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A field proof-of-concept of tomographic slug tests in an anisotropic littoral aquifer

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SUMMARY

Hydraulic tomography is increasingly recognized as a characterization approach that can image pathways or barriers to flow as well as their connectivity. In this study, we assess the performance of a transient analysis of tomographic slug test head data in estimating heterogeneity in horizontal hydraulic conductivity (K_h), hydraulic conductivity anisotropy (the ratio between vertical and horizontal hydraulic conductivity – K_v/K_h) and specific storage (S_s) under actual field conditions. The tomographic experiment was carried out between two wells in a moderately heterogeneous and highly anisotropic silt and sand littoral aquifer. In this field proof-of-concept, the inversion of the two-dimensional (2D) head dataset was computed with a 2D radial flow algorithm that considers K_h, K_v/K_h, S_s and wellbore storage effects. This study demonstrated that a transient analysis of tomographic slug tests is able to capture the key features of the littoral environment of the test: the vertical profiles of K_h and K_v are indeed in agreement with those from other field and laboratory tests, and S_s values exhibit physically plausible profiles. Furthermore, the simulation of independent inter-well hydraulic tests (slug and pumping tests screened over the entire aquifer) using resolved K_h, K_v/K_h and S_s tomograms produce responses very close to field observations. This study demonstrates that the effects of fine scale heterogeneity that induces K-anisotropy at larger scales can be captured through a transient analysis of tomographic slug tests, which are very difficult to quantify otherwise with conventional hydraulic tests, thus allowing a better representation of properties controlling flow and transport in aquifer systems.

1. Introduction

Hydrogeological investigations, carried out to understand either groundwater flow or contaminant transport, require representative data about the spatial distribution of hydraulic properties in aquifer systems (e.g., Koltermann and Gorelick, 1996; de Marsily et al., 2005; Butler, 2005). The geometry and texture of geological materials in aquifer systems vary naturally through space as a result of complex geological processes, leading to heterogeneity in hydraulic properties that greatly influences groundwater flow and contaminant transport at different scales (e.g., Sudicky, 1986; Freyberg, 1986; Garabedian et al., 1991; Leblanc et al., 1991; Adams and Gelhar, 1992; Boggs et al., 1992). Hydraulic tomography, which consists in the simultaneous analysis of inter-well responses at various observation points to multiple hydraulic tests, such as pumping (e.g., Bohling, 1993; Tosaka et al., 1993; Gottlieb and Dietrich, 1995; Butler et al., 1999; Yeh and Liu, 2000; Bohling et al., 2002, 2007; Zhu and Yeh, 2005; Illman et al., 2007, 2008; Fienen et al., 2008; Cardiff et al., 2009; Illman et al., 2009; Berg and Illman, 2011, 2013, 2015; Cardiff and Barrash, 2011; Huang et al., 2011; Cardiff et al., 2012, 2013b; Sun et al., 2013; Hochstetler et al., 2015), slug tests (e.g., Brauchler et al., 2003, 2007, 2011; Paradis et al., 2015a) or more recently oscillatory tests (Cardiff et al., 2013a), is a promising alternative to more conventional hydraulic testing approaches to image the heterogeneity of hydraulic properties, in particular hydraulic conductivity (K), in aquifer systems at field-scale.

Paradis et al. (2015a) investigate the influence of factors such as signal-to-noise ratio, experimental configuration, and magnitude of hydraulic properties on parameter resolution, concluding that tomographic slug tests have the potential to provide relatively detailed information about aquifer heterogeneity in horizontal hydraulic conductivity (K_h), K-anisotropy (K_v/K_h) and specific storage (S_s). Here we aim to assess the performance of this approach using field data. The main motivation to study tomographic slug tests as proposed by Paradis et al. (2015a) is two-fold. First, given the complexity of most aquifer systems, with heterogeneity that induces K-anisotropy at different scales, and the difficulty in design-

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ing hydraulic tests that can capture the finest structures of geological materials, hydrogeological characterization would benefit from field methods that can estimates *K*-anisotropy in order to capture the effects of the heterogeneity at a scale of inter-well separation. While the knowledge of K_v/K_h (or vertical hydraulic conductivity (K_v) along with K_h) is important for many hydrogeological studies (e.g., design of remediation systems, wellhead protection areas, regional groundwater flow), only a few methods are available to estimate it: tests with laboratory permeameter on samples collected in the field (e.g., Wenzel, 1942); single-well tests such as dipole-flow tests (Kabala, 1993; Zlotnik and Ledder, 1996; Xiang and Kabala, 1997; Zlotnik and Zurbuchen, 1998; Zlotnik et al., 2001; Hvilshoj et al., 2000; Sutton et al., 2000), vertical pulse interference tests (Burns, 1969; Hirasaki, 1974; Onur et al., 2004; Sheng, 2009), vertical interference slug tests (Paradis and Lefebvre, 2013); and multiple-wells tests, such as tandem circulation well tests (Goltz et al., 2008). Second, as pointed out by Cardiff and Barrash (2011), hydraulic tomography is mostly based on pumping tests. From a time-efficiency perspective, that could however be questioned as a pumping test is generally longer to perform than a slug test under the same hydrogeological conditions (Paradis et al., 2015b), which can be obtained within a few minutes (Kruseman and de Ridder, 2000). While in practice pumping test durations for tomography experiments can be shortened (e.g., Bohling et al., 2007; Cardiff et al., 2012, 2013b; Hochstetler et al., 2015) or early time data used (e.g., Brauchler et al., 2013; Jiménez et al., 2013) to reduce data acquisition time, the effects of this practice on parameter resolution have not yet been evaluated with respect to a transient analysis using full drawdown records (e.g. until steady-state conditions are reached). Likely because slug tests have been performed for a long time using buckets or rods, which produce small and erratic head perturbations, it is still often assumed that slug tests can only determine the characteristics of a small volume of aquifer surrounding the stressed well. However, with modern equipment, large and sharp head perturbations can be produced within wells, which can now be accurately detected far away from the stressed well (>10 m).

