HYDROGEOLOGY AND GROUNDWATER MONITORING OF FRACTURED DOLOMITE IN THE UPPER DOOR PRIORITY WATERSHED, DOOR COUNTY, WISCONSIN

Final Report to the Wisconsin Department of Natural Resources

by

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CHAPTER 1

INTRODUCTION

Project Background

Door County, Wisconsin, has a long history of perceived problems with groundwater quality. Groundwater is the source of drinking water for most Door County residents (Bradbury, 1989), and past studies reported frequent occurrences of elevated nitrate, coliform bacteria, turbidity, and other constituents in water samples from drinking water supply wells (Sherrill, 1978; Bradbury, 1989). Many of these water-quality problems have been attributed to agricultural and other land-use practices that are poorly suited to the hydrogeologic setting of Door County, which consists primarily of fractured, highly permeable dolomite aquifer beneath very thin soils. The Upper Door Watershed was selected in 1984 as a priority watershed project under the Wisconsin Nonpoint Source Water Pollution Abatement Program due to "....(1) the severity of water-quality problems in the watershed; (2) the importance of controlling nonpoint sources of pollutants in order to attain water-quality improvement or protection; and (3) the capability and willingness of local government agencies to carry out the planning and implementation of the project" (Schuster and others, 1989). The Upper Door Priority Watershed consisted of the portion of the Door Peninsula north of Sturgeon Bay and the Sturgeon Bay Ship Canal.

Objectives of the priority watershed project with respect to groundwater were to protect "safe" groundwater from the impacts of nonpoint sources of pollution and to decrease the frequency of contaminated wells in the project area affected by nonpoint sources of pollution (Bachhuber and Schuster, 1987). One part of this effort was an assessment of hydrogeology and long-term groundwater quality in a small groundwater basin in the Town of Sevastopol. This small basin was chosen because it had a high incidence of reported water quality problems and because several Best Management Projects funded by the Priority Watershed Project were located there.

In July, 1986, the Wisconsin Department of Natural Resources (WDNR) contracted with the Wisconsin Geological and Natural History Survey to establish methods to monitor the impacts of land use on groundwater quality in the Upper Door Priority Watershed, and initiated the work described in this report. The WDNR Groundwater Monitoring Program provided additional funding from 1987 through June 30, 1990, when the project terminated.

Several previous publications report on various aspects of this research. Blanchard (1988) reported extensive findings from the first three years of the project, and Schuster and others (1989) also reported a portion of the data collected during the project. Other reports generated wholly or in part by this project include Bradbury and others (1988; 1991), Bradbury (1989), Bradbury and Muldoon (1990), and Muldoon and

Bradbury (1990). Simultaneously, Johnson (1987), Check (1990) and Saunders (1990) conducted research on various aspects of the hydrogeology of Door County.

Purpose and Scope

This project has two primary areas of focus. The first was to undertake a detailed study of hydrogeology and groundwater flow systems in a small groundwater basin near Sevastopol, Wisconsin. Objectives of this part of the study include the following:

1. to characterize groundwater flow systems in the area, and to determine the relationships of the flow systems to stratigraphy, fractures, and karst features in the dolomite aquifer;

2. to determine rates and directions of groundwater movement in the study area;

3. to determine rates and timing of groundwater recharge in the study area;

4. to characterize the hydrogeologic properties of the dolomite aquifer in the study area;

The second focus of the project was a detailed program of long-term groundwater monitoring in the project area. Objectives of the groundwater monitoring program included the following:

1. to determine the chemical composition of drinking water produced by domestic wells in central Door County with respect to commonly-accepted drinking-water-quality criteria (nitrate, bacteria, etc.);

2. to determine temporal and spatial variations in groundwater chemistry, and to provide guidelines for groundwater monitoring and the collection of well-water samples for regulatory and public health purposes in fractured-rock settings;

3. to examine variations in groundwater chemistry in relation to depth below the land surface and the presence or absence of fracture conduits;

4. to examine relationships between well-water quality and land-surface features, soil characteristics, and land use in a fractured-rock setting;

5. to use isotopes of hydrogen and oxygen to determine the age of groundwater in the fractured dolomite aquifer

Acknowledgements

Many people participated in this project. Mr. William E. Schuster, Door County Soil and Water Conservation Department, originally conceived much of the groundwater monitoring portion of the project and provided invaluable support and contacts with local land owners. Professors Ronald Stieglitz and James Wiersma of the University of Wisconsin-Green Bay supervised the collection and analysis of water samples and contributed numerous insights about the hydrogeology of Door County. Julie Kuhr, Catherine Saunders, James Check, and Robert Herubin assisted in sample collection and analysis. Margaret Blanchard carried out much of the field work during the first three years of the project as part of her M.S. thesis at the University of Wisconsin-Madison. Numerous staff members and students at the Wisconsin Geological and Natural History Survey contributed to this project. Finally, we thank the landowners in the study area who participated in the groundwater sampling program. Special appreciation is extended to the Kenneth Staats and Milton Staats families for allowing drilling and well installation on their land.

CHAPTER 2

METHODOLOGY

Homeowner Sampling Program

Site Selection

One goal of the Upper Door Priority Watershed study was to define and identify the physical characteristics of the landscape and the land use-practices that influence groundwater quality. As part of that study, the Door County Soil and Water Conservation Department undertook a detailed walking survey of approximately 36 square miles in central Door County in early 1986 in order to identify potential contamination sources; locate sinkholes, major fractures, and springs; and contact homeowners who would be willing to participate in a water-sampling program. The well-sampling program concentrated on the central portion of northern Door County because that area contains many dairy farms and fruit orchards which can produce potential groundwater contaminants such as manure, fertilizers, and pesticides. The survey located five springs and identified 45 homeowners willing to collect biweekly water samples. Sampling of these 50 locations began in February of 1986 and continued through June of 1986 (Blanchard, 1988).

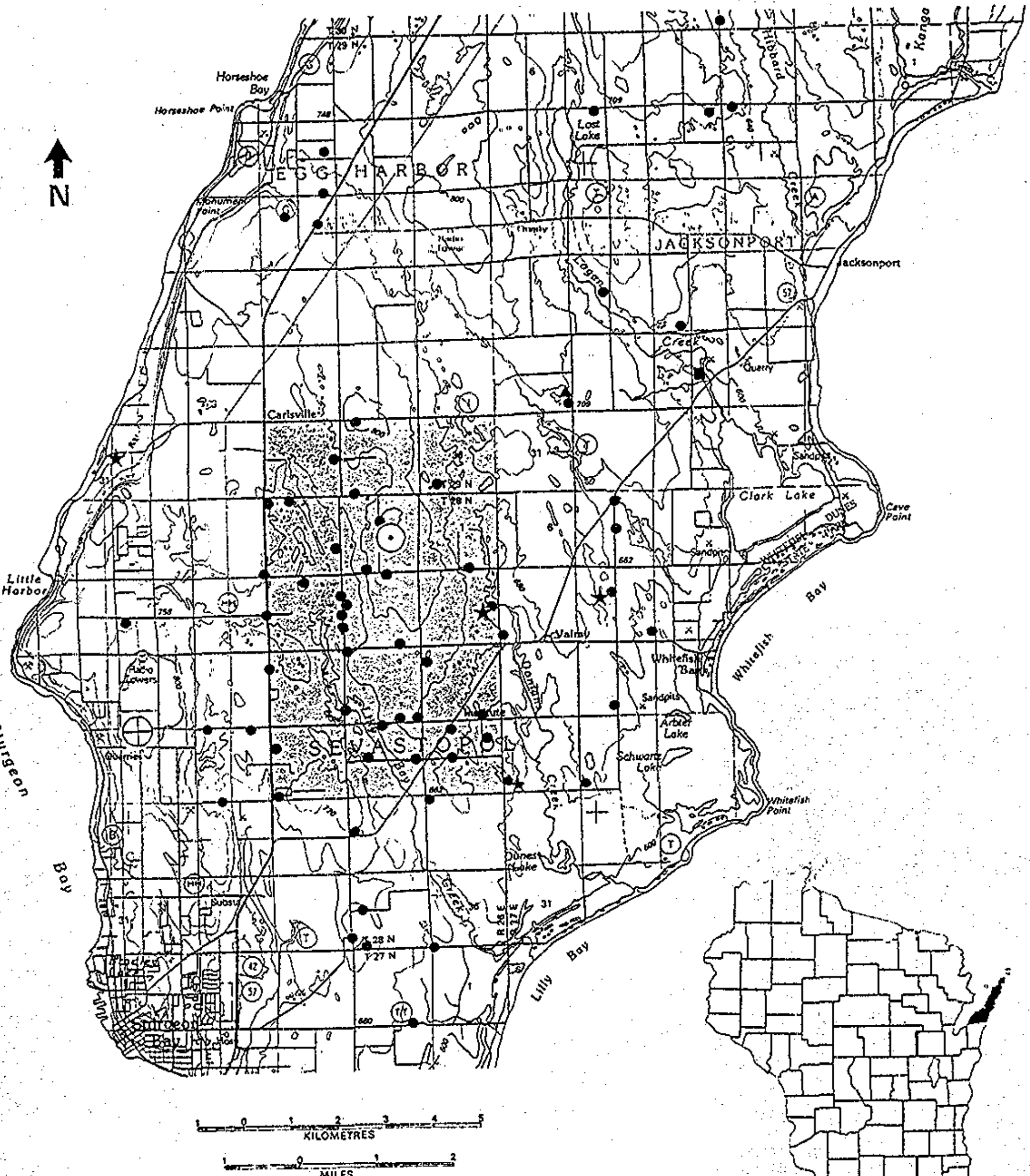
The Wisconsin Geological and Natural History Survey (WGNHS) became involved in the project in July, 1986 and after a review of the data, the sampling groupings and frequencies were changed in order to focus the study on a smaller geographic area and to add additional wells for which well construction reports were available. In June 1987, sampling was discontinued for all wells except those in a smaller subarea where sampling of 14 wells continued biweekly through August 1988 and monthly through July 1990.

Figure 2-1 shows well and spring locations. Appendix A contains a list of all wells and springs sampled as part of this project, the locations of the sampling points, and the dates sampled.

Water Sampling

The water samples were tested for coliform bacteria, specific conductance, turbidity, ammonium, nitrate, chloride, sulfate, and potassium. These eight parameters were chosen for analysis because 1) they are common constituents of groundwater, 2) sampling procedure is relatively simple, 3) elevated levels of these constituents indicate that surface contaminants may be entering the well, and 4) analysis of these parameters is relatively inexpensive, allowing more intensive sampling of a greater number of wells over a longer period of time. Each of the parameters is described below.

Figure 2-1. Map of study area showing location of all sampling points, the two research sites, and the 15 mi^2 sub-area (shaded).



Key:
- • private wells
- ★ springs
- ⊙ Jarman Road research site
- ⊕ County HH research site

Coliform Bacteria

Legally, a safe drinking water supply must contain no coliform bacteria. While the coliform group of bacteria are not pathogenic organisms, they are good indicator organisms for the following reasons:

--coliform has regular fecal occurrence,
--when none are present the water is free of pathogens,
--number of colonies is roughly proportional to level of pollution,
--coliform organisms are more hardy than pathogens,
--they are easily detectable,
--they are safe to grow.

The disadvantages of using the coliform group as indicator organisms are that they are ubiquitous and aftergrowth is possible.

The determination of microbiological activity is the primary water quality measurement for drinking water. The tests are straightforward but time consuming and contamination of a sample is easy, resulting in false positive readings. The water samples in this study were analyzed following the Standard Total Coliform Membrane Filter Procedure (Standard Methods 909A).

Specific Conductance

Specific electrical conductance, or conductivity, is a measure of the ability of water to transmit an electrical current, and is proportional to the total dissolved solids and the ionic content of water. Distilled water with no dissolved solids has a specific conductance of essentially zero. Specific conductance was measured with a Yellow Springs Instrument Model 59 Conductivity Meter. Relative conductivities of different solutions vary with temperature. As is commonly done, all results were corrected to 25° Celsius. Conductivity is a property of the sample only and has units of μmhos/cm.

Turbidity

Turbidity is a measure of the clarity of water; elevated turbidity values are the result of suspended particles in the water. Water samples were analyzed for turbidity using the Nephelometric Method - Nephelometric Turbidity Units Method (214A in Standard Methods, 1985). This method compares the intensity of light scattered by the sample with the intensity of light scattered by a standard reference suspension and the results are reported in Nephelometric Turbidity Units (NTU). The detection limit using this method is 0.1 NTU; turbidity levels greater than approximately 25 NTU are visible to the naked eye.

Nitrate (NO_3^-)

Dissolved nitrogen, in the form of nitrate (NO_3^-) is one of the most common contaminants in groundwater. Commercial fertilizers and human and animal wastes contain nitrogen in several forms including organic nitrogen, nitrate (NO_3^-), ammonia (NH_3), and ammonium (NH_4^+). Soil bacteria quickly convert ammonia-nitrogen to nitrite and nitrate. Nitrate does not adsorb onto soil particles and as a result it is easily transported in groundwater. Nitrate can pose a health threat for young children if the concentration exceeds 10 mg/L (NO_3^- as N). Groundwater that has not been impacted by human activities generally has low concentrations of nitrate and elevated levels of nitrate (above 0.5 mg/L) are an indication of possible contamination from the land surface.

Water samples were analyzed for nitrate using the Automated Cadmium Reduction Method (418F in Standard Methods, 1985) and the results are reported in mg/L nitrate as nitrogen. The detection limit for nitrate-N using this method is 0.1 mg/L.

Ammonium (NH_4^+)

Ammonium is a form of nitrogen found in human and animal wastes and commercial fertilizers (the term ammonium is used to describe the presence of both the ammonium and ammonia forms of nitrogen). Usually ammonium is quickly converted into nitrite or nitrate by bacteria in the unsaturated zone. However, if recharge is rapid, it is possible that ammonium can reach the water table with little attenuation. Ammonium is not commonly detected in groundwater since most nitrogen is converted to nitrate before it reaches the saturated zone. There is no drinking water standard for ammonium, however, its presence in groundwater indicates that human or animal wastes are directly entering groundwater.

Water samples were analyzed for ammonium using the Automated Phenate Method (Standard Methods, 1985) and the results are reported in mg/L ammonium as nitrogen. The detection limit for ammonium-N using this method is 0.03 mg/L.

Chloride (Cl^-)

The common minerals that contain chloride (halite, NaCl; sylvite, KCl) are simple salts that are easily dissolved in water. The dolomite in Door County probably contains trace amounts of these minerals which contribute a background amount of chloride to the groundwater. The observed elevated levels of chloride are probably a result of winter road-salting, leaching from waste disposal areas, fertilizers, septic systems, and landfills. Chloride does not pose any health threat, however, concentrations greater than 250 mg/L result in a salty taste. Elevated levels of chloride are an indication of possible contamination from the land surface.

Water samples were analyzed for chloride using the Automated Ferricyanide Method (407D in Standard Methods, 1985) and results are reported in mg/L. The detection limit for this method is 0.2 mg/L.

Sulfate (SO_4^{2-})

Sulfate is a common anion in groundwater from carbonate aquifers and typical concentrations range from 10 to 100 mg/l (Freeze and Cherry, 1979, p. 263). The common minerals containing sulfate are gypsum ($CaSO_4 H_2O$) and anhydrite ($CaSO_4$). Both of these minerals are found in trace amounts in most sedimentary rocks including dolomite. High sulfate concentrations in drinking water can cause taste problems and may have a laxative effect on individuals unaccustomed to the water. Wisconsin has set the enforcement standard for sulfate at 250 mg/L.

The water samples were analyzed for sulfate using the Turbidimetric Method (426C in Standard Methods, 1985). The detection limit for this method is 1.0 mg/L.

Potassium (K^+)

Although potassium is a relatively abundant element, potassium concentrations in groundwater are relatively low, usually less than a few mg/L (Hem, 1985, p. 105). In sedimentary rocks, potassium is contained in unaltered feldspars or mica which are somewhat resistant to weathering; in addition, clay particles tend to adsorb potassium. As a result, low potassium concentrations in natural waters are usually low. Elevated potassium concentrations may be caused by the leaching of commercial fertilizers, septic systems, or animal wastes. There is no drinking-water standard for potassium, however, concentrations greater than a few mg/L may indicate that surface activities are impacting the groundwater quality. Wisconsin's Preventive Action Limit for potassium is either background plus 3 standard deviations or an increase of 5 mg/L or more over background level; whichever is greater.

The water samples were analyzed for potassium using Atomic Absorption (Standard Methods, 1985). The detection limit for this method is 0.5 mg/L.

Sample Collection Procedure

Homeowners were responsible for collection of samples from their wells and WGNHS personnel periodically collected samples from the springs. Using bottles that were labeled with the sample date and a sample identification number, they were instructed to collect a sample from a cold water, unsoftened tap, after the water had run for several minutes to ensure sampling fresh groundwater. On the same day that the samples were collected, they were transported to Green Bay for analysis. The inorganic analyses were performed at the water chemistry laboratory at the University of Wisconsin Green Bay and the bacteria analyses were performed at Robert E. Lee and Associates Laboratory also in Green Bay. The Robert E. Lee Lab provided the sterile bottles for the bacteria samples.

Detailed Monitoring Sites (Jarman Road and Highway HH)

While the homeowner sampling program provided data on the variation of groundwater chemistry with time, it did not provide detailed data on the hydrogeologic characteristics of the fractured dolomite aquifer. To acquire such information, two monitoring sites were equipped with nests of piezometers in order to study the dolomite stratigraphy, locate major horizontal fracture zones, measure aquifer parameters, determine the vertical head distribution, and collect groundwater samples for more detailed chemical analyses. The Jarman Road site (figure 2-1) was monitored beginning in March 1987 while monitoring of the Highway HH site began in March 1989.

Site Selection

The Jarman Road site was chosen for a variety of reasons. First, the site is topographically high, suggesting that it is a local recharge area, and thereby limiting the number of possible upgradient contaminant sources in the groundwater system. Second, land use at the site includes dairy farming and maple sugar production and is typical of central Door County. Third, the site is centered in the larger study area which includes all of the homeowner wells and springs sampled for this project (Blanchard, 1988).

The Highway HH site, a cherry processing plant and former pesticide mixing site, was chosen by UW-Green Bay investigators as the research site for a lead migration study (Wiersma and Stieglitz, 1989). Once their research was completed, the WGNHS assumed responsibility for the wells and began to monitor the site.

Drilling and Piezometer Installation

Jarman Road Site

Seven monitoring wells (MW1-MW7) were installed at the Jarman Road site (figure 2-2) using air-rotary drilling. Five of the wells (MW1-MW5) are oriented approximately along a groundwater flow line and also along a major fracture feature. Two of the wells (MW1 and MW2) reach a depth of approximately 240 ft, the common depth of newly constructed wells in the area. Three shallow wells (MW3, MW4, and MW5) were installed on a line between the two deep wells (MW1 and MW2), to depths of 24, 42 and 64 feet respectively. Two additional wells (MW6 and MW7, 60 ft and 200 ft deep respectively) are oriented at right angles to the line formed by MW1 through MW5.

Samples of the rock cuttings were collected every two feet to a depth of 40 feet during drilling of the two deep wells (MW1 and MW2). Samples were collected every five feet from depths of 40 to 240 feet for MW1 and MW2 and for the entire depths of MW3, MW4, MW5, and MW6. Samples were collected every 10 ft from MW7. Geologic logs for these drillholes can be found in Appendix B and are on file at the

WGNHS (WGNHS log numbers DR339 to DR343, DR361, and DR366).

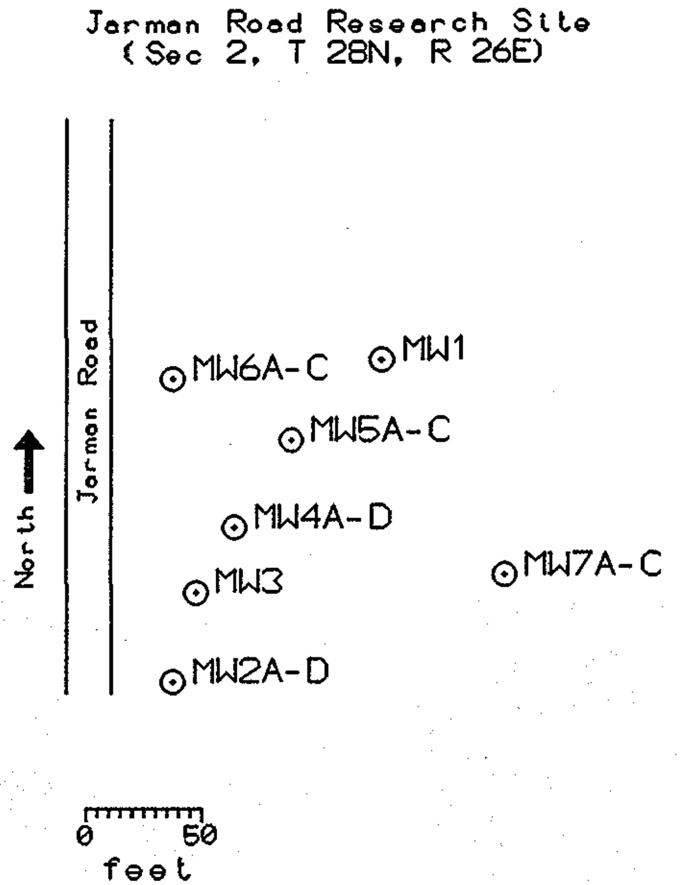


Figure 2-2. Detailed diagram of Jarman Road site.

Piezometer nests were installed in five of the wells (MW2, MW4, MW5, MW6, and MW7). Piezometers in each well are designated by the letters A, B, C, etc. The annular space between piezometers was sealed with a mixture of bentonite and cement grout, and the piezometers were developed using compressed air. Table 2-1 lists the construction details for all wells and piezometers.

Table 2-1. Well and piezometer data, Jarman Road and Highway HH research sites. All measurements are in feet.

Well or Piezometer	Total Depth	Depth Open Interval	Length Open Interval	Measuring Point Elevation (feet above msl)
Jarman Road Test Site				
MW1	240	40-240	200.0	798.2
MW2A	242	219.2-242	22.8	794.7
MW2B	161	149.7-161	11.3	794.7
MW2C	147	127.3-147	19.7	794.7
MW2D	81.3	41-81.3	40.3	794.7
MW3	60	10-60	50.0	794.8
MW4A	44.5	39.6-44.5	4.9	796.0
MW4B	30.8	25.4-30.8	5.4	796.0
MW5A	24	22.3-24	1.7	797.6
MW5B	21.4	19.5-21.4	1.9	797.5
MW5C	18.9	16.3-18.9	2.6	797.5
MW6A	60.5	54.4-60.5	6.1	794.9
MW6B	40.4	32.9-40.4	7.5	794.9
MW6C	20	12-20	8.0	794.9
MW7A	184.6	173.5-184.6	11.1	797.3
MW7B	153	143.5-153	9.5	797.3
MW7C	110.2	97-110.2	13.2	797.3
Highway HH Research Site				
CH2A	52.5	40-52.5	12.5	809.1
CH2B	180	171-180	9.0	809.1
CH2C	264	250-264	14.0	809.1
CH3	60	10-60	50.0	810.2

Highway HH Site

Three monitoring wells were installed at the Highway HH site in June of 1987 using air rotary drilling. Stieglitz and Wiersma (1989) report that Wells 1 and 2 were installed downgradient of the former pesticide mixing site while Well 3 was installed upgradient of the site (figure 2-3). In this report the wells are designated CH1, CH2, and CH3 which are 260, 264, and 60 ft deep respectively. Samples of rock cuttings were collected every 5 ft and detailed descriptions of the cuttings can be found in Stieglitz and Wiersma (1989, Appendix II). Chemical analyses, including trace metal analyses, of these cuttings can be found in Check (1990).

Well CH1 was abandoned in June of 1988. The WGNHS assumed responsibility for the other wells on the site. Three piezometers were installed in CH2 in March, 1989 by CTW Corporation of Waukesha; construction details are given by Stieglitz and Wiersma (1989, Appendix III). The piezometers were developed using compressed air.

Investigation Methods

Studies conducted at the Jarman Road and Highway HH research sites from 1986 through 1990 examined, in detail, the hydrogeologic characteristics of the dolomite aquifer by using geophysical logs to identify horizontal fracture zones within the bedrock, measuring aquifer parameters, measuring vertical hydraulic gradients, determining the position of the water table, and sampling groundwater at various depths below the surface.

Geophysical logs, including three-arm caliper, spontaneous potential, single-point and normal resistivity, natural gamma radiation, borehole temperature, and borehole fluid flow were obtained at most of the monitoring wells at the Jarman Road site prior to casing installation. In addition, television logs provided a visual inspection of fractures and other features inside four boreholes (MW1, MW3, MW6, and MW7). A ground-penetrating radar survey (GPR) of the site (Attig and others, 1987) gave details on depth to bedrock and delineated shallow fractures. Normal resistivity and spontaneous potential logs were run on the three Highway HH site wells.

A variety of methods was employed to determine the transmissivity (T) and hydraulic conductivity (K) of the dolomite aquifer. These methods ranged from simple office calculations of hydraulic conductivity based on data available in well constructor's reports to several field-work intensive multi-well pumping tests.

In order to accurately record water-level variations at the Jarman Road research site heads in three of the piezometers were monitored by pressure transducers from late September 1987 to mid-May 1989; readings were taken every ten minutes and then averaged over a six-hour period to provide four daily measurements which were recorded by a datalogger. Other piezometers at the site were hand-measured approximately monthly or bi-monthly throughout the study period; piezometers at the Highway HH site were measured monthly to bi-monthly from April 1989 to July 1990.

Although detailed groundwater elevations were available at the Jarman Road test site, the construction of reliable water-table maps of the surrounding area required additional field measurements. In September of 1989 and March of 1990, field personnel measured groundwater levels in approximately 50 domestic and irrigation wells in the area surrounding the site. After corrections for land-surface elevation, these data, in conjunction with piezometer data and surface-water elevations, allowed the construction of a water-table and a potentiometric-surface map of the area. The March data represent the maximum water-levels in the aquifer while the September data, represent low-flow conditions in the aquifer.

Water samples were collected approximately monthly to bi-monthly from the piezometers and analyzed for major cations/anions as well as for nitrogen species, chloride, and alkalinity.

CHAPTER 3

RESULTS OF GROUNDWATER SAMPLING

This chapter reports the results of long-term monitoring of groundwater chemistry in central Door County. Water samples were obtained from numerous domestic potable wells and also from monitoring wells and piezometers at a research site installed especially for this study. The Door County groundwater sampling program produced a large data set of groundwater chemistry results. The number of samples obtained from each well or spring ranged from 10 to 99, with a total of over 2060 water samples collected and analyzed. Appendix A contains a statistical summary of the data from each sample site.

Results at Private Wells and Springs

Concentrations of chemical parameters varied greatly in both space and time during the sampling period, and some parameters frequently exceeded drinking water quality standards. Table 3-1 presents a statistical summary of geochemical parameters for the entire data set, and table 3-2 gives a breakdown of geochemical results for various categories of sampling sites. The following discussion summarizes sampling results by parameter.

