ground water

Site Characterization in Densely Fractured Dolomite: Comparison of Methods

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Abstract

One of the challenges in characterizing fractured-rock aquifers is determining whether the equivalent porous medium approximation is valid at the problem scale. Detailed hydrogeologic characterization completed at a small study site in a densely fractured dolomite has yielded an extensive data set that was used to evaluate the utility of the continuum and discrete-fracture approaches to aquifer characterization. There are two near-vertical sets of fractures at the site; near-horizontal bedding-plane partings constitute a third fracture set. Eighteen boreholes, including five coreholes, were drilled to a depth of ~10.6 m. Borehole geophysical logs revealed several laterally extensive horizontal fractures and dissolution zones. Flowmeter and short-interval packer testing identified which of these features were hydraulically important. A monitoring system, consisting of short-interval piezometers and multilevel samplers, was designed to monitor four horizontal fractures and two dissolution zones. The resulting network consisted of >70 sampling points and allowed detailed monitoring of head distributions in three dimensions.

Comparison of distributions of hydraulic head and hydraulic conductivity determined by these two approaches suggests that even in a densely fractured-carbonate aquifer, a characterization approach using traditional long-interval monitoring wells is inadequate to characterize ground water movement for the purposes of regulatory monitoring or site remediation. In addition, traditional multiwell pumping tests yield an average or bulk hydraulic conductivity that is not adequate for predicting rapid ground water travel times through the fracture network, and the pumping test response does not appear to be an adequate tool for assessing whether the porous medium approximation is valid.

Introduction

The purpose of this paper is to compare and contrast continuum and discrete-fracture approaches for hydrogeologic characterization in a fractured-carbonate aquifer. Carbonate rocks, which underlie 40% of the United States east of the Mississippi River (Quinlan 1990), have extremely variable hydrogeologic characteristics and can range from low-permeability aquitards to highly transmissive karstic aquifers (LeGrand 1977; Brahana et al. 1988). Fractured-carbonate aquifers, which lie somewhere near the middle of this range, are important but vulnerable sources of drinking water. The dual-porosity nature of these aquifers—high-permeability fractures transmit the majority of the water and the lower-permeability matrix blocks provide the storage capacity—makes them exceedingly susceptible to contamination, challenging to characterize, and difficult to model. Most efforts to characterize fractured-carbonate aquifers fall along a continuum between two different methodologies. The first approach, which we term the continuum approach, ignores individual fractures or conduits and treats the aquifer as a homogeneous porous medium for which bulk hydraulic and transport parameters are adequate to characterize flow and transport. A second approach, which we term a discrete-fracture approach, involves characterizing the hydraulic and transport properties of specific discrete fractures or flow conduits. Such discrete characterization is usually much more time and cost intensive than continuum methods. It has been our experience that in current

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professional practice, discrete approaches to the characterization of contaminated sites in fractured-carbonate rock are often dismissed as too expensive or infeasible, and more "traditional" continuum approaches are used instead, with little or no evaluation of the potential errors in doing so. This paper presents field data illustrating the different interpretations each method can yield when applied to a densely fractured–carbonate aquifer.

Although it is common to articulate an explicit conceptual model when constructing a numerical flow model, it is less common to do so prior to designing a monitoring system for the detection of contaminants. Yet, how one conceptualizes flow in the aquifer dictates, to a large degree, the approach to hydrogeologic site characterization. Work in fractured-crystalline aquifers has highlighted the importance of characterizing higher-permeability, interconnected fracture pathways (e.g., Hsieh et al. 1993). For fractured sedimentary sequences, several workers have noted the importance of locating and characterizing fractures when designing monitoring systems (e.g., Paillet et al. 1993; Michalski and Britton 1997; Nativ et al. 1999, 2003). For densely fractured–sedimentary aquifers, however, there are often questions as to whether the porous medium approximation is valid at the problem scale and whether site-characterization techniques and remediation technologies developed for unlithified aquifers are appropriate. In densely fractured rocks, several workers have concluded that the porous medium approximation is valid when fracture density is sufficiently high. For example, Bair and Roadcap (1992) used pumping test response, measured water levels, and drillers' logs to conclude that the fractured dolomite in Richfield, Ohio, was densely fractured and functioned as a leaky confined aquifer, and that porous medium-based models were appropriate for the delineation of time-of-travel-based capture zones. Podgorney and Ritzi (1997), who were also evaluating capture zone geometry in fractured carbonates, concluded that the upper 4 to 5 m of the fractured dolomite at their site functioned as an anisotropic continuum; below ~5 m, the dolomite functioned as a discretely fractured medium. They used a variety of site-characterization techniques to reach this conclusion, including pumping test response, borehole flowmeter data, and video logs. They state that in the upper bedrock, the fractures are "sufficiently dense and persistent such that it can be treated as a continuum."

For the practicing hydrogeologist, who is often more familiar and more comfortable with characterization techniques developed for granular media, little guidance currently exists as to whether the continuum approach or a discrete-fracture approach is more appropriate for characterization and design of a monitoring system at a given fractured-rock site (Jardine et al. 1996). Many workers have used numerical simulations of theoretical fracture networks to determine at which scale the porous medium approximation becomes appropriate (e.g., Long et al. 1982; Hsieh et al. 1985; Neuman 1987), and other workers have tried to develop "field-based" criteria (e.g., Bradbury et al. 1991; Rovey and Cherkauer 1995). To date, no clear consensus has been achieved (National Research Council [Committee on Fracture Characterization and Fluid Flow] 1996). Although guidance documents exist for the characterization of fractured-rock sites (e.g., ASTM 1995; Cohen 1995; National Research Council [Committee on Fracture Characterization and Fluid Flow] 1996; U.S. EPA 2001), the default approach still appears to be a continuum approach to site characterization (U.S. EPA 2001).

We have characterized a small field site in a densely fractured dolomite. Although this field site is uncontaminated, it is representative in size and scope of many sites we have seen in fractured-carbonate rocks where shallow ground water has become contaminated and where remediation systems are being designed. The primary goals of the site characterization were (1) to compare traditional continuum and discrete-fracture methods of hydrogeologic characterization in fractured-carbonate aquifer, (2) to obtain a better understanding of hydraulic conductivity distributions in these aquifer, and (3) to test the effectiveness of standard monitoring wells in a fractured-carbonate setting. Continuum characterization techniques included long-interval wells that provided head measurements integrated over the length of the borehole and an "open-hole" pumping test that provided measures of the bulk hydraulic conductivity of the dolomite. Discrete-fracture characterization techniques included fracture mapping, borehole geophysical logging, short-interval packer tests to measure hydraulic conductivity, heat-pulse flowmeter logs to identify hydraulically significant fractures, and tracer tests to measure ground water flow velocities. After characterization of the fracture network, we installed a multilevel sampling network designed to monitor specific fracture zones, dissolution zones, and matrix blocks. In this paper, we describe the site-characterization and monitoring system and evaluate which characterization approach is most appropriate for this site and similar fractured-carbonate settings.

Site Description

Geologic Setting

The Door Peninsula, located in northeastern Wisconsin between Green Bay and Lake Michigan, is underlain by dolomite of Silurian age, which forms an important regional aquifer along the western flank of the Michigan Basin from Canada to northeastern Illinois (Figure 1A). The dolomite forms a prominent escarpment along the western edge of the peninsula, adjacent to Green Bay. The Silurian strata dip gently into the Michigan Basin to the east-southeast at ~0.5° or 8 to 9 m/km and are underlain by Ordovician-age shale, which forms a regionally extensive confining unit (Sherrill 1978). The dolomite is >150 m thick along the eastern shore of the peninsula and thins to the southwest. The dolomite is densely fractured and covered by thin soils (Figure 2); secondary dissolution has enlarged fracture apertures and primary porosity.

