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Pumping tests in networks of multilevel sampling wells: Motivation and methodology

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Abstract. The identification of spatial variations in hydraulic conductivity (K) on a scale of relevance for transport investigations has proven to be a considerable challenge. Recently, a new field method for the estimation of interwell variations in K has been proposed. This method, hydraulic tomography, essentially consists of a series of short-term pumping tests performed in a tomographic-like arrangement. In order to fully realize the potential of this approach, information about lateral and vertical variations in pumping-induced head changes (drawdown) is required with detail that has previously been unobtainable in the field. Pumping tests performed in networks of multilevel sampling (MLS) wells can provide data of the needed density if drawdown can accurately and rapidly be measured in the small-diameter tubing used in such wells. Field and laboratory experiments show that accurate transient drawdown data can be obtained in the small-diameter MLS tubing either directly with miniature fiber-optic pressure sensors or indirectly using air-pressure transducers. As with data from many types of hydraulic tests, the quality of drawdown measurements from MLS tubing is quite dependent on the effectiveness of well development activities. Since MLS ports of the standard design are prone to clogging and are difficult to develop, alternate designs are necessary to ensure accurate drawdown measurements. Initial field experiments indicate that drawdown measurements obtained from pumping tests performed in MLS networks have considerable potential for providing valuable information about spatial variations in hydraulic conductivity.

1. Introduction

Theoretical, laboratory, and field research on the mechanisms of large-scale solute transport has identified the spatial distribution of hydraulic conductivity (K) as a significant factor in determining how a plume of a conservative tracer will move in the subsurface [e.g., *Sudicky and Huyakorn*, 1991]. Unfortunately, the description of spatial variations in K on a scale of relevance for contaminant transport investigations has proven to be a difficult task. Although tracer tests performed in networks of multilevel sampling wells can be the source of valuable information about K variations [e.g., *Freyberg*, 1986; *Hess et al.*, 1992], such tests are very expensive in terms of time, money, and effort. Thus other techniques are needed if information about spatial variations in hydraulic conductivity is to be incorporated into models of contaminant transport on a routine basis.

A wide variety of methods for obtaining information about spatial variations in K has been reported in the literature. These techniques range from laboratory analysis of sampled cores [e.g., *Sudicky*, 1986; *Burger and Belitz*, 1997] to single-well hydraulic and tracer tests [e.g., *Taylor et al.*, 1990; *Boggs et al.*, 1992; *Boman et al.*, 1997; *Butler*, 1997; *Zlotnik and Zurbuchen*, 1998] to the coupling of tracer data with results of geophysical surveys [e.g., *Copty et al.*, 1993; *Hyndman et al.*, 1994; *Hubbard et al.*, 1997]. All of these methods, however, have significant limitations. For example, parameter estimates obtained from core analyses and most single-well tests represent conditions in the immediate vicinity of the test well. Solute transport, however, depends critically on the connectivity of regions of high or low hydraulic conductivity, conditions which cannot be reliably determined even from a suite of single-well tests because of the lack of sensitivity of these tests to just such features. While some success has been obtained in describing patterns of K variation outside of the near-well region using geophysical techniques (to characterize major lithologic structures) in conjunction with tracer data (to estimate the hydraulic properties of the geophysically delineated zones), the dependence of this approach on data from costly tracer experiments limits its practical utility. Thus, although several of the current methods show promise, all appear to have significant limitations for the description of spatial variations in hydraulic conductivity over scales of relevance for transport investigations.

A new field method for the estimation of spatial variations in K between wells, hydraulic tomography, has been independently proposed by several investigators [e.g., *Bohling*, 1993; *Tosaka et al.*, 1993; *Gottlieb and Dietrich*, 1995]. As shown in Figure 1, this method essentially consists of the performance of a series of short-term pumping tests in which the position of the stressed interval in the pumping well, isolated with packers, is varied between tests to produce a "crossed" streamline pattern similar to the crossed ray paths of a typical cross-hole seismic tomography experiment [e.g., *Peterson et al.*, 1985]. Numerical investigations of flow through synthetic cross sections [*Bohling*, 1993, 1999; *Tosaka et al.*, 1993; *Gottlieb and Dietrich*, 1995] have found that the drawdown measurements from the complete series of pumping tests can be jointly inverted, using a variety of procedures, to produce two- and three-dimensional images of hydraulic conductivity that reproduce the major features of the input K field. These numerical demonstrations indicate that hydraulic tomography may be

