A Method for Estimating Effective Porosity and Ground-Water Velocity

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Abstract

Estimates of ground-water velocity, based either on Darcy's law or on the single-well drift and pumpback tracer method, require prior knowledge of effective porosity. That is, after field data have been collected, the equation for ground-water velocity, using either method, still contains the two unknowns, velocity and porosity. If the local hydraulic gradient is known and if a drift and pumpback tracer test is conducted at a well whose hydraulic conductivity has been determined, two independent functional relationships between velocity and porosity are established. By treating these functions as nonlinear simultaneous equations, a unique solution for the local velocity and porosity can be obtained.

Introduction

Accurate estimates of ground-water velocity and effective porosity are important in studies that consider aqueous mass transport in aquifers. This paper is based on data gathered during an aquifer characterization project conducted for the purpose of designing an efficient well field for an aquifer thermal energy storage system. In this application, the velocity determines the rate of downgradient displacement of chilled or heated water that has been injected into the aquifer, and the effective porosity determines the volume of aquifer required to contain a given volume of the water.

Darcy's law, an equation that describes laminar ground-water movement in aquifers, contains three variables: (1) ground-water velocity, (2) hydraulic gradient, and (3) hydraulic conductivity. To calculate average linear ground-water velocity (seepage velocity), a fourth variable, effective porosity, is also required. To use Darcy's law to accurately predict advective ground-water mass transport within an aquifer, at least three of the four variables must be known. Gradient is established by measuring water levels. Hydraulic conductivity is measured using aquifer tests, such as the constant discharge pumping test used for the present study. Velocity can be measured directly using a two-well tracer test conducted under natural gradient, but this requires a directly downgradient monitoring well at a convenient distance from the test well. Effective porosity also can be measured using tracer tests, given at least one suitable monitoring well, or it can be based on laboratory testing of cores recovered from the aquifer. However, the results of laboratory tests generally reflect total porosity rather than effective porosity (the total volume of interconnected pore spaces that can contribute to ground-water flow).

Budget and schedule constraints for ground-water investigations can easily preclude the installation of monitoring wells for the purpose of conducting dual- or multiwell tracer tests. Coring and laboratory testing may be impractical for the same reason. Thus, both velocity and porosity often remain as unknowns, and Darcy's equation cannot be solved.

Leap and Kaplan (1988) described a single-well drift and pumpback tracer test useful for estimating ground-water velocity. Unlike Darcy's law, analysis of the test results is independent of gradient and conductivity. The test is performed by injecting a tracer solution into the test well, by allowing the tracer to drift under the influence of the natural hydraulic gradient for a period of time, and by pumping the test well to recover the tracer. No monitoring well is required. The ground-water velocity is calculated as a function of the time the tracer was allowed to drift, the time required to recover the center of mass of the tracer, the pumping rate, the aquifer thickness, and (like Darcy's law) the effective porosity. Leap and Kaplan (1988) also provide a brief review of other pertinent tracer methods.

It is the purpose of this paper to show that Darcy's law and the equation for the drift and pumpback test, when applied to testing at the same well, can be treated as two nonlinear simultaneous equations having two unknowns: (1) velocity and (2) effective porosity. By solving the equations either graphically or algebraically, a unique solution for these parameters is obtained. This approach has been tested in the field and corroborated using a dual-well tracer test conducted under natural gradient.

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Received January 1990, revised July 1990, accepted July 1990.

Discussion open until September 1, 1991.

Formulae

Darcy's law (including an effective porosity term) can be written

$$V = KI/n \tag{1}$$

where V is the average linear ground-water velocity; K is the horizontal hydraulic conductivity; I is the horizontal hydraulic gradient; and n is the effective porosity.

The equation for the drift and pumpback test described by Leap and Kaplan (1988) can be written as

$$V = (Qt/\pi nb)^{1/2}/d \tag{2}$$

where Q is the pumping rate during recovery of the tracer; t is the time elapsed from the start of pumping until the center of the mass of the tracer is recovered; b is the aquifer thickness; and d is the time elapsed from the injection of the tracer until the center of the mass of the tracer is recovered by pumping (i.e., drift time plus t). It is important to note that equation (2) was derived for homogeneous confined aquifers dominated by steady-state horizontal advective transport, and having a locally constant hydraulic gradient.

In equation (2), factor b is the same aquifer thickness used to calculate hydraulic conductivity from transmissivity for equation (1).

