

MINNESOTA DEPARTMENT OF NATURAL RESOURCES

*Insert to the*

**GEOLOGIC ATLAS  
STEARNS COUNTY, MINNESOTA**

**COUNTY ATLAS SERIES, ATLAS C-10**

**PART A**

*(Published separately by the Minnesota Geological Survey)*

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*Plate 2, Bedrock geology*

*Plate 3, Surficial geology*

*Plate 4, Quaternary stratigraphy*

*Plate 5, Depth to bedrock and  
thickness of Cretaceous strata*

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**PART B**

***Plate 8, Hydrogeology of the Quaternary water-table system***

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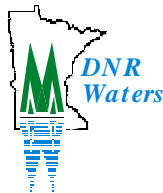
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**PART C**

*(Published separately by the Minnesota Geological Survey)*

Text supplement



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# Summary of Ground-Water Chemistry

by

Hua Zhang

## Introduction

The study of natural water chemistry is important in evaluating ground-water resources of a county. By sampling and analyzing ground water, hydrogeologists can determine its characteristics and describe aquifers. A study of general water chemistry can provide indicators of the quality and age of a county's ground water.

The purpose of this report is to describe the composition of Stearns County's ground water based on field and laboratory testing of water samples. The testing involved physical parameters, major and selected minor ions, and isotopes. Physical parameters measured in the field were water temperature, acid concentration (pH), oxidation-reduction potential (Eh), conductivity, dissolved oxygen, and alkalinity.

Laboratory chemical analysis was completed by the Department of Geology and Geophysics at the University of Minnesota. Major ions analyzed were calcium, magnesium, sodium, potassium, bicarbonate, sulfate, and chloride. Additional ions analyzed included nitrate, iron, manganese, and phosphate. Isotope analysis coordinated by the department included tritium ( $^3\text{H}$ ), carbon-14 ( $^{14}\text{C}$ ), and stable isotopes of oxygen and hydrogen. The amount of tritium in all collected water samples was measured to determine whether the water entered the ground before or after 1953. Samples from 15 wells with undetectable tritium were analyzed by carbon-14 radioisotope dating to evaluate the age of older ground waters. Stable isotopes of oxygen and

hydrogen ( $^{18}\text{O}$  and  $^2\text{H}$ ) were analyzed in samples from nine wells and four lakes to evaluate sources of ground water and mixing processes.

Water samples from 59 domestic wells and 5 lakes were collected throughout the county by Department of Natural Resources (DNR) staff during 1994-96. Most samples came from Quaternary confined aquifers (30 samples); fewer samples came from the Cretaceous aquifer and the Precambrian bedrock (15 and 8 samples, respectively). A small number of samples were collected from lakes (5) and the Quaternary water-table system (6) because data were available from Clark and others (1998). The locations of the sampled wells and lakes are shown on Figure 1.

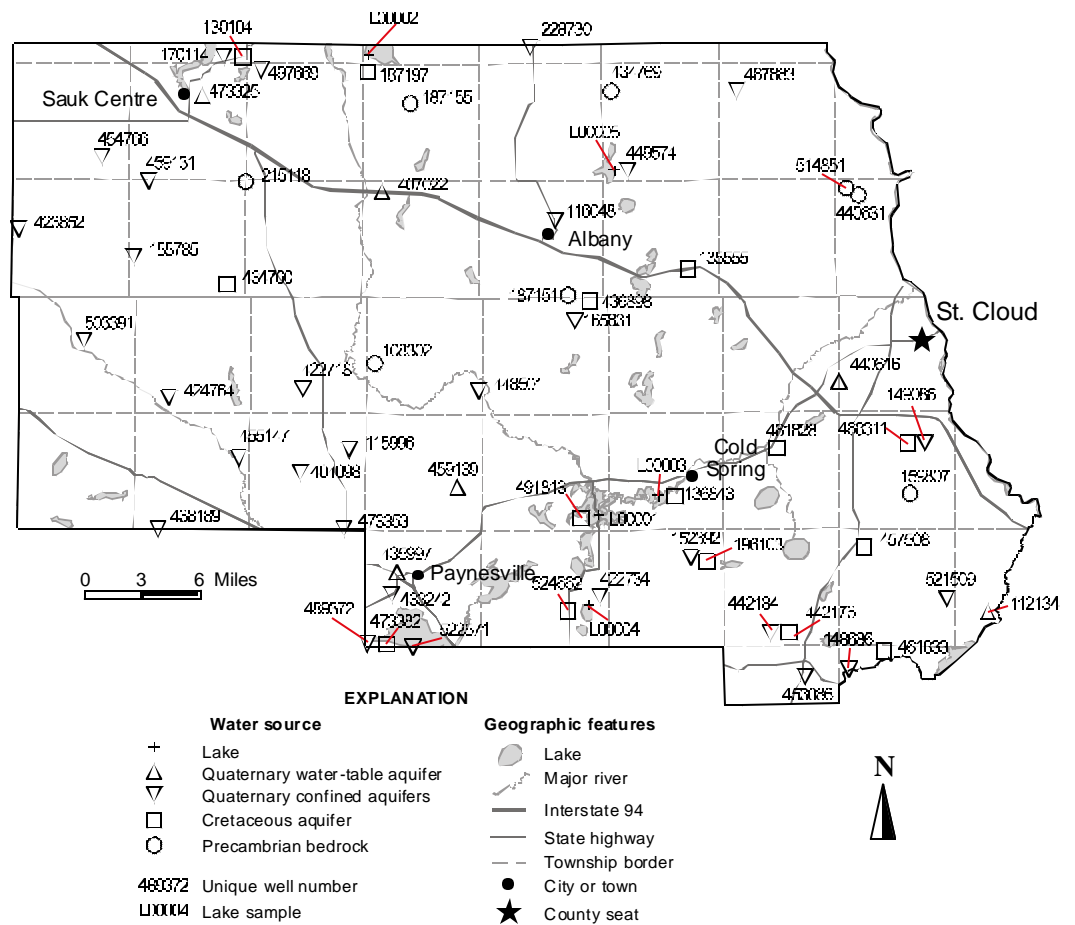


FIGURE 1. Location of sampling sites

**TABLE 1. Characteristics of natural waters in Stearns County.**

[Samples collected from 1994 to 1996 by Minnesota Department of Natural Resources staff; Eh corrected for sample temperature; nitrate (NO<sub>3</sub>) expressed as nitrogen (N); 1 milligram per liter (mg/L) nitrogen = 4.5 mg/L nitrate; phosphate (PO<sub>4</sub>) expressed as phosphorus (P); 1 mg/L phosphorus = 3.1 mg/L phosphate; alkalinity expressed as CaCO<sub>3</sub>; TDS, total dissolved solids, is the sum of cation and anion concentrations expressed in mg/L; hardness is total hardness expressed as CaCO<sub>3</sub>; 2.5(Ca<sup>2+</sup>) + 4.1(Mg<sup>2+</sup>), where Ca<sup>2+</sup> and Mg<sup>2+</sup> are concentrations of the ions in mg/L; μS/cm, microsiemens per centimeter; mV, millivolts; TU, tritium units; --, not applicable; <, less than]

