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How to chase a tracer – combining conventional salt tracer testing and direct push electrical conductivity profiling for enhanced aquifer characterization

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ABSTRACT

Tracer testing is a well-established technique in hydrogeological site characterization. However, certain a priori knowledge of the hydraulic regime is required beforehand to avoid test failure, e.g. miss of tracer. In this study, we propose a novel tracer test concept for the hydraulic characterization of shallow unconsolidated sedimentary deposits when only scarce a priori information on the hydraulic regime is available. Therefore, we combine conventional salt tracer testing with direct push vertical high resolution electrical conductivity logging. The proposed tracer test concept was successfully tested on coarse, braided river deposits of the Tagliamento River, Italy. With limited a priori information available two tracer tests were performed in three days to reliably determine ground water flow direction and velocity allowing on-site decision-making to adaptively install observation wells for reliable breakthrough curve measurements. Furthermore, direct push vertical electrical profiling provided essential information about the plume characteristics with outstanding measurement resolution and efficiency.

1. Introduction

Tracer testing is an established method in field hydrogeology to obtain information about ground water flow and transport characteristics (e.g. Leblanc et al., 1991; Koltermann and Gorelick, 1996; Cassiani et al., 2006) for various fields of application, e.g. water resource management, contaminant hydrogeology or geothermal reservoir engineering. Hence, a variety of tracer testing approaches and interpretation routines has been developed over the last decades; see Ptak et al., (2004) for an overview. In general, a tracer is injected into the subsurface and the spread of the tracer under natural flow conditions or under a forced gradient is monitored. A large variety of conservative and reactive tracers are described in literature, see Davis et al., (1980) for examples. Tracer tests are interpreted through the analysis of the tracer breakthrough curve or computation of temporal moments, e.g. Gupta and Cvetkovic (2000). Non-reactive tracers are frequently applied in natural gradient tracer testing to collect information about the undisturbed ground water flow direction and velocity as well as to determine basic hydrogeological properties (e.g. effective porosity and dispersivity) on different scales.

A common challenge in natural gradient tracer testing is that a basic understanding of the hydrogeological regime is required for tracer test set up. This includes understanding of the degree of heterogeneity and anisotropy of the hydraulic conductivity distribution and, where necessary, on the boundary conditions of the flow field. A lack of or erroneous a priori information on the hydraulic regime, e.g. expected main tracer propagation direction and tracer propagation velocity, can introduce large uncertainty in tracer interpretation or lead to test failure (see Davis et al., 1980, 1985). This uncertainty has to be compensated with higher efforts in site characterization (see Ptak et al., 2004) or higher monitoring efforts such as increased number of observation points or higher monitoring frequency, leading to an increase in costs. In order to overcome the aforementioned limitations, geophysical techniques (such as electrical resistivity tomography) have successfully been employed for tracer monitoring on different scales (e.g. Perri et al., 2012; Pollock and Cirpka 2012; Singha et al., 2005). Despite its proven applicability, the required time for data acquisition and data analysis during geophysical monitoring (e.g. Hermans et al., 2015) and the

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inherent non-uniqueness of the geophysical non-linear data inversion (e.g. Ellis and Oldenburg, 1994) are remaining challenges for tracer monitoring in hydrogeological practice.

A tracer test concept is needed that is based on a reliable but rapid method for vertical high resolution in-situ tracer detection which allows adaption of the monitoring network and sampling strategies with on-site decision making. In this study, we present a novel tracer test concept that combines conventional sodium chloride tracer testing with direct push high resolution electrical conductivity profiling. To test field applicability, the proposed tracer test concept was applied at the banks of the Tagliamento River near the city of San Daniele de Friuli in northeastern Italy to determine ground water flow direction and velocity in the braided river deposits; see Huber and Huggenberger (2015) for a detailed description of the study site in terms of morphodynamics and sedimentology. Site conditions are challenging for tracer testing: a priori information on the subsurface flow regime was limited because braided river deposits exhibit a complex sedimentary architecture with hydraulic conductivity distribution that is strongly dependent on depositional features and vary over short distances (Huggenberger et al., 1988; Siegenthaler and Huggenberger, 1993; Jussel et al., 1994) resulting in a complex flow pattern (Huber and Huggenberger, 2016). In addition, the hydrological regime can shift from a losing to a gaining stream depending on the river stage.

2. Method

The objective of this study is to combine tracer testing and direct push profiling to design the monitoring network "on the fly" and to gain additional knowledge on the tracer distribution in order to maximize the information that can be gained from the tracer test even under challenging site conditions. Direct push probing is frequently used for hydrogeological and geotechnical site characterization of weakly consolidated or unconsolidated sedimentary deposits and refers to a growing family of tools used for performing subsurface investigations by driving, pushing, and/or vibrating small-diameter hollow steel rods into the ground (EPA, 1997). By attaching sensor probes at the end of the rod string continuous or discontinuous in-situ information about the vertical distribution of soil specific properties can be collected very rapidly (Butler, 2005; Dietrich and Leven, 2006; McCall et al., 2006; Liu et al., 2012). Hence, direct push holds several advantages over traditional site investigation approaches. These include collection of in situ data, monetary efficiency as well as real-time data transmission during direct push probing allowing for on-site decision making (EPA, 1997; Dietrich and Leven, 2006; McCall et al., 2006).

Prior to tracer testing direct push was used to very efficiently install ground water monitoring wells up to 2″ diameter. To identify a suitable depth interval for the tracer injection