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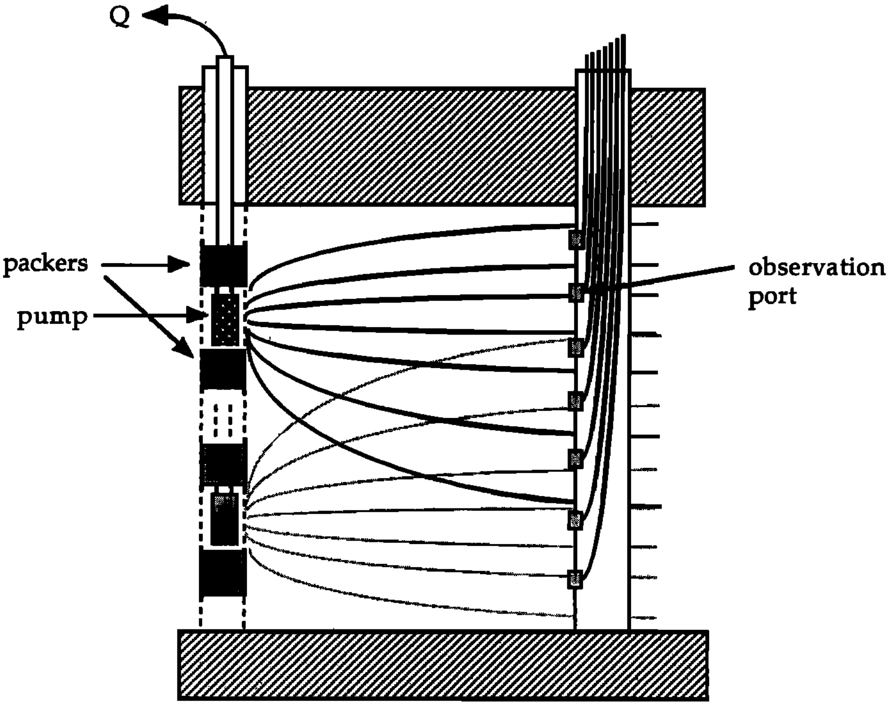

Figure 1. Schematic cross-sectional view of hydraulic tomography arrangement. Two separate tests are represented where packers and pump are moved between tests; lines emanating from the two positions of the stressed interval represent pumping-induced flow lines.

able to overcome many of the limitations of current field techniques to produce significantly improved descriptions of K variations between wells. In particular, these numerical experiments indicate that hydraulic tomography may be quite useful for the identification of laterally contiguous zones of relatively high hydraulic conductivity, which have a very significant influence on contaminant transport at a site.

The viability of hydraulic tomography hinges on the availability of detailed information about vertical and lateral variations in pumping-induced head changes (drawdown). Nests of piezometers placed in a series of relatively closely spaced boreholes could provide the needed data density if the piezometers were small enough that a large number could be placed together. The logical extension of such an approach would be the utilization of the multilevel sampling wells commonly employed in large-scale tracer tests [e.g., *Pickens et al.*, 1978; *Boggs et al.*, 1988]. These wells (henceforth designated MLSs) consist of bundles of small-diameter (often <5 mm ID) tubing. Given the large number of tubes (often 15–17) in a MLS, the performance of pumping tests in an MLS network could yield descriptions of spatial variations in drawdown at a scale that has previously been unobtainable. Unfortunately, however, the small diameter of MLS tubing has made the measurement of drawdown a significant challenge. Thus the considerable potential of hydraulic tomography has remained unrealized.

The primary purpose of this paper is to discuss the motivation and methodology for the performance of pumping tests in networks of multilevel sampling wells. Two new techniques for the measurement of drawdown in the small-diameter MLS tubing are described, and laboratory and field evaluations of these approaches are discussed. The results of an initial series of field experiments to demonstrate the importance of well design and development and the potential value of information from pumping tests in MLS networks are then presented. The paper concludes with a brief discussion of the implications of this methodology for hydraulic tomography.