Hydrologic Setting

In the Door Peninsula, the Silurian Aquifer is a self-contained unconfined aquifer system, bounded on three

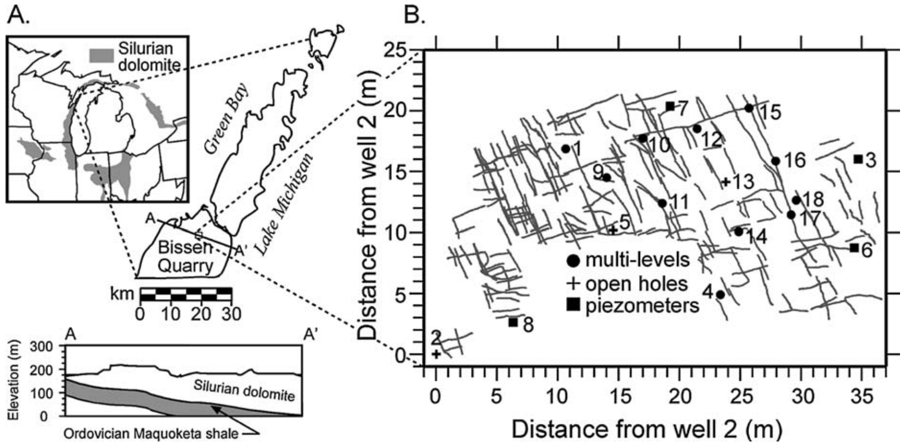

Figure 1. Location of study site. (A) Map of generalized Silurian subcrop shown as shaded area (modified from Shaver et al. 1978), location of study area within Door County, and simplified cross section of southern Door County. (B) Diagram of study site showing location of boreholes. Fractures >1.5-m (5-feet) length are also shown.

sides by surface water and beneath by the Ordovician Maquoketa shale (Figure 1A). The dolomite is the primary aquifer for the Door Peninsula, providing over 99% of all water used for agriculture, industry, and drinking water supply (based on data in Ellefson et al. 1987). The area receives ~76.5 cm/year of precipitation, including rain and snow. Due to the thin soils and permeable bedrock of the study area, runoff is negligible and ~24.1 cm/year recharges the ground water (Bradbury 1989). Ground water recharge does not occur uniformly throughout the year; the primary recharge period is during spring snowmelt, and additional recharge usually occurs in the fall of the year when vegetation has gone quiescent (Rayne et al. 2001). Ground water flow is characterized by recharge through vertical fractures and rapid lateral movement along horizontal high-permeability zones (Sherrill 1978; Bradbury and Muldoon 1992) that appear to be laterally continuous on the scale of miles (Muldoon et al. 2001a). Accounts of contaminant releases suggest that ground water flow rates can be very rapid. Bradbury and Muldoon (1992) reported flow rates of 64 and 116 m/d calculated for a nitrate release during manure-pit construction.

Field Site

The study site, located in an active dolomite quarry in southern Door County, measures ~40 × 25 m (Figure 1B); depth to ground water is ~1 to 1.5 m below the quarry floor. Site investigation has included stratigraphic and geophysical characterization of the dolomite, characterization of the three-dimensional fracture network, and detailed measurements of the hydraulic conductivity distribution (Muldoon 1999a). Eighteen boreholes were drilled to a depth of ~10.6 m (below ground surface), including 5 coreholes (7.6-cm diameter), 10 small-diameter (7.6 cm) boreholes, and 3 large-diameter (15.2 cm) boreholes installed using air-rotary drilling methods. Figure 1B shows the location of the boreholes relative to the mapped vertical fractures at the site. The five coreholes (holes 1 to 5) are widely spaced in order to characterize the geology at the site. The small-diameter boreholes (holes 9 to 18) were placed in a grid pattern with holes ~4.6 m (15 feet) apart. Five of the small-diameter holes were drilled along vertical fracture traces (holes 10, 12, 15, 16, and 17). Budget constraints precluded the installation of angled boreholes, which are the preferred method of characterizing the hydraulic properties of the vertical fractures. All

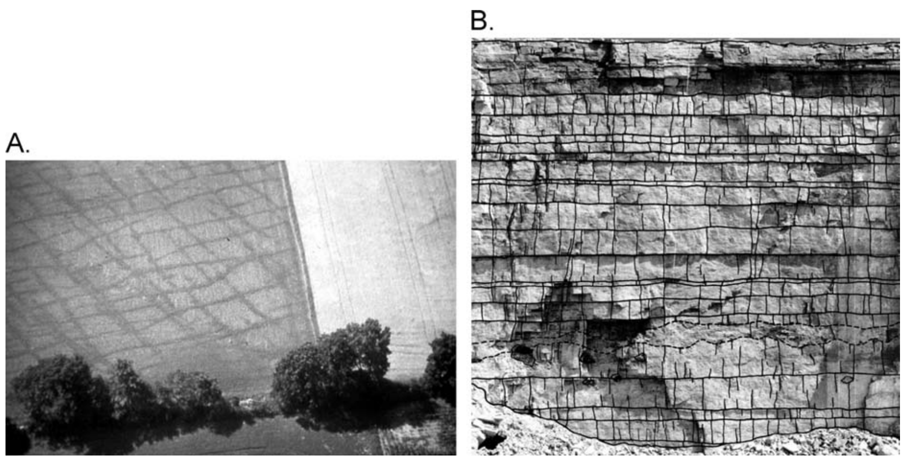

Figure 2. Density of vertical fractures in the Silurian dolomite. (A) Oblique aerial view of fracture traces in an alfalfa field in north-central Door County (photo by Bradbury). (B) Photo and fracture map of the Byron Formation exposed in a quarry wall; horizontal distance across the photo is ~13 m (modified from Underwood 1999).

holes were cased to ~0.6-m depth prior to installation of the monitoring system. Well elevations, determined by rod-and-level surveying, are relative to the top of well 5, which was arbitrarily set at 30.5 m.

The five coreholes provided a means of assessing lithologic controls on fracture distribution and hydraulic conductivity. The rocks in the subsurface beneath Bissen Quarry belong to the Byron Formation and consist of two dominant lithologies: fossiliferous, medium to coarsely crystalline dolomite deposited in subtidal, open marine environments, and laminated, fine-grained dolomite deposited in supratidal to shallow-tidal, restricted marine environments, and are characterized by frequent shallowing-upward depositional cycles that range in thickness from 0.15 to 1 m. Lithologic units are laterally continuous across the site. The upper 4.27 m of dolomite (Figure 3) and the lower part of the core (7.16- to 11.13-m depth) consist of medium-bedded, coarse dolomite (open marine facies). The middle part of the core (4.27- to 7.16-m depth) belongs to the restricted marine facies and consists of several shallowing-upward cycles. Complete cycles contain a lower part with mudstones and an upper part characterized by algal lamination; most of the cycles are capped by a diagenetic cap and overlain by a surface with depositional relief (millimeter to centimeter scale). Cycle boundaries separate the very well-cemented laminite/diagenetic cap and the overlying less cemented mudstones. At these contacts, thin and discontinuous organic-rich mudstones may occur and often represent a horizontal discontinuity. Rock textures range from mudstones to boundstones (Dunham's [1962] classification).

There are two near-vertical sets of fractures at the site, oriented ~75° and 160° (Figure 1B). Characterization of the vertical fracture pattern included clearing the quarry floor of sediment, photographing 3.05 × 3.05 m (10 × 10 feet) grid squares, and mapping and digitizing vertical fractures >0.3 m (1 feet) in length. Near-horizontal bedding-plane partings constitute a third fracture set. Several workers have investigated the vertical fracture patterns in the Door Peninsula (e.g., Roffers 1996; Underwood 1999; Muldoon et al. 2001b, Underwood et al. 2003) and several estimates of fracture density are available for the Byron Formation. Roffers reported fracture densities as length/area and noted a density of 1.92 m/m^2 for Bissen Quarry. Underwood (1999) explored the relationship between lithostratigraphy and fracture patterns. On the basis of fracture maps of vertical quarry walls, he noted that fracture densities were highest in restricted marine facies of the Byron Formation (2.40 fractures/m) and lowest in the open marine facies of the Manistique Formation (0.17 fractures/m). Scanline maps of the upper pavement at Bissen Quarry (Muldoon 1998) noted a total of 73 fractures in two scanlines with a total length of 56.7 m for a density of 1.29 fractures/m.

