09/01/93	28	18.2	6.8	.007	<.001	<.2	.79	--
T139NR36W13AAA	25	08/06/92	21	18.0	1.0	.017	.001	<.2	.11	--
		10/28/92	21	18.7	.3	<.002	<.001	<.2	.10	--
		05/11/93	21	17.5	1.5	<.002	<.001	<.2	.15	--
		09/01/93	21	14.6	4.4	.004	<.001	<.2	.11	--
T140NR35W31DAA	irrigation well	07/15/93	163	--	--	.493	.001	.8	.06	--
		09/02/93	163	--	--	.448	<.001	.7	.01	--
T139NR35W04BAB	waste-water lagoon	07/15/93	NA	NA	NA	.045	.005	1.5	.04	--
		09/01/93	NA	NA	NA	.028	.030	1.7	.08	--
T140NR36W25ADB	precipitation	07/16/93	NA	NA	NA	.174	.009	.4	.12	--

[1] Negative values indicate depth below top of screen to water level.

North of the Straight River median nitrate-nitrogen concentrations determined for ground-water samples from monitoring wells screened near the bottom of the surficial aquifer ranged from less than 5 mg/L in the upgradient part of the study area to as much as 10 to 15 mg/L in the downgradient part of the study area (fig. 6). The hydrogeologic section in figure 7 shows ground-water flow and the distribution of nitrate nitrogen in the surficial aquifer determined from water-levels and median concentrations for sampled monitoring wells.

Figure 7 indicates that the concentration was less than 5 mg/L throughout the saturated zone in the upgradient part of the section. The concentration generally was from 5 to greater than 20 mg/L near the water table and was less than 5 mg/L near the bottom of the aquifer in the middle part of the section. The increased concentration near the water table in the middle part of the section probably resulted from downward movement of nitrate from cultivated croplands.

The concentration was less than 5 mg/L near the water table and was from 5 to less than 10 mg/L near the bottom of the aquifer in the downgradient part of the section near the Straight River. The increased concentration near the bottom of the aquifer in the downgradient part of the section may be attributable to mixing with nitrate-enriched recharge from the middle part of the section. This recharge probably flowed into and mixed with water near the bottom of the aquifer in the downgradient part of the section.

Areal Appraisal of Selected Pesticides in Relation to Land Use

Trace amounts of the pesticides atrazine, metolachlor, and alachlor were detected in 4 of 8 ground-water samples collected from 8 monitoring wells screened near the water table during post-planting conditions of 1993 (table 3). Detection of a pesticide indicated presence at a concentration equal to or greater than the analytical reporting limit. The concentrations of the following pesticides were below their respective reporting limits: propachlor; butylate; simazine; prometon; de-ethylatrazine; cyanazine; fonofos; alpha-BHC; *p,p'*-DDE; chloropyrifos; lindane; dieldrin; malathion; parathion; diazinon; metribuzin; 2,6-di-ethyl-analine; trifluralin; dimethoate, ethalfluralin; phorate; terbacil; linuron; methylparathion; EPTC; pebulate; tebuthiuron; molinate; ethoprop; benfluralin; carbofuran; terbufos; pronamide; disulfoton; triallate; propanil; carbaryl; thiobencarb; DCPA; pendimethalin; napropamide; propargite; methylazinphos; and *cis*-permethrin.

Atrazine was detected in samples from 3 (local identifiers 6, 12, and 14) of 5 monitoring wells where the local land use predominantly was cultivated cropland, and at 1 (local identifier 18) of 3 monitoring wells where the local land use predominantly was forest. These results weakly suggest that atrazine detection was more likely beneath cultivated croplands than beneath forests. The concentrations ranged from 0.01 µg/L for monitoring well 18 to 0.11 µg/L for monitoring well 12. These concentrations were well below the USEPA MCL of 3 µg/L for atrazine. Alachlor and metolachlor were

Table 3.--Pesticides in ground-water samples from monitoring wells completed in the surficial aquifer of the Straight River study area, north-central Minnesota, 1992-93.
[µg/L, micrograms per liter; --, not detected]

Site location	Local identifiers, shown on figure 1	Date	Depth to water below land surface (feet)	Atrazine, dissolved (µg/L)	Metolachlor, dissolved (µg/L)	Alachlor, dissolved (µg/L)
T139NR35W04ABA	6	08/04/92	25.1	0.04	--	--
T139NR35W02BAB	12	08/05/92	26.1	.11	--	--
T140NR35W31ADB	14	08/03/92	25.9	.03	0.01	0.02
T140NR35W28CBB	16	08/04/92	17.4	--	--	--
T140NR36W14DDD	18	08/04/92	19.4	.01	--	--
T140NR36W20CCC	21	08/03/92	16.6	--	--	--
T140NR36W34ADD	23	08/04/92	28.7	--	--	--
T139NR35W06CCC	24	08/05/92	21.2	--	--	--