2. Measurement of Drawdown in Multilevel Sampling Wells

Relatively little work has been reported on measuring water levels or drawdown in multilevel sampling wells. *Pickens et al.* [1978] describe a method for water-level measurement in MLS tubing using a vacuum pump and a mercury manometer. This approach, however, is too involved and time consuming for measurement of drawdown. Small-diameter electric tapes are commercially available for use in tubing as small as 6 mm ID [*Solinst Canada Ltd.*, 1998], and *Dunn et al.* [1998] describe a study in which these devices have provided valuable information. Electric tapes, however, are not practical for applications involving the measurement of drawdown through time in the large number of small-diameter tubes that compose a network of multilevel sampling wells. Thus there is a pressing need for rapid and accurate approaches for measurement of drawdown in a MLS network. In the remainder of this section, two new measurement methods are described.

Conventional submersible pressure transducers used in hydrogeologic field studies are too large for MLS tubing. However, fiber-optic pressure sensors developed for biomedical and various process-control applications present a viable small-diameter alternative. These sensors, which are small enough (<2–3 mm OD) to be readily positioned within the water column in an MLS tube, essentially consist of a miniature Fabry-Perot interferometer that is attached to a fiber-optic cable [*Wolthuis et al.*, 1991; *Photonetics*, 1996]. The interferometer consists of a cavity, etched in glass, one end of which is

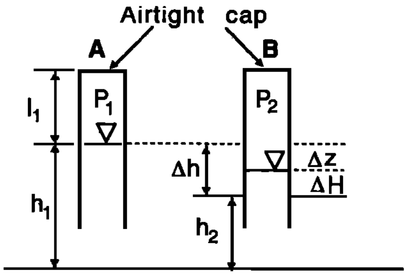

Figure 2. Cross-sectional views of a hypothetical multilevel sampling (MLS) tube: (a) prepumping conditions and (b) pumping conditions (notation explained in text).

fixed, while the other is a pressure-sensitive diaphragm. The length of the cavity thus changes as a function of pressure. Both ends of the cavity are partially reflective surfaces, so the light reflected from the interferometer is a combination of reflections from the two surfaces. A minispectrometer in a surface data-acquisition unit is used to detect the position of the reflection minimum (destructive combination) in a certain spectral range within which the position is a unique function of cavity length and thus pressure [*Photonetics*, 1996]. Although certainly usable for the measurement of drawdown in MLS tubing, the current cost of the fiber-optic sensors and accompanying equipment makes this approach of limited practical utility (e.g., four sensors and a four-channel acquisition unit from one manufacturer exceed $20,000).

An economical alternative to the fiber-optic sensors is the use of air-pressure transducers to measure air pressure changes in sealed MLS tubing and relate these to hydraulic head changes in the formation. This alternative is illustrated in Figure 2, which displays two hypothetical cross sections of a single MLS tube. Figure 2a displays conditions prior to the onset of pumping. The air pressure in the sealed tube is P_1, and the air column has length l_1. After a period of pumping the hydraulic head in the formation has changed by Δh (equal to $h_2 - h_1$ [L]), while air pressure in the tubing has changed by ΔP (equal to $P_2 - P_1$ [M L^{-1} T^{-2}]). The relationship between Δh and ΔP is not strictly linear. However, as shown in the appendix, use of the ideal gas law and first-order approximations allows the following linear relationship to be obtained:

$$\Delta h \approx \frac{\Delta P}{\gamma}\left(1 + \frac{l_1\gamma}{P_1}\right), \tag{1}$$

where γ is the weight density of water [M L^{-2} T^{-2}] and $\Delta P \ll P_1$ (atmospheric pressure). Laboratory calibrations can be used to assess whether this relationship is appropriate for the range of head changes expected in field applications. Figure 3 is a plot of Δh versus $\Delta P/\gamma$ from a laboratory calibration in an apparatus similar to that of Figure 2. The major departures from the best fit straight line are primarily a product of air leaks, measurement error, and a small degree of nonlinearity. Note that the laboratory calibrations were performed with the polyethylene tubing commonly utilized in multilevel sampling wells; tubing with a higher gas permeability may not be appropriate for this approach. A series of laboratory calibrations were performed over the range of l_1 expected in planned field experiments. In all cases, results similar to those presented in Figure 3 were obtained, indicating that (1) is a reasonable representation of the governing physics over the range of conditions expected in field settings. Thus use of inexpensive air-pressure transducers appears to be an effective approach for measurement of drawdown in MLS tubing.