There is always concern that exposed surfaces such as quarry walls and fracture pavements will provide an overestimate of fracture density. In order to assess whether fracture density decreased with distance from

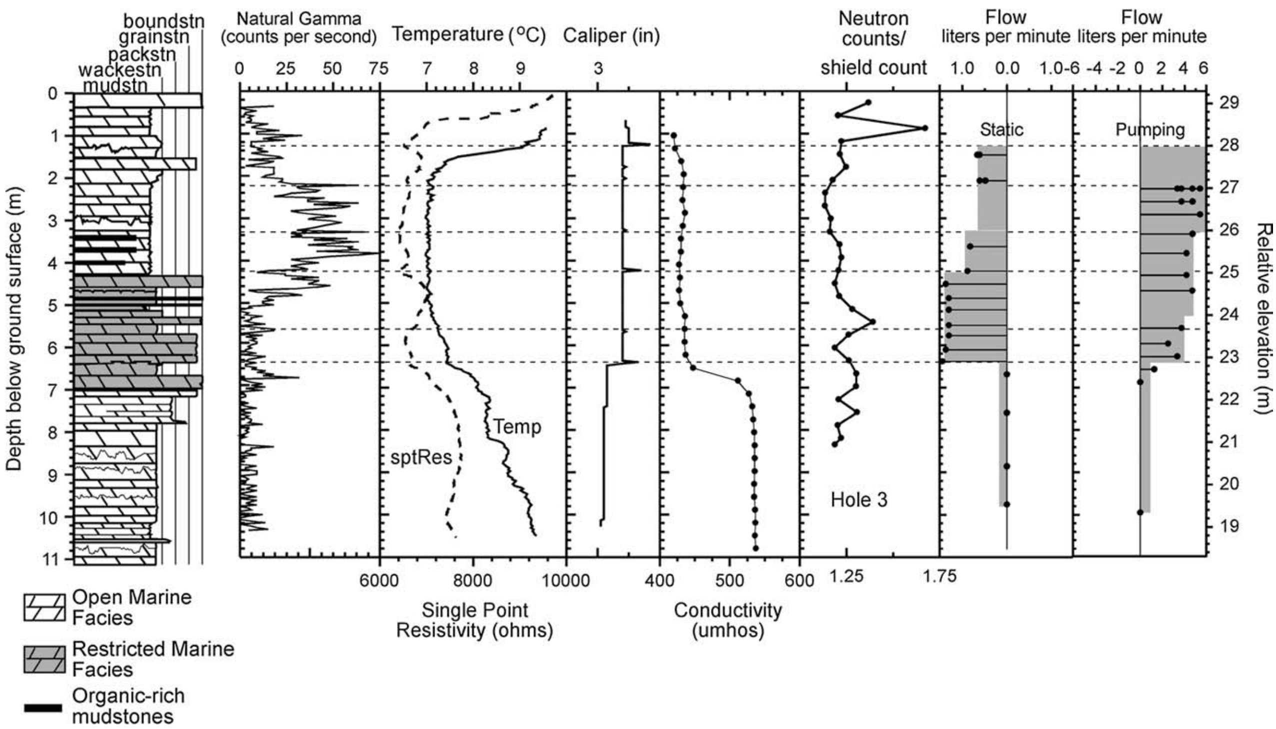

Figure 3. Stratigraphic log from hole 5 showing rock textures and facies associations. Natural gamma, fluid temperature and single-point resistivity, caliper and fluid conductivity logs for hole 5; neutron log for hole 3, and heat-pulse flowmeter logs (run under both static and pumping conditions) for hole 13. Dashed horizontal lines indicate horizontal fractures. For the heat-pulse flowmeter logs, measured flow rates are shown at the top of the logs (positive values indicate upward flow and negative values indicate downward flow). The black lines with dots indicate the measured vertical flow rates at specific points in the hole. The gray-shaded boxes illustrate interpreted changes in measured flow rates. Note difference in flow scale for the two heat-pulse logs.

a quarry face, Muldoon et al. (2001b) measured fracture density in a horizontal core drilled perpendicular to a quarry face that exposed the Byron Formation. In logging the core, they discounted fractures that appeared to be caused by the drilling and only counted those that appeared to be preexisting fractures in that they had staining or evidence of weathering. Surprisingly, the measured fracture density from the core (5.2 fractures/m) was more than twice that measured by Underwood (1999) for the same quarry face (2.4 fractures/m). It is believed that the drilling opened small preexisting fractures that would have been too faint to observe in outcrop.

All the previous measures suggest that the vertical fracture density of the Byron Formation is quite high. Given that fracture density is a function of mechanical unit thickness (e.g., Gross 1993) and that the Byron Formation consists of thinly bedded dolomite, it is not surprising that measured fracture densities are so high.

The horizontal fractures have been identified in core and by subsurface logging. Logs run on most holes include (1) caliper, which measures borehole diameter and can help identify fractures and dissolution zones; (2) natural gamma, which measures natural radiation and can be used to identify zones with shale or clay; (3) single-point resistivity; (4) spontaneous potential, which is useful for stratigraphic correlation; and (5) temperature, which can sometimes be used to identify horizontal fractures or solution features where water of differing temperature is leaving or entering the borehole. Most holes were video logged prior to the installation of the monitoring system. Additional logs run on selected holes include neutron (which provides a qualitative estimate of porosity), electrical conductivity (which identifies differences in total dissolved solids of the water in the hole), and heat-pulse flow logs (which can be used to identify hydraulically significant fractures). Figure 3 summarizes the geologic and geophysical logs for hole 5, a neutron log from hole 11 (~5 m away), and the heat-pulse flow logs from hole 13 (~10 m away). The location of near-horizontal fractures was estimated using a combination of (1) the caliper logs; (2) inflections in the fluid temperature and conductivity logs; and (3) changes in flow rate in the heat-pulse logs. Prominent near-horizontal fractures in the subsurface are preferentially developed at contacts of the contrasting lithologies and at cycle boundaries within the restricted marine facies.

Monitoring System

Multilevel samplers, each with five to six ports, were installed in 11 of the 7.6-cm holes (Figure 4) during the summer of 1994. The multilevel samplers have a minimum port length of 15.2 cm (0.5 feet) and a packer length of 0.9 m (3 feet). The system of multilevel samplers was designed to monitor four horizontal fractures (relative elevations 28.1, 25.1, 23.6, and 22.9 m) and two dissolution zones (relative elevations 26.5 and 21.6 m). Piezometers were installed in the three large-diameter holes and two of the small-diameter holes; screens were placed in gravel packs of silica pea-gravel, and the annular space between screens was sealed using 0.6-cm bentonite pellets. Piezometer installation was carried out in phases. In 1994, several of the boreholes (specifically holes 2, 3, 5, 7, 8, and 13) were left open to provide some flexibility in pumping configurations. In 1995, piezometers were installed in holes 3, 7, and 8 and temporary packer strings were installed in holes 2, 5, and 13 so that there were no open boreholes while the natural-gradient tracer tests were conducted. The resulting monitoring network, consisting of >70 sampling points, was used to monitor head distributions and tracer movement in three dimensions.

Hydraulic Conductivity Distribution

Bulk aquifer hydraulic conductivity (continuum approach) was estimated from an open-hole pumping test, and the hydraulic conductivity distribution of the matrix blocks and individual fractures (discrete-fracture approach) was estimated using short-interval packer tests. Resulting hydraulic conductivity values were used

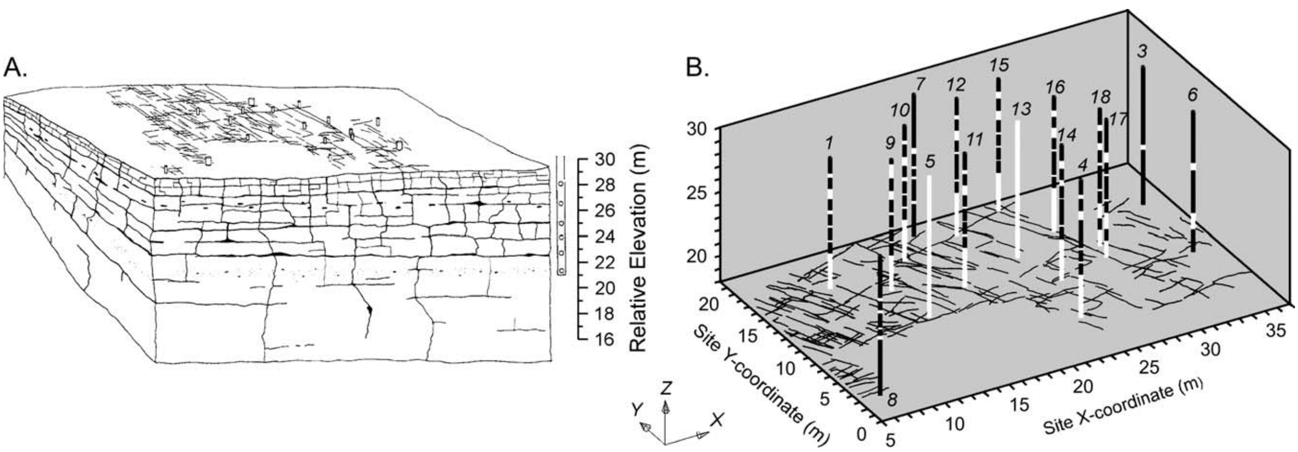

Figure 4. Block diagrams of site. (A) Schematic diagram illustrating the six monitoring zones. Relative elevations are shown on the right along with a schematic multiport sampler. Ports were installed in four horizontal fractures and two zones of vuggy porosity. The horizontal fractures appear to be laterally continuous across the site. The upper dissolution zone has sparse but large vugs; the lower zone has abundant small vugs. (B) Block diagram of site showing the open intervals (white zones) of the monitoring system. Site coordinates and relative elevations (m) are shown on the axes.

to calculate ground water velocities at the site under a gradient that was typical of heads measured when the monitoring network consisted of open boreholes. These calculated velocities were compared to velocities measured in natural-gradient tracer tests.