Coliform Bacteria

Coliform bacteria was the most frequently detected contaminant in the study area. The presence of a single coliform colony in a water sample was counted as a positive

Table 3-1. Summary of geochemical parameters for the entire data set.

Parameter		N	Min value	Max value	Mean value	Standard deviation	Drinking water std
NO_3-N	(mg/L)	2064	0.0	267.0	7.4	8.2	10*
Cl	(mg/L)	2071	0.4	204.0	19.5	17.4	250**
Cond	(μmho/cm)	2043	296	23800	632	558	none
NH_4-N	(mg/L)	583	0.0	3.02	0.05	0.17	none
Turb	(NTU)	1839	0.1	98	0.4	3.0	1***
SO_4	(mg/L)	1019	0.0	129.1	27.5	12.0	250**
K	(mg/L)	883	0.0	58.0	5.4	6.8	none

*Primary drinking water standard (NR 109.11, Wis. Admin. Code)
**Secondary drinking water standard (NR 109.60, Wis. Admin. Code)
***as determined by a monthly average (Driscoll, 1986)

Table 3-2. Summary of mean geochemical parameters at sample sites. The numbers of samples obtained at any particular site ranged from 1 to 99, with a mean of 29 samples per site.

ALL SAMPLE SITES

Parameter		No of sites	-------Averages for individual sites-------			
			minimum	maximum	mean	s.d.*
NO_3-N	(mg/L)	72	0.0	37.8	6.4	5.8
Cl	(mg/L)	72	1.0	119.5	17.8	18.3
Cond	(μmho/cm)	72	420	1303	605	148
NH_4-N	(mg/L)	15	0.0	0.72	0.08	0.20
Turb	(NTU)	72	0.1	17.8	0.4	0.4
SO_4	(mg/L)	26	0.0	84.3	28.4	16.5
K	(mg/L)	17	0.4	23.3	6.3	6.4
Coli	(% pos)	72	0.0	91.3	35.3	28.6

*standard deviation

detection of coliform for that sample date. Based on this criterion, the percentage of positive detections at a single well or spring (computed as the number of positive detections divided by the number of samples) ranged from 0.0 to 91.3 (table 3-2), and the average well contained coliform bacteria in 35% of the samples. Eighteen of the sites sampled contained coliform less than 10% of the times they were sampled, 20 of the sites contained coliform over 50% of the times they were sampled, and seven of the sites contained coliform over 80% of the time. The presence of coliform bacteria in drinking water can be the result of poor well construction or plumbing problems as well as groundwater contamination, and it is often impossible to determine the cause of coliform contamination for a specific well. The effect of well construction on the frequency of coliform detections is examined later in this report.

Nitrate (NO_3-N)

Water samples from many wells exceeded the drinking water standard (10 mg/L) or nitrate-N. With the exception of outliers at several individual wells, the nitrate-N data were normally distributed, and the mean and standard deviation give accurate representations of the central tendency of the data. For all wells and springs sampled, single-sample nitrate-N values ranged from not detectable to 267 mg/L, with an overall sample mean of 7.4 mg/L (table 3-1). At individual sites, mean nitrate-N concentrations determined from multiple samples ranged from not detectable to 38 mg/L (table 3-2), and the mean of all the individual site means was 6.4 mg/L. In the absence of historical data on nitrate in groundwater in Door County, the background nitrate levels in the dolomite aquifer are unknown. Blanchard (1988) examined the distribution of nitrate-N in a portion of this data set and concluded that a reasonable value for "uncontaminated" groundwater is 1 mg/L.

Chloride (Cl^-)

Many water samples contained elevated chloride concentrations although no groundwater sample exceeded the recommended drinking water standard for chloride (250 mg/L). Single-sample chloride values ranged from 0.4 to 204 mg/L (table 3-1), and chloride averages at specific sites ranged from 1 mg/L to 120 mg/L (table 3-2). Blanchard (1988) concluded that the median chloride concentration of uncontaminated groundwater in the study area is about 5 mg/L; concentrations significantly above this level indicate groundwater contamination from surface sources.

Specific Conductance

Specific electrical conductance of single samples (corrected to 25° C) ranged from 296 μmho/cm to 23,800 μmho/cm (table 3-1), and site averages ranged from 420 μmho/cm to 1303 μmho/cm (table 3-2). As specific conductance values increase in water so do the total dissolved solids. The specific conductance of ambient groundwater in the study area is about 500 μmho/cm (Blanchard, 1988). There is no drinking water standard for specific conductance.

Ammonium (NH_4-N)

Ammonium concentrations in single samples ranged from below detection limits to 3 mg/L (table 3-1). Although ammonium is a common constituent of human and animal wastes, it is an unstable form of nitrogen in groundwater for the pH range that occurs in central Door County; and it should rapidly oxidize to NO_3^- in the subsurface. The presence of ammonium is a general indicator of rapid movement of contaminated water from the land surface into a well. Average ammonium levels at specific sites ranged from not detectable to 0.7 mg/L.

Turbidity

Turbidity measures the amount of suspended particulate matter in water. Turbidity values ranged from 0.0 to 98 Nephelometric Turbidity Units (NTU) in single samples (table 3-1). Turbidity at most sites was log-normally distributed, and the geometric mean gives a measure of the central tendency of log-normal populations. The geometric mean for turbidity at specific sites ranged from 0.01 to 0.7 NTU (table 3-2). In the fractured aquifer of Door County, turbid water is most often the result of rapid movement of soil particles through fractures or solution openings. Occurrences of turbid water are usually transient and related to periods of rapid recharge by snowfall or rainfall. Another potential contribution to turbidity is the precipitation of dissolved iron as ferric hydroxide ($Fe(OH)_3$). This process occurs when oxygen enters the water during the process of obtaining a water sample and oxidizes ferrous iron to insoluble ferric iron.

Sulfate $(SO_4)^{-2}$

Sulfate in the study area ranged from not detectable to 129 mg/L in single samples (table 3-1), and averages at specific sites ranged from not detectable to 84 mg/L (table 3-2). No sulfate values approached the drinking water standard of 250 mg/L although many samples exceeded Blanchard's (1988) estimated background level of 12 mg/L.

Potassium (K^+)

Although potassium was not expected to be an abundant constituent in groundwater in the study area, potassium values in single samples ranged from not detectable to 58 mg/L (table 3-1), and average values at specific sites ranged from 0.4 to 23 mg/L (table 3-2). Elevated potassium in water samples probably indicates contamination from fertilizers, human waste, or animal waste.

Variations in Groundwater Chemistry

The chemical quality of water from the wells and springs sampled during this study varied with the type of site sampled. Chemical composition also varied significantly in space and time.

Variations Related to Site Type

Sites sampled during the study fell into four categories: wells conforming to the WDNR well construction code (Chapter NR112, Wisconsin Administrative Code), wells failing to conform to the WDNR code, wells of unknown construction, and springs. The occurrence of poor-quality well water in fractured-rock terrain is often attributed to poor well construction practices. In 1971 the Wisconsin Department of Natural Resources adopted special well construction codes for much of Door County, including all of the study area. This requirement was incorporated as section NR112.14 of the Wisconsin Administrative Code. The current code requires a minimum of 170 ft of pressure-grouted well casing and an above-grade termination of the well at the land surface. Wells constructed prior to 1971 often contain shallower casings and are completed below grade in well pits. Such wells are generally more susceptible to contamination from surface sources close to the well. Springs are not a source of potable water in Door County but were sampled during this study to assess their utility as groundwater monitoring points.

For most sites, conformity with DNR well construction codes (NR112) appears to

Table 3-3. Geochemical sampling results grouped by site type. Average numbers of samples per site were 29 for wells meeting code, 31 for wells failing to meet code, and 17 for springs.

WELLS MEETING THE WELL CODE

Parameter		No of sites	minimum	maximum	mean	s.d.
			------Averages for individual sites------			
NO_3-N	(mg/L)	30	0.0	24.0	5.5	2.4
Cl	(mg/L)	30	1.2	58.9	16.7	15.1
Cond	(μmho/cm)	30	439	1047	587	125
NH_4-N	(mg/L)	6	0.01	0.05	0.03	0.02
Turb	(NTU)	34	0.1	18.0	1.0	3.5
SO_4	(mg/L)	10	0.0	44.9	19.3	12.3
K	(mg/L)	7	0.4	23.3	5.9	7.6
T. Coli	(% pos)	30	0.0	84.0	26.2	23.8

WELLS FAILING TO MEET THE WELL CODE

Parameter		No of sites	minimum	maximum	mean	s.d.
			--------Averages for individual sites-------			
NO_3-N	(mg/L)	13	0.0	15.3	6.5	4.5
Cl	(mg/L)	13	1.0	55.9	19.6	16.1
Cond	(μmho/cm)	13	420	823	630	119
NH_4-N	(mg/L)	3	0.03	0.08	0.05	0.02
Turb	(NTU)	13	0.1	1.9	0.4	0.3
SO_4	(mg/L)	6	22.6	45.7	32.0	9.0
K	(mg/L)	4	20.4	41.8	10.4	5.8
T. Coli	(% pos)	13	11.0	99.0	31.0	26.9

SPRINGS

Parameter		No of sites	minimum	maximum	mean	s.d.
			--------Averages for individual sites-------			
NO_3-N	(mg/L)	5	1.8	7.1	4.6	1.9
Cl	(mg/L)	5	5.5	29.1	14.3	8.0
Cond	(μmho/cm)	5	463	629	552	56
Turb	(NTU)	5	0.3	4.8	1.4	0.4
T. Coli	(% pos)	5	67.0	85.0	78.0	7.9

be unrelated to mean concentrations of the constituents monitored. Grouping the monitoring data into three of the categories listed above (table 3-3), and eliminating wells for which construction information was not available, there was little difference in the mean percentage of coliform detections between wells meeting the well code (26% positive) and wells failing to meet the well code (31% positive). As expected, samples from springs contained the most frequent coliform detections (78% positive) and the highest mean turbidity (1.4 NTU), both probably the result of surface-water contamination in the spring pools surrounding the sampling points. Nitrate-N, chloride, and specific conductance were not significantly different between the three sample groups, and sulfate and potassium were not sampled often enough to draw reliable conclusions.

Variations with Time

Groundwater chemistry varies significantly with time at most wells sampled in the study area. Figures 3-1, 3-2, and 3-3 show the variation of all chemical parameters for three domestic wells of differing construction over the duration of the 5-year monitoring study, and also show precipitation measured at the Sturgeon Bay Experiment Farm over the same period. Variations in the concentrations of the parameters measured in water samples from these wells are typical of the temporal variations seen in groundwater chemistry throughout the study area.

Well 54 (figure 3-1) is typical of most wells constructed to meet the well code in central Door County. This well is 212 ft deep and is cased to 171 ft. Water produced by this well met water quality standards for all parameters except coliform bacteria, which were detected in 29% of the samples. Well 54 contained an average nitrate-N level of 6.8 mg/L, and concentrations of most other parameters were also low and varied little with time.

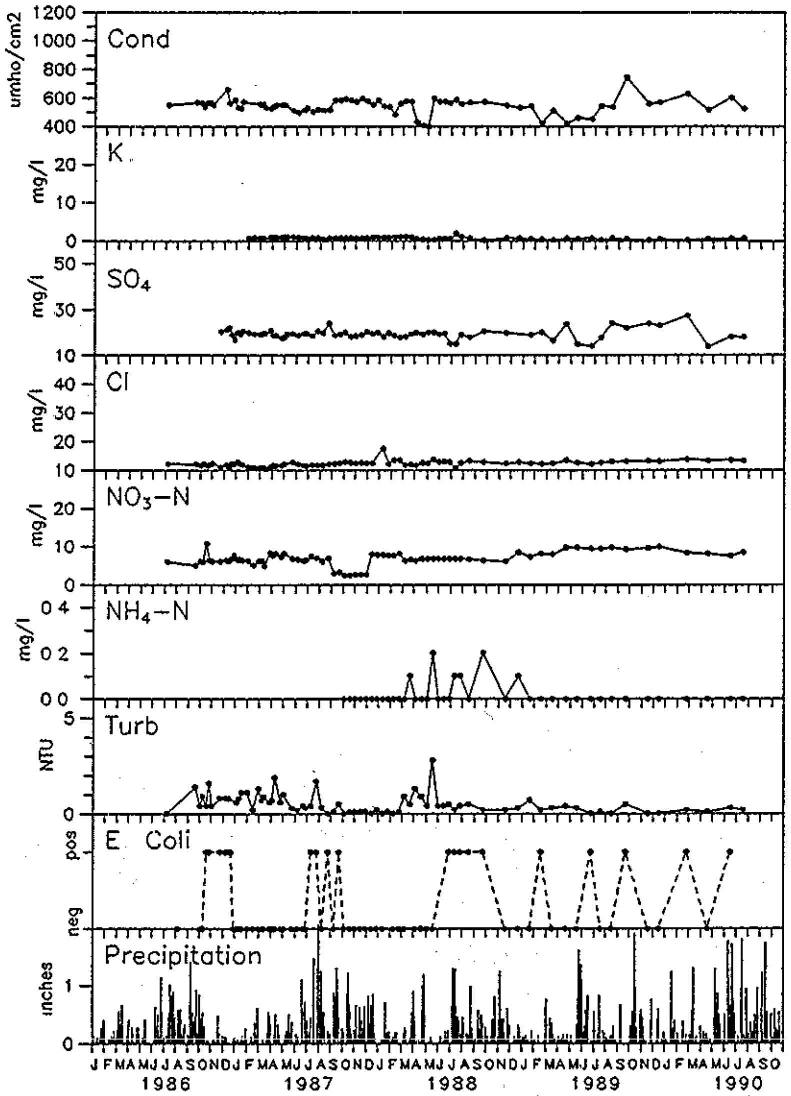


Figure 3-1. Variation of groundwater chemistry with time at domestic well 54. The well is 212 ft deep, cased to 171 ft, and conforms to WDNR well construction codes.

Well 63 (figure 3-2) is an unusually deep well showing water quality problems. This well is constructed to code and is 317 ft deep, cased to 251 ft. In spite of its deep casing, water produced by well 63 frequently exceeded drinking water standards for bacteria and nitrate-N. As shown in figure 3-2, coliform bacteria were present in 75% of the samples from this well, and nitrate-N concentrations frequently exceeded the drinking water standard. The average nitrate-N concentration was 14.1 mg/L. Concentrations of ammonium, chloride, and potassium were higher than in well 54 and varied significantly with time. In addition, a significant turbidity spike occurred at this well in early 1987.

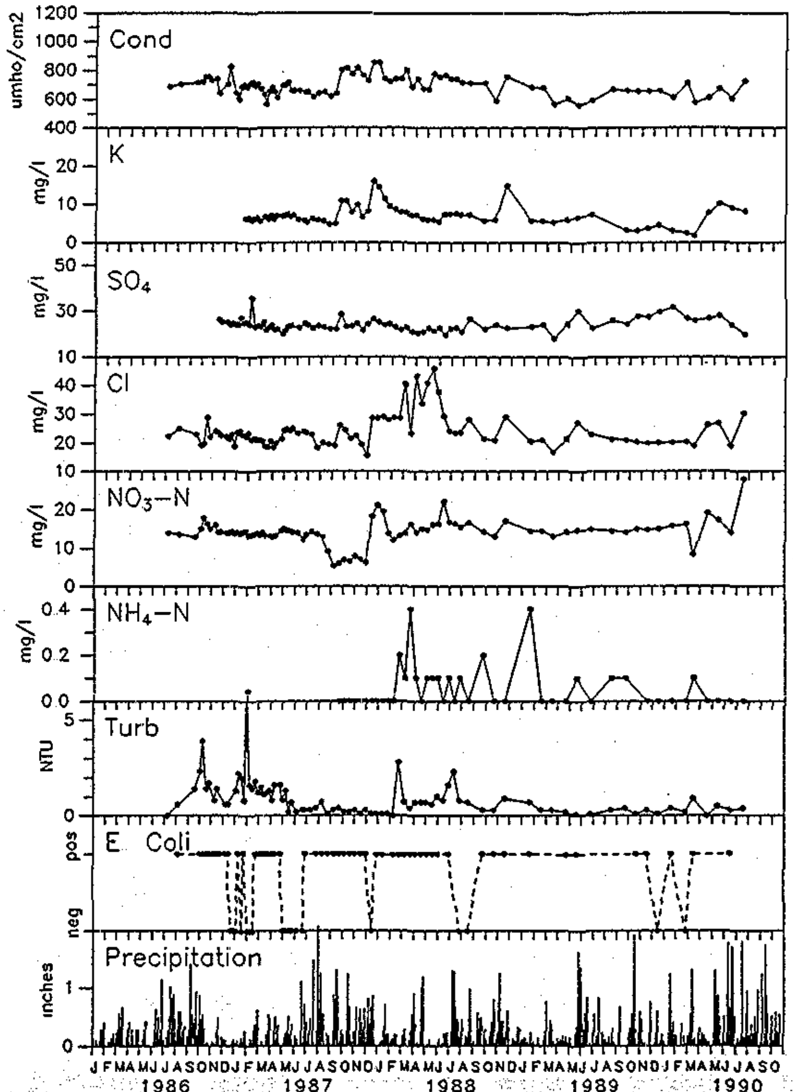


Figure 3-2. Water chemistry variation with time at domestic well 63. The well is 317 ft deep, cased to 251 ft, and meets WDNR well construction codes.

Well 20 (figure 3-3) is a well which does not conform to the well code and which produces groundwater of unusually poor drinking water quality. The total depth and casing depth of this well are unknown, and the well head is located in a well pit about 10 ft below grade. Water produced by this well almost always exceeded drinking water standards, with average nitrate-N of 13.6 mg/L and coliform detected in 89% of the samples. The concentrations of all constituents measured in water produced by this well were elevated and varied significantly with time. For example, nitrate-N concentrations in groundwater from this well varied from 1.8 mg/L to 28.7 mg/L (Appendix A), chloride varied from 47 mg/L to 79 mg/L, sulfate varied from 25 mg/L to 72 mg/L, and

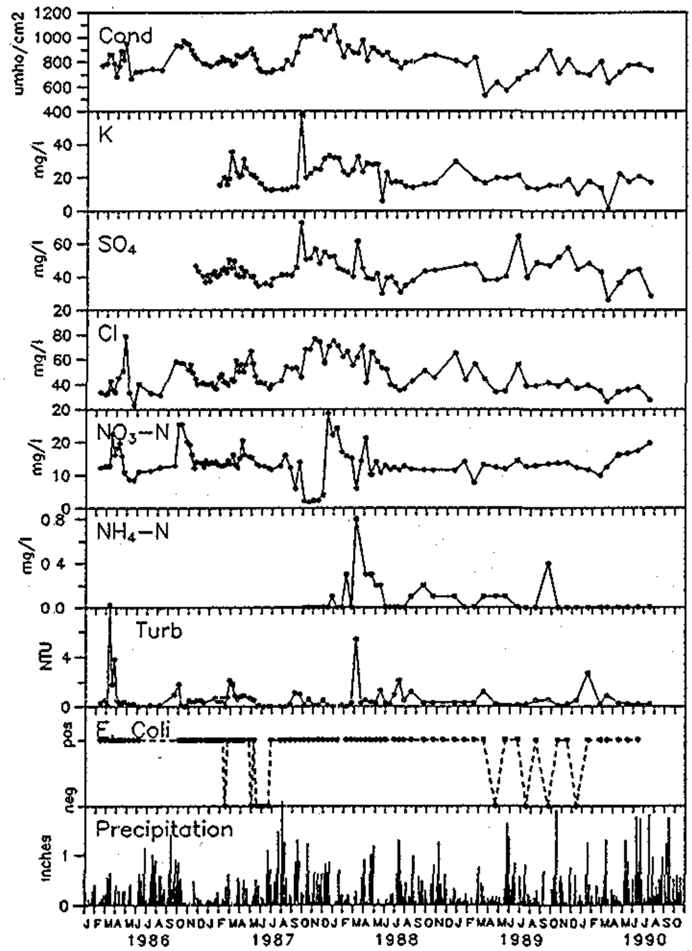


Figure 3-3. Variation of water chemistry with time at domestic well 20. Well depth and casing depth unknown. Well does not comply with current WDNR well construction codes.

potassium varied from 1 mg/L to 58 mg/L. Ammonium and turbidity spikes during early 1988 suggest rapid movement of surface contaminants into this well.

Simultaneous variations in parameter concentrations in wells several miles apart suggest that water-quality problems are frequently related more to the regional hydrogeologic setting and land-use practices than to point sources of contamination at individual wells. Figure 3-4 shows nitrate-N concentrations in four wells oriented along a north-south line about one mile east of the village of Carlsville. The figure also shows precipitation at the Sturgeon Bay Experimental Farm. The distance between well 66 (the northernmost well) and well 64 (the southernmost well) is three miles. Simultaneous variations in nitrate-N concentrations occur in these four wells.

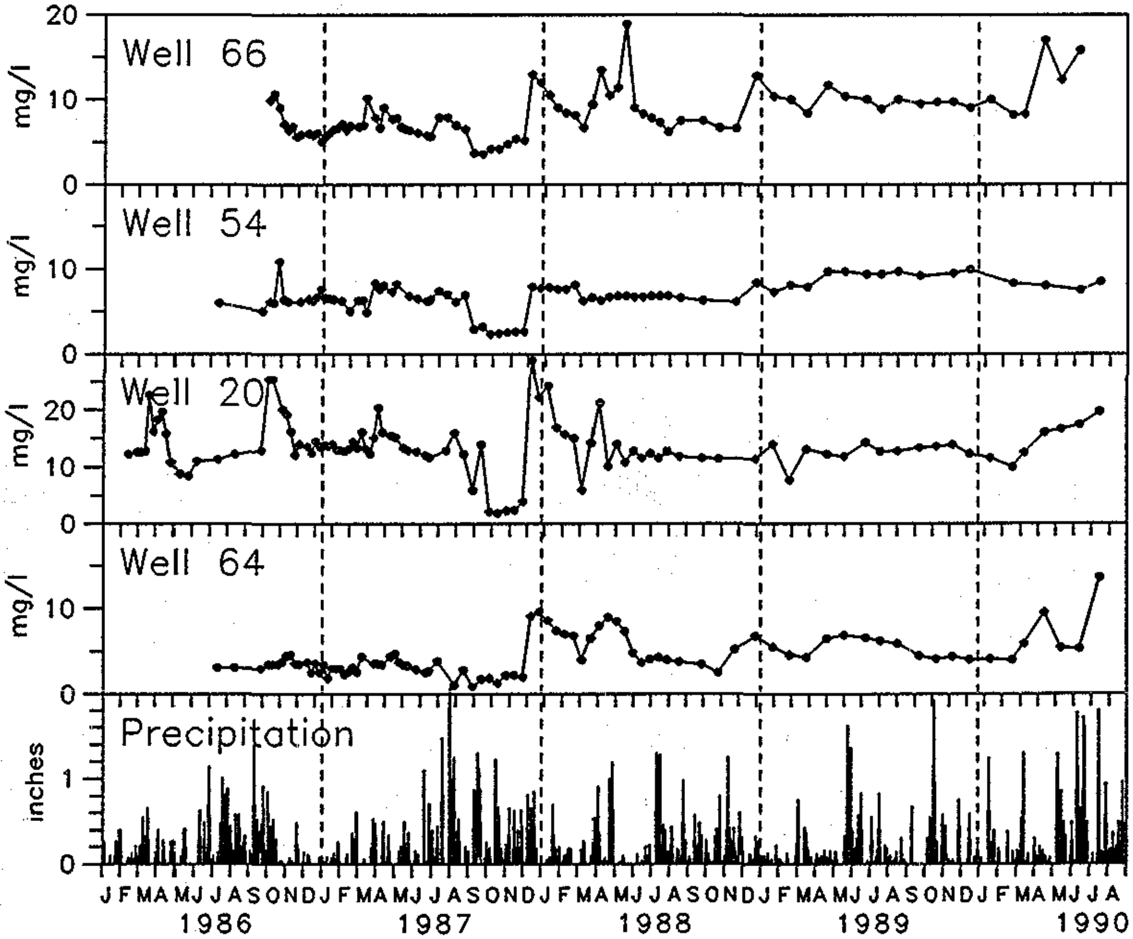


Figure 3-4. Variation of nitrate-N concentrations with time at four domestic wells. See figure 2-1 for well locations. Dashed vertical lines mark the beginning of calendar years.

For example, a significant increase in nitrate-N concentrations occurred in all four wells in December 1987, followed by a gradual decrease in concentrations during the spring of 1988. Other simultaneous changes in concentration include an increase in October 1986, December 1988, and April 1990.

Average concentrations of some indicator parameters in groundwater varied systematically throughout the year, and these variations are related to seasonal changes in precipitation and groundwater recharge. Figure 3-5 shows plots of the mean concentrations of several indicator parameters by month for 13 wells sampled monthly

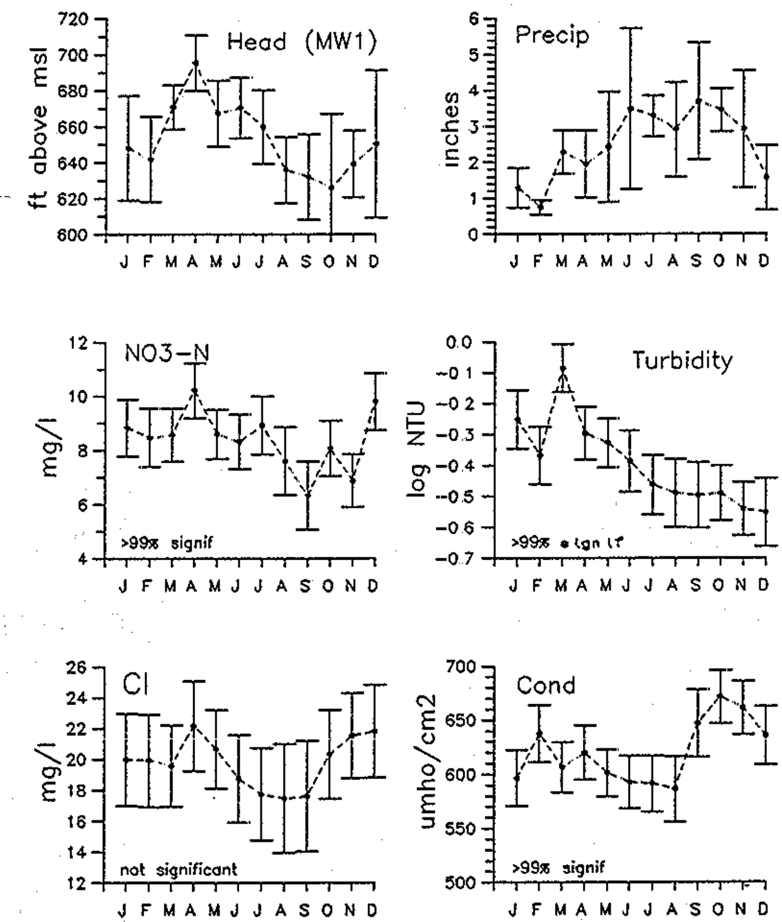


Figure 3-5. Average monthly concentrations of geochemical parameters in selected domestic wells, precipitation at the Sturgeon Bay Experiment Farm, and water levels at the Jarman Road site. Error bars equal one standard deviation.

from 1986 to 1990. The vertical bars on the figure represent one standard deviation about the monthly means. The figure shows that the average nitrate-N concentration was highest during April and December and lowest during September. Turbidity was highest during March and gradually decreased from April through December. Specific conductance was elevated during February and April, generally decreased from May through August, and was elevated during September and October. Using a one-way analysis of variance test on parameter averages versus month, monthly variations in nitrate-N, conductivity, and turbidity are significant at greater than the 99% confidence level, while monthly variations in chloride are not significant above the 50% confidence level.