A number of tests were carried out to compare and evaluate the performance of both types of sensors under field conditions. One test involved measuring drawdown in a 0.05 m ID well by a variety of methods. In this experiment, two sets of MLS tubing were placed in the well, and drawdown was measured using a fiber-optic sensor inside an MLS tube, an air-pressure transducer monitoring pressure changes in an MLS tube sealed at the top, a conventional submersible pressure transducer inside the well, and an electric tape. Each set of measurements was normalized by the drawdown measured by that sensor immediately prior to cutting off the pump (~0.24 m) in order to remove the influence of calibration parameters [see *Butler*, 1997, chapter 4]. Figure 4 shows the close agreement found between all measurement methods. *Butler et al.*

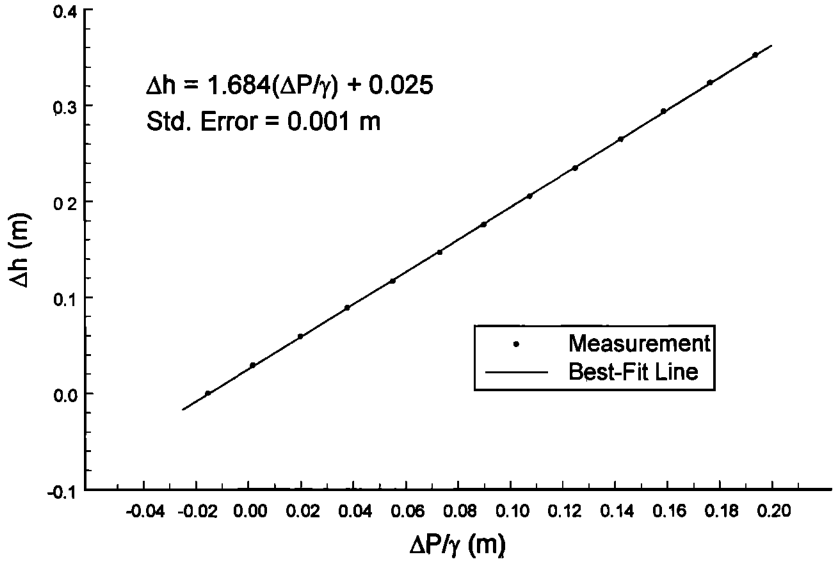

Figure 3. Δh versus $\Delta P/\gamma$ plot from laboratory calibration of air-pressure transducer in configuration similar to that of Figure 2 (notation explained in text).

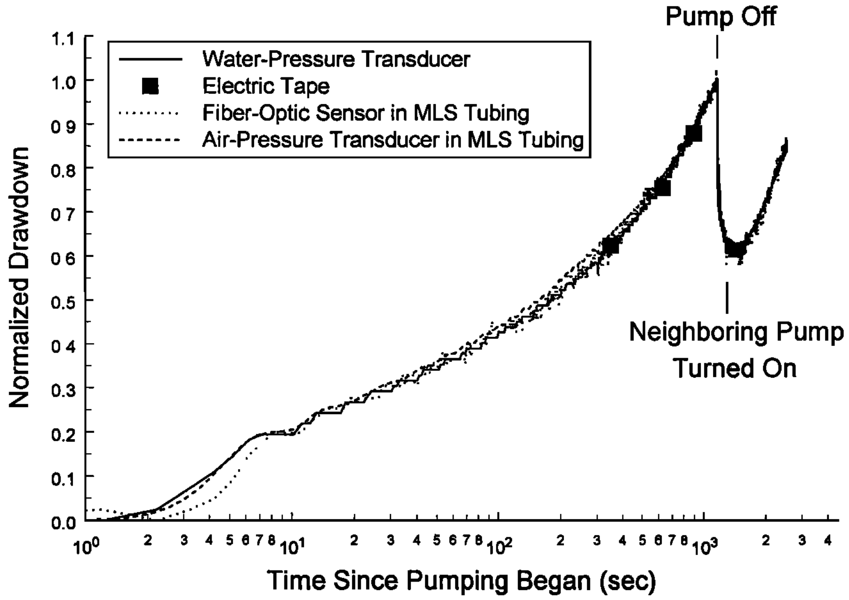

Figure 4. Normalized drawdown versus logarithm of time plot for four different measurement methods used in a 0.05 m ID observation well (normalized drawdown of 1.0 is equivalent to actual drawdown of 0.24 m).