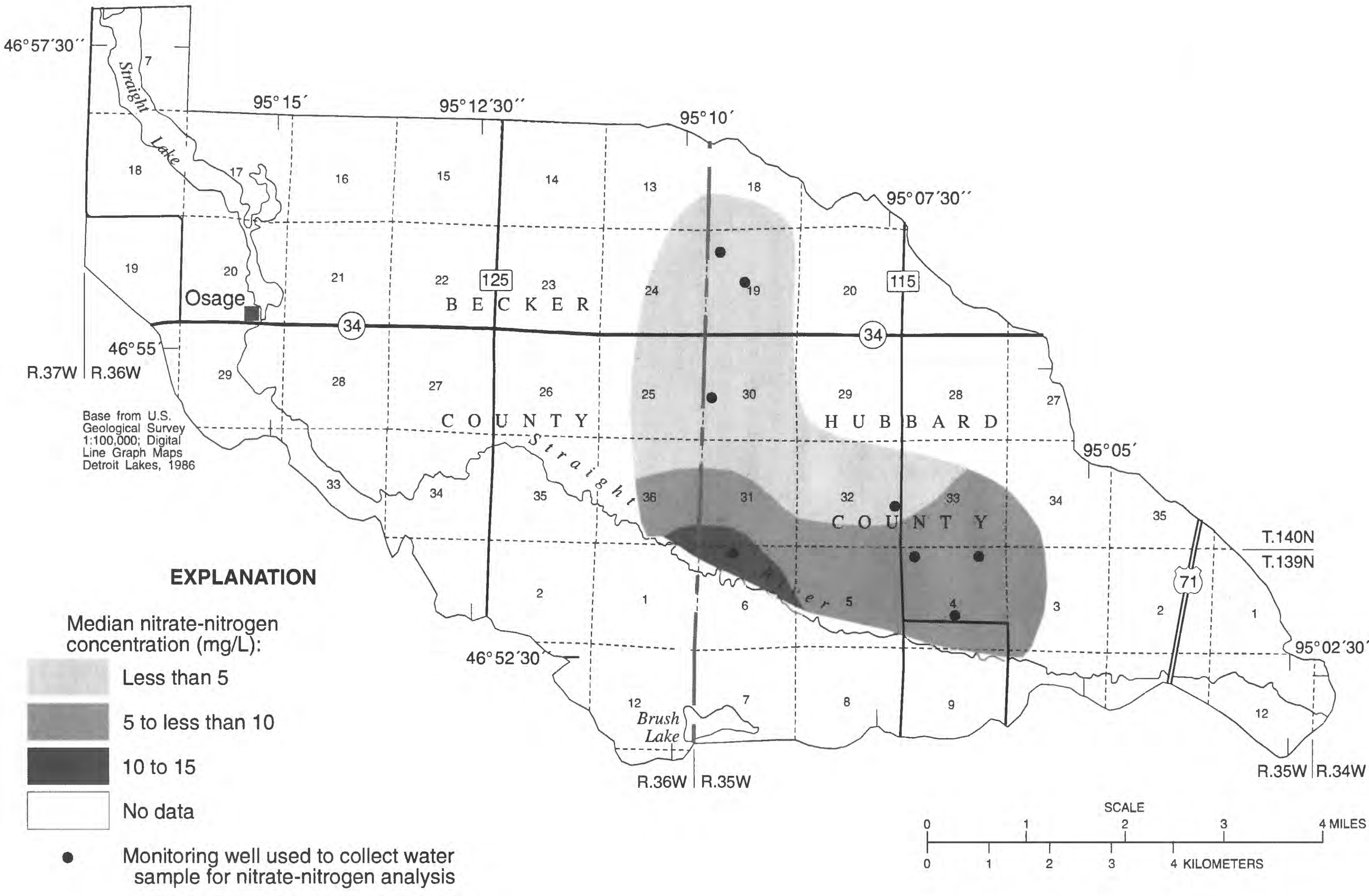


Figure 6. Median nitrate-nitrogen concentration near the bottom of the surficial aquifer of the Straight River study area, north-central Minnesota, 1992-93.

