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Research papers

On the importance of geological data for three-dimensional steady-state hydraulic tomography analysis at a highly heterogeneous aquifer-aquitard system

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ABSTRACT

Hydraulic tomography (HT) has been shown to map subsurface heterogeneity accurately through the joint interpretation of multiple pumping tests. Previous research has shown that smooth hydraulic conductivity (K) estimates are obtained beyond where pumping/observation data are available using the geostatistical inversion approach, when the inversion begins with a homogeneous K and when data densities are not high. However, geological data are typically available through outcrops and borehole logs to provide geological variability. Therefore, we investigate the usefulness of geological data for HT analysis at a highly heterogeneous field site by: (1) comparing calibrated geological models of two different resolutions to two homogeneous and four highly parameterized geostatistical inverse models, in terms of both model calibration and validation performances as well as correspondence of estimated K values with permeameter-estimated K profiles along boreholes; and (2) using geological models as prior information for the geostatistical inversion approach. Results reveal that the simultaneous calibration of geological models to seven pumping test data yields K values that correctly reflect the general patterns of vertical distributions of permeameter-estimated K. We also find that the geostatistical inversion approach using a geological model as prior information performs better for both model calibration and validation than using a homogenous K as a prior, and more importantly, improves the correspondence of K estimates to permeameter test results along wells, as well as in preserving geological features where drawdown measurements are lacking. Overall, our results suggest the joint use of both geological and pumping test data for HT analysis when accurate geological data are available.

1. Introduction

The accurate characterization of subsurface heterogeneity has long been recognized as critical for predictions of groundwater flow and solute transport. Thus far, numerous efforts have been devoted to the issue of subsurface heterogeneity (e.g., Koltermann and Gorelick, 1996; Carrera et al., 2005). During the past two decades, hydraulic tomography (HT) has been developed as a useful method to image subsurface heterogeneity (e.g., Gottlieb and Dietrich, 1995; Yeh and Liu, 2000) and tested under synthetic, laboratory, and field conditions (e.g., Bohling et al., 2002; Brauchler et al., 2003, 2007, 2011, 2012; Zhu and Yeh, 2005; Illman et al., 2007, 2009, 2010, 2015; Cardiff et al., 2009, 2012, 2013; Cardiff and Barrash, 2011; Berg and Illman, 2011a,b, 2012, 2013, 2015; Mao et al., 2013).

During a HT survey, multiple sets of head responses are collected to identify the heterogeneity within an aquifer. Yeh et al. (1996) developed an iterative geostatistical technique to successively incorporate the nonlinear relationship between hydraulic pressure head and parameters such as hydraulic conductivity (K) and concentration. Based on this early work, Yeh and Liu (2000) developed the Sequential Successive Linear Estimator (SSLE) for three-dimensional steady-state hydraulic tomography (SSHT) analysis, which jointly inverts multiple pumping tests to map the K field and corresponding uncertainties. Then, Zhu and Yeh (2005) extended the SSLE for transient analysis. Their work showed promising results on utilizing transient HT (THT) to characterize accurate estimates of both K and specific storage (S_s) fields. Since then, geostatistics-based inverse methods have been extensively used for HT data interpretation by several research groups (e.g., Li et al., 2005, 2007, 2008; Illman et al., 2007, 2009, 2010; Castagna and Bellin, 2009; Liu et al., 2007, 2014; Berg and Illman, 2011a,b, 2012, 2013; Cardiff et al., 2012, 2013; Schöniger

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et al., 2012, 2015; Lee and Kitanidis, 2014). In addition, another approach of HT has also been proposed by Brauchler et al. (2003) based on the asymptotic estimation method developed by Vasco et al. (2000), which uses the travel times of pressure pulses between two boreholes to estimate the distribution of diffusivity, instead of solving the groundwater flow equation directly with given pressure head data to obtain the K and S_s distributions. This travel-time based HT approach is computationally-efficient and the reconstructed diffusivity tomograms are found to be useful in providing valuable structural information of K distributions through numerous studies (e.g., Brauchler et al., 2003, 2007, 2011, 2013; Hu et al., 2011; Jiménez et al., 2013).

So far, the HT algorithm based on geostatistics has been extensively tested in the field (e.g., Straface et al., 2007; Illman et al., 2009; Cardiff et al., 2009, 2012, 2013; Castagna et al., 2011; Berg and Illman, 2011b, 2013, 2015; Huang et al., 2011; Hochstetler et al., 2016). In particular, Straface et al. (2007) conducted a two-dimensional THT analysis at a well field in Italy, yielding results that are consistent with geology. Illman et al. (2009) applied the THT code of Zhu and Yeh (2005) at the Mizunami Underground Research Laboratory (MIU) in Japan to characterize the hydraulic properties of fractured granite at the kilometer scale in three-dimensions. Berg and Illman (2011b) performed a THT analysis of four pumping tests at the North Campus Research Site (NCRS) in Waterloo, Canada yielding promising results in comparison to inversions of single pumping tests. Cardiff et al. (2012) performed a three-dimensional THT analysis at the Boise Hydrogeophysical Research Site (BHRS) in Idaho, USA.