In aquifers where both equation (1) and equation (2) are valid, the equations can be substituted and rearranged to yield algebraic expressions for velocity and porosity, where

$$V = Qt/\pi bd^2KI \tag{3}$$

and

$$n = \pi bK^2I^2d^2/Qt \tag{4}$$

Thus, velocity and porosity can be directly calculated from experimental results. Although the hydrologic and tracer tests are both conducted at the same well, an assumption of local homogeneity and isotropy is nevertheless inherent in equations (3) and (4). The hydrologic test interrogates the aquifer radially from the test well, while the tracer test interrogates a relatively narrow volume within the aquifer downgradient from the test well.

Note that well transmissivity, T, may be substituted for the product bK in equation (3), so velocity (although not effective porosity) can be calculated directly from transmissivity values if aquifer thickness is not known with certainty.

Leap and Kaplan (1988) provide an important caveat regarding the drift and pumpback test. They describe a "velocity shadow" that exists for some distance downgradient from the well bore and note that if the tracer is not allowed to drift beyond the effects of that shadow before pumpback, the test results will be biased toward a velocity that is too small. In their experiments, calculated velocity was as much as 30% below known true value where drift times were brief. They do not provide a means to predict the extent of the shadow in an aquifer, but their clear implication is that repeated testing, using various drift times, will result in data that converge to the correct unbiased velocity as drift time increases.

Another source of error in the test results, but having the opposite effect, can be envisioned. Inspection of equations (2) and (3) shows that as true ground-water velocity approaches zero, the pumpback time, t, must approach zero, regardless of the allowed drift time, to yield a correct result for the velocity calculation. However, the volume of the tracer is necessarily finite, so the time required to recover the center of the mass of the tracer can never be zero. That is, the slower the true ground-water velocity and the larger the tracer volume, the more likely it is that the calculated velocity will be too high. It is not possible to predict the degree to which the effect of the velocity shadow might compensate for the effect of a finite tracer volume. Consideration of these kinds of errors shows that the results of a drift and pumpback tracer test must be interpreted cautiously where velocity is low, tracer volume is large, or drift time is brief.

Equation (2) was derived for confined aquifers, but in the field application described below, it was applied with satisfactory results to an unconfined aquifer.

Experimental

The foregoing method was applied at a test site in Tuscaloosa, Alabama, in the unconfined aquifer, consisting of unconsolidated sands, gravelly sands, and clayey sands. The aquifer, which overlies compact clay at the test site, has an average saturated thickness of 50 ft. Geologic studies indicate that the aquifer may, in fact, exist as two hydrogeologic units, one confined and one unconfined, separated by a clay layer. The horizontal hydraulic gradient in the vicinity of the test well is 0.005, based on water-level measurements in the test well and three observation wells, the farthest of which was 150 ft from the test well. The test well and the observation wells fully penetrate the aquifer. The test well was rotary-drilled, cased with 10-inch diameter slotted PVC, and gravel-packed. Data regarding slot size, gravel size, and the diameter of the uncased borehole are not available.

A constant discharge pumping test was conducted at the rate of 260 gpm, and analysis of data from the observation wells indicate a transmissivity of 2000 ft/day. Hydraulic conductivity is, therefore 40 ft/day. One of the observation wells, at a distance of 80 ft, was found to be directly downgradient from the test well.

After water levels fully recovered from the constant discharge pumping test, a drift and pumpback test was performed. A tracer solution was prepared by dissolving 0.330 lb of lithium bromide in 160 gal of ground water reserved from the pumping test. The tracer was injected into the test well at the rate of 4 gpm. The tracer solution was immediately followed by injection of 106 gal of untreated ground water as a chaser, and was injected at the same rate. The chaser was intended to force the tracer solution out of the well bore and into the sediments to minimize the effect of the velocity shadow described by Leap and Kaplan (1988). It was assumed that forcing the tracer into the sediments would result in a donut-shaped tracer slug centered about the bore axis and that at least part of the tracer solution would never lie within the shadow. Unfortunately, design data for the test well indicated a 6-in.-diameter bore rather than the 10-in.-diameter bore discovered on the site, so the volume of water that had been reserved for the chaser was less than the full standing bore volume. Therefore, the tracer solution was only partially forced into the aquifer.

The tracer was allowed to drift under natural gradient for 3760 min. from the midpoint of tracer injection. Pumpback was conducted at the rate of 60 gpm, with the pump set 15 ft above the bottom of the aquifer. At this pumping rate, maximum drawdown at the test well was not more than about 5 ft, or 10% of the saturated thickness of the aquifer. Tracer recovery was monitored at the test site by frequent sampling of the discharge stream and field analysis using a bromide ion-selective electrode. Figure 1 shows the results of laboratory bromide measurements for the collected samples. The figure shows that the bromide concentration was approximately 1.4 mg/l just after pumping began and that the concentration was nearly zero after approximately 5 min. The initial spike of bromide is probably a result of the fact that the well bore penetrates several feet of the compact clay beneath the aquifer, creating a dead volume within the bore. A small amount of the injected tracer solution may have mixed into the water near the top of the dead volume but would not have drifted into the aquifer. Turbulence within the well bore during pumpback may have drawn bromide from the dead volume into the sample stream.

