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GROUND WATER QUALITY IN SOUTHEASTERN MINNESOTA

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FOREWORD

This bulletin is published in furtherance of the purposes of the Federal Water Research and Development Act of 1978, P.L. 95-467. The purpose of the Act is to stimulate, sponsor, provide for, and supplement present programs for the conduct of research, investigations, experiments, and the training of scientists in the field of water and resources which affect water. The Act is promoting a more adequate national program of water resources research by furnishing financial assistance to non-Federal research.

The Act provides for establishment of Water Resources Research Centers at Universities throughout the Nation. On September 1, 1964, a Water Resources Research Center was established (under the Water Resources Research Act of 1964, P.L. 88-379) in the Graduate School as an Interdisciplinary component of the University of Minnesota. The Center has the responsibility for unifying and stimulating University research with water resources programs of local, State and Federal agencies and private organizations throughout the State; and assisting in training additional scientists for work in the field of water resources through research.

This Bulletin is number 109 in a series of publication designed to present information bearing on water resources research in Minnesota and the results of some of the research sponsored by the Center.

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ABSTRACT

Water quality of 21 private wells in the karst area of southeastern Minnesota was studied from February 1977 to May 1979. The wells were located within a one-township area and were chosen for study following a questionnaire survey by type of construction and aquifer(s) in which they were completed. Thirteen routine and six runoff samples were collected from each well during the study and were examined for 18 biological, physical and chemical parameters.

The parameters measured in samples from wells in the Galena Formation had the most variation with total coliform and nitrate nitrogen concentrations exceeding recommended limits for drinking water in 68 and 72 per cent of the samples, respectively. Generally, it was found the median routine concentrations of all parameters studied were lower than the median runoff concentrations. There was evidence that the chemical quality of the water in the deeper aquifers supposedly protected by a major aquitard was affected rapidly by surface runoff.

The parameters found to be the best indicators of surface water contamination of the aquifers and therefore indicators of possible health effects as a result of consumption of such water were: bacterial counts (total coliform, fecal coliform, fecal streptococci), nitrate nitrogen, turbidity, conductivity, sulfate, chloride, phosphate, total organic carbon, and sulfate/chloride and nitrate nitrogen/chloride ratios. No acute health effects possibly due to consumption of contaminated ground water were documented among those interviewed during the initial sanitary survey or among study participants during the actual study. However, no attempt was made to ascertain if any sub-acute health effects, due to water consumption, occurred.

The results of this study indicate an urgent need to initiate a ground-water monitoring program in southeastern Minnesota for purposes of determining the short and long-term trends in water quality.

CONTENTS

FIGURES

TABLES

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INTRODUCTION

Ground water occurs in four hydrogeologic environments in Minnesota. These consist of fractures in crystalline rocks, glacial drifts, Cretaceous sedimentary rocks, and Paleozoic sedimentary rocks. The latter hydrogeologic environment, comprised of sandstone, limestone, dolomite and shale, underlies the southeastern region of Minnesota.[1] This area, approximately 20,700 square kilometers (1,000 square miles) in size, is composed of three major carbonate rock aquifers separated by less soluble rocks, mainly shales. These aquifers serve as the source for all municipal and private water supplies in the region.

The cavernous limestones in this area are highly permeable. The intervening shales are generally of very low permeability and it is believed that they prevent rapid interchange of water between the carbonate aquifers and locally may isolate one or more of the carbonate aquifers from the surface. However, the area is characterized by karst features which include sinkholes, allogenic (disappearing) streams, caves and large springs. This is particularly significant since, in karst terrains, surface contaminants (biological and chemical) can enter the ground water through sinkholes and travel swiftly in open channels for considerable distances with little or no filtration, adsorption, and/or chemical reaction. In addition, the surface carbonate aquifer may have direct hydrologic connections with lower carbonate aquifers when improperly constructed production wells or improperly sealed abandoned wells penetrate the shale aquitards. Because of the dependence on these aquifers for primary water sources in southeastern Minnesota, there is concern about the short-term (immediately following surface water runoff) and long-term effects that surface contamination may have on the ground water quality.

Studies by the Minnesota Department of Health[2] have documented widespread bacteriological and chemical contamination of wells in southeastern Minnesota. Well water in Fillmore, Winona and Houston Counties showed evidence of elevated levels of nitrate nitrogen and coliform bacteria. In Fillmore County, 77 of 80 wells sampled contained increased nitrate nitrogen concentrations. Water from 33 (47%) wells contained 10 or more milligrams of nitrate nitrogen per liter. The water from 25 of the 80 supplies had coliform bacteria present. These wells varied in depth from 8 to 135 meters. with the majority more that 30 meters in depth. Similar findings were documented in Winona and Houston Counties.

In addition, Tjostem, et al.[3] identified major well water contamination in areas of Iowa immediately south of the Minnesota-Iowa border. Thirty-two (64%) of 50 wells finished in limestone and dolomite formations in northeastern Iowa had coliform bacteria and elevated nitrate nitrogen levels. In limited testing, *Salmonellae* bacteria were also isolated.

Despite the documentation of well water contamination is this area, very little is known about adverse health effects resulting from consumption of these waters. In 1943, Kingston[4] established that transmission of eleven typhoid fever cases was due to consumption of contaminated ground water in Fillmore County. He concluded, "It is obvious that there is a real danger of underground contamination of municipal and private water supplies situated in the fissured and cavernous limestone area of southeastern Minnesota."

Bosch, et al.[5] documented the occurrence of methemoglobinemia in infants in Minnesota for the period of January 1947 - December 1948 due to consumption of well water with high nitrate nitrogen concentrations. Despite elevated nitrate nitrogen levels in well water in southeastern Minnesota, none of the identified infant cases resided in the karst region.

The only other epidemiologic study of illness associated with consumption of contaminated ground water in southeastern Minnesota to date was conducted by the College of Veterinary Medicine, University of Minnesota.[6] A preliminary report of the study findings indicated that there was an increased risk of diarrheal illness among infants who consumed ground water with fecal coliform bacteria present as opposed to infants consuming water with no evidence of direct fecal contamination.

Although there have been efforts to better define the occurrence of ground-water contamination problems and possible human and animal health effects that result from consumption of such water, no serious attempt has been made to identify and determine the significance of indicators of surface contamination in water wells in the karst region of southeastern Minnesota. In past studies in Minnesota and other states with karst areas,[7] the presence of total coliform bacteria, elevated nitrate nitrogen levels and surfactants commonly have been used as indicators of contamination of well water. These indicators are often interpreted as evidence of contamination from livestock confinement areas and individual sewage disposal systems. Other chemicals, such as chlorides, have been used as indicators of contamination when it was known that a source of the chemical was in close proximity to the well.

Based upon the need to obtain more definitive data on the effect of surface drainage resulting from runoff, this study was initiated to attempt to (1) identify and determine the significance of specific physical, chemical and biological indicators of such surface contamination in water wells in the carbonate (limestone and dolomite) and sandstone aquifers of the karst region of southeastern Minnesota; (2) determine the magnitude and distribution of identified indicators of surface contamination in these same aquifers; (3) relate the magnitude and distribution of specific surface contamination indicators with respect to (a) water well construction, location and abandonment, (b) land use practices, and (c) precipitation; (4) relate potential public health aspects to the identification, concentration and distribution of indicators of surface contamination; and (5) project possible changes in ground-water quality in the karst region of southeastern Minnesota in the future, based on current water quality data and anticipated farm or land use practices that might influence recharge of surface or subsurface carbonate aquifers.

GEOLOGICAL CHARACTERISTICS OF THE KARST REGION IN SOUTHEASTERN MINNESOTA

Geological characteristics of southeastern Minnesota, including the karst region, have been reported.[8-18] The karst area lies almost entirely in Fillmore and Olmsted counties, 80 kilometers west of the Mississippi River (Figure 1). Karst signifies terrain with distinctive characteristics of relief and drainage arising primarily from a higher degree of rock solubility in natural water than is found elsewhere.[19] The terrain is generally underlain by limestone, in which extensive channeling, closed depressions, subterranean drainage and caves exist. Karst features develop where water containing carbon dioxide has been able to move on and through carbonate rock and remove some of the rock in solution. LeGrand[20] has identified five practical problems with respect to permeability that effect all karst areas. They include (1) scarcity and poor predictability of ground water supplies, (2) scarcity of surface streams, (3) instability of the cavernous ground, (4) leakage of surface reservoirs, and (5) an unreliable waste-disposal environment.

While a five-county area (Fillmore, Goodhue, Houston, Olmsted and Winona) in southeastern Minnesota is frequently referred to as the "karst area" of the state, only the area described previously actually meets the geological definition of karst terrain. The Ordovician and Devonian carbonates in which the karst is developed include the Cedar Valley (Devonian) and the Maquoketa, Dubuque, and Galena (Ordovician) formations (Figure 2).[16] This region is undergoing geologic change with constant development of new sinkholes. Most activity occurs in areas with less than 15 meters of overlying drift and underlain by the Decorah Shale.

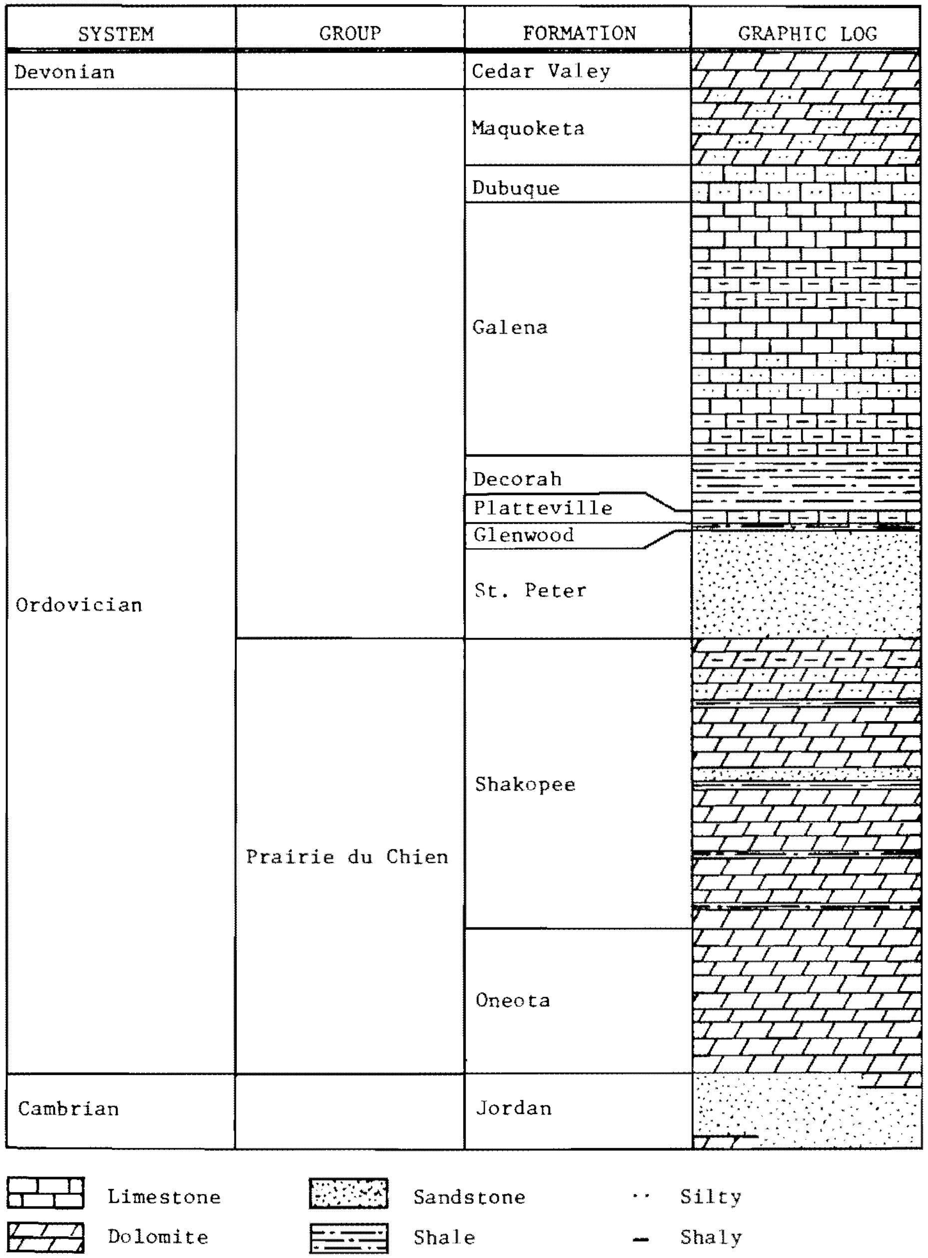
The primary landforms of the karst are sinkholes or dolines. They are closed depressions occurring at joint intersections and are formed chiefly by solution processes and partly by collapse and mechanical erosion.[21] According to Howard,[22] "...bedrock solution depressions... have no surface expression, solutional lowering being counter balanced by inward soil creep. The process of removal of the unconsolidated mantle material through bedrock openings is capable of producing the funnel-shaped surface depressions of sinks."

New sinkholes (less than one year old) frequently have vertical dirt walls but tend to develop evenly sloping conical walls as the sinkhole ages.[17] The aging process is the result of removal of unconsolidated matter from a joint or joint intersection by moving ground water in the joint. The diameter of the closed depression expands as the process continues. In addition, the centripetal drainage to the sinkhole increases. Wopat[17] reported that sinkholes in southeastern Minnesota range from 0.3 to more than 60 meters in diameter with depths ranging from 0.15 to 10.67 meters. He also estimated the average density of sinkholes in the southeastern Minnesota karst area as approximately 12 per square kilometer (30 per square mile) with an observed maximum of about 100 per square kilometer (264 per square mile). The higher the frequency of sinkholes per area, the greater the possibility that surface runoff can directly enter the surface carbonate aquifer with little or no filtration or chemical change.

Another characteristic land form of karst terrain is allogenic (disappearing or sinking) streams.[20] Such streams are "pirated" by sinkholes and often flow for several miles through subterranean channels before resurfacing as springs. Three major allogenic streams (Deer and Bear Creeks, which form the Middle Branch of the Root River at their

Figure 1. Regions of high densities (greater than four per quarter section) of sinkholes in the karst area in south-eastern Minnesota.

Figure 2. Generalized graphic log of bedrock units used as aquifers in the study area.



confluence, and the South Branch of the Root River) entrench into the Galena Limestone in the western portion of the karst area. The site of entrenchment of the South Branch of the Root River is located near the study area in Forestville Township.