Implications for groundwater monitoring

The significant variability of parameter concentrations with time has important implications for water-well approval and groundwater monitoring in Door County. The current Wisconsin well code for domestic wells requires only a single water analysis for bacteria and nitrate following the completion of a new well. The data in figures 3-1 - 3-4 and Appendix A clearly show that a single water analysis is almost meaningless for describing the water quality for most of the wells in the study area. For example, water drawn from each of the wells in figure 3-4 sometimes exceeded the 10 mg/l nitrate-N drinking water standard, but water from none of the wells always exceeded the standard. Clearly, an accurate evaluation of the chemistry of groundwater produced by a given well requires multiple samples from that well.

Basic parametric statistics offer some guidelines for the minimum number of water samples required for a statistically meaningful description of groundwater chemistry from an individual well in the study area. This analysis assumes that 60 to 90 samples from a single well (available for 15 wells, see Appendix A) provide sufficient data to establish the "true" mean and standard deviation for that well and that the population of nitrate concentrations is normally distributed. Under these assumptions, we can use the Student's t-distribution (Sokal and Rohlf, 1969) to calculate the minimum number of samples required to characterize the mean nitrate concentration for an individual well at a given level of significance. The Student's t-distribution gives a confidence interval about a sample mean as follows.

$$CI=\pm t^{*}\times\frac{s}{\sqrt{n}} \qquad (1)$$

In this equation, CI is the width of the confidence interval about the mean, s is the population standard deviation, n is the number of samples required, and t^* represents the Student's t-statistic with probability p and n-1 degrees of freedom. To calculate the number of samples required to describe a population with a given level of significance, we rearrange the equation as

$$n = \left[\frac{s \times t^*}{CI}\right]^2 . \tag{2}$$

Representing the confidence interval, CI, as a fraction of the mean by CI = $\overline{Y}$ x ERR leads to

$$n = \left[\frac{s \times t^*}{ERR \times \overline{Y}}\right]^2 \tag{3}$$

where $\overline{Y}$ is the population mean, and ERR is the desired error criterion, say 0.1 (or 10%). For example, well 54 (fig 3-1), sampled 76 times, had a mean nitrate-N of 6.8 mg/L and standard deviation of 1.8. Assuming that the 76 samples were sufficient to yield a true population mean, we can use equation 3 to calculate the minimum number of samples necessary to estimate the mean with a confidence interval of $\pm$10% at a 90% significance level. Using equation 3, we have

$$n = \left[\frac{1.721 \times 1.8}{0.1 \times 6.8}\right]^2 \cong 21 \ samples. \tag{4}$$

This means that a minimum of 21 random samples from well 54 would be necessary to conclude that the mean nitrate value is within 10% of 6.8 mg/l with 90% significance. Because the t^*-statistic depends on the sample size (n), solving equation 3 requires trial and error.

Calculating the minimum number of samples necessary to establish the average nitrate concentrations in several wells for which long-term data exist demonstrates that many samples are needed to determine the average nitrate-N concentration for individual wells. Table 3-4 shows that between 15 and 100 samples would be needed to describe the mean nitrate-N concentration for each of 9 domestic wells monitored for several years during this study. The required number of samples increases significantly for wells with more variable nitrate concentrations, as shown by larger standard deviations.

For routine monitoring and well approval, the acquisition of such large numbers of samples may not be practical. For regulatory purposes, the knowledge of a one-time exceedence of a water quality standard may be more useful than a statistically valid estimate of the mean concentration of a given parameter in groundwater. For such regulatory objectives, figure 3-5 shows that water samples collected in March or April are likely to contain the highest annual concentrations of indicator parameters, while samples collected in July, August, or September are likely to contain the lowest concentrations of indicator parameters.

Table 3-4. Minimum number of water samples needed to describe the mean nitrate-N composition at a well with an accuracy within 10% of the true mean composition.

Well	Total samples*	Mean (mg/L)	Standard deviation	Minimum number of of samples required for confidence interval 90%	95%
20	99	13.6	4.6	32	45
54	76	6.8	1.8	21	30
56	87	6.7	2.0	32	35
61	80	8.7	3.4	38	60
63B	86	14.1	3.3	18	25
64	87	4.4	2.2	70	100
66	85	8.4	3.1	40	56
68	67	4.7	1.8	42	60
69	57	12.1	2.5	15	20

*number of samples actually analyzed

Spatial variations

Relationships to soils and land use

Concentrations of indicator parameters vary spatially in the study area. Over much of the area, the sampling density was too sparse to allow a detailed examination of spatial relationships. However, analyzing a subset of the monitoring data in the area of densest sampling shows the spatial variation of various parameters and the relationship of these parameters to activities at the land surface. Thirty-eight sampling sites were distributed over a 15 mi^2 rectangular area southeast of the town of Carlsville (figure 3-6). This area is located high in the groundwater flow system, just west of the regional groundwater divide. The regional potentiometric surface, shown on figure 3-6, slopes from about 680 ft above sea level in the northeast corner of the area to about 610 ft in the southwest corner of the area. Regional groundwater movement is generally perpendicular to the lines of equal potentiometric-surface elevation. The area is a prime location for groundwater recharge, and receives little or no groundwater from outside its boundaries. Therefore, land-use practices, soil characteristics, and local geology are the major controls on the composition of groundwater within this area. In order to evaluate

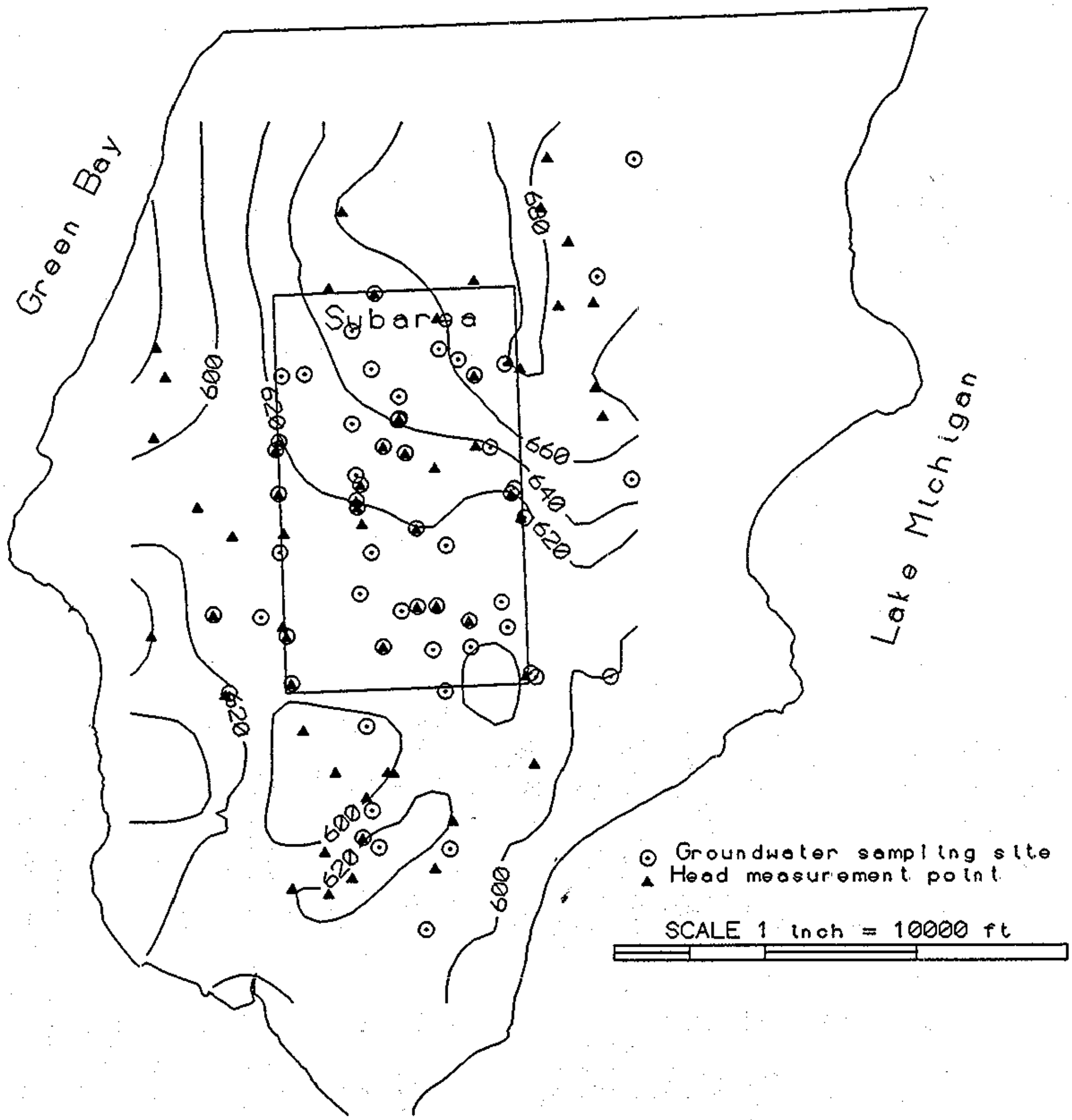


Figure 3-6. Location of subarea in central Door County. Potentiometric surface (in feet above sea level) as measured in September, 1989; contour interval 20 ft.

the relationships between these factors we constructed a computerized geographic information system (GIS) for the subarea using ARC-INFO software. The GIS stores information about the boundaries of various geographic areas, such as mapped soil series, and the locations of specific features, such as septic tanks and wells. We used the GIS software to study the degree of correlation between various land-use practices and groundwater chemistry at specific wells.

Data used in the GIS analysis included soil type, land use (row crop, orchard, or fallow land), highway locations, and the locations of barnyards, septic tanks, bedrock outcrops, sinkholes, and wells. Soils data were digitized from 1:15,840 scale maps in the county soil survey (Link and others, 1978). Agricultural land use and the locations of barnyards, septic tanks, outcrops, and sinkholes were digitized from 1:24,000 scale field maps provided by the Door County Soil and Water Conservation Department. Well locations were digitized from 1:24,000 topographic maps. Details of the weighting scheme used by Bachhuber and Schuster (1987) to rate the susceptibility of various Door County soils for groundwater contamination were obtained from Schuster (written communication) and were incorporated into the GIS system to reproduce part of the contamination potential map of Bachhuber and Schuster (1987).

Figures 3-7 and 3-8 show soil characteristics and land use in the subarea. Figure 3-7 divides the area into five categories based on the relative ability of the soil to attenuate contaminates, category 1 being most susceptible to groundwater contamination and category 5 being least susceptible. Figure 3-8 shows land use and the locations of barnyards. Row crops are the dominant land use, covering 49% of the area. Orchards cover 37% of the area, and the remaining 14% is fallow, residential, or in woodlots. The subarea contains 40 barnyards and 191 homes with septic tanks.

Statistical analyses of relationships between concentrations of parameters in groundwater and the various land-use factors in the subarea indicate significant correlations between the presence of barnyards, highways, or row crops in the vicinity of a well and the chemical content of water produced by that well. Table 3-5 shows the results of statistical tests between groups of wells located near these land-use practices. For these tests, wells were divided into groups based on the presence of particular land-use factors, such as a barnyard in the vicinity of the well. The distribution of the average long-term parameter concentrations at each well in these groups was then compared by a one-way analysis of variance test using the MINITAB statistical program (Ryan and others, 1976). The one-way analysis of variance tests the null hypothesis that two or more groups of samples have identical means and thus come from the same population. When this hypothesis fails, the two groups probably represent different populations.

Several land-surface features correlate with the concentrations of indicator parameters in groundwater. The presence of barnyards near the site of a well (i.e., on the same or adjacent farmstead) is correlated with significantly higher average nitrate concentrations in water produced by that well. Table 3-5 shows that the mean nitrate-N concentration in wells near barnyards was 9.1 mg/L, while the concentration in wells not near barnyards was 6.2 mg/L, with a statistical significance of greater than 97%. Likewise, the presence of row crops or primary highways near wells is also significantly correlated to elevated nitrate.

The presence of primary highways adjacent to wells is very highly correlated with elevated chloride and highly correlated with elevated specific conductance and turbidity.

Figure 3-7. Groundwater contamination potential based on soil characteristics in the subarea.

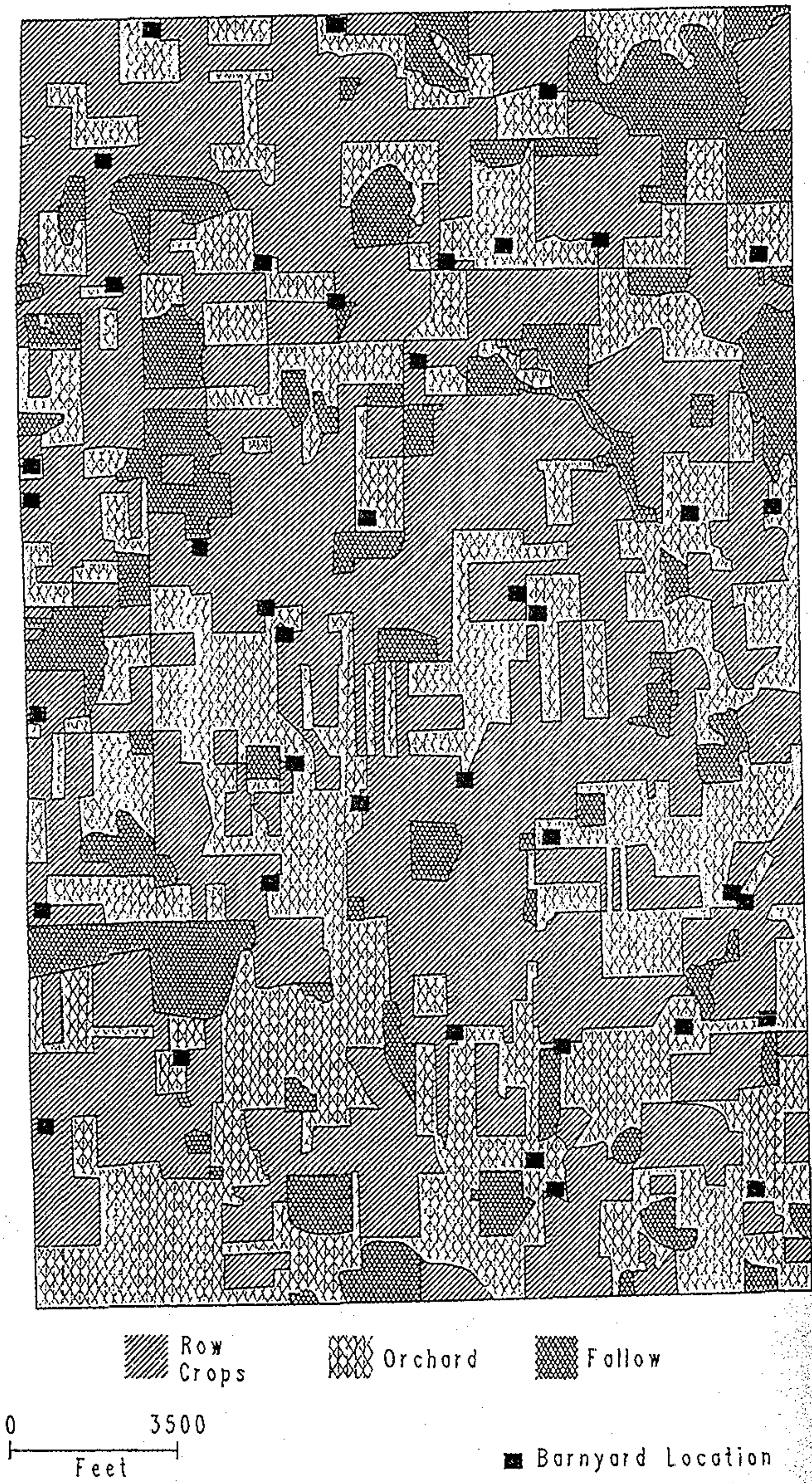


Figure 3-8. Land use in the subarea.

Table 3-5. Summary of the results of one-way analysis of variance tests of relationships between indicator parameters and adjacent land uses.

Land use factor	Absent mean (N*)	Present mean (N)	Significance
	Nitrate-N (mg/l)		
Barnyard	6.2, (25)	9.2, (13)	>97.5
Row crops/orchards	4.0, (4)	7.6, (34)	>90.0
Primary highways	6.7, (28)	9.1, (10)	>90.0
	Chloride (mg/l)		
Primary highways	15.5, (28)	32.1, (10)	>99.9
	Specific Conductance (μmho/cm)		
Primary highways	610, (28)	688, (10)	>90.0
	Turbidity (NTU)		
Primary highways	0.6, (28)	1.2, (10)	>90.0

N* = number of wells tested

Primary highways in or adjacent to the subarea are US Highway 42, US Highway 57, and County Highway P. Other highways in the area are lightly used town roads. Wells near primary highways contained a long-term average of 32.1 mg/l Cl^-, while other wells contained only 15.5 mg/l.

Primary highways in the subarea have two attributes that help explain their high correlation with elevated parameters in nearby wells. First, primary highways receive significant deicing salt (sodium chloride) during the winter, while secondary highways receive little or no salt. Second, roadside drainage ditches along primary highways are frequently excavated to the fractured bedrock surface, and are kept open by highway maintenance crews. These ditches offer a direct pathway into the dolomite aquifer for both deicing salts and runoff from adjacent fields.

Other statistically significant relationships between soil and land-use attributes and the concentration of indicator parameters in groundwater in the subarea are not apparent. For example, the soil classifications on figure 3-7 are not significantly related to variations in average nitrate or chloride concentrations. However, such lack of clear correlation does not mean that areas are incorrectly mapped in regard to their susceptibility to contamination. It may only indicate that contamination has not occurred in susceptible areas due to a lack of sources.

The areal distributions of nitrate, chloride, and other parameters suggest that both point and nonpoint source contamination of groundwater are occurring in the subarea. Nonpoint source contamination causes generally elevated levels of nitrate and chloride over broad areas, while point source contamination causes higher concentrations at specific wells. Figure 3-9 shows the distribution of long-term average concentrations of nitrate-N at wells monitored in the subarea (see figure 2-1 for well identification numbers). Over most of the subarea, average nitrate-N concentrations were less than 10 mg/l. However, average nitrate-N concentrations exceeded the 10 mg/l drinking water standard at six wells in the subarea. Each of these wells is adjacent to or hydraulically down gradient from a barnyard which is a possible point source of nitrate (Table 3-6). Likewise, each well having a long-term chloride concentration exceeding 40 mg/l (approximately one standard deviation greater than the population mean) is either adjacent to or hydraulically downgradient from an animal holding area or primary highway.

Table 3-6. Wells having long-term average concentrations of nitrate-N exceeding 10 mg/l or chloride exceeding 40 mg/l, with potential sources of contamination. Averages exceeding these values are in boldface type.

Well	Concentration (mg/l) NO_3-N	Cl	Potential Contaminant Sources
3	**11.3**	29.6	barnyard adjacent to well
7	**13.2**	**56.8**	adjacent to Hwy 42
17	3.7	**51.9**	adjacent to County Hwy P
20	**13.6**	**47.2**	adjacent to barnyard on exposed rock
25	7.8	**47.2**	adjacent to Hwy 42
62	9.7	**55.9**	adjacent to Hwy 42; downgradient of barnyard
63	**14.1**	23.9	downgradient from barnyard
65	**15.3**	24.0	adjacent to barnyard on exposed rock
67	**13.9**	21.4	downgradient from barnyard on exposed rock
69	**12.1**	25.7	adjacent to barnyard; downgradient from barnyard

Given the available data, a positive identification of specific contamination sources responsible for parameter concentration levels in individual wells is not possible.

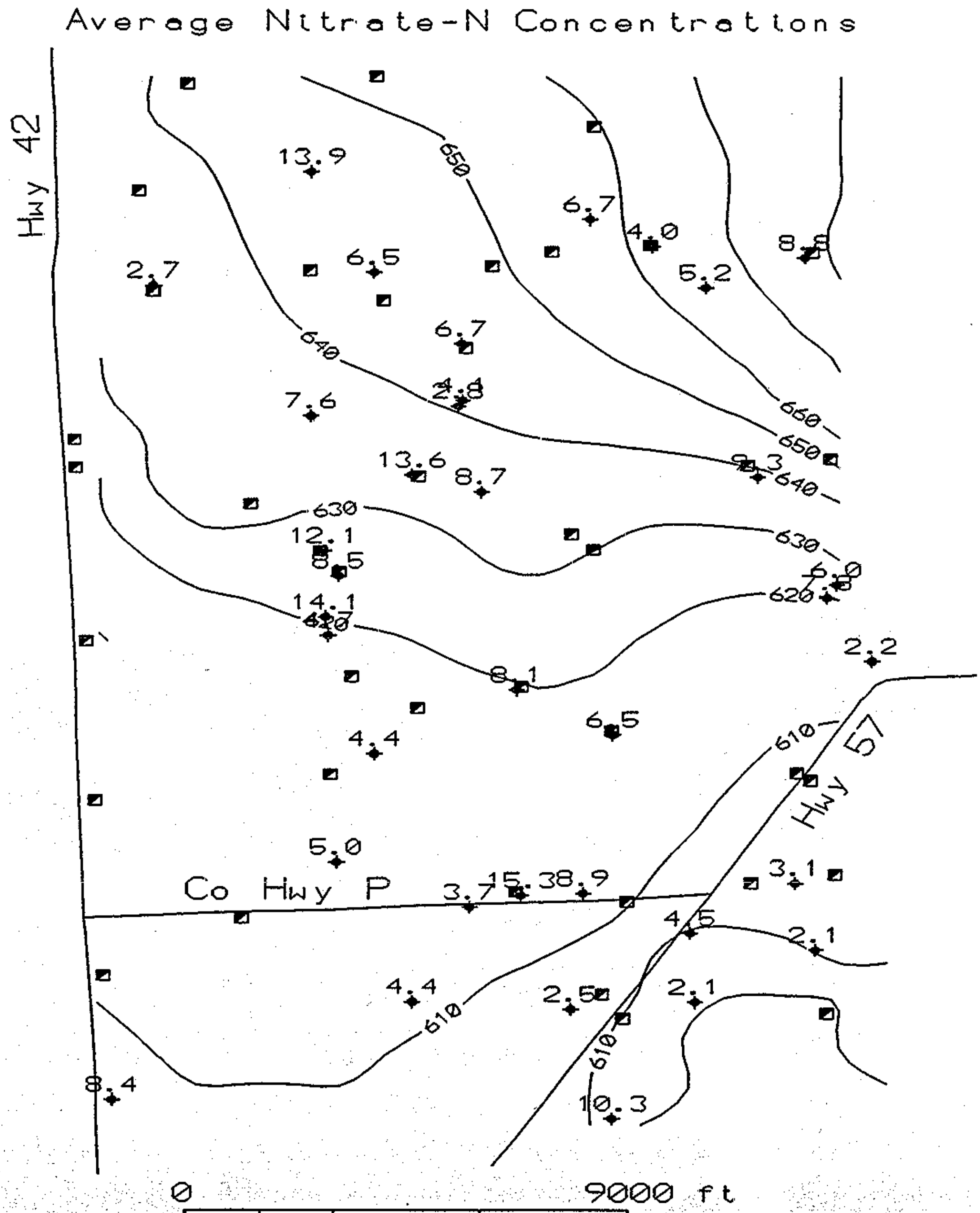


Figure 3-9. Long-term average nitrate-N concentrations (mg/l) in the subarea. Also shown are hydraulic heads in September, 1989. The small boxes represent barnyards, and the dots indicate well locations.

The multiple unknowns of well construction and plumbing, specific contamination sources at individual homesites, and changes in land-use practices over time would make any such conclusions very tenuous. However, the strong statistical correlation between concentration levels and the presence of barnyards and primary highways, combined with the location of these features relative to probable groundwater flow paths to individual wells, suggests that these features are important contaminant sources in the study area.

Sampling of Monitoring Wells and Piezometers

Rationale and Methodology

Although sampling existing domestic wells is an attractive and economical method for monitoring groundwater composition in fractured rocks, the methodology is open to criticism on several fronts. First, water samples from domestic wells might be subject to change or contamination during passage through the domestic pump and plumbing system. Second, domestic wells in fractured rock commonly are open to large (tens or hundreds of feet) vertical intervals of the aquifer. Samples from wells having such long open intervals may not be representative of groundwater if some stratification of groundwater composition exists. Third, and possibly most important, water samples from private wells could be biased by the common association of the wells with potential contamination sources. For example, many wells in central Door County are located on farms and are in the vicinity of septic tanks, barnyards, driveways, and animal waste storage areas. If such wells were locally contaminated the data might give an overly negative impression of regional groundwater quality. In order to obtain depth-stratified samples of groundwater in an area believed to be unaffected by adjacent surface contamination sources we constructed a series of monitoring wells and piezometers at a research site located in the central part of the study area along Jarman Road in the Town of Sevastopol (figure 2-2). The Jarman Road site was located in a maple woodlot surrounded by agricultural fields used for grazing, alfalfa production, or corn production. The nearest building or farmstead was over 1200 ft from this site.

The Jarman Road site consisted of seven boreholes instrumented with a total of 13 piezometers completed with short screens at various depths. Chapter 4 of this document discusses the site hydrogeology in detail. Groundwater samples were periodically obtained from each piezometer following accepted techniques for geochemical groundwater sampling (WDNR, 1987). Temperature, pH, conductivity, and dissolved oxygen were determined in the field. One sample was filtered in the field and acidified for preservation of metal ions; a second sample (not acidified) was collected for determination of bicarbonate, chloride, and nitrate. The Soil and Plant Analysis Laboratory of the University of Wisconsin-Extension analyzed the water samples for major cations and anions. The analyses were then speciated using the geochemical speciation program PHREEQE (Parkhurst and others, 1980), and saturation indices were determined relative to various mineral phases. Each analysis was required to have a cation-anion charge balance error of less than 15%.

