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Comparative study of transient hydraulic tomography with varying parameterizations and zonations: Laboratory sandbox investigation

Ning Luo [a,*], Zhanfeng Zhao [a,b], Walter A. Illman [a], Steven J. Berg [a,c]

[a] Department of Earth and Environment Sciences, University of Waterloo, Waterloo, ON N2L3G1, Canada
[b] Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China
[c] Aquanty Inc, Waterloo, ON N2L5C6, Canada

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A B S T R A C T

Transient hydraulic tomography (THT) is a robust method of aquifer characterization to estimate the spatial distributions (or tomograms) of both hydraulic conductivity (K) and specific storage (S_s). However, the highly-parameterized nature of the geostatistical inversion approach renders it computationally intensive for large-scale investigations. In addition, geostatistics-based THT may produce overly smooth tomograms when head data used to constrain the inversion is limited. Therefore, alternative model conceptualizations for THT need to be examined. To investigate this, we simultaneously calibrated different groundwater models with varying parameterizations and zonations using two cases of different pumping and monitoring data densities from a laboratory sandbox. Specifically, one effective parameter model, four geology-based zonation models with varying accuracy and resolution, and five geostatistical models with different prior information are calibrated. Model performance is quantitatively assessed by examining the calibration and validation results. Our study reveals that highly parameterized geostatistical models perform the best among the models compared, while the zonation model with excellent knowledge of stratigraphy also yields comparable results. When few pumping tests with sparse monitoring intervals are available, the incorporation of accurate or simplified geological information into geostatistical models reveals more details in heterogeneity and yields more robust validation results. However, results deteriorate when inaccurate geological information are incorporated. Finally, our study reveals that transient inversions are necessary to obtain reliable K and S_s estimates for making accurate predictions of transient drawdown events.

1. Introduction

The detailed and accurate characterization of subsurface heterogeneity in hydraulic conductivity (K) and specific storage (S_s) are of great importance to groundwater resource management, its security, and remediation of contaminants. Typically, detailed mapping of subsurface heterogeneity in K is accomplished through the geostatistical analyses of small-scale K values obtained from core samples, slug tests, flowmeter surveys, and single-hole pumping or injection tests. In contrast, heterogeneity in S_s has been ignored in many studies as its variability is considered to be much less than K. Hence, little work has been done in characterizing S_s heterogeneity.

One alternative to the geostatistical analysis of small scale data is hydraulic tomography (HT). The performance of HT has been evaluated through a number of numerical (Yeh and Liu, 2000; Bohling et al., 2002; Zhu and Yeh, 2005), laboratory (Liu et al., 2002, 2007; Illman et al., 2007, 2008, 2010, 2015; ; Berg and Illman, 2011a, 2012; Zhao et al., 2015, 2016), and field (Bohling et al., 2007; Straface et al., 2007; Illman et al., 2009; Cardiff et al., 2009, 2012, 2013; Berg and Illman, 2011b, 2013, 2015; Brauchler et al., 2011; Castagna et al., 2011; Paradis et al., 2016; Zha et al., 2015, 2016; Zhao and Illman, 2017) studies.

Fundamentally, HT involves the inverse modeling of hydraulic head data obtained during multiple pumping/injection tests. There are a number of inverse modeling approaches (e.g., Yeh and Liu, 2000; Bohling et al., 2002; Brauchler et al., 2003; Zhu and Yeh, 2005, 2006; Xiang et al., 2009; Cardiff and Barrash, 2011; Mao et al., 2013) to map the spatial variations of hydraulic parameters. For instance, Yeh and Liu (2000) proposed a sequential successive linear estimator (SSLE) to interpret steady state HT (SSHT) data. They evaluated this approach through the examination of uncertainties associated with input parameters, such as mean values and correlation scales. However, the uncertainty related to the assumption of boundary conditions was not addressed. Zhu and

* Corresponding author.
E-mail address: nluo1222@gmail.com (N. Luo).

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Yeh (2005), then developed a transient hydraulic tomography (THT) algorithm based on SSLE to jointly estimate the heterogeneity in K and S_s as well as their uncertainties.

To overcome the impact of uncertain boundary conditions on K estimation and to maintain computational efficiency, Bohling et al. (2002) proposed a steady shape analysis of transient drawdown data for HT. Later, through a field study conducted in an alluvial aquifer located in Kansas, USA, Bohling et al. (2007) concluded that the steady shape analysis of transient drawdown data yields similar performance in estimating K profiles when compared to THT, suggesting the viability of the steady shape inversion approach. Nevertheless, the steady-state and steady shape approaches do not allow for the estimation of S_s, which is critical for assessing the availability of groundwater in a basin and is of paramount importance to groundwater resource management (Wu et al., 2005).

Hu et al. (2011) proposed an inversion procedure combining travel time (Brauchler et al., 2003) and steady shape (Bohling et al., 2002) for subsurface heterogeneity characterization. In their study, the K distribution was estimated from steady shape inversion, while S_s values were calculated based on the estimated K profile and the obtained diffusivity (D) distribution from the travel time inversion ($S_s = K/D$). Therefore, S_s values were not jointly estimated with K during the inversions. Brauchler et al. (2013) then demonstrated through a field study at the Stegemuhle site in Germany that the combination of travel time and steady shape inversions is an efficient approach to characterize the spatial distributions of hydraulic parameters.