In addition to allogenic streams, there are a number of blind valleys that exist in the karst area. Blind valleys occur where sinkholes serve as the lowest land depression in a surface watershed drainage area. Frequently, these areas do not have permanent surface water flows. However, during periods of surface runoff, temporary or intermittent streams will entrench within the blind valleys, allowing quick entry of potentially contaminated surface water to the aquifer. An example of this karst land form is the Fairview Blind Valley, which is located within the study area (Figure 3).

Another characteristic karst land form is the presence of caves.[20] More than 253 caves have been recorded in southeastern Minnesota.[17] The caves are developed to the greatest extent along joints of the Galena Formation.[23,24] The length of the explorable passage in these caves ranges from less than 15 meters to about 1,500 meters, with an estimated mean length of about 90 meters.[24] This does not include the long Mystery Cave system which is over 24 kilometers in total length.

The last characteristic land form of the karst region is the presence of numerous and sometimes large springs.[25] The movement of water from aquifer recharge areas (e.g., sinkholes) to the spring site(s) is difficult to predict since subsurface water movement in carbonate aquifers is frequently through a network of subterranean solution channels.[26,27] When this occurs, geological boundaries rather than simple hydraulics are the flow rate limiting factors. LeGrand[20] suggested that centralization of water discharge in karst areas, because of the presence of springs and lack of surface streams, poses subtle management problems because competition arises between users of well water and users of spring water.

The selected study site is approximately 75 square kilometers (29 square miles) in area and is located in Forestville and southern Fillmore Townships, Fillmore County. The area has an abundance of karst terrain land forms including a high density of 4 to 38 sinkholes per square kilometer (10 to 99 sinkholes per square mile),[28] several blind valleys, one allogenic stream and several large springs. More that 50 caves have been documented in Forestville Township.[17] Soil depths vary from 0.2 to 15 meters.[17]

The surface carbonate rock aquifer is the Galena Formation (Figure 2). It is predominantly limestone with interlayers of shale and dolomitic limestone.[29] The Decorah Shale which is immediately below the Galena, is characterized by gray-green shale with scattered thin limestone beds. It is approximately 10 to 15 meters thick in Forestville Township. The Platteville and Glenwood Formations are composed of dolomite or dolomitic limestone, and grayish-green or yellow shale and a basal argillaceous quartz sandstone, respectively.[16] Neither serve as important aquifers. Regionally, the Decorah Shale, Platteville Limestone, and Glenwood Shale are reported to form a confining bed which retards vertical flow between the upper carbonate and lower aquifers.[29]

The St. Peter Sandstone is a light yellow or white medium-grained,

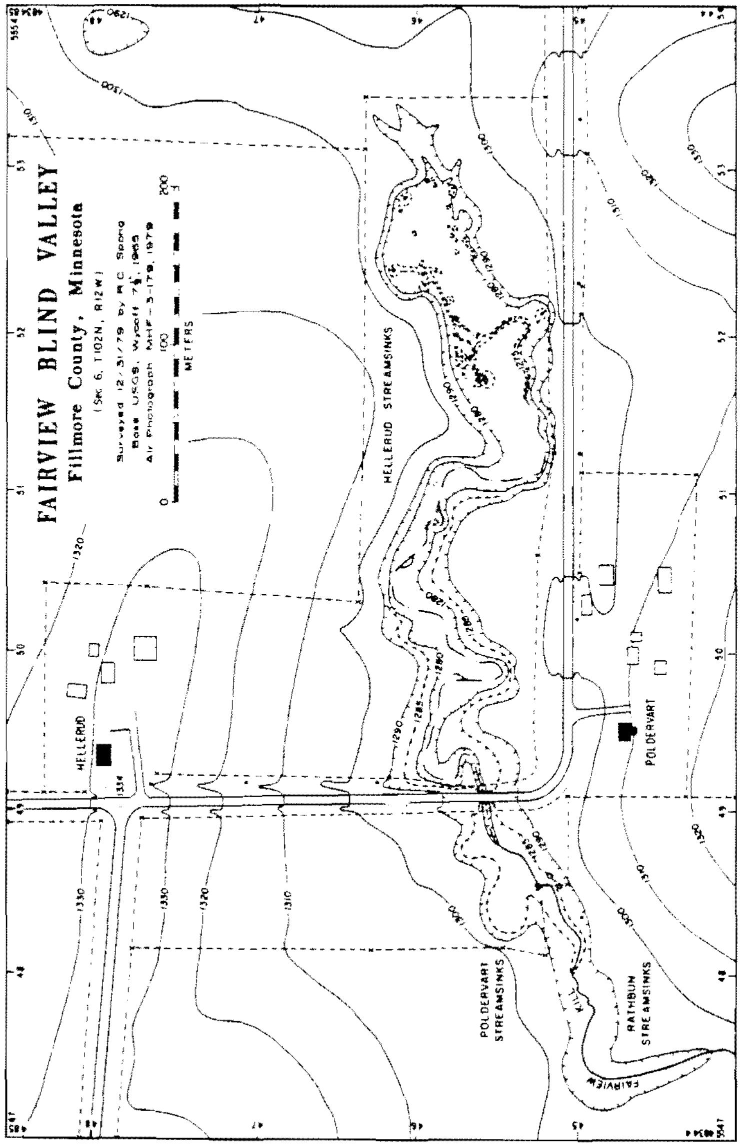


Figure 3. Fairview Blind Valley (from unpublished data, Minnesota Geological Survey).

but locally fine-grained, orthoquartzite.[16] Water movement through the St. Peter is more predictable than in the upper carbonate aquifer since most of the movement is largely through intergranular pores.[29]

The Shakopee-Oneota Formations are primarily dolomite with some quartzose sandstone and minor amounts of shale present. In localized areas, siltstone at the base of the St. Peter is reported to retard vertical flow to the Shakopee-Oneota Formations,[29] although no evidence of this siltstone was apparent in the study area. As in the upper carbonate aquifers, ground-water flow in the dolomite is predominantly through solution channels and fractures.

The Jordan Sandstone contains three members: the Norwalk Member, a yellow silty, fine-grained quartzose sandstone; the Van Oser Member, a white or yellow, coarse to medium-grained orthoquartzite; and the Sunset Point Member, a dolomitic quartz sandstone.[16] The Shakopee Dolomite, Oneota Dolomite and Jordan Sandstone are hydraulically connected and are frequently considered as one aquifer.[29]

METHODOLOGY

After discussion with Environmental Health personnel from the Minnesota Department of Health, a study area in Forestville and southern Fillmore Townships in Fillmore County, Minnesota was selected. It was determined that this area had (1) a diversity of types of well construction (cased with or without grout, or uncased) and (2) a diversity of wells that are completed in the Galena, St. Peter, Shakopee-Oneota, and Jordan geologic formations. The study area is located approximately 13 kilometers southeast of Spring Valley, Minnesota and is in the karst area of southeastern Minnesota. The study site has been identified as a currently active karst area, with a high density of sinkholes.[17,28]

From November 1, 1976 to January 15, 1977 land owner and/or farm tenants in Forestville Township were contacted. Permission was sought to use their wells as sampling sites for the study. In addition, a survey was conducted to obtain information regarding well construction, location of the well with respect to potential sources of contamination, farm and land use practices, and animal and human health histories. The survey was approved by the University of Minnesota Committee on Use of Human Subjects in Research. Forty-six landowners and/or tenants were interviewed and the above information obtained.

Twenty-one wells subsequently were chosen for study classified by construction and aquifer(s) in which the well was completed as shown in Table 1.

The depth and construction of the wells was determined from well logs provided by the driller or from other records provided by the land owner and/or farm tenant. The wells terminating in the Galena Formation were generally constructed with a surface casing through the soil overburden but because of the karst features of the area, they were considered to be uncased wells.

Table 1. Classification of study wells by aquifer and by construction.

Well Number	Galena	St. Peter	Shakopee-Oneota	Jordan	Cased	Grouted
	Aquifer(s) in which well is completed					
2-4-1	X					
2-4-2			X		X	X
2-5-2	X					
2-6-1	X					
2-6-2	X					
2-8-2			X		X	
2-9-1	X					
2-9-2	X					
2-9-3		X	X		X	
2-10-1		X			X	
2-11-1			X		X	
2-11-2			X		X	
2-15-2	X					
2-16-2		X	X		X	
2-26-1				X	X	X
3-31-3		X			X	
3-32-1			X		X	X
3-32-3		X	X		X	X
3-33-1	X					
3-35-1		X			X	X
3-35-3			X		X	X

Routine well water sampling began in February 1977 and was continued at approximately every three months for the remainder of the study. The month of sampling of each well was rotated annually to determine water quality with seasonal change.

Wells were also sampled following periods of snowmelt or heavy rainfall. No specific amount of rainfall was predetermined to be considered suitable for obtaining a well sample that might be affected by surface runoff. Rather, a local observer (participant in the study) notified the authors when runoff from field and road ditches was visually evident. Six samples were collected and all were obtained within 24 hours following notification of runoff.

Since two runoff samples were collected in July 1978, the previously scheduled routine sample was not collected for that month. Because elevated analytical results were obtained from these runoff samples, it was decided that additional samples should be taken throughout the remainder of that year to determine the time required for the well water to return to pre-runoff conditions. The lag time between sampling and receipt of analytical results made it necessary to collect samples without knowledge of whether or not the conditions had normalized. The dates on which all samples were collected are shown in Table 2.

A continuous monitoring rain gauge was furnished by the Minnesota State Climatologist and was maintained throughout the study by one of the participants. The rain gauge was located near the center of the study area.

Water samples were examined for eighteen biological, physical, and chemical parameters.* These parameters are listed in Table 3.

Water samples were taken from faucets which had immediate connection with the well (no softeners, filters, etc.). Water was allowed to run from the faucets for approximately five minutes (or until the water reached a constant temperature) before collection. When and where possible, water was obtained from faucets where large quantities had been drawn earlier in the day, such as in milk houses. Samples were taken according to Standard Methods.[30] Four containers were used for each sample collected from a well for (1) bacteriologic, (2) phosphate, (3) phenol, and (4) all other analyses. Samples for phosphate and phenol analyses were preserved with hydrochloric acid and copper sulfate, respectively.[30]

Total coliform, fecal coliform and fecal streptococci procedures were conducted according to Standard Methods using the membrane filter procedure.** Samples collected for bacteriologic examination were packed in ice immediately after collection and were processed within eight hours in a School of Public Health laboratory.

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*Due to the magnitude of data collected, the results of the analyses of every sample from each well are not included in this paper. Interested persons may obtain the data by writing directly to the authors.

**These analyses were done by one of us (MTO).

Table 2. Dates of sample collections.

Routine Samples	Runoff Samples	
Feb. 2, 1977	Mar. 9, 1977	(snowmelt)
May 4, 1977	June 1, 1977	(rainfall)
Aug. 10, 1977	Mar. 23, 1978	(snowmelt)
Oct. 3, 1977	July 1, 1978	(rainfall)
Jan. 14, 1978	July 8, 1978	(rainfall)
Apr. 15, 1978	Mar. 19, 1979	(snowmelt)
Sept. 7, 1978		
Oct. 7, 1978		
Nov. 11, 1978		
Dec. 20, 1978		
Feb. 19, 1979		
Apr. 25, 1979		
June 2, 1979		

Table 3. Biological physical, and chemical parameters examined.

Biological	Physical	Chemical
Total coliform bacteria	Temperature	pH (field and laboratory)
Fecal coliform bacteria	Turbidity	Nitrate nitrogen
Fecal streptococci bacteria	Color	Nitrite nitrogen
	Conductivity	Ammonia
	Total filterable residue	Alkalinity
		Chloride
		Sulfate
		Phosphate (total)
		Total organic carbon (TOC)
		Phenol

Analyses of pH and water temperature were done in the field using a Beckman® battery-operated pH meter and a standard mercury thermometer, respectively.

All other physical and chemical analyses were conducted by the Minnesota Department of Health, Division of Environmental Health Analytical Laboratories. All test methods, except those for chloride and phenol followed Standard Methods and are as follows:

Turbidity - Visual method, Jackson Turbidity Units
Color - Spectrophotometric method
pH (Laboratory) - Standardized electronic pH meter
Nitrate nitrogen - Cadmium reduction method
Nitrite nitrogen - Diazotization method
Ammonia - Nesslerization method
Alkalinity - Potentiometric titration method
Phosphate - Preliminary digestion and ascorbic acid method
Sulfate - Turbidimetric method
Total Organic Carbon - Combustion-infrared method

Chloride and phenol methods were:

Chloride[31] - Colorimetric manual ferricyanide
Phenol[32] - 3 methyl-2-benzothiazolinone hydrazone hydrochloride monohydrate method

Statistical data analyses were accomplished using methods described in Snedecor and Cochran[33] and included the computation of well and aquifer mean, median, mean standard deviation, minimum and maximum values for each parameter. Two-way analysis of variance was done to determine the source and significance of variation between wells within a specific aquifer(s) and between dates of routine or runoff sampling. Collected data were coded on computer cards and SPSS (Statistical Package for the Social Sciences) programs that were written in MS/FORTRAN were used for all the statistical analyses. The programs were run on a Cyber 172 computer.

RESULTS AND DISCUSSION

The quality of water in a specific aquifer in this study as determined by the results obtained from analysis of the routine and runoff samples from each well receiving water from the aquifer must be interpreted very carefully. First, the water quality obtained from a well in the St. Peter, Shakopee-Oneota, or Jordan Formation may not be indicative of the water quality in the aquifer from which it supposedly receives its water. If the well is constructed improperly, or the existing casing deteriorates, water from the overlying Galena aquifer may enter the well casing or flow down the outside of the casing contaminating or affecting the quality of the lower aquifer. Where these situations occur, the quality of water from that well would most likely represent a mixture of the water qualities from the different aquifers. Evidence that mixing occurs in the wells studied will be discussed later and is considered at this time only to add perspective to the interpretation of water quality.

A second consideration regarding the interpretation of water quality data from an aquifer is the variability that exists between (1) wells receiving water from the aquifer(s) and (2) samples from different dates, including routine or runoff samples. Two-way analysis of variance assesses the influence of two factors (wells and dates of sampling) individually and in combination. It was used to determine the variation among the group means (all wells in a specific aquifer on a specific day) and within the group means (all samples from one well in a specific aquifer over the duration of the study) for either routine or runoff samples. It is necessary to determine the influence of each factor individually and in combination upon a variable (bacterial, physical or chemical parameter) before it is possible to test for differences in the means of parameters of different aquifers. Only if there is no significant difference ($p > 0.05$) in the means of the aquifer by well and time is it possible to compare aquifer means.

