



Identification of small-scale low and high permeability layers using single well forced-gradient tracer tests: Fluorescent dye imaging and modelling at the laboratory-scale

Gareth L. Barns^{*}, Steven F. Thornton, Ryan D. Wilson¹

Groundwater Restoration and Protection Group, Department of Civil and Structural Engineering, University of Sheffield, Kroto Research Institute, Broad Lane, Sheffield, S3 7HQ, United Kingdom

ARTICLE INFO

Article history:

Received 16 February 2014

Received in revised form 9 November 2014

Accepted 12 November 2014

Available online 22 November 2014

Keywords:

Imaging

Fluorescent dye

Solute transport

Mass flux

Forced-gradient tracer test

Heterogeneous aquifers

ABSTRACT

Heterogeneity in aquifer permeability, which creates paths of varying mass flux and spatially complex contaminant plumes, can complicate the interpretation of contaminant fate and transport in groundwater. Identifying the location of high mass flux paths is critical for the reliable estimation of solute transport parameters and design of groundwater remediation schemes. Dipole flow tracer tests (DFTTs) and push-pull tests (PPTs) are single well forced-gradient tests which have been used at field-scale to estimate aquifer hydraulic and transport properties. In this study, the potential for PPTs and DFTTs to resolve the location of layered high- and low-permeability layers in granular porous media was investigated with a pseudo 2-D bench-scale aquifer model. Finite element fate and transport modelling was also undertaken to identify appropriate set-ups for *in situ* tests to determine the type, magnitude, location and extent of such layered permeability contrasts at the field-scale. The characteristics of flow patterns created during experiments were evaluated using fluorescent dye imaging and compared with the breakthrough behaviour of an inorganic conservative tracer. The experimental results show that tracer breakthrough during PPTs is not sensitive to minor permeability contrasts for conditions where there is no hydraulic gradient. In contrast, DFTTs are sensitive to the type and location of permeability contrasts in the host media and could potentially be used to establish the presence and location of high or low mass flux paths. Numerical modelling shows that the tracer peak breakthrough time and concentration in a DFTT is sensitive to the magnitude of the permeability contrast (defined as the permeability of the layer over the permeability of the bulk media) between values of 0.01–20. DFTTs are shown to be more sensitive to deducing variations in the contrast, location and size of aquifer layered permeability contrasts when a shorter central packer is used. However, larger packer sizes are more likely to be practical for field-scale applications, with fewer tests required to characterise a given aquifer section. The sensitivity of DFTTs to identify layered permeability contrasts was not affected by test flow rate.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

It is well recognised that aquifers rarely have homogeneous and isotropic groundwater flow fields. Spatial variability in aquifer properties that affect groundwater flow (e.g. hydraulic conductivity, porosity), solute spreading (e.g. dispersivity) and reactive transport (e.g. sorption, contaminant decay) can create high- and/or low-mass flux paths that influence the distribution, migration and natural attenuation of contaminants in the

Abbreviations: DFTT, Dipole Flow Tracer Test; PPT, Push-Pull Test.

^{*} Corresponding author at: WYG, Arndale Court, Headingley, Leeds, LS6 2UJ.
Tel.: +44 113 278 7111; fax: +44 113 278 3487.

E-mail address: gareth.barns@wyg.com (G.L. Barns).

¹ Present Address: AMEC Environment & Infrastructure, Cambridge, Canada, N3H 4R7.

subsurface (Devlin et al., 2002; Wilson et al., 2004). Heterogeneity in aquifer hydraulic conductivity (e.g. value, distribution and physical geometry) and porosity (e.g. value, distribution and type) can create preferential flow paths for contaminant transport at the centimetre- to metre-scale (Bianchi et al., 2011a; Freyberg, 1986; Korte et al., 2000; Stauffer, 2007; Sudicky, 1986), when flow is predominantly in sedimentary layers or lenses of higher permeability, or at the pore-scale (Welty and Gelhar, 1994; Zheng et al., 2011) by causing non-equilibrium or dual domain flow conditions. A better understanding of the location, magnitude and relative contribution of high- and low-mass flux paths for solute transport in aquifers can improve the design and efficacy of engineered groundwater remediation schemes based on contaminant removal or injection of amendments, such as pump and treatment, *in situ* chemical oxidation and enhanced bioremediation (Chambers et al., 2010; Suthersan et al., 2010), as well as those for passive management concepts such as monitoring of natural attenuation (Papapetridis and Paleologos, 2011). Therefore it is essential to identify aquifers in which high- or low-mass flux paths may dominate flow and solute transport in the field and to develop field-based techniques which support *in situ* interpretation of these features.