Open-Hole Pumping Test

The open-hole test was conducted for 21.3 h at a pumping rate of ~0.17 m^3/min (43.8 gpm). At the time of the pumping test, the monitoring network consisted of seven boreholes open from the water table to ~10.6 m depth and two piezometers screened over 0.305-m intervals. Drawdowns were recorded in the pumping well and observation wells 1, 4, 7, and 8 with pressure transducers; wells 2 and 3 and piezometers 6-1 and 6-2 were hand measured. Figure 5A shows the locations of the pumping well and monitoring points, and the drawdown cone at the completion of the test. The elliptical shape of the drawdown cone suggests that the bulk horizontal conductivity is slightly anisotropic, with the major axes of the hydraulic conductivity ellipse aligning approximately with the dominant vertical fracture sets mapped at the site. Inspection of the drawdown curves (Figure 5B) indicates that all of the observation points responded similarly to pumping except for piezometer 6-1, which is completed in a matrix block. Results from this piezometer were not included in subsequent analyses. The somewhat oscillatory behavior of the drawdown response in the first few minutes of the test results from adjustments to the discharge line during this time period. At a very late time, some of the wells appear to show an increase in the rate of drawdown. This can be interpreted as either the delayed-yield response of an unconfined aquifer or the dual-porosity response of a fractured medium.

When analyzing data from an open-hole pumping test in a fractured-rock aquifer, the practicing hydrogeologist must first determine if it is appropriate to analyze the data using standard analytic solutions or if it necessary to develop a numerical model that incorporates the known heterogeneities at the site (e.g., Tiedeman and Hsieh 2001). Typically, the aquifer's response to pumping is used as one of the criteria for this decision, and a relatively uniform response to pumping is often used as a justification for analyzing the data with a standard analytic solution. If an aquifer functions as a homogeneous continuum, one should be able to match measured drawdown data from multiple wells to an analytic solution using a single set of aquifer parameters. For highly heterogeneous aquifers, the use of standard analytic solutions (which assume a homogeneous continuum) will yield erroneous interpretations of the hydraulic properties of the aquifer. Because we were interested in contrasting continuum vs. discrete-fracture approaches to site characterization, and since the drawdown data presented in Figure 5B suggest that the observation points (except 6-1) responded similarly to pumping, we analyzed the pumping test data using two analytic solutions. We chose to analyze the data using both the Neuman (1974) and Moench (1984) solutions because the delayed-yield response of an unconfined aquifer looks similar to the dual-porosity response of a fractured aquifer. The Neuman (1974) solution for unconfined aquifers provides estimates of transmissivity (T), storage coefficient (S), specific yield (S_y) and the dimensionless β parameter which is defined as $\beta = r^2K_z/b^2K_r$ where r is the distance from pumping well, K_z is the vertical hydraulic conductivity, b is aquifer thickness, and K_r is the horizontal hydraulic conductivity. The Moench (1984) solution for fractured media yields values for fracture hydraulic conductivity (K), fracture specific storage (S_s), matrix hydraulic conductivity (K'), specific storage of the matrix (S_s'), wellbore skin (S_w), and fracture skin (S_f). Analyses were completed using the automatic curve-matching option in Aqtesolv® for Windows® Pro 3.5 (Duffield 2003).

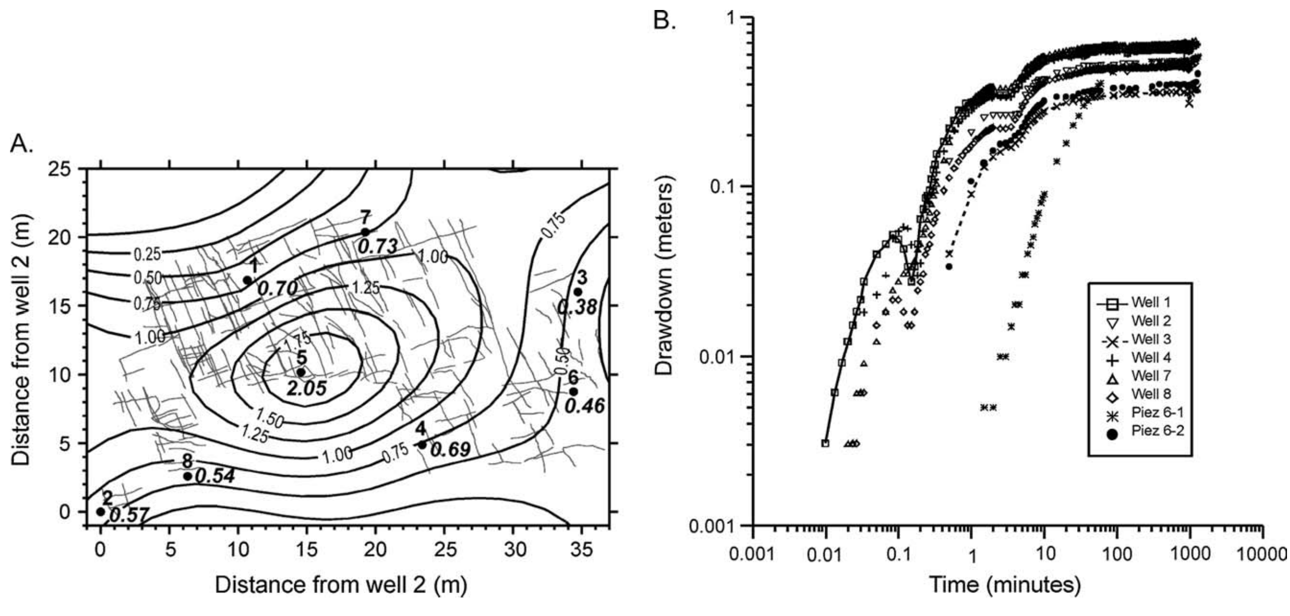

Figure 5. Results of open-hole pumping test. (A) Map of drawdown at the end of 24-h test. Black dots indicate monitoring points, well numbers are shown above (bold), and measured drawdowns are shown in italics; contour interval is 0.25 m. (B) Time-drawdown plot for all observation wells.

Two separate analyses were completed using the Neuman method: one in which the drawdown data for each well or piezometer were used to determine parameters for each observation point and one in which the drawdown data from all wells were used to determine a single set of aquifer parameters (homogeneous, isotropic aquifer). Although it is ideal to match data from all of the observation points to a single set of aquifer parameters, it is not uncommon to see consulting reports in which data from each individual observation point are matched to an analytic solution and the geometric mean of these results is reported as the measure of overall aquifer parameters. The matching of individual well responses will yield a representative transmissivity if the aquifer truly functions as a homogeneous continuum. For those fractured aquifers that exhibit highly heterogeneous responses to pumping, the analysis of individual well responses will yield a highly erroneous interpretation of the hydraulic properties of the aquifer. To convert transmissivities to hydraulic conductivities (K), a saturated aquifer thickness of 14.5 m (48 feet) was assumed. The dolomite at the site is ~91.44 m (300 feet) thick, but it is likely that the pumping stress was limited to shallow depths. Regional correlation of high-permeability features indicates that there is a large fracture at a depth of 15.5 m (Muldoon et al. 2001a). Heat-pulse logging of many holes in the dolomite of Door County indicates that these regional fractures can supply enough yield so that the aquifer below them is essentially “unstressed” at pumping rates on the order of 10s of gpm (Gianniny et al. 1996). Essentially, the large fracture at 15.5-m depth functions as the base of the shallow aquifer at the site.

For the analysis with the Moench method, all wells were analyzed together to yield a single set of aquifer parameters. The Moench solution conceptualizes the fracture network as either spherical or slab-shaped blocks. Our analyses were completed for an aquifer with slab-shaped blocks 1 m in thickness and a K_v/K_r ratio of 0.0025 (based on results of the Neuman analysis using all wells). Table 1 summarizes the aquifer parameters determined from the various analyses of the pumping test data.