[1997] report another field comparison in which drawdown records from the air- and water-pressure transducers are virtually indistinguishable. Such field experiments demonstrate that accurate drawdown measurements can be obtained in MLS tubing with both of the methods described here.

3. Impact of Well Design and Development on Drawdown Measurements

The standard MLS port design [e.g., *LeBlanc et al.*, 1991] involves placing a fine mesh over the lower end of the tubing, the purpose of which is to prevent pumping of particulate matter during water sampling. This design, however, creates problems for the measurement of drawdown because the mesh filters out fine particulate matter, which forms a low-*K* cake around the port. Figure 5 is a drawdown record obtained with air-pressure transducers in an undeveloped MLS well. In this case the low-*K* cake was so thick that there was virtually no response to the cessation of pumpage. Unfortunately, standard overpumping or back flushing development methods have little effect on the low-*K* cake. These wells can only be successfully developed by threading a small-diameter steel cable through the tubing, breaching the mesh at the lower end, and removing fines in the vicinity of the port with a peristaltic pump. Al-

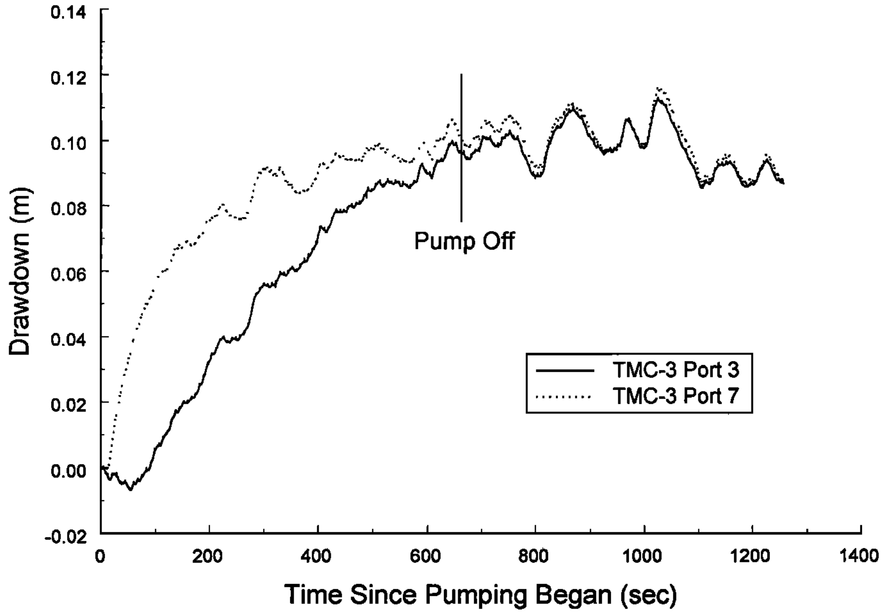

Figure 5. Drawdown versus time plot for predevelopment pumping test (drawdown measured in ports 3 and 7 of MLS TMC-3).