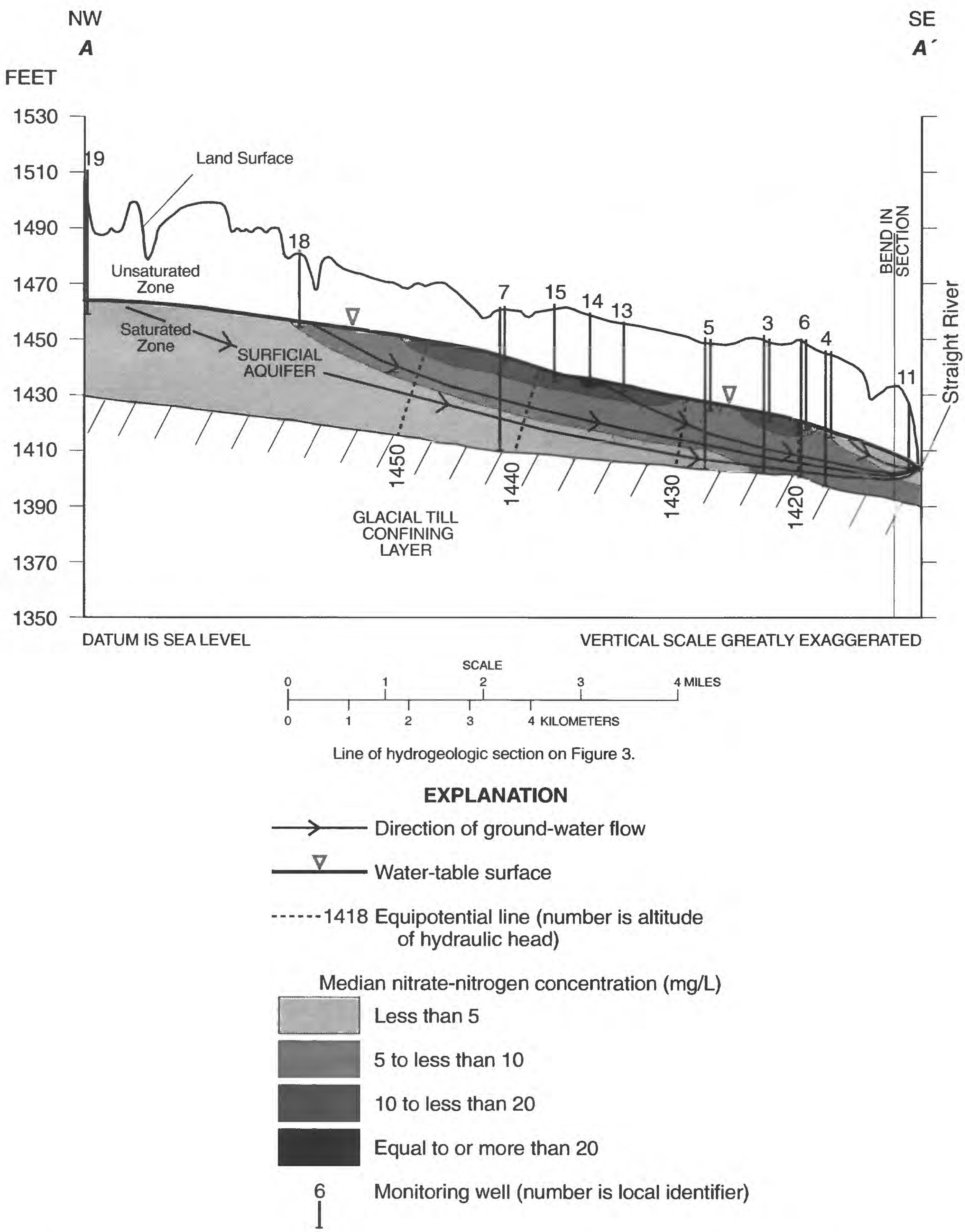


Figure 7. Hydrogeologic section showing ground-water flow and median nitrate-nitrogen concentration in the surficial aquifer of the Straight River study area, north-central Minnesota, 1992-93.

present in a ground-water sample from monitoring well 14 at concentrations of 0.02 and 0.01 μg/L, respectively. No USEPA MCL has been established for either of these two pesticides. Pesticides were not detected in ground-water samples from monitoring wells 16, 21, 23, and 24.

