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Bradbury, Kenneth R. (Kenneth Rhoads); Blanchard, Margaret C.; Muldoon, Maureen A.

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HYDROGEOLOGY AND GROUNDWATER GEOCHEMISTRY IN FRACTURED DOLOMITE, NORTHEASTERN WISCONSIN

By Kenneth R. Bradbury, Margaret C. Blanchard, and Maureen A. Muldoon

Wisconsin Geological and Natural History Survey
3817 Mineral Point Road, Madison, Wisconsin 53705

ABSTRACT

The fractured Silurian dolomite of northeastern Wisconsin falls about midway along a continuum between diffuse-flow fractured aquifers and true karst and exhibits some characteristics of each environment, as shown by a field study of spatial and temporal variations in hydraulic head and geochemical parameters in Door County, Wisconsin.

At a regional scale, repeated sampling of 65 wells showed rapid and sometimes unpredictable spatial and temporal variations in concentrations of indicator parameters. Horizontal groundwater movement can be rapid, and indicator parameters can be traced up to 2.7 mi (4.4 km) following a large contamination event.

At a local scale, data from standpipe piezometers along a potentiometric divide suggest that the common practice of constructing water-table maps using

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existing supply wells in fractured dolomite may lead to incorrect interpretations of the configuration of the water table and the thickness of the unsaturated zone. Vertical hydraulic gradients are relatively large. Aquifer tests suggest that the aquifer is highly anisotropic at the piezometer site, but tritium and ^{18}O data indicate fairly rapid recharge and vertical groundwater movement. Temperature logs appear to be particularly useful in delineating zones of rapid groundwater movement in boreholes.

INTRODUCTION

Purpose and Scope

Dolomite of Silurian age forms an important aquifer in parts of central North America, including portions of the states of Wisconsin, Illinois, Indiana, Michigan, New York, and the Province of Ontario. The Door Peninsula of northeastern Wisconsin, which lies between Lake Michigan and Green Bay, is an area of thin soils underlain by fractured Silurian dolomite (Figure 1) and is the focus of this paper. This area (Door County) has a history of elevated nitrate, chloride, bacteria, and occasionally lead and arsenic levels in groundwater samples collected from private and public wells (Blanchard, 1988; Wiersma and others, 1984). Such groundwater contamination is believed to be a direct result of agricultural and other land-use practices in areas where the fractured dolomite is overlain by thin soils. However, with the exception of Sherrill (1975; 1978) there has been little past research on the interrelationships between the fracture system, groundwater movement, and groundwater geochemistry in the dolomite of northeastern Wisconsin. This paper examines the relationships between groundwater flow systems and the fracture network in the dolomite at a regional scale and at a detailed research site in a groundwater recharge area.

Geologic Setting

In the study area dolomite of Silurian age lies beneath a thin cover of unlithified Pleistocene sediment. The dolomite is more than 500 ft (150 m) thick along the eastern shore of Door county (Sherrill, 1975) and thins to the southwest. The dolomite dips to the southeast at approximately 45 ft/mi (8 m/km), and forms a prominent escarpment that extends along the western edge of the county adjacent to Green Bay. The Silurian dolomite is a major aquifer in eastern Wisconsin and extends from the northern tip of Door County south into Illinois. In northern Door County, however, the dolomite aquifer is a self-contained and easily studied unconfined aquifer system, covered only thinly by unlithified materials and bounded on all sides by surface water and beneath by the Maquoketa Shale Group, a regional aquitard.

Numerous vertical and horizontal fractures in the dolomite apparently control the hydraulic conductivity of the bedrock aquifer. Figure 2 shows vertical fracture expression in an alfalfa field in the study area. The depth to bedrock at this location is approximately 6 in. (15 cm), as determined by ground-penetrating radar and by hand augering. Apparently, the vertical fractures are filled with fine-grained soil, which holds more moisture than surrounding areas. The photo shows the high frequency of and the regular spacing between the fractures. The three visible sets vary in the degree of regular spacing. Rosen (1984) and Sherrill (1978) document principal joint azimuths in Door County at about 25, 70, and 155 degrees. Each fracture, if open, can provide a direct route for infiltrating water to recharge the groundwater system; however, most fractures are filled with clayey or silty sediment.

REGIONAL STUDY

Methodology

The goal of the regional study was to examine temporal and spatial distributions of several groundwater indicator parameters over a large area of fractured rock and thin soils by using groundwater samples from existing domestic wells. The regional study area covers approximately 90 mi^2 (233 km^2) in central Door County, and was selected after a detailed survey of fracture features, karst features, soil thickness, and land use (Blanchard, 1988). Figure 1 shows the location of the sampling points. Sixty-five private wells and five springs were sampled frequently between February 1986 and August 1987. Water samples were tested for nitrate, chloride, specific conductance, sulfate and turbidity. Samples were collected by the well owners and shipped to laboratories at the University of Wisconsin-Green Bay, where they were analyzed using standard methods (APHA, 1985).

