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EXPERIENCES WITH AQUIFER TESTING AND ANALYSIS IN FRACTURED LOW-PERMEABILITY SEDIMENTARY ROCKS EXHIBITING NONRADIAL PUMPING RESPONSE[1]

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ABSTRACT

Multiple-well aquifer pumping tests have been used successfully to measure the bulk hydraulic properties of limestone and shale formations of the Conasauga Group of East Tennessee and to define directional components in transmissivity associated with joints and small-scale folds. This experience demonstrates that multiple-well pumping tests can be used to measure the characteristics of low-permeability fractured rocks, and it illustrates the application of data interpretation techniques that are based on models of nonradial aquifer pumping response. Analytical models that have been used to interpret pumping test data include models for simple anisotropic response and for complex pumping response in an anisotropic aquifer intersected by a single high-conductivity vertical fracture. Comparisons of results obtained using nonradial flow methods with those obtained using traditional (radial flow) analytical methods indicate that the error from radial flow methods is generally less than an order of magnitude, an insignificant error in most low-

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permeability settings. However, the nonradial flow methods provide much more information on structural controls on groundwater movement.

Special challenges encountered in conducting aquifer pumping tests in this hydrogeologic environment include selecting a pumping rate that can be sustained after fracture storage is depleted and laying out a test configuration that is consistent with the test geometry required by the nonradial flow interpretive models. Effective test design and data interpretation thus require extensive insight into site geology.

INTRODUCTION

One important difference between low- and high-permeability rocks may be the dominant role that fractures and other secondary features often play in the hydrology of low-permeability media. When the hydraulic conductivity of the matrix is low, the contrast between the properties of the matrix and secondary features becomes quite large, so the secondary features (e.g., fractures) are likely to control such hydrologic phenomena as solute transport and system response to pumping. The hydraulic heterogeneity of low-permeability rocks, which is due in large part to the hydraulic dominance of secondary features, is one important reason that conventional aquifer pumping test techniques are not widely used in low-permeability media. Aquifer pumping tests have been used on a few occasions, however, to investigate the hydraulic characteristics of fractured low-permeability sedimentary rocks on the U.S. Department of Energy's Oak Ridge Reservation in East Tennessee. In this paper we review some of that experience and present our observations on the uses and limitations of conventional aquifer testing procedures in this type of hydrogeologic environment.

HYDROGEOLOGIC SETTING OF THE AQUIFER TESTS

The Oak Ridge Reservation, the site of the aquifer pumping tests discussed here, is located in the Ridge and Valley province of the southern Appalachian Mountains. The overall character and alignment of geologic and topographic features in this province are controlled by a series of thrust faults that developed during the Appalachian orogeny. The pumping tests have been conducted in strata of the Middle to Late Cambrian Conasauga Group, which is about 550 m thick in the Oak Ridge area and occurs on the Reservation in two parallel valley outcrop belts. Lithologically, the Conasauga is a very heterogeneous association of siltstones, silty limestones, shaley limestones, limey shales and mudstones, subdivided stratigraphically into six formations (Haase and Vaughan, 1981). In ascending order, these are the Pumpkin Valley Shale, Rutledge Limestone, Rogersville Shale, Maryville Limestone, Nolichucky Shale, and Maynardville Limestone. Regional thrust fault motion caused much internal structural deformation in the Conasauga Group. Deformation structures include low-amplitude isoclinal folds, secondary bedding thrust faults, high-angle reverse faults, and two major joint sets normal to bedding at about 0 and 90° to strike (Sledz and Huff, 1981).

The C nasauga is usually treated as a single hydrostratigraphic unit, and in many areas it is quite difficult to differentiate the geologic units that make up the Group. Well capacities in the Group are too low to encourage extensive use as a water supply aquifer, though the Conasauga does supply a few area domestic wells. Most radioactive waste disposal on the Reservation has been on or in strata of the Conasauga Group. Permeability associated with primary porosity is very low in the Conasauga; movement and storage of water are usually attributed to secondary porosity. Sledz and Huff (1981) hypothesized, based on study of the Pumpkin Valley Formation, that permeability in the Conasauga is developed along bedding planes and along the two joint sets.

AQUIFER TEST CASE HISTORIES

Several multiple-well aquifer pumping tests have been conducted in the Conasauga in connection with hydrogeologic investigations of sites that have been used or considered for disposal of radioactive wastes. Drawdown patterns observed in these tests indicate that flow in response to pumping is nonradial. This complicates data interpretation because traditional models for aquifer test analysis are based on radial flow. We have found, however, that meaningful qualitative and quantitative interpretation of test results is feasible, using flow models developed for fractured rock s ttings. We believe this experience demonstrates that it is possible to obtain useful information by using conventional aquifer testing techniques in a low-permeability sedimentary rock. Two case histories of aquifer tests in the Conasauga illustrate some special challenges in test design, implementation, and data interpretation that would be encountered in similar hydrogeologic settings.

