CHARACTERIZING FRACTURED ROCK AQUIFERS USING RADAR, TRACER AND HYDRAULIC DATA

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INTRODUCTION

Aquifer characterization in fractured-rock settings is difficult because measurements of hydraulic properties are local and sparse, permeability varies by orders of magnitude over short distances, and the three-dimensional configuration of transmissive fractures and fracture zones is complex. Innovative strategies for the improved interpretation and combination of available data are needed to facilitate the development of accurate predictive models of ground-water flow and solute transport. To this end, we present and demonstrate approaches to (a) incorporate hydraulic-connection data into a geostatistical simulation procedure, and (b) analyze cross-borehole radar data collected during saline tracer tests. We use experimental data collected at the FSE well field at the U.S. Geological Survey Fractured-Rock Hydrology Research Site near Mirror Lake, in Grafton County, New Hampshire (fig. 1).

The FSE well field is a 120 by 80-meter (m) area consisting of 13 wells. The bedrock at the site is schist intruded by granite, pegmatite and lamprophyre. The overburden consists of about 20 m of glacial deposits. Based on results of single- and multiple-well hydraulic tests, Hsieh and Shapiro (1996) identified four high transmissivity (high-*T*) zones in the bedrock underlying the well field. Borehole intervals isolated by hydraulic packers exhibit similar drawdown responses if they are connected by a high-*T*, whereas intervals not connected by a high-*T* zone show very different drawdown response. Hsieh and Shapiro (1996) developed a conceptual model of heterogeneity at the site (fig. 2), in which high-T zones consist of a number of connected, highly transmissive fractures that are embedded within a surrounding network of less transmissive fractures. To analyze the hydraulic test data, Hsieh et al. (1999) constructed and calibrated a deterministic ground-water flow model. Day-Lewis et al. (2000) presented a geostatistical approach to generate alternative models consistent with inferred hydraulic connections, and identified several models that approximate the field data.

Day-Lewis et al. (2000) and Hsieh et al. (1999) demonstrated that consideration of tabular high-*T* features could explain hydraulic-test data from the FSE well field. However, to explain tracer data collected at the site, a more detailed description of heterogeneity is necessary. One approach to identifying preferential flow paths in fractured rock is to combine radar tomography and saline tracer tests (e.g., Olsson et al., 1991). The presence of electrically conductive saline tracer illuminates fractures or high-permeability pathways for tomographic imaging.

In this extended abstract, we review the results of Day-Lewis et al. (2000) and present a combined interpretation of experimental difference-attenuation and tracer-test data collected at the FSE well field. Taken together, these two studies provide insight into several scales of heterogeneity at the site, and the different data requirements necessary to reproduce (a) hydraulic data and (b) tracer data.