Regional Sampling Results

Groundwater samples from the 70 sites show that groundwater chemistry varies spatially and temporally over the regional study area. This upland study area is entirely rural, and major land uses are dairy farms and fruit orchards. Therefore, observed wide variations in concentrations of chemical parameters in groundwater samples probably result more from local variations in hydrogeology and soil thickness than from radically different land uses. Table 1 shows the results of statistical analysis of the inorganic parameters for all sample results, (i.e., for all samples from all wells). Table 2 lists the ranges of sample means and standard deviations for the inorganic parameters for the 70 sampling sites, and shows wide variation in both absolute parameter values and in ranges of variation from site to site. The mean and median values (Table 1) are often quite different, and significant numbers of extreme values result in skewed distributions, suggesting that the populations are not normally distributed. The median value is more informative than the mean, which can be affected by a few extreme values (Ryan and others, 1985). The ranges of site means and standard deviations in Table 2 show the high variability in indicator parameters in groundwater from sites only a few miles apart, and also shows that some sites were much more variable than others.

Table 1. Summary of groundwater sampling results for all sites in large study area

Parameter	Number of samples	Mean	Median	Range	Standard deviation
Nitrate (mg/L)	1476	6.8	6.1	0.0-72.0	6.1
Turbidity (NTU)	1427	1.3	0.4	0.0-98.0	5.3
Specific Conductance (umhos/cm)	1414	619.0	585.0	296-1621	156.0
Sulfate (mg/L)	469	28.3	24.9	0.0-106.4	11.9
Chloride (mg/L)	1450	19.0	13.6	0.4-204.1	18.5

Table 2. Ranges of site means and standard deviations for groundwater samples from large study area

Parameter	Number of sites	Range of site means	Range of site standard deviations
Nitrate (mg/L)	70	0.0-37.8	0.0-19.6
Turbidity (NTU)	70	0.1-20.1	0.1-14.8
Specific conductance (umhos/cm)	70	420-1303	7.5-258
Sulfate (mg/L)	26	0.0-84.3	0.0-15.6
Chloride (mg/L)	70	1.0-104.7	0.5-26.0

The wide range of site means and standard deviations (Table 2) for wells finished at similar depths in the same aquifer suggests that some wells intersect major fracture conduits while others do not. Shuster and White (1971) showed that limestone springs dominated by conduit flow exhibited much greater temporal variability in chemical indicator parameters than did springs dominated by diffuse flow. The results reported here suggest that the dolomite aquifer in the study area may have regions of diffuse flow and conduit flow. The sampling results also suggest that current land uses in the study area are contributing to contamination of the dolomite aquifer.

Nitrate concentrations in groundwater are closely monitored because there is a health limit of 10 mg/L nitrate as nitrogen. Nitrate concentrations ranged from not detected to 72.0 mg/L. The tremendous variability in these results causes the median value to be the same as the standard deviation (6.1 mg/L). Elevated nitrate values suggest surface-water contamination of the aquifer because there are few known natural nitrate sources present in the study area.

Figure 3 shows how nitrate levels in three wells varied significantly through time, and that this variation can, in some cases, be related more to major periods of precipitation rather than to individual storm events. For example, nitrate in well 20 shows little or no response to individual storms but increases significantly followed by a gradual decline during rainy periods in the spring and autumn of 1986. Well 52 shows a similar peak and decline during late 1986. All wells in Figure 3 showed rapid increases in nitrate during a contamination event in the fall of 1987, described below. One implication of such high variation in nitrate and other parameters (not shown) through time is that one-time well-water samples, currently required in Wisconsin before a new well is approved, have little meaning toward predicting longer-term groundwater quality in fractured-rock settings.

Large-Scale Contamination Event

In September 1987, a contamination event, demonstrating extremely rapid groundwater movement through fracture conduits, occurred within the regional sampling area. Well 67 produced a water sample containing 267 mg/L nitrate, an order of magnitude greater than the drinking-water health standard of 10 mg/L, and four other wells down-gradient (southwest) of this site also showed unusually high nitrate (Figure 4). The nitrate source was apparently at a farm where an animal waste holding facility was being constructed. The construction project involved bedrock excavation 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. Site 67 is a little over 0.5 mi (0.3 km) from site 66, the location of the construction project. Well 66, located slightly upgradient of the barnyard construction site, showed no change in concentrations on September 22nd, suggesting that the contamination moved by advection in the direction of the hydraulic gradient.

Inferred Regional Groundwater Flow Rates

The unplanned and unanticipated contamination event at site 66 allows calculation of minimum regional groundwater flow velocities based on the detection of elevated nitrate levels in various nearby wells. These calculations rely on several key 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 this time, and site 66 is hydraulically upgradient from all other wells discussed here. Second, we assume that the elevated nitrate levels in surrounding 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 show elevated nitrates during this period. Third, we assume that the first arrival of contaminants in various 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 minimum flow rates. Dividing the linear separation between wells by the maximum arrival time gives groundwater velocities ranging from 230 to 1100 ft/day (70-340 m/day). Such values are several orders of magnitude higher than would be expected based on Darcy's law if we assume a uniform porous medium and use generally-accepted values for local hydraulic gradient (0.003), hydraulic conductivity (3-10 ft/day), and porosity (10-20 percent). 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.