	Well depth Units	Temperature feet °C	pH pH unit	Conductivity μS/cm	Eh mV	Dissolved oxygen mg/L	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	Al mg/L	Fe mg/L	Mn mg/L	Sr mg/L	Ba mg/L	Si mg/L	HCO <sub>3</sub> <sup>-</sup> mg/L	Cl mg/L	Br mg/L	NO <sub>3</sub> -N mg/L	SO <sub>4</sub> mg/L	PO <sub>4</sub> -P mg/L	F mg/L	Alkalinity mg/L	TDS mg/L	Hardness mg/L	Tritium TU	
<b>Lakes</b>																												
Number of samples	--	5	5	5	5	5	5	5	5	5	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Minimum	--	17.5	8.47	340	230	9.3	32.1	21.4	6.5	4.39	<0.005	<0.01	0.006	0.097	0.055	0.17	94	8.20	<0.02	<0.01	9.5	<0.03	0.14	154	181	168	10.5	
25th percentile	--	18.7	8.60	360	326	11.0	52.6	25.4	8.1	4.82	0.010	0.04	0.023	0.136	0.062	0.32	120	18.90	<0.02	<0.01	17.5	<0.03	0.18	196	252	236	11.4	
Median	--	21.9	8.77	360	336	12.3	57.5	25.6	8.1	5.41	0.013	0.04	0.036	0.142	0.067	0.83	131	19.70	<0.02	<0.01	20.5	<0.03	0.18	215	273	249	12.0	
75th percentile	--	26.1	8.78	370	353	12.4	61.6	26.2	8.7	5.50	0.027	0.12	0.051	0.145	0.083	1.52	156	22.20	<0.02	0.11	21.6	<0.03	0.19	255	302	261	12.2	
Maximum	--	28.9	8.83	373	505	14.7	68.7	27.1	14.6	5.57	0.062	0.12	0.117	0.164	0.084	4.19	162	25.10	0.03	0.24	24.8	<0.03	0.21	265	323	283	13.4	
<b>Quaternary water-table aquifer</b>																												
Number of samples	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
Minimum	43	7.6	7.06	400	47	0.2	77.0	25.4	5.4	1.45	<0.005	0.07	0.071	0.116	0.070	9.18	146	7.66	<0.02	<0.01	12.6	<0.03	0.09	239	310	297	2.2	
25th percentile	45	9.3	7.16	443	215	0.5	81.6	28.5	7.2	2.25	<0.005	0.31	0.095	0.138	0.108	9.80	168	10.43	<0.02	0.09	15.7	<0.03	0.10	275	368	321	6.4	
Median	46	9.3	7.34	456	324	0.8	97.7	31.2	8.8	2.91	0.006	0.99	0.264	0.158	0.170	12.15	201	19.25	<0.02	0.27	33.0	<0.03	0.12	330	437	372	12.5	
75th percentile	48	9.4	7.48	483	366	1.4	103.0	35.1	10.8	3.69	0.008	1.20	0.443	0.195	0.247	13.18	219	31.75	<0.02	1.47	45.9	<0.03	0.15	359	441	401	13.6	
Maximum	49	9.7	7.80	510	491	8.6	104.6	41.5	30.7	7.51	0.057	5.31	0.866	0.275	0.270	13.30	224	44.60	0.05	6.68	58.8	0.04	0.20	368	452	432	18.6	
<b>Quaternary confined aquifers</b>																												
Number of samples	30	30	30	30	30	30	30	30	30	30	29	30	30	30	30	30	30	30	30	30	29	30	30	30	30	30	30	30
Minimum	37	7.7	6.94	310	48	<0.1	47.1	15.2	3.0	1.24	<0.005	<0.01	<0.001	0.064	0.046	8.90	90	0.18	<0.02	<0.01	<0.03	<0.03	0.07	148	210	180	<0.8	
25th percentile	59	8.6	7.16	440	131	<0.1	77.2	27.4	6.3	1.80	<0.005	1.04	0.070	0.193	0.090	11.20	185	1.15	<0.02	<0.01	3.8	<0.03	0.13	303	358	307	<0.8	
Median	81	8.8	7.27	483	232	0.2	94.5	33.6	14.4	2.40	<0.005	1.46	0.114	0.287	0.152	12.40	214	2.88	<0.02	0.02	19.8	<0.03	0.19	350	402	381	1.0	
75th percentile	122	9.3	7.40	525	338	0.9	112.2	40.7	18.5	2.83	0.018	2.68	0.181	0.410	0.216	13.78	236	11.19	0.04	0.47	40.7	<0.03	0.24	387	480	434	12.7	
Maximum	193	11.3	7.79	915	920	7.5	348.0	106.3	35.5	5.32	0.078	8.28	0.431	0.573	0.383	16.80	300	120.00	0.20	10.40	150	0.38	0.34	491	735	1306	41.0	
<b>Cretaceous aquifer</b>																												
Number of samples	15	15	15	15	15	15	15	15	15	15	13	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
Minimum	61	7.5	7.17	380	-12	<0.1	40.5	16.7	8.7	1.93	<0.005	0.21	0.012	0.140	0.006	3.58	78	0.61	<0.02	<0.01	<0.03	0.01	0.12	128	256	170	<0.8	
25th percentile	121	8.9	7.37	425	83	<0.1	60.6	26.1	10.1	2.12	<0.005	0.53	0.044	0.329	0.063	4.50	150	1.41	<0.02	<0.01	6.4	<0.03	0.23	246	340	258	<0.8	
Median	156	9.5	7.52	480	124	0.2	82.8	30.8	21.7	2.98	0.006	1.81	0.074	0.389	0.117	10.90	190	6.39	0.05	<0.01	19.4	<0.03	0.26	311	380	333	<0.8	
75th percentile	208	10.0	7.67	555	244	0.4	98.1	33.2	42.6	3.96	0.010	2.28	0.121	0.568	0.160	12.30	214	19.65	0.07	0.11	81.5	<0.03	0.36	350	451	381	3.1	
Maximum	247	11.4	8.03	1130	312	4.2	266.0	109.6	178.3	12.20	0.074	3.21	0.317	3.160	0.271	13.20	270	45.90	0.33	1.20	1270	0.38	1.39	442	1892	1114	14.5	
<b>Precambrian bedrock</b>																												
Number of samples	8	7	8	8	7	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Minimum	148	8.1	7.08	250	75	<0.1	32.8	14.8	4.0	1.50	<0.005	0.04	0.002	0.102	0.005	3.45	79	0.58	<0.02	<0.01	<0.03	<0.03	0.06	130	173	143	<0.8	
25th percentile	197	9.1	7.34	420	130	<0.1	40.0	22.1	9.3	2.62	<0.005	0.09	0.016	0.337	0.037	7.82	121	3.09	0.03	0.02	13.1	<0.03	0.19	199	309	191	<0.8	
Median	220	9.1	7.44	479	336	0.2	69.8	25.4	21.1	3.85	0.007	0.57	0.025	0.535	0.043	9.21	154	6.35	0.05	0.22	32.0	<0.03	0.32	252	397	278	<0.8	
75th percentile	336	9.6	7.58	590	354	0.8	91.3	32.7	85.5	6.27	0.013	0.85	0.034	0.930	0.120	10.45	198	8.99	0.10	0.52	119.6	<0.03	0.40	325	497	362	7.3	
Maximum	350	9.9	7.98	810	529	3.7	98.2	40.3	160.6	8.18	0.065	2.46	0.183	1.283	0.210	13.80	227	107.00	0.37	11.60	352	<0.03	0.46	372	839	411	15.4	