Case 1: *Tests in the Maryville Limestone*

Two aquifer pumping tests were conducted at a site on the Maryville Limestone as part of a field study on factors in the performance of low-level radioactive waste disposal facilities in humid regions. The site was instrumented with 12 15-cm-diameter wells, 10 to 15 m deep, with 1.2-m screens and gravel packs. All observation wells were less than 40 m from the pumping well (Figure 1). Geologic and geophysical investigations indicated that the site is bisected by a pair of narrow, tight anticlinal folds; the fold axes are intensely fractured (Vaughan et al., 1982).

The first pumping test at this site is described by Vaughan et al. (1982). Partial recoveries of the water level in the pumped well occurred several times during the test. The water-level recoveries led field personnel to believe that the pumping rate was too low, so the pumping rate was increased several times (finally to 6.4 L/min) during the test, with the result that the pumping well was dewatered after 7 h and test results could not be interpreted effectively.

The experience of the first test was used as a basis for selecting a sustainable pumping rate (3.3 L/min) for the second test. To ensure a relatively constant pumping rate in the second test the water pumped was discharged to calibrated carboys whose fill rate was monitored by project personnel. As in the first test, however, water levels in the pumped well rose abruptly (as much as 1 m in 60 min) several times during the pumping period, which lasted 24 h. Measured drawdown at the end of the pumping period is plotted in Figure 1; the zone of greatest drawdown is not concentric about the pumping well, but coincides roughly with the location of the two anticlinal folds that were identified in geologic investigation of the site. Wells 1, 2, 9, and 10, which are located in this zone, showed water-level increases at the same times as some of the water-level recovery episodes in the pumping well, which is also located on or near the two fold axes. This observation lent further credence to a hypothesis that the aquifer's hydraulic response is controlled by the local bedrock structure.

Results of this second pumping test were interpreted (Smith and Vaughan, submitted) according to a method described by Gringarten and Witherspoon (1972). This method is based on a conceptual model of a homogeneous, horizontally anisotropic aquifer of infinite areal extent, fully penetrated by a straight, planar, transmissive vertical fracture of finite length, with the pumping well located at the center of the fracture. Groundwater flow in response to pumping is toward the fracture, which transmits the water to the pumping well.

Selection of the Gringarten-Witherspoon model as the best available approximation of hydraulic response at the test site was based on inference from geologic information and on graphical analysis of test results. First, the deviation of the observed drawdown pattern from the classic concentric pattern expected for radial flow suggested that flow in response to pumping was nonradial. The coincidence of the zone of greatest drawdown with the fold axes suggested that zones of dense fracturing in the fold axes might control aquifer pumping response. Semilog plots of observation well drawdown vs elapsed pumping time were distinctly curvilinear, not the straight-line plots predicted by radial flow theory.

Plots of drawdown vs the square root of elapsed pumping time ($t^{1/2}$) are linear, which is the pattern expected when flow traces a linear flow path to a planar sink, such as a transmissive fracture in communication with the pumping well (Jenkins and Prentice, 1982). Jenkins and Prentice (1982) used graphs of drawdown vs $t^{1/2}$ to analyze pumping test results from sites with fractures intersecting the pumping well. Their method could not be applied successfully with these data, however, suggesting a possible deviation from the method's assumption of an isotropic aquifer.

Finally, the shapes of graphs of drawdown data were compared with the shapes of published theoretically derived type curves characteristic of a variety of aquifer geometries. Log-log plots of drawdown vs time for five observation wells are shown in Figure 2. Gringarten and Witherspoon's (1972) family of log-log drawdown-vs-time type curves for an anisotropic aquifer intersected by a vertical fracture seemed to show the best overall resemblance to site data. There is no single vertical fracture at the test site, but it is reasonable to hypothesize that near-vertical zones of intense fracturing in the fold axes control the aquifer's hydraulic response and can be modeled as a single vertical fracture.

In the model presented by Gringarten and Witherspoon (1972), the characteristic shape of drawdown-vs-time plots for observation wells depends on both the location of the observation well relative to the master fracture and the ratio of the principal transmissivities of the aquifer matrix. Because the Gringarten-Witherspoon method uses many different type curves, it was much more difficult to apply than the conventional curve-matching methods for radial flow conditions. It was not sufficient merely to match the field data to a type curve and solve the associated match-point equations, but it was first necessary to select a type curve that was appropriate for the location of the observation well relative to the pumping well and the master fracture. As with any interpretive technique involving type-curve matching, it is possible to match virtually any data set to more than one type curve. Each type-curve match point is associated with three equations involving six unknown variables (T_x, T_y, S, x, y, and x_f; see "Notation" for definitions of variables). Unless independent estimates are available for some of the variables, a complex iterative process of curve matching and solution of simultaneous equations is required to arrive at an approximation of aquifer parameters consistent with data from several observation wells.