There was considerable variation among wells and by date of sampling within a routine or runoff sampling period. Table 4 lists parameters by aquifer, routine or runoff samples, and source of significant variation (no variation, variation among wells within an aquifer only, or variation by date of sampling only). All parameters examined had at least one routine or runoff sample mean that showed significant variation. Phenol had the least variation with only the Galena routine mean showing significant difference by wells and the St. Peter/Shakopee-Oneota routine mean by date of the sample. The bicarbonate/sulfate ratio had the most frequent significant variation, differing by wells and date of sampling for each aquifer-sampling period category except for the St. Peter/Shakopee-Oneota samples. In the latter instance, it differed by well distribution only.

The two-way analysis of variance results indicate that it is improper to establish a mean value for certain parameters based on the number of samples taken in this study and then use the mean values to characterize the quality of water in an aquifer. As demonstrated in this study, there can be significant differences (1) between wells within the aquifer, and (2) within the specific well by date of sampling.

The cause of the difference in variation between wells and by date of sampling relates in part to the quality of recharge water that enters the aquifer. The Galena Formation is directly influenced by surface runoff and as anticipated had the greatest number of parameters that showed significant variation. Ten of 19 (53%) routine and nine of 19 (47%) runoff parameters in the Galena had significant variation among wells and by date of sampling. The aquifer with the least variation in parameters was the St. Peter with only two (11%) parameters for both the routine and runoff samples showing significant variation among wells and by date, whereas nine (47%) parameters in both groups did not have any significant variation.

The Decorah and Glenwood Shales supposedly restrict vertical movement of water from the Galena Formation and therefore it would be expected that the underlying aquifers would have a slower and more uniform movement of water, particularly through the sandstone. In addition, as deeper aquifers are encountered there should be less variation, due to dilution

Table 4. Two-way analysis of variance of parameter analysis results to determine source of variation among wells completed in a specific aquifer(s) and among dates of sample within the routine or runoff samples.

	Galena				St. Peter				St. Peter/ Shakopee-Oneota				Shakopee-Oneota			
	Routine*		Runoff*		Routine*		Runoff*		Routine*		Runoff*		Routine*		Runoff*	
Parameter	Among Wells	Among Dates	Among Wells	Among Dates	Among Wells	Among Dates	Among Wells	Among Dates	Among Wells	Among Dates	Among Wells	Among Dates	Among Wells	Among Dates	Among Wells	Among Dates
Total coliform	W	D	W	D	-	-	-	-	-	D	W	D	-	-	-	-
Fecal coliform	W	D	W	D	-	-	-	-	-	-	-	-	-	-	-	-
Fecal streptococci	W	D	W	D	-	-	-	-	-	-	W	D	-	-	-	-
Temperature	-	D	-	D	-	D	-	D	-	D	-	D	-	D	-	D
Turbidity	W	-	-	D	W	-	W	-	-	D	-	-	W	D	W	D
Color	W	-	W	-	W	-	W	-	-	D	-	-	W	-	W	-
pH (Field)	-	D	-	D	-	-	-	-	-	-	-	D	-	D	-	D
ph (Laboratory)	W	D	W	D	-	D	-	D	-	-	-	D	W	D	-	D
Nitrate nitrogen	W	D	W	D	-	-	-	-	W	-	W	-	-	-	-	-
Nitrite nitrogen	-	-	-	-	-	-	-	D	-	-	-	D	-	D	-	-
Ammonia	-	D	-	-	-	-	-	-	-	-	-	D	-	D	-	D
Alkalinity	W	D	W	D	W	D	W	D	W	-	-	-	W	D	W	D
Chloride	W	-	W	-	W	-	W	-	W	-	W	D	W	D	-	D
Phosphate	W	D	-	D	-	D	-	-	-	-	W	D	-	D	-	-
Sulfate	W	-	W	D	W	-	-	-	W	-	W	-	W	-	W	D
Phenol	W	-	-	-	-	-	-	-	-	D	-	-	-	-	-	-
Total Organic Carbon	W	D	-	D	-	-	-	D	-	-	W	D	-	D	-	D
Conductivity	W	D	W	D	W	-	W	D	W	-	W	D	W	-	W	D
Total filterable residue	W	D	W	D	W	D	W	-	W	-	W	-	W	D	W	-
Ratios																
Sulfate/chloride	W	-	W	-	W	D	W	-	W	-	W	-	W	D	W	D
Bicarbonate/sulfate	W	D	W	D	W	D	W	D	W	-	W	D	W	D	W	D
Nitrate nitrogen/ chloride	W	D	W	-	W	D	W	-	-	-	-	-	W	D	W	D

* W = Significant difference ($p \leq 0.05$) among wells
D = Significant difference ($p \leq 0.05$) among dates
\- = No difference ($p > 0.05$)

of recharge waters. However, a relationship between the depth of the aquifers and parameter variation by well or date could not be established. The number of parameters that had significant well and date variation was greater in the Shakopee-Oneota than either the overlying St. Peter or St. Peter/Shakopee-Oneota combination.

The parameters which showed the most variation following runoff in the Galena Formation were the total coliform, fecal coliform, and fecal streptococci bacteria. The total coliform (routine) and total and fecal coliform (runoff) in the St. Peter/Shakopee-Oneota were the only other bacteriological parameters to show significant variation.

Precipitation in the study area occurs in the form of rain and snow. Rainfall and snowmelt are partitioned as temporary storage in soils and runoff into streams and farm ponds. The greater share of precipitation is returned to the atmosphere as vapor by the energy-consuming processes of evapotranspiration when plants are present and by evaporation in the winter.[34] The normal annual precipitation for the Root River Valley for 1941-1970 was 0.78 meters (30.66 inches) per year while the average annual runoff was 0.19 meters (7.66 inches) per year.[34] The mean evapotranspiration in the same area is approximately 0.56 meters (22 inches) per year. This means an average of less than 0.03 meters (1 inch) per year of precipitation could be attributed to aquifer recharge by infiltration. Most of this recharge occurs during the months of April, May and June (spring recharge) or September, October and November (fall recharge). During the winter months the ground is frozen and little recharge occurs. Despite the fact that precipitation is usually greatest during the summer months, there is a net loss of soil moisture and reduction of aquifer recharge due to evapotranspiration.

The karst region ground-water recharge is unique because both soil moisture infiltration and runoff may be involved. Various amounts of runoff will serve as a direct recharge to the Galena aquifer when allogenic streams submerge. Also, during spring runoff, frozen ground does not permit infiltration of moisture into the soil and actually facilitates drainage into sinkholes.

It is necessary to evaluate the amount of precipitation and subsequent aquifer recharge in the karst area in light of the intensity of precipitation over a given period of time and the moisture level and temperature of the soil (frozen or unfrozen). An example of this is the difference between the amount of annual precipitation in 1977 and 1978 and the actual occurrence of major runoff events. During 1977, 0.88 meters (34.62 inches) of precipitation occurred, while in 1978 only 0.72 meters (28.49 inches) of precipitation was documented in the study area. However, in 1977, the highest intensity storm occurred on August 27 and resulted in 0.04 meters (1.75 inches) of rainfall in 24 hours. At the time there was considerable vegetative cover on all fields. There was no visible surface runoff following the storm and in general little surface runoff occurred during the year. On June 30, 1978, 0.05 meters (2.07 inches) of rainfall occurred, saturating the soil with moisture. Six days later (July 5) a high-intensity storm resulted in 0.13 meters (5.20 inches) of rainfall in 24 hours (this rainfall actually occurred in a four-hour period although it was reported for the 24-hour period. There

was considerable surface runoff with the blind valleys in the study area filling with water. The influence of this storm runoff was evident in both the upper and lower aquifers within 36 hours. In summary, the effect of precipitation on water quality in the karst region is a combination of factors, including precipitation intensity, existing soil mositure, soil temperature, and the amount of vegetation present.

Well Construction

As described previously, the upper aquifer is the Galena Limestone. It serves as the source of water for the majority of farms in the study area. The flow of water in this aquifer is mainly through solution channels and fractures. The quality and quantity of water yielded to a well depends on the number and/or size of the fractures and channels intercepted by the well. Those wells receiving water from solutions channels generally will show a greater variation in quality and, in the karst area, will react quickly to surface runoff occurrences. Wells completed in this aquifer usually have an ungrouted surface casing installed through the soil overburden and are then finished as an open hole in the limestone. These wells were all considered to be uncased since proper casing and grouting would likely have little effect on protecting the wells from surface contamination as shown in Figure 4. Therefore, these wells are not considered when examining the effects of well construction on water quality.

The lower aquifers, consisting of the St. Peter, Shakopee-Oneota and Jordan Formations, are separated from the upper aquifer by the Decorah and Glenwood Shales which have been reported to restrict vertical flow between the upper and lower aquifers.[29] Types of wells completed in the lower aquifers also are shown in Figure 4. Wells selected for this study included (1) one well cased and grouted into the St. Peter that terminates in the St. Peter; (2) one well that is cased and grouted into the St. Peter with open hole through the remaining St. Peter and into the Shakopee-Oneota; (3) three wells that are cased and grouted into the Shakopee-Oneota and terminate in the Shakopee-Oneota; (4) one well that is cased and grouted into the Jordan and terminates in the Jordan; (5) two wells that are cased but not grouted into the St. Peter and terminate in the St. Peter; (6) two wells that are cased but not grouted into the St. Peter with open hole through the remaining St. Peter and into the Shakopee-Oneota; and (7) three wells that are cased but not grouted into the Shakopee-Oneota that terminate in the Shakopee-Oneota.

The St. Peter, Shakopee-Oneota and Jordan Formations are hydraulically connected and are usually considered to act as a single aquifer. Water in this aquifer was expected to be protected from surface contamination because of the overlying shale aquitard and therefore, to remain at a relatively constant quality. Some variation in the quality of water from the different formations would reflect water contact with the different rock materials making up these formations. This appears to be the case with sulfate concentrations. Therefore, any significant changes in water quality that might indicate surface contamination would have to occur as a result of improper construction (i.e., cased but not grouted). Such contamination could be introduced by surface water flowing through openings between the casing and the outer edge of the borehole in ungrouted wells. However, this situation was not expected since it was anticipated that the

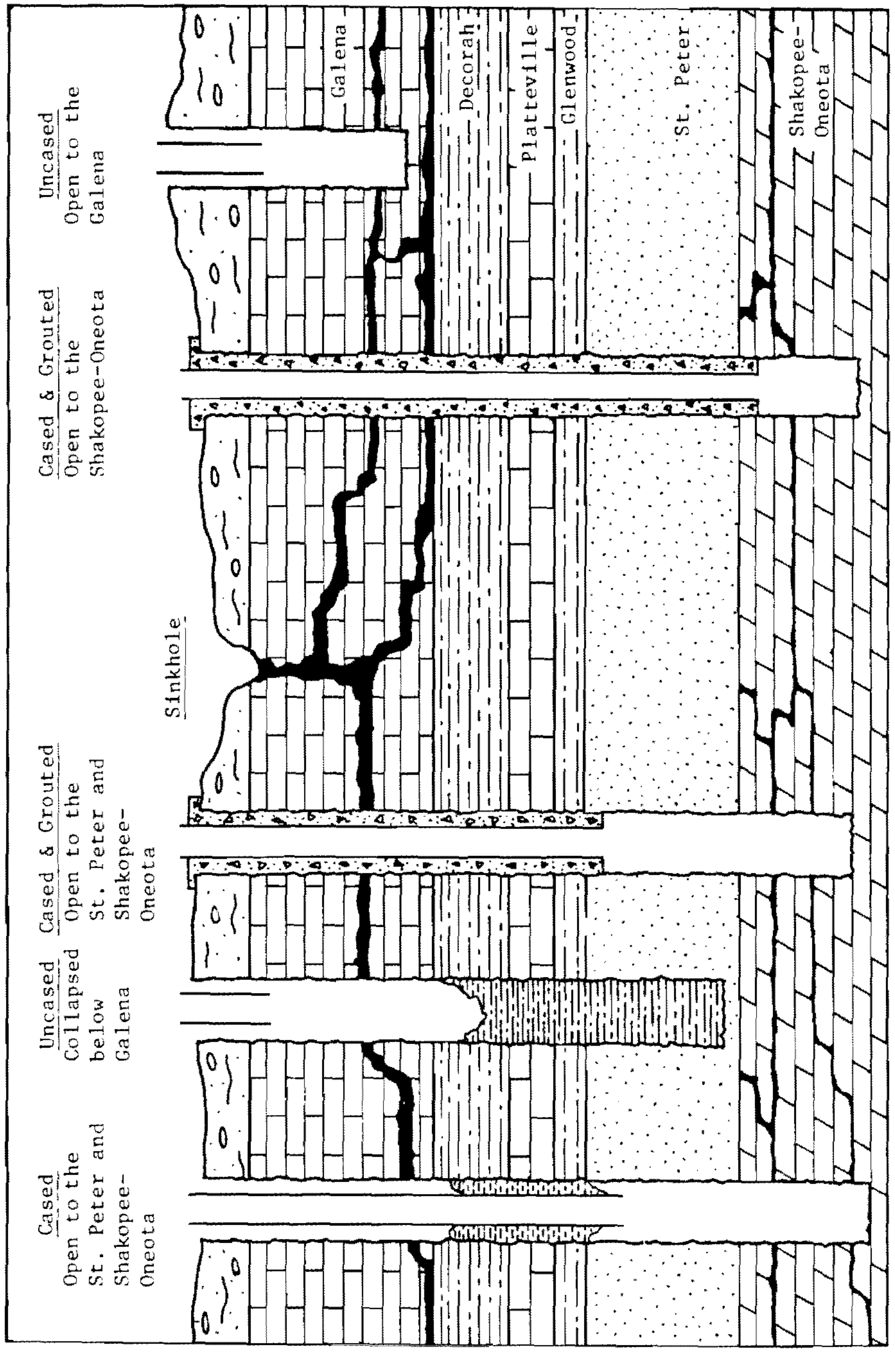


Figure 4. Typical examples of well construction in the study area with respect to geological features.

shale layers would cave in and swell around the casing so as to completely fill any such openings and thus provide an effective seal.

