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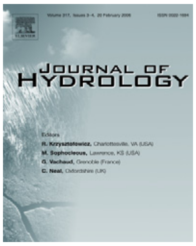

An inversion strategy for hydraulic tomography: Coupling travel time and amplitude inversion

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Summary We present a hydraulic tomographic inversion strategy with an emphasis on the reduction of ambiguity of hydraulic travel time inversion results and the separation of the estimated diffusivity values into hydraulic conductivity and specific storage. Our tomographic inversion strategy is tested by simulated multilevel interference slug tests in which the positions of the sources (injection ports) and the receivers (observation ports) isolated with packers are varied. Simulations include the delaying effect of wellbore storage on travel times which are quantified and shown to be of increasing importance for shorter travel distances. For the reduction of ambiguity of travel time inversion, we use the full travel time data set, as well as smaller data subsets of specified source–receiver angles. The inversion results of data subsets show different resolution characteristics and improve the reliability of the interpretation. The travel time of a pressure pulse is a function of the diffusivity of the medium between the source and receiver. Thus, it is difficult to directly derive values for hydraulic conductivity and specific storage by inverting travel times. In order to overcome this limitation, we exploit the great computational efficiency of hydraulic travel time tomography to define the aquifer structure, which is then input into the underlying groundwater flow model MODFLOW-96. Finally, we perform a model calibration (amplitude inversion) using the automatic parameter estimator PEST, enabling us to separate diffusivity into its two components hydraulic conductivity and specific storage.

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Introduction

Knowledge about the spatial distribution of the parameters hydraulic conductivity (k) and specific storage (S_s) are of particular interest for analyzing engineering, geotechnical, and hydrogeological problems within the context of groundwater resources management. Hydraulic conductivity and specific storage characterize the ease with which water flows and is stored or released in a geological formation. These two parameters are combined to form the diffusivity (D), the ratio of hydraulic conductivity to specific storage which is a measure of the rapidity with which a pressure disturbance propagates through a formation. The equation governing the pressure distribution in space and time is the diffusivity equation.

''Traditional hydrogeological approaches appear to have difficulties providing high resolution parameter estimates of these parameters'' (Butler, 2005). Pumping tests often lead to reliable estimates in k and S_s but the determined hydraulic properties represent spatial averages over a large aquifer volume. Laboratory-based methods, such as parameter analyses and methods using particle size statistics, can provide information at a very small scale. Unfortunately, many questions about the reliability of the hydraulic conductivity estimates obtained from these analyses have been reported (Klute and Dirksen, 1986; Rovey, 1998; Gee and Bauder, 1986; Danielson and Sutherland, 1986). More recently developed methods, such as dipole-flow tests (Kabala, 1993; Zlotnik and Zurbuchen, 1998; Zlotnik and Ledder, 1996; Peursem et al., 1999), borehole flow meter tests (Molz et al., 1989; Molz and Young, 1993; Young and Pearson, 1995; Boman et al., 1997), and multilevel slug tests (Melville et al., 1991; Butler et al., 1994, 1996; Butler, 1998) do provide detailed information about vertical variations in k but only in the vicinity of the well.

Tomographic geophysical methods such as electrical tomography (e.g. Ramirez et al., 1999; Schima et al., 1996; Bing and Greenhalgh, 2000; Slater et al., 2000; Kemna et al., 2002; Yeh et al., 2002), crosswell radar (e.g. Ramirez and Lytle, 1986; Olsson et al., 1992; Hubbard et al., 2001; Tronicke et al., 2004), and seismic tomography (e.g. Peterson et al., 1985; Harris, 1990) are often applied to obtain structural spatial information between wells. Although it is possible to collect high resolution three-dimensional data sets allowing to resolve a site's stratigraphic zonation and to monitor tracer and contaminants at low costs in terms of time, effort, and money, the difficulty of converting geophysical parameters into flow and transport properties still remains. A number of studies have focused on estimating hydrogeological parameters and their spatial distribution from geophysical data (e.g. Han et al., 1986; Marion et al., 1992; Yamamoto et al., 1994, 1995; Pride, 2005). However, Hyndman and Tronicke (2005) stated that estimating the relation between geophysical and hydrogeophysical parameters is a site specific endeavor, since no general relation is expected.

Over the last decade and a half, several research groups have begun to work on a new approach, hydraulic tomography, that has the potential to yield information on spatial variation of k, S_s and D between wells. In contrast to geophysical methods, hydraulic tomography allows to directly determine hydraulic properties. Hydraulic tomography consists of a series pumping or slug tests. Varying the location of the source stress (pumping or slug interval) and that of the receivers (pressure transducers) generates streamline patterns that are comparable to the crossed ray paths of a seismic tomography experiment. The pumping or slug intervals are usually separated by double-packer-systems (Butler et al., 1999). Two approaches with identical experimental set-up and test performance but different evaluation of results can be distinguished. The most common approach is based on the analysis of drawdown as a function of time (Bohling et al., 2002, 2007; Gottlieb and Dietrich, 1995; Butler et al., 1999; Yeh and Liu, 2000; Liu et al., 2000; Vesselinov et al., 2001a,b; Zhu and Yeh, 2005, 2006). The other approach is based upon inversion of travel times of the pressure disturbances (Vasco and Datta Gupta, 1999a; Vasco et al., 1999b, 2000; Kulkarni et al., 2000; Datta-Gupta et al., 2001; Zhong et al., 2006).

In this study we introduce a hydraulic tomographic inversion strategy which simultaneously focuses on (a) the reduction of ambiguity of hydraulic travel time inversion results and (b) the coupling of the two above mentioned inversion approaches:

(a) The travel time inversion follows the procedure of seismic ray tomography. The main feature of this procedure is a travel time integral relating the square root of the peak travel time, assuming a Dirac point source at the origin, to the inverse square root of D (Vasco et al., 2000; Kulkarni et al., 2000; Datta-Gupta et al., 2001). Brauchler et al. (2003) have further proposed to invert all travel times of a recorded transient pressure signal for a Dirac source. Their analysis also covers a Heaviside source at the origin. The similarity between hydraulic travel time tomography and seismic/radar ray tomography enables us to use the same inversion techniques. For the inversion, iterative methods based on least square solutions are applied (e.g. Dines and Lytle, 1979; Peterson et al., 1985). Commonly, in ray tomography, a homogeneous starting model and the full travel time data set is used for the inversion. However, Becht et al. (2004) showed that the usage of data subsets with specified ray angles reduces ambiguity in inversion results. Following this approach, we invert data subsets of hydraulic pressure responses of small to intermediate source—receiver angles in order to reduce vertical smearing effects of layered systems.

(b) The travel time of a pressure signal between two boreholes depends on the diffusivity D, the ratio of hydraulic conductivity k and specific storage S_s. Thus, it is a challenge to separately determine hydraulic conductivity and specific storage by means of hydraulic travel time tomography. Vasco et al. (2000) suggested that cycling between high- and low-frequency data may result in resolving spatial variations in both k and S_s. We have decided to overcome this problem by coupling the two existing inversion approaches. Travel time inversion allows to invert a huge amount of data in a short time on a PC and the resulting diffusivity distribution can be used as a starting model for the computationally intensive amplitude inversion. The computation time of the amplitude inversion can be strongly reduced by using the diffusivity structure determined by the travel time inversion. The amplitude inversion will thus