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Research papers

On the importance of geological data for hydraulic tomography analysis: Laboratory sandbox study

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ABSTRACT

This paper investigates the importance of geological data in Hydraulic Tomography (HT) through sandbox experiments. In particular, four groundwater models with homogeneous geological units constructed with borehole data of varying accuracy are jointly calibrated with multiple pumping test data of two different pumping and observation densities. The results are compared to those from a geostatistical inverse model. Model calibration and validation performances are quantitatively assessed using drawdown scatterplots. We find that accurate and inaccurate geological models can be well calibrated, despite the estimated K values for the poor geological models being quite different from the actual values. Model validation results reveal that inaccurate geological models yield poor drawdown predictions, but using more calibration data improves its predictive capability. Moreover, model comparisons among a highly parameterized geostatistical and layer-based geological models show that, (1) as the number of pumping tests and monitoring locations are reduced, the performance gap between the approaches decreases, and (2) a simplified geological model with a fewer number of layers is more reliable than the one based on the wrong description of stratigraphy. Finally, using a geological model as prior information in geostatistical inverse models results in the preservation of geological features, especially in areas where drawdown data are not available. Overall, our sandbox results emphasize the importance of incorporating geological data in HT surveys when data from pumping tests is sparse. These findings have important implications for field applications of HT where well distances are large.

1. Introduction

Hydrogeological problems such as contaminant transport investigations rely heavily on the accurate characterization of aquifer heterogeneity. As a method for characterizing aquifer heterogeneity, Hydraulic Tomography (HT) has been proposed and developed (e.g., Gottlieb and Dietrich, 1995; Yeh and Liu, 2000) over the past two decades. During HT tests, multiple pumping tests are conducted in order to generate different hydraulic responses throughout the investigated aquifer. These data are analyzed with a suitable inverse method to yield distributions or tomograms of hydraulic conductivity (K) and specific storage (S_s).

Thus far, numerous studies have been published to demonstrate the robust performance of HT via laboratory (e.g., Liu et al., 2002; Illman et al., 2007, 2008, 2010a, 2015; Liu et al., 2007; Berg and Illman, 2011a, 2012; Zhao et al., 2015) and field experiments (e.g., Straface et al., 2007; Bohling et al., 2007; Illman et al., 2009; Brauchler et al., 2011; Berg and Illman, 2011b, 2013, 2015; Castagna et al., 2011; Cardiff et al., 2012, 2013a; Paradis et al., 2016). Meanwhile, different HT data interpretation codes have been developed (e.g., Yeh and Liu, 2000; Bohling et al., 2002; Brauchler et al., 2003; Zhu and Yeh, 2005, 2006; Xiang et al., 2009; Castagna and Bellin, 2009; Cardiff and Barrash, 2011; Liu and Kitanidis, 2011; Schöniger et al., 2012; Mao et al., 2013; Soueid Ahmed et al., 2015) to yield estimates of hydraulic parameters for different types of hydrogeological problems.

The fundamental idea of the HT approach is to obtain hydraulic data with a high-density observation network through multiple pumping tests, to “image” K and S_s heterogeneity. Through synthetic, laboratory and field studies, loss of resolution in heterogeneity has been documented when pumping and observation densities are reduced (e.g., Cardiff et al., 2013a; Illman et al., 2015). Based on a synthetic case study, Yeh and Liu (2000) concluded that the optimal horizontal observation density should be approximately half the horizontal correlation scale of the K field, when the data are interpreted with geostatistical inverse models. The vertical observation density should be as small as possible,

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and in particular, less than half the vertical correlation length to capture the most salient features of heterogeneity. They also concluded that the pumping interval in the vertical direction has a minor impact on the effectiveness of HT. Through a field study, Cardiff et al. (2013a) suggested that using pumping and observation intervals close to the vertical correlation length of aquifer heterogeneity could significantly improve the accuracy of *K* estimates. Using sandbox experiments, Illman et al. (2015) found a systematic loss of *K* heterogeneity when pumping and observation data were gradually removed in both horizontal and vertical directions.

At sites managed for groundwater resources or utilized for contaminant transport investigations, wells and monitoring intervals containing pressure transducers are typically not available at high densities. Recently, harmonic pumping tests have been analyzed (Cardiff et al., 2013b; Cardiff and Barrash, 2015) and showed potential to provide valuable information of aquifer heterogeneity for contaminated sites. Implementations of such a method in a tomographic fashion have been tested in the laboratory (Zhou et al., 2016b) as well as under field (Jardani et al., 2012) conditions. So far, groundwater models built by practitioners almost always rely on geological data obtained from boreholes and outcrops. In this traditional approach, the area of interest is divided into several hydrogeological zones based on available geological data, such as outcrops, geological maps and borehole logs, and homogeneous hydraulic parameters are assumed throughout each zone. These deterministic groundwater models are typically built for regional scale studies (e.g., Martin and Frind, 1998; Troldborg et al., 2007; Refsgaard et al., 2012; Seifert et al., 2008). While the approach may be practical, neglecting intralayer heterogeneity may result in the oversimplification of heterogeneity in complex aquifers. Another fundamental issue related to deterministically conceptualized models is that the stratigraphy of geological models is practically impossible to accurately obtain in three-dimensions, which leads to persistent discussions over the topics of structural adequacy (e.g., Gupta et al., 2012) and of the necessity to evaluate alternative models (e.g., Troldborg et al., 2007; Refsgaard et al., 2012; Schöniger et al., 2015). Added to this complication is that core samples obtained from boreholes to help determine stratigraphy can be lost during drilling resulting in errors in geological models (e.g., Alexander et al., 2011).