### Atoms, Ions, and Chemical Units

Most dissolved materials in ground water are present as charged atoms or molecules, called ions. Positively charged ions are given the name cations, while negatively charged ions are called anions. Major cations in natural waters include calcium ( $\text{Ca}^{+2}$ ), magnesium ( $\text{Mg}^{+2}$ ), sodium ( $\text{Na}^+$ ), and potassium ( $\text{K}^+$ ). Major anions are bicarbonate ( $\text{HCO}_3^-$ ), sulfate ( $\text{SO}_4^{-2}$ ), and chloride ( $\text{Cl}^-$ ). The total number of positive charges in any water sample must equal the total number of negative charges. This electrochemical balance provides one tool for checking the accuracy of water analyses.

Ion concentrations in ground water are commonly expressed in two units, milligrams per liter (mg/L) and parts per million (ppm). In fresh water, the two units are numerically equal. One part per million is the same as one milligram (mg) of solute per thousand grams of solution because one liter (L) of fresh water weighs one kilogram. Milligram equivalents per liter (meq/L) is another concentration unit used in presenting ground-water chemical data. Meq/L values are based on the number of electrical charges present in the dissolved ions. To convert from mg/L to meq/L, the ion concentration is multiplied by the charge (valence) of the ion and then divided by the atomic weight of the ion or by the molecular weight of a molecule.

### Summary of Water Sample Analysis

The results of field and laboratory testing of water samples are presented by water source in Table 1. A complete compilation of these data describing the natural waters in Stearns County is available from DNR Waters. The section directly below summarizes the major characteristics of water samples, including concentrations of ions and other constituents. The two following sections summarize the results of isotope analysis for age dating and identifying sources of ground water.

### Constituents and Quality of Water

Analysis of the major ions indicates that ground water in Stearns County resembles ground water in most aquifers of Minnesota. Calcium ( $\text{Ca}^{+2}$ ), bicarbonate ( $\text{HCO}_3^-$ ), and magnesium ( $\text{Mg}^{+2}$ ) were the predominant ions in sampled waters. Slightly acidic precipitation infiltrating through the soil zone reacts with dissolved carbon dioxide gas and carbonate minerals resulting in relatively high concentrations of calcium, magnesium, and bicarbonate. The bicarbonate buffers ground water so the pH remains stable and nearly neutral, which is characteristic of Stearns County ground water. The average concentrations of calcium and bicarbonate decrease with depth from the water-table aquifer to the Precambrian bedrock because of changes in rock types and water mixing with deeper water sources enriched by sodium ( $\text{Na}^+$ ) and potassium ( $\text{K}^+$ ). Higher concentrations of calcium in shallower aquifers could result from human activities. For example, the nitrogen-rich fertilizer applied to farmland is oxidized and then reacts with calcite and dolomite in soil to release calcium and magnesium into soil water.

Calcium had the highest median concentration (97.7 milligrams per liter [mg/L]) in water samples from the Quaternary water-table aquifer, and bicarbonate had the highest median concentration (214 mg/L) in samples from the Quaternary confined aquifers. Median concentrations of both calcium and bicarbonate were lowest in lake water samples. Magnesium is the second most abundant cation in Stearns County ground water. Similar to bicarbonate ion concentrations, median

magnesium concentrations were higher in water samples from Quaternary confined aquifers and lower in samples from lakes and the Precambrian bedrock.

Calcium and magnesium contribute to water hardness. Water exceeding a concentration of 200 mg/L of hardness causes scale deposits in pipes and increases soap consumption. Most samples in Stearns County had hardness concentrations greater than 200 mg/L. The highest concentration (1306 mg/L) was in a water sample from the Quaternary confined aquifers. Water with hardness values greater than 200 mg/L is usually softened for household usage. Many public water supplies are softened to reduce hardness concentrations to less than 100 mg/L.

Sodium and potassium were two other major cations in water samples; however, they were less abundant than calcium and magnesium. Sodium concentrations were higher in water samples from the Cretaceous aquifer and the Precambrian bedrock and lower in lakes, while water samples from the Quaternary water-table system and confined aquifers had moderate sodium concentrations. Potassium concentrations, in contrast, were higher in the water-table aquifer and lake samples. The difference was probably due to the sources of sodium and potassium. Sodium in water samples was contributed mostly from interaction of ground water with Cretaceous and Precambrian rocks. Potassium was relatively higher in the water-table aquifer and lake samples. The likely sources of potassium are activities on the land surface. For example, a part of potassium-rich "potash" fertilizers applied on farmland can run off to surface water or infiltrate shallow water systems.