HYDROGEOLOGY AT THE DETAILED STUDY SITE

Methodology

The goal of the local scale study was to examine in detail the vertical and horizontal movement of groundwater through a small area of fractured dolomite, by determining the position of the water table, measuring any vertical hydraulic gradients present, measuring aquifer parameters, and sampling groundwater at various depths below the surface in a groundwater recharge area. The location of the monitoring well site (Figure 5) was chosen for three 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 fruit orchards and is typical of central Door County. Third, the site is centered in the regional study area described above.

Five monitoring wells were installed during March 1987, using air-rotary drilling. The wells are oriented approximately along a groundwater flow line and also along a major fracture feature (Figure 5). Two wells (MW1 and MW2) reach a depth of approximately 240 ft (73 m), the common depth of newly constructed domestic wells in the area. Three shallow wells (MW3, MW4, and MW5) were installed on a line between two deep wells (MW1 and MW2), to depths of 24, 42, and 64 ft (7, 13, and 20 m) respectively. To investigate changes in hydraulic head and water chemistry with depth, 1.5 in. (3.8 cm) I.D. PVC piezometers with 5 ft (1.5 m) screens were installed to various depths in boreholes MW2 and MW5. The annular space between piezometers was sealed with a mixture of bentonite and cement grout, and the piezometers were developed using compressed air. The resulting piezometer and well nests were used for measurements of the vertical distribution of hydraulic head in the dolomite, for two pumping tests, and for obtaining high-quality groundwater samples that were analyzed for major cations and anions as well as environmental isotopes (^3H, ^{18}O).

Location of Horizontal Fractured Zones

At the detailed monitoring site, less than 2 ft (0.3 m) of silty soil covers the dolomite. Direct evidence of fracture discontinuities observed during installation of well MW1 included loss of drilling fluids at elevations of 577 and 600 ft (176 and 183 m) above sea level and voids at 577 and 582 ft (176 and 177 m). While drilling at an elevation of 563 ft (172 m) at MW2, water erupted 40 ft (12 m) above the ground at MW1. This shows a direct connection between wells MW1 and MW2, which are 170 ft (52 m) apart.

Geophysical logs, including three-arm caliper, spontaneous potential, single-point resistivity, natural gamma radiation, and borehole temperature were obtained at several monitoring wells prior to casing installation. Figure 6 shows a suite of logs for well MW1, which is cased from the surface to 40 ft (12 m) and has a total depth of 242 ft (74 m). Numbers on the left-hand axis of Figure 6 are corrected elevations relative to mean sea level. Offsets appear in the temperature log at elevations of 555 ft (169 m) and 652 ft (199 m). This log was run in the spring of 1988, 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 these 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. The log suggests the presence of thin zones of clay at elevations of approximately 700, 660, and 580 ft; these zones may be horizontal fractures filled with fine-grained material washed down from the surface. Television logs confirm the presence of these fracture zones. The SP and resistivity logs can be easily correlated between boreholes at the site, and appear to be related more to lithologic changes than to fracture locations.

Vertical Distribution of Hydraulic Head

Vertical hydraulic gradients at the monitoring site are steeply downward. Vertical gradients are much greater than horizontal gradients, suggesting that the aquifer is highly anisotropic. Figure 7 shows the distribution of total hydraulic head in the subsurface in July 1987. The water table at the site is at an elevation of about 780 ft, or about 20 ft (6 m) below the land surface, as shown by the heads in shallow piezometers MW5A and MW5B. The continuous presence of water in these piezometers was unexpected on the basis of previous research (Sherrill, 1978; Bradbury, 1982), which placed the water table in the area about 150 ft (46 m) below the land surface. Below the water table, hydraulic heads decrease significantly with depth. A change in the vertical hydraulic gradient occurs at about elevation 650 ft, the approximate position of the horizontal fracture zone described above.

Although possible explanations for the large decrease in total hydraulic head with depth include a perched water table above a deeper unsaturated zone, to date we have no evidence of unsaturated conditions at depth at the site. For example, in piezometer MW2C, a piezometer of intermediate depth screened above the level of the standing water in the deeper piezometers (Figure 7), water stood continuously almost 30 ft (9 m) above the water in deeper piezometer MW2A. If in fact the true water table is much shallower than previously thought, with strong vertical hydraulic gradients in the saturated zone beneath it, then previous "water table" maps of the area, based on measurements in deeply-cased domestic wells, incorrectly delineate a deeper potentiometric surface as the water table. 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). Additional instrumentation is currently being installed at the monitoring site to measure the variation of hydraulic head in the subsurface.