Results

Geochemistry of groundwater

The geochemical results from the Jarman Road site (table 3-7 and figure 3-10) show that groundwater at the site is a calcium-magnesium-bicarbonate water, typical of a dolomite terrain. The waters are either in near equilibrium with calcite and dolomite or are slightly undersaturated with respect to these minerals, as shown by the slightly negative saturation indices. A saturation index of zero identifies a water in perfect equilibrium with respect to the mineral phase, while negative saturation indices indicate undersaturation (the mineral phase can dissolve) and positive saturation indices indicate oversaturation (the mineral phase can precipitate). Dissolved carbon dioxide in the waters, indicated by the pCO_2 values, are generally on the order of $10^{-2.0}$ bars, significantly higher than the equilibrium atmospheric pCO_2 value of $10^{-3.5}$ bars. The elevated pCO_2 in groundwater suggests that infiltrating water dissolves significant carbon dioxide in the soil and root zone even though this zone is less than five feet thick at the Jarman Road site. Table 3-7 shows that recharging groundwater comes to geochemical equilibrium with the aquifer within a few feet of the surface. Calcium and magnesium concentrations and saturation indices in one of the shallow piezometers (MW5C, 18 ft below the surface) are nearly equal to those in the deepest piezometer (MW2A, 242 ft below the surface). This means that most dissolution of the dolomite aquifer probably occurs near the surface, with little additional dissolution at depth.

Table 3-7. Summary of average geochemical parameters at the Jarman Road monitoring site. All values in mg/l, except pH (units), electrical conductivity (μmho/cm), saturation indices (units), and pCO_2 (bars).

Well or piez	Midpoint of open interval (ft below surface)	pH	D.O.	Elec Cond	Ca	Mg	Na	K	Fe	Mn	HCO_3	NO_3	Cl	SO_4	S.I. Calc	S.I. Dol	$_pCO_2$
		AVERAGE OF ALL SAMPLES															
MW6C	16.0	7.65	9.3	760	62.3	34.3	22.9	4.0	0.03	0.04	302.8	2.1	20.0	61.8	+0.13	+0.02	-2.29
MW5C	17.6	7.58	10.9	487	42.6	21.6	31.3	2.8	0.00	0.00	240.8	1.2	5.0	43.9	-0.03	-0.28	-2.19
MW4B	27.2	7.48	7.2	549	72.3	36.4	16.7	4.5	0.01	0.01	338.4	1.7	5.0	67.9	+0.09	-0.09	-2.05
MW3	35.0	7.29	8.4	602	65.2	33.7	1.3	3.1	0.02	0.00	308.3	4.2	10.2	17.2	-0.14	-0.47	-1.91
MW6B	36.7	7.38	4.7	693	70.4	34.6	13.0	1.6	0.04	0.13	349.5	1.8	9.5	43.1	+0.02	-0.19	-1.94
MW4A	42.0	7.35	3.2	582	65.4	34.3	10.0	2.6	0.15	0.24	349.5	0.0	5.8	28.9	-0.05	-0.28	-1.92
MW6A	57.5	7.33	4.0	532	58.9	28.3	2.3	3.2	0.02	0.01	269.7	3.6	9.8	17.2	-0.19	-0.62	-2.00
MW2D	61.2	7.29	5.9	545	64.5	33.2	1.8	3.9	0.09	0.01	306.0	3.9	10.9	19.0	-0.12	-0.41	-1.91
MW7C	103.6	7.42	6.4	705	88.5	43.1	5.0	2.5	0.07	0.02	365.8	4.0	19.0	38.3	+0.17	+0.09	-1.96
MW2C	137.2	7.37	7.9	625	62.3	31.7	2.9	2.2	0.00	0.00	274.3	4.8	13.0	17.8	-0.08	-0.34	-2.01
MW1	140.0	7.32	7.8	614	66.0	34.1	1.8	2.5	0.02	0.00	304.8	4.1	12.3	16.6	+0.01	-0.19	-2.08
MW7B	148.3	7.31	4.2	541	56.5	27.4	3.5	6.1	0.00	0.00	249.9	5.6	12.5	15.1	-0.14	-0.41	-1.98
MW2B	155.4	7.45	4.9	678	67.0	36.7	12.9	7.5	0.02	0.00	326.1	4.5	18.8	22.0	+0.04	-0.11	-2.09
MW7A	179.1	7.55	9.8	532	56.1	27.7	3.4	5.4	0.01	0.00	253.0	5.9	15.5	15.41	+0.04	-0.09	-2.21
MW2A	230.6	7.28	4.1	566	63.9	32.6	5.5	1.8	0.02	0.00	306.3	2.8	11.4	18.9	-0.18	-0.56	-1.91

The variations in geochemistry with depth are consistent with the conceptual model of predominantly vertical flow near the surface but significant horizontal flow through horizontal fracture zones at depth. Figure 3-10 shows the average concentrations of several geochemical parameters versus depth; horizontal bars on the diagrams span one standard deviation, and illustrate the variability of parameters at various depths. In the upper 50 feet of the aquifer, the geochemical patterns are consistent with rainwater recharging and moving vertically through the dolomite aquifer.

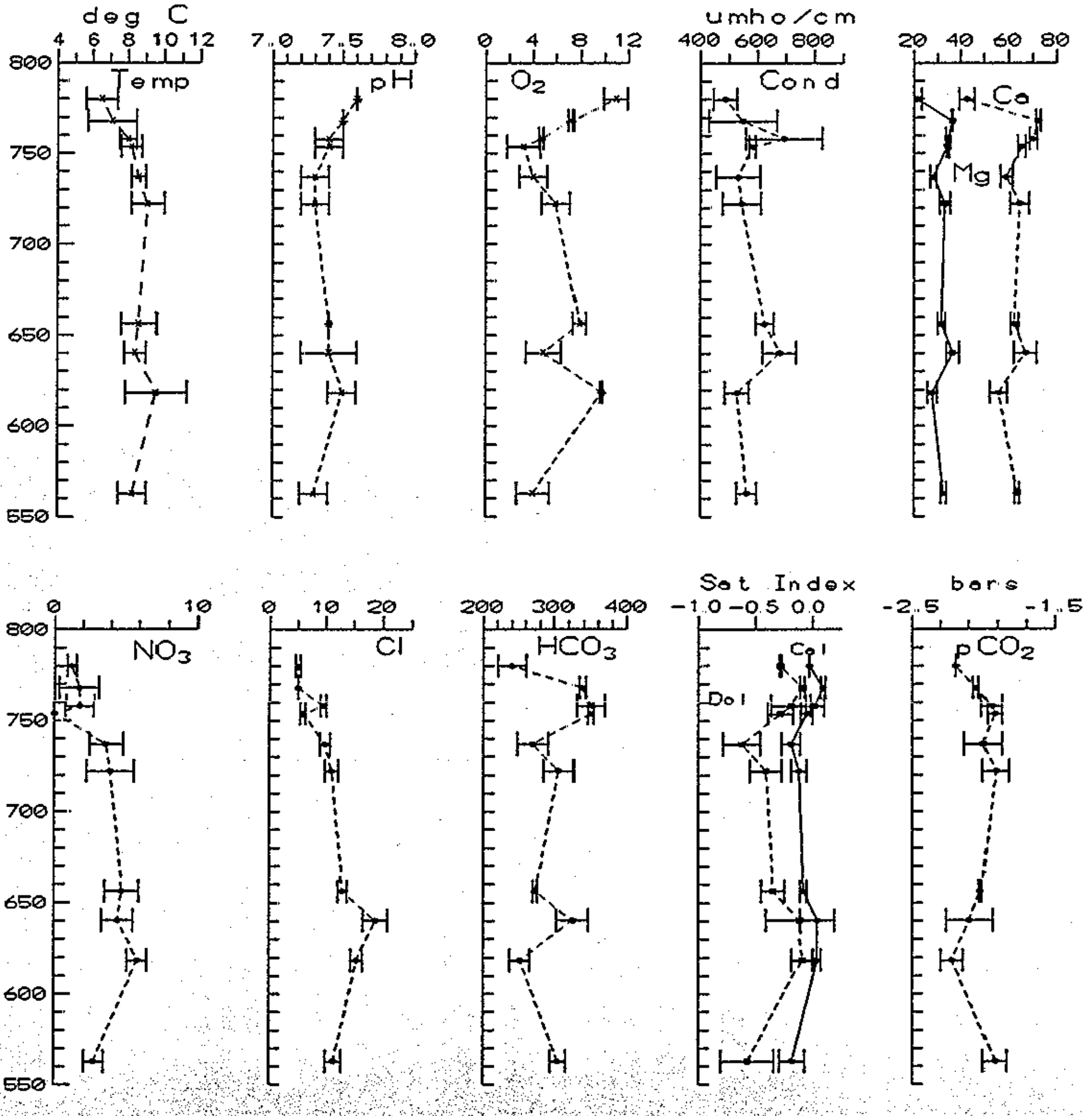


Figure 3-10. Vertical distribution of various geochemical parameters at the Jarman Road monitoring site, averaged from all sampling rounds. Horizontal bars represent one standard deviation. Units are mg/l except as indicated.

Dissolved oxygen concentrations decrease with depth, while electrical conductivity, calcium, magnesium, and bicarbonate increase with depth. Concentrations of nitrate and chloride are very low near the surface but increase with depth, suggesting an offsite source for these constituents.

Geochemical parameters fluctuate in response to recharge events. Figure 3-11 shows chemical hydrographs from piezometers MW2A, 240 ft deep, and MW4A, 42 ft deep, from 1987 through 1990. Geochemical parameters in these two wells fluctuated significantly over this period, and concentrations in the shallow piezometer fluctuated more than concentrations in the deep piezometer. The similarity of both the chemical and water-level hydrographs for the shallow and deep wells shows that recharge of the shallow and deep parts of the aquifer can occur simultaneously and quickly. Concentrations of constituents from natural sources (Ca, Mg, HCO_3) tend to decrease due to dilution during recharge periods while concentrations of contaminants (NO_3, Cl) tend to increase corresponding to peak recharge events as surface contaminants are flushed into the aquifer.

Implications for groundwater monitoring

The monitoring well results provide additional evidence that the water chemistry observed in samples from private wells is probably representative of groundwater chemistry in central Door County. Chemical analyses of groundwater samples from the Jarman Road monitoring site are similar to results from domestic wells. Table 3-8 shows

Table 3-8. Comparison of results from two wells at the Jarman Road monitoring site with results from domestic wells.

Parameter		Domestic sites		MW-2A		MW-4A	
		mean	sd*	mean	sd*	mean	sd*
NO_3-N	(mg/l)	6.4	5.8	2.5	1.5	1.3	1.4
Cl	(mg/l)	17.8	18.3	8.9	4.6	9.0	9.1
E. Cond.	(μmho)	605	148	503	190	563	167
SO_4	(mg/l)	28.4	16.5	17.3	5.9	27.4	7.5

*standard deviation

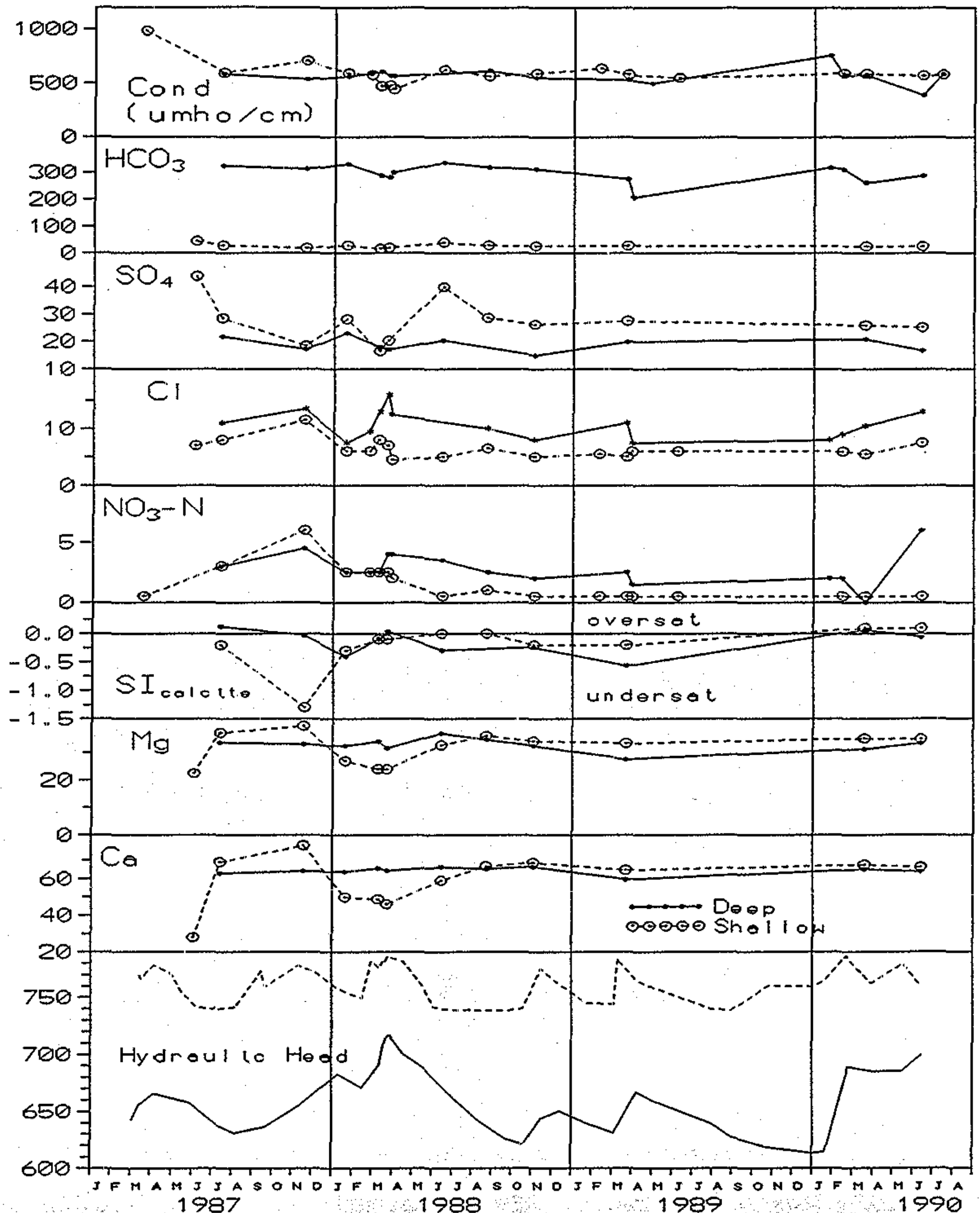


Figure 3-11. Variation of geochemical parameters (mg/l, except as indicated) and hydraulic head (ft above mean sea level) with time at piezometers MW2A (deep, solid lines) and MW4A (shallow, dashed lines).

a comparison of average values of parameter concentrations from the domestic well sampling with average values of the same parameters at two piezometers at the Jarman Road site. The standard deviations about the means are large enough that there is no statistical difference between the mean concentrations at monitoring piezometers and domestic wells. Thus the sampling of existing domestic wells appears to be an appropriate method for monitoring regional groundwater chemistry in central Door County and possibly in other fractured dolomite aquifers.

Isotopic Estimates of Groundwater Age

Methodology

The environmental isotopes tritium (^{3}H) and oxygen-18 (^{18}O) provide estimates of relative groundwater age in central Door County. Such environmental isotopes are naturally present in groundwater, and the concentrations of these isotopes in groundwater samples are related to groundwater age and source area.

Tritium (^{3}H) is a naturally occurring radioactive isotope of hydrogen which entered the earth's atmosphere in elevated amounts as a consequence of atmospheric testing of nuclear weapons beginning about 1953. Atmospheric tritium levels reached a maximum about 1963, and steadily declined following the cessation of atmospheric testing in the mid-1960's. Tritium is an unstable isotope, and its concentration in water declines exponentially with time by radioactive decay. The half-life of tritium (12.3 yr) is relatively short, making it an excellent indicator of recent groundwater recharge and relative groundwater age (Egboka and others, 1983; Knott and Olimpio, 1986), where age is defined as the time since the water was in contact with the atmosphere. Because of this rapid decay, water which entered the subsurface prior to 1953 would today contain no detectable tritium using routine measurement techniques. Hendry (1988) summarized the several possible qualitative interpretations of groundwater age that can be based on tritium concentrations.

By using the known history of atmospheric tritium input for a given area it is possible to make semi-quantitative estimates of the minimum age of groundwater samples that are more meaningful than simple qualitative interpretations. The actual tritium input to groundwater is calculated as a weighted yearly average of tritium and precipitation, calculated as described by Bradbury (1991) and Knott and Olimpio (1986). Due to the presence of thin soils and open fractures, groundwater recharge in central Door County can occur following precipitation during any time of the year, with winter precipitation entering the ground immediately following snowmelt in early spring. The concentration of tritium in precipitation varies seasonally, and multiplying the amount of rainfall for each month in a given year by the tritium content for that month and then dividing the result by 12 gives a precipitation-weighted tritium value for that year. After the weighted tritium inputs are calculated, the radioactive decay equation can be used to correct the tritium concentrations for radioactive decay over the elapsed time between precipitation and groundwater sampling (Bradbury, 1991). Figure 3-12 shows the weighted tritium input corrected for radioactive decay to 1987 and 1988, years when groundwater sampling for tritium occurred in central Door County. These curves represent the theoretical amount of tritium remaining in the groundwater system in 1987 and 1988 after entering the system in each of the years from 1954 to 1986. For example, although the precipitation entering the ground in 1964 contained almost 3000 TU (figure 3-12) this amount would have decayed to only about 700 TU by 1987. Corrected tritium levels range from about 700 TU for water recharged in 1964 to about 5 TU for water recharged in 1955, with several peaks and valleys due to years of high and low precipitation and corresponding variations in tritium input. Combining the historical record of tritium in precipitation with measurements of tritium in groundwater samples allows estimates of minimum ages of groundwater samples, as described by Bradbury (1991).

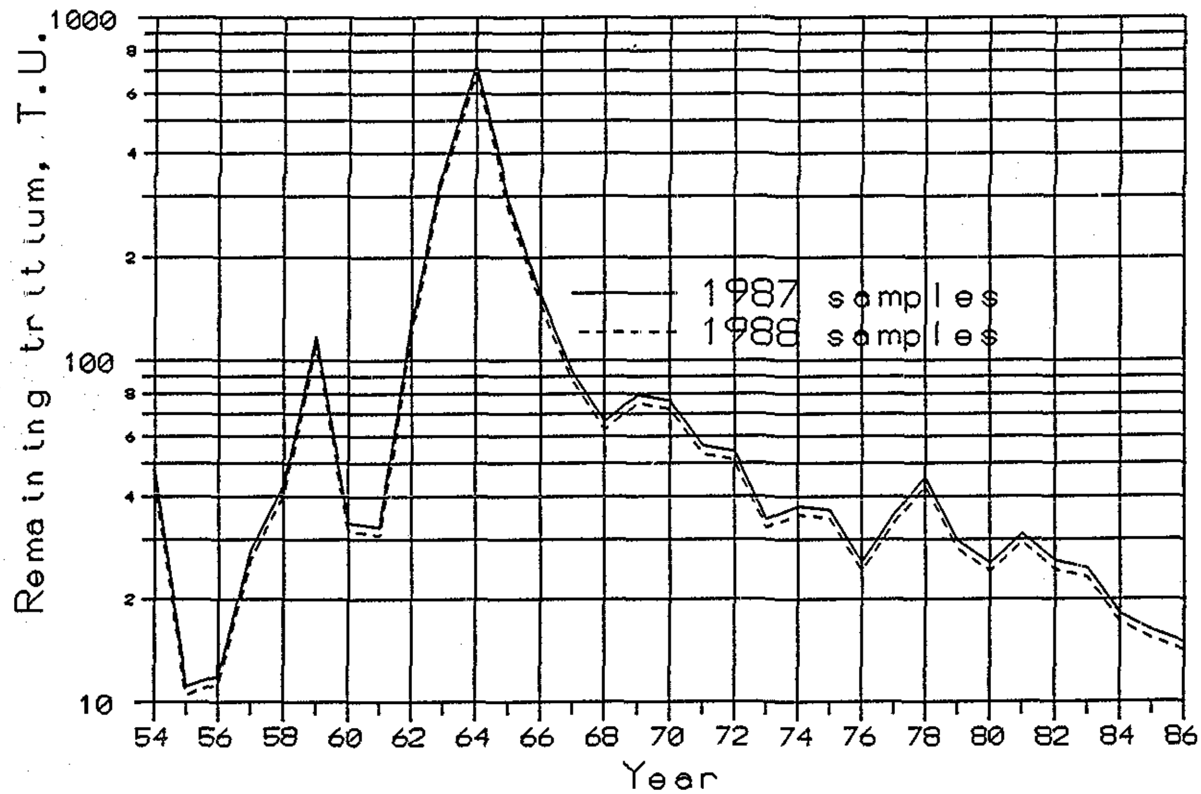


Figure 3-12. Tritium input history for Door County, Wisconsin, showing remaining tritium for groundwater samples obtained in 1987 and 1988.

Significant errors in age estimates are possible when using tritium to date groundwater younger than about ten years in a fractured rock environment. The tritium input curve assumes that mixing of precipitation occurs during infiltration through the unsaturated zone, and that this mixing smooths out seasonal tritium anomalies. In Door County, however, flow through the unsaturated zone might be so rapid that recharge is almost instantaneous following precipitation. In this case, the tritium content of groundwater would be highly biased by seasonal fluctuations in atmospheric tritium. Therefore, it is unlikely that tritium dating can reliably discriminate the ages of groundwater samples in Door County less than about ten years of age.

Oxygen-18 (^{18}O) is a naturally occurring isotope of oxygen present at low concentrations in air and water. The ratio of ^{18}O to the more common ^{16}O is a function of climate, season, latitude, and weather patterns. In general, the $^{18}O/^{16}O$ ratio becomes lower in more northerly latitudes and colder climates, and so the ^{18}O content of groundwater is often used as an indicator of climate at the time the water recharged. In addition, the $^{18}O/^{16}O$ varies seasonally, and variations in this ratio are often used to distinguish groundwater originating from different recharge areas. As with tritium, ^{18}O values are reported as a ratio deviation from a standard. For ^{18}O the standard is Standard Mean Ocean Water (SMOW); results are reported as permil (parts per thousand) deviations from this standard.

During 1987 and 1988, 12 water samples were collected from wells and piezometers at the Jarman Road research site. Sample depths, controlled by the positions of the piezometer screens, ranged from 23 to 231 ft below the land surface. The samples were tested for enriched tritium and oxygen-18 at the University of Waterloo (Ontario) Isotope Laboratory. Enriched tritium was determined by direct liquid scintillation counting, which has a detection limit of approximately 0.2 TU and an analytical precision of ± 8 TU. Oxygen-18 was determined by mass spectrometry.

Results

Tritium contents of groundwater samples at the research site ranged from 13 to 33.6 TU (table 3-9). All of the tritium samples generated interpreted ages of less than ten years. These estimates are consistent with qualitative age estimates based on Hendry (1988) and are included in the last column in table 3-9. The tritium results confirm that groundwater in central Door County is relatively young, as would be expected in a fractured rock environment with high hydraulic conductivity. There is no apparent variation in groundwater age with depth at the Jarman Road research site.

^{18}O results at the Jarman Road site (table 3-9) ranged from -9.6 to -11.2 permil. The ^{18}O values are similar to values for modern rainwater, and are consistent with the hypothesis that fairly rapid recharge occurs in central Door County. The variation in ^{18}O content with depth at the Jarman Road site is very small, suggesting little variation in age or source area for waters at various depths at the site.

Table 3-9. Results of isotope sampling. All tritium results are ±8 Tritium Units (TU).

Well or piezometer	Mid-point Open length (ft)	Sample date	Tritium content (TU)	del ^{18}O (permil)	Interpreted minimum ground-water age (yr)	Qualitative ground-water age (yr)
MW5A	23.2	11/02/88	26	-9.7	<10	<35
MW4	27.2	07/14/87	33	-10.8	<10	<35
MW3	35.0	07/14/87	28	-11.2	<10	<35
MW4A	42.0	11/02/88	13	-9.6	<10	<35
MW6A	57.5	11/02/88	23	-11.2	<10	<35
MW2D	61.2	07/14/87	21	-11.2	<10	<35
MW2D	61.2	11/02/88	18	-11.1	<10	<35
MW1	140.0	07/14/87	33	-11.0	<10	<35
MW1	140.0	11/02/88	25	-11.2	<10	<35
MW2B	155.4	07/14/87	34	-10.8	<10	<35
MW2A	230.6	11/02/88	17	-11.2	<10	<35
MW2A	230.6	07/14/87	30	-11.2	<10	<35

CHAPTER 4

REGIONAL FLOW SYSTEM AND AQUIFER CHARACTERISTICS

Hydrogeologic Setting

Dolomite of Silurian age lies beneath a thin cover of unlithified Pleistocene sediment, mostly clayey till on the uplands. The dolomite is more than 500 ft thick along the eastern shore of Door County (Sherrill, 1975) and thins to the southwest; it forms a prominent escarpment along the western edge of the county, adjacent to Green Bay. In northern Door County, the dolomite aquifer is a self-contained, unconfined aquifer system, covered only by thin unlithified materials and bounded on all sides by surface water and beneath by the Ordovician Maquoketa shale, a regional confining bed.

Geology

Previous hydrogeologic workers in Door County have generally divided the dolomite aquifer into an Upper Niagaran and Lower Alexandrian Series and included all the Silurian carbonate rocks in the "Dolomite Aquifer System" (Sherrill, 1978; Bradbury, 1982; Nauta, 1987). Geologists have long recognized several stratigraphic formations within the dolomite (Chamberlin, 1877; Shrock, 1940; Thwaites and Bertrand, 1957; Sherrill, 1978). Figure 4-1 summarizes the bedrock stratigraphy of Door County. Because these units are somewhat difficult to distinguish and because it was assumed that fracture zones rather than lithologies controlled groundwater movement, stratigraphy has not been incorporated into many groundwater investigations. Recent work in southeastern Wisconsin (Cherkauer and Rovey, 1991) and in Door County (Muldoon and Bradbury, 1991) suggests that dolomite stratigraphy may play a more important role in groundwater movement than was previously assumed.

In order to better define the stratigraphy in the study area, and assess the role it might play in groundwater movement, a detailed cross-section was constructed using data gathered from outcrops, drillhole cuttings, and borehole geophysical logs (figure 4-2). Each of the units is described below.

The *Mayville Formation*, which forms much of the escarpment in southern Door County, lies unconformably above the Maquoketa shale, a low-permeability unit that functions as the base of the dolomite aquifer. The Mayville is quite variable in color, ranging from light tannish grey to buff color, and weathering to medium grey in outcrop. The unit tends to be cherty, coarse-grained, porous, massively-bedded, and fossiliferous. Thwaites and Bertrand (1957) report an average thickness of 100 ft.

The *Burnt Bluff Group* contains the Byron and Hendricks Formations; the contact with the underlying Mayville Formation appears relatively sharp based on drill cuttings.

SERIES	GROUP	FORMATION	MEMBER
NIAGARAN		Engadine	
NIAGARAN		Manistique	Cordell
NIAGARAN		Manistique	Schoolcraft
NIAGARAN	Burnt Bluff	Hendricks	
NIAGARAN	Burnt Bluff	Byron	
ALEX-ANDRIAN		Mayville	
		Maquoketa	

Figure 4-1. Summary of Door County bedrock stratigraphy.