Thus, to assess the quality of the information provided by an analysis of tomographic slug tests data, we compare the results of the inversion of a tomography experiment based on slug tests performed in moderately heterogeneous and highly anisotropic littoral aquifer with estimates obtained from other field and laboratory tests, and by the simulation of independent hydraulic tests not used in the inversion. This is preceded by a description of the study site, the experimental design with the dataset and the inversion approach. Previous assessments of hydraulic tomography have been done on field data for tomographic pumping tests by Bohling et al. (2007), Berg and Illman (2011), Cardiff et al. (2012, 2013b) and Hochstetler et al. (2015) as well as by Brauchler et al. (2011) for tomographic slug tests analyzed using a ray tracing approach. To our knowledge this paper presents the first field proof-of-concept of a transient analysis of tomographic slug tests that explicitly considers *K*-anisotropy. This will contribute to addressing the need to develop accurate and time-efficient hydraulic properties characterization approaches. The dataset acquired in this study is provided as Supplemental electronic material of this paper to facilitate the verification of results and the application of alternative interpretation approaches by other researchers.

2. Site description and tomography experiment design

This section describes the test site and provides details about the experimental design, including direct-push well installation, data collection, and slug test procedures.

2.1. Site description

This study was carried out at a research site located in Saint-Lambert, 40 km south of Quebec City, Canada, at a research site (Fig. 1a and b). This 12 km^2 aquifer hosts a decommissioned

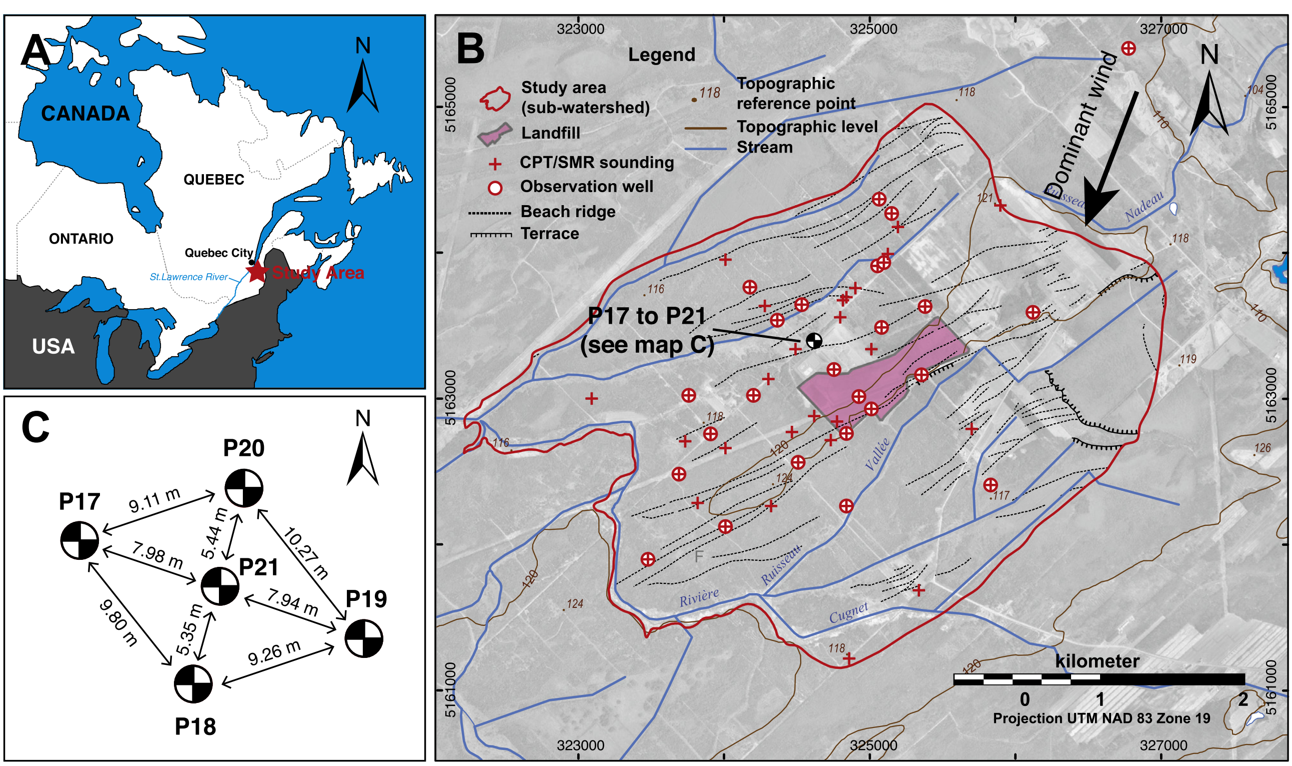

Fig. 1. Location of the St-Lambert (Canada) study area (a); location of the testing site within the sub-watershed enclosing the former sanitary landfill (b); and the relative position of the wells used for the tomographic experiment (c).