Estimates of aquifer parameters obtained using the Gringarten-Witherspoon method are presented in Table 1. These estimates are consistent with our tentative hypothesis that a zone or zones of intense fracturing in the axes of the two anticlinal folds controlled the aquifer's response to pumping and could be modeled as a single vertical fracture. We did not obtain a single solution that simultaneously satisfied all of the equations for all of the observation wells. Instead, we list (Table 1) estimates for each observation well that are generally consistent with data for the other observation wells and with a single conceptual model for the entire site. Figure 3 illustrates the effective location of the master fracture, as determined from the calculated x-y coordinate locations of the various observation well match points, together with the axial traces of the two anticlinal folds mapped at the site. Although a more precise solution could have been obtained using computer optimization methods, we believe that because of deviations from the assumptions underlying the Gringarten-Witherspoon method (e.g., inhomogeneities in the aquifer system, effects of other fractures on the response of some observation wells, approximation of the complex fold axis structure as a single planar vertical fracture), a more precise solution is not scientifically justifiable. However, Table 1 does list our best estimates of the average equivalent porous-medium parameters of the aquifer matrix. These estimates are based on geometric means of the parameter estimates obtained for the individual observation wells and on examination of the ranges of values obtained in a trial-and-error solution process.

Table 1. Solutions for the Maryville Limestone aquifer pumping test

	Sringarten-Witherspoon analysis								Theis analysis[1]	
		Aquifer parameters								
		Transmissivity (10^{-5} m^2/s)					Well location[2]			
Well	Type curve used	$(T_xT_y)^{1/2}$	T_x	T_y	S	x_f (m)	x (m)	y (m)	T (10^{-5} m^2/s)	S
1	r_D=0.5, x=0	1.7	3.7	0.74	2.9×10^{-3}	15	0	3.4	2.7	5.1×10^{-4}
2	r_D=1, x=0	1.8	5.0	0.61	9.1×10^{-3}	20	16	4	--	--
3	--	--	--	--	--	--	--	--	7.3	1.0×10^{-2}
8	r_D=1, x=0	5.1	11.	2.3	1.4×10^{-2}	20	1	9	6.2	3.0×10^{-2}
9	r_D=1.1, y=0	0.60	2.3	0.15	4.7×10^{-3}	15	13	2.5	2.1	1.0×10^{-2}
10	r_D=0.8, y=0	1.2	2.5	0.58	2.9×10^{-3}	18	7.5	0	2.9	3.3×10^{-4}
Best estimates:		1.6	3.5	0.69	5.0×10^{-3}		Geometric means:		3.7	3.5×10^{-3}

[1]Report by Davis et al., 1984. Reference reported arithmetic mean values; geometric means calculated by present authors.

[2]Relative to the center of the hypothetical vertical fracture.

Our analysis of the Maryville Limestone aquifer test, as summarized in Table 1, indicates that the aquifer matrix is relatively transmissive for a "low-permeability" rock, but has a very low storage coefficient (S). The low storage coefficient accounts for the Conasauga Group's characteristic poor well yields and may be largely responsible for the Group's reputation as a low-permeability rock. Matrix transmissivity parallel to strike (T_x) appears to be about 5 times the matrix transmissivity perpendicular to strike (T_y), and locally the aquifer's response to pumping is strongly dominated by a high-transmissivity zone associated with the axes of the two anticlinal folds that bisect the site. Estimates of hydraulic parameters have not been obtained for the high-transmissivity zone, but the estimates of the directional components of matrix transmissivity and evidence of the hydraulic importance of the fold axes could be very useful in predicting contaminant transport behavior in this unit.

In spite of the evidence of nonradial flow, an attempt was also made to interpret the results of the Maryville Limestone aquifer pumping test according to traditional radial flow techniques. Numerical results of an analysis using the Theis solution (reported by Davis et al., 1984) are included in Table 1. The transmissivity estimated by the Theis method is larger than the geometric mean transmissivity estimated by the Gringarten-Witherspoon method, but the estimates of storage coefficient are quite close. The Theis analysis may overestimate aquifer transmissivity because it does not treat the highly transmissive fold axes separately from the aquifer matrix. Differences between the estimates of aquifer parameters generated by the two methods are not large enough to justify using the more difficult Gringarten-Witherspoon method. The Gringarten-Witherspoon analysis is preferred, however, because the conceptual model on which it is based is a better approximation of site conditions than is the radial flow model and because it yields important qualitative and quantitative information on structural controls on groundwater movement that might not be available from other sources.