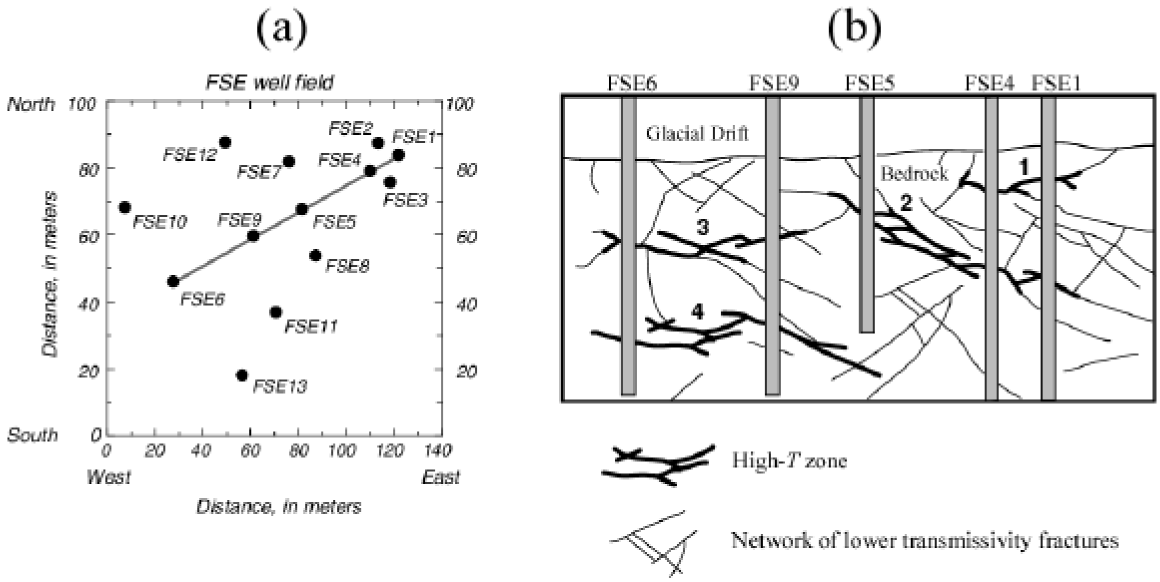

FIGURE 1. (a) Map of the U.S. Geological Survey Fractured Rock Hydrology Research Site, and (b) Conceptual model of high-T zones in the FSE6-FSE1 cross section (after Hsieh et al., 1999).

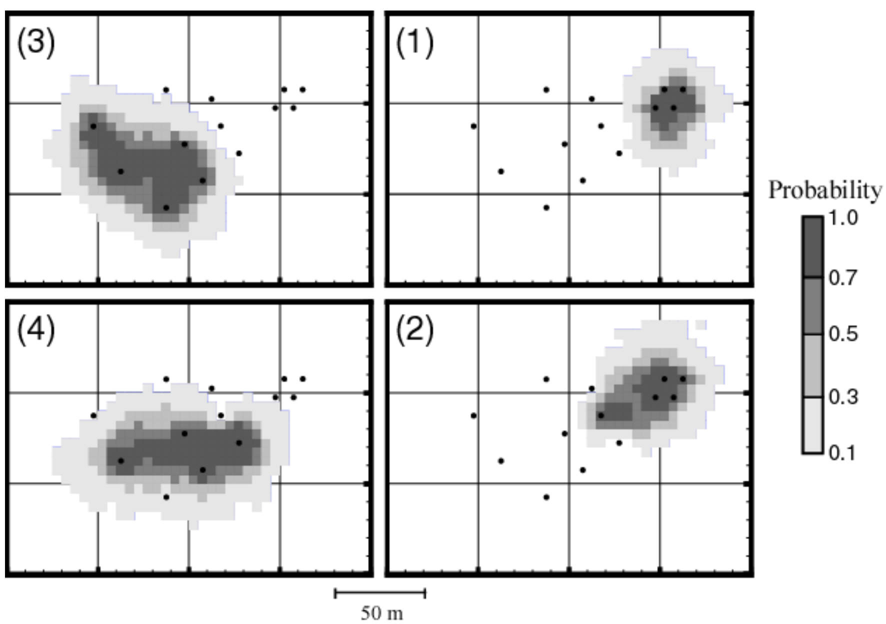

Figure 2. Maps of the probability of intersecting high-T zones with additional wells (after Day-Lewis et al., 2000).

GEOSTATISTICAL SIMULATION CONDITIONED TO CONNECTION DATA

Hydraulic-connection data are traditionally underutilized in characterization of fractured-rock aquifers. At the Mirror Lake Site, packer-isolated well intervals that are connected by a fracture-induced high-transmissivity zone tend to exhibit similar hydraulic responses during pumping or drilling. Day-Lewis et al. (2000) used a simulated-annealing algorithm to generate realizations of the three-dimensional configuration of high-T, conditioned or constrained to hydraulic connections inferred from pumping-test data. The simulated annealing objective function is composed of three weighted terms including (a) an indicator variogram, (b) the proportion of rock volume occupied by high-*T*, and (c) hydraulic connections. Two cells are considered to be connected by a high-*T* feature if (a) both cells are high-*T*, and (b) a path exists between the cells through vertical or lateral faces of other high-*T* cells. We do not consider connections through cell edges or corners, as there is no conductance through corners or edges in the flow model.

The approach was applied to data from the Mirror Lake Site in an effort to explore alternative conceptual models of the distribution of high-*T* zones consistent with field data. Based on the ensemble of realizations, the likely extents and areas of overlap between specific high-*T* zones were computed (fig. 2). Flow models based on the realizations were calibrated to pumping-test data to estimate the hydraulic parameters of the high-*T* zones and surrounding bedrock. The incorporation of hydraulic-connection data into the geostatistical simulation procedure proved an effective and computationally efficient use of hydrologic insight and judgement.