Results of Aquifer Tests

Results of two pumping tests conducted at the monitoring site suggest that the shallow and deep parts of the aquifer have differing hydraulic properties. Both tests were conducted for 24 hours at pumping rates of about 0.05 ft^3/sec (1.3 X 10^{-3} m^3/sec), and drawdowns were measured in adjacent wells and piezometers as well as in the pumped wells. The drawdown curves showed a characteristic double-porosity response, and the data analyses emphasized the late-time portions of the curves. Table 3 summarizes results of these tests. The pumping tests have two important results. First, the transmissivity of the shallow zone is about sixty times 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 rates used is additional evidence that this upper zone contains significant quantities of groundwater.

Table 3. Results of aquifer tests at the monitoring site

Test Zone:	Shallow, 0-60 ft (0-18 m)	Deep, 150-240 ft (46-73 m)
Date of Test:	3/88	7/87
Pumped Well:	MW3	MW1
Observation Wells:	MW4, MW5, MW2D	MW2A, MW2B, MW2C
Transmissivity:	1.1×10^{-3} ft^2/sec (3.4×10^{-4} m^2/sec)	6.7×10^{-2} ft^2/sec (2.0×10^{-2} m/sec)
Specific Yield:	0.04	0.09

Results of Geochemical and Isotopic Sampling

Major-ion and isotopic results indicate little variation with depth at the monitoring site and suggest that the groundwater is well mixed (Figure 8). As expected, groundwater at the site is of the calcium-magnesium-bicarbonate type. Groundwater at the site enters as precipitation on the land surface and moves vertically downward through the aquifer. As shown in Figure 8, the geochemical evolution of the water occurs very near the ground surface. Dissolved calcium and magnesium increase from, respectively, 20 to 30 and 40 to

60 ppm in the upper 10 ft (3 m) of the aquifer and are relatively stable below this depth. Likewise, pH decreases from about 7.7 to 7.4 in the same zone. Nitrate is stable with depth, and chloride increases slightly around elevation 650 ft, near the observed horizontal hydraulically conductive zone at 652 ft.

Two environmental isotopes, ^{18}O and tritium (^{3}H), also suggest that the aquifer water is relatively uniform in age and source area, though both show deviations near the elevation 652 ft conductive zone. ^{18}O results are presented as a permil deviation from Standard Mean Ocean Water (SMOW). Because the ^{18}O composition of shallow groundwater is not influenced by geochemical processes in the subsurface, variations in the ^{18}O composition are often used to distinguish groundwater recharge areas or climatic zones (Freeze and Cherry, 1979). The mean annual ^{18}O composition of precipitation at a given site is relatively constant from year to year, although large variations can occur seasonally and even with individual storms. For example, monthly ^{18}O values at Chicago, about 150 mi (46 km) south of the study area, vary from about -2 to -20 permil (IAEA, 1983), and a similar range of variation would be expected in precipitation in the study area. However, groundwater at the monitoring site has ^{18}O values of about -11 permil regardless of depth, suggesting a well mixed groundwater system. Likewise, the tritium data range from 20 to 33 tritium units, which is the approximate range of tritium in modern precipitation in eastern Wisconsin, and is characteristic of groundwater less than 35 years old (Hendry, 1988). Lower values, in the range of 5 TU or less, would have indicated groundwater recharged longer than about 30 years ago, but no such values were detected. This result confirms that groundwater in the study area is relatively young, and that groundwater movement is rapid.

SUMMARY

Dolomite of Silurian age makes up most of the Door Peninsula of northeastern Wisconsin, where it forms an important shallow unconfined aquifer. An extensive system of regular vertical fractures is visible on the land surface where the dolomite is covered by thin soils, and horizontal fractures are visible in vertical faces and are encountered in wells. A regional study involving frequent sampling of various chemical indicator parameters in existing wells showed that extreme spatial and temporal variations in parameter concentrations occur in groundwater in the dolomite, and these variations may be due to rapid groundwater movement through fractures. In particular, data from one contamination event suggested that groundwater might move laterally as rapidly as 230 to 1100 ft/day (70-335 m/day) through the fracture system.

Data from a smaller-scale monitoring site showed that horizontal zones of high hydraulic conductivity occur at least at two depths, and probably represent extensive horizontal fractures. In this upland recharge area, total hydraulic head decreases significantly with depth, and the top of the saturated zone can be as shallow as 20 ft (6 m) below the land surface. Geochemical data showed that geochemical evolution of the groundwater occurs rapidly within the top portion of the aquifer, and isotopic data suggested that groundwater at depth is relatively homogeneous, with the exception of groundwater near a horizontal fracture zone about midway through the profile.

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FIGURE CAPTIONS

Figure 1. Location of the Door Peninsula in Wisconsin, and location of sampling points in the regional study area.

Figure 2. Surface expression of fracture traces in alfalfa field. Top: Oblique air photo showing vigorous alfalfa growth over fractures. Bottom: Highlighted locations of fracture traces.