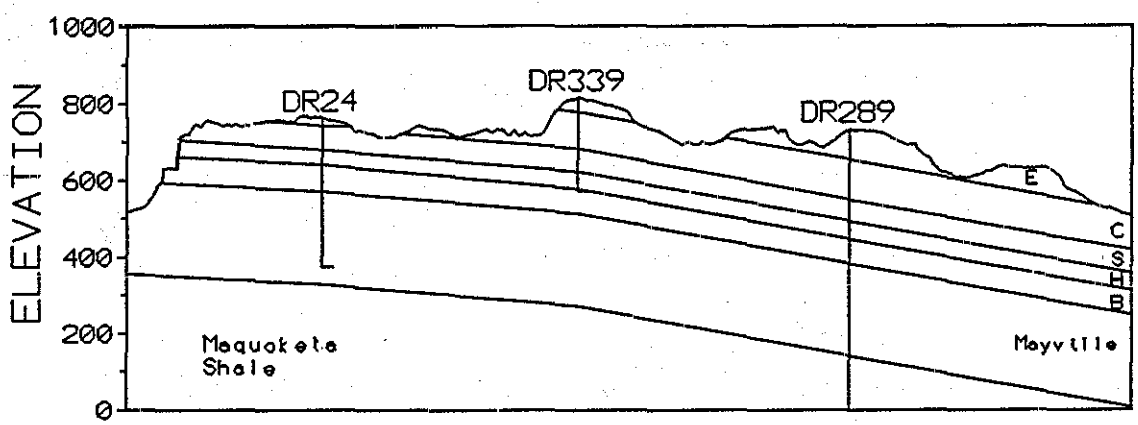


Figure 4-2. Geologic cross-section of Door County. Horizontal axis is 65,500 ft, vertical axis is 1000 ft.; vertical exaggeration is approximately 25X. B=Byron Formation, H=Hendricks Formation, S=Schoolcraft Member of the Manistique Formation, C=Cordell Member of the Manistique Formation, E=Engadine Formation. DR24, DR339, and DR289 are drillholes with cuttings, geologic logs, and electric logs. The western end of the cross-section starts in a dolomite quarry where the stratigraphic section was measured.

The *Byron Formation*, ranging in thickness from 65 to 100 ft, is medium to light tannish grey in color, weathering to white in outcrop. The unit is distinctive in that it is thin-bedded, very fine-grained, with little to no chert or fossils. The unit does exhibit many mud cracks and ripple marks. The *Hendricks Formation* was called the Transition beds by Chamberlin (1877) because it is gradational between the fine-grained Byron Member and the coarser, fossiliferous Manistique Formation which overlies it. The medium grey to medium tannish grey unit is 30 to 45 ft thick, and consists of thin-bedded very fine-grained beds alternating with thick-bedded, unfossiliferous granular dolomite.

The *Manistique Formation*, called the "Coral Beds" in older reports, contains the *Schoolcraft* and *Cordell Members* which are sometimes difficult to distinguish. Both are thin-bedded, light grey to buff in color, weathering to buff in outcrop; texture is granular. Both units are fossiliferous and contain many bioherms; chert is common but rarely abundant in the Schoolcraft while chert is abundant in the Cordell. The Schoolcraft is 60 to 70 ft thick while the Cordell is 90 to 100 ft thick.

The *Engadine Formation* has somewhat limited outcrop in the study area and it appears somewhat variable in drillhole cuttings. At Cave Point, in Whitefish Dunes State Park, the unit varied from massive to thin-bedded and texture ranged from dense and fine-grained to granular. Many bioherms were apparent. In drillhole DR289 (see fig. 4-2) there appeared to be two distinctive lithologies within the formation. The lower unit is medium gray, 15 to 20 ft thick, with a moderately granular texture, few dissolution features, and little to no chert or fossils. The upper unit is white to light tannish grey, 65 ft thick, with moderately granular texture, small dissolution features are present and little chert and no fossils were noted. The difference between these units may be that the upper 65 ft of drillhole DR289 is more heavily weathered since the Engadine forms the surficial unit in the area of the drillhole.

All of these units dip to the east at 20 to 40 ft per mile (figure 4-2). The control points for the cross-section include a measured section from a quarry wall on the western edge of the county and the three drillholes shown in figure 4-2. The contacts for the Engadine, Cordell, Schoolcraft, Hendricks, and Byron are encountered in at least two of the four control points. The change in the dip of the units, as shown on figure 4-2, may not be as sharp as depicted, however, the contact lines were drawn to intersect the drillholes at the contact points. The Mayville formation is fully penetrated only by drillhole DR289. The thickness of the unit was assumed to be constant across the county and the contact between the Mayville and Maquoheta Formations was drawn based on that assumption. The outcrop pattern of the units appears to control the location of the potentiometric divide and the distribution of surface water features. These relationships are explained more fully in the "Groundwater Flow Systems" section of this chapter.

Fracture Distribution

Numerous vertical and horizontal fractures in the dolomite apparently control the hydraulic conductivity of the aquifer. Figure 4-3 shows near-vertical fracture expression in an alfalfa field across from the Jarman Road research site. The depth to bedrock in the field is approximately 6 in., as determined by ground-penetrating radar and by hand augering. Apparently, the near-vertical fractures are filled with fine-grained soil, which holds more moisture than surrounding rocks. The photo shows that fractures in the predominant joint set are spaced approximately 10 to 20 ft apart near the research site. Aerial photographs from other areas of the county indicate a similar frequency and regularity of fracture spacings. Rosen (1984) and Sherrill (1978) document principaljoint azimuths over the entire county at about 25°, 70°, and 155°. At the Jarman Road site, major visible fractures are oriented approximately N30°E. Each fracture, if open, can provide a direct route for infiltrating water to recharge the groundwater system; however, most fractures are at least partially filled with clayey or silty sediment.

Direct evidence of fracture discontinuities observed during installation of well MW1 included loss of drilling fluids at elevations of 600 and 577 ft above mean sea level (msl) (198 and 221 ft below land surface) and voids at 582 and 577 ft above msl (221 and 216 ft below land surface). While drilling at MW2 and MW7, there was a loss of circulation and water was forcefully rejected through MW1. This shows a direct connection among wells MW1, MW2, and MW7, which are each over 200 ft apart. The loss of circulation occurred at a depth of 190 ft in both wells, and water eruption occurred when drilling at 190 ft in MW7 and 235 ft in MW2.

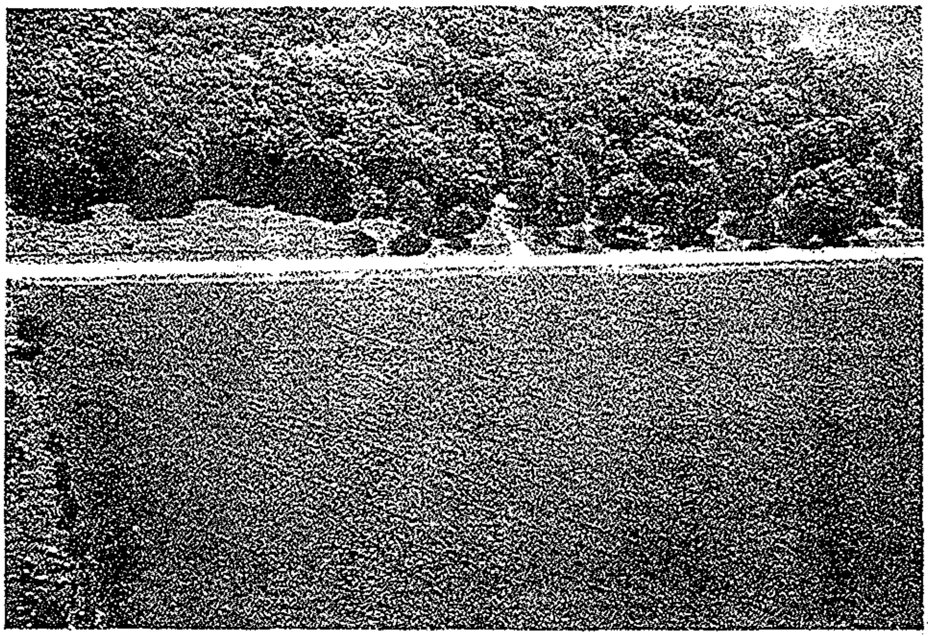
A suite of logs from the Jarman Road site demonstrates how geophysical logs can be used to detect horizontal fracture zones. Figure 4-4 shows logs for well MW1; numbers on the left-hand axis of the figure are corrected elevations relative to mean sea level. Offsets appear in the temperature log at elevations of 648 ft and 563 ft above msl (depths of 150 and 235 ft). This log was run in the spring, when cold recharge water was entering the aquifer. Temperature increases at the offsets suggest that either the cold water was leaving or warmer water was entering the borehole through horizontal fractures or solution features at these elevations. Slight increases in borehole diameter occur at the same elevations, and also at other elevations where temperature changes were not observed.

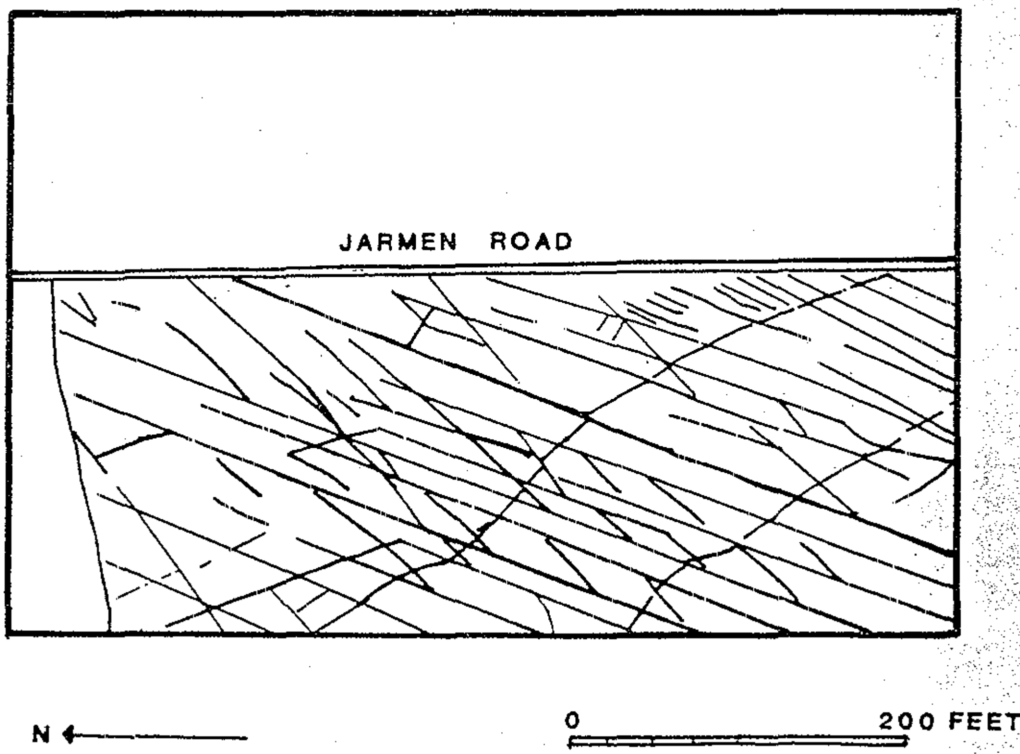
The gamma log shows much variation over short vertical distances, suggesting small-scale variability in lithology. Highest gamma values generally should coincide with zones of clay or other fine-grained material. Television logs show fractures and vugs that have been enlarged by dissolution. The television log confirmed the presence of a permeable zone between 650 and 640 ft above msl (approximately 150 ft deep); this zone has a dissolved, "Swiss cheese" appearance rather than the appearance of a discrete fracture. The spinner flow meter detected significant borehole flow at an elevation of about 615 ft above msl, a depth at which the television log showed numerous vugs.

Water-Level Measurements

In order to determine the vertical distribution of hydraulic head in the dolomite

Figure 4-3. Expression of bedrock fractures in alfalfa field at the Sevastopol site, Door County, Wisconsin. **Top:** Oblique air photo showing vigorous alfalfa growth over fractures. **Bottom:** Highlighted locations of fracture traces.





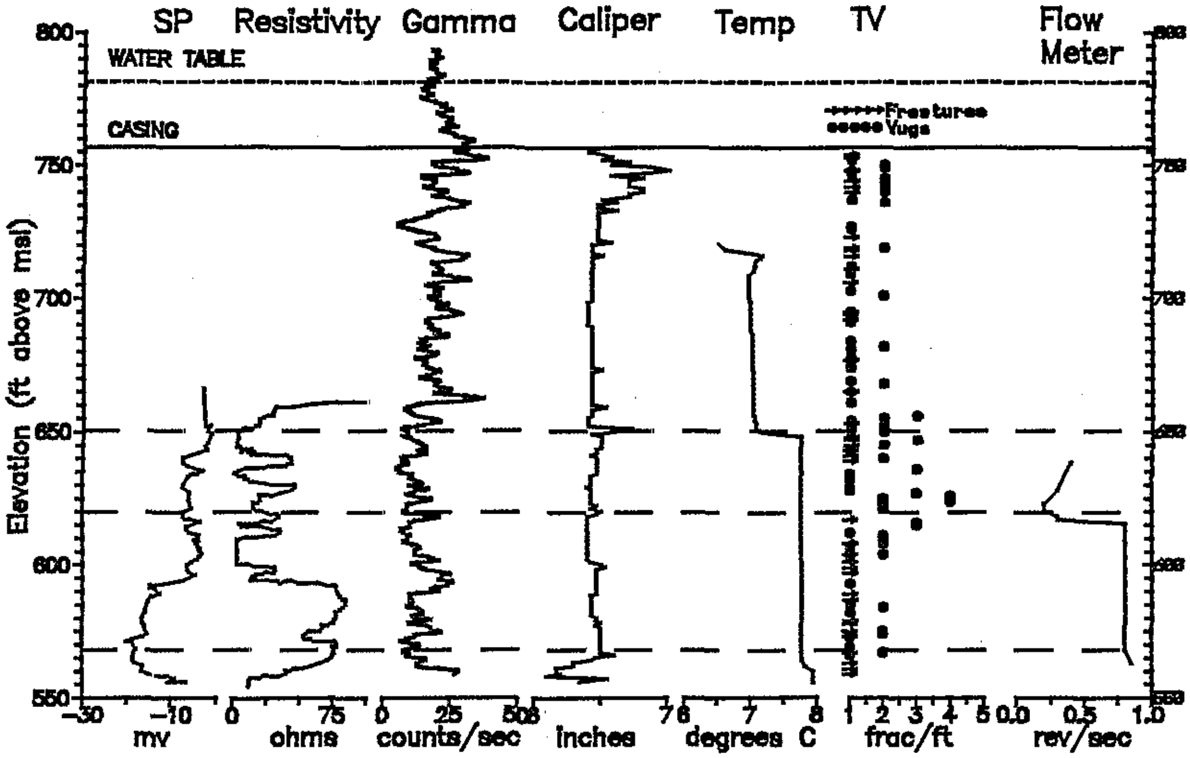


Figure 4-4. Geophysical logs for well MW1 at the Sevastopol site. Dashed horizontal lines indicate horizontal fracture zones.

aquifer and to monitor water-level fluctuations over time, long-term water-level data were collected from wells and piezometers at the Jarman Road site. These data indicate the presence of distinct shallow and deep flow systems. Figure 4-5 shows hydraulic head measurements from 2 wells and 4 piezometers at the site. Well MW1 and piezometer MW2A represent the deep flow system, while piezometers MW2D, MW6A and well MW3 represent the shallow system. These wells and piezometers continually contained water, while the intermediate piezometer, MW7C, was frequently dry. Similar conditions were observed at the Highway HH site. The continuous presence of water in the shallow piezometers was unexpected on the basis of previous research (Bradbury, 1982; Sherrill, 1978), which placed the water table in the area about 150 ft below the land surface. Previous water-table maps of the area, based on measurements in deeply cased domestic wells, delineated only the deeper potentiometric surface. Water levels in such deep wells are a function of the head differential, the hydraulic conductivity, and the rate of recharge to the system (Saines, 1981). Water-table measurements in shallow wells, combined with observed surface features such as wetlands and ponded water, show that a relatively shallow groundwater flow system occurs at the site, in addition to the deeper system. During most of the year, the two systems are separated by an unsaturated zone as indicated by the dry readings in piezometer MW7C. In the spring, however, the two

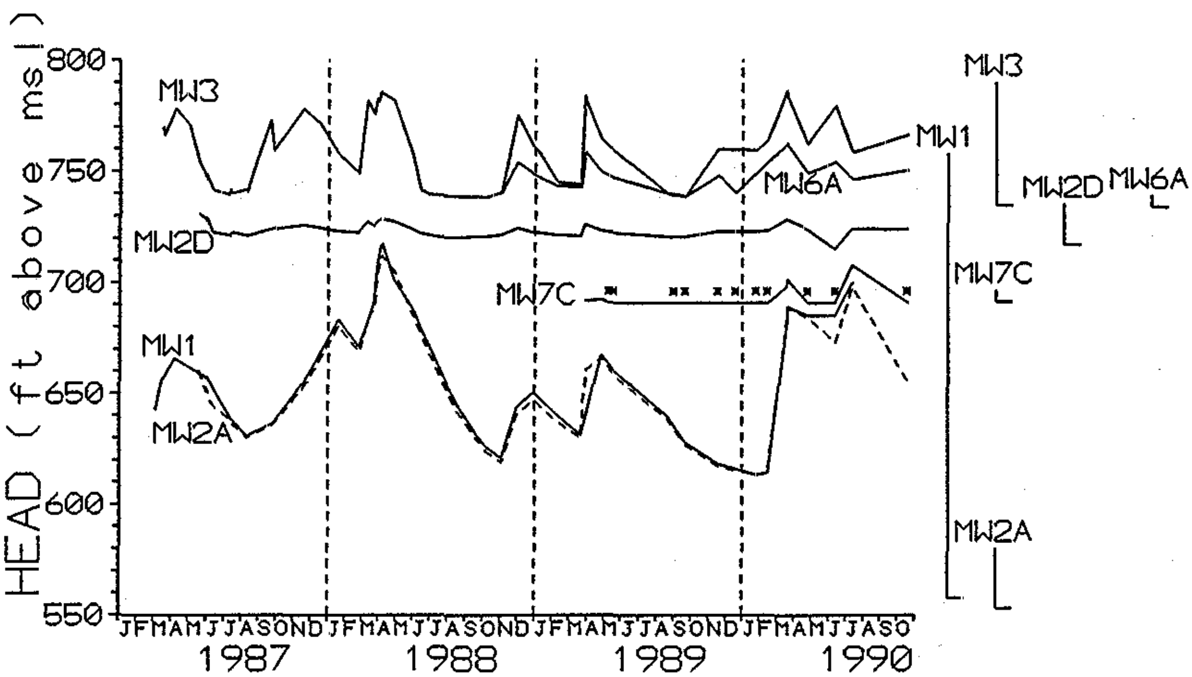


Figure 4-5. Hydraulic head of wells and piezometers at the Jarman Road site. Lines on the right side of the figure indicate the open interval of the well or piezometer.

systems merge to form a continuous saturated section.

Vertical Distribution of Hydraulic Head

Vertical hydraulic gradients at the Jarman Road site are steeply downward for the shallow flow system and are much greater than horizontal gradients, suggesting that the aquifer is highly anisotropic. Figure 4-6 shows the distribution of total hydraulic head in the subsurface in November 1989 and March 1990. The head distribution of March 1990 typifies wet times of year when the water table is about 10 ft below the land surface and the entire section appears to be saturated. Under these conditions the shallow flow system exhibits a relatively steep downward gradient, while the deeper flow system exhibits little vertical gradient, suggesting that flow in the deep system is predominantly horizontal. The head distribution in November of 1989 typifies dry times of the year; the water table is about 40 ft below the land surface as indicated by the water-level in piezometer MW6B. Piezometer MW5A appears to contain water even when wells below it go dry; we believe that this is because the piezometer is completed in a relatively dense block of dolomite and intersects few fractures. The low hydraulic conductivity measured for this piezometer (6.9×10^{-9} ft/sec) tends to support this idea. The potentiometric surface is approximately 155 ft below the land surface in November, 1989 as shown by the water-level in MW2C. The deep system exhibits a relatively steep

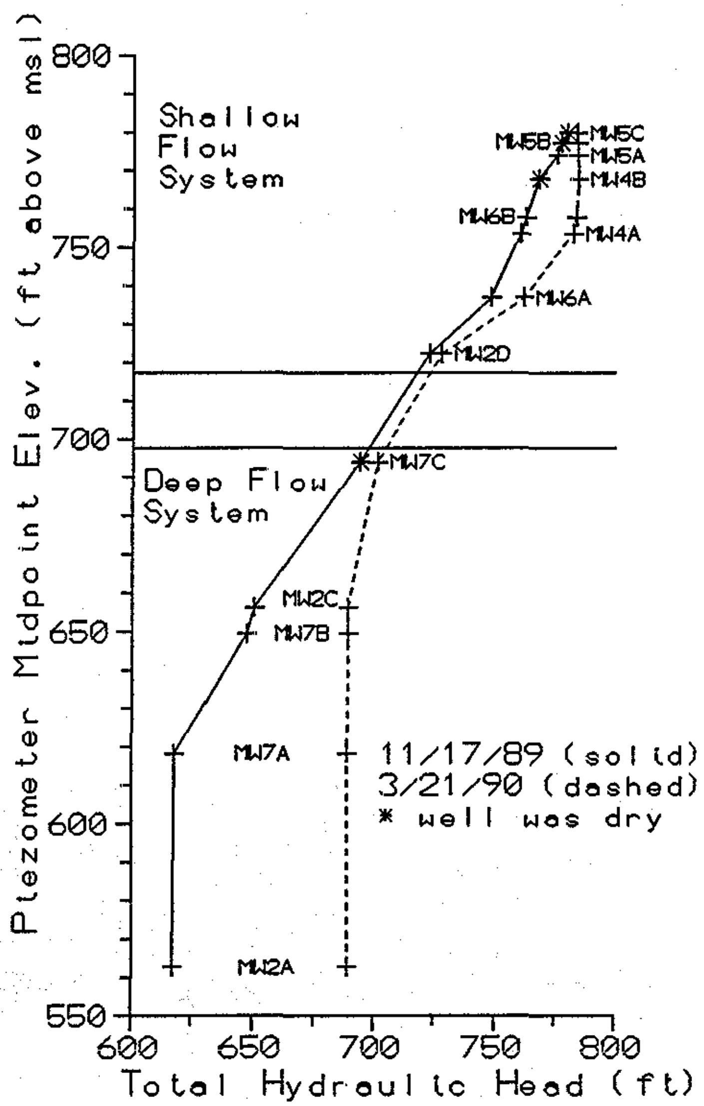


Figure 4-6. Distribution of hydraulic head in the subsurface at the Jarman Road site in November 1989 (solid line) and March 1990 (dashed line).

downward gradient during dry times of the year (compare head in MW2C and MW2A).

Groundwater Flow Systems

In order to evaluate how land-use practices influence water quality, it was necessary to construct up-to-date water-table and potentiometric-surface maps for the study area. In September of 1989 and March of 1990, field personnel measured groundwater levels in approximately 50 domestic and irrigation wells in the area surrounding the site. After corrections for land-surface elevation, these data, in conjunction with piezometer data and surface-water elevations, allowed the construction of a water-table and a potentiometric-surface map of the area. The March data represent the maximum water-levels in the aquifer while the September data, represent low-flow conditions in the aquifer.

Deep Flow System

Significant temporal fluctuations occur in the deep flow-system; these variations lead to reversals in groundwater flow directions in the central portion of the county. Figure 4-7 shows the configuration of the potentiometric surface for the subarea near the Jarman Road site (see figure 2-1). Comparison of the September and March figures reveals that the deep flow system fluctuated by over 90 ft in response to the spring snowmelt event. The September figure represents the usual configuration of the flow system for this part of the county; groundwater tends to flow from northeast to the west/southwest. In spring, however, a large groundwater mound forms under the central portion of the county and in the eastern half of the subarea, groundwater flows from west to east. Such dramatic reversals in flow direction make it more difficult to assess how activities at the land surface impact groundwater quality.

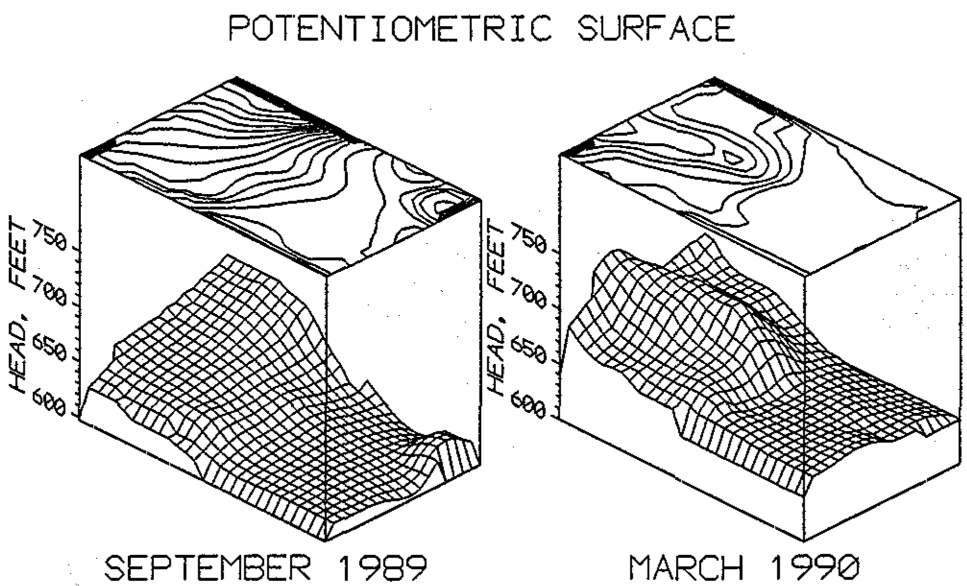


Figure 4-7. Configuration of the potentiometric surface in the 15 mi^2 subarea of central Door County in September 1989 and March 1990. Contour interval is 20 ft.

Shallow Flow System

The shallow flow system does not fluctuate as much as the deep system and no significant reversals in flow direction occur. Figure 4-8 shows the configuration of the water table for the subarea near the Jarman Road site (see figure 2-1). The water-table essentially mimics the topography of the land surface and no major changes in the configuration of the water table occur between fall and spring. Comparison of the two figures reveals that the water table fluctuated over 40 ft in response to spring snowmelt.