Evidence of the fact that the shales collapse when open holes are constructed from the Galena into the St. Peter has been presented by Hult.[29] In examining the concentrations of various parameters for wells completed in the St. Peter Formation, it was noted that the results for 3-31-3 differed from the other wells. This situation was also noted on the original trilinear plots of the percentages of bicarbonate, chloride and sulfate ions. The reason for this was not immediately apparent; however, it was subsequently noted that the well casing terminated in the Galena rather than being extended through the shales. It was then assumed that the well had collapsed somewhere below the upper level of the Decorah Shale and actually receives water from the Galena aquifer. Although this was not confirmed by measuring the present well depth, the analytical data for this well are more consistent with those from Galena wells than from the other St. Peter wells. For this reason, Well 3-31-3 was reclassified as a Galena well and appears as such in the data presented in this paper.

With the exception of Well 2-9-3, indicator bacteria usually were not found in the routine samples from either the grouted or ungrouted wells. Both Wells 2-9-3 and 2-16-2 had evidence of considerable bacterial contamination in the runoff samples. (Explanations for occasional indicator bacteria concentrations in samples from the other wells are presented subsequently under Bacterial Indicators.) In reviewing the chemical analyses, it was noted that the quality of the water from Well 2-9-3 was more similar to the Galena wells than to the St. Peter/Shakopee-Oneota wells. The analytical data for Well 2-16-2 showed greater similarity to the other St. Peter/Shakopee-Oneota well than to wells from other aquifers but was slightly higher in sulfate.

Well 2-9-3 had the highest values for conductivity of any well in the study area. During the study, the discharge pipe from the pump was replaced because of water loss through holes produced by corrosion. This well was constructed more than 20 years ago and was cased, but not grouted, into the St. Peter Formation. Based on this information, it was concluded that the casing had corroded through at the base of the Galena to the extent that water from the Galena aquifer (which has a higher potentiometric surface than the lower aquifer) entered the well at a sufficiently high rate to permit delivery of water of a quality very similar to the bacterial and chemical quality of other Galena wells. Well 2-9-3 also was reclassified as a Galena well and is reported as such in this paper.

Well 2-16-2 showed a higher level of nitrate nitrogen, chloride and sulfate concentrations than did the other St. Peter/Shakopee-Oneota well. However, when both were plotted on a trilinear diagram only a higher percentage of chloride ions was apparent. This fact, together with the higher bacterial concentration in the runoff samples indicated the well received surface contamination. Although this well is not grouted, this does not appear to be the route of entry as the concentrations of chemical parameters remain consistently elevated even when no indicator bacteria are present. It is suspected that the well intercepts a solution channel or large fracture "downstream" from a well such as 2-9-3 which permits surface contamination to enter the Shakopee/Oneota aquifer.

No particular difference could be noted between grouted and ungrouted wells when concentrations of chemical parameters were plotted with respect to time. However, both types of wells responded quite rapidly to the heavy rainfall which occurred on July 5, 1978. The reasons for this response are unknown but are not likely to be related to construction.

Bacterial Indicators

Bacterial indicators have had a long history of use as measures of water quality. The prime concern was to diminish the possibility of humans and animals becoming infected as a result of consumption of water contaminated with pathogenic organisms. In this study, all of the samples collected were examined for total coliform, fecal coliform and fecal streptococci bacteria. The total coliform group of bacteria is a heterogeneous collection of bacterial species consisting of four major groups: *Escherichia coli*, *Escherichia freundii*, *Enterobacter aerogenes* and *Klebsiella sp*. Of these four groups, only *E. coli* is of fecal origin. Although the presence of total coliform in ground water would indicate surface contamination, it does not distinguish between contamination of fecal or non-fecal origin.

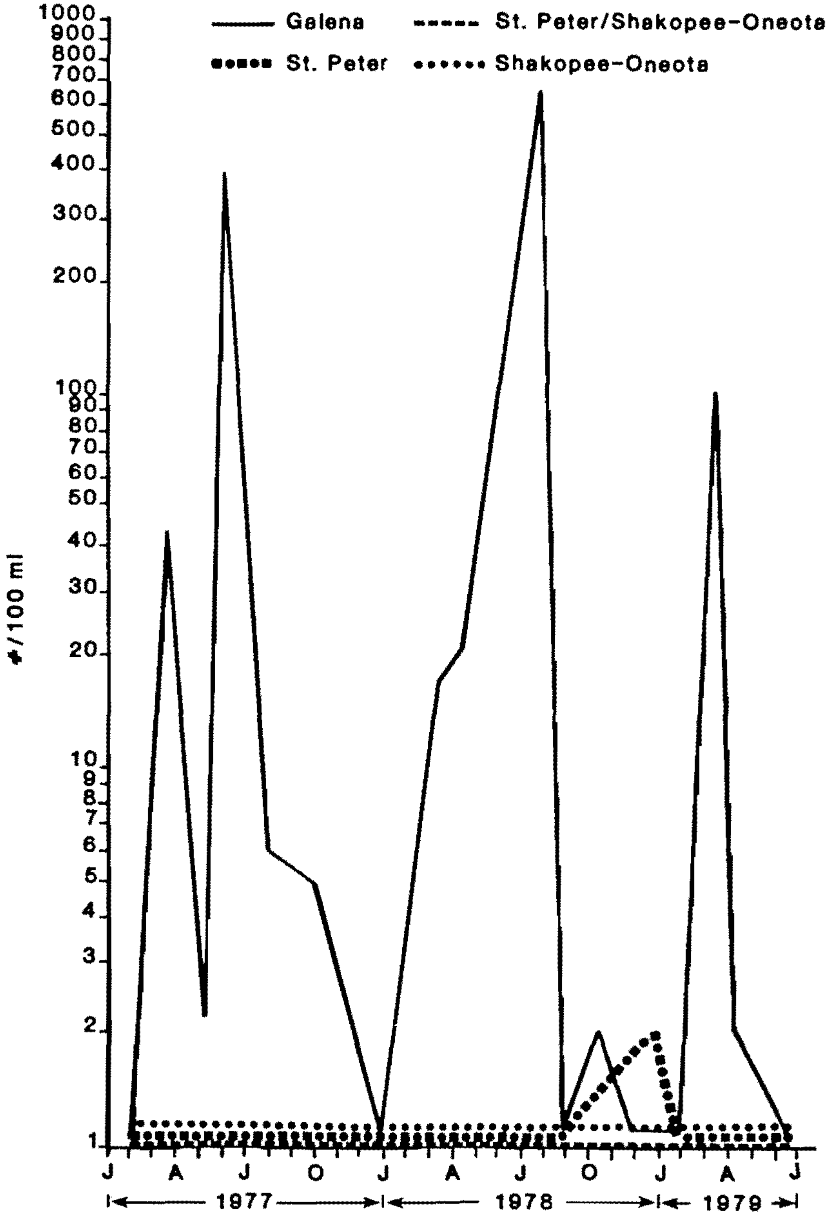
In order to differentiate between fecal and non-fecal organisms, the fecal coliform test has been developed.[35] While the fecal coliform test does distinguish between fecal and non-fecal coliforms, it does not differentiate between the human and non-human warm-blooded animal wastes. However, because human feces contain neither *Streptococcus bovis* nor *S. equinus* but animal fecal material does, it is possible to differentiate, under appropriate conditions and when dealing with fresh fecal materials, between human and non-human contamination by examining the ratio of fecal coliform to fecal streptococci. Geldreich[35] found a ratio of 4:1 or greater would represent human feces whereas a ratio of less than 0.7:1 would indicate that the fecal matter is of non-human origin. A value between these two given ratios would indicate a mixture of human and animal fecal contamination.

In this study, 38 percent of all routine samples and 80 percent of all runoff samples in the Galena showed evidence of fecal contamination. Samples collected from wells in other aquifers showed fecal contamination in two (8%) routine samples from the St. Peter, two (20%) runoff samples from the St. Peter/Shakopee-Oneota, and two (15%) routine samples from the Jordan. The fecal coliform results from the July 8, 1978 runoff were not included in the analysis because of problems with the media quality control. Median fecal coliform values by aquifer and date are shown in Figure 5.

The fecal coliform concentrations ranged from 0 to 1,000 per 100 ml for routine Galena samples and from 0 to 6,000 per 100 ml for Galena runoff samples. The two routine St. Peter samples with fecal coliform present had only one and two fecal coliform per 100 ml, respectively. The very low concentrations of fecal coliform bacteria could be a result of contamination of water samples at the tap or during the test procedure.

The two runoff samples from wells in the St. Peter/Shakopee-Oneota aquifer which showed contamination were collected from the same well (2-16-2). It is most likely that the July 8, 1978 runoff sample also would have had fecal coliform present since there were 70 total coliform

Figure 5. Median fecal coliform values by aquifer and date.



per 100 ml and 49 fecal streptococci per 100 ml in the sample from that date. It does not appear that bacteria enter well 2-16-2 as a result of surface water recharge near the well site. Rather, surface contamination probably enters as the result of another Shakopee-Oneota well in the area which has a corroded well casing somewhere in the Galena Formation. In this case, water from the Galena aquifer would enter into the deteriorated Shakopee-Oneota well and travel quickly through the fractured dolomite. This possibility was discussed in the section on Well Construction.

Of the samples collected from the Jordan well which showed fecal coliform contamination, one was taken from a hydrant near the barnyard rather than the usual sampling site in the house. The presence of fecal coliform bacteria in this sample is due most likely to contamination of the water at the hydrant faucet rather than in the aquifer. The second sample was taken from the usual sampling site; however, it had only one fecal coliform per 100 ml.

The ranges of total coliform in the Galena routine and runoff samples were 0 to 2,850 per 100 ml and 0 to 76,000 per 100 ml, respectively. Fecal streptococci ranged from 0 to 2,330 per 100 ml in routine and 0 to 26,800 per 100 ml in runoff samples. Well 3-31-3, originally calssified as a well terminating in the St. Peter aquifer and later reclassified as a Galena well after evaluation of the chemical data, showed one sample with one total coliform per 100 ml present. While this low total coliform count is inconsistent with those found for a well in the Galena aquifer, there are possible explanations. First, there is significant variation in the bacteriologic quality of water in the Galena because of the heterogenous nature by which the water travels through the aquifer. The presence of subterranean streams in the Galena means it is possible to have waters of very different bacteriologic quality in channels only meters apart. This has been demonstrated by bacteriologic sampling of subterranean streams inside a karst cave.[36] It is possible therefore, for Well 3-31-3 to have received an uncontaminated water. Another explanation is that water in the Galena aquifer passes through a shallow but sufficient thickness or depth of sand or shale material to permit removal of the bacteria by filtration before delivery to the well. Lastly, if all the water yielded to the well has infiltrated through the soil and then into fractures in the Galena it may be of excellent bacterial quality as compared to water derived from surface runoff that has entered solution channels through sinkholes.

The fecal coliform/fecal streptococci ratio was calculated for 53 (42%) routine and 44 (88%) runoff samples from the Galena Formation which showed both indicators. The median values for the routine and runoff samples are 0.42 and 0.28, respectively. The range of ratios for the routine samples is 0.1 to 7 and for runoff samples 0.005 to 2.51. Nine routine samples had ratios greater than one and only three had ratios greater than 2. Eight runoff samples had ratios greater than one and only two had ratios greater than 2. These results indicate that most of the fecal contamination found in the Galena aquifer is of animal origin. Both livestock and wildlife would contribute to the fecal contamination.

In the few samples where ratios were greater than one, human fecal material discharged into septic tank drain fields located immediately above the Galena Foundation may have been the source of ground-water contamination or they may have contributed directly to aquifer recharge by drainage through a sinkhole.

It was possible to calculate fecal coliform/fecal streptococci ratios for only two samples taken from all other aquifers since only these two samples showed both bacterial indicators. The ratios were 0.12 and 1.0.

Physical Indicators

The physical indicators used in the study were water temperature, pH (field and laboratory), color, turbidity, total filterable residue (total dissolved solids), and conductivity. Because of problems with securing appropriate sample bottles for the July 8, 1978 runoff sample, color and total filterable residue were not done on that date.

pH

The field pH values of the Galena aquifer ranged from 6.7 to 8.4 (median 7.6) for routine samples and 6.8 to 7.9 (median = 7.4) for runoff samples. The laboratory pH values ranged from 7.0 to 7.9 (median = 7.4) for routine samples and 7.0 to 8.6 (median = 7.4) for runoff samples. The ranges of routine field pH values for the other aquifers were similar to the Galena, with the St. Peter, St. Peter-Shakopee/Oneota and Jordan aquifers showing median values of 7.7, 7.65, 7.6 and 7.7, respectively. The runoff field pH minimum and maximum values were also similar to the runoff pH values found in the Galena Formation. The median runoff values in the St. Peter, St. Peter/Shakopee-Oneota, Shakopee-Oneota and Jordan aquifers were 7.6, 7.6, 7.7, and 7.6, respectively. Routine and runoff laboratory pH data for the same aquifers were similar to the field values found for each aquifer with the exception of slightly lower routine maximum values and higher runoff maximum values.

Temperature

Temperatures in the Galena Formation ranged from 6 to 13°C for routine samples and 6 to 15°C for runoff samples. Median temperature values for the St.Peter, St. Peter/Shakopee-Oneota and Shakopee-Oneota routine samples were 9°C, 9.2°C and 8.6°C, and runoff samples were 10.4°C, 12.5°C, and 11.7°C, respectively. The ranges for the three groups of wells were 7 to 13°C for routine samples and 7 to 15.5°C for runoff samples. The Jordan aquifer was the only aquifer which did not show an increase in runoff sample median temperature (7°C) when compared to the routine sample median temperature (8°C). The range of temperature values in the Jordan was 4 to 10°C for routine samples and 3 to 11°C for runoff samples.

Turbidity

Seventy-three to 92 percent of routine samples in all the aquifers had turbidity values between 0.6 to 15 JTU (Galena - 78%, St. Peter - 73%, St. Peter/Shakopee-Oneota - 73%, Shakopee-Oneota - 83%, Jordan - 92%).

All wells in the study, with the exception of two, had runoff minimum and maximum values which exceeded the respective routine minimum and maximum values. Well 2-15-2, which is located in the Galena Formation, had a maximum routine value of 120 JTU on February 2, 1977. The second highest routine turbidity value in that well was only 37 JTU. We have no explanation for the markedly increased value on February 2. The second well (2-4-2), which is located in the Shakopee-Oneota, had a minimum routine value of 2.5 JTU while the minimum runoff value was only 2.2 JTU. The highest median turbidity value for each aquifer by date occurred in the March 23, 1979 spring runoff sample. The median turbidity values in samples collected that day in the Galena, St. Peter, St. Peter/Shakopee-Oneota, Shakopee-Oneota and Jordan aquifers were 18, 16, 17, 18, and 18 JTU, respectively. The increased but similar values in all aquifers would indicate rapid response to the surface runoff by the lower aquifers.