Site-Specific Appraisal of Nitrate Beneath Five Land-Use Settings

Changes in nitrate-nitrogen concentration in the direction of ground-water flow were analyzed at the following land-use settings: (1) a feedlot and an adjacent manured field; (2) cultivated croplands irrigated with municipal waste water from three treatment lagoons; (3) cultivated croplands irrigated with ground water from the uppermost confined-drift aquifer; (4) a residential development with septic systems; and (5) three municipal waste-water treatment lagoons (fig. 8). Median nitrate-nitrogen concentrations were determined for ground-water samples collected from nested pairs of monitoring wells screened near the water table and near the bottom of the surficial aquifer. These wells were located upgradient and downgradient from each setting. (Only one well screened near the water table was installed upgradient from the feedlot and manured field because the aquifer was only about 5 feet thick.) If the median nitrate-nitrogen concentration increased from the upgradient to downgradient wells, then the land-use setting was considered to be a nitrate source area.

The largest increase was at the feedlot and manured field (fig. 9). The median concentration increased from slightly greater than 0 mg/L (upgradient) to 50 mg/L (downgradient) near the water table. The median concentration downgradient and near the bottom of the aquifer was 18 mg/L. These results indicate that animal waste was a nitrate source for ground water beneath this land-use setting.

At the cultivated croplands irrigated with municipal treated waste water, the median concentration increased from 8.0 mg/L (upgradient) to 16 mg/L (downgradient) near the water table and from 4.0 mg/L (upgradient) to 6.7 mg/L (downgradient) near the bottom of the aquifer. These results indicate that fertilizer probably was a nitrate source for ground water beneath this land-use setting. Small nitrate-nitrogen concentrations of 0.04 mg/L and 0.08 mg/L in two waste-water lagoon samples (table 2) indicate that the irrigation water was not a nitrate source for ground water beneath this land use setting.

At the cultivated croplands irrigated with ground water, the median concentration remained 17 mg/L (upgradient and downgradient) near the water table. The median concentration near the bottom of the aquifer increased from slightly greater than 0 mg/L (upgradient) to 14 mg/L (downgradient). The increased nitrate upgradient and near the water table may be attributable to nitrate sources in cultivated croplands upgradient from this land-use setting. These results indicate that fertilizer probably was a nitrate source for ground water beneath this land-use setting.

Increased nitrate-nitrogen concentrations, from about 20 to 25 mg/L, were present in five ground-water samples collected during the 1993 growing season from a monitoring well (local identifier 14) that was located within the cultivated croplands irrigated with ground water (table 2). This monitoring well was screened near the water table beneath a potato field. The increased concentrations in ground-water samples from this monitoring well also indicate that fertilizer probably was a nitrate source for ground water beneath this land-use setting.

At the residential development the median concentration increased from 1.6 mg/L (upgradient) to 3.7 mg/L (downgradient) near the water table and from slightly greater than 0 mg/L (upgradient) to 2.8 mg/L (downgradient) near the bottom of the aquifer. These results weakly suggest that septic-system leachates and possibly lawn fertilizer may have been nitrate sources for ground water beneath this land-use setting.

At the waste-water lagoons the median concentration decreased from 14 mg/L (upgradient) to 2.6 mg/L (downgradient) near the water table, and increased from 7.0 mg/L (upgradient) to 9.6 mg/L (downgradient) near the bottom of the aquifer. The decreased concentration downgradient near the water table, combined with the small concentration in two waste-water samples, indicates that waste water was not a nitrate source for ground water beneath this land-use setting. The decreased and small concentrations in the ground- and waste-water samples suggest that ground water downgradient near the water table may have been slightly diluted by the waste water with respect to nitrate. The increased concentration downgradient near the bottom of the aquifer may be attributable to nitrate-enriched recharge from cultivated croplands upgradient from this land-use setting.

Analysis of Nitrogen Isotopes

Under certain hydrogeologic conditions, the isotopic composition of nitrate nitrogen in ground water is a qualitative indicator of nitrate sources (Gormly and Spalding, 1979; Kreitler and Browning, 1983; Flipse and Bonner, 1985; Heaton, 1986; Kaplan and Magaritz, 1986; Wells and Krothe, 1989; and Komor and