Besides being analyzed for major ions, the samples were analyzed for constituents related to public drinking water standards. The federal government has set primary and secondary standards for safe drinking water in public systems. Concentrations of nitrate, fluoride, chloride, sulfate, iron, manganese, and total dissolved solids were compared to those standards. Table 2 presents the standards and the number and percent of samples that exceeded the standards. The federal government also has recommended constituent concentrations (e.g., sulfate, total dissolved solids) for drinking water used by livestock. Water samples from all sources in Stearns County had constituent levels

**TABLE 2. Selected constituents in water samples from five water sources compared with the primary and secondary drinking water standards.**

[Total samples from each source: lake – 5, Quaternary water-table aquifer – 6, Quaternary confined aquifers – 30, Cretaceous aquifer – 15, Precambrian bedrock – 8; mg/L, milligrams per liter; TDS, total dissolved solids]

Constituent	Maximum standard	Lake		Quaternary water-table aquifer		Quaternary confined aquifers		Cretaceous aquifer		Precambrian bedrock	
	(mg/L)	Number exceeding standard	Percent	Number exceeding standard	Percent	Number exceeding standard	Percent	Number exceeding standard	Percent	Number exceeding standard	Percent
<b>Primary standards</b>											
Nitrate	10	0	0	0	0	1	3	0	0	1	12
Fluoride <sup>1</sup>	4	0	0	0	0	0	0	0	0	0	0
<b>Secondary standards</b>											
Iron	0.3	0	0	4	67	25	83	14	93	4	50
Manganese <sup>2</sup>	0.05	2	40	6	100	23	77	10	67	1	12
Chloride	250	0	0	0	0	0	0	0	0	0	0
Sulfate	250	0	0	0	0	0	0	2	13	2	25
TDS	500	0	0	0	0	3	10	3	20	2	25

<sup>1</sup>No samples exceeded the fluoride secondary standard of 2 mg/L.

<sup>2</sup>The Minnesota Department of Health has established the Health Risk Limit of 0.1 mg/L.

within the range that is satisfactory for livestock; however, livestock unaccustomed to water with higher concentrations of these constituents may experience temporary diarrhea (Carson, 1993).

Nitrate (NO<sub>3</sub><sup>-</sup>) is a contaminant with a primary standard for drinking water because elevated concentrations are potentially toxic to infants (Driscoll and others, 1986). Results from this study indicate low nitrate concentrations in Stearns County waters. Of 64 water samples, only two samples had nitrate-nitrogen concentrations greater than the 10-mg/L standard. Six samples from the Quaternary water-table aquifer had a nitrate-nitrogen concentration range of less than 0.01 mg/L to 6.68 mg/L and a median concentration of 0.27 mg/L. Eight water-table samples collected in Stearns County by Anderson (1993) had a slightly greater range (less than 0.1 mg/L to 14 mg/L) and higher median (3.1 mg/L). The difference in results might be attributed to sample locations, types of wells sampled, and seasonal variations.

The median concentrations of nitrate in samples from other ground-water sources were generally low. Samples from Quaternary confined aquifers had a low median concentration of nitrate (0.02 mg/L). Only one water sample taken from this aquifer exceeded the nitrate concentration standard. Samples from the Cretaceous aquifer had a median value below the detection limit (less than 0.01 mg/L). Samples from the Precambrian bedrock had the second highest median nitrate level. The highest observed nitrate concentration (11.6 mg/L) was in a sample from a 148-foot-deep well in the Precambrian bedrock. Elevated nitrate concentrations in the Precambrian bedrock might be caused by fracture flow in the bedrock.

Although this study found that ground water in Stearns County is generally low in nitrate, that condition does not necessarily imply that the shallower aquifers are protected from surface contamination. Certain conditions might contribute to the low nitrate

concentration. Infiltrating water from the soil layer may contain less nitrate or ground water may be somewhat denitrified, a process by which bacteria convert nitrate to nitrogen gas in a reducing environment.

The maximum chloride (Cl<sup>-</sup>) concentration in water samples from Stearns County was 120 mg/L, well below the secondary drinking-water standard of 250 mg/L. The samples from the Quaternary water-table aquifer and lakes had the highest median chloride concentration (about 19 mg/L). The Quaternary confined aquifers had the lowest chloride concentration (2.9 mg/L). The deeper Precambrian bedrock and Cretaceous aquifer had chloride concentrations of about 6 mg/L. The potential sources of chloride in near-surface aquifers are potash fertilizer, water softener salt, and road deicing salt. Chloride in deeper aquifers can also originate from rocks containing pore water high in chloride concentration or from the dissolution of chloride-rich minerals.

Although sulfate (SO<sub>4</sub><sup>-2</sup>) concentrations in Stearns County water samples varied greatly, from less than 0.03 mg/L to 1270 mg/L, the median sulfate concentrations were between 20 mg/L and 33 mg/L. The maximum sulfate concentrations of samples from both the Quaternary water-table aquifer and lakes were less than 60 mg/L. The maximum concentrations of samples from both the Cretaceous aquifer and the Precambrian bedrock exceeded the secondary drinking water standard for sulfate (250 mg/L), including a sample from the Cretaceous aquifer that had the maximum concentration of 1270 mg/L. Some Cretaceous water samples with high sulfate values had a rotten egg smell because of hydrogen sulfide gas. Sulfate is mainly produced by oxidation of sulfide (mostly pyrite) or dissolution of sulfate minerals (such as gypsum) in rock and soil. Detergents in household wastes, wastewater from treatment plants, and agricultural fertilizers can also contribute sulfate to the shallow ground-water system (Safe Drinking Water Committee, 1977).