Color

The Galena, St. Peter/Shakopee-Oneota, Shakopee-Oneota and Jordan aquifers had a very similar distribution of color concentrations in both routine and runoff samples. More than 90 percent of all routine or runoff samples in these aquifers had less than 15 color units. However, the St. Peter Formation had 23 and 30 percent of routine and runoff samples, respectively, with color unit values greater than 15. The increase was attributed to only one of the two wells in the formation. One of the wells (2-10-1) had median values for routine and runoff samples of 19.1 and 20 color units, respectively, while the other well (3-35-1) had routine and runoff median values of 1.2 and 4.4 color units, respectively. There was no apparent explanation for this occurrence.

Total Filterable Residue

Total filterable residue (TFR) values in the Galena Formation ranged from 220 to 4,300 mg/l for routine samples and 230 to 860 mg/l for runoff samples. Twenty percent of the routine and 34 percent of the runoff samples collected from this formation exceeded 500 mg/l. The highest median TFR value (615 mg/l) by date of sampling in the Galena Formation was from the July 1, 1978 runoff sample. None of the other aquifers had any TFR values greater than 500 mg/l. The Jordan Formation had the lowest TFR median, minimum and maximum values for both routine and runoff samples and showed the least variation.

Conductivity

Ninety-three percent of both the routine and runoff samples in the Galena Formation had conductivity values of 500 μS/cm or greater. No other aquifer had more than 50 percent of the routine or runoff sample values greater than 500 μS/cm. The Jordan aquifer had the lowest distribution of conductivity values with 100 percent of the routine samples and 83 percent of the runoff samples less than 500 μS/cm. The range of conductivity values in the Galena Formation was 394 to 1,230 μS/cm for routine samples and 230 to 1,300 μS/cm for runoff samples. There was much less variation of values in the other aquifers. Median conductivity values by date were highest in each aquifer, with the exception of the Jordan

Formation, in the July 8, 1978 runoff samples (Figure 6). This is particularly evident in the St. Peter, St. Peter/Shakopee-Oneota and Shakopee-Oneota, where the median values on July 8 were 620, 630 and 550 μS/cm, respectively. The second highest median conductivity values by date in the three aquifers were 540, 585 and 500 μS/cm, respectively. This again indicates that surface runoff on July 8 had a very rapid effect on these aquifers. The Jordan aquifer had the highest conductivity value for July 1, 1978 sample (560 μS/cm) while the July 8, 1978 sample (500 μS/cm) was the second highest. No other conductivity value in the Jordan aquifer throughout the study exceeded 460 μS/cm.

Chemical Indicators

The chemical indicators used in the study were nitrate nitrogen, nitrite nitrogen, ammonia, sulfate, chloride, alkalinity, total phosphate, total organic carbon, and phenol. In addition, sulfate/chloride, bicarbonate (alkalinity)/sulfate, and nitrate nitrogen/chloride anion ratios were determined. Because of problems with securing appropriate sample bottles for the July 8, 1978 runoff sample, analyses for nitrate nitrogen, ammonia, alkalinity, phenol and total filterable residue were not done on that date. In addition, due to a laboratory accident involving July 8, 1978 samples, chloride, sulfate, laboratory pH and total organic carbon analyses were not done for Well 2-26-1 and laboratory pH, chloride and total organic carbon analyses were not done for Well 2-16-2.

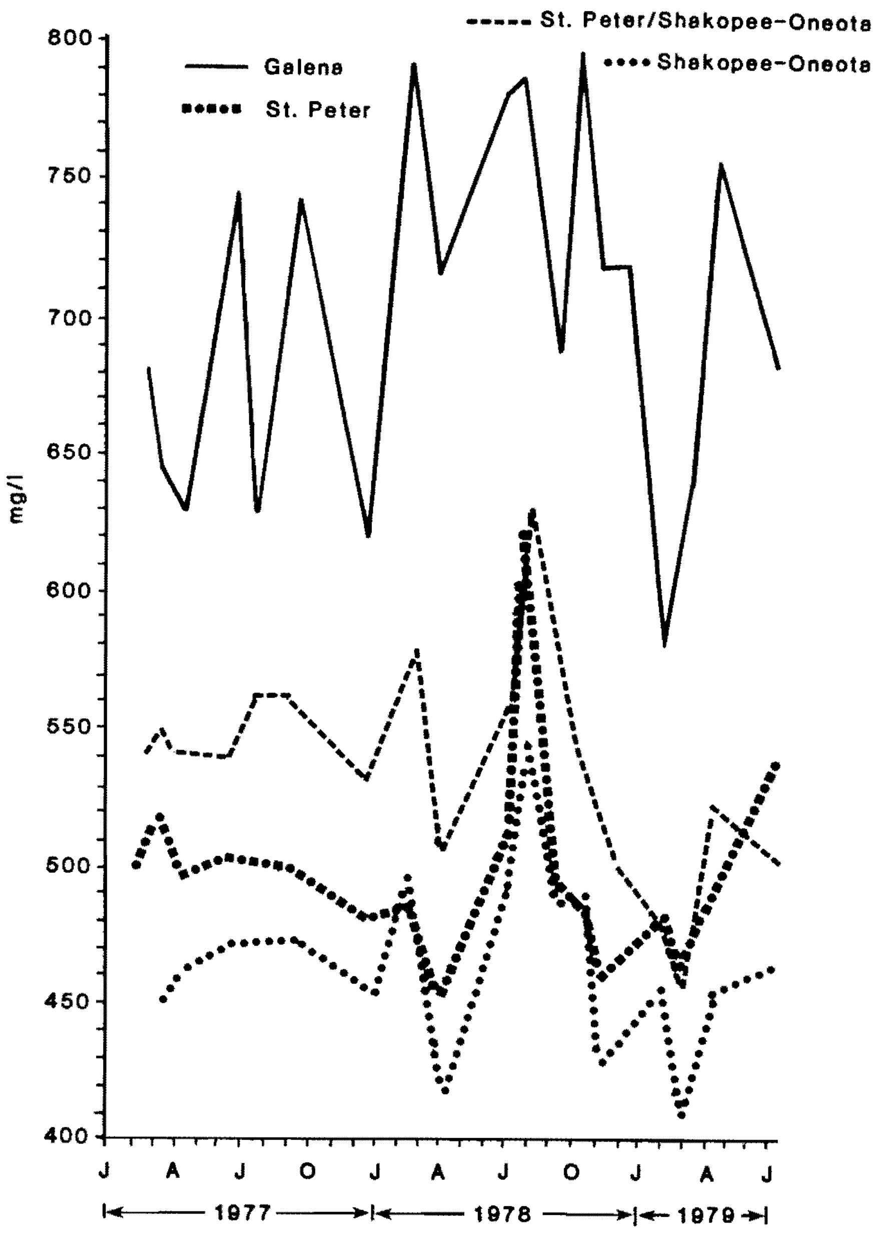
Nitrate nitrogen

Major sources of nitrogen compounds in ground water are plant residue, manure, rainfall, chemical fertilizers and domestic wastewater.[37] The maximum permissible concentration of nitrate nitrogen recommended in the United States Environmental Protection Agency's national interim primary drinking water regulations for community and non-community public water supplies is 10 mg/l.[38] The nitrate ion is the thermodynamically stable form of combined nitrogen for oxygenated water systems, so there is a tendency for all nitrogenous materials in water, including nitrite nitrogen and ammonia, to be converted to nitrate nitrogen.

The range of nitrate nitrogen values in the Galena Formation was 0.2 to 41 mg/l for routine samples and 0.2 to 50 mg/l for runoff samples. The median routine and runoff nitrate nitrogen values in the Galena Formation were 11 and 16 mg/l, respectively. Forty-one percent of the routine samples and 67 percent of the runoff samples in the Galena Formation exceeded 10 mg/l of nitrate nitrogen. Well 3-31-3, originally classified as a St. Peter well, was later reassigned to the Galena Formation following review of well construction and anion concentration analysis. This well had evidence of nitrate nitrogen in only two routine samples (April 15, 1978 - 3.5 mg/l and April 25, 1979 - 4.6 mg/l) and two runoff samples. However, one of the two runoff samples had 23 mg/l nitrate nitrogen. It occurred in the July 8, 1978 runoff sample.

Only one well not in the Galena Formation showed consistent presence of nitrate nitrogen. Well 2-16-2, which is in the St. Peter/Shakopee-Oneota aquifer, had detectable concentrations of nitrate nitrogen in 12 of

Figure 6. Median conductivity values by aquifer and date.



13 (92%) routine samples (range: 0.2 to 2.7 mg/l) and all six of the runoff samples (range: 0.4 to 2.7 mg/l). The highest median value (23 mg/l) in the Galena aquifer by date occurred in the July 8, 1978 runoff sample. The range of values in the Galena Formation on that day was 9 to 50 mg/l. No association between runoff and the presence of nitrate nitrogen could be identified in any aquifers except the Galena Formation.

Nitrite nitrogen

With the exception of two routine (2%) and three runoff (6%) samples in the Galena Formation, nitrite nitrogen values for all samples in the study were less than 0.05 mg/l. The median routine and runoff nitrite nitrogen values in the Galena Formation were 0.006 and 0.016 mg/l, respectively. The range of routine and runoff values was 0.005 to 0.09 mg/l and 0.005 to 0.8 mg/l, respectively.

Ammonia

The median routine and runoff ammonia values in the Galena Formation were 0.098 and 0.099 mg/l, respectively. The minimum routine ammonia value was less than 0.02 mg/l in each aquifer, while maximum routine ammonia values ranged from 0.23 mg/l for the Jordan Formation to 0.57 mg/l for the Galena Formation. The minimum runoff ammonia values were less than 0.02 mg/l in the St. Peter, St. Peter/Shakopee-Oneota, Shakopee-Oneota and Jordan aquifers and 0.025 mg/l in the Galena aquifer. The maximum runoff ammonia values were less than 0.02 mg/l in the Jordan Formation, 0.1 mg/l in the St. Peter, St.Peter/Shakopee-Oneota and Shakopee-Oneota Formations, and 0.49 mg/l in the Galena Formation. Most of the samples in the study had less than 0.02 mg/l of ammonia, ranging from 56 percent of Galena routine samples to 100 percent of the St. Peter and Jordan runoff samples.

Alkalinity

Alkalinity is imparted to water by bicarbonate, carbonate, or hydroxide components. In this study, bicarbonate is equal to alkalinity at the pH levels encountered. When soil moisture percolates through soil, it comes in contact with the carbon dioxide produced by decomposition. Some of the gas becomes dissolved in the water. The reaction between the carbon dioxide and water results in the formation of carbonic acid. When this weak acid encounters carbonate-holding rocks, such as limestone, the latter dissolve as calcium bicarbonate.

Sixty-one percent of routine samples and sixty-six percent of runoff samples in the Galena Formation had alkalinity concentration values greater than 250 mg/l. None of the routine or runoff samples in the Jordan had alkalinity values greater than 250 mg/l. In the St. Peter, St. Peter/Shakopee-Oneota and Shakopee-Oneota Formations the distribution of alkalinity concentrations ranged from 35 percent of the St. Peter routine samples to only 6 percent of the Shakopee-Oneota runoff samples with values greater than 250 mg/l. The concentration of alkalinity generally decreased with depth of the formation and was higher in routine samples than runoff samples in all aquifers with the exception of the Galena and Jordan aquifers.

The range of alkalinity values in the Galena Formation for routine samples was 110 to 466 mg/l and for runoff samples was 120 to 440 mg/l. In the Jordan Formation, all routine and runoff sample values were between 150 and 220 mg/l. Well 2-9-3, originally classified as a St. Peter/Shakopee-Oneota well, but reassigned to the Galena Formation after review of the bacteriological and chemical results, had the second highest (460 mg/l) maximum routine alkalinity value and highest (440 mg/l) maximum runoff alkalinity value in the study. The median routine and runoff values for Well 2-9-3 were 336 and 387 mg/l, respectively. The median routine and runoff values for the two wells in the St. Peter/Shakopee-Oneota aquifer were only 225 and 216 mg/l, respectively.

Sulfate

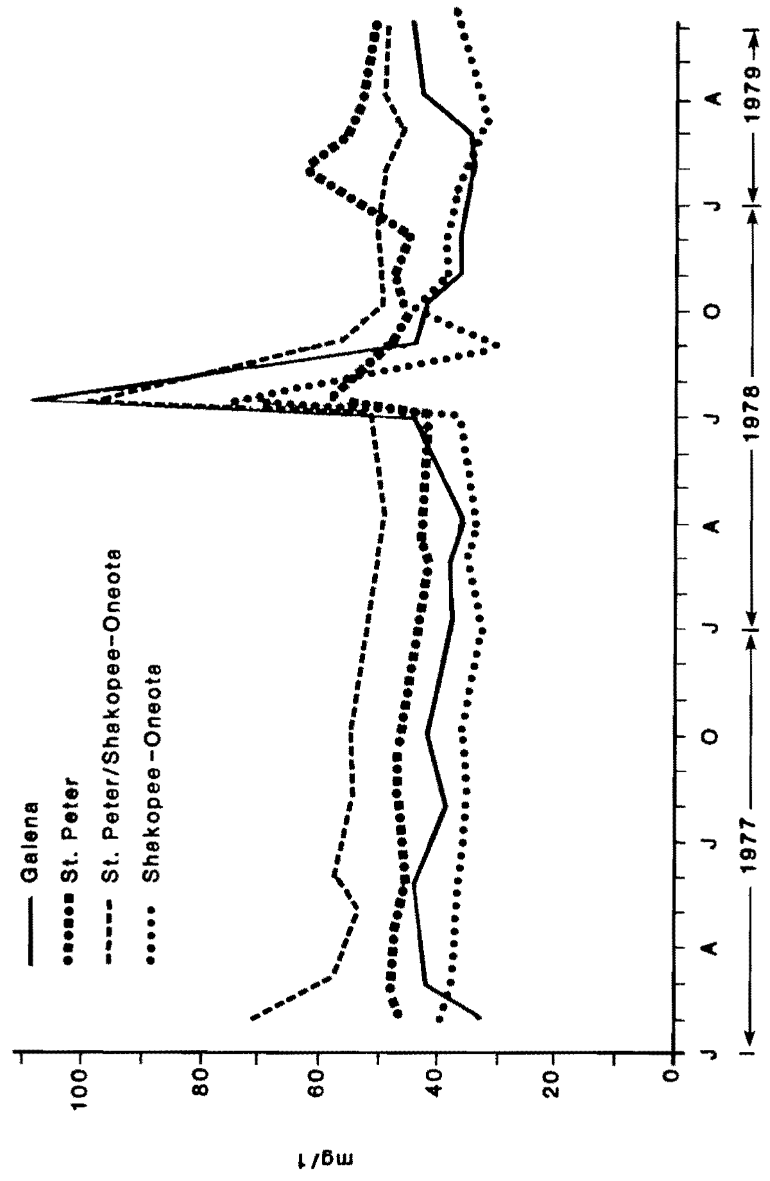
Sulfate occurs in ground water in varying concentrations. Sources include rainfall, evaporite sediment, oxidative decay of organic matter, chemical fertilizers and waste discharges.