The Neuman solution was somewhat insensitive to specific yield (S_y) because the pumping test was not run long enough to see a well-developed, delayed-yield response. The automatic curve-matching technique returned an unrealistic value of 0.5 for several wells. Wells in which specific yield was varied as part of the matching process yielded an average value of 0.20, so this value was fixed prior to completing the analyses with multiple wells. The geometric mean transmissivity estimated from matching the data from individual observation wells ($T = .12$ m^2/min) is very close to the transmissivity estimated from the analysis of all wells ($T = .13$ m^2/min). Matching the data from individual wells produces a very good match between the analytic solution and the measured drawdown. The residual sum of squares indicates that the fit for well 1 was the worst fit of all of the individual matches; the match for this well is shown in Figure 6A. Figure 6B shows the match using all wells. Although the drawdown data for each individual wells are not always well matched, the analytic curves bracket the observed drawdowns. Results of these analyses suggest that the aquifer test data are reasonably well matched by the Neuman solution for flow in unconfined aquifers.

For the Moench analysis, drawdown data from all wells were used to estimate a single set of aquifer parameters. The Moench solution can be conceptualized as two overlapping continua—aquifer parameters are determined for both a fracture network continuum and a matrix continuum. The results of the Moench analysis are summarized in Table 1 and illustrated in Figure 6C. The match to the Moench is not entirely convincing; however, it is similar to the match of the Neuman method for all wells (Figure 6B).

Table 1
Aquifer Parameters from Open-Hole Pumping Test as Estimated by the Neuman (1974) and Moench (1984) Solutions

Wells	T (m^2/min)	K (m/s)	S	S_y[1]	K_z/K_r	RSS[2]
Neuman analysis—Individual observation points						
1	0.12	1.3×10^{-4}	7.5×10^{-4}	.5	6.3×10^{-3}	0.063
2	0.14	1.6×10^{-4}	2.9×10^{-4}	.5	1.2×10^{-3}	0.024
3	0.14	1.6×10^{-4}	5.2×10^{-4}	.30	4.3×10^{-3}	0.006
4	0.11	1.3×10^{-4}	5.0×10^{-4}	.27	4.3×10^{-3}	0.005
6-2	0.15	1.7×10^{-4}	6.2×10^{-4}	.08	3.7×10^{-3}	0.008
7	0.08	9.5×10^{-5}	4.1×10^{-4}	.25	8.8×10^{-3}	0.053
8	0.13	1.5×10^{-4}	8.2×10^{-4}	.5	4.1×10^{-3}	0.038
Geometric mean	0.12	1.4×10^{-4}	5.3×10^{-4}			
Neuman analysis—Homogeneous, isotropic aquifer						
All wells	0.13	1.5×10^{-4}	5.0×10^{-4}	.20	2.6×10^{-3}	4.14
Moench analysis (all wells)						
K (m/min)	S_s	K' (m/min)	S'_s	S_w	S_f	RSS
7.6×10^{-3}	2.2×10^{-5}	1.5×10^{-8}	0.030	7.45	.080	3.79

[1]S_y was held constant at .20 for the analyses with multiple wells. For the individual analyses, it was included as an active curve-matching parameter.
[2]Residual sum of squares calculated by Aqtesolv.

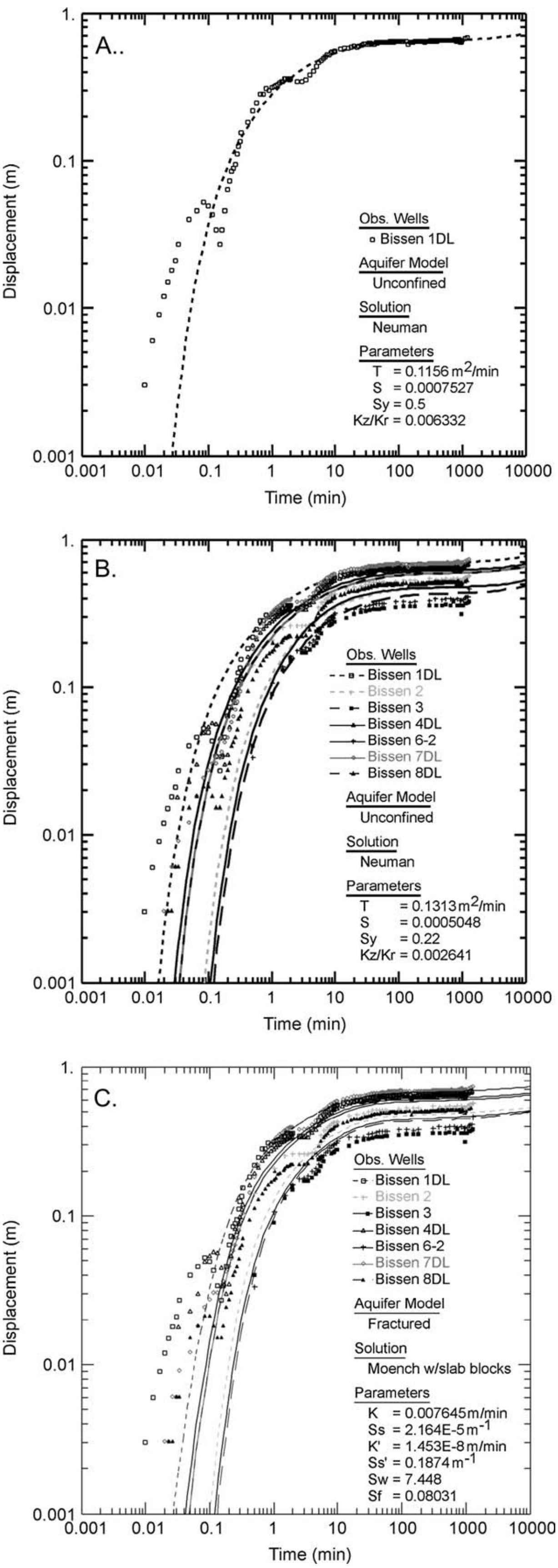

Figure 6. Results of pumping test analysis. (A) Observed time-drawdown data from hole 1 along with Neuman (1974) solution (individual well analysis). (B) Time-drawdown data from all holes (symbols) along with the Neuman solution (lines). Data from all wells were analyzed together to yield a single set of aquifer parameters. (C) Time-drawdown data from all holes along with the Moench (1984) solution.

Short-Interval Packer Tests

A straddle packer with an open interval of 0.27 m was used to perform slug tests at vertical intervals of 0.23 m in 11 of the small-diameter boreholes at the site. The short measurement interval was chosen to minimize the averaging inherent with most packer tests and to isolate and test individual fractures. Water levels were monitored using pressure transducers and recorded with a datalogger. Tests were initiated 10 to 15 min after packer inflation, and recovery was recorded for 10 to 15 min. Tests were analyzed using the Hvorslev (1951) method. To account for the geometry of boreholes and the packer assemblage, the following version of the Hvorslev equation was used:

$$K_{\mathrm{H}} = \frac{d^2 \ln \left[\left(\frac{mL}{D} \right) + \sqrt{1 + \left(\frac{mL}{D} \right)^2} \right]}{8LT_{\mathrm{o}}}$$

In this equation, m is a transformation factor, $\sqrt{K_{\mathrm{H}}/K_{\mathrm{V}}}$, which was assumed to equal 1 (i.e., isotropic conditions), K_{H} is horizontal hydraulic conductivity, d is the diameter of the standpipe, D is the diameter of the borehole, L is the length of the open interval, T_{o} is the time taken for the water level to recover to 37% of the initial change.

A best-fit line, fit to the recovery data, was used to calculate T_{o}. Test data can be found in Muldoon (1999b).

Although the short measurement interval was designed to isolate and test individual fractures and to minimize the averaging inherent with most packer tests, this methodology has limitations. Resulting hydraulic conductivities are still averaged over the length of the test interval; for matrix-dominated test intervals, this is probably appropriate. For fracture-dominated test intervals, the bulk of the flow is carried through an individual fracture or a small number of fractures; yet, the apertures of the fractures are a minor percentage of the overall test-interval length. As a result, the actual conductivity of the fracture(s) will be underestimated by this method.