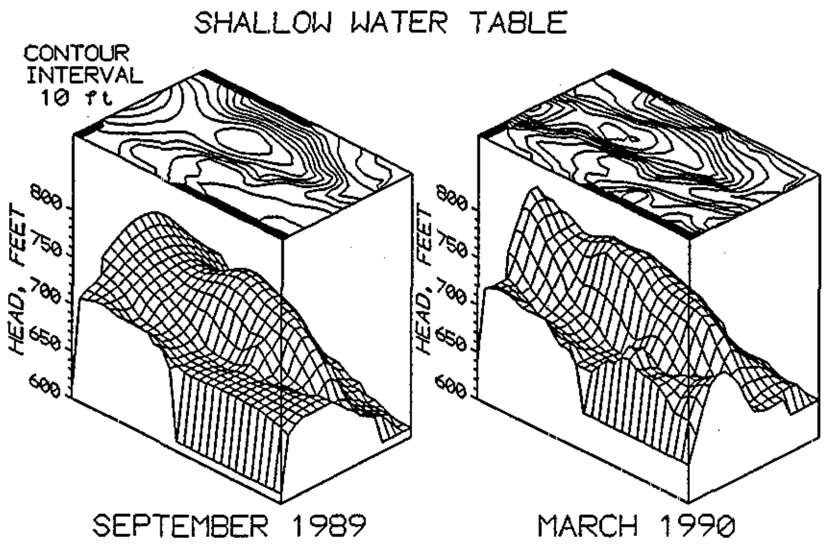


Figure 4-8. Configuration of the water table in the 15 mi^2 subarea of central Door County in September 1989 and March 1990.

Relationship of Flow Systems to Stratigraphy

The dolomite stratigraphy and geologic structure determine the characteristics of the northern Door County flow systems. There appears to be a layer within the Cordell Member of the Manistique Formation that impedes the vertical movement of groundwater and causes the "perching" of the shallow flow system above the deeper potentiometric surface. Figure 4-9 is a cross-section illustrating the position of the September 1989 water table and potentiometric surface in relation to the dolomite

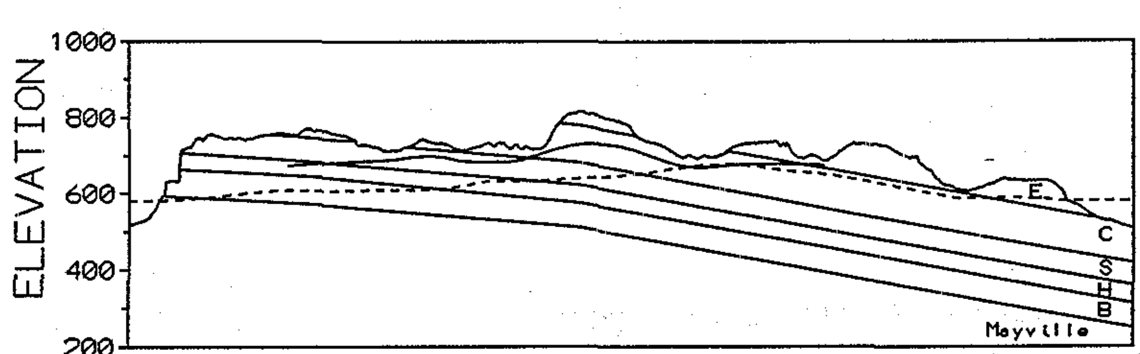


Figure 4-9. Cross-section showing the water table and potentiometric surface from September 1989 in relation to stratigraphic units. The dashed line is the potentiometric surface while the solid line represents the water table.

stratigraphy. Note that the potentiometric divide is located in a topographic low point a little east of the central point of the county where the Cordell Member is near the land surface. The Jarman Road site is located at the topographic high point in the cross-section where the entire thickness of the Cordell Member is present in the subsurface. At the site, the division between the upper and lower flow systems lies between 690 and 720 ft elevation which is within the Cordell Member. In the eastern half of the cross-section, the Cordell is near the land surface and both the water table and the potentiometric surface closely follow the topography, whereas in the western half of the cross-section there is a much larger separation between the water table and the potentiometric surface. Once the Cordell is no longer the surficial unit, neither the water table nor the potentiometric surface tend to mimic the topography.

The occurrence of the Cordell Member also appears to control the distribution of surface-water features in northern Door County. Figure 4-10 contains a cross-section of the dolomite stratigraphy in the lower half of the figure and a map of the distribution of surface-water features in the upper half of the figure. The two figures are at different scales, however well DR339 marks the location of the Jarman Road site. The site marks the location where the entire thickness of the Cordell Member is first present in the subsurface (lower figure) and it continues to the east. The map (upper figure) shows that surface-water features are generally lacking in the western half of the county, but are common in the eastern half. The outcrop pattern of the Cordell approximately outlines the area where surface-water features are common.

<u>Groundwater Flow Rates</u>

Two tracer events, one planned and one accidental, demonstrate that very rapid rates of groundwater flow are possible in central Door County.

Tracer Test

In order to determine rates of groundwater flow in a small portion of the study area we conducted a qualitative natural-gradient tracer test at the Jarman Road research site on August 21, 1989. The bromide ion, Br^-, was chosen as a tracer because it is conservative, nontoxic, and is not present in significant concentrations in groundwater in the study area. A tracer solution was prepared by mixing granular potassium bromide with ambient groundwater from wells at the research site to obtain an initial concentration of 2800 mg/L Br^-. We injected 5 gallons of this solution as a slug into piezometer MW7A, followed by 5 gallons of ambient groundwater to force the tracer out of the piezometer screen. Piezometers MW2A and MW2B, both 150 feet away and hydraulically down-gradient from MW7A, were the monitoring points for this test. Each of these wells was periodically sampled using a bailer, and Br^- concentrations determined using a specific ion electrode. In addition, water levels in all piezometers were monitored throughout the test.

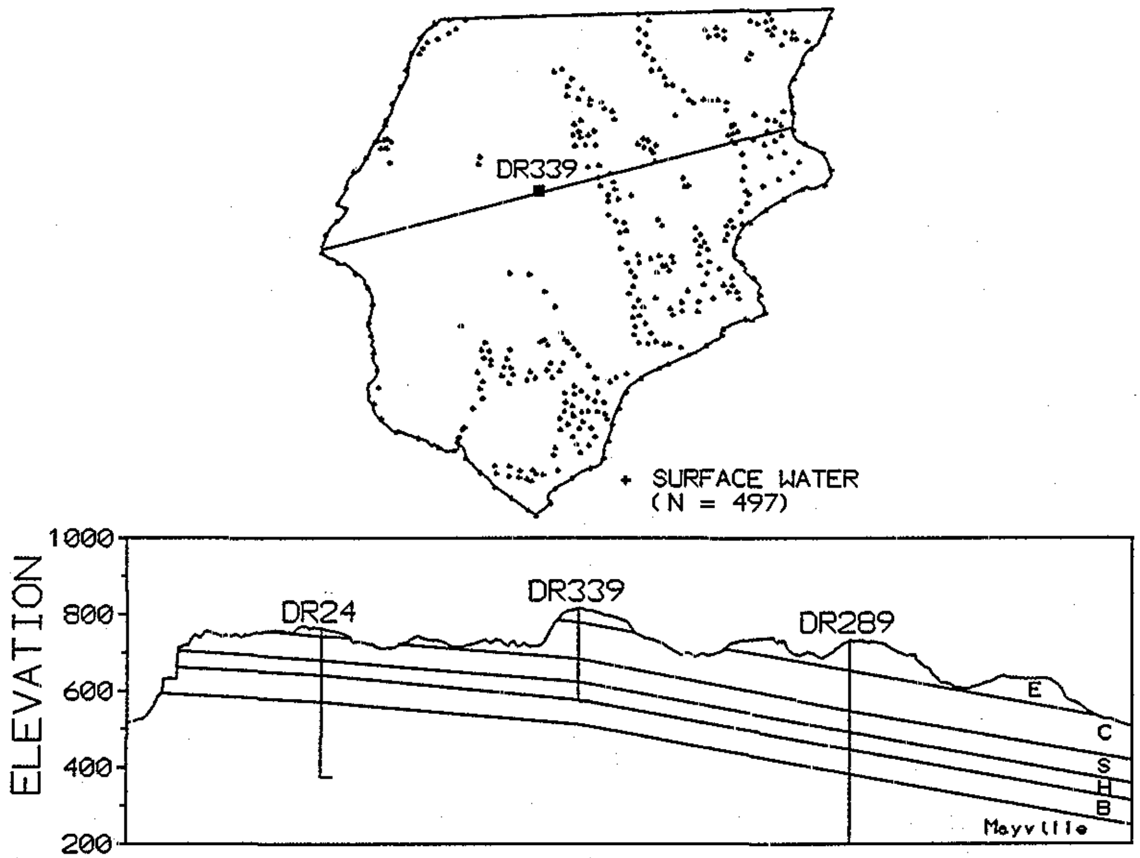


Figure 4-10. Figure showing relationship between stratigraphy and surface-water features in northern Door County.

The tracer moved more rapidly than expected, and the first arrival at the monitoring points occurred approximately 66 hr after tracer injection (figure 4-11). Due to the rapid arrival, the peak tracer concentration was probably not measured, and no data were collected during the declining phase of the tracer pulse. A sample taken 220 hr after injection showed that the Br^- levels at the two monitoring points had returned to background levels by that time.

The tracer test indicated a groundwater flow rate of 55 ft/day at the Jarman Road site. This rate was calculated using horizontal gradients and hydraulic conductivity measured at the site and an effective porosity of 0.05 for the fractured dolomite. Although these calculations ignore the effects of dispersion, such effects are probably small in proportion to the high advective flow rate at the site.

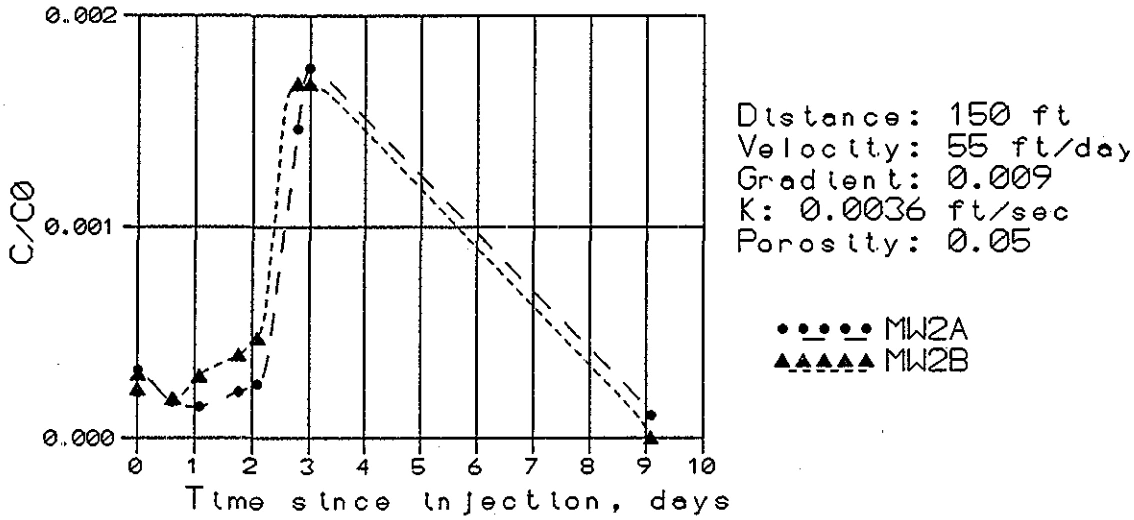


Figure 4-11. Results of qualitative tracer test at the Jarman Road research site.

Large-scale Contamination Event

In September 1987, a contamination event, demonstrating extremely rapid groundwater movement through fracture conduits, occurred near the village of Carlsville. The well at site 67 produced a water sample containing 267 mg/L nitrate-N, over an order of magnitude greater than the drinking-water health standard of 10 mg/L, and the well at site 52 produced a water sample containing 57 mg/L nitrate-N. Both sites are downgradient from site 66, a farm where an animal waste holding facility was being constructed at the time (figure 4-12). The construction project involved bedrock excavation, flushing of fractures, and blasting at a heavily-used animal feedlot, and these activities could have flushed large quantities of animal waste, feedlot soil, and blasting residues into the exposed fracture system. Well 67 is 2700 ft from the construction site, and well 52 is 4900 ft from the site. The well at site 66, located upgradient of the barnyard construction site, showed no change in concentrations on September 22nd, suggesting that the contamination moved in the direction of the hydraulic gradient by advection.

The contamination event at site 66 allows calculation of minimum regional groundwater flow velocities based on the detection of elevated nitrate levels in the two nearby wells. These calculations rely on several assumptions. First, we must assume that site 66 was the sole contamination source. The construction project at site 66 was the only known unusual activity occurring in the area at the time, and site 66 is hydraulically upgradient from the two contaminated wells. Second, we assume that the elevated nitrate levels in the wells are a direct result of contamination near site 66. No other obvious nitrate source is apparent, and wells in other parts of the study area did not

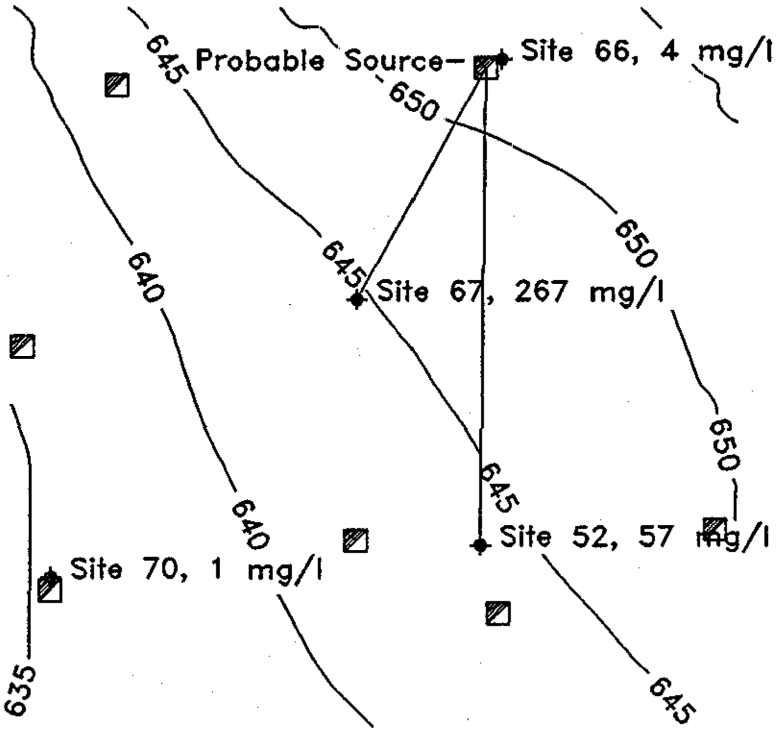


Figure 4-12. Concentrations of nitrate-N in domestic wells 2 weeks after the contamination event. Equipotential lines represent distribution of hydraulic head. Boxes represent locations of barnyards.

show elevated nitrate levels during this period. Third, we assume that the first arrival of contaminants in the wells occurred some time between sampling runs on September 8 and September 22, giving a maximum arrival time of 13 days. The resulting flow rate estimates are thus <u>minimum</u> flow rates. Dividing the linear separation between wells by the maximum arrival time gives groundwater velocities of 210 ft/day at site 67 and 380 ft/day at site 52. Using a hydraulic conductivity of 1300 ft/day measured in a horizontal fracture zone at the detailed monitoring site (see next section) and an effective porosity of between 0.5 and 1 percent, Darcy's law predicts velocities similar to those observed during the contamination event. Such results suggest that lateral groundwater transport in the dolomite can be extremely rapid, and may be controlled on the regional scale by the intersecting network of vertical and horizontal fractures combined with low effective porosity.

Aquifer Parameters

Specific capacity data, piezometer slug tests, and aquifer pumping tests provided data on the distribution of transmissivity (T) and hydraulic conductivity (K) in the fractured dolomite.

Specific Capacity Data

Specific capacity data contained in well constructors' reports in the files of the WGNHS allowed regional estimates of hydraulic conductivity using the program TGUESS (Bradbury and Rothschild, 1985). Table 4-1 presents results of these analyses. On the basis of 246 well constructors' reports, the transmissivity of the dolomite varied from 3.7×10^{-5} ft^2/sec to 1.9×10^{-1} ft^2/sec. Because the specific capacity, transmissivity, and hydraulic conductivity values were log-normally distributed, the geometric means of these parameters probably represent the best estimates of each parameter throughout the study area (Bouwer, 1978).

Table 4-1. Results of transmissivity and hydraulic conductivity estimates based on specific capacity tests.

Statistic	Specific Capacity (gpm/ft)	Transmissivity (ft^2/sec)	Hydraulic conductivity (ft/sec)
Number of tests	246	246	246
minimum	0.005	3.7×10^{-5}	8.3×10^{-8}
median	0.25	3.0×10^{-3}	5.9×10^{-6}
maximum	27.99	1.9×10^{-1}	4.0×10^{-4}
geometric mean	0.33	4.1×10^{-3}	8.3×10^{-6}
standard deviation	1.48	1.52	1.51
distribution	log-normal	log-normal	log-normal

Slug Tests

Results of 11 slug tests (table 4-2) gave the distribution of hydraulic conductivity in the dolomite. Slug tests consisted of instantaneously changing the water level in a

Table 4-2. Results of piezometer slug tests at the Jarman Road site.

Well or Piezometer	K (ft/sec)
<u>Jarman Road</u>	
MW2A	1.6×10^{-4}
MW2B	1.0×10^{-5}
MW2D	4.1×10^{-6}
MW3	4.2×10^{-4}
MW4A	8.1×10^{-8}
MW4B	6.4×10^{-8}
MW5A	6.9×10^{-9}
MW5B	3.3×10^{-7}
MW6A	4.3×10^{-5}
MW6B	5.5×10^{-8}
MW7A	3.6×10^{-3}
Maximum	3.6×10^{-3}
Minimum	6.9×10^{-9}
Geometric Mean	3.1×10^{-6}

well or piezometer by inserting or removing a solid slug of inert material and measuring water-level recovery using a recording datalogger. Slug tests were analyzed by the Hvorslev (1951) and Cooper and others (1967) methods. Hydraulic conductivities ranged from 6.9×10^{-9} ft/sec to 3.6×10^{-3} ft/sec, with a geometric mean of 3.1×10^{-6} ft/sec (table 4-2). The highest hydraulic conductivity, 3.6×10^{-3} ft/sec, was recorded in piezometer MW7A, which is screened across a fracture zone at an elevation of 618 ft above msl (depth 179 ft, see table 2-1). Very low hydraulic conductivities at piezometers MW5A, MW6B, MW4A, and MW4B suggest that these piezometers intersect very few fractures, and these results are probably characteristic of the hydraulic conductivity of unfractured dolomite blocks or massive units with few fractures.

<u>Pumping Tests</u>

Multi-well pumping tests suggested that the shallow and deep parts of the aquifer have different hydraulic properties. One test, on wells finished in the shallow zone, was conducted for 24 hours at a pumping rate of about 0.05 ft^3/sec (22 gpm); a second test, on wells finished in the deep zone, was conducted for 19 hours at a pumping rate of 0.079 ft^3/sec (35 gpm). Drawdowns were measured in adjacent wells and piezometers and in the pumped wells. Table 4-3 summarizes results of these tests. The pumping tests have three important results. First, the transmissivity of the shallow zone is significantly less than the transmissivity of the deeper zone. Second, the ability of the shallow part of the aquifer to sustain a 24-hour pumping test at the rate used is additional evidence that this upper zone contains significant quantities of ground water. Third, the aquifer is significantly anisotropic vertically and horizontally.

An analysis of directional transmissivity using the method of Papadopoulos (1965) yielded the following values for the deep zone:

T_{xx}: 0.15 ft^2/sec; azimuth N33°E
T_{yy}: 0.037 ft^2/sec; azimuth N123°E
Sy: 0.0014

where T_{xx} and T_{yy} are the principal directions of the transmissivity tensor, and by definition are perpendicular to each other. This result is based on only two observation wells, so the transmissivity ellipse cannot be determined uniquely. However, this result is consistent with the assumption that for the Jarman Road site the principal directions of the transmissivity tensor are approximately parallel to the major fracture directions observed in the field. The horizontal anisotropy ratio is then T_{xx}/T_{yy} = 4.2. The ratio of horizontal to vertical conductivity could not be determined with the limited number of observation wells available at the site.

Table 4-3. Results of pumping tests at the Jarman Road site.

Test Zone:	Shallow, 0-60 ft	Deep, 150-240 ft
Date of Test:	March 1988	May 1989
Test Duration:	24 hours	19 hours
Pumped Well:	MW3	MW1
Pumping Rate:	0.05 ft^3/sec (22 gpm)	0.079 ft^3/sec (35 gpm)
Observation Wells:	MW4, MW5, MW2D	MW2A, MW7A
Transmissivity:	$1.1x10^{-3}$ ft^2/sec	$5.9x10^{-2}$ ft^2/sec
Specific Yield:	0.04	0.0014

Groundwater Recharge

All groundwater produced by wells in the study area begins as precipitition within the study area. Groundwater enters the aquifer system by percolating downward from the soil zone to the water table, a process called **groundwater recharge**. Groundwater recharge is only a small part of the area's water budget. The area receives about 30.1 in/yr of precipitation; including both rain and snow. Most of this water (about 20.6 in/yr) either evaporates from the land surface or is transpired by vegetation (Bradbury, 1989). Due to the thin soils and permeable bedrock of the study area runoff is negligible, leaving about 9.5 in/yr (in an average year) for groundwater recharge.

Groundwater recharge does not occur uniformly throughout the year; as a result, groundwater levels fluctuate significantly with the seasons. Figure 4-13 shows precipitation and groundwater levels at piezometer MW2A at the Jarman Road research site from 1987 through 1990. This piezometer is not near any groundwater pumping centers, and water-level fluctuations occur solely in response to groundwater recharge and discharge. Figure 4-13 shows that most recharge at the site occurred during the spring snowmelt periods of 1988, 1989, and 1990.

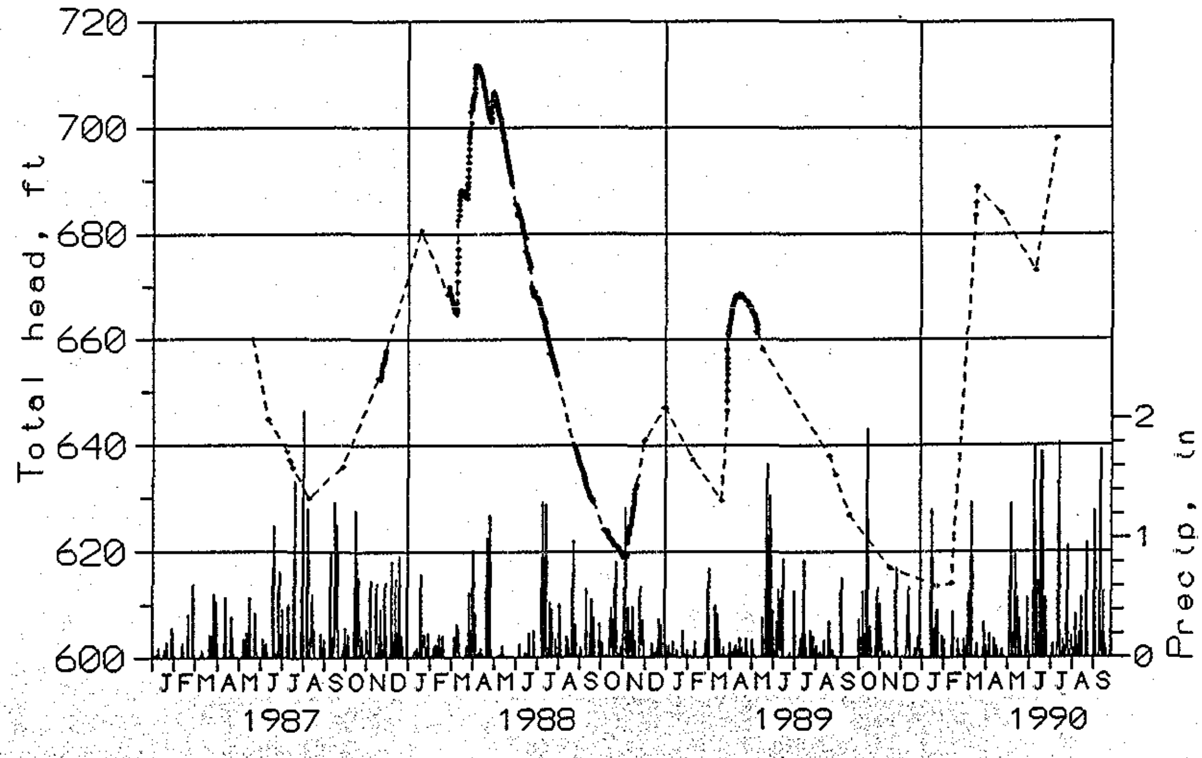


Figure 4-13. Hydrograph of piezometer MW2A from 1987 through 1990. Dark dots represent measurement points.

Table 4-4. Recharge periods during 1988.

Period	Dates	No of days	Precip-itation (in)	Potential evapotrans-piration (in/day)	recharge (in)	recharge rate (in/day)
1	3/7-3/16	8	0.59	0	0.59	0.07
2	3/25-4/6	12	2.17	0	2.17	0.18
3	4/28-5/1	3	1.2	0	1.20	0.4
4	11/5-12/29	46	6.1	0.05	3.85	0.08
Total		69	10.06	--	7.81	--

During 1988, groundwater recharge occurred during only about 69 days of the year, with no significant recharge during the remainder of the year. Figure 4-14, a detailed hydrograph for piezometer MW2A during 1988, shows that significant recharge occurred only during four relatively short periods in 1988. Table 4-4 gives the dates and lengths of these four periods. The climatological data include measurements of depth of snow on the land surface. The snowmelt contribution to precipitation was calculated by assuming that 1 inch of snowmelt equals 0.1 inch of precipitation. Precipitation was calculated from climatological observations recorded at the Sturgeon Bay Experimental Farm and includes all rainfall and snowmelt that occurred during these four periods. The amount of precipitation during these periods is clearly sufficient to account for all the yearly recharge. During these periods, recharge rates are very high.

The high but temporally brief recharge rates in the study area have implications for groundwater and land-use management in central Door County and in similar hydrogeologic environments. Clearly, most groundwater enters the aquifer during several very brief periods of the year, particularly during a spring recharge event following snowmelt. During such periods extra precautions should be taken to protect the quality of recharging groundwater. Later in the growing season little or no recharge occurs even following intense summer storms because of the rapid uptake of soil water by crops.