COMBINED RADAR AND TRACER EXPERIMENTS

A second innovative source of information for characterization of fractured rock aquifers is difference-attenuation radar tomography. Cross-borehole radar has been used at a number of fractured rock sites to monitor the migration of saline tracers, thereby providing detailed images of the spatial distribution of tracer at multiple times. In an experiment at the Mirror Lake Site, difference-attenuation tomography was performed in three adjoining planes that form a triangular prism (fig. 3) (Lane et al., 2000). These tests were conducted in a previously identified high-*T* zone (zone 2) (Hsieh and Shapiro, 1996).

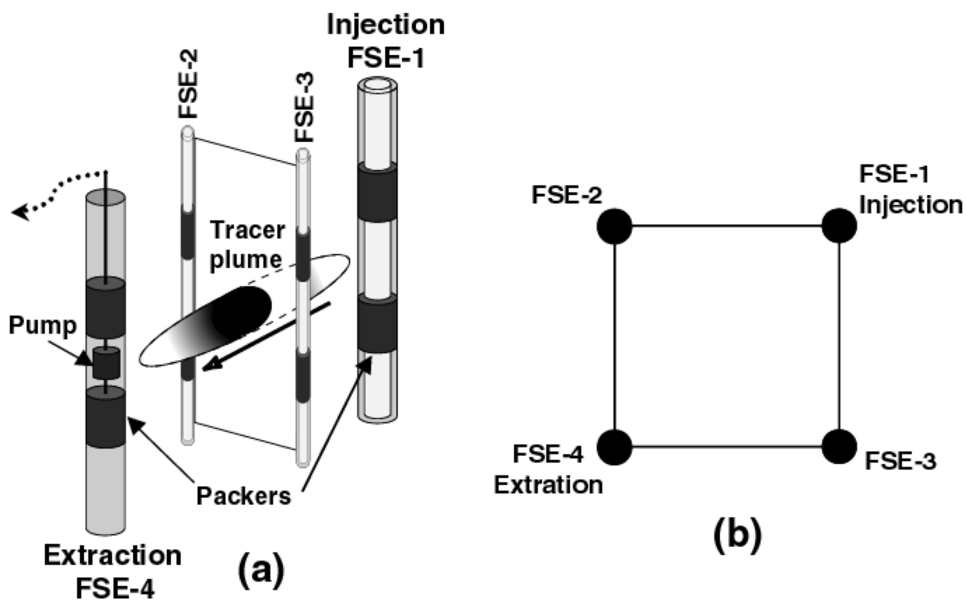

FIGURE 3. (a) Cross section and (b) plan view of the experimental setup for cross-hole radar and tracer experiments. Tracer injection was in FSE1 , extraction was from FSE4, and the tomographic imaging was in the FSE1-FSE2, FSE2-FSE3, and FSE3-FSE1 planes.

We used a sequential tomographic inversion method to estimate difference attenuation on a time-series of 3-D nodal meshes. Tomographic inversion yields a time-series of tomograms at ten-minute intervals. These results indicate that tracer migration is focused along a preferential flow path from FSE1 to FSE4 that crosses the FSE2-FSE3 plane in the vicinity of FSE2. This pathway has a width of several meters. A suite of numerical models of ground-water flow and solute transport were constructed, each model qualitatively consistent with the geophysical results. The models were calibrated to the tracer and head data using non-linear regression. For calibrated models, simulated breakthrough curves in the image planes were compared to difference-attenuation histories from the tomograms. Several models were identified that (1) explain the timing and shape of the difference-attenuation breakthrough in the image planes and (2) provide reasonable matches to the observed tracer data. Our results indicate that heterogeneity diverts much of the tracer outside the prism of the three image planes. Despite this, the co-interpretation of radar and tracer data provides new insight into preferential flow paths.

CONCLUSIONS

To reproduce hydraulic data from the FSE well field, it is sufficient to resolve several high-*T* zones, which can be modeled as homogeneous, tabular features. An important feature in reproducing hydraulic response is inter-well connections. Tracer transport is sensitive to finer-scale heterogeneity that may be unresolved by hydraulic data alone. Our results suggest that heterogeneity within the high-*T* zones at the site must be considered to reproduce observed tracer data. The combination of tracer tests and radar tomography is a promising approach to identifying the locations and properties of preferential flow paths.

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