The hydraulic conductivity is quite variable with depth, ranging over 5 orders of magnitude in each hole. Figure 7A shows the profile of hydraulic conductivity values for hole 4; results from other holes were quite similar except for holes 13 and 17, which appear to intersect vertical fractures at depth. Laterally continuous zones of high hydraulic conductivity appear to develop along some bedding planes (relative elevations 26.1, 25.1, and 23.0 m) and within the vuggy zones (~26.2-m and between 20.7- and 21.3-m elevation). Measured hydraulic conductivities from all 11 holes range from 4.2×10^{-3} to 7.0×10^{-9} m/s; the geometric mean of all tests is 3.0×10^{-6} m/s. Figure 7B shows the distribution of results from 372 packer tests; the histogram is interpreted to represent two distinct populations of fracture and matrix conductivities.

Hydraulic Head Distribution

The distribution of hydraulic head in fractured-rock aquifers can be difficult to measure because these aquifers commonly exhibit significant spatial and temporal

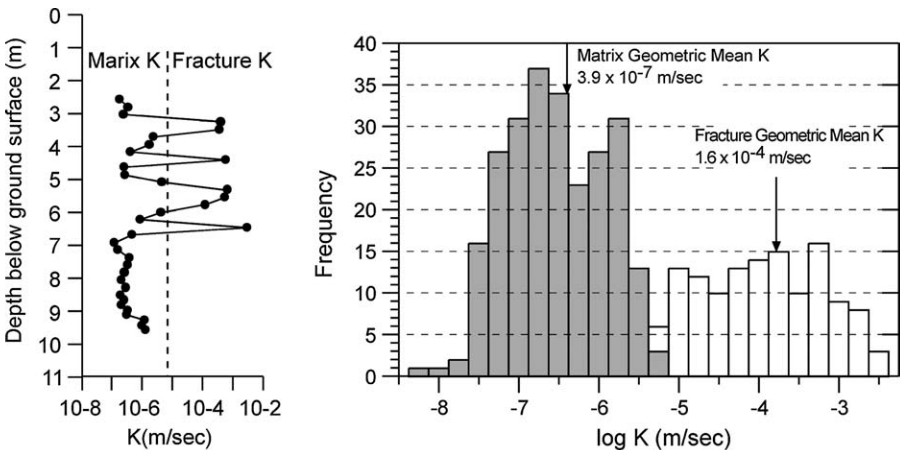

Figure 7. (A) Hydraulic conductivity profile for hole 4. X-axis of profile is logarithmic. (B) Histogram of 372 hydraulic conductivity values measured with short-interval packer tests. The geometric mean of all values is 3.0×10^{-6} m/s. Assuming that there are distinct populations of matrix and fracture hydraulic conductivities, the vertical lines indicate the geometric means of these individual distributions.

variations in head as well as complex responses to recharge events. Detailed measurements of water levels in wells in northern Door County (Bradbury and Muldoon 1992) suggest that hydraulic head within an open borehole may be controlled by a limited number of high-permeability fractures. Given that the head distributions in fractures may be very different from the head distribution in matrix blocks, it is clear that choice of monitoring method will significantly influence measured head distributions. Heads were monitored in open boreholes that provide measurements integrated over approximately a 10-m saturated section as well as in the discrete intervals of the multilevel samplers. All head measurements are included in Muldoon (1998). Water levels were measured using either a tape and popper or electrical water level measuring tapes that were marked in 0.01-feet increments. Measurements were recorded to ±0.005 feet. Hydraulic heads were subsequently converted to meters; the converted measurement error is ±0.0015 m. Contour maps presented subsequently use a minimum contour interval of 0.002 m.

Open Boreholes

Water levels were measured 17 times during the period August 1993 to June 1994; these data suggest a very dynamic flow system with water-level variations in individual wells of ~0.35 m. Data from the original eight open boreholes and a staff gauge installed in the drainage ditch in August 1993 suggest that ground water flowed west (Figure 8A) prior to the installation of the drainage ditch in June 1993. After ditch installation, the gradient became less steep and switched to the south-southeast (Figure 8B). Water levels from 10 additional boreholes, drilled in August 1993, provide a more detailed picture of the local water table response to recharge. At the site scale, local ridges and drain points develop due to the distribution of transmissive fractures. Figure 8C shows the water table configuration after 1 week without rain. Flow is generally toward the ditch; however, a ridge of higher heads has developed from the northeast to southwest corner of the site. After a heavy rain in September, the gradient reverses and water flows out of the ditch, forming a ridge of higher heads from the southeast to the northwest corner of the site (Figure 8D).

Multilevel Samplers

Installation of the multilevel samplers and piezometers allowed determination of the head distribution in discrete transmissive zones as well as assessment of the vertical components of the hydraulic gradient. Head data were collected primarily from spring to fall from June 1994 to January 1997. Approximately 20 rounds of head measurements were collected each year for a total of 4400 discrete head values.

Figure 9 shows water levels vs. time for hole 11. The magnitude of annual head variation is variable; in 1994, heads varied ~0.3 m (Figure 9A); in 1995, heads fluctuated over 1.3 m (Figure 9B). Vertical gradients also vary with time. The data from 1994 indicate consistently downward hydraulic gradients. During both 1995 and 1996, the vertical gradient exhibits a complete reversal in direction. In both years, there is an upward gradient in spring that gradually decreases in intensity throughout the summer. The reversal to downward gradients occurs in July 1995 (Figure 9B) and August 1996 (Figure 9C); the magnitude of the downward gradient then increases throughout the late summer and early fall. The site is located >0.5 mile from the nearest domestic well, and there are no high-capacity wells within several miles. The reversals in gradient are attributed to seasonal variations in the flow system.

The data from 1995 (Figure 9B) illustrate that open boreholes can complicate the distribution of head within individual fractures by providing "short-circuit" pathways between discrete-fracture zones. Several boreholes were open during 1994, the spring of 1995, and 1996. Strings of temporary packers were used to seal off the entire saturated length of all open boreholes during the period August to October 1995. Once the packers were installed, the magnitude of the vertical gradient between

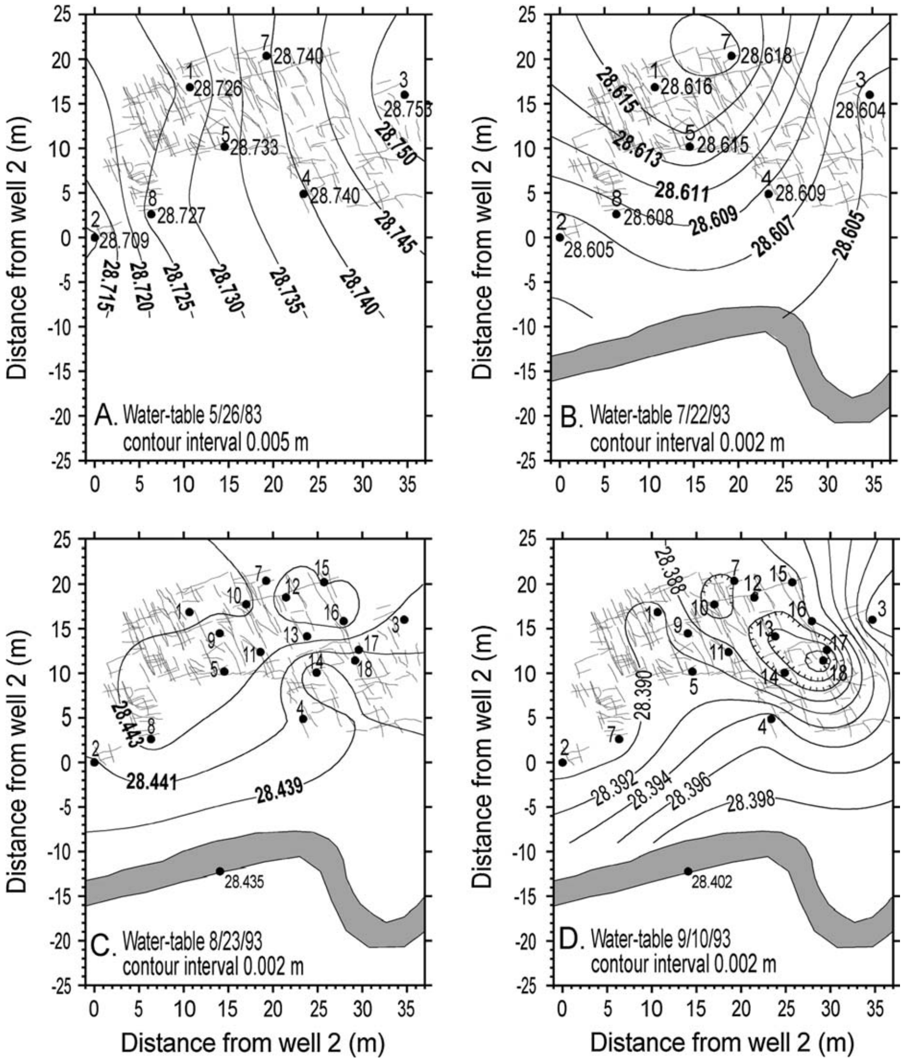

Figure 8. Hydraulic head distribution at Bissen Quarry in open boreholes. Measurement points are shown on each map; maps A and B also show head values. Note that the contour interval varies for the different plots. (A) Water table elevation on May 26, 1993, prior to installation of the drainage ditch. (B) Water table elevation on July 22, 1993, after installation of drainage ditch. (C) Water table elevation on August 23, 1993. (D) Water table elevation on September 10, 1993, after rain of 0.36 cm the previous day.

the top and bottom port in hole 11 increased from an average of 0.012 prior to packer installation to 0.029 after packer installation.