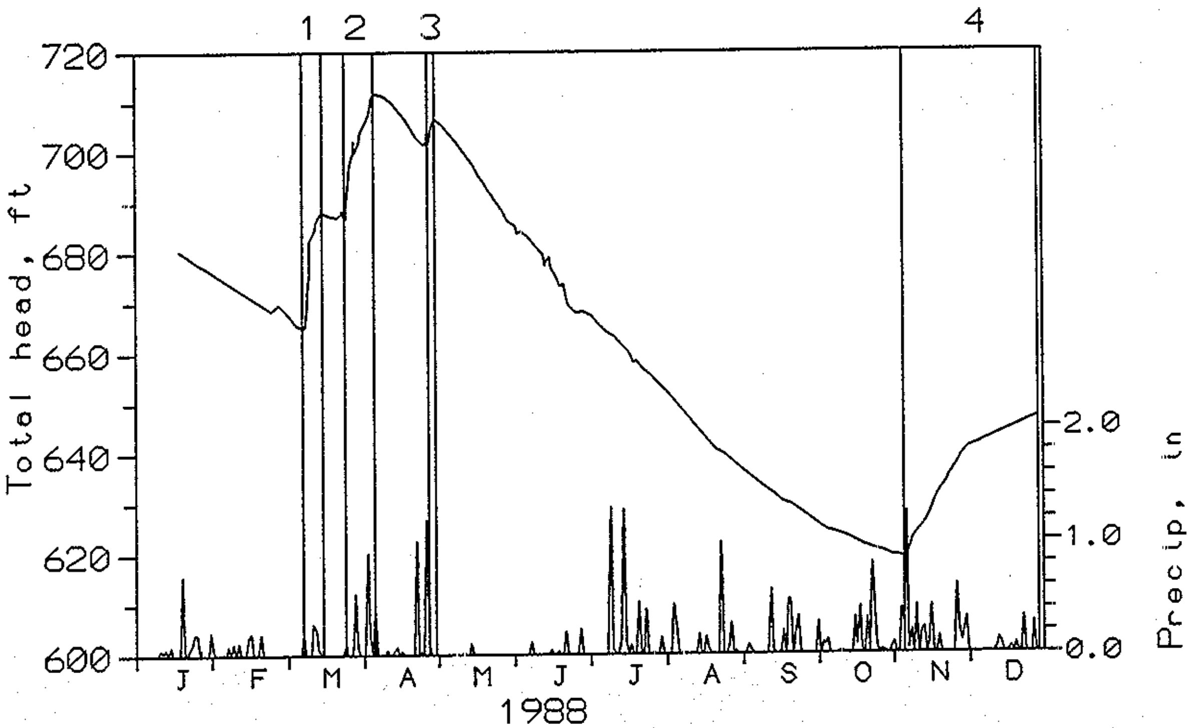


Figure 4-14. Hydrograph for piezometer MW2A during 1988. Number 1-4 indicate recharge periods. See table 4-4 for details.

CHAPTER 5

CONCLUSIONS

A five-year program of water sampling from domestic wells and springs, detailed monitoring of water chemistry and isotopes at two research sites, characterization of aquifer parameters, and detailed mapping of the groundwater flow systems provide new insights into the understanding of groundwater chemistry and groundwater occurrence and movement in the fractured dolomite aquifer of central Door County.

The most important implications of the groundwater sampling results are as follows.

1. Concentrations of chemical constituents used as water quality indicators varied greatly in both space and time during the sampling period, and some parameters frequently exceeded drinking-water quality standards.

2. Although exceedances of water-quality standards occurred in many wells, some wells never exceeded any water-quality standard.

3. Coliform bacteria was the most frequently detected contaminant in the study area, with the average well producing water with a positive coliform detection over 35% of the times it was sampled.

4. Water samples from many wells exceeded the 10 mg/l drinking water standard for nitrate-N.

5. Accurate evaluations of the chemistry of groundwater produced by a given well require multiple samples from that well.

6. Simultaneous variations in parameter concentrations in wells several miles apart suggest that water-quality problems are frequently related more to the regional hydrogeologic setting and land-use practices than to point sources of contamination at individual wells.

7. Statistical analyses of relationships between concentrations of parameters in groundwater and the various land-use factors in the subarea indicate significant correlations between the presence of barnyards, highways, and row crops in the vicinity of a well and the chemistry of water produced by that well. In particular the presence of barnyards near the site of a well (ie on the same or adjacent farmstead) is correlated with significantly higher average nitrate concentrations in water produced by that well. Likewise, the presence of primary highways adjacent to wells is very highly correlated with

elevated chloride and highly correlated with elevated specific conductance and turbidity.

8. The areal distributions of nitrate, chloride, and other parameters suggest that both point and nonpoint source contamination of groundwater are occurring in the subarea. Nonpoint source contamination causes generally elevated levels of nitrate and chloride over broad areas, while point source contamination causes higher concentrations at specific wells.

9. Similarities in monitoring results from domestic wells and research piezometers suggest that the sampling of domestic wells is an adequate method of groundwater monitoring in fractured dolomite terrain.

10. Based on isotopic data, most groundwater in central Door County is less than ten years old.

Detailed characterization of aquifer parameters and flow-system mapping leads to the following conclusions.

1. Numerous vertical and horizontal fractures in the dolomite apparently control the hydraulic conductivity of the aquifer. Slug tests performed at the Jarman Road site in a piezometer completed in a fracture zone at a depth of 150 ft yielded a hydraulic conductivity of 3.6×10^{-3} ft/sec while slug tests on a piezometer that may be completed in an unfractured dolomite block yielded a hydraulic conductivity of 6.9×10^{-9} ft/sec.

2. Long-term water-level measurements from wells and piezometers at the Jarman Road site and at the Highway HH site indicate the presence of distinct shallow and deep flow systems.

3. Significant temporal fluctuations of hydraulic head occur in both the shallow and deep flow systems; head in the deep system fluctuates approximately 90 ft and the shallow system approximately 40 ft in response to seasonal variation in recharge.

4. The dolomite stratigraphy and geologic structure determine the characteristics of the northern Door County flow systems. In the western half of the peninsula minor karst features are present and there are few surface-water features; the eastern half of the peninsula contains numerous surface-water features and a much shallower flow system. The surface and sub-surface occurrence of the Cordell Member of the Manistique Formation roughly parallels the differences in surface-water distribution and flow system geometry on the western and eastern half of the peninsula.

5. Flow rates in central Door County are very rapid; a tracer test at the Jarman Road site indicated a groundwater flow rate of 55 ft/day and a large-scale contamination event suggests flow rates of 210 to 380 ft/day.

6. Groundwater recharge does not occur uniformly throughout the year, rather most recharge occurs during spring snowmelt periods with minor recharge taking place in late fall or early winter.

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APPENDICES

Appendix A. Statistical summary of data from private wells and springs. Column explanations as follows:

Well ID- WGHNS project identification for the sampling site

WUWN- Wisconsin Unique Well Number

DNR code- "y": well meets sanitary codes; "n" well does not meet sanitary codes; "u" well construction unknown; "s": spring

xcoord, ycoord- state plane coordinates of site (in feet)

Monitoring dates- beginning and ending months of sampling at this site

Well ID	WUWN	DNR code	x-coord	y-coord	Monitoring dates	No samples	Cl (mg/l)			NO_3 (mg/l)			Coliform % pos	E. Cond (µmho)			SO_4 (mg/l)			Turbidity (NTU)			K (mg/l)			NH_4 (mg/l)		
							avg	max	min	avg	max	min		avg	max	min	avg	max	min	avg	max	min	avg	max	min	avg	max	min
1 a	EG861	y	685462	397613	Feb-86 May-87	24	6.3	7.6	2.5	2.8	3.9	0.0	15.0	523	628	368				0.4	1.9	0.0						
2 a	EG862	y	690658	393016	Feb-86 May-87	26	23.3	31.6	10.5	8.4	12.5	0.0	36.0	601	719	461	0.0	0.0	0.0	0.4	6.1	0.1						
3 a	EG863	y	690324	396183	Feb-86 May-87	27	29.6	41.0	25.0	11.3	16.3	0.0	84.0	760	852	693	0.0	0.0	0.0	0.3	3.2	0.0						
4 a	EG864	u	695673	390181	Feb-86 May-87	26	29.3	66.4	12.5	6.3	9.3	0.0	91.3	676	896	458				0.5	3.8	0.1						
5 a	EG865	y	679867	405265	Feb-86 Aug-86	16	4.1	4.7	3.0	2.1	2.4	1.6	7.7	478	509	444				0.1	0.4	0.1						
6 a	EG866	u	686508	392381	Feb-86 Mar-87	19	9.7	15.5	1.8	4.7	11.6	1.0	0.0	536	609	449				0.2	1.5	0.0						
7 a	EG867	u	689828	401771	Feb-86 May-87	26	56.8	110.	20.0	13.2	19.4	10.2	85.7	824	1178	538				0.3	1.4	0.1						
8 a	EG868	n	696053	384580	Feb-86 Jun-86	14	6.5	9.6	4.4	1.1	1.5	0.6	0.0	604	636	571				0.1	0.4	0.1						
9 a	EG869	u	720811	440741	Feb-86 Jun-86	13	15.3	18.2	12.8	8.8	9.7	7.3	0.0	621	678	575				0.1	0.4	0.1						
10 a	EG870	y	699632	376681	Feb-86 Oct-86	18	18.2	20.9	16.4	14.3	16.2	11.0	6.7	650	698	620				0.1	1.8	0.0						
11 a	EG871	u	701169	382042	Feb-86 May-87	26	10.3	13.1	7.5	6.4	8.3	4.0	16.7	621	723	553				0.2	0.7	0.0						
12 a	EG872	y	699981	395305	Feb-86 Jun-86	14	4.6	5.4	3.8	2.5	2.9	2.0	0.0	495	528	466				0.2	0.7	0.0						
13 a	EG873	y	706093	404120	Feb-86 May-87	25	9.6	12.1	6.3	2.2	6.3	1.3	19.0	545	594	499				0.5	1.7	0.0						
14 a	EG874	y	702384	397231	Feb-86 Nov-86	17	16.2	21.1	12.8	4.5	5.5	0.2	8.3	556	639	493				0.2	1.0	0.0						
15 a	EG875	n	695463	382787	Feb-86 Jun-86	14	33.7	41.4	24.5	7.6	12.3	4.5	0.0	782	847	677				0.1	0.5	0.1						
16 a	EG876	n	700215	398237	Feb-86 Jun-86	13	10.1	16.0	5.0	8.9	10.7	7.4	0.0	532	604	463				0.1	0.4	0.1						
17 a		y	697904	397892	Feb-86 Apr-86	10	26.2	45.9	14.1	2.6	7.0	1.5	0.0	646	761	529				0.2	0.7	0.1						
17 b	EG877	y	697904	397892	May-86 May-87	15	51.9	71.4	12.2	3.7	8.4	0.3	54.5	731	1002	460				1.9	14.	0.1						
18 a	EG878	y	704537	398489	Feb-86 May-87	25	10.2	12.1	9.1	3.1	3.8	1.3	13.0	530	567	504				0.3	3.1	0.0						
19 a	EG879	u	710830	420204	Feb-86 Jun-86	14	1.5	3.4	0.5	0.9	3.5	0.1	35.7	422	513	313				0.3	1.3	0.1						
20 a	EG880	n	696653	408851	Feb-86 Jul-90	99	47.2	78.6	23.1	13.6	28.7	1.8	89.4	823	1093	537	43.	72.	25.4	0.4	8.2	0.0	20.	58.	1.4	0.1	0.8	0.0
21 a	EG881	y	713775	399051	Feb-86 Jun-86	14	5.0	6.4	3.6	0.6	0.9	0.2	0.0	462	516	422				0.3	0.8	0.1						
22 a	EG882	u	711817	393513	Feb-86 May-87	25	7.5	18.2	3.4	1.7	6.5	0.3	21.7	463	593	313				0.5	1.6	0.1						
23 a	EG883	u	706547	393752	Feb-86 Apr-87	24	6.4	26.6	2.8	0.9	4.6	0.0	27.3	469	630	395				0.3	6.0	0.1						
24 a	EG884	u	700815	392543	Feb-86 Apr-87	21	15.4	23.4	6.7	10.3	14.6	6.1	35.0	686	793	557				0.3	4.4	0.0						
25 a	EG885	u	689732	405675	Feb-86 May-87	27	47.2	69.6	17.2	7.8	11.9	5.4	21.7	801	944	628				0.6	2.1	0.1						
26 a		u	695182	406296	Feb-86 Jun-87	44	58.9	83.8	23.0	24.0	42.9	17.5	39.0	104	1169	789	44.	51.	38.8	0.4	5.7	0.0	23.	48.	2.8			

Well ID	WUWN	DNR code	x-coord	y-coord	Monitoring dates	No samples	Cl (mg/l)			NO_3 (mg/l)			Coliform % pos	E. Cond (μmho)			SO_4 (mg/l)			Turbidity (NTU)			K (mg/l)			NH_4 (mg/l)		
							avg	max	min	avg	max	min		avg	max	min	avg	max	min	avg	max	min	avg	max	min	avg	max	min
26 b	EG886	y	695182	406296	Jun-87 Jul-90	49	18.1	53.2	14.4	8.5	23.9	1.0	43.5	606	1028	461	25.	72.	18.3	0.2	1.6	0.0	1.7	3.1	0.3	0.0	0.2	0.0
27 a	EG887	y	698850	403405	Feb-86 Jun-86	14	10.7	12.8	9.0	8.1	10.2	7.1	42.9	539	623	503				0.1	0.4	0.0						
28 a	BJ433	u	696510	382149	Feb-86 Nov-88	37	19.9	36.6	14.0	1.9	25.3	0.0	88.2	621	778	504	47.	73.	10.2	0.4	1.9	0.1	10.	12.	3.0	0.7	3.0	0.1
29 a	EG888	y	705167	405735	Feb-86 May-87	25	24.4	66.3	18.2	7.8	8.9	6.4	27.3	635	693	579				0.3	2.5	0.0						
30 a	EG889	u	718557	425575	Feb-86 Jun-86	14	2.5	4.1	1.9	0.1	0.2	0.0	0.0	441	525	416				0.3	0.8	0.1						
31 a	BJ534	y	722372	441041	Feb-86 Jun-86	12	5.3	6.7	3.9	1.0	1.3	0.8	10.0	469	508	371				0.2	0.8	0.0						
32 a	EG890	u	712757	440881	Feb-86 Jun-86	13	12.2	21.0	3.3	7.7	9.8	5.6	61.5	608	673	395				0.2	0.5	0.0						
33 a	EG891	u	713250	428055	Feb-86 Jun-86	12	7.1	11.4	3.8	2.5	3.7	1.2	40.0	503	590	417				0.2	1.9	0.0						
34 a	EG892	u	721603	447030	Feb-86 May-86	12	3.8	5.4	2.6	3.4	5.6	2.4	66.7	510	593	436				0.1	0.3	0.0						
35 a	EG893	y	695170	399030	Feb-86 May-87	25	9.4	11.6	7.2	5.0	11.2	0.3	22.7	531	589	493				0.4	1.5	0.1						
36 a	EG894	y	713695	407126	Feb-86 Jun-86	13	3.6	4.9	2.3	0.6	0.9	0.2	25.0	452	479	436				0.1	0.3	0.0						
37 a	EG895	y	713945	411347	Feb-86 Jun-86	12	2.9	4.5	2.4	0.0	0.0	0.0	0.0	448	482	414				18.	35.	4.2						
38 a	EG896	u	703730	408801	Feb-86 May-87	26	35.9	63.6	22.0	9.3	13.9	5.2	52.2	844	1014	701				0.2	0.7	0.0						
39 a	EG897	n	693461	433187	Feb-86 Jun-86	13	8.5	12.1	4.6	3.8	6.2	2.2	15.4	528	615	394				0.2	0.7	0.0						
40 a	EG898	y	691207	433686	Feb-86 Jun-86	14	2.0	4.0	1.3	0.1	0.5	0.0	0.0	494	522	473				0.7	2.1	0.1						
41 a	EG899	y	694096	438256	Feb-86 Jun-86	13	1.2	2.8	0.7	0.0	0.1	0.0	38.5	439	554	414				3.1	8.3	0.3						
42 a	EG900	n	693917	435217	Feb-86 Jun-86	12	6.8	9.0	4.8	2.4	3.2	1.6	0.0	517	590	436				1.9	7.8	0.2						
43 a	EG901	n	696724	395493	Feb-86 Mar-87	23	7.0	10.2	4.6	4.4	8.7	2.3	46.7	549	613	493				0.2	1.9	0.0						
44 a	EG902	n	716343	404109	Feb-86 Jun-86	11	1.0	1.7	0.4	0.0	0.1	0.0	9.1	420	444	389				0.8	2.8	0.2						
45 a	EG903	u	713841	413469	Feb-86 Jun-86	11	15.1	38.0	2.3	2.0	3.1	0.3	20.0	499	560	426				0.1	0.5	0.0						
46 a	EG904	s	706918	393483	Feb-86 May-87	23	14.8	22.8	5.0	3.4	7.3	0.1	66.7	589	785	424				0.4	15.	0.0						
47 a	EG905	s	705373	406058	Feb-86 May-87	23	29.1	149.	8.4	6.0	8.3	0.0	84.0	629	831	557				0.4	66.	0.0						
48 a	EG906	s	713178	406663	Feb-86 Jun-86	13	10.9	14.6	8.6	7.1	10.9	0.5	84.6	530	630	296				0.8	13.	0.0						
49 a	EG907	s	719999	422236	Feb-86 Jun-86	13	5.5	7.2	3.4	1.8	2.7	1.3	83.3	463	526	384				4.8	98.	0.1						
50 a	EG908	s	679260	416731	Feb-86 Jun-86	13	11.2	15.0	9.9	4.7	5.1	4.2	69.2	549	664	506				0.3	11.	0.0						
51 a	EG909	y	689870	413509	Jul-86 Mar-87	10	7.5	8.0	6.6	2.3	2.6	1.9	28.6	487	519	447	15.	16.	14.7	0.4	2.3	0.1						
52 a	EG910	u	695859	413998	Jul-86 Jul-90	68	16.1	28.5	9.4	6.5	57.4	1.6	73.4	621	893	431	47.	129	12.7	0.6	3.4	0.0	5.5	8.8	1.9	0.0	0.2	0.0
53 a		u	701554	414655	Jul-86 May-87	12	16.6	23.7	12.5	4.0	7.0	2.1	70.0	608	737	562	30.	35.	27.7	1.0	3.4	0.3						
54 a	EG951	y	689730	409138	Jul-86 Jul-90	75	12.3	17.5	10.6	6.8	10.8	2.3	29.0	546	745	402	19.	27.	13.8	0.4	2.8	0.0	0.7	1.9	0.2	0.0	0.2	0.0
55 a	EG952	u	694601	410354	Jul-86 May-88	58	12.5	17.4	4.2	7.6	14.1	2.8	38.6	578	713	388	22.	28.	18.2	1.0	15.	0.0	5.7	17.	1.5	0.1	0.2	0.0
56 a	BJ446	n	697666	412184	Jul-86 Jul-90	88	22.7	36.7	12.5	6.7	12.4	2.1	38.6	637	810	424	26.	35.	18.2	0.4	5.8	0.0	7.1	14.	1.7	0.0	0.2	0.0
57 a	EG953	u	700809	402268	Jul-86 May-87	12	11.0	12.0	8.7	6.5	7.4	4.8	0.0	534	546	526	22.	23.	20.8	0.4	1.3	0.1						
58 a	EG954	n	702492	395483	Jul-86 May-87	13	15.7	19.2	11.8	2.1	6.9	1.3	30.0	690	768	435	45.	69.	23.8	0.4	1.0	0.1						
59 a	EG955	u	704962	396798	Jul-86 May-87	12	9.5	11.7	7.3	2.1	4.0	0.8	18.2	585	685	410	29.	34.	25.4	0.6	1.5	0.0						
60 a	EG956	u	688577	397451	Jul-86 May-87	10	119.	204.	52.8	37.8	72.0	16.9	55.6	130	1621	927	84.	106	69.9	0.5	1.2	0.2						
61 a	EG957	u	698103	408423	Jul-86 Jul-90	79	23.9	50.2	12.8	8.7	23.2	2.0	67.1	636	832	421	27.	41.	16.8	0.4	21.	0.0	3.2	9.2	0.8	0.1	0.7	0.0
62 a	EG958	n	689505	408600	Jul-86 Apr-87	12	55.9	109.	19.1	9.7	12.7	3.6	50.0	802	958	571	22.	24.	21.7	1.0	52.	0.0	6.1	6.1	6.1			
63 b	EG959	y	694922	405249	Jul-86 Jul-90	87	23.9	45.9	15.5	14.1	28.0	5.3	75.7	692	854	562	24.	35.	17.8	0.5	6.5	0.0	7.0	16.	1.7	0.1	0.4	0.0
64 a	EG960	y	695921	401784	Jul-86 Jul-90	88	6.2	23.2	3.0	4.4	13.6	0.9	21.4	538	682	400	20.	29.	15.0	0.3	1.4	0.0	1.0	1.9	0.1	0.0	0.2	0.0
65 a	EG961	n	698950	398185	Jul-86 May-87	13	24.0	32.0	19.1	15.3	17.6	12.6	60.0	706	757	648	27.	32.	22.0	0.4	1.5	0.0						
66 a	EG962	n	696060	419066	Oct-86 Jul-90	86	16.2	30.8	11.7	8.4	20.8	3.6	33.3	599	754	443	26.	38.	17.8	0.3	1.3	0.0	8.1	19.	0.6	0.0	0.7	0.0
67 a	AP068	u	694571	416551	Oct-86 Jul-90	85	21.4	45.7	7.4	13.9	267.	2.4	51.8	932	2380	421	27.	45.	20.5	0.3	2.6	0.0	2.9	11.	0.1	0.0	0.2	0.0
68 a	AP069	y	694971	404787	Mar-87 Jul-90	61	6.9	26.6	4.1	4.7	14.4	1.7	8.2	637	7920	434	19.	26.	12.9	0.3	3.5	0.0	0.4	1.5	0.0	0.0	0.2	0.0
69 a	AP070	u	694874	406930	Mar-87 Jul-90	58	25.7	44.2	6.6	12.1	17.0	3.9	76.8	646	772	346	27.	40.	19.1	0.3	7.3	0.0	3.9	6.4	1.0	0.0	1.2	0.0
70 a	AP071	u	691405	413655	Mar-87 Jul-90	62	5.8	24.7	2.6	2.7	13.6	0.5	11.3	462	569	354	11.	18.	4.7	0.4	2.0	0.0	0.5	1.7	0.0	0.		0.0

APPENDIX B
WELL LOGS

WISCONSIN GEOLOGICAL and NATURAL HISTORY SURVEY
3817 Mineral Point Road • Madison, WI 53705

Log No. R17-Dr-342

Well name	Maple Woods Monitoring Well #4 Town of Sevastopol	County:	Door
Owner	Wis. Geological & Natural History Survey	Completed	3/16/87
Address	3817 Mineral Point Rd Madison, WI 53705	Field check	WG&NHS-M. Blanchard
Driller	Erwin Jorns & Sons	Altitude	
Engineer		Use	Monitoring
		Static w.l.	44.72'
		Spec. cap.	

R. 26 E.
T. 28 N.
Sec. 2

Quad. Institute 7½'

Drill Hole						Casing & Liner Pipe or Curbing							
Dia.	from	to	Dia.	from	to	Dia.	Wgt.& Kind	from	to	Dia.	Wgt.& Kind	from	to
10" 6"	0 10'	10' 40'				6"	steel	+0.6'	10'				

Drilling method: air rotary
Samples from 2" to 40' Rec'd: 3/16/87 (2"-10')
4/20/87 (10'-40')

Grout	from	to
Cement	0	10'

Studied by: Kathleen Massie-Ferch

Issued: 5/13/87

Formations: Surface, Silurian Undifferentiated.

Remarks:

LOG OF WELL:

	Depths	Graphic Section	Rock Type	Color	Grain Size Mode	Grain Size Range	Miscellaneous Characteristics
2" Sfc.	0-2'		NO SAMPLE. Driller reports soil.				
S	2"-10'		Dolomite	V pl brown	M	Fn/M	Limy. Trace soil, calcite, limonite staining, limonite.
I	10-15		"	Lt gy to gy	"	"	Trace limonite staining, calcite, pyrite, dark gray shale partings
L	15-20		"	"	"	"	Same plus trace stylolites, dark gray staining.
	20-25		"	Lt bn gray	"	"	Tr dk gy stng, pyr, fos molds/frags, dk bn sh prtgs, calc, lim, lim stng.
	25-30		"	"	"	"	Same plus trace white chert.
	30-35		"	"	"	"	Same.
39'10"	35-40		"	"	"	"	Limy. Little white fossiliferous chert. Trace fossil molds/fragments, dark brown shale partings, pyrite, limonite, limonite staining, calcite.
				END OF LOG			

UNIVERSITY OF WISCONSIN GEOLOGICAL & NATURAL HISTORY SURVEY
3817 Mineral Point Rd., Madison, Wisconsin 53705

Geologic Log No. R14-Dr-339

Well name	Maple Woods Monitoring Well #1 Town of Sevastopol	County:	Door
Owner	Wis. Geological & Natural History Survey	Completed	3/5/87
Address	3817 Mineral Point Rd Madison, WI 53705	Field check	WG&NHS-M. Blanchard
Driller	Erwin Jorns & Sons	Altitude	796.2' (rod & level)
Engineer		Use	Monitoring
		Static w.l.	145'
		Spec cap	

R.26 E. T. 28 N. Sec. 2

Location: SE¼,NE¼,SW¼,NW¼,NW¼,NW¼,SE¼,Sec. 2, T28N, R26E Quad. Institute 7½'

Drill Hole						Casing & Liner Pipe or Curbing							
Dia.	from	to	Dia.	from	to	Dia.	Wgt.& Kind	from	to	Dia.	Wgt.& Kind	from	to
10"	0	40'	6"	40'	242'	6"	steel	+2.0'	40'				

Drilling method: air rotary
Samples from 0 to 242' Rec'd: 3/16/87

Grout	from	to
cement	0	40'

Studied by: Kathleen Massie-Ferch

Issued: 5/13/87
Updated: 3/20/89

Formations: Surface, Silurian Undifferentiated

Remarks: Borehole was televised for WG&NHS.
No instrumentation was installed in this well.
Well drilled on land owned by Milton J. Staats
5706 County View Rd.
Sturgeon Bay, WI 54235

LOG OF WELL:

	Depths	Graphic Section	Rock Type	Color	Grain Size Mode	Grain Size Range	Miscellaneous Characteristics
1' Sfc.	0-1		Soil & clay	Dk bn & dk yl bn	—	—	Siliceous(clay). Much gravel(Gran/M peb),sand,silt. / dol.
	1-6		Dolomite	Wh to v pl yl	M	Fn/M	1'-4':Tr vugs,lim stng,drsy dol. 4'-6':Tr vugs,lim,cvd mat,drsv
	6-12		"	"	"	"	6'-10':Limy. Tr vugs,lim,drsy dol,cvd mat. 10'-12':Same as 6'-
S	12-14		"	"	"	"	Limy. Ltl lim stng. Few vugs. Tr drsy dol,cvd mat. \ 10' but ltl
I	14-15		"	V pl brown	"	"	Limy. Tr dk yl bn sh prtgs,vugs,lim stng,cvd mat. \ cvd mat.
L	15-18		"	"	"	"	Limy. Tr lim stng,dk gy stng,pyr,vugs,dk yl bn sh prtgs,cvd mat
U	18-20		"	Light gray	"	"	Limy. Tr dk gy sh prtg/mot,lim stng,gy stng,pyr,cvd mat. / glauc.
R	20-24		"	"	"	"	Tr dk gy sh prtg/mot,pyr,gy stng,calc xls. / pyr,calc,mssv
I	24-26		"	Lt gy to lt bn	"	"	Limy. Few fos molds/frags. Tr dk bn sh prtgs,dk gy sh prtgs/mot,
	26-30		"	"	"	"	Same but tr fossils,plus tr wh chert,minus massive glauconite.
A	30-32		"	Lt bn gray	"	"	Limy. Tr dk bn shale prtgs,fossil frags(w/shale),pyrite,stylo.
N	32-36		"	Lt gy bn	"	"	32'-34':Same. 34'-36':Same as 32'-34' plus tr wh fossif chert.
	36-38		"	"	"	"	Ltl wh cht w/tr fos. Tr fos frags,dk bn sh prtgs,pyr,drsy qtz,
	38-40		"	"	"	"	Same but little limonite staining. \ calc,
	40-45		"	Pale brown	"	"	Samp pulv. Mch wh to lt gy fossif cht. Tr fos frags,dk bn sh
	45-55		"	"	"	"	Same but sample not pulverized. \ prtgs,pyr,drsy qtz,calc.
	55-60		"	"	"	"	Tr wh fossif chert,dk bn sh prtgs,fos frags,pyr,drsy qtz,calc
	60-70		"	"	"	"	Same but little chert.
	70-75		"	"	"	"	Tr wh fossif chert,dk bn shale prtgs,pyrite,calc,fossil frags
U	75-80		"	"	"	"	Same.
N	80-85		"	"	"	"	Same but little white chert.
D	85-90		"	"	"	"	Same plus trace dolomite crystals,drusy quartz.
I	90-95		"	"	"	"	Mch wh to tn fossif cht. Tr dk bn sh prtgs,pyr,fos frags,calc,
F	95-100		"	"	"	"	Same. \ lim stng.
	100-105		"	"	"	"	Same but little white to tan chert,plus trace drusy quartz
F.	105-110		"	"	"	"	Same.
	110-115		"	"	"	"	Slgtly limy. Tr wh fossif cht,fos molds & frags,lim stng,dk bn
	115-120		"	"	"	"	Same. \ sh prtgs,drsy qtz,calc
	120-125		"	"	"	"	Same plus trace dark gray staining.
	125-130		"	"	"	"	Same.
	130-135		"	Pl bn&lt gy	"	"	Limy. Tr wh cht,dk bn sh prtgs,lim stng,dk gy stng,pyr,fos
	135-140		"	V pl brown	"	"	Limy. Tr wh cht,dk bn sh prtgs,lim stng. \ frags,calc

WISCONSIN GEOLOGICAL and NATURAL HISTORY SURVEY
3817 Mineral Point Road • Madison, WI 53705

Well name: Maple Woods Monitoring Well #1

	Depths	Graphic Section	Rock Type	Color	Grain Size Mode	Grain Size Range	Miscellaneous Characteristics
S	140-145		Dolomite	Pale brown	M	Fn/M	Limy. Trace wh fossif chert,dk bn shale partings,limonite stng.
I	145-150		"	V pl brown	"	"	Limy. Trace brown shale partings,pyrite,limonite staining.
L	150-155		"	Pale brown	"	"	Same.
I	155-160		"	V pl brown	"	"	Limy. Mch wh cht w/tr fos frags. Tr pyr,bn sh prtgs,drsy qtz.
U	160-165		"	"	"	"	Limy. Trace wh chert,pyrite,bn shale partings,dk gy staining.
R	165-170		"	"	"	"	Same plus trace calcite.
I	170-175		"	"	"	"	Same.
	175-180		"	Pale brown	"	"	"
A	180-185		"	"	"	"	Sug & limy. Few vugs. Tr dk bn shale prtgs,wh chert,calc,pyr.
N	185-190		"	"	"	"	Same.
	190-195		"	Lt gy bn to pl bn	"	"	The pl bn is sug aa. Tr dk bn sh prtgs,pyr,dk gy stng,calc,drsy qtz.
	195-200		"	Lt gy to gy	"	"	Trace gn gy shale partings,pyrite,dk gy staining.
U	200-205		"	"	"	"	Trace dark gray shale partings,dark gray staining,pyrite.
N	205-210		"	Lt gy bn	"	"	Tr dk gy & dk bn shale prtgs,dk gy staining,pyrite,stylolite.
D	210-215		"	Light gray	"	"	Trace dark gray shale partings,dark gray staining,pyrite.
I	215-220		"	"	"	"	Same.
F	220-225		"	Lt gy bn to pl bn	"	"	Trace dark bn shale partings,dark gy staining,pyrite,calcite.
F	225-230	G	"	Lt gy to v pl bn	"	"	Tr dk bn & dk gy shale prtgs,dk gy staining,pyrite,mssv glauc.
.	230-235	G	"	Lt gy&pl bn	"	"	Same but limy(especially gray).
	235-240		"	Light gray	Fn	"	Limy. Tr pyr,calc,dk gy stng,lt bn vl dol,dk gy shale prtgs.
241'	240-242		"	Gray	"	"	Limy. Trace pyrite,dark gray staining,dark gray shale partings.
				END OF	LOG		
			Duplicate	Sample.			
	40-40.5		Dolomite	Pale brown	M	Fn/M	Much white to light gray fossiliferous chert. Trace fossil fragments,dark brown shale partings,pyrite,drusy quartz, calcite.

WISCONSIN GEOLOGICAL and NATURAL HISTORY SURVEY
3817 Mineral Point Road • Madison, WI 53705

Log No. R16-Dr-341

Well name: Maple Woods Monitoring Well #3
Town of Sevastopol
Owner: Wis. Geological & Natural History Survey
Address: 3817 Mineral Point Rd.
Madison, WI 53705
Driller: Erwin Jorns & Sons
Engineer:

County: Door
Completed: 8/14/87
Field check: WG&NHS-M. Blanchard
Altitude:
Use: Monitoring
Static w.l.: 27.25'
Spec. cap.:

R. 26E.
T. 28 N.
Sec. 2

Quad. Institute 7½'

Drill Hole						Casing & Liner Pipe or Curbing							
Dia.	from	to	Dia.	from	to	Dia.	Wgt.& Kind	from	to	Dia.	Wgt.& Kind	from	to
10"	0	10.5'				6"	steel	+0.8'	10.5'				
6"	10.5'	64'											

Drilling method: air rotary
Samples from 0 to 64' Rec'd: 3/16/87

Studied by: Kathleen Massie-Ferch

Grout	from	to
cement	0	10.5'

Issued: 5/13/87

Formations: Surface, Silurian Undifferentiated

Remarks:

LOG OF WELL:

	Depths	Graphic Section	Rock Type	Color	Grain Size Mode	Grain Size Range	Miscellaneous Characteristics
2' Sfc.	0-2		Soil	Dk strg bn	—	—	Mch sand,silt,clay. Ltl v dk bn soil,gravel(Gran/M peb),org.
SILURIAN	2-5		Dolomite	V pl brown	M	Fn/M	Limy. Little soil. Trace calcite,limonite staining.
	5-10		"	Lt bn gray	"	"	Limy. Trace limonite,limonite staining,caved soil.
	10-15		"	Light gray	"	"	Limy. Tr limonite staining,dk gy staining,neat cement,pyrite.
	15-20		"	"	"	"	Limy. Tr limonite,limonite stng,dk gy staining,pyrite,calcite.
	20-25		"	Gray brown	"	"	Limy. Tr fossil frags,dk bn shale/prtgs,pyrite,limonite,calcite.
	25-30		"	Brown	"	"	Same.
	30-35		"	Gray brown	"	"	Same plus trace white fossif chert. / pyr,calc,lim stng.
	35-40		"	Bn & gy bn	"	"	Limy. Ltl wh to lt gy fossif cht. Tr fos frags,dk bn sh prtgs,
	40-45		"	Lt bn gray	"	"	Limy. Mch wh to lt gy fossif cht. Tr fos frags,dk bn sh prtgs,
	45-50		"	"	"	"	Same but little chert. \ pyr,calc,lim stng,drsy qtz.
	50-55		"	"	"	"	Same.
	55-60		"	"	"	"	Same but much chert.
62'	60-64		"	"	"	"	Same.

END OF LOG

WISCONSIN GEOLOGICAL and NATURAL HISTORY SURVEY
3817 Mineral Point Road • Madison, WI 53705

Geologic Log No. R28-Dr-343

Well name Maple Woods Monitoring Well #5
Town of Sevastopol
Owner..... Wis. Geological & Natural History Survey
Address... 3817 Mineral Point Rd.
Madison, WI 53705
Driller.. Erwin Jorns & Sons
Engineer.

County: Door
Completed.... 3/18/87
Field check. WG&NHS-M. Blanchard
Altitude..... 795.25' (rod & level)
Use.......... Monitoring
Static w.l... 25.42'
Spec. cap....

R. 26 E.
T. 28 N.
Sec. 2

Location: NE¼, SE¼, SW¼, NW¼, NW¼, NW¼, SE¼, Sec. 2, T28N, R26E   Quad. Institute 7½'

Drill Hole						Casing & Liner Pipe or Curbing							
Dia.	from	to	Dia.	from	to	Dia.	Wgt.& Kind	from	to	Dia.	Wgt.& Kind	from	to
10" 6"	0 10'	10' 24'				6"	Steel	+1.5'	10'				

Drilling method: air rotary
Samples from 0 to 24' Rec'd: 3/23/87

Studied by: Kathleen Massie-Ferch

Grout	from	to
Cement	0	10'

Issued: 5/13/87
Updated: 3/20/89

Formations: Silurian Undifferentiated

Remarks: Three 1¼" PVC piezometers installed in this well. For further information contact Wis. Geological & Natural History Survey.
Well was constructed on land owned by Milton J. Staats
5706 Country View Rd.
Sturgeon Bay, WI 54235

LOG OF WELL:

	Depths	Graphic Section	Rock Type	Color	Grain Size Mode	Grain Size Range	Miscellaneous Characteristics
S	0-5		Dolomite	V pl brown	M	Fn/M	Limy. Trace yellow staining, pyrite, soil, limonite, calcite.
I	5-10		"	Light gray	"	"	Limy. Tr limonite staining, limonite, pyrite, calcite, caved soil.
L.	10-15		"	V pl bn to gy	"	"	Limy. Tr lim stng, lim, pyrite, calc, dk bn shale prtgs, dk gy stng.
	15-20		"	"	"	"	Same plus trace dark gray shale partings.
24'	20-24		"	Gy to gy bn	"	"	Trace dark brown & dark gray shale partings, fossil fragments, pyrite, calcite.
				END OF LOG			

WISCONSIN GEOLOGICAL and NATURAL HISTORY SURVEY
3817 Mineral Point Road · Madison, WI 53705

Geologic Log No. S75-DR-361

Well name Maple Woods Monitoring Well #6
Town of Sevastopol
Owner .... Wis. Geological & Natural History Survey
Address .. 3817 Mineral Point Rd.
Madison, WI 53705
Driller ... Jorns Well Drilling, Inc.
Engineer .

County: Door
Completed ... 6/21/88
Field check . MAM-WG&NHS
Altitude ..... 794' (rod & level)
Use .... monitoring
Static w.l .
Spec. cap ...

R. 26 E.
T. 28 N.
Sec. 2

Location: NW corner, SW¼,SW¼,NW¼,NW¼,NW¼,SE¼,Sec. 2,T28N, R26E   Quad. Institute 7½'

Drill Hole						Casing & Liner Pipe or Curbing							
Dia.	from	to	Dia.	from	to	Dia.	Wgt. & Kind	from	to	Dia.	Wgt. & Kind	from	to
8" 6"	0 10'	10' 60'				6"	Standard wt. bk. stl. csg. New P.E. ASTM-A-53 Wt./ft. 18.97	+1'	10'				

Drilling method: rotary
Samples from 0 to 60'   Rec'd: 7/7/88

Grout	from	to
Neat cement	0	60'

Studied by: Kathleen Massie-Ferch

Published: 4/3/89

Formations: Silurian Undifferentiated.

Remarks: Borehole was televised for WG&NHS.
Three 2" PVC piezometers were installed in this well. For further information contact Wis. Geological & Natural History Survey.
Borehole was constructed on land owned by Milton J. Staats, 5706 Country View Rd. Sturgeon Bay, WI 54235

LOG OF WELL:

	Depths	Graphic Section	Rock Type	Color	Grain Size Mode	Grain Size Range	Miscellaneous Characteristics
S	0-5		Dolomite	V pl brown	M	Fn/M	Ltl bn uncons clay. Tr vugs,dol xtls,lim,limonite staining.
I	5-15		"	"	"	"	Tr vugs,dol xtls,lim,lim staining,caved brown clay.
L	15-18		"	"	"	"	Tr vugs,dol xtls,lim,lim staining,pyrite,dark grey staining.
U	18-20		"	V pl bn to lt gy	"	"	Ltl dk gy stng. Tr dol xtls,lim,lim stng,pyr,dk bn sh prtgs,dk
R	20-25		"	Gy & dk gy bn	"	"	Tr fos frags,dk gy stng,dol xtls,lim,lim stng,pyr, \gy sh prtgs.
I	25-30		"	Gy to gy bn	"	"	Same plus tr wh fossif cht,drsy qtz.\dk bn sh prtgs,dk gy sh
A	30-35		"	Brown	"	"	Tr fos frags,dol xtls,pyr,dk bn sh prtgs,wh fossif cht, \prtgs.
N	35-40		"	Pale brown	"	"	Mch wh fossif cht. Ltl lt yl bn dol. Tr fos frags,dol\drsy qtz.
	40-45		"	"	"	"	Same.\xtls,pyrite,dark brown shale partings,drusy quartz.
	45-50		"	"	"	"	Mch wh fossif cht. Tr fos frags,dol xtls,pyr,dk bn sh prtgs,
	50-55		"	Pl yl & bn	"	"	Same plus tr lim,lim staining. \drusy quartz
60'	55-60		"	Brown	"	"	Mch wh fossif cht. Tr fossil frags,dol xtls,pyrite,dk brown
							\shale partings,drusy quartz,limonite,limonite staining.
				END OF LOG			
			Unwashed duplicate sample.				
	10-15		Dolomite	V pale brown	M	Fn/M	Trace vugs,dolomite crystals,limonite,limonite staining,caved
							\ brown clay.

UNIVERSITY OF WISCONSIN GEOLOGICAL & NATURAL HISTORY SURVEY
3817 Mineral Point Rd., Madison, Wisconsin 53705

Geologic Log No. S80-DR-36

Well name Maple Woods Monitoring Well #7
Town of Sevastopol
Owner Wis. Geological & Natural History Survey
Address 3817 Mineral Point Rd.
Madison, WI 53705
Driller Jorns Well Drilling, Inc.
Engineer

County: Door
Completed 6/21/88
Field check MAM-WG&NHS
Altitude 796.5' (rod & level)
Use monitoring
Static w.l. 121' (6/21/88)
Spec. cap.

R. 26 E.
T. 28 N.
Sec. 2

Location: NE corner, NW¼, NE¼, SW¼, NW¼, NW¼, SE¼, Sec. 2, T28N, R26E   Quad. Institute 7½'

Drill Hole						Casing & Liner Pipe or Curbing							
Dia.	from	to	Dia.	from	to	Dia.	Wgt. & Kind	from	to	Dia.	Wgt. & Kind	from	to
8"	0	20'				6"	Standard wt. bk. stl. csg New P.E. ASTM-A-53 Wt./ft. 18.97	+1'	20'				
6"	20'	200'											

Drilling method: air rotary
Samples from 0 to 200'   Rec'd: 7/7/88

Grout	from	to
Neat cement	0	20'

Studied by: Kathleen Massie-Ferch
Formations: Silurian Undifferentiated
Published: 5/22/89
Remarks: Field geologist noted that larger pieces of dolomite from 150'-160' exhibited fine laminae of pale brown alternating with yellow.
Borehole was televised for WG&NHS.
Two 2" piezometers and one 1¼" piezometer were installed in this well.
Well drilled on land owned by Milton J. Staats
5706 County View Rd.
Sturgeon Bay, WI 54235

LOG OF WELL:

	Depths	Graphic Section	Rock Type	Color	Grain Size Mode	Grain Size Range	Miscellaneous Characteristics
SILURIAN	0-10		Dolomite	White	M	Fn/M	Tr lim, lim staining, vugs, dolomite crystals, unconsolidated clay.
	10-20		"	V ol brown	"	"	Ltl gy dolomite. Tr lim, lim staining, vugs, dol xtls, hematite.
	20-30	G	"	Lt gy & ol bn	"	"	Ltl dk gy stng. Tr mssv glauc, fos frags, pyr, dk bn sh prtgs, dk gy shale prtgs, lim, lim stng, pyrolusite.
	30-40		"	Gy brown	"	"	Tr wh chert, fossil frags, dk bn shale partings, pyrite, limonite.
	40-50		"	Gy bn & bn yl	"	"	Mch wh cht (some fossif), bn yl dol. Tr fos frags, dk bn sh prtgs, pyrite, drusy quartz, limonite.
	50-60		"	Pl brown	"	"	Ltl wh fossif cht. Tr bn yl dol, fos frags, dk bn sh prtgs, pyrite, limonite, dolomite crystals.
UNDIFFERENTIATED	60-70		"	Pl bn to bn	"	"	Same minus brown yellow dolomite.
	70-80		"	Pl brown	"	"	Mch wh fossif cht. Tr fos frags, dk bn shale prtgs, pyr, lim, dol crystals.
	80-90		"	"	"	"	Same but little white fossiliferous chert.
	90-100		"	Pl bn to bn	"	"	Same but much white fossiliferous chert.
	100-110		"	"	"	"	Same.
	110-120		"	"	"	"	"
	120-130		"	Pl brown	"	"	Tr wh fossif cht, fos frags, dk bn shale prtgs, dol xtls, pyrite.
	130-140		"	"	"	"	Same plus trace immature ooliths.
	140-150		"	"	"	"	Tr wh fossif cht, fos frags, dk bn sh prtgs, dol xtls, pyr, lim, dk grey staining.
	150-160		"	V ol bn & ol bn	Fn	"	Mch ol bn dol (as above). Tr limonite, lim staining, pyrite.

UNIVERSITY OF WISCONSIN GEOLOGICAL & NATURAL HISTORY SURVEY
3817 Mineral Point Rd., Madison, Wisconsin 53705

Geologic Log No. S80-DR-3

Well name: Maple Woods Monitoring Well #7

	Depths	Graphic Section	Rock Type	Color	Grain Size Mode	Grain Size Range	Miscellaneous Characteristics
S	160–170		Dolomite	Lt bn grey	M	"	Trace pyrite, limonite, grey brown shale partings.
I	170–180		"	V pl brown	Fn	"	Ltl M-grained sugary v pl bn dolomite. Tr lim, lim stng, pyrite.
L	180–190	Δ Δ G	"	V pl bn & gy	M	"	Mch gy dol(as below). Tr lim, lim stng, pyrite, white chert.
200	190–200	G	"	Grey	"	"	Ltl v pl bn dolomite(as above). Tr finely disseminated pyrite, massive glauconite.
			END OF LOG				
			Unwashed duplicate sample.				
	50–60	Δ Δ Δ Δ Δ Δ	Dolomite	Pl brown	M	Fn/M	Mch white fossiliferous chert. Trace brown yellow dolomite, fossil fragments, dark brown shale partings, pyrite, limonite, dolomite crystals, drusy quartz.
			Driller's log:				
			Topsoil		0–6"		
			Limestone		6"–200'		

WISCONSIN GEOLOGICAL and NATURAL HISTORY SURVEY
3817 Mineral Point Road • Madison, WI 53705

Geologic Log No. R15-Dr-340

Well name	Maple Woods Monitoring Well #2 Town of Sevastopol	County: Door	
Owner	Wis. Geological & Natural History Survey	Completed	3/12/87
Address	3817 Mineral Point Rd Madison, WI 53705	Field check	WG&NHS-M. Blanchard
		Altitude	792.8' (rod & level)
		Use	Monitoring
Driller	Erwin Jorns & Sons	Static w.l.	143.5'
Engineer		Spec. cap.	

R.26 E. T.28 N. Sec 2

Location: SW¼,NW¼,SW¼,NW¼,NW¼,SE¼,Sec. 2, T28N, R26E Quad. Institute 7½'

Drill Hole						Casing & Liner Pipe or Curbing							
Dia.	from	to	Dia.	from	to	Dia.	Wgt.& Kind	from	to	Dia.	Wgt.& Kind	from	to
10"	0	41.5'				6"	Steel	+1.55	41.5'				
6"	41.5'	242'											

Drilling method: air rotary
Samples from 0 to 242' Rec'd: 3/16/87

Grout	from	to
Cement	0	40'

Studied by: Kathleen Massie-Ferch
Formations: Surface, Silurian Undifferentiated.
Issued: 5/13/87
Updated: 3/20/89
Remarks: Well was drilled on land owned by Milton Staats, 5706 Country View Rd. Sturgeon Bay, WI 54235.

Well #2 is located approximately 170' from Well #1(Dr-339). While drilling Well #2 at a depth of ~205'-210' we noticed the well cap had blown off Well #1. While drilling at 234' water erupted from Well #1. The water was forced 35'-45' into the air above Well #1, repeatedly, just like a volcanic eruption.-M. Blanchard
Four 1¼" PVC piezometers installed. Contact WG&NHS for more information.

LOG OF WELL:

	Depths	Graphic Section	Rock Type	Color	Grain Size Mode	Grain Size Range	Miscellaneous Characteristics
2' Sfc.	0-2		NO SAMPLE.		Driller	reports soil.	
	2-5		Dolomite	Lt yl gray	M	Fn/M	Limy. Trace limonite staining,calcite,soil.
	5-10		"	Lt gy to v pl bn	"	"	Same.
S	10-15		"	"	"	"	Same plus little dark gray staining.
I	15-20		"	"	"	"	Limy. Tr dk gy shale prtgs,lim,pyrite,calcite,stylo,dk gy stng.
L	20-25	G	"	Lt gy to bn	"	"	Limy. Tr dk bn sh prtgs,fos frags(w/sh),pyr,calc,lim,stylo,mssv glauc.
	25-30		"	"	"	"	Same but little calcite.
U	30-35		"	Pl bn to gy bn	"	"	Limy. Tr dk bn sh prtgs,wh fossif cht,fos frags,pyr,calc,lim,dk gy stng.
R	35-40		"	"	"	"	Same but little white chert.
I	40-41.5		NO SAMPLE.				
	41.5-45		Dolomite	Pale brown	M	Fn/M	Limy. Mch wh fossif cht. Tr dk bn sh prtgs,fos frags,pyr,calc, lim,dk gy stng.
A	45-55		"	"	"	"	45-50:Same plus tr stylo. 50-55:Same as 45'-50' but ltl wh cht.
N	55-60		"	"	"	"	Limy. Grny. Mch wh to tn fossif cht. Tr dk bn sh prtgs,pyr,fos frags,calc,lim,stylo.
	60-65		"	V pl brown	"	"	Same minus grainy.
	65-70		"	Pale brown	"	"	Same.
	70-75		"	Pl bn to gy bn	"	"	Limy. Tr wh to tn fossif cht,dk bn sh prtgs,pyr,fos frags,dk gy stng,calc,lim.
	75-80		"	Pale brown	"	"	Same but little chert.
	80-85		"	"	"	"	Same but much chert.
	85-90		"	"	"	"	Same.
U	90-95		"	"	"	"	Same plus trace drusy quartz/chert.
N	95-100		"	"	"	"	Limy. Ltl wh to tn fossif cht. Tr dk bn sh prtgs,pyr,fos frags, dk gy stng,calc,lim.
D	100-105		"	"	"	"	Same but much chert.
I	105-110		"	V pl bn to pl bn	"	"	Limy. Tr wh cht,dk bn shale prtgs,stylo,pyr,calc,fossil frags.
F	110-115		"	"	"	"	Same.
F.	115-120		"	"	"	"	"
	120-125		"	"	"	"	"
	125-130		"	Pl bn&lt gy	"	"	Same but chert is fossiliferous.
	130-135		"	V pl bn to pl bn	"	"	Same.
	135-140		"	Lt gy brown	"	"	Limy. Tr wh to tn fossif cht,dk bn sh prtgs,stylo,calc,pyr,fos frags.
	140-145		"	Pale brown	"	"	Limy. Tr limonite stng,pyrite,dk bn shale mottling.
	145-150		"	V pl brown	"	"	Limy. Tr dk gy shale mot,dk gy staining,pyrite,limonite stng.
	150-155		"	Pale brown	"	"	Limy. Much white fossiliferous chert. Trace dark brown shale partings,calcite,pyrite.

Well name: Maple Woods Monitoring Well #2

	Depths	Graphic Section	Rock Type	Color	Grain Size Mode	Grain Size Range	Miscellaneous Characteristics
S	155-160	⊥ Δ	Dolomite	Pale brown	M	Fn/M	Limy. Tr wh fossif chert,dk bn shale prtgs,calcite,pyrite.
I	160-165	⊥	"	Pl bn & lt gy	"	"	Limy. Tr dk bn shale prtgs,pyrite,dk gy stng,calcite,lim stng.
L	165-170	⊥	"	V pl brown	"	"	Limy. Trace pyrite,dk bn shale partings,calcite,fossil frags.
U	170-175	⊥	"	Pl bn&gy	"	"	Limy. Tr pyrite(gy),lim,lim stng(pl bn),calc,dk bn sh prtgs.
U	175-180	⊥	"	V pl brown	"	"	Limy. Tr limonite,lim stng,calcite,pyrite,dk bn shale prtgs.
R	180-185	⊥	"	Pale brown	"	"	Same plus trace strong brown siliceous clay.
I	185-190	⊥	"	Pl bn to lt gy	"	"	Limy. Ltl dk gy stng. Tr pyr,dk gy sh prtgs,calc,dk bn sh prtgs
A	190-195	⊥ G	"	Gray	"	"	Limy. Tr dk gy stng,pyrite,mssv glauc,dk gy shale prtgs,calc.
N	195-200	⊥	"	"	"	"	Same minus glauconite.
	200-205	⊥	"	Pl bn gray	"	"	Same.
	205-210	⊥	"	"	"	"	"
	210-215	⊥	"	V pl bn to lt gy	"	"	Same plus trace dark brown shale partings.
	215-220	⊥	"	"	"	"	Same.
	220-225	⊥ G	"	"	"	"	Limy. Tr dk gy stng,mssv glauc,pyr,calc,dk gy & dk bn sh prtgs.
	225-230	⊥	"	"	"	"	Limy. Tr pyr,lim,lim stng,dk bn sh prtg. The gy dol is fn grnd.
	230-235	⊥ Δ	"	Gray	Fn	"	Limy. Tr pyrite,wh chert,pl bn limonite dol,dk bn shale prtgs.
	235-240	⊥	"	Bn to gray	"	"	Limy. Few fos molds(w/gy). Tr dk gy sh prtgs,pyr,lim,dk bn sh prtgs.
240	240-242	⊥	"	"	"	"	Limy. Trace dark gray staining,massive glauconite,dark brown shale partings,pyrite.
				END OF	LOG		
			Duplicate Sample.				
	230-233	⊥	Dolomite	V pl bn to lt gy	M	Fn/M	Limy. Trace pyrite,limonite staining,dark brown shale partings,limonite.