Ex situ methods used to estimate hydraulic conductivity, such as permeameter tests with aquifer core samples (e.g., Bianchi et al., 2011a) can provide high resolution data, but may not provide results which represent *in situ* conditions, while geophysical methods such as electrical resistivity tomography offer some advantages (Chambers et al., 2010) but may not be cost-effective and require data processing which may introduce inaccuracies. Cone penetration tests with a membrane interface probe (Suthersan et al., 2010) can be used to identify higher permeability zones and location of layers which may host contaminants within a vertical profile. Field tracer tests using monitoring wells installed in an aquifer provide a cost effective *in situ* method for identifying flow paths. In addition they can also be used to estimate aquifer properties which contribute to reactive transport (e.g. dispersivity, solute distribution coefficients) which are not measured with cone penetration tests. Ideally it would be preferable to use natural gradient tracer tests in which aquifer properties are estimated by spatial interpretation of tracer plumes injected under existing flow conditions (e.g. Freyberg, 1986; LeBlanc et al., 1991). These tests offer the potential to measure the natural groundwater velocity at discrete points and contaminant concentrations at high resolution using multilevel samplers (Schillig et al., 2011). However they take a long time to perform and may require the analysis of a large number of samples. Therefore they are often impractical for the time-efficient determination of aquifer properties in porous media with complex physical heterogeneity or flow fields.

Forced-gradient tests involve the injection of tracer into an imposed groundwater flow system to estimate the solute transport parameters of aquifers. This minimises test duration and number of samples required for analysis (Fetter, 1994). Two-well convergent tests (Ptak and Schmid, 1996), where the injection rate is less than extraction rate, and two-well dipole flow tracer tests (Bianchi et al., 2011b), where the injection and extraction rates are the same, have been evaluated using multilevel samplers to assess the variability in horizontal flow paths along well screen intervals. By using a multilevel sampler in the extraction well, a vertical profile of velocity and

dispersivity can be resolved from injected tracer concentrations, although these values are an average along the flow path between injection and extraction wells.

With single-well forced gradient tests such as the dipole flow tracer test (DFTT) or push-pull test (PPT), there is the flexibility to estimate relevant aquifer parameters at a sub-meter scale using a packer assembly in a single long-screened well. Such tests can be performed in less than a day, making them a cost effective alternative to other methods. The dipole flow test was initially developed by Kabala (1993) to characterise the vertical and horizontal hydraulic conductivity and specific storativity of an aquifer. The methodology was extended by Sutton et al. (2000) to include a groundwater tracer component: herein referred to as DFTTs. This addition improved the reliability of tests, as hydraulic short circuits could be identified, and allowed values of aquifer dispersivity to be estimated from tracer breakthrough curves. A DFTT involves installing three inflatable packers to isolate two sections of well screen. Tracer-tagged water followed by tracer-free water is injected in one screen and extracted from the other. The extracted water is then re-injected with periodic sampling to interpret the tracer concentration history. DFTTs induce vertical flow and solute transport perpendicular to the generally horizontal flow of groundwater and are hence sensitive to vertical variations in hydraulic conductivity, which may result from horizontal layers with different permeability or porosity. Sutton et al. (2000) used DFTTs to interpret anisotropy in the hydraulic conductivity of an aquifer and (Xiang and Kabala (1997) found discrete layering of hydraulic conductivity to significantly affect hydraulic pressure readings in injection and extraction chambers in dipole flow tests. This sensitivity to vertical variation in aquifer properties is also observed in other single well hydraulic tests, including multilevel slug tests (e.g. Chen et al., 2012) and interference slug tests (Paradis and Lefebvre, 2013), which have been used to identify discrete changes in hydraulic conductivity in aquifers. It is considered likely that heterogeneity in the permeability distribution of an aquifer also affects solute transport in DFTTs. A hypothesis evaluated in this paper is that discrete changes in aquifer hydraulic conductivity can be accurately inferred *in situ* from the DFTT extraction chamber breakthrough curve to identify the vertical location and extent of high and low-flux solute transport paths.

PPTs (also known as a single well pulse tests) have been well characterised for the *in situ* estimation of biodegradation parameters for organic compounds, e.g. Istok et al. (1997). These tests have also been used to estimate sorption of inorganic and organic compounds (Hageman et al., 2003; Pickens et al., 1981). In a PPT, a volume of tracer-tagged water is injected (pushed) into an isolated section of well screen, which may be followed by a slug of tracer-free water. Water is then extracted (pulled) from the same screen and sampled to characterize the concentration history of returning tracer. The flow-field induced in a PPT is often assumed to be spherical (Bauer et al., 2001; Huang and Goltz, 2006). When there is significant layered anisotropy or a confining layer, Schroth and Istok (2005) predicted cylindrical flow of tracer. While, under homogenous anisotropic conditions, Mathias (2010) predicted a plume to form an ellipsoid shape. However, it was concluded by Mathias (2010) that the effect of “realistic” (i.e. heterogeneous) permeability conditions on the plume radius was unclear.

Download English Version:

<https://daneshyari.com/en/article/4546492>

Download Persian Version:

<https://daneshyari.com/article/4546492>

[Daneshyari.com](https://daneshyari.com)