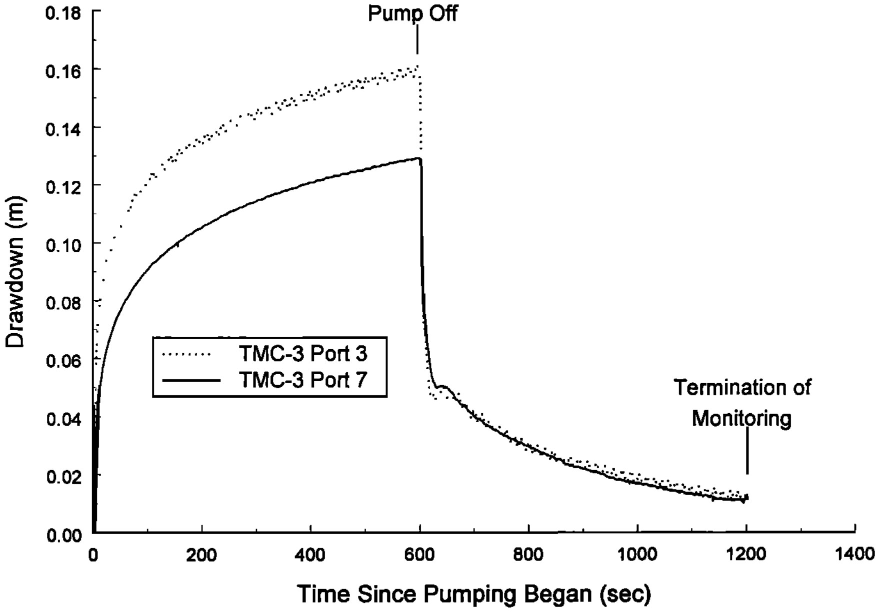

Figure 6. Drawdown versus time plot for postdevelopment pumping test (drawdown measured in ports 3 and 7 of MLS TMC-3; pumping well and rate same as for test in Figure 5).

though this procedure results in drawdown records such as that of Figure 6, it is too involved for routine use. Thus, when MLS wells are to be utilized for drawdown measurements, port designs with coarser meshes are recommended so that near-well fines can be readily removed using standard development methods. Note that the oscillations displayed in Figure 5, which were most dramatic in undeveloped MLS wells, were commonly observed during tests performed in direct sunlight in midsummer temperatures and are thought to be a product of heating via insolation. Styrofoam boxes placed over individual multilevel sampling wells served as excellent insulators and virtually completely removed these insolation-induced oscillations (e.g., Figure 6).

4. Example Field Application

A series of field experiments was carried out to demonstrate the viability and potential of pumping tests performed in networks of multilevel sampling wells. These experiments were performed at the Geohydrologic Experimental and Monitoring Site (GEMS), a research area near Lawrence, Kansas. The shallow subsurface at GEMS consists of an alluvial facies assemblage of approximately 21.3 m in thickness. The upper half is primarily clay and silt, while the lower half, the focus of this work, is primarily coarse sand and gravel, which behaves as a confined aquifer for short-term pumping tests. Previous studies have found that hydraulic conductivity at the core scale varies by over 5 orders of magnitude within the coarse sand and gravel interval [*McElwee and Butler*, 1995]. An extensive network of MLSs, which had been constructed for a multiwell tracer experiment [*McElwee and Butler*, 1995; *Bohling*, 1999], was used in this series of pumping tests. In all cases a fully penetrating central well (0.13 m ID) was pumped at a constant rate of approximately 4.4 L s^{-1} (70 gpm), and head responses were monitored in several MLSs using air-pressure transducers. Figure 7 displays drawdown at two sets of ports from multilevel sampling wells positioned along a straight line at distances of 4.6 m (TMC-3) and 10.7 m (TMC-7) from the pumping well. Note that even in the presence of significant heterogeneity, plots of late-time drawdown from a pumping test in a confined aquifer are expected to be parallel, reflecting the large-scale hydraulic characteristics of the aquifer [e.g., *Butler and Liu*, 1993; *Schad and Teutsch*, 1994; *Meier et al.*, 1998]. As shown in Figure 7, this expectation was fulfilled in this series of tests. The slope of the line fit to the latter portions of the drawdown in port 3 of TMC-3 is within 2.5% of that of lines fit to the other drawdown records shown in Figure 7 and within 3.6% of the slope of a plot of drawdown from a nearby 0.05 m ID observation well recorded with a conventional submersible pressure transducer. The consistency of late-time changes in drawdown from ports at different positions within the network, as well as from a standard observation well, demonstrates the quality of the drawdown data that can be obtained from MLS tubing. The drawdown differences seen at the same MLS ($\Delta h_{\mathrm{TMC\text{-}3}}$ and $\Delta h_{\mathrm{TMC\text{-}7}}$ on Figure 7) are primarily a product of spatial variations in K between the pumping well and the MLS ports. Numerical experiments performed with a cylindrical-coordinate, finite-difference model revealed that such drawdown differences could only be found in the presence of significant media heterogeneity [e.g., *Bohling*, 1999], indicating that drawdown from pumping tests performed in MLS networks could potentially be exploited to yield valuable information about spatial variations in K. Note that the S-shaped pattern in the early-time drawdown on Figure 7 is primarily a product of well bore storage in the pumping well [e.g., *Horne*, 1995, Figure 2.8] and can readily be diminished through appropriate placement of packers in the pumping well.