Figure 3. Variation of NO_3 concentration in water from several domestic wells and precipitation in the regional study area.

Figure 4. Nitrate concentrations and inferred straight-line flow paths during contamination event in September, 1987. Numbers identify sampling points; numbers in parentheses are nitrate concentrations in mg/L. At unnumbered points nitrate was less than 10 mg/L.

Figure 5. Location map of detailed monitoring site, showing monitoring well placement.

Figure 6. Suite of geophysical logs from well MW1.

Figure 7. Vertical profile of total hydraulic head at the monitoring site in July, 1987. Plotted points indicate midpoints of piezometer screens.

Figure 8. Major ion and environmental isotope distributions at the detailed monitoring site.

Fig 1

ET Al

Fig 1

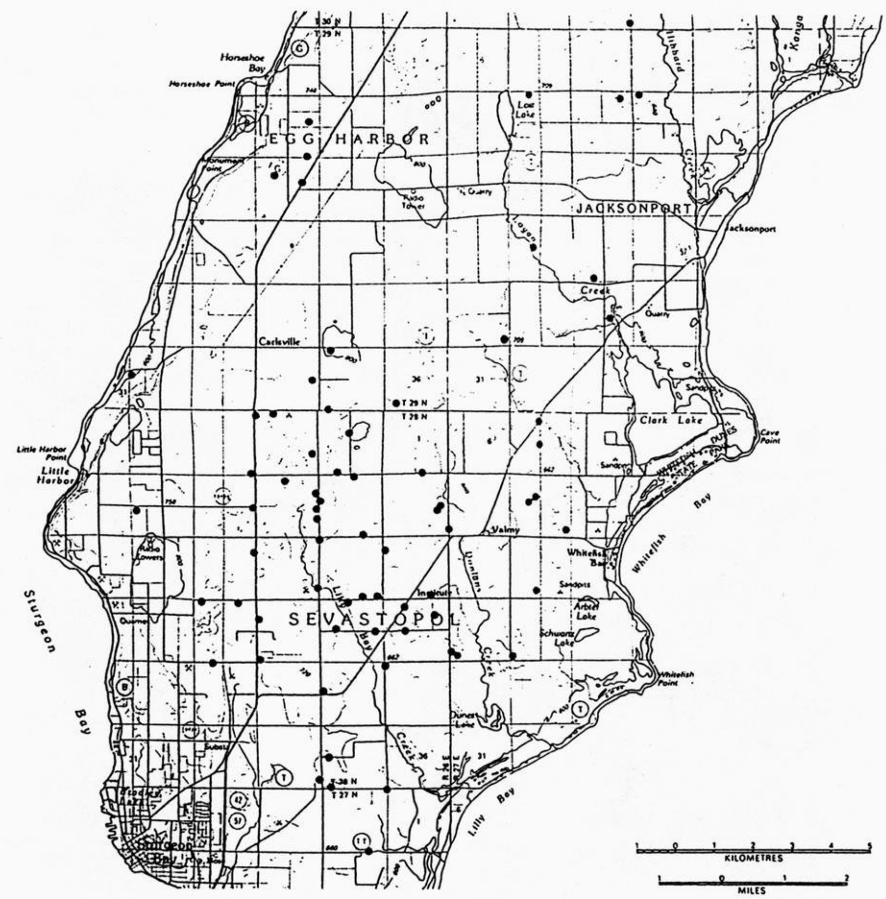


Figure 2

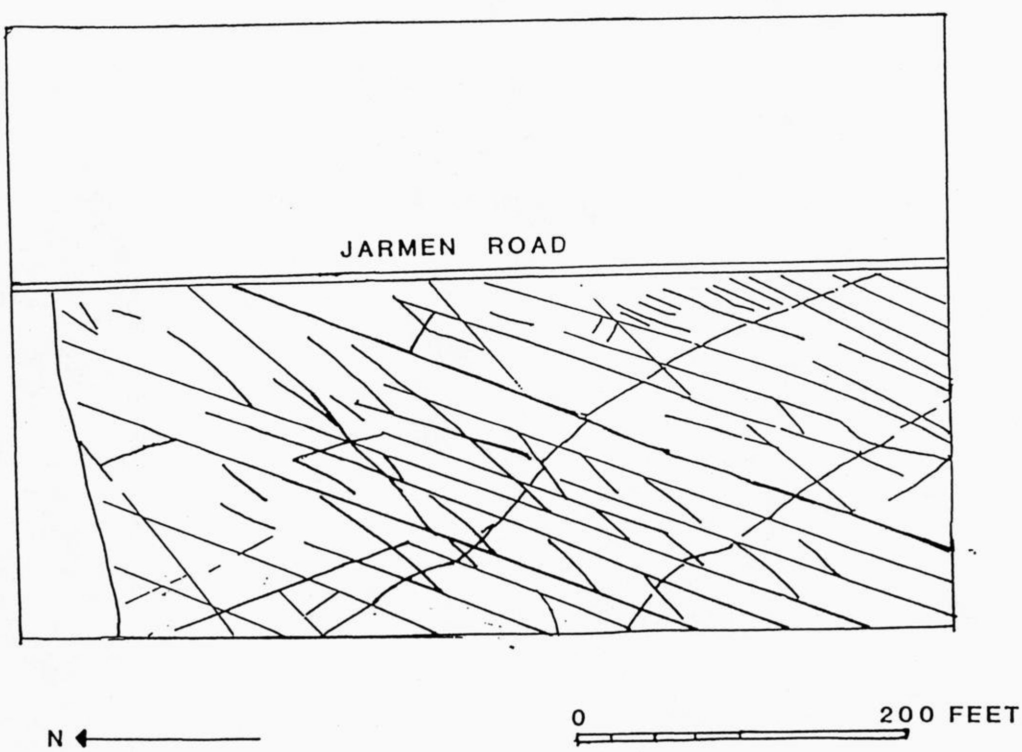
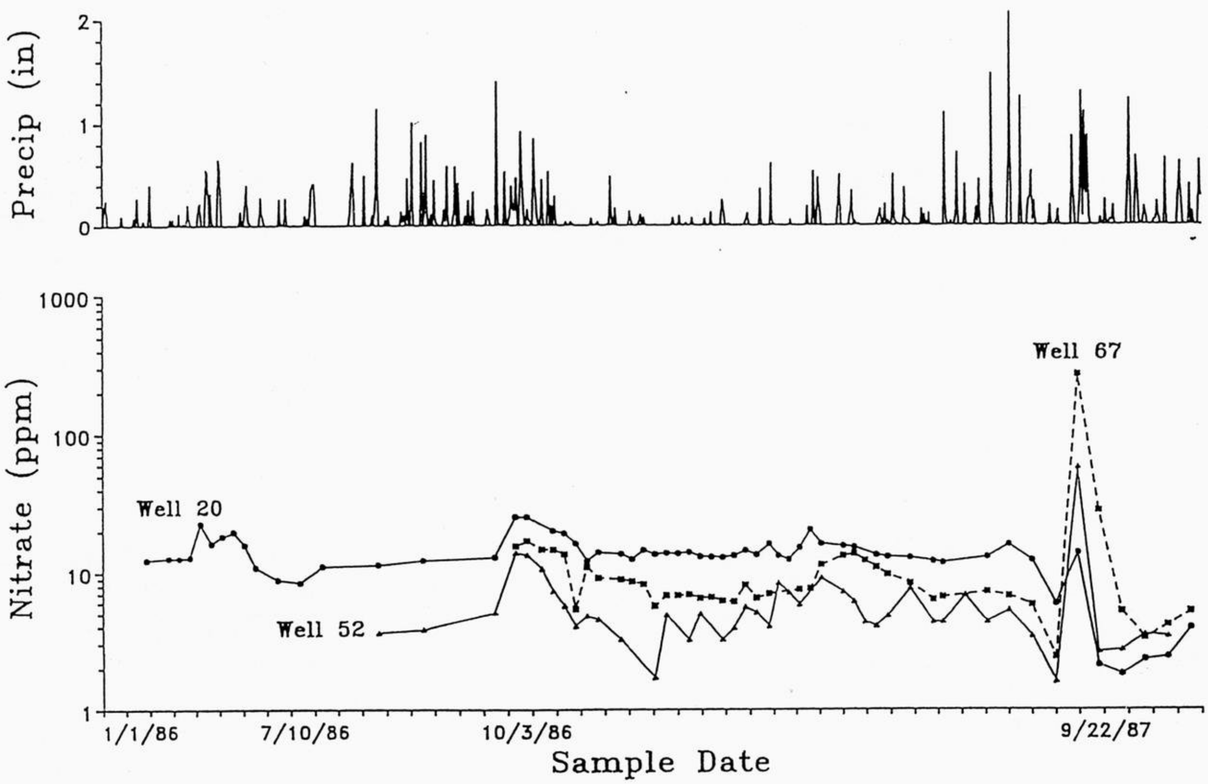


Fig 3



Precip (in)
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1
0
1000
100
10
1
Nitrate (ppm)
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Well 52
Well 67
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7/10/86
10/3/86
9/22/87
Sample Date