The sulfate concentrations in the Galena Formation ranged from 15 to 83 mg/l for routine samples and 17 to 180 mg/l for runoff samples. The median routine value in the Galena was 38 mg/l and the median runoff value was 43.5 mg/l. The median, minimum and maximum values for routine and runoff samples in the St. Peter Formation were 53, 41 and 83 mg/l and 46, 39 and 70 mg/l, respectively. The same values for the Shakopee-Oneota Formation were 36, 15, and 193 mg/l and 36, 18 and 160 mg/l, respectively. The Shakopee-Oneota Formation had the highest number of routine and runoff samples with sulfate values over 100 mg/l. However, 12 of 13 routine samples and all six of the runoff samples in the Shakopee-Oneota Formation with concentrations greater than 100 mg/l were in one well (2-11-1). The significance of this finding will be discussed later in the section on chloride, sulfate and bicarbonate ion relationships. The median values for aquifers by date showed a dramatic increase in sulfate concentrations in the July 8, 1978 runoff samples for the Galena, St. Peter/Shakopee-Oneota, and Shakopee-Oneota Formations (Figure 7). In these three groups of wells, the median sulfate values for July 8 were approximately twice the next highest median values for all other samples. The median values for the Galena, St. Peter/Shakopee-Oneota and Shakopee-Oneota Formations on July 8 were 110, 100 and 76 mg/l, respectively. The second highest median value by date of sampling occurred in the July 8, 1978 runoff sample for the St. Peter Formation (59 mg/l). No value for July 8 was obtained for the Jordan Formation due to a laboratory accident.

Chloride

Chloride is present in rainfall and waste materials. Its presence in ground water also may be related to highway deicing salts and chemical fertilizers. Thirty-five percent of the routine samples and 54 percent of the runoff samples in the Galena Formation had concentrations of chloride greater than 20 mg/l. Neither the St. Peter nor Jordan Formations had any samples with chloride concentration over 20 mg/l. Eight percent of the routine samples and 18 percent of the runoff samples in the St. Peter/Shakopee-Oneota and 8 percent of the runoff samples in the Shakopee-Oneota samples had chloride concentrations greater than 20 mg/l. Of in-

Figure 7. Median sulfate values by aquifer and date.



terest are the chloride concentrations in the St. Peter/Shakopee-Oneota wells. If this group of wells draws its water from combined yield of the St. Peter and Shakopee-Oneota Formations, it would be expected that the chloride concentration would reflect that combination. However, the St. Peter/Shakopee-Oneota wells had higher concentrations than either individual aquifer. Ninety-six percent and 100 percent of the St. Peter Formation routine and runoff samples, respectively, and 100 percent and 89 percent of the Shakopee-Oneota Formation routine and runoff samples, respectively, had chloride values less than 10 mg/l. Only 50 percent of the routine samples and 46 percent of the runoff samples from the St. Peter/Shakopee-Oneota Formation had chloride values less than 10 mg/l. All 13 (50%) of the routine chloride values and five of the six runoff chloride values greater than 10 mg/l in the St. Peter/Shakopee-Oneota formation were from one well (2-16-2). This occurrence is due most likely to the actual source of recharge water for this well and was discussed previously in the Well Construction section.

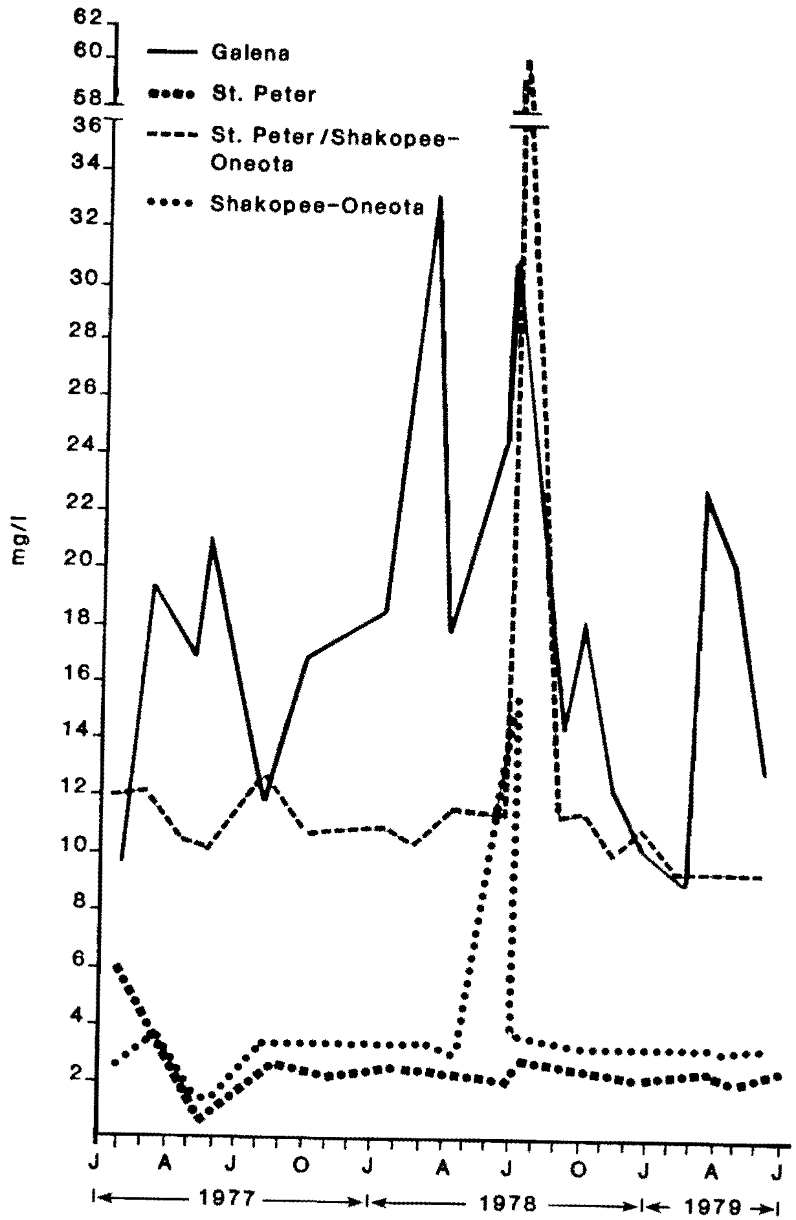
The range of chloride values in the Galena Formation was 1.6 to 83 mg/l for routine samples and 1.6 to 100 mg/l for runoff samples. The range in the chloride values for routine samples from all other wells in the study with the exception of Well 2-16-2 was from 0.7 to 11 mg/l. There was significantly more variation in the range of values for these same wells for runoff samples. Two wells in the Shakopee-Oneota aquifer (Wells 3-32-1 and 3-35-3) had chloride values of 85 to 110 mg/l in the July 8, 1978 runoff samples. In addition, Well 3-32-3 in the St. Peter/Shakopee-Oneota did not have any other runoff chloride values greater than 3.1 mg/l, but had 60 mg/l of chloride in the July 8, 1978 sample. The well from that same aquifer (2-16-2) which routinely had elevated chloride values was not tested for chloride on July 8 because of a laboratory accident. As previously discussed, the July 8, 1978 surface runoff had a very marked effect on the chemical parameters of some wells in the deeper aquifers, and this is demonstrated again for chloride concentrations (Figure 8).

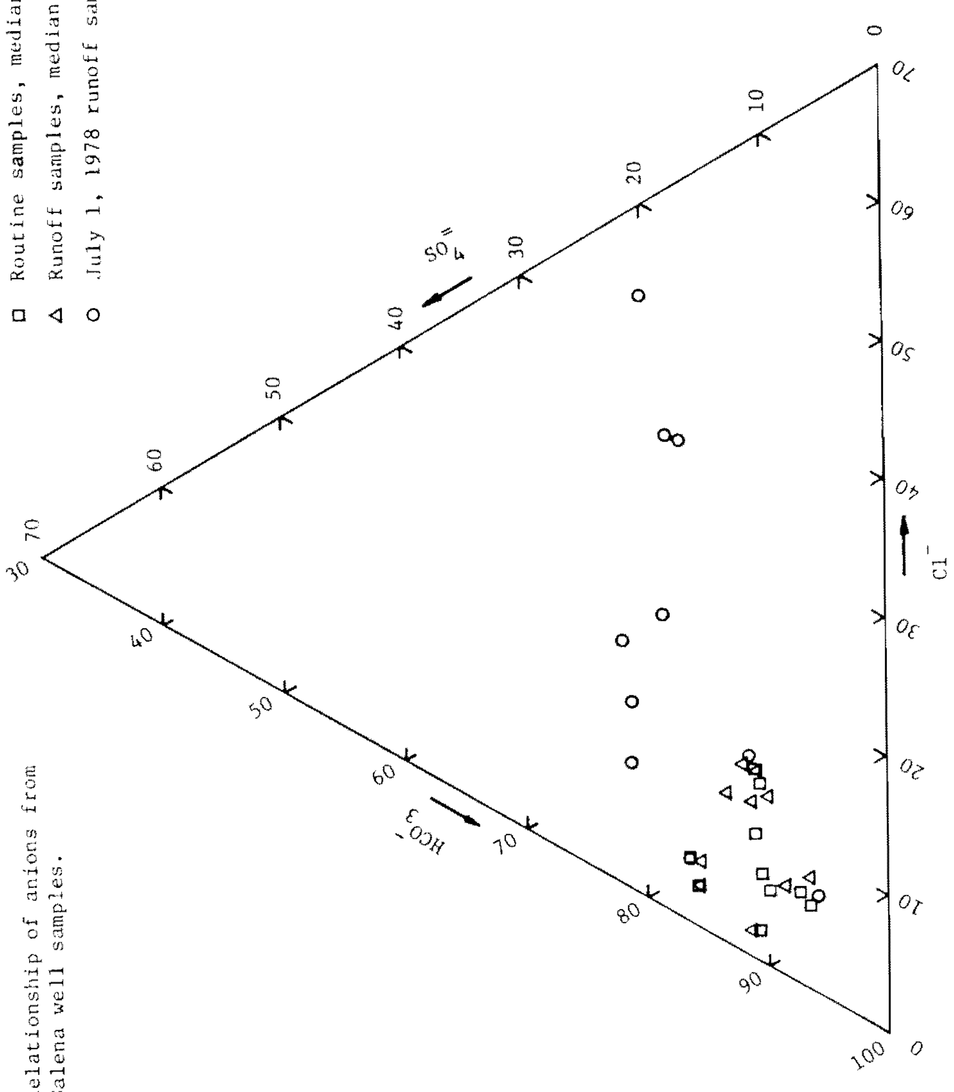
Chloride, sulfate and bicarbonate ion relationships

Trilinear diagrams were constructed to show the relationship between chloride, sulfate and bicarbonate ions in the water samples from wells in each aquifer. In preparing these diagrams, bicarbonates were considered to be equal to alkalinity. Median concentration values (mg/l) for the routine and runoff samples from each well were determined for each anion. These values, along with the values for the July 1, 1978 runoff sample, were first converted to milliequivalents per liter (meq/l) and then to percentages of the anion content. The percentages for all wells in each aquifer were then plotted on a separate trilinear diagram.

Figure 9 shows the relationship between the percentages of bicarbonate, chloride and sulfate ions for wells in the Galena aquifer. The scatter between points for the routine and runoff samples appears to confirm earlier findings of variability between wells in this formation. While there is only a slight increase in the percentage of chloride ions during runoff overall, a marked increase in the sulfate and chloride ion percentages occurred in the July 1, 1978 runoff samples.

Figure 8. Median chloride values by aquifer and date.





□ Routine samples, median values
△ Runoff samples, median values
○ July 1, 1978 runoff sample

Figure 9. Relationship of anions from Galena well samples.

The presence of sulfides in the upper member and pyrites in the lower member of the Galena aquifer had been reported.[15] Additional water flooding more channels during heavy runoff and coming into contact with these compounds may account for some of the increases noted in the percentage of sulfate ions. Leaching from sulfate-rich chemical fertilizers also may be responsible for some of the increases in the percentage of sulfate ions. The increase in the percentage of chloride ions with runoff in the Galena aquifer suggests surface contamination from livestock wastes and chemical fertilizers or possibly from septic tank effluents.

The relationship between the three anions for wells in the St. Peter aquifer is shown in Figure 10. These samples were characteristically low in the percentage of chloride ions and demonstrated no difference between the routine and runoff samples. However, a slight increase in the percentage of sulfate ions did occur with the July 1, 1978 runoff. The wells receiving water from both the St. Peter and the Shakopee-Oneota Formations are shown in Figure 11. Very little difference occurs between samples from these wells. This stiuation would be expected if the Decorah Shale restricts vertical flow from the Galena.

Figure 12 shows the anion relationship for wells finished in the Shakopee-Oneota only. These samples again are characteristically low in the percentage of chloride ions except for one July 1, 1978 runoff sample. The variation noted among wells in this aquifer is between the bicarbonate and sulfate ion percentages. The reason for this is unclear except that traces of sulfides also have been reported in the dolomite[15] which may be oxidized to sulfates when exposed to water by construction of the well. The higher concentrations of sulfates in a particular well water may indicate that more layers containing sulfides were penetrated by the well. A slight increase in the percentage of sulfate ions also is noted in only two of the six wells for the July 1, 1978 runoff samples.

The authors have no explanation for the increase in the percentage of sulfate ion with the July 1, 1978 runoff that occurred in the wells in the St. Peter aquifer and two of the six wells in the Shakopee-Oneota aquifer except that the increase appears to be associated with heavy runoff. This could imply that the Decorah and Glenwood Shales do not effectively restrict vertical flow from the Galena, that the shales may be discontinuous, or that direct connections exist between the aquifers. All of the well logs examined described the presence of clay or shale at an elevation that would indicate the shales were not discontinuous even though the thickness of the formations vary. The only other suspected source of direct connections would be improperly constructed or abandoned wells; but while these may exist, they are believed to be few in number and would not transmit great volumes of water in short times.