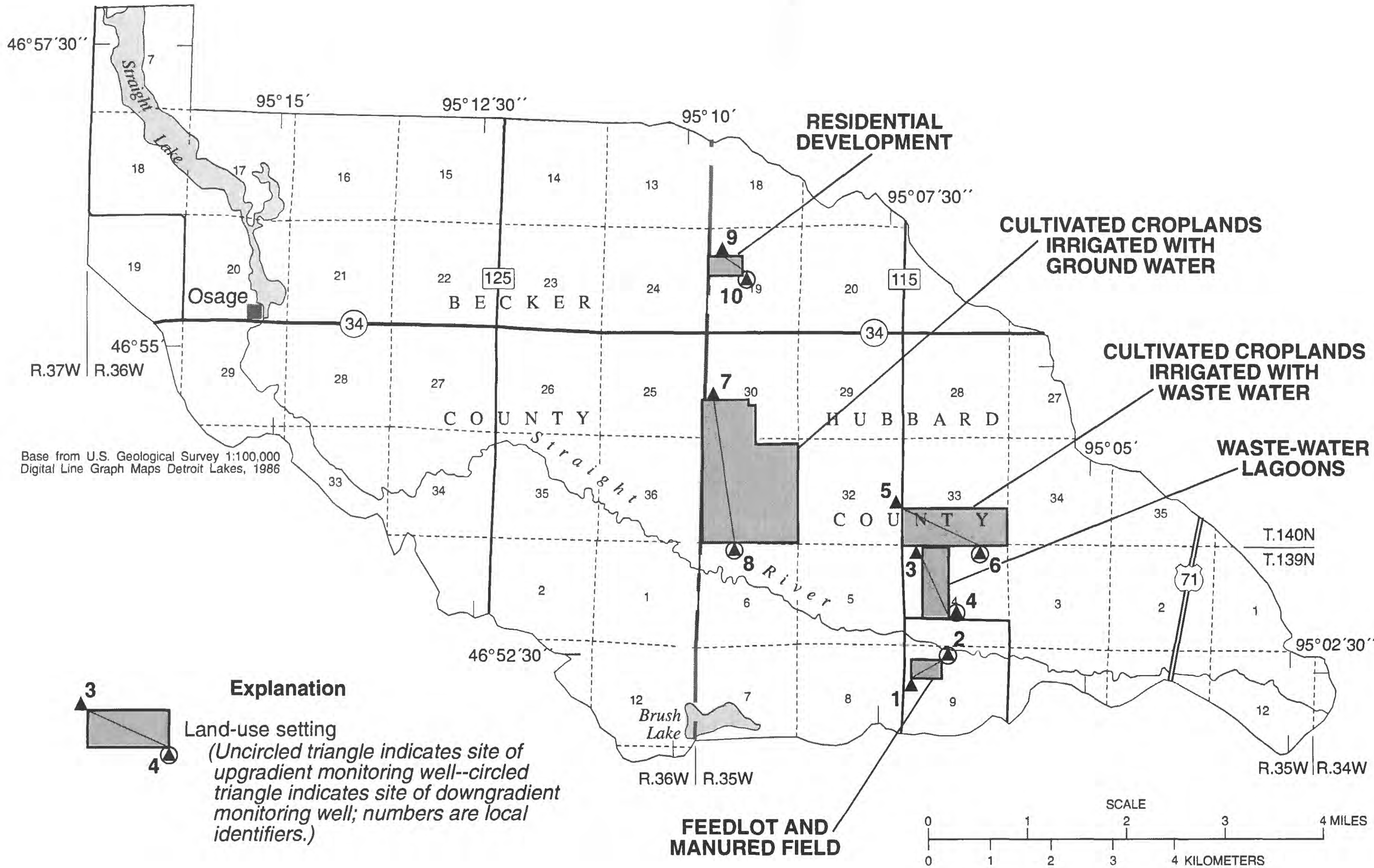


Figure 8. Land-use settings and monitoring wells used in site-specific appraisals of nitrate in the surficial aquifer of the Straight RIver study area, north-central Minnesota, 1992-93.