However, through a HT survey conducted in one isolated subhorizontal bedrock fracture, Castagna et al. (2011) concluded that accurate knowledge of the spatial structures of S_s would help to obtain consistent representations of K and S_s fields. In contrast, the inaccurate assumption of spatial S_s structures (i.e., spatially heterogeneous S_s field is assumed to be homogeneous) would lead to misrepresentations of the S_s fields or poor representations of both K and S_s fields. Furthermore, based on the pilot point inversion results of HT data collected at the Stegemuhle site, Germany, Jiménez et al. (2015) pointed out that the inclusion of S_s in addition to K in inversions could help to minimize model misfit to field data. Contrasting results were obtained by Cardiff and Barrash (2011) that K estimation is slightly degraded if storage parameters are jointly estimated. Therefore, additional research is necessary in evaluating the results from the simultaneous estimation of K and S_s from transient head data during HT surveys.

Another issue that deserves significant attention is what level of model complexity is required for HT analysis? To answer this question, Illman et al. (2015) compared HT with different model complexities through the analysis of laboratory sandbox data of Illman et al. (2010). In particular, they compared the performance of: (1) isotropic and anisotropic effective parameter models, (2) a geological model with constant K value in each layer, and (3) a geostatistical model with a spatially variable K field. Only steady state head data were utilized for calibration and validation purposes. Results revealed that the geological model with perfect knowledge of stratigraphy performed nearly as well as the geostatistical model, especially when the number of pumping test data utilized for model calibration was reduced. Schöniger et al. (2015) also examined the issue of groundwater model complexity and experimental effort through a Bayesian model selection analysis using the steady state head data utilized by Illman et al. (2015). They concluded that the geological zonation approach was most robust, but only if the zonation is accurate.

Illman et al. (2015) also concluded that the resulting resolution and accuracy of aquifer heterogeneity from the geostatistical interpretation of steady state head data depended on the amount of information included for model calibration, affirming the conclusions by Yeh and Liu (2000) and Cardiff et al. (2013). Results from the study by Illman et al. (2015) revealed that details of aquifer heterogeneity were lost when the number of hydraulic head data was reduced for geostatistical inverse modeling, especially at or near locations where observation data were lacking. In particular, the estimated K tomograms from the sequential or simultaneous geostatistical inversions of head data were able to recover the major layers of high and low K values, but distinct layer boundaries were not recovered. These relatively smooth K fields were adequate in predicting the distributions of drawdowns from independent pumping tests not used in the calibration effort. However, the recovery of a finer scale resolution tomogram including layer boundaries is likely needed for improved predictions of solute and contaminant transport.

Parallel to the findings by Illman et al. (2015), Ahmed et al. (2015) demonstrated that K tomograms obtained from the geostatistical interpretation of steady state head data might still suffer from the issue of smoothness due to the inherent estimation of conditional means implied in most geostatistical inversion approaches, such as the quasi-linear geostatistical approach (Kitanidis, 1995) as well as the SSLE (Yeh and Liu, 2000) or the Simultaneous Successive Linear Estimator (SimSLE) (Xiang et al., 2009).

The issue of smooth distributions of estimated hydraulic parameters has also been discussed by Hu et al. (2011) and Jiménez et al. (2013, 2015). In particular, Jiménez et al. (2015) applied the travel time inversion of hydraulic head response data to obtain the information of domain structural features, which in turn was used to guide the pilot point inversion of head data to estimate K and S_s tomograms. Zhou et al. (2014) also incorporated geological information in their inverse modeling of geophysical data. They proposed an image-guide inversion approach, in which, structural information was extracted from known geology and introduced to regularize the inversion process. More recently, Zhao et al. (2016) examined the value of integrating geological information on a HT survey through the SSHT analyses of multiple pumping test data from a laboratory sandbox (Illman et al., 2010). They found that utilizing an accurate geological model as a prior estimate for geostatistical inversions was beneficial in improving the K tomograms, layer boundaries and their connectivity.

Most recently, Zhao and Illman (2017) investigated the value of geological information on SSHT analysis of multiple pumping tests at the North Campus Research Site located on the University of Waterloo campus in Waterloo, Canada. Both the laboratory (Zhao et al., 2016) and field-based (Zhao and Illman, 2017) studies suggested the importance of including accurate geological information to improve the results of SSHT analyses of pumping test data. However, whether this conclusion translates to THT analysis in which both K and S_s are jointly estimated remains unknown.

The main objectives of this study are: (1) to extend the work of Illman et al. (2015) to the transient case to compare HT inversions of varying model complexities; and (2) to extend the work of Zhao et al. (2016) to evaluate the utility of geological information for THT analysis through the analyses of laboratory sandbox data collected by Illman et al. (2010). Since the investigation is performed in a controlled sandbox with perfect knowledge of geological structures, this study will be helpful in identifying conditions in which geological models can be useful for future field HT studies.

2. Experimental setup

2.1. Sandbox description and collected data

A two-dimensional synthetic heterogeneous aquifer constructed in a laboratory sandbox is characterized using inverse models of various parameterization and zonations. The length,