The figure also shows a depression in the bromide concentration that occurs after approximately 100 min. of pumping, and that appears to divide the tracer recovery curve into two poorly resolved peaks. The dual peaks may have been caused by the use of the fresh-water chaser to force the bromide solution out of the well bore and into the sediments. That is, the peaks may represent recovery of first one side, and then the other, of a donut-shaped tracer slug. An alternative explanation is that the aquifer consists of two zones having somewhat different hydraulic properties, and that the two peaks in the recovery curve actually represent different rates of ground-water velocity. For example, the aquifer units above and below the clay layer may possess different flow rates. The data analysis, as follows, ignores the dual peaks, and the results are interpreted as net properties of the aquifer.

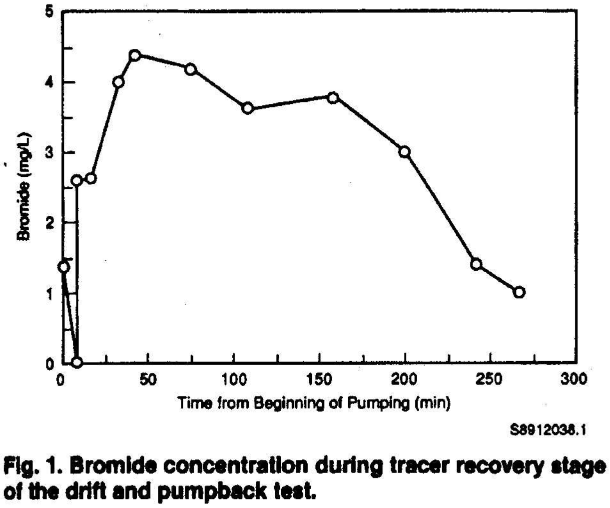

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Fig. 1. Bromide concentration during tracer recovery stage of the drift and pumpback test.

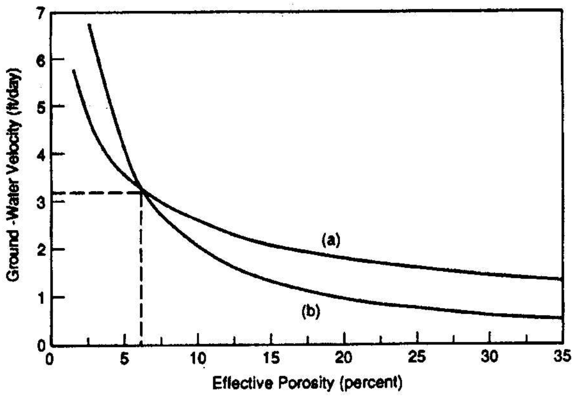

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Fig. 2. Ground-water velocity calculated as a function of effective porosity based on (a) the drift and pumpback tracer test and on (b) Darcy's law. The point of intersection of the curves represents a unique solution for velocity and porosity at the test site.

Integrating bromide recovery data from Figure 1 shows that the center of mass of the tracer; i.e., one-half of the injected bromide, was recovered 91 min. into the pumping campaign. Applying equations (3) and (4) yields a velocity of just over 3 ft/day and an effective porosity of 6%. The graphic solution is shown in Figure 2, in which velocity is plotted as a function of porosity for both equations (1) and (2). The point of intersection of the curves represents a solution that satisfies both equations (1) and (2), and that point represents the same values calculated from equations (3) and (4). The graphic solution has the advantage that, if desired, error bands representing experimental uncertainty can be placed about one or both functions and the effect of uncertainty on the test results becomes apparent.

An effective porosity of 6% is less than was expected for this unconsolidated sandy aquifer, and is probably caused by the significant presence of clay and clay layers and by poor sorting of the sediments.

Dual-Well Tracer Test

Gradient analysis showed that one of the observation wells, at a distance of 80 ft, was directly downgradient from the test well, and could, therefore serve as a monitoring well for a dual-well tracer test conducted under natural gradient. The test was initiated by preparing a 3000-gal tracer solution using potassium bromide. The bromide concentration was 10 mg/l. The tracer solution was injected at the rate of approximately 75 gpm. The 3000 gal of tracer would occupy approximately 6500 ft^3 of sediments, based on the calculated effective porosity of 6%. Because the aquifer is 50 ft thick, the resulting tracer should have a plan view diameter of approximately 13 ft, assuming a cylindrical volume. Thus, with angular error of up to slightly more than 4 degrees in the estimation of ground-water flow direction, one side of the tracer would still pass through and be detectable at the monitoring well.