Case 2: Test in the Nolichucky Shale

Alexander et al. (1983) reported on an aquifer test conducted in the Nolichucky Shale Formation on another part of the Oak Ridge Reservation. The nine wells used in the test were 21 m deep, screened through the lower 15 m and gravel-packed to about 3 m below ground surface. Casing diameters were 15 cm for the pumping well and 10 cm for the eight observation wells. Coordinate locations of observation wells are given in Table 2.

Pumping in this test was for 24 h, at a rate of 11.4 L/min, monitored by a flow meter on the discharge valve. As in the Maryville Limestone aquifer tests, water levels in some of the observation wells rose during the pumping period. The most significant rises in water level were recorded in wells 3 and 7. In well 3, a water-level rise of approximately 2 m occurred over a 4-h period beginning after 3 h of pumping. The water level in well 7 began to rise after 4 h of pumping, and rose 0.6 m in a 5-h period. Water-level data for the pumping well were not reported, but it is likely that the water level in this well also rose during the pumping period.

The drawdown pattern observed at the end of the pumping period (Table 2) was not concentric about the pumping well, but instead observed drawdown was greater in the wells aligned along bedrock strike than in observation wells at other orientations to the pumping well. This suggested aquifer anisotropy associated with bedrock structure. The drawdown pattern was also distinctly asymmetric, in that the wells to the west and south of the pumping well (wells 2, 3, 6, and 7) exhibited somewhat greater drawdowns than wells at similar distances and orientations to the east and north (wells 1, 4, 5 and 8). Log-log graphs of drawdown vs time, presented by Alexander et al. (1983), follow the Theis curve at early times but tend to flatten out at later times, resembling the characteristic type curves for response of a leaky artesian aquifer or for a site near a recharge boundary. Alexander et al. (1983) interpreted this pattern as indicative of a leaky artesian aquifer and analyzed the test results according to a published radial-flow method for

Table 2. Results of the Nolichucky Shale aquifer pumping test, with results of data analysis according to a leaky artesian aquifer model[1]

Well	Coordinate location[2] y (m)	Coordinate location[2] x (m)	Drawdown at end of test (m)	Drawdown data T (m^2/s)	Drawdown data S	Recovery data T (m^2/s)
1	0.9	5.8	3.48	3.5×10^{-5}	3.7×10^{-4}	2.3×10^{-5}
2	-6.1	0.3	1.60	1.8×10^{-5}	3.3×10^{-3}	1.9×10^{-5}
3	-0.6	-6.1	4.91	--	--	5.3×10^{-6}
4	12.5	-0.9	0.40	4.2×10^{-5}	2.9×10^{-3}	9.5×10^{-5}
5	10.0	7.3	0.57	--	--	1.5×10^{-4}
6	-9.8	-7.3	1.91	1.1×10^{-5}	4.6×10^{-4}	1.9×10^{-5}
7	-1.2	-15.2	2.71	5.1×10^{-6}	1.7×10^{-4}	1.0×10^{-5}
8	1.2	23.8	0.68	2.2×10^{-5}	5.7×10^{-4}	9.9×10^{-5}
Geometric means:				1.8×10^{-5}	7.4×10^{-4}	3.0×10^{-5}

[1]Alexander et al., 1983. Reference reported arithmetic mean values; geometric means calculated by present authors.

[2]Distances from the pumping well measured along the axes of the site coordinate system. The x-axis is approximately parallel to bedrock strike.

aquifer test interpretation in leaky artesian systems. Table 2 lists their estimates of aquifer transmissivity and storage coefficient; no estimates of confining-layer characteristics were reported in the reference.

The aquifer characteristics reported by Alexander et al. (1983) are for an equivalent isotropic porous medium and do not include any measurements of the aquifer anisotropy, heterogeneity, or apparent leakage effect observed during the te:t. We examined the test data to determine whether alternative data-interpretation models might better approximate test conditions and yield more realistic estimates of aquifer characteristics. Observation well drawdown and recovery data were plotted against log t, and the resulting graphs were mostly straight lines or straight-line segments, whereas graphs of drawdown vs $t^{1/2}$ did not show a consistent pattern. These characteristics of the data indicated to us that aquifer response was probably not controlled by a major structural feature and that methods for interpreting aquifer test results in a homogeneous anisotropic aquifer might therefore be appropriate for interpreting results from this test. We also noted that the shape of the log-log data plots is not diagnostic of a leaky artesian aquifer system, but could also result from proximity to a recharge boundary or delayed release of water from aquifer storage. There is no compelling evidence that the shallow portion of the Nolichucky Formation stressed during this test is a leaky artesian aquifer; instead, the most plausible explanation we have found for the observed time-drawdown behavior is that the Nolichucky behaves like a double-porosity medium, consisting of a system of porous, low-permeability matrix blocks and higher-permeability fissures that transmit water readily but have little storage capacity.