Past research efforts (e.g., Illman et al., 2010, 2015; Berg and Illman, 2011a, 2015) have shown promising results of HT based on the geostatistical inversion method when compared to traditional aquifer characterization and modeling approaches. In particular, Illman et al. (2010) compared the performance of SSHT in their abilities of predicting independent pumping tests of laboratory sandbox experiments, to those from other traditional approaches typically used by groundwater modelers. They concluded that the K distribution obtained from SSHT corresponded well to the synthetic aquifer and yielded an excellent correspondence between measured and simulated drawdowns. Then, Berg and Illman (2011a) performed similar comparisons using transient pumping test data using field data from the NCRS. Furthermore, Berg and Illman (2015) compared THT to five 'traditional' methods including kriging, effective parameter, transition probability/Markov Chain geostatistics, geological, and stochastic inverse models conditioned to local K data. In the previous comparison studies of Illman et al. (2010) and Berg and Illman (2015), traditional methods were only calibrated to single pumping tests, while the HT analysis integrated information from multiple pumping tests.

More recent studies have shown that when pumping test data are scarce, the geostatistical inversion approach yields overly smooth parameter fields (e.g., Cardiff et al., 2013; Illman et al., 2015). In particular, in the field studies by Cardiff et al. (2013) and Berg and Illman (2011a, 2013, 2015), the geostatistical model yielded K estimates that are inconsistent with geological knowledge for the areas where no pumping and observation data are available. Cardiff and Barrash (2011) through a synthetic study using conditional realizations of heterogeneity and Berg and Illman (2015) through a field investigation have tried to estimate the K tomograms conditioned on prior information of aquifer heterogeneity, such as permeameter K data, in order to improve the consistency of K estimates with geological knowledge. However, the improvements to the K tomogram depended on the availability of hard data and could potentially cause the prediction performance to deteriorate if the local-scale or other data used to improve the estimated parameter fields contained errors (Berg and Illman, 2015).

While it is possible to collect more data for inverse analysis, more efforts are required to obtain additional hydraulic response data or other complementary information (e.g., flux measurements, geological, concentration, temperature and geophysical data) other than pressure heads to calibrate an inverse model. For example, Li et al. (2008) jointly inverted the steady state depth-averaged drawdown HT data and the vertical profile of relative K data obtained from flowmeter tests from fully-screened wells. Brauchler et al. (2012) assessed a sequential inversion approach based on hydraulic and seismic tomography at a field site in Germany. Zha et al. (2014) developed a new approach that can incorporate flux measurements in HT analysis and demonstrated significant improvements to K estimates through a two-dimensional synthetic study. Through a cross-correlation analysis, Tso et al. (2016) showed the benefits of utilizing flux measurements in addition to drawdown data in HT surveys through a three-dimensional synthetic case. Soueid Ahmed et al. (2014) conducted a synthetic study to jointly interpret self-potential and pressure head data for K estimation and illustrated the value of self-potential data.

While geophysical data and flux measurements along boreholes may be available at a field site, geological data are more commonly available from outcrops, borehole logs or core samples extracted through drilling. However, geological structures do not necessarily represent the zoning of hydrogeological properties (Meyer et al., 2014), due to intralayer heterogeneity and also do not provide direct hydraulic information (e.g., Carrera et al., 2005; Illman et al., 2010; Berg and Illman, 2011a,b). Still, geological models are convenient to provide insight into geological variability and to conceptualize ground water flow systems (Koltermann and Gorelick, 1996; Martin and Frind, 1998; Refsgaard et al., 2012). To investigate the utility of geological models in HT, Illman et al. (2015) compared the performance SSHT based on the geostatistical inversion approach to those from the geological zonation model with perfectly known stratigraphy using the same amount of data. One key finding from the work of Illman et al. (2015) was that when the geological model is perfect, it can yield calibration and validation performances that are comparable to the highly parameterized geostatistical model. In parallel, Schöniger et al. (2015) examined the issue of groundwater model complexity and experimental effort through a Bayesian model selection analysis. Schöniger et al.'s (2015) results indicated that aquifer characterization via HT does not necessarily require an inverse approach based on geostatistics. Instead, an approach based on geological zonation may be more robust, but only if the zonation is geologically accurate.

An important assumption in the works of Illman et al. (2015) and Schöniger et al. (2015) was the perfect knowledge of zonation models based on geological information. However, such information is impossible to obtain with currently available technology. Therefore, to investigate the issue of utilizing inaccurate geological models for HT analysis and using them as prior information in geostatistics-based HT approach, Zhao et al. (2016) conducted a model comparison study involving four geological models of different accuracies using laboratory sandbox data showing mixed results in terms of model calibration and validation. Results revealed that geological models built based on the accurate knowledge of stratigraphy from borehole logs or with errors in stratigraphy could all be well calibrated due to the compensational effect of estimated parameters for model structure error (Refsgaard et al., 2012), while the K estimates for each unit can be quite inconsistent from the permeameter K measurements and model validation results were poorer for those geological models with inaccurate stratigraphy information. Moreover, they found that the performance gap between the geological model and geostatistical approaches decreased in terms of model calibration and validation,