The one well finished in the Jordan aquifer also was low in the percentage of chloride ions and did not show any increase in sulfate ion percentage with the July 1, 1978 runoff. Because all trilinear points essentially coincided, the diagram is not included. Since the Jordan and Shakopee-Oneota aquifers are considered to be closely hydraulically connected, it was expected that the water quality would be similar and that they would react in the same manner to runoff occurrences. The fact that this does not occur in the Jordan may be due to both the time lag and

Figure 10. Relationship of anions from St. Peter well samples.

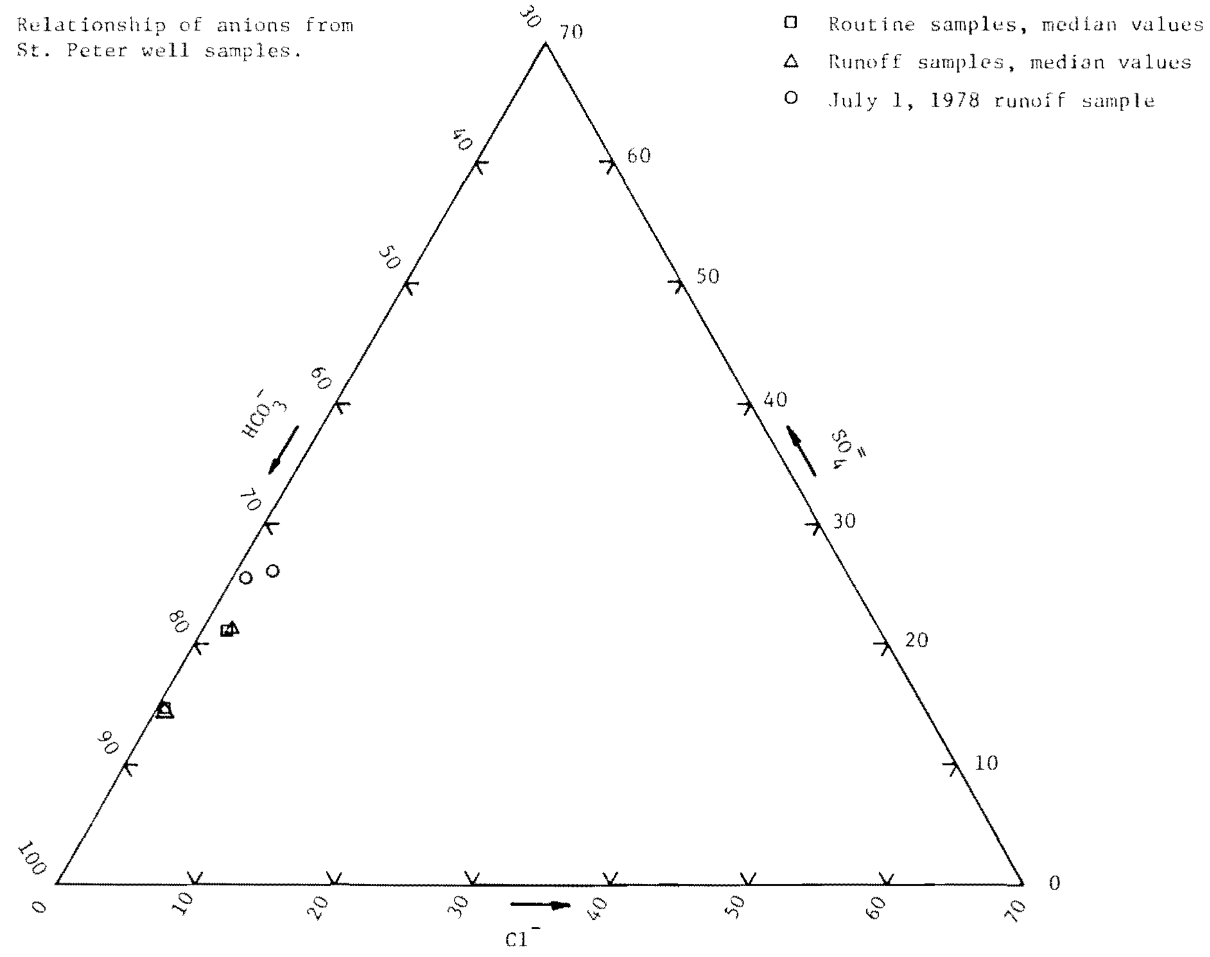
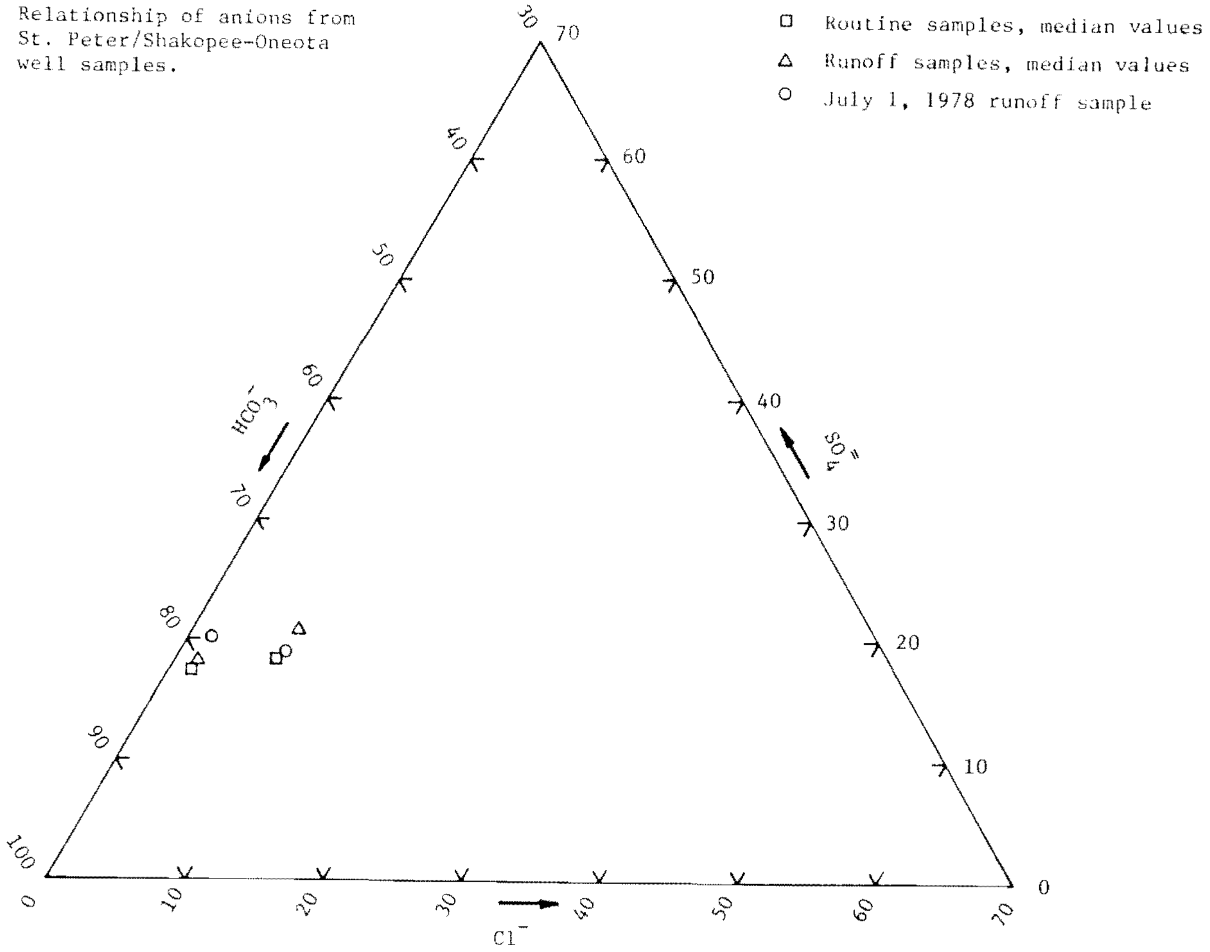


Figure 11. Relationship of anions from St. Peter/Shakopee-Oneota well samples.



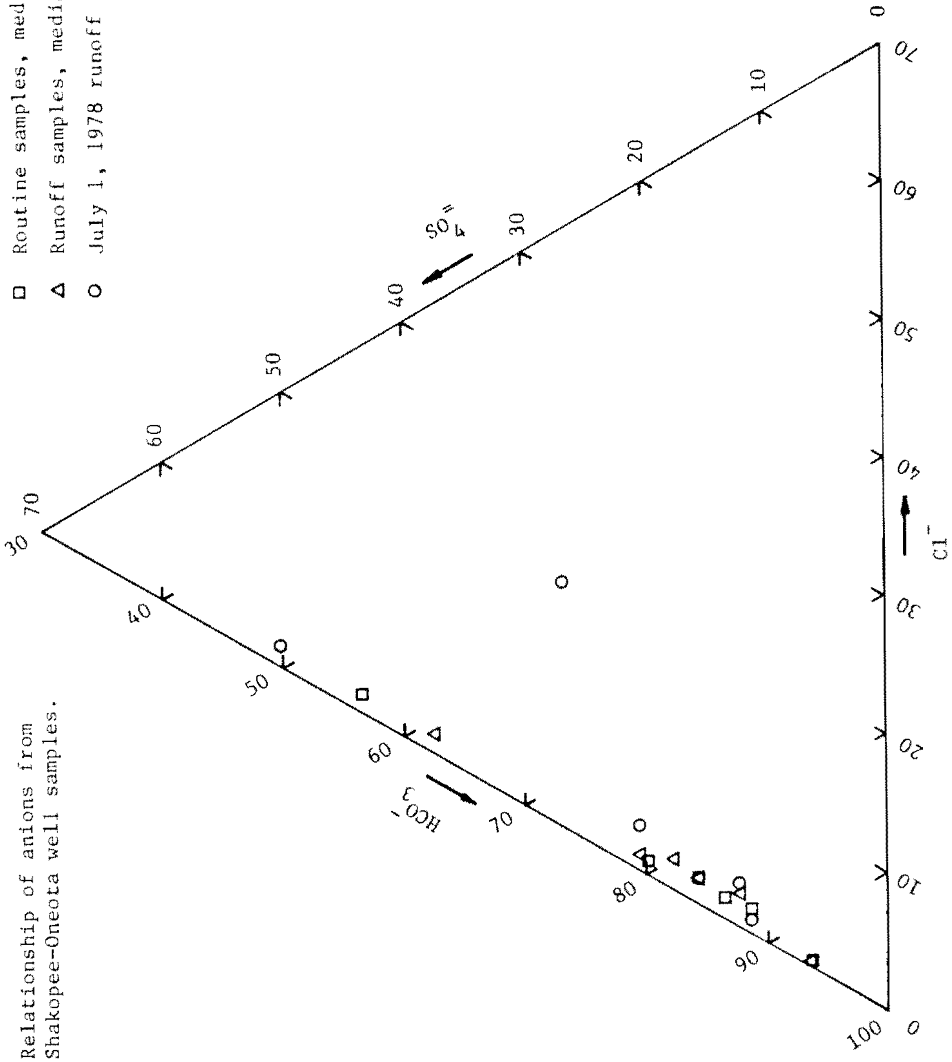


Figure 12. Relationship of anions from Shakopee-Oneota well samples.

dilution that occurs because of the slower and more uniform movement of water through the sandstone.

Phosphate

The major sources of phosphate in ground water are organic wastes, leaching of soils and, in some areas, phosphate fertilizer. Even though 14 percent of routine samples and 24 percent of runoff samples in the Galena Formation had phosphate values greater than 0.075 mg/l, none exceeded 1.28 mg/l. Minimum routine values in all the other aquifers were less than 0.001 mg/l. The maximum routine values ranged from 0.022 mg/l in the Jordan Formation to 1.28 mg/l in the Galena Formation. An interesting unexplained variation in phosphate values occurred in the October 7 and November 11, 1978 routine samples in all the aquifers except the Galena. In the October sample the phosphate median values in the St. Peter, St. Peter/Shakopee-Oneota, Shakopee-Oneota and Jordan Formations were 0.003, 0.002, <0.001 (0.0005) and 0.003 mg/l, respectively. These were either the minimum values by date documented throughout the study for the aquifer or were within 0.002 mg/l of the minimum values. In the November sample the median values for the St. Peter, St. Peter/Shakopee-Oneota, Shakopee-Oneota and Jordan Formations were 0.052, 0.049, 0.32, and 0.022 mg/l, respectively. The latter values were the maximum median values for each aquifer and showed a 7 to 640 fold rise in phosphate levels. There was no clear relationship between levels of phosphate and turbidity concentrations in any of the aquifers.

Phenol

Phenol concentrations were examined to determine whether petroleum products used to fuel or service farm equipemnt were contaminating the ground water. Although detectable amounts were found, the levels were so low as to indicate that the source was probably from the pumping equipment in the well rather than from some surface source.

The median routine and runoff sample values in the Galena Formation were less than 2.0 µg/l. Median values of all other routine samples were similar to those in the Galena Formation. Median values of all other runoff samples were slightly less than the runoff samples in the Galena Formation. Twenty percent of the routine samples and 27 percent of the runoff samples in the Galena Formation had phenol present in detectable amounts. No routine or runoff samples in other aquifers except the St. Peter/Shakopee-Oneota routine samples had detectable phenol in more than thirteen percent of the samples. Seven routine samples (27%) in the St. Peter/Shakopee-Oneota Formation had measurable concentrations of phenol.