The geologic setting of the Nolichucky Shale aquifer test (i.e., jointed shale) and the observed response of the aquifer to pumping are both consistent with a double-porosity aquifer model. As Gringarten (1982) points out, the characteristic pumping response of a double-porosity medium observed in observation wells open to the fissures is very similar to that of an unconfined aquifer exhibiting "delayed yield." At early times water supply to the pumping well comes only from the fissures, and the values for aquifer transmissivity and storage coefficient estimated from early-time response data are representative only of the fissures. As pumping proceeds, water stored in the matrix moves into the fissures and is supplied to the pumping well. The values for aquifer storage coefficient estimated from late-time response data represent the greater storage capacity of the aquifer matrix. At intermediate times, there is a temporary plateau in drawdown-vs-time graphs, and during this transition period, the aquifer response could be mistaken for the characteristic response of a leaky artesian aquifer or an aouifer with a recharge boundary. We suspect that the Nolichucky Shale pumping test ended before the aquifer's late-time behavior was clearly established, leading Alexander et al. (1983) to misinterpret the double-porosity response pattern as the response of a leaky artesian aquifer.

We concluded from the observations summarized above that the most appropriate model for interpreting the results of the Nolichucky Shale aquifer test would probably be one of a homogeneous, horizontally anisotropic, double-porosity medium. There are few published analytical solutions specific to this type of system, but Gringarten (1982) reviews several theoretically derived solutions for aquifer pumping test analysis in double-porosity media, and Papadopulos (1965) has modified simple radial-flow isotropic-medium solutions to solve for the directional components of aquifer transmissivity in anisotropic media. We were not able to make full use of the solutions for double-porosity media because the pumping period was not long enough to permit observation of the system's late-time response. Instead we estimated the equivalent porous-medium hydraulic properties of the fissure system by matching the early-time drawdown data to the conventional Theis curve and solving for the anisotropic-medium properties by the method of Papadopulos (1965). If late-time pumping test results had been available, it might also have been possible to estimate the storage coefficient and other hydraulic characteristics of the matrix, using double-porosity techniques (Gringarten, 1982).

Table 3 lists the results of our analysis of the Nolichucky Shale aquifer pumping test according to the homogeneous anisotropic aquifer model. In an ideal homogeneous anisotropic medium, traditional Theis analysis of drawdown data would yield the same value of transmissivity for all observation wells [actually, this is the geometric mean of the directional components of transmissivity, $(T_x T_y)^{1/2}$], but calculated values of the storage coefficient would vary. The transmissivity values calculated from our Theis curve match points for early-time drawdown data from seven of the Nolichucky Shale observation wells are included in Table 3; they range over nearly one order of magnitude,[1] indicating the heterogeneity of the Nolichucky Shale aquifer. In the method of Papadopulos (1965), type-curve match points from three observation wells at different angles to the pumping well are sufficient to determine the aquifer storage coefficient (in this case, the storage coefficient of the fissure system), the orientation of the principal axes of transmissivity, and the magnitudes of the components of transmissivity along these axes. Attempts to apply the Papadopulos solution with data from various sets of three observation wells were unsuccessful, yielding results that were either counterintuitive (e.g., orientations of the transmissivity axes that were inconsistent with field observations) or mathematically illegal (e.g., negative values for aquifer parameters). We attribute this to the heterogeneity of the aquifer; different regions of the aquifer seemed to respond differently to pumping, and there are few possible groupings of three wells that are at different orientations to the pumping well and in the same general region of the aquifer. To overcome this problem, we reduced the number of unknown variables by assuming that the maximum transmissivity was

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[1]The square of this quantity is used in the Papadopulos (1965) solution, which assumes that this term has the same value for all members of a pair or triplet of observation wells. In applying the Papadopulos method, we followed a suggestion of Neuman et al. (1984), and substituted the geometric mean of the values determined for the individual wells in each pair or triplet.