The spatial distribution of head, illustrated in Figure 10 for August 23, 1995, is complex. Horizontal gradients are quite low within individual fractures in monitoring zones 1, 3, 4, and 5 (28-, 25.1-, 24-, and 23-m elevation, respectively), and flow direction varies from one fracture to the next. Flow is generally eastward in zones 1 and 4 and to the southwest in zone 5. In the fracture at 25.1-m elevation (zone 3), a "drain point" or low in hydraulic head is centered on hole 9 where water appears to move downward through a vertical fracture. The vuggy zone at 26.2 m (zone 2) exhibits a slightly higher gradient and a central drain point. The vuggy zone at 21.9 m (zone 6) exhibits a relative strong and regular gradient to the south and west. Plots for other dates suggest that although the head fluctuated in response to recharge events, the head configurations for the various monitoring zones remained relatively stable in August and September 1995.

Tracer Velocities

Space limitations preclude a detailed description of test configurations, sampling frequencies, and analysis of the eight tracer tests conducted at the site; a more complete discussion can be found in Muldoon (1999a). The following summary is intended to provide sufficient information on test procedures to support the validity of the tracer velocities summarized in Figure 11.

Two natural-gradient tracer tests, conducted during the summer of 1995, consisted of pulse injections of ~40 L of a 1000 mg/L bromide solution into multilevel ports located in zone 2. Tracer was injected at port 12-2 for the first test and at port 14-2 for the second test. Tracer injection, at a rate of ~160 mL/min, continued for 4 h and was followed by an injection of ambient ground water from the site for an additional 4 h. Small-diameter injection and sampling lines were placed within the multiple-level samplers, and small rubber washers were installed on the end of the injection tubing and sampling lines to isolate the injection and monitoring ports from the water

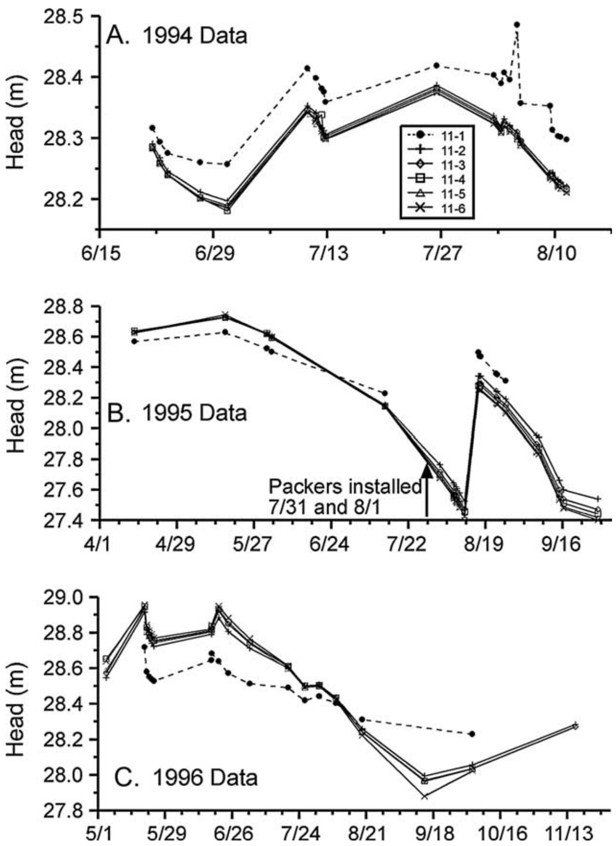

Figure 9. Water levels vs. time for multilevel ports in hole 11; 11-1 is the uppermost port.

standing in the multilevel tubing. The first test was monitored for 9 d, the second for 13 d. Samples were analyzed using ion-specific electrodes and ion chromatography. Breakthrough curves for both tests can be found in Muldoon (1999a). Test results indicate that horizontal and vertical fractures provide pathways for rapid ground water movement.

Tracer velocities can be calculated in many ways, including (1) first arrival of tracer, (2) peak arrival, or (3) center of mass of tracer breakthrough. Traditionally, the peak concentration or center of mass is used. Results of tracer tests can be analyzed by choosing a model (typically an analytic solution) and then adjusting the model parameters until the modeled breakthrough curve matches the observed data. The center of mass is determined by integrating under the modeled breakthrough curve. There are no published analytic solutions describing tracer movement in multiple-fracture pathways. Given this limitation, we chose to use peak arrivals to calculate velocities. For each test, tracer velocities were calculated as

$$\frac{\text{shortest distance between injection and monitoring port}}{\text{peak arrival time} - \text{midpoint time for tracer injection}}$$

The midpoint time of tracer injection was subtracted from the peak arrival time to account for the fact that tracer injection was not instantaneous. Calculated velocities from the natural-gradient tracer tests are presented in Figure 11. Velocities range from 0.5 to 32 m/d with a mean velocity of 8.6 m/d and a median velocity of 4.5 m/d. The histogram indicates that the majority of the observed velocities were between 0.5 and 5 m/d. Many of these values were calculated on the basis of the arrival of tracer at ports completed in zones of vuggy porosity, particularly in zone 6. Tracer reaching these ports, however, may also have traveled within a fracture for a portion of its flowpath. Thus, these values are believed to represent a mix of fracture and matrix velocities. The values >15 m/d were calculated from tracer breakthroughs where the inferred pathway, from injection to detection, was entirely within the fracture network. Thus, these values are believed to be representative of velocities within the fracture network.

Discussion

The hydrogeologic site characterization completed at the Bissen Quarry yielded an extensive and unique data set that can be used to evaluate the utility of the continuum and discrete-fracture approaches to aquifer characterization.

Hydraulic Conductivity Distribution

A simple comparison of hydraulic conductivity values measured at Bissen Quarry illustrates the difference between continuum and discrete-fracture approaches to site characterization quite well. Assume a horizontal hydraulic gradient of 0.0005 m/m (which is typical of the gradients measured at the site with the open boreholes) and an effective porosity of 1% for the densely fractured rock. Calculated ground water velocities are summarized in Table 2. The open-hole pumping test, a standard continuum characterization method, provided an estimate of the bulk hydraulic conductivity using the Neuman solution for unconfined aquifers and an estimate of the hydraulic conductivity of a fracture continuum using the Moench solution. The short-interval packer tests provide estimates of the hydraulic conductivity of discrete fractures. The gradient used in the previous calculation was based on head measurements from the open boreholes; as such, it is an oversimplification of the head distribution at the site. Nonetheless, this type of head data are frequently employed when trying to predict travel times from contaminated sites.

Velocities measured in two natural-gradient tracer tests conducted at the site ranged from 0.5 to 32 m/d (Figure 11). Comparison with the velocities calculated in Table 2 suggest that the hydraulic conductivity values determined by standard continuum techniques (the Neuman and Moench values from the open-hole pumping test) can adequately predict the low end of the measured tracer velocities; however, they are not appropriate for estimating the high end of the measured tracer velocities. These faster velocities are often the ones of concern when trying to estimate the potential velocity of a contaminant moving off-site. The hydraulic conductivity values measured by the discrete-fracture approach (such as the maximum value from the short-interval packer tests) are more appropriate for prediction of the faster tracer velocities.