5. Implications for Hydraulic Tomography

The concept of performing a series of pumping tests in a tomographic-like arrangement is nothing new. *Hsieh and Neuman* [1985] and *Hsieh et al.* [1985], for example, describe such

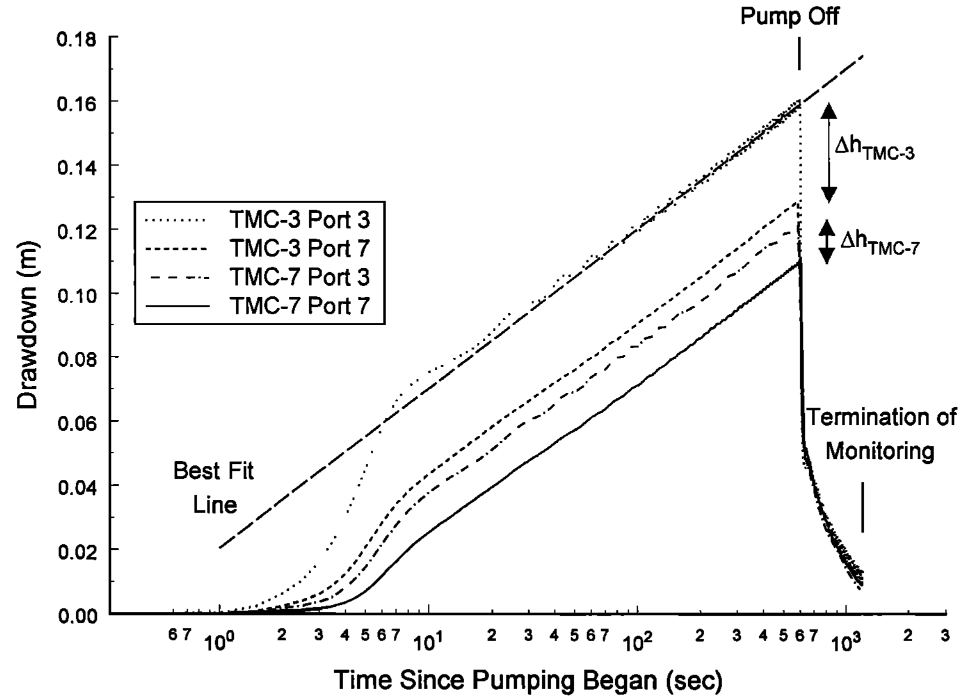

Figure 7. Drawdown versus logarithm of time plot for August 12, 1997, pumping test 1 ($\Delta h_{\mathrm{TMC-3}}$ equals drawdown difference between ports 3 and 7 at MLS TMC-3; $\Delta h_{\mathrm{TMC-7}}$ equals drawdown difference between ports 3 and 7 at MLS TMC-7; vertical separation of ports 3 and 7 is 2.44 m).

an approach for estimation of the three-dimensional conductivity tensor in a homogeneous, anisotropic formation. *Karasaki and Galloway* [1990] describe a series of planned pumping tests for characterizing the K field at Yucca Mountain in a "crude tomographic fashion," while *Cook* [1995] discusses a series of constant-head injection tests performed in fractured granite in a tomographic-like arrangement. Hydraulic tomography as defined here differs from such previous approaches in its emphasis on the collection of drawdown data in a very dense sampling network and on the simultaneous inversion of data from the full set of pumping tests. Although numerical investigations [e.g., *Bohling*, 1993, 1999; *Tosaka et al.*, 1993; *Gottlieb and Dietrich*, 1995] have demonstrated the theoretical potential of hydraulic tomography, no detailed field assessments of the approach have been attempted. Until now, the difficulty and expense of acquiring the drawdown data have been the primary limitation on this methodology. However, the two measurement techniques described in section 2 provide the means by which drawdown data can accurately and rapidly be acquired in the small-diameter tubing composing a MLS network. Given these measurement techniques and inexpensive methods for installing multilevel sampling wells in unconsolidated materials [e.g., *Dunn et al.*, 1998], hydraulic tomography, implemented as a series of short-term pumping tests in a MLS network, appears to be a viable technique for use in practical applications in shallow hydrogeologic settings.