Table 3. Analysis of the Nolichucky Shale aquifer pumping test according to a homogeneous anisotropic aquifer model

Type-curve matching results		Results of Papadopulos analysis using data from pairs of observation wells				
Well	$(T_x T_y)^{1/2}$ (m^2/s)	Well pair	T_x (m^2/s)	T_y (m^2/s)	T_x/T_y	S
1	1.3×10^{-5}	1&2	2.7×10^{-5}	1.3×10^{-5}	2.1	1.1×10^{-3}
2	2.8×10^{-5}	1&5	3.7×10^{-5}	6.8×10^{-6}	5.4	1.4×10^{-3}
3	--	2&8	4.5×10^{-5}	1.5×10^{-5}	2.9	1.3×10^{-3}
4	7.0×10^{-5}	4&8	5.7×10^{-5}	3.0×10^{-5}	1.9	1.6×10^{-3}
5	2.0×10^{-5}	5&8	6.0×10^{-5}	8.1×10^{-6}	7.4	1.7×10^{-3}
6	1.5×10^{-5}	6&7	1.5×10^{-5}	8.8×10^{-6}	1.7	4.0×10^{-4}
7	9.1×10^{-6}					
8	2.5×10^{-5}					
Geometric means:			3.6×10^{-5}	1.2×10^{-5}	3.0	1.1×10^{-3}

aligned with bedrock strike and the other principal axis of transmissivity was perpendicular to strike (this assumption was supported by the observed drawdown pattern) and used the Papadopulos (1965) solution to calculate estimates of aquifer parameters from data for six pairs of wells located in the same general regions of the aquifer. The results of this analysis are given in Table 3.

The aquifer characteristics calculated in the two different analyses of the Nolichucky Shale aquifer test differ very little: the geometric mean of the average T_x and T_y would be very close to the average value of T calculated in the leaky artesian aquifer analysis of drawdown data, and the two calculated values of S are quite close. The anisotropic aquifer analysis, however, provides an explanation of the raw data that is more complete and internally consistent than that provided by the leaky artesian aquifer analysis. Not only did the anisotropic aquifer analysis provide quantitative estimates of aquifer anisotropy, but estimates of average aquifer parameter values (T_x, T_y, and S) vary by less than a factor of 5 among the six well pairs, compared with differences of up to a factor of 20 among the six wells considered in the leaky artesian aquifer analysis. Both methods estimate only the equivalent porous-medium parameters of the fissure system; a longer pumping period is needed to supply the data required to obtain estimates of matrix characteristics.

DISCUSSION

The two case histories of aquifer pumping tests described here show that conventional aquifer pumping test techniques can be useful investigative tools in fractured, low-permeability sedimentary rock. In each case, our analysis of the test data according to a nonradial flow model provided insight into the large-scale hydraulic character of the site, together with estimates of the equivalent porous-medium transmissivity, hydraulic anisotropy, and storage coefficient of the fracture system. Analyses according to radial flow models yielded fewer parameter estimates, less qualitative insight into site hydrology, and an overestimate of transmissivity for the site affected by a major hydraulic discontinuity.

Parameter estimates for the two formations tested are quite similar (Tables 1 and 3). They indicate higher transmissivity than would be expected in a true low-permeability material, moderate anisotropy, and very little hydraulic storage in the fracture system. There was also an indication that the Nolichucky Shale Formation behaves like a double-porosity medium with significant hydraulic storage in its low-permeability porous matrix, but no estimates of matrix storage were obtained.

Our observations, together with the work of Sledz and Huff (1981), suggest that the Conasauga Group can be conceptualized as a medium in which flow occurs mainly in an intersecting network of discontinuous fractures, and in which maximum hydraulic conductivity is associated with the intersections of fracture sets, in this case the intersection of bedding plane fractures with a strike joint set. Long et al. (1982) have shown that such a medium is usually anisotropic and can appear very heterogeneous when observed on a relatively small scale. The degree of heterogeneity decreases, however, as the scale of observation increases. Multiple-well aquifer pumping tests are an appropriate tool for measuring the larger-scale "average" hydraulic properties of the flow medium and thus resolving some of the scatter in parameter measurements from single-well or laboratory tests. The experiences described here demonstrate, however, that hydraulic heterogeneity can still be significant at the scale of aquifer testing and that this heterogeneity can interfere with data interpretation by nonradial flow models. We also observed that minor structures can be major hydraulic discontinuities (e.g., the fold axes at the Maryville Limestone test site) at the scale of a waste disposal site investigation.

We believe that the conditions encountered in the Conasauga may be fairly typical of low-permeability sedimentary environments. Difficulties encountered in conducting these tests may therefore be met in aquifer testing in other low-permeability sedimentary rocks, and the case histories presented here suggest refinements in testing procedures to enhance the usefulness of aquifer pumping tests in this hydrogeologic environment. This environment challenges the investigator to anticipate site conditions and to plan for anisotropy, heterogeneity, and other structural controls on groundwater flow when designing tests.