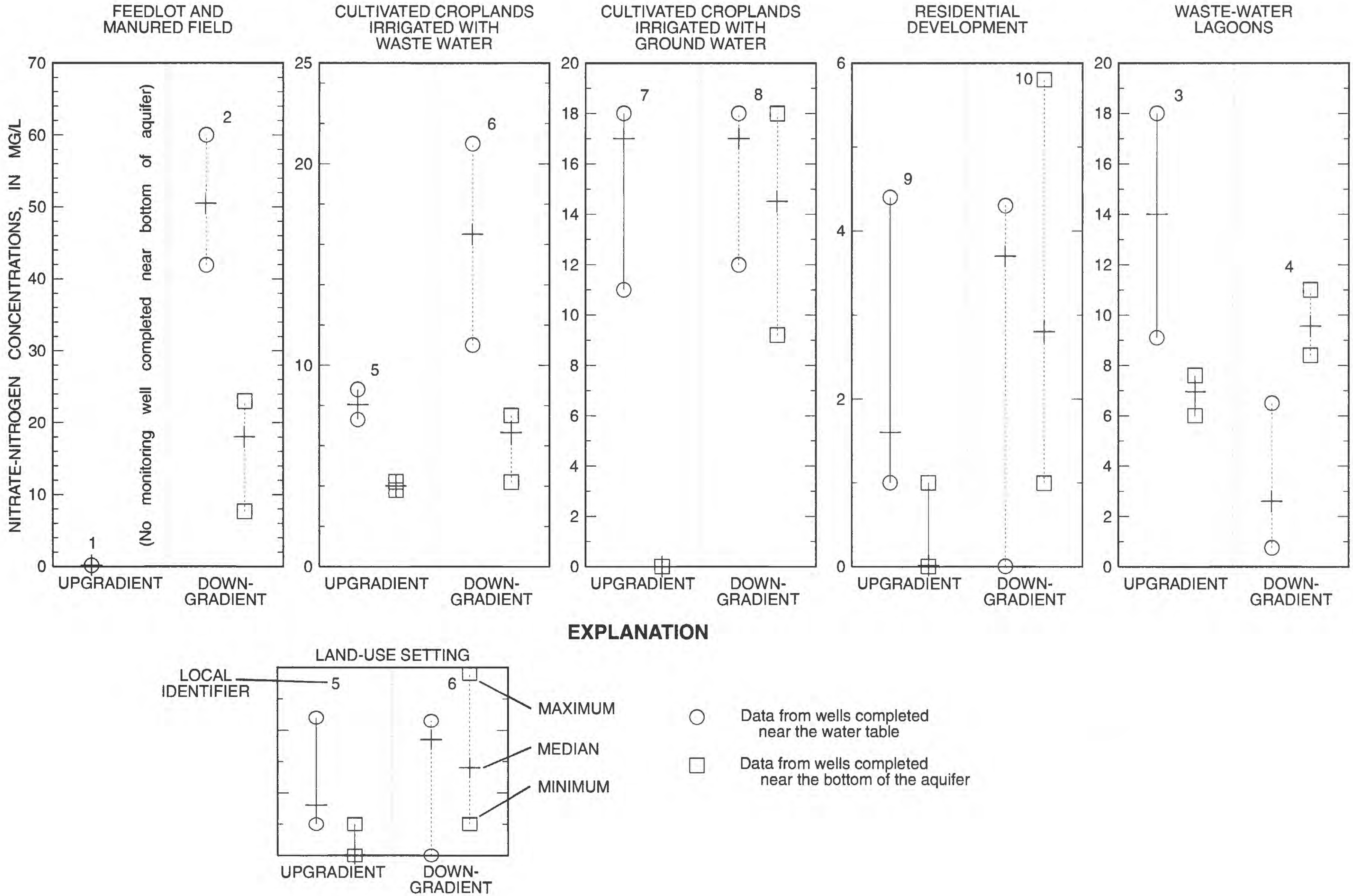


Figure 9. Nitrate-nitrogen concentration in ground-water samples from near the water table and near the bottom of the surficial aquifer at sites upgradient and downgradient from five land-use settings in the Straight River study area, north-central Minnesots, 1992-93.

Anderson, 1993). Nitrogen-isotope $\delta^{15}N$ values are expressed as ‰ (delta units in parts per thousand). These values are determined from the ratio of heavy (^{15}N) to light (^{14}N) nitrogen isotopes in water-sample nitrogen and in N_2, and are defined by the following expression:

$$\delta^{15}N = \{ [(^{15}N/^{14}N)\ \text{Water-sample N} / (^{15}N/^{14}N)\ N_2] - 1 \} \times 1{,}000\ ‰.$$

A positive $\delta^{15}N$ value indicates that the heavy ^{15}N isotope is more abundant in water-sample nitrogen than in N_2, and a negative $\delta^{15}N$ value indicates that the heavy ^{15}N isotope is less abundant in water sample nitrogen than in N_2.

The interpretation of nitrogen isotope data in the present study is based on differences in the expected ranges of $\delta^{15}N$ values for nitrate nitrogen derived from three principal sources. These expected ranges and sources are: (1) from -4 to 4 ‰ for commercial fertilizer; (2) from 4 to 9 ‰ for soil organic matter; and (3) from 10 to 22 ‰ for animal waste (Heaton, 1986).

Interpretations of nitrogen isotope data must be made with regard to potential limitations of the method (Hauck and others, 1972; Edwards, 1973; Bremner and Tabatabai, 1973; Meints and others, 1975; and Broadbent and others, 1980). First, the $\delta^{15}N$ value for soil organic nitrogen may vary outside the expected range of 4 to 9 ‰. Second, increases in the $\delta^{15}N$ value of nitrate nitrogen may result from fractionation caused by chemical transformations, such as denitrification, and by physical processes, such as volatilization of ammonia during nitrification.