6. Conclusions

The performance of a series of short-term pumping tests in a tomographic-like format is the basis of hydraulic tomography, a recently proposed methodology that has considerable potential for providing valuable information about interwell variations in hydraulic conductivity. Until now, the need for detailed information about lateral and vertical variations in drawdown has discouraged field implementation of this promising approach. This limitation, however, can be overcome through performance of the pumping tests in networks of multilevel sampling wells, which provide an excellent vehicle for acquisition of drawdown data at a scale that has previously been unobtainable. Drawdown can accurately and rapidly be measured in the small-diameter MLS tubing using either miniature fiber-optic pressure sensors or inexpensive air-pressure transducers. Initial field experiments have demonstrated the quality of the drawdown data that can be obtained from pumping tests in MLS networks when appropriate port designs and/or development procedures are used.

Appendix

In this section the mathematical derivation of (1) is presented. Figure 2 illustrates the quantities referenced in the derivation. Note that the initial air pressure in the MLS tube (P_1) will be approximately equal to atmospheric pressure, which is assumed constant as would be expected for short-term pumping tests.

The change in head in the formation (Δh) is related to the change in water level in the MLS tube (Δz) as follows:

$$\Delta h = \Delta z + \Delta H. \tag{A1}$$

Note that the decrease/increase in air pressure produced by the fall/rise of water in the MLS tube prevents the water level change in the tubing from equating to the head change in the formation (i.e., ΔH will always be nonzero).

The first step in the development is to obtain an expression for Δz in terms of Δh and the air pressure in the tubing. This can be done by writing P_2 as

$$P_2 = \gamma \Delta H + P_1, \tag{A2}$$

where γ is the weight density of water [M L^{-2} T^{-2}] and ΔH is positive for an increase in water level. Equation (A2) can be rearranged to yield

$$\Delta H = (P_2 - P_1)/\gamma. \tag{A3}$$

The ideal gas law can then be invoked to derive a relationship between P_2 and P_1

$$P_2 = P_1 l_1/(l_1 - \Delta z), \tag{A4}$$

where Δz is positive for an increase in water level. Equation (A4) can be substituted into (A3), which can then be substituted into (A1) to obtain

$$\Delta z = \Delta h - \left(\frac{P_1 l_1}{(l_1 - \Delta z)} - P_1\right)\frac{1}{\gamma}. \tag{A5}$$

Equation (A5) can be rearranged and solved for Δz:

$$\Delta z = \left(l_1 + \Delta h + \frac{P_1}{\gamma}\right)\left[\frac{1}{2} \pm \frac{1}{2}\sqrt{1 - \frac{4\Delta h l_1}{\left(l_1 + \Delta h + \frac{P_1}{\gamma}\right)^2}}\right]. \tag{A6}$$

Since only the negative root of the quadratic is physically plausible, the expression under the square root can be expanded in a power series, and all terms above first order can be neglected to produce the following approximation of (A6):

$$\Delta z \approx \Delta h l_1 \Big/ \left(l_1 + \Delta h + \frac{P_1}{\gamma}\right). \tag{A7}$$

The final step in the development is to obtain an expression for Δh solely in terms of the air pressure in the tubing. This can be done by substituting (A7) and (A3) into (A1) and solving for Δh:

$$\Delta h = \left(\frac{(2P_1 - P_2)}{\gamma}\right)\left[-\frac{1}{2} \pm \frac{1}{2}\sqrt{1 + \frac{4\,\frac{(P_2 - P_1)}{\gamma}\left(l_1 + \frac{P_1}{\gamma}\right)}{\left(\frac{2P_1 - P_2}{\gamma}\right)^2}}\right]. \tag{A8}$$

Since only the positive root of the quadratic is physically plausible in this case, the term under the square root can be expanded in a power series, and all terms above first order can be neglected to produce the following approximation of (A8):

$$\Delta h \approx \frac{(P_2 - P_1)\left(l_1 + \frac{P_1}{\gamma}\right)}{(2P_1 - P_2)}. \tag{A9}$$

If $P_2 - P_1$ is defined as ΔP (the quantity measured by an air-pressure transducer in a sealed MLS tube) and ΔP is assumed to be much less than atmospheric pressure (P_1), (A9) can be rewritten as

$$\Delta h \approx \frac{\Delta P}{\gamma}\left(1 + \frac{l_1 \gamma}{P_1}\right),$$

which is the linear relationship given as (1) in the main body of the text.

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