The well layouts at the test sites were inadequate to define the extent of hydraulic influence of the fold axis at the Maryville Limestone site (the pumping well was on the site periphery) or to provide the optimum geometric arrangement of wells for applying anisotropic flow models to results of the Nolichucky Shale test. In both cases, however, a single-well test or a pumping test with a minimal array of three or four wells would have failed to indicate the anisotropic and heterogeneous character of the sites. Investigators should plan for anisotropy by locating observation wells at several orientations to the structural grain (emphasis on along-strike alignment is inappropriate). One way to plan for heterogeneity is to provide more than a minimum number of observation wells. Proximity to unseen hydraulic discontinuities may cause some wells to respond anomalously, but the data from "extra" wells may help in detecting such anomalies in the response of individual wells and in ensuring a minimum amount of useable data.
A puzzling feature of the pumping tests at both locations was the occurrence of significant rises in water levels during the pumping period, even in the pumping well. We suspect that this may be a common problem in fracture-dominated hydrogeologic settings, and we believe that investigators should be

aware of it. The storage capacity of fractures is very small, so dramatic changes in water elevation might result from relatively small changes in the volume of water present in the fracture system. We advance four hypotheses for the cause of the water-level increases observed during these tests:

1. Release of water from storage in the porous aquifer matrix of a double-porosity medium does not occur immediately in response to pumping, and the delayed release of this water could result in local increases in water level in the fracture system. This hypothesis alone is probably insufficient to explain water-level increases in the pumping well.

2. Deformation of the fracture system as a result of pumping may decrease the storage capacity of the fractures.

3. Water stored in isolated cavities (e.g., formed by dissolution along joints) may be released into the fracture system only after pumping distorts the fractures or the distribution of hydrostatic pressure, or cleans out sediment-filled fractures, opening new conduits for flow from the cavities.

4. Water removed from the pumping well may have been discharged to the ground surface above fractures in hydraulic communication with the pumping well, recharging the aquifer during the test.

It may be especially difficult to plan the rate and duration of pumping in this hydrogeologic environment. As demonstrated by the first Maryville Limestone pumping test, a pumping rate that appears feasible early in the test may simply dewater the fracture system near the pumping well and may not be sustainable. Extensive advance testing may be needed to find a pumping rate that is high enough to be maintained relatively constant but low enough to be sustained for more than a few hours. Aquifer pumping tests are infeasible in some low-permeability settings because it is not possible to pump at a rate low enough to be sustained over time. Long pumping periods may be necessary to permit data interpretation by double-porosity methods, which can supply important information on the interchange of water and solutes between fractures and matrix in a double-porosity system. It may be prudent to carry out preliminary data analysis in the field to ensure that pumping continues until sufficient data are collected.

Additional pumping tests, using different wells as pumping wells, would have been a useful addition to both site investigations. At the Maryville Limestone site, additional testing might have confirmed the role of the fold axes in the aquifer's hydraulic response. Additional tests at the Nolichucky Shale site might have provided the data necessary to calculate the locations of the principal transmissivity axes, using either the original three-well Papadopulos (1965) method or a recent modification of that method (Neuman et al., 1984) which permits a complete solution with data from pumping tests in two different wells in a three-well set. Other data-interpretation techniques (e.g., Gringarten, 1982) may suggest additional testing refinements.

Finally, and most importantly, these experiences demonstrate that effective use of aquifer testing techniques (or any hydrogeologic investigation technique) in fractured low-permeability media demands above-average hydrogeologic insight to identify appropriate conceptual models for data interpretation.

NOTATION

S	Storage coefficient, dimensionless
T	Transmissivity, L^2/T
T_x	Transmissivity along the axis of maximum transmissivity, L^2/T

T_y Transmissivity along the axis of minimum transmissivity, L^2/T

$(T_x T_y)^{1/2}$ Geometric mean of horizontal transmissivity, L^2/T

r_D Dimensionless distance from the observation well to the center of the hypothetical vertical fracture, $r_D = [x^2 + y^2(T_x/T_y)]^{1/2} / x_f$

t Elapsed pumping time, T

x Coordinate location of observation well on the axis of maximum transmissivity, L

x_f Half-length of the master fracture in the Gringarten-Witherspoon method, L

y Coordinate location of observation well on the axis of minimum transmissivity, L

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List of Figures

Figure 1. Map of the site of the Maryville Limestone aquifer test, showing well locations and measured drawdown at the end of the 24-h pumping period.

Figure 2. Log-log plots of drawdown vs time for five observation wells at the pumping test site in the Maryville Limestone.

Figure 3. Map of the site of the Maryville Limestone aquifer test, showing fold axis locations and the effective location of the hypothetical master fracture at the site of the Maryville Limestone aquifer test, as determined by the method of Gringarten and Witherspoon (1972). The hypothetical vertical fracture that controls pumping response is located in the shaded region; the center of the fracture is located in the cross-hatched region. Principal axis of matrix transmissivity is the x axis.

