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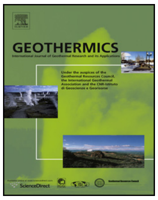

Study of the effects of the chaser in push–pull tracer tests by using temporal moment analysis

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ABSTRACT

"Push–pull" tracer tests are a suitable tracer test method for hydrochemical characterization of an aquifer in a single-well setting (e.g. in deep geothermal systems). A known amount of selected solutes as conservative and reactive tracers is injected into the aquifer ("push") and afterwards extracted ("pull"). In many cases, a so-called "chaser", which is just original groundwater without any added solutes, is injected directly after the injection of the test solution. Its objective is to push the test solution out of the borehole into the aquifer and therefore to minimize the influence of the gravel pack on the shape of the breakthrough curve. The influence of the chaser on the tracer breakthrough curve is unknown so far. Also, the determination of the appropriate volume for the chaser is a difficult task if at all applied. A first experiment was conducted with the objective to compare three push–pull tests with similar injection volumes, two tests with and one without a chaser. Results show that the application of a chaser lowers the main peak concentration. However, it does not alter the tailing of the breakthrough curve nor does it have a negative influence on tracer mass recovery. In a second experiment, a new method was developed to determine the optimal chaser volume by testing seven different chaser injection volumes combined with temporal moment analysis. As a result, the application of a chaser is recommended, when reactions of injected solutes within the open well or the gravel pack should be avoided. If a chaser is used, the new method mentioned above can easily be used to determine the required chaser injection volume. The experiments were conducted at the Hamasato test site in Horonobe (Hokkaido, Japan).

1. Introduction

In single-well settings, fully developed techniques used in hydrogeology for aquifer characterization, like multiple-well tracer tests, are impossible to apply (Hebig et al., 2012). The single-well injection-withdrawal "push–pull" tracer test method offers an alternative to obtain information about aquifers with only single-well access. In a push–pull test, tracer spiked water is injected and afterwards withdrawn from the same well.

Push–pull tracer tests have a great potential for application in geothermal studies especially to determine in situ geochemical reactions and aquifer characteristics. Push–pull tests are already reported for being used in geothermal energy research, especially in single-well settings applying the hot-dry rock method (Herfort et al., 2003). Pauwels (1997) and Pauwels et al. (1992) used push–pull tests during the exploration phase of geothermal heat to study energy reservoirs. Various approaches are dealing with analytical solutions for thermal push–pull tests regarding reservoir lifetime, heat recoveries, diffusion coefficients, and fluid residence times (Gringarten, 1978; Herfort et al., 2003; Ghergut et al., 2007; Kehrer et al., 2007; Jung and Pruess, 2012).

Further applications of this method are often reported for hydrochemical aquifer characterization. Push–pull tests are used to proof and to quantify processes regarding organic pollutants at contaminated sites, like in situ determination of microbial activity, transformation and degradation rates, denitrification rates, and simulation of large recharge events in shallow (<20 m depth) wells

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using so-called partitioning push–pull tests (e.g. Addy et al., 2002; Cunningham et al., 2001; Haggerty et al., 1998; Istok et al., 1997; Kleikemper et al., 2002; McGuire et al., 2002).

In deeper settings, the application of the push–pull test method was reported for the investigation of mixing, cation exchange, and oxidation–reduction reactions caused by the change of salinization (Vandenbohede et al., 2008). For the investigation of the deeper subsurface, push–pull tests may also be a suitable test method for the characterization of groundwater flow velocity, dispersion or dispersion coefficients, and matrix or effective porosities (e.g. Hall et al., 1991; Leap and Kaplan, 1988; Novakowski et al., 1998; Riemann et al., 2002). Though, the travel distance of the injected and afterwards extracted tracer plume, as well as the original groundwater gradient will remain unknown in single-well settings and therefore the reliability of the published approaches for the hydraulic analysis of push–pull tests to determine groundwater flow velocity and effective porosity is limited.

A general push–pull test includes the following steps:

(1) Injection ("push") of the test solution,
(2) Injection of a chaser (optional),
(3) Drift/reaction phase (optional), and
(4) Extraction ("pull") of the test solution.

No systematic evaluation of the push–pull method regarding its reproducibility and influence of the test setup on the results has been published so far. Therefore, the repeatability of this method and the influence of changes of its setup on the resulting breakthrough curves (BTCs) are unknown. To fill this gap, a large-scale experiment was conducted at the Hamasato site in Horonobe (Hokkaido, Japan). Various tests were conducted in a groundwater monitoring well to investigate the influence of individual setup parameters on the test results. As part of this method evaluation, also the role and influence of the so-called chaser was evaluated in two individual experiments. The aim of the injection of a chaser, usually groundwater or tap water without any added solutes or tracers, is to push the test solution out of the well and gravel pack into the formation of interest. The volume of the chaser should be large enough to fill the whole well and gravel pack volume and should push the test solution completely out into the aquifer. For this, the volume of all used tubes, pipes, the tested well, and its gravel pack has to be known. However, in most cases the effective porosity of the gravel pack and accordingly its volume is unknown and has to be estimated, which may result in ambiguous results. An approach for the determination of the optimal chaser volume was not available so far.