Total organic carbon

The organic particulate matter found in ground water is from organic matter associated with soil particles (humus), plant and animal debris, microorganisms, and organic colloids. All of the routine samples from St. Peter, St. Peter/Shakopee-Oneota, and Jordan Formations had less than 5 mg/l of total organic carbon (TOC). There were two (2%) routine samples in the Galena Formation and one (1%) routine sample in the Shakopee-Oneota which had TOC concentrations between 5 and 10 mg/l. Each of the aquifers except the Jordan had runoff samples with TOC concentrations greater than 5 mg/l. The range of TOC values in the Galena Formation was less than 1.0 to 5.6 mg/l for routine samples and less than 1.0 to 77 mg/l for runoff samples. The median routine and runoff sample TOC concentrations in the Galena Formation were 1.75 and 2.2 mg/l, respectively. The median routine values in the St.Peter, St. Peter/Shakopee-Oneota and Shakopee-Oneota were 0.8, 1.25 and 1.0 mg/l respectively. The median runoff values for the same aquifers were 0.8, 1.1 and 1.0 mg/l, respectively. Despite the almost identical median routine and runoff values there were marked differences in the ranges of values. The maximum routine values in the St.Peter, St. Peter/Shakopee-Oneota, and Shakopee-Oneota were 3.3, 12 and 4.1 mg/l, respectively. The maximum runoff values in the same aquifers were 38, 32, and 33 mg/l, respectively. The maximum values in these aquifers occurred in the July 8, 1978 runoff samples. The median TOC concentrations in the Galena, St. Peter, St. Peter/Shakopee-Oneota and Shakopee-Oneota in the July 8 sample were 46.5, 33.5, 32 and 30.5 mg/l, respectively (Figure 13). The second highest median concentration by date in the same aquifers was 3.4, 2.1, 2.9 and 1.65 mg/l, respectively. The 10-to 20-fold increase in TOC values in the July 8 samples, compared to the second highest median values, is another example of the rapid and significant effect of surface runoff on the lower aquifers. The July 8 sample from the Jordan wells was not analyzed for TOC due to a laboratory accident, therefore making it impossible to determine the effect of the runoff on the TOC concentrations in that aquifer. However, the Jordan Formation had the least variation, with routine and runoff sample ranges of less than 1.0 to 3.5 mg/l, and less than 1.0 to 1.6 mg/l, respectively.

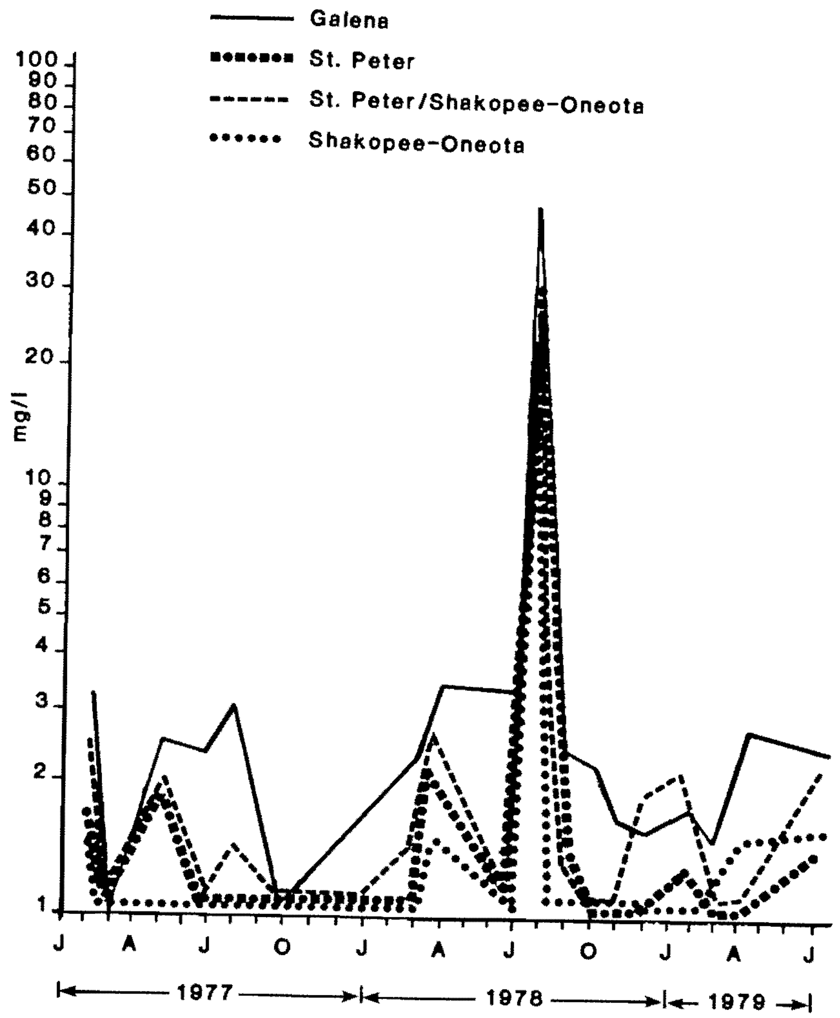
Sulfate/chloride ratio

The sulfate/chloride ratio in the Galena Formation ranged from 0.53 to 21.87 for routine samples and 0.63 to 22.5 for runoff samples. The median routine and runoff values in the Galena Formation were 1.95 and 1.38, respectively. The median routine values in the St. Peter, St. Peter/Shakopee-Oneota, Shakopee-Oneota and Jordan Formations were 25.49, 8.44, 14.29, and 7.43, respectively. The median runoff values in the same aquifers were 24.64, 8.17, 14.55, 6.65, respectively. While there was difference of ratios between aquifers, little difference was noted between routine and runoff samples within the respective aquifer. The highest median ratio by date in the Galena, St. Peter, St. Peter/Shakopee-Oneota, Shakopee-Oneota and Jordan Formations was 4.51, 50.83, 15.28, 32.16 and 17.36, respectively. The maximum Galena Formation ratio occurred in both the July 8, 1978 and March 19, 1979 runoff samples. The St. Peter/Shakopee-Oneota and Shakopee-Oneota Formations showed marked decreases in the ratio in the July 8, 1978 runoff sample. The St. Peter/Shakopee-Oneota sample had a ratio value of 0.83. The range of the other median ratios by date in that aquifer was 6 to 15.28. In the Shakopee-Oneota Formation the July 8 sample ratio was 7.47. The range of the other median ratios by date was 9.47 to 32.16.

Bicarbonate/sulfate ratio

The range of the bicarbonate/sulfate ratios in the Galena Formation was 1.7 to 18.66 for routine samples and 0.66 to 18.82 for runoff samples. The median routine and runoff ratios in the Galena were 6.89 to 6.17.

Figure 13. Median total organic carbon values by aquifer and date.



The median routine ratios in the St. Peter, St. Peter/Shakopee-Oneota, Shakopee-Oneota and Jordan Formations were 4.83, 4.29, 5.14 and 6.45, respectively. The median runoff ratios in the same aquifers were 4.4, 3.93, 4.99 and 6.64, respectively. There was no discernable trends in the ratio changes with time of sample, however, the ratios for the July 8, 1978 samples were not determined because the bicarbonate (alkalinity) analyses were not done.

Nitrate nitrogen/chloride ratio

Nitrate nitrogen/chloride ratios in the Galena Formation for routine and runoff samples ranged from 0.04 to 1.72 and 0.03 to 1.54, respectively. The median routine and runoff values were 0.51 and 0.56, respectively. The median routine values for the St. Peter, St. Peter/Shakopee-Oneota, Shakopee-Oneota, and Jordan Formations were 0.11, 0.07, 0.06, and 0.05, respectively. The median runoff values for the same aquifers were 0.11, 0.05, 0.08 and 0.05, respectively. The highest median ratio (0.72) by date in the Galena Formation occurred in the July 8, 1978 sample. However, the lowest median ratio in both the St. Peter/Shakopee-Oneota (0.001) and Shakopee-Oneota (0.001) Formations also occurred in that sample. The lower ratios in these aquifers were twenty-fold lower than the next lowest ratio. Inspection of the actual nitrate nitrogen and chloride concentrations in these aquifers indicates the influx of chloride with runoff and little or no change in nitrate nitrogen concentrations. The St. Peter Formation showed little effect of the July 8, 1978 runoff sample on the nitrate nitrogen/chloride ratio. A ratio was not calculated for the Jordan Formation for the July 8 sample since the chloride concentration was not determined in that sample on that date.

CONCLUSIONS

The following conclusions may be drawn from an evalution of the data collected during the study:

1. Although there was considerable variation in the parameters measured in samples from wells in the Galena Formation, most values except those reported for total coliform organisms and for nitrate nitrogen were within acceptable limits. The Primary Interim Drinking Water Standards[38] recommend limits of one coliform per 100 ml and 10 mg of nitrate nitrogen per liter. These standards apply to waters used as sources of public or semi-public water supply and would serve as useful guidelines for evaluating the quality of water extracted from private wells. High nitrate nitrogen concentrations have been associated with the causation of methemoglobinemia in infants under three months of age where these waters were used in the preparation of the infant's formula. Total coliform, on the other hand, has been used by public health personnel as a measure of the bacteriological quality of water supplies. The presence of coliform organisms has been associated with the possible presence of human and animal pathogens, but is no guarantee of their presence. Similarly, a low coliform count is not a guarantee of the absence of possible pathogenic organisms. The bacteriological data obtained following periods of runoff show much higher concentrations of total coliform, fecal coliform, and fecal streptococci in samples taken from wells in the Galena Formation.

Although the presence of total coliforms was detected in water sampled in other formations, the total counts were not as high nor was the marked increase noted for samples collected following runoff in the Galena Formation evident in the other aquifers. The determination of the fecal coliform to the fecal streptococci ratio, which differentiates between fecal contamination from human and animal sources, showed a decrease following runoff implying additional contribution of fecal matter from non-human sources.

2. More variation in the chamical parameters was noted in the Galena Formation in comparison with the data from the other aquifers.

a. As noted above, nitrate nitrogen levels were highest in the Galena Formation and, in general, showed increased concentrations in the runoff samples. Only one well in the St. Peter/Shakopee-Oneota showed this response. In the other formations, nitrate nitrogen concentrations showed little, if any, difference in levels found in routine or runoff samples.

b. Chloride concentrations were highest in the Galena Formation and were approximately an order of magnitude lower in the remaining formations. However, almost all wells in all formations showed increased concentrations during the periods of heaviest runoff.

c. Sulfate concentrations were relatively uniform in routine samples from the Galena Formation and in most wells in other formations. Slight increases in the median values were observed in the runoff samples, but maximum runoff values were somewhat higher in samples collected from the Galena Formation. There were variations in median routine values and in the median runoff sulfate concentrations particularly in the Shakopee-Oneota Formation. The Jordan Formation (single well) showed no difference between routine and runoff samples.

d. There was some variation in the phosphate concentrations found in the Galena Formation but the variations were not consistent. Some of the median values showed an increase in the runoff samples, others a decrease. Maximum values for both routine and runoff samples showed similar variations. Differences in the median values in the lower formations were less marked.

e. The median phenol concentrations in both the routine and runoff samples were at the less than 2 μg/l level. Some fluctuations in the maximum values occurred for both the routine and runoff samples, and the maximum concentrations observed were identified with the Galena Formation.

F. Slightly higher median concentrations of total organic carbon were observed in the routine samples collected in the Galena Formation. Runoff median concentrations were also a little higher in the Galena than in the other formations. Maximum runoff values were very nearly the same in all formations, but higher than routines.

g. Generally, it was found that the highest median routine conductivity concentrations were in the Galena Formation (range: 540 to 1010 μS/cm) with median concentrations being within a range of 410 to 640 μS/cm in the other formations. There was little change overall in the runoff median values found.

h. Although there were some differences in median values for wells sampled in the various formations, in general, higher concentrations of total filterable residue were found in the Galena Formation than in the lower formations. Differences were irregular with some increase or some decrease in the runoff median concentrations compared to the routine samples.

3. The physical parameters that exceeded recommended standards were turbidity and color. In most instances, the runoff samples showed higher median concentrations than did the routine samples.

4. The data show that the chemical quality of the water in the deeper aquifers is affected rapidly by surface runoff implying that the Decorah Shale "only partially" protects the lower aquifers from chemical contamination. Additional collection of samples from these and other wells in these formations during periods of runoff would provide further confirmation of this observation. Furthermore, the rapid contact with surface waters stresses the need for controlling surface pollution to minimize further deterioration of these ground water resources.

5. Regarding well construction, there was no evidence of extensive contamination entering aquifers underlying the Decorah Shale via surface water flowing through openings between the casing and outer edge of the borehole in ungrouted wells. The Decorah Shale apparently caves in and swells around the casing so as to completely fill the opening. While grouting of the wells into the deeper aquifers does not appear to be important with respect to water flowing down the outer edge of the borehole, its presence is very significant in the prvention of corrosion of the well casing in the Galena aquifer. This study clearly documents direct entry of surface water contaminants to a well in the Shakopee-Oneota Formation. It is suspected that water from the Galena aquifer enters through corroded casing at the base of the Galena Formation. In addition, there was evidence that this well may contribute to, or be the source of, the contamination entering the Shakopee-Oneota well located on a nearby farm. This finding is extremely important since a number of wells completed in the karst area in the St. Peter and the Shakopee-Oneota Formations from the 1950's to the mid 1970's were constructed without grout. In the next 10 years many of these wells may experience marked deterioration of casings due to corrosion in the Galena Formation. Such corrosion could result in widespread contamination of the St. Peter (chemcial) and the Shakopee-Oneota (bacterial and chemical) aquifers. Since the Jordan aquifer is reported to be connected hydraulically to the Shakopee-Oneota aquifer, it can only be inferred that such contamination ultimately may affect that aquifer also.

6. The parameters found to be the best indicators of surface water contamination of the aquifers were: bacterial counts (total coliform, fecal coliform, fecal streptococci) and nitrate nitrogen in the Galena and St. Peter Formations only, turbidity, conductivity, sulfate, chloride,

phosphate, total organic carbon, sulfate/chloride, and nitrate nitrogen/chloride ratios. Each of these parameters indexed the influence of surface water runoff in the aquifers studies and should be included in future studies of ground water contamination. While cations were not measured in this study, they should be included in any future monitoring program.

7. The results of this study indicate a rather urgent need to initiate a ground-water monitoring program in southeastern Minnesota for the purposes of determining the short- and long-term trends in water quality. As more individuals abondon water wells in the Galena Formation and seek a higher quality of water in the lower aquifers, the importance of these aquifers as continued sources of water supply becomes evident. However, if chemical (and possibly bacterial) contamination is entering these aquifers, it is only a matter of time before serious degradation of water quality may occur. A monitoring program, which includes routine sampling of a series of wells which terminate in the various aquifers, would provide environmental health officials the opportunity to assess changes in water quality in these aquifers and would permit rational and timely evaluation of methods of preventing further quality degradation. This would mean a renewed interest in minimizing the impact of agricultural and domestic sources on ground-water contamination in the Galena Formation despite the fact it cannot be considered a safe and reliable source of drinking water. Rather, the need for minimizing ground-water contamination in that aquifer is obvious if contamination of the lower aquifers is to be avoided.

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