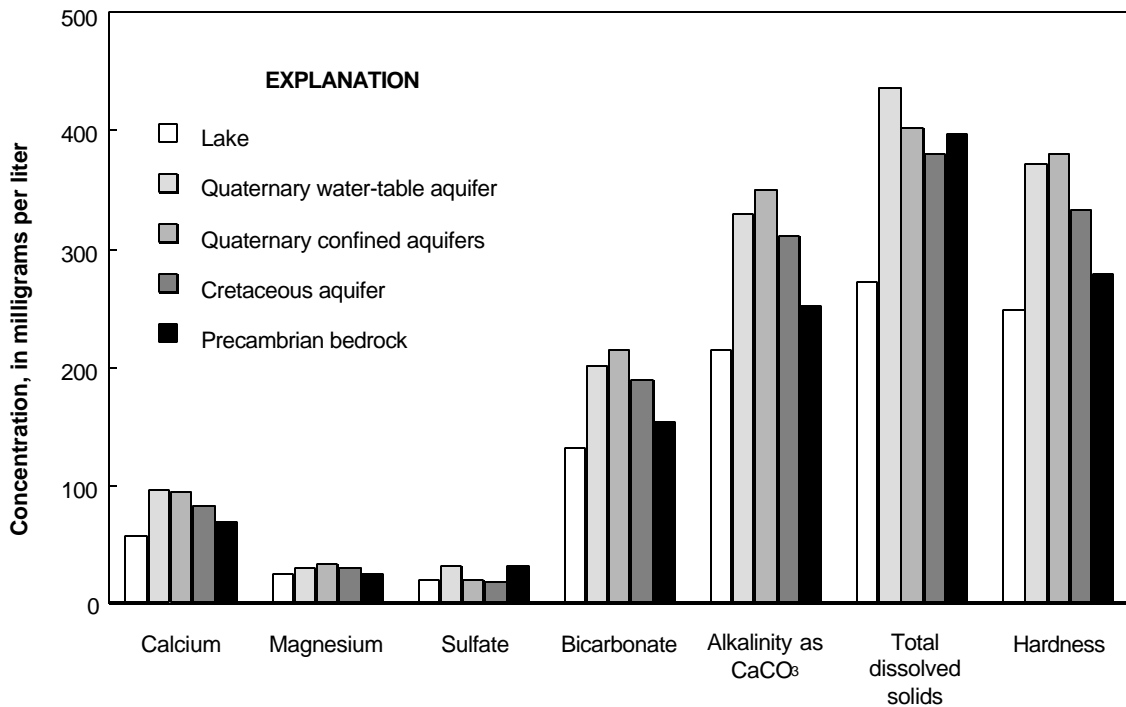
Stearns County ground water has relatively high concentrations of iron. Most ground-water samples had median iron concentrations greater than the secondary drinking-water standard (0.3 mg/L). The water samples from the Quaternary and Cretaceous aquifers had higher iron concentrations than the iron concentrations found in lake and Precambrian bedrock water samples. The highest iron concentration (8.28 mg/L) was observed in a sample from a well in the Quaternary confined aquifers. Dissolved iron in ground water occurs in ferrous ( $Fe^{+2}$ ) and ferric ( $Fe^{+3}$ ) forms, depending on the oxidation-reduction potential (Eh) of water. Ground water in the shallow water systems contains more dissolved oxygen and is more oxidizing than ground water in the deeper aquifers (e.g., median concentration of dissolved oxygen was 0.8 mg/L in the Quaternary water-table system versus 0.2 mg/L for the other aquifers). Most ferrous iron, after exposure to dissolved oxygen, is oxidized to ferric iron and will precipitate out of the water. Iron in ground water probably results from dissolution of iron-bearing minerals such as iron oxides and sulfides in sedimentary rocks, although water from industrial waste can contribute some iron to shallow aquifers. High concentrations of iron can present problems for water users. Water rich in ferrous iron has a “metallic” taste, tends to appear cloudy after oxidation, and favors the growth of iron bacteria. Iron precipitates stain bath fixtures and laundry, encrust well screens, and clog pipes (Driscoll and others, 1986).

Manganese (Mn) is another constituent with concentrations that mostly exceeded the secondary drinking water standard (0.05 mg/L) in Stearns County

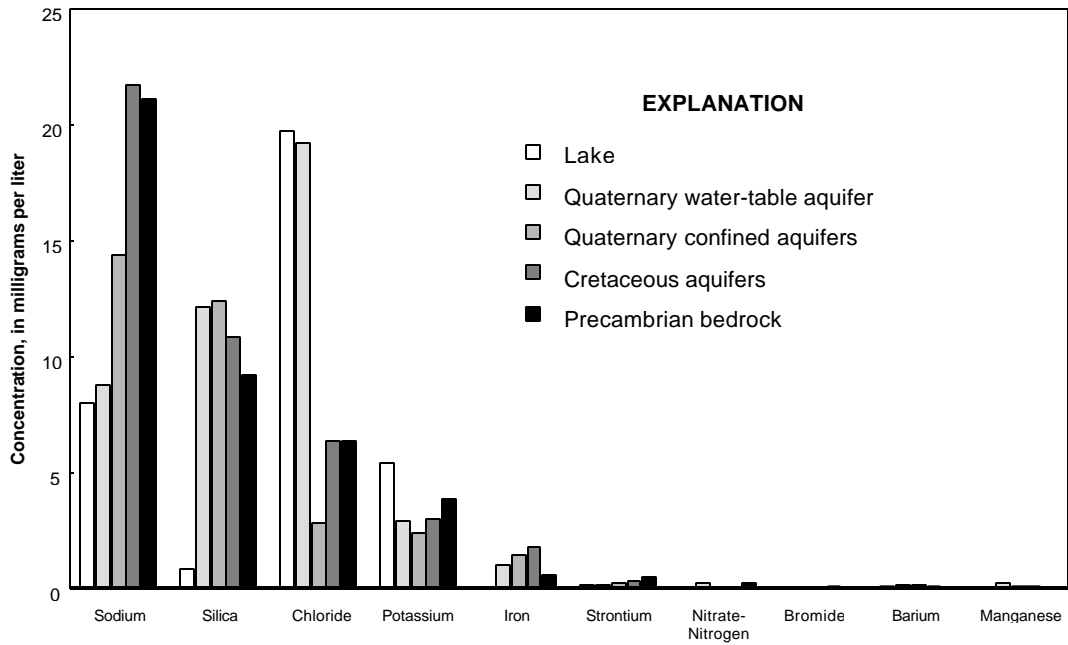
ground water. More than 76 percent of water samples from the Quaternary and Cretaceous aquifers had manganese concentrations higher than 0.05 mg/L. Samples from the Quaternary water-table aquifer had the highest median (0.264 mg/L) and maximum (0.866 mg/L) manganese concentration of the aquifers. The Precambrian bedrock and lake water samples tended to have lower manganese concentrations (less than 0.2 mg/L). Similar to iron, manganese in ground water results from dissolution of manganese-bearing minerals. When exposed to oxygen, the dissolved manganese precipitates out of the water as an insoluble oxide. Although manganese is an essential element for both plant and animal life, it is an undesirable impurity in water supplies because it tends to deposit black oxide stains.

Total dissolved solids (TDS) is a measure of the concentration of material dissolved in the water. TDS values of sampled waters ranged from 173 mg/L to 1892 mg/L. The median TDS values from all water sources were between 273 mg/L and 437 mg/L, which are below the 500-mg/L secondary drinking-water standard. The highest TDS concentration (1892 mg/L) from this study was found in a sample from a 156-foot-deep well in the Cretaceous aquifer. Lake water had the lowest median TDS of all the sample sources.