Also, the influence of a chaser on the BTC of the prior injected tracer is not known. Expected effects may be dilution of the test solution (in the worst case below the detection limit), pushing the tracer plume too far into the aquifer, e.g. beyond the radius of the cone of influence (means the cone of elevation in the push phase or cone of depression in the pull phase), or any other kind of shifting or alteration of the BTC. The injection of a chaser directly after the injection of the tracer test solution will disturb the idealized cylindrical tracer plume and therefore change its shape into a more "donut" form (Hall et al., 1991), which could make hydraulic interpretation (e.g. estimation of groundwater flow velocity) even more challenging. The application of a chaser was reported from Hall et al. (1991), Istok et al. (1997, 1999), Luthy et al. (2000), McGuire et al. (2002), Meigs and Beauheim (2001), Molz et al. (1985), Nordqvist et al. (2012), and Tomich et al. (1973). There are many experiments reported with no application of a chaser, among them are Addy et al. (2002), Azizian et al. (2005), Davis et al. (2002), Hellerich et al. (2003), Kim et al. (2004), Schroth et al. (2001), and Vandenbohede et al. (2008). However, it is not always clear how the decision in favor or against a chaser was made in published experiments. There is no evaluation of the positive or negative effects of the application of a chaser on the BTC of the actual test solution reported. We focus on the role of the chaser during push–pull tests and its potential influence on the BTC of the actual test solution. We discuss the influence of the chaser and give suggestions for its application. Furthermore, we present a new method for estimation of the optimal chaser volume (which means the volume needed to fill the well and the gravel pack), when the effective porosity of the gravel pack is unknown. This new approach can help to avoid poor results from under- or overestimated chaser volumes during push–pull tests.

2. Study area

The Hamasato test site is part of the municipality of Horonobe, at the north-western coast of the northern Japanese main island of Hokkaido (Fig. 1). Horonobe is located within a sedimentary coastal basin, which is composed of poorly compacted Neozoic sand-, silt- and mudrocks. The distance of the well field to the shoreline of the Sea of Japan is approx. 250 m and the elevation of the site is approx. 5 m above mean sea level. The experiments were performed in the groundwater monitoring well DD-2, which is screened within the upper aquifer of the Sarabetsu Formation (Fig. 2). The Sarabetsu Formation consists of poorly compacted quaternary alluvial deposits with interbedded strata by channeling of coarse sand and fine gravel channels, fine sand matrix, and clay lenses (Fig. 3). In the uppermost part of the Sarabetsu Formation the aquifer is composed of sand and gravel. This aquifer is located between 93.8 and 99.0 m below ground level surface (bgl). At the top, the aquifer is confined by an alternation of silty fine sand and silt, and at the bottom by clay. No detailed information on hydraulic gradient and average groundwater flow velocity at the groundwater monitoring well are available, but the overall groundwater flow is directed from the recharge area located about 10 km in the north-east (Horonobe Anticline) toward the Sea of Japan in the south-west. From analysis of isotopic data from samples obtained from the Upper Sarabetsu aquifer and numeric steady-state groundwater flow simulation, groundwater ages range between 8000 and 18,000 a (Ikawa et al., 2014). From the distance of the recharge area to the well and the groundwater ages an average groundwater flow velocity within the basin of about 0.56–1.25 m a^{-1} can be derived.

The diameter of the drilling is 11.6 cm and the depth is 100 m bgl. The inner diameter of the pipes and well screen of DD-2 is 5.08 cm (2 in.) and the outer diameter is 6 cm. Therefore, the thickness of the gravel pack should be 2.8 cm and is constructed of pea gravel (5–10 mm). However, uncased air rotary drilling ("mist drilling") was used for the construction of DD-2 and it cannot be excluded that the excavated diameter may be larger than the size originally planned (11.6 cm). The screened section is located between 90.7 and 99.7 m bgl and the gravel pack is constructed between 91 and 100 m bgl. An inflatable packer was used during injection and extraction. The bottom of the packer was installed in a depth of 90.3 m bgl. For the experiments it was necessary to estimate the volume of the pipes and of the gravel pack. The volume of the pipe V_{pipe} was calculated as the volume of a cylinder:

$$V_{pipe} = (r_{i\_pipe})^2 \cdot \pi \cdot L_{pipe} + V_{dead} \qquad (1)$$

in which r_{i_pipe} is the inner radius of the pipe and L_{pipe} is the length of the open pipe from the bottom of the packer down to the end of the well screen and sump pipe (9.7 m). The term V_{dead} = 5.7 L and is the measured volume of the used pipes and tubes at the surface. The resulting volume of the pipe is 25.4 L. The gravel pack volume V_{gravel} was calculated as the volume of a hollow cylinder:

$$V_{geavel} = [(r_{borehole})^2 \cdot \pi \cdot L_{gravel\,pack} - (r_{o\_pipe})^2 \cdot \pi \cdot L_{gravel\,pack}] \cdot n_{eff} \qquad (2)$$