Alternatively, surface and borehole geophysical methods, such as ground-penetrating radar and seismic surveys, have also been utilized to identify subsurface geological structures (e.g., Hyndman et al., 1994; Hubbard et al., 2001; Bowling et al., 2005; Parra et al., 2006; Moret et al., 2006). Unlike geological information obtained from borehole logs, which mainly provide vertical layering information, surficial and cross-hole geophysical techniques can provide lateral structural information between wells. For example, Bohling et al. (2007) developed a zonation model based on a cross-hole radar profile to interpreted HT data at the Geohydrologic Experimental and Monitoring Site in Kansas, USA. In particular, they demonstrated that the zonation model constructed through the radar survey provided useful information regarding the *K* field geometry resulting in a reduction of parameter uncertainty compared to the analysis using a simple, equal-thickness, layered zonation. However, ground-penetrating radar could perform poorly in electrically conductive medium such as sites rich of clays (Hubbard et al., 2001).

Recently, Illman et al. (2015) simultaneously calibrated different groundwater models with varying subsurface conceptualizations and parameter resolutions using a laboratory sandbox aquifer in order to investigate: (a) whether HT should be interpreted using a geostatistical inverse modeling approach; and (b) whether alternative conceptual approaches (effective parameters, geological model) can yield calibration and validation results comparable to the geostatistics approach. The compared models included: (1) isotropic and anisotropic effective parameter models; (2) a heterogeneous model that faithfully represented the geological stratigraphy and treated *K* to be constant within a given layer; and (3) a heterogeneous model based on geostatistical inverse modeling. The performance of these models was assessed by quantitatively examining the results from model calibration and validation. Results revealed that the geostatistical inversion approach performed best, but the geological modeling with perfect knowledge of stratigraphy came a close second, especially when the number of pumping tests available for inverse modeling was small. An important assumption in the work of Illman et al. (2015) was that the geological model compared against other modeling approaches had perfectly known layers for the entire simulation domain. Therefore, Illman et al. (2015) examined the “best case” geological model and errors in layer-based geological models were not evaluated against effective parameter and geostatistical approaches in inverse modeling. It is important to keep in mind that in the field, such perfect knowledge of stratigraphy is not available with current technology. Therefore, it is unknown whether inaccurate geological models could approach the model performance of HT based on geostatistical inverse modeling.

In addition, researchers to date have not evaluated the importance of zonation based on geological data of varying accuracy for HT data interpretation through laboratory or field experiments. Such a study is necessary to gain more insight in utilizing geological models where both geological and pumping test data are available. Thus, the first objective of this study is to evaluate geological models of varying accuracy for their abilities in conducting steady-state HT analysis. Specifically, we use data of two different pumping and observation resolutions from a synthetic aquifer built in a well-studied laboratory sandbox (Illman et al., 2010a, 2015; Berg and Illman, 2011a) for this purpose.

Another issue is whether to utilize geological information as prior information in HT analysis, as such data are typically more abundant than pumping tests and corresponding drawdown data at field sites. Geological information has been incorporated in geophysical inverse models through the image-guided inversion approach (Zhou et al., 2014, 2016a; Zhang and Revil, 2015) and used to create conditional realizations for HT data interpretation through the transition probability/Markov Chain approach (Carle and Fogg, 1997). In particular, Zhou et al. (2014) proposed an image-guided method by extracting the structure information from the cross sections of complete known geology and incorporating in the inversion of geophysical data. Later, Zhou et al. (2016a) extended the method to include the Markov-chain Monte Carlo sampler to update and select the most plausible geological models for the geophysical inverse problem. This image-guided inversion approach was then tested by Soueid Ahmed et al. (2015) through synthetic HT studies and was shown to be an alternative way to incorporate geological information to reconstruct hydraulic parameter fields. The main feature of the image-guided inversion approach is that a weighted matrix containing structure information is used to regularize the inversion process of geophysical or pressure head data. While this approach offers some advantage in regularizing the inversion process, the potential value of using geological data as prior information for geostatistical inversion still remains uninvestigated for both laboratory and field studies.

Thus far, researchers have conducted HT analyses using the geostatistical inversion approach with prior information of *K* that represents some average value. The use of such a homogeneous initial value has been found to be suitable through synthetic (e.g., Yeh and Liu, 2000; Zhu and Yeh, 2005) and laboratory studies (e.g., Liu et al., 2002; Illman et al., 2007, 2008, 2010a,b; Berg and Illman, 2011a). Specifically, Illman et al. (2008) through synthetic and real sandbox experiments and Cardiff and Barrash (2011)