Fig 4

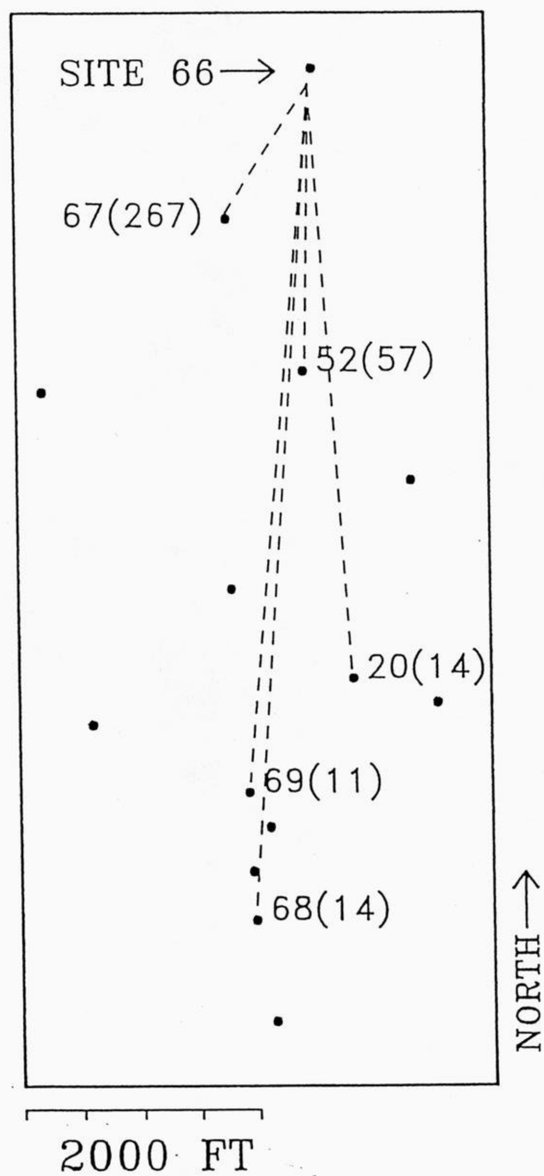
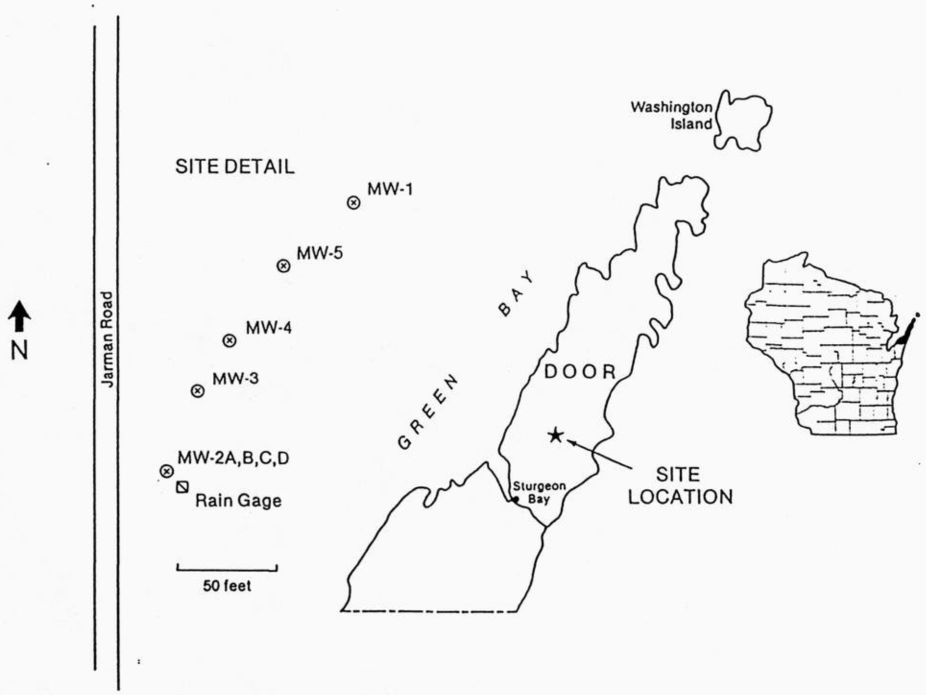
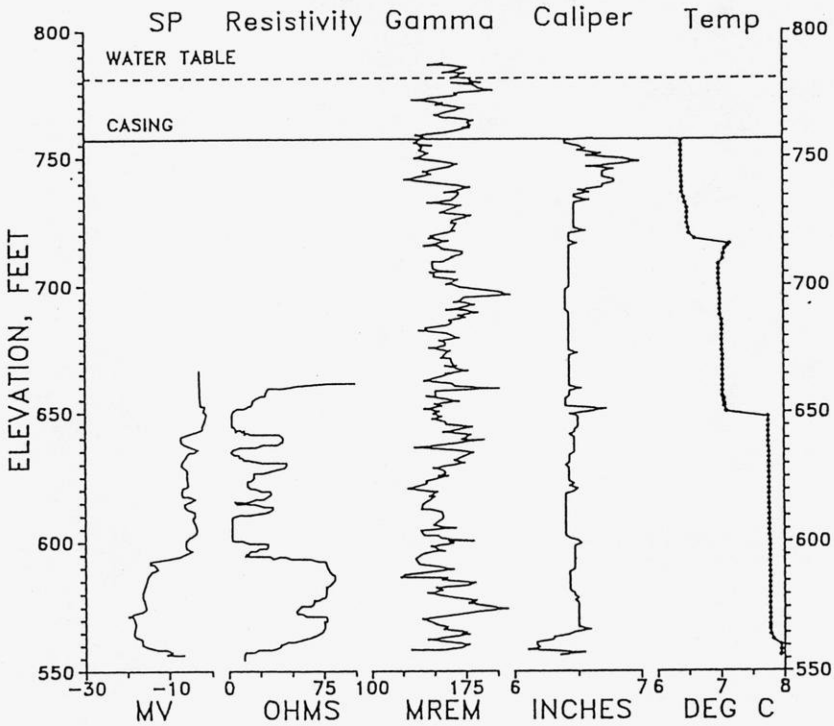