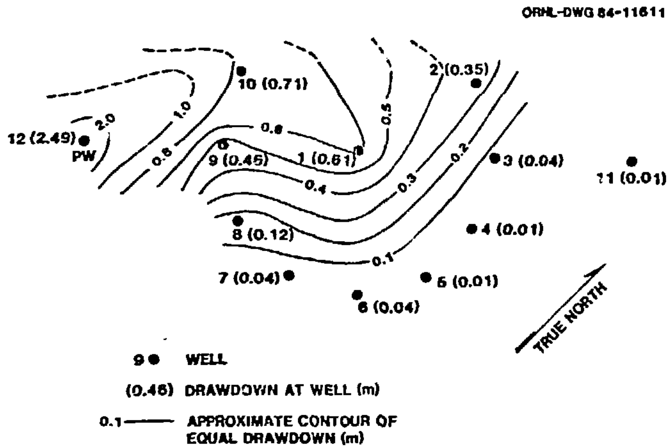
ORNL-DWG 84-11611
12 (2.49)
PW
2.0
1.0
0.8
0.6
10 (0.71)
9 (0.45)
1 (0.61)
0.5
0.4
0.3
0.2
0.1
2 (0.35)
3 (0.04)
11 (0.01)
4 (0.01)
8 (0.12)
7 (0.04)
6 (0.04)
5 (0.01)
TRUE NORTH
9 WELL
(0.45) DRAWDOWN AT WELL (m)
0.1 APPROXIMATE CONTOUR OF EQUAL DRAWDOWN (m)

Figure 1

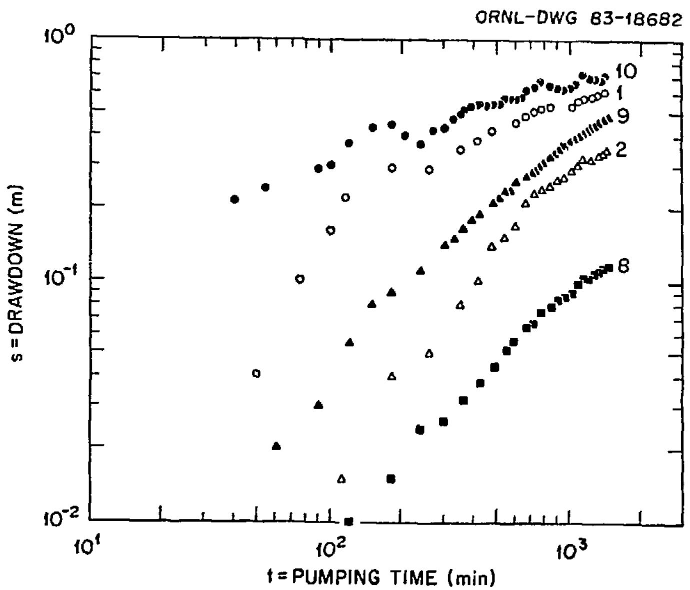
ORNL-DWG 83-18682
10^0
10^{-1}
10^{-2}
s = DRAWDOWN (m)
10^1
10^2
10^3
t = PUMPING TIME (min)
10
1
9
2
8

Figure 2

ORNL-DWG 83-18681

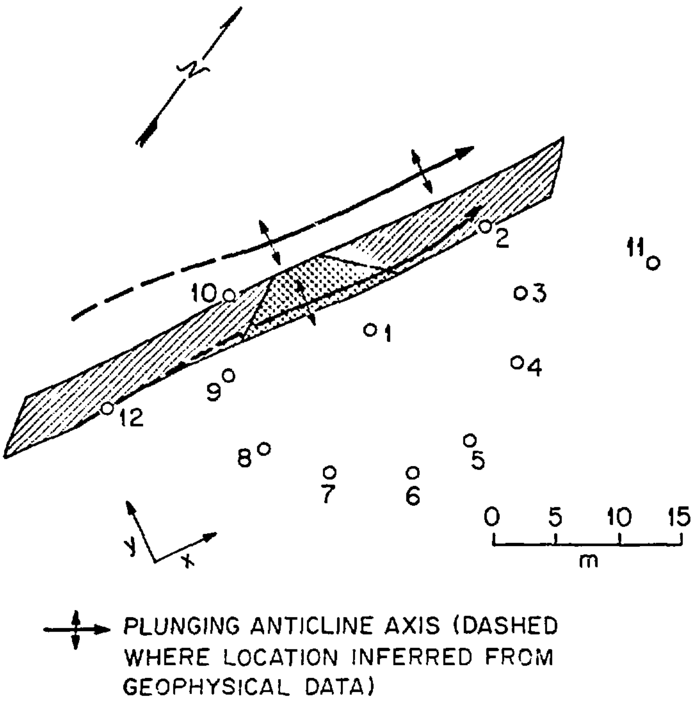

Figure 3