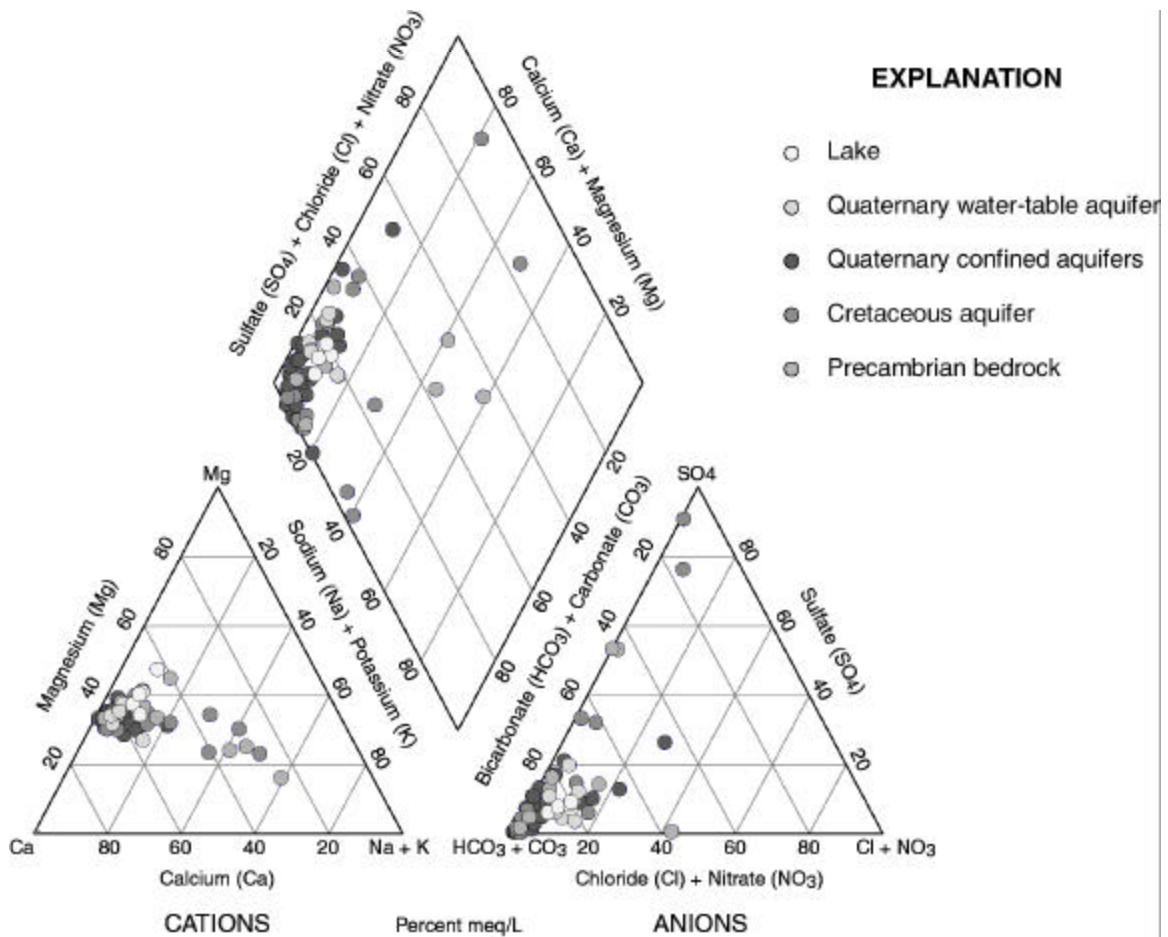
Three figures summarize this evaluation of Stearns County waters. Figures 2 and 3 compare the median concentrations of constituents from all water sources. Figure 4 is a trilinear plot showing relative proportions of major ions dissolved in water and indicating the predominance of calcium, magnesium, and bicarbonate.



**FIGURE 2. Comparison of median concentrations of major chemical parameters by water source.**



**FIGURE 3. Comparison of median concentrations of less abundant chemical parameters by water source.**



**FIGURE 4. Trilinear plot of major cations and anions by water source.**



### Trilinear Diagram

Trilinear diagrams are used to show the relative concentrations of the major cations (Ca<sup>+2</sup>, Mg<sup>+2</sup>, Na<sup>+</sup>, and K<sup>+</sup>) and anions (HCO<sub>3</sub><sup>-</sup>, CO<sub>3</sub><sup>-2</sup>, Cl<sup>-</sup>, SO<sub>4</sub><sup>-2</sup>, and NO<sub>3</sub><sup>-</sup>) in a water sample (Figure 4). In the two bottom triangles, cations are plotted on the left triangle and anions on the right triangle. The numbers along the sides of each triangle indicate the relative percentage of the specific ion in the sample. Thus, the relative concentration (in milligram equivalents per liter) of three ions or ion groups can be shown in each triangular diagram. The diamond-shaped diagram above the cation and anion triangles can be used to present both anion and cation groups as a percentage of the sample. This point is found by extending the plotted cation point parallel with the magnesium axis into the upper diagram. Similarly, another extension is made from the plotted point in the anion triangle parallel with the sulfate axis into the upper diamond. This point indicates the relative composition of the water sample in regard to the cation-anion pairs that correspond to the four sides of the diamond-shaped area.

### Ground-Water Residence Time

A major effort in this study was to estimate the time since water left the atmosphere and entered the ground-water system (i.e., residence time) in Stearns County. The analysis involved determining the amount of radioactive isotopes of hydrogen (<sup>3</sup>H, commonly called tritium) and carbon (<sup>14</sup>C, or carbon-14) in water samples. This information allows recent, possibly human-affected waters to be distinguished from older waters and provides a better evaluation of travel time: how long contaminants from surface sources might take to reach an aquifer. Figure 5 displays tritium data for 36 sample sites from three water sources and the carbon-14 data for 15 of those 36 sample sites.

The tritium levels measured in a water sample can indicate the water's age. Tritium data from lakes can be used as a baseline of tritium levels for local precipitation, which helps evaluate the residence time of ground-water samples. Tritium levels were measured in tritium units (TU) for all water samples, and the data are summarized in Table 1 for all five water sources. Figure 5 displays the spatial distribution of selected tritium results in the county by water source. Included on Figure 5 are well depths and tritium values for all the Quaternary confined aquifer samples and selected samples from the Cretaceous aquifer and the Precambrian bedrock with carbon-14 data.

Lake water samples

had a homogeneous tritium value of about 12 TU. A comparison of tritium levels of lake water samples with those of the aquifers in Stearns County indicates that the Quaternary water-table aquifer had the most "recent water" component. Samples from the Quaternary confined aquifers had much lower median tritium levels (1.0 TU), indicating a longer residence time for ground water. Tritium levels in most Cretaceous and Precambrian water samples indicated that ground water was generally "vintage." However, the maximum tritium levels in ground-water samples were greater than those of lakes, reflecting the massive influx of tritium released into the atmosphere from nuclear testing during the 1950's and 1960's.