Mean or individual $\delta^{15}N$ values for nitrate nitrogen were determined in ground-water samples from monitoring wells screened near the water table and located upgradient and downgradient from the five land-use settings. Estimates of the importance of fertilizer as a nitrate source from the isotope data probably are conservative. Denitrification and volatilization of ammonia may have increased the $\delta^{15}N$ values of nitrate nitrogen from fertilizer above the expected range. This fractionation would have resulted in underestimation of the importance of fertilizer as a nitrate source.

At the feedlot and manured field, mean $\delta^{15}N$ values were 5.1 ‰ (upgradient) and 4.0 ‰ (downgradient), respectively. The upgradient value was in the lower part of the expected range for soil organic matter and close to the expected range for fertilizer. This value was weakly consistent with local land use. Forests were upgradient from this land-use setting. The downgradient value was borderline between the expected ranges for soil organic matter and fertilizer and less than the expected range for animal waste. This result was inconsistent with local land use because the nitrate appeared to be predominantly from soil organic matter rather than from animal waste.

At the cultivated croplands irrigated with waste water mean $\delta^{15}N$ values were 1.1 ‰ (upgradient) and 0.9 ‰ (downgradient), respectively. These values were within the expected range for fertilizer and were consistent with local land use. Nitrogen fertilizer was applied upgradient from and within this land-use setting. Waste water used for irrigation did not appear to be a nitrate source, based on the isotope ratios.

At the cultivated croplands irrigated with ground water mean $\delta^{15}N$ values were 3.8 ‰ (upgradient) and 2.7 ‰ (downgradient), respectively. A mean $\delta^{15}N$ value determined within this setting in a potato field (local identifier 14) was 1.9 ‰. The upgradient value was close to the expected range for soil organic matter and within the expected range for fertilizer. The downgradient and potato field values were within the expected range for fertilizer and were consistent with local land use. Nitrogen fertilizer was applied within this land-use setting. During the 1993 growing season the potato field received 240 pounds of fertilizer-nitrogen per acre (Dr. Carl Rosen, Department of Soil Science, University of Minnesota, written commun., 1994).

At the residential development, $\delta^{15}N$ values were 3.4 ‰ (upgradient) and 4.9 ‰ (downgradient), respectively. These values were borderline between the expected ranges for soil organic matter and fertilizer. No predominant nitrate source, including septic-system leachates that would be expected to have $\delta^{15}N$ values in the range for animal waste, could be clearly identified from the isotope ratios.

At the waste-water lagoons, mean $\delta^{15}N$ values were 1.7 ‰ (upgradient) and 3.0 ‰ (downgradient), respectively. The upgradient value was within the expected range for fertilizer and consistent with local land use. Cultivated croplands fertilized with nitrogen were upgradient from this land-use setting. The downgradient value was in the upper part of the expected range for fertilizer and slightly less than the expected range for soil organic matter. No predominant nitrate source, including waste water that would be expected to have $\delta^{15}N$ values in the range for animal waste, could be clearly identified from the isotope ratios.

SUMMARY

This study investigated the presence, distribution, and potential sources of nitrate and selected pesticides in ground water in the surficial aquifer along the Straight River in north-central Minnesota. The surficial aquifer is a glacial outwash deposit of sand and gravel. In recent years local residents and officials of government agencies have become concerned about nitrate and pesticides in ground water in this aquifer. Increased concentrations of these chemicals can create health risks for humans and livestock. Ground water in the surficial aquifer is particularly vulnerable to nitrate and pesticides that may move downward from near the surface of land used for cultivation, livestock production, residential development, and municipal waste-water treatment.

The surficial aquifer along the Straight River is part of an extensive outwash deposit known as the Pineland Sands. In the study area, this aquifer generally ranged in saturated thickness from 15 to 40 ft. The depth below land surface to the water table generally ranged from 20 to 30 ft. From the northeastern and central parts of the study area ground water generally flowed east to southeast and discharged into the Straight River. Calcium, magnesium, and bicarbonate were the principal dissolved ions in the ground water.

Land use was analyzed in terms of potential source areas of nitrate. Ground water near the water table ranged in nitrate-nitrogen concentration (median values determined from sampled monitoring wells) from less than 5 to a little greater than 20 mg/L except at a location where the concentration was 50 mg/L. The spatial variation indicated that increased nitrate probably was attributable to nonpoint sources. Relatively large concentrations generally were coincident with cultivated croplands and concentrations less than 5 mg/L generally were coincident with forests. The highest concentration of 50 mg/L was downgradient from a feedlot and an adjacent manured field.