Pumping Test Response

Some investigators (e.g., Bradbury et al. 1991; Hickey 1984; Davis and DeWiest 1966) have suggested

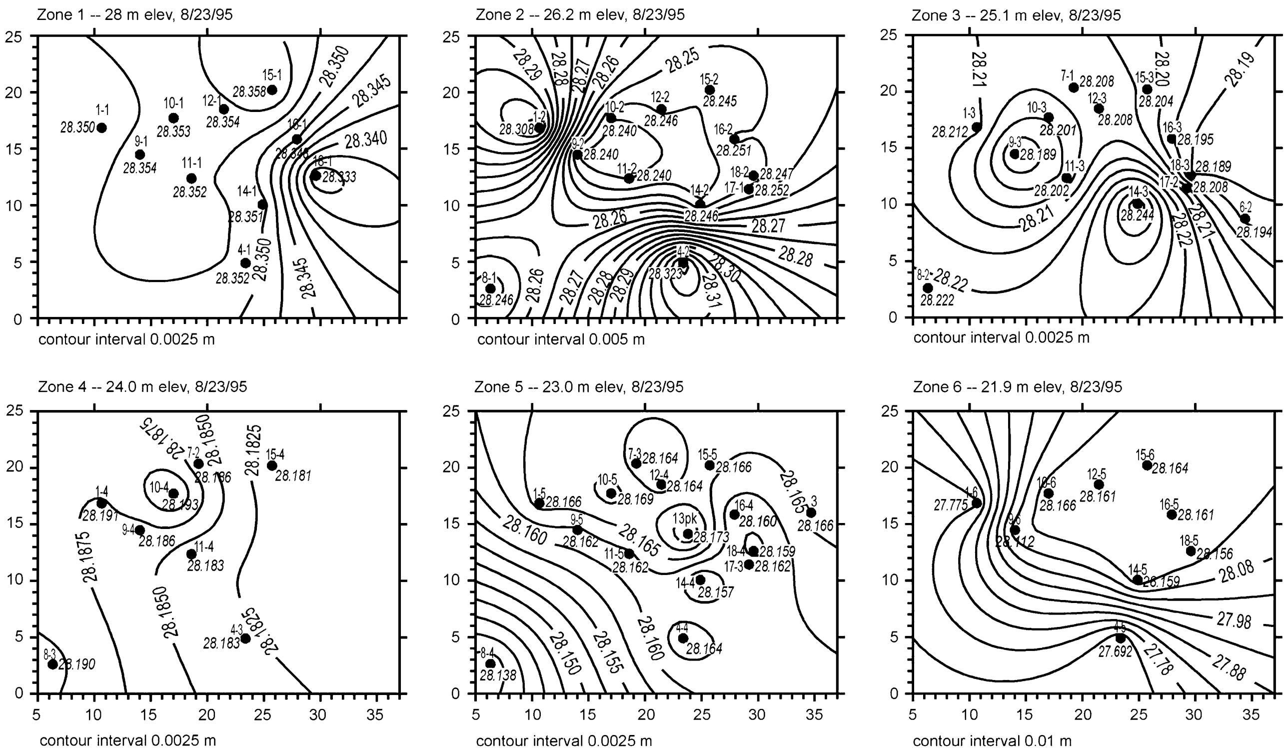

Figure 10. Hydraulic head distribution measured on August 23, 1995, for specific monitoring zones located in horizontal fractures and vuggy zones. Measuring points, shown as nonitalicized text, are designated 4-2 for port 2 in hole 4. Measured head values are shown in italicized text. Note that the contour interval varies for the different plots.

that an aquifer's response to pumping provides a method of evaluating whether the porous medium approximation is appropriate. The following behaviors are considered to be indicative of porous medium behavior:

- Drawdowns observed in pumping tests increase linearly with increases in the discharge rate of the pumped well when values are plotted on arithmetic axes
- Time-drawdown curves for observation wells located in two or more different directions from the pumped well are similar in shape
- A circular or elliptical drawdown cone for a pumping test using multiple observation wells.

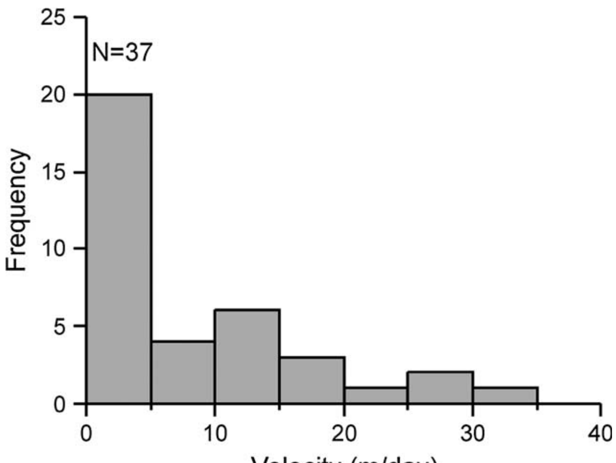

Figure 11. Histogram of tracer velocities observed in two natural-gradient tracer tests conducted during the summer of 1995.

The hydrogeologic characterization of the Bissen Quarry illustrates the ambiguity of pumping test data quite well. The elliptical drawdown cone (Figure 5A) observed in the open-hole pumping test suggests a uniform but anisotropic porous medium. Drawdown curves from the open-hole pumping test (Figure 5B) are similar in shape for each monitoring point and are adequately matched by standard analytic solutions for flow to wells

Table 2
Comparison of Measured Hydraulic Conductivity Values and Calculated Velocities

Test Method	Hydraulic Conductivity (m/s)	Velocity[1] (m/d)
Open-hole pumping test		
Neuman		
Individual wells		
Maximum	1.7×10^{-4}	0.72
Minimum	9.5×10^{-5}	0.41
Geometric mean	1.4×10^{-4}	0.60
All wells	1.5×10^{-4}	0.65
Moench		
Fracture *K*	1.3×10^{-4}	0.55
Packer tests		
Maximum	4.2×10^{-3}	18
Minimum	7.0×10^{-9}	3.0×10^{-5}
Geometric mean	3.0×10^{-6}	0.013

[1]Calculations assume a horizontal hydraulic gradient of 0.0005 m/m and an effective porosity of 1%.

in a porous medium (Figure 6). Other workers have used similar results to conclude that a fractured-carbonate aquifer behaved as a continuum and that porous medium-based modeling approaches were suitable for the delineation of well capture zones based on time-of-travel criteria. Yet, the Bissen tracer experiments (Muldoon 1999a) suggest that a continuum characterization of the study site would grossly underestimate both ground water and contaminant velocities.

Head Distribution

The head data from Bissen Quarry can be used to support several differing conceptualizations of flow at the site. The temporal fluctuations of water levels in the open-hole wells and the multilevel samplers indicate that the site responds rapidly and uniformly to recharge events. The similarity of water-level response to recharge suggests that the site is well integrated hydraulically and that perhaps a continuum conceptualization is valid. The three-dimensional distribution of head (Figure 10), however, suggests that the site behaves as a discretely fractured medium and that vertical fractures and a limited number of horizontal, bedding-plane, parallel fractures provide the primary pathways for flow.

Summary and Conclusions

Even in a carbonate aquifer containing a dense network of vertical and horizontal fractures, a continuum approach using traditional monitoring wells and piezometers is probably inadequate to characterize and/or monitor ground water movement and contaminant concentrations for the purposes of regulatory monitoring or site remediation. Both the head data and the hydraulic conductivity measurements from Bissen Quarry suggest that the fracture network geometry must be considered during site-characterization and monitoring system design. Standard long-interval monitoring wells, with a 0.9- to 3.0-m (3- to 10-feet) screen, are not capable of providing the detailed head information required for determination of ground water flowpaths at site-specific scales in fractured-carbonate aquifers. Traditional open-hole pumping tests yield an average or bulk hydraulic conductivity that is not adequate for predicting rapid ground water travel times through the fracture network. In addition, the pumping test response does not appear to be an adequate tool for assessing whether the porous medium approximation is valid.

The characterization of Bissen Quarry was a research effort, and few contaminated sites are characterized to this level of detail. In addition, the geometry of the vertical fracture sets was easily characterized because these fractures were exposed on the quarry floor. Ideally, monitoring systems for similar densely fractured-carbonate aquifers should be designed to monitor vertical fractures as well as the horizontal bedding-plane fractures. Although vertical fractures are best monitored by angled boreholes, the high cost of these holes precluded their use in this study. Monitoring systems designed to monitor the horizontal high-permeability pathways are cost effective and relatively likely to intercept contaminants. Given the importance of designing a monitoring system that intersects the fracture network, it is necessary to develop site-characterization tools that will locate the hydraulically significant fractures.

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