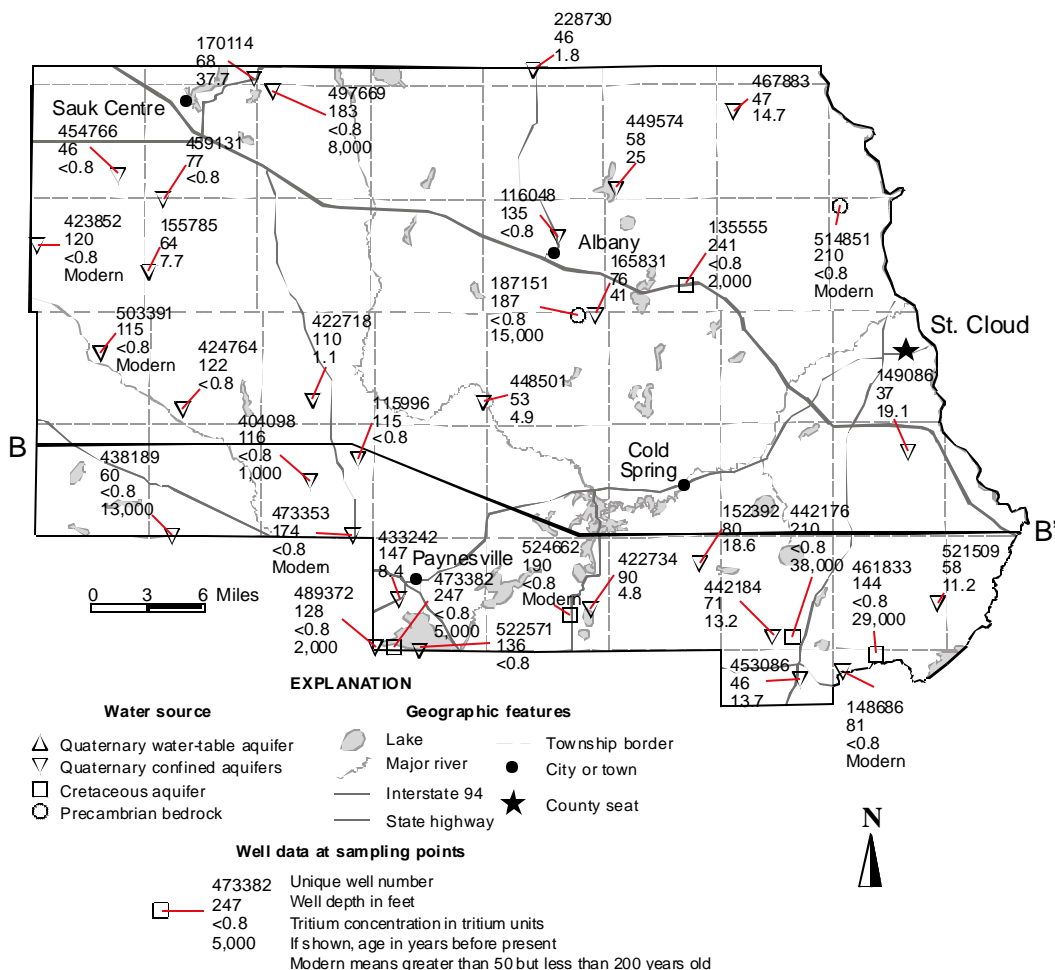


FIGURE 5. Selected locations and results of tritium and carbon-14 samples. B-B' shows the position of the interpretive cross section of residence time on Plate 10.

### Radioactive and Stable Isotopes

Isotopes of a particular element have the same number of protons but different numbers of neutrons. Isotopes are called stable if they are not involved in any natural radioactive decay. Stable isotopes are used to understand water sources or the processes that have affected them. Radioactive isotopes decay at known rates and can be used to measure the length of time water has been removed from the atmosphere.

The important stable isotopes are oxygen ( $^{16}\text{O}$  and  $^{18}\text{O}$ ) and hydrogen ( $^1\text{H}$  and  $^2\text{H}$ ). The mass differences between  $^{16}\text{O}$  and  $^{18}\text{O}$  or  $^1\text{H}$  and  $^2\text{H}$  can cause the concentrations of these isotopes to change during evaporation and precipitation, resulting in different  $^{16}\text{O}/^{18}\text{O}$  and  $^1\text{H}/^2\text{H}$  ratios in rain, snow, rivers, and lakes. The  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  values ( $\delta$  means the relative difference from standard mean ocean water) in precipitation generally plot close to a straight line known as the meteoric water line. The departure of  $^{18}\text{O}$  and  $^2\text{H}$  values from the meteoric water line can indicate evaporation or mixing of water from different sources.

Tritium ( $^3\text{H}$ ) is a radioactive isotope of hydrogen that is produced naturally by nuclear reactions in the upper atmosphere. Atmospheric nuclear testing between 1953 and 1963 also created tritium. Once created, tritium decays with a half-life of 12.43 years. The amount of tritium measured in a sample of ground water can indicate when it entered the subsurface. Tritium levels are reported in tritium units (TU), the equivalent of 1 tritium atom to  $10^{18}$  hydrogen atoms. Ground water in Minnesota has been classified into three age categories based on tritium levels (Alexander and Alexander, 1989). Waters with tritium levels of 10 TU or higher are “recent waters” and entered the ground water after 1953. Waters with less than 0.8 TU are classified as “vintage waters” that entered the ground water prior to 1953. Waters with 0.8 to 10 TU are “mixed waters” of the previous two.

Carbon-14 ( $^{14}\text{C}$ ) is a radioactive isotope of carbon with a half-life of 5730 years. It can be used to establish ground-water residence times as old as 35,000 years. Carbon-14 is produced in the earth’s upper atmosphere and enters the ground-water system with precipitation. The amount of carbon-14 in the atmosphere remains relatively constant over time; therefore, that amount can be compared with carbon-14 in a ground-water sample to estimate how long the water has been isolated from the atmosphere.

Two factors that contribute to low tritium levels are well depth and confining units separating aquifers. In the Quaternary confined aquifers in western Stearns County, for example, most wells were about 100 feet deep. These aquifers are sand and gravel lenses separated by low-permeability till. As a result of these conditions, tritium levels were generally low (less than 0.8 TU) for water samples from Quaternary confined aquifers. Elsewhere in the county and under different conditions (e.g., shallower wells or less confining conditions, or both), tritium levels were generally higher for samples from

Quaternary confined aquifers.