Fig 5



SITE DETAIL
Jarman Road
N
MW-1
MW-5
MW-4
MW-3
MW-2A,B,C,D
Rain Gage
50 feet
Washington Island
GREEN BAY
DOOR
Sturgeon Bay
SITE LOCATION

Fig 6


SP
Resistivity
Gamma
Caliper
Temp
WATER TABLE
CASING
ELEVATION, FEET
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750
700
650
600
550
-30
-10
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100
175
6
7
6
7
8
MV
OHMS
MREM
INCHES
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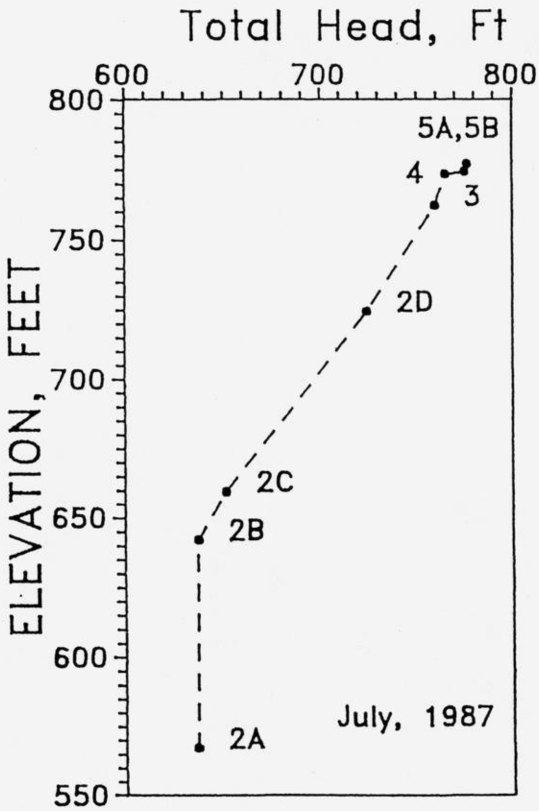
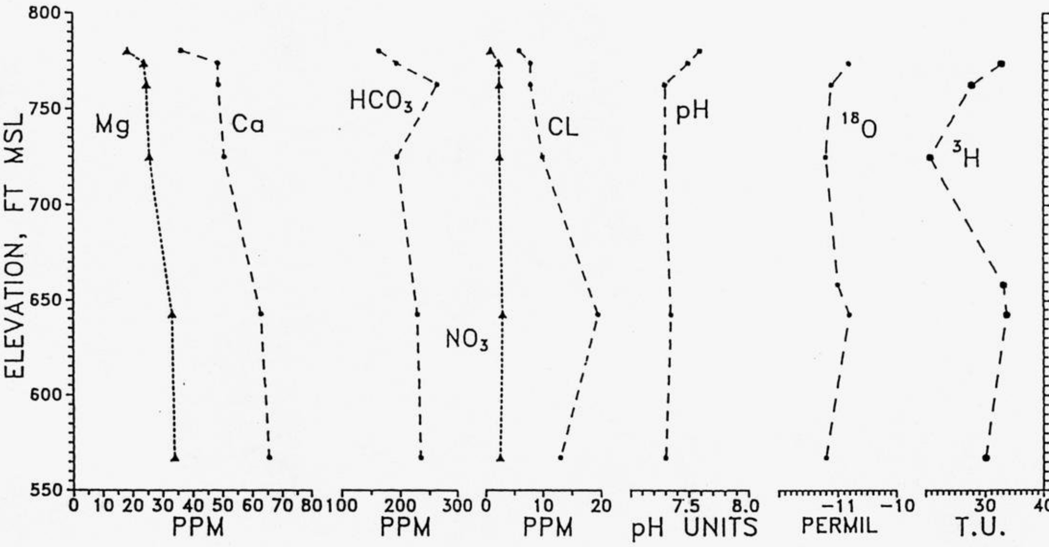
Fig 7



Total Head, Ft
600
700
800
800
750
700
650
600
550
ELEVATION, FEET
5A,5B
4
3
2D
2C
2B
2A
July, 1987

Figure 8


ELEVATION, FT MSL
Mg
Ca
HCO3
NO3
CL
pH
18O
3H
PPM
PPM
PPM
pH UNITS
PERMIL
T.U.