The monitoring well was periodically sampled beginning on the 27th day following injection of the tracer. Data prior to the 27th day were lost as a result of logistical

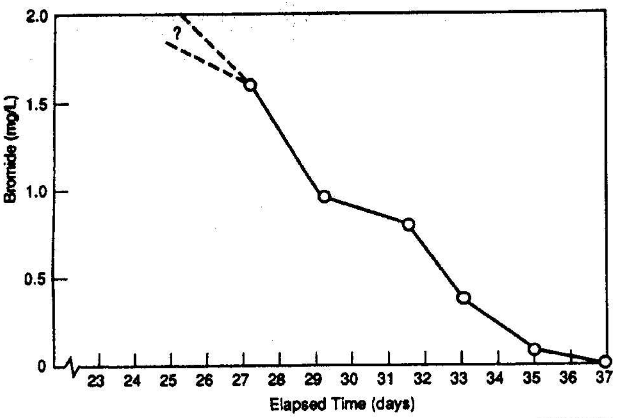

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Fig. 3. Mean bromide concentration versus time in the downgradient monitoring well during the dual-well tracer test conducted under natural gradient.

difficulties in obtaining suitable sampling equipment. Grab samples were collected at 5-ft-depth intervals each day that the well was sampled, and the collected samples were analyzed for bromide. Figure 3 shows the mean bromide concentration for the 5- to 50-ft interval plotted against elapsed time. Note that, by the 27th day, the tracer had already arrived at the well and that, from the 27th to the 37th day, the mean bromide concentration decreases. It is clear that the peak of the tracer passed through the monitoring well on or before the 27th day. Therefore, based on this test, the average ground-water velocity must be equal to or greater than 3.0 ft/day.

No distinct pattern in the vertical distribution of bromide emerged for the 5- to 50-ft interval. However, there was some indication that ground-water flow rate may decrease somewhat with depth.

Conclusions

If the transmissivity of a well and the local horizontal hydraulic gradient are known, application of a drift and pumpback tracer test at the same well can provide sufficient information to calculate ground-water velocity. Neither an estimate of effective porosity nor knowledge of aquifer thickness is required. If aquifer thickness is known, effective porosity also may be calculated. Although the method presented here is strictly correct only for confined aquifers, it has been applied successfully to an unconfined aquifer. In conducting the described test, it was assumed that by choosing a pumping rate that would result in moderately small drawdown (relative to aquifer thickness), error that may be introduced by applying the method to an unconfined aquifer would also be small. At the Tuscaloosa, Alabama, test site, the method was partially verified using a dual-well tracer test conducted under natural gradient. The dual-well test provided a lower bounding limit for ground-water velocity that was favorably close to the analytical results.

The test well and observation wells used for this study fully penetrated the aquifer. Further, experimental verification of equation (2) by Leap and Kaplan (1988) was performed using full penetration. The use of partially penetrating wells may introduce error to the method presented here, depending on relative penetration and on the ratio of vertical to horizontal hydraulic conductivity within the aquifer.

To avoid biased test results for a drift and pumpback tracer test, it is important to allow the tracer to drift beyond the influence of the velocity shadow. In the test described, the tracer would have drifted approximately 8.5 ft downgradient from the 10-in.-diameter test well. It is reasonable to expect that the velocity shadow will increase with well diameter. Similarly, a gravel or sand pack may contribute to the velocity shadow, depending on the contrast in hydraulic parameters between the packing material and the aquifer.

Finally, a practical note regarding tracer concentrations. Because of dilution during pumpback, tracer solutions for a drift and pumpback test must be more concentrated than are generally needed for dual-well tests. In the test described, the peak bromide concentration observed during pumpback was less than 2% of the concentration of the injected tracer solution. In contrast, the peak bromide concentration observed during the confirmatory dual-well test was approximately 24% of the injected concentration, despite dispersion along the 80-ft drift path, possible angular error in estimating flow direction, and probable miss in sampling the concentration peak as it passed through the bore of the monitoring well.

Acknowledgments

The authors are grateful to Professor C. Everett Brett, Director of the University of Alabama Natural Resources Center, and Yeong K. Song, University of Alabama College of Engineering, for their aid in conducting the field experiments.

This work was supported by the Pacific Northwest Laboratory Seasonal Thermal Energy Storage Program.

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