North of the Straight River the nitrate-nitrogen concentration near the bottom of the surficial aquifer increased from less than 5 to as much as 10 to 15 mg/L along the general direction of ground-water flow. Nitrate-enriched recharge from cultivated croplands probably flowed into and mixed with water near the bottom of the aquifer in downgradient areas.

An areal appraisal of pesticides found that trace amounts of atrazine were detected in 4 of 8 ground-water samples collected from 8 monitoring wells screened near the water table. The detections were more frequent in cultivated croplands (detections at 3 of 5 monitoring wells) than in forests (detections at 1 of 3 monitoring wells). Thus detection of atrazine may be more likely in cultivated croplands than in forests. The concentrations were well below the MCL of 3 μg/L for atrazine established by the USEPA. Trace amounts of metolachlor and alachlor were detected in water from one of the wells where atrazine was detected. MCLs for these two pesticides have not been established by the USEPA.

Five land-use settings were analyzed as potential nitrate source areas on a site-specific basis. Upgradient to downgradient changes in median nitrate-nitrogen concentrations determined for sampled monitoring wells along the direction of ground-water flow through these settings were: (1) an increase from slightly greater than 0 to 50 mg/L near the water table for a feedlot and an adjacent manured field; (2) increases from 8.0 to 16 mg/L near the water table and from 4.0 to 6.7 mg/L near the bottom of the aquifer for cultivated croplands irrigated with waste water; (3) no change from 17 mg/L near the water table and an increase from slightly greater than 0 to 14 mg/L near the bottom of the aquifer for cultivated croplands irrigated with ground water; (4) increases from 1.6 to 3.7 mg/L near the water table and from slightly greater than 0 to 2.8 mg/L near the bottom of the aquifer for a residential development with septic systems; and (5) a decrease from 14 to 2.6 mg/L near the water table and an increase from 7.0 to 9.6 mg/L near the bottom of the aquifer for three waste-water treatment lagoons.

These results indicate that: (1) animal waste was a nitrate source at the feedlot and adjacent manured field; (2) fertilizer probably was a nitrate source at the cultivated croplands irrigated with waste water (the irrigation waste water probably was not a nitrate source because nitrate-nitrogen concentrations in two waste-water samples were small); (3) fertilizer probably was a nitrate source at the cultivated croplands irrigated with ground water; (4) septic system leachates, and possibly lawn fertilizer, may have been nitrate sources at the residential development; and (5) waste water was not a nitrate source at the three treatment lagoons.

Nitrogen isotope $\delta^{15}N$ values for nitrate nitrogen were analyzed to qualitatively estimate nitrate sources based on the following ranges: (1) from -4 to 4 ‰ for commercial fertilizer; (2) from 4 to 9 ‰ for soil organic matter; and (3) from 10 to 22 ‰ for animal waste. Mean $\delta^{15}N$ values were determined for sampled monitoring wells in the direction of ground-water flow beneath the five land-use settings. The mean upgradient and downgradient values were: (1) 5.1 ‰ and 4.0 ‰ for the

feedlot and adjacent manured field; (2) 1.1 ‰ and 0.9 ‰ for the cultivated croplands irrigated with waste water; (3) 3.8 ‰ and 2.7 ‰ for the cultivated croplands irrigated with ground water; (4) 3.4 ‰ and 4.9 ‰ for the residential development; and (5) 1.7 ‰ and 3.0 ‰ for the three waste-water treatment lagoons. A mean value for a sampled monitoring well within the cultivated croplands irrigated with ground water was 1.9 ‰.

The mean $\delta^{15}N$ values were within the expected range for fertilizer upgradient from the waste-water lagoons, upgradient and downgradient from the cultivated croplands irrigated with waste water, and downgradient from and beneath the cultivated croplands irrigated with ground water. These results were consistent with local land use. Nitrogen fertilizer was applied to croplands upgradient from and within these land-use settings. The mean $\delta^{15}N$ value was in the lower part of the expected range for soil organic matter and close to the expected range for fertilizer upgradient from the feedlot and manured field. This result was weakly consistent with local land use. Forests were upgradient from this land-use setting. The mean $\delta^{15}N$ value was less than the expected range for animal waste downgradient from the feedlot and manured field. This result was inconsistent with local land use because the nitrate appeared to be predominantly from soil organic matter rather than from animal waste. The mean $\delta^{15}N$ values for the residential development, waste-water lagoons, and cultivated croplands irrigated with waste water indicated that septic-system leachates and waste water were not nitrate sources.

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