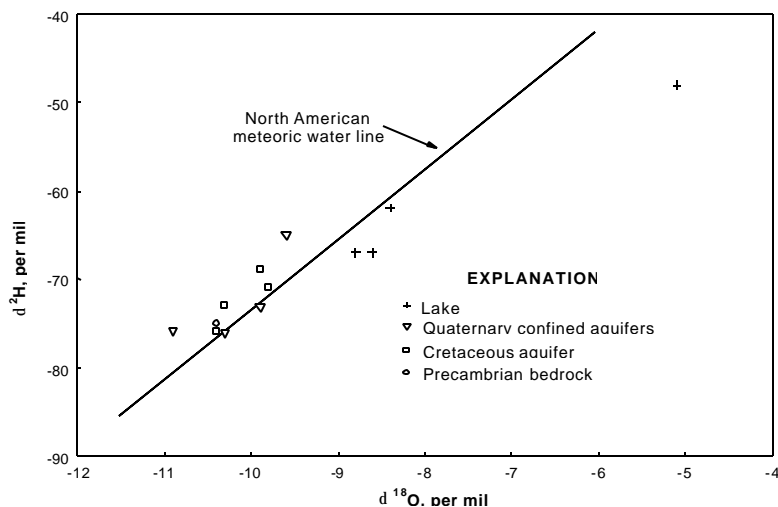
An interpretation of ground-water residence times based on tritium data developed for the B-B’ cross section (see Figure 5) is shown on Plate 10. The correlation between residence time and pollution sensitivity is explained on Plate 10.

In areas where ground waters infiltrated more than 40 years ago, more information about residence times can be obtained by analyzing another radioactive isotope produced in the atmosphere, carbon-14. Listed in Table 3 are results of 15 analyses for carbon-14 of water

**TABLE 3. Summary of carbon isotope data for water samples from three water sources.**

[ $\delta$ , relative difference from standard mean ocean water; per mil, parts per thousand; B.P., before present; modern, greater than 50 but less than 200 years old; --, not available]

Well number	Well depth (feet)	Depth to static water level (feet)	$\delta^{13}\text{C}$ (per mil)	$^{14}\text{C}$ (percent modern)	$^{14}\text{C}$ corrected (percent)	Age (B.P., in 1000 years)
<b>Quaternary confined aquifers</b>						
148686	81	-9	-10.8	0.74	1.50	modern
404098	116	40	-6.3	0.47	0.85	1
423852	120	28	-9.5	0.80	1.86	modern
438189	60	15	-11.0	0.11	0.21	13
473353	174	--	-10.2	0.50	1.09	modern
489372	128	3	-9.0	0.42	0.79	2
497669	183	35	-4.8	0.22	0.39	8
503391	115	30	-9.5	0.55	1.27	modern
<b>Cretaceous aquifer</b>						
135555	241	52	-6.9	0.46	0.83	2
442176	210	50	-18.2	0.01	0.01	38
461833	144	86	-12.1	0.02	0.03	29
473382	247	30	-8.9	0.30	0.57	5
524662	190	14	-9.7	0.74	1.69	modern
<b>Precambrian bedrock</b>						
187151	187	36	-11.8	0.09	0.17	15
514851	210	15	-10.5	0.62	1.31	modern



**FIGURE 6. Stable isotope values by water source.**

samples from the Quaternary confined aquifers, the Cretaceous aquifer, and the Precambrian bedrock. Figure 5 shows the distribution of samples analyzed for carbon-14 and the age values. Half of the samples analyzed for carbon-14 from the Quaternary confined aquifers had a “modern” age, meaning that the residence time was less than the range of carbon-14 dating (about 200 years) but greater than the range of tritium dating (about 50 years). The oldest ground water sampled in Stearns County had a carbon-14 age of more than 35,000 years and was from

Quaternary confined aquifers, the Cretaceous aquifer, and the Precambrian bedrock were analyzed for stable isotopes (Table 4). The  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  isotope values plotted on Figure 6 are generally close to the meteoric water line, indicating a strong component of normal precipitation with little evaporation. Lake samples have  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  values that are slightly heavier (more positive) than ground water, reflecting evaporative effects.

a well in the Cretaceous aquifer. Older carbon-14 ages (longer residence times) imply that recharge to those aquifers occurred long ago and indicate a reduced potential for the aquifers to become contaminated by surface pollutants. However, if these older waters do become contaminated, such as by poorly constructed wells, they could remain contaminated for a long time.

### **Stable Isotopes of Hydrogen and Oxygen**

Stable isotopes of hydrogen and oxygen have been widely used for identifying sources of ground water and detecting water-mixing or evaporation processes. Samples from lakes, the

### **Summary**

Ground water in Stearns County is generally of calcium, magnesium, and bicarbonate type. The chemical composition of waters differs in terms of hardness, total dissolved solids, tritium and nitrate levels, and stable isotopic composition. Samples from lakes and wells in shallower water-table systems were generally low in total dissolved solids, although surface contamination was detected by nitrate-nitrogen content greater than 10 mg/L in two samples. The deeper ground-water systems are well protected from surface contamination, although they have higher concentrations of total dissolved solids, iron, and sulfate. Median tritium levels are higher in the Quaternary water-table aquifer and lakes than in other, deeper water sources; however, the maximum tritium level was found in the Quaternary confined aquifers. Stable isotope data of oxygen and hydrogen indicate a preserved precipitation component for most water samples.

**TABLE 4. Summary of oxygen and hydrogen isotope data for water samples from four water sources.**

[ $\delta$ , relative difference from standard mean ocean water; TU, tritium units; per mil, parts per thousand; --, not applicable; <, less than]

Lake or well number	Well depth (feet)	Depth to static water level (feet)	Tritium (TU)	$\delta^{18}\text{O}$ (per mil)	$\delta^2\text{H}$ (per mil)
<b>Lake</b>					
L00002	--	--	12	-5.1	-48
L00003	--	--	11.4	-8.6	-67
L00004	--	--	13.4	-8.4	-62
L00005	--	--	12.2	-8.8	-67
<b>Quaternary confined aquifers</b>					
165831	76	50	41	-9.9	-73
170114	68	21	37.7	-10.3	-76
422734	90	6	4.8	-9.6	-65
449574	58	32	25	-10.9	-76
<b>Cretaceous aquifer</b>					
130104	205	50	1.1	-9.8	-71
136843	61	9	3.3	-10.3	-73
187197	155	35	<0.8	-10.4	-76
436898	210	52	9.5	-9.9	-69
<b>Precambrian bedrock</b>					
187151	187	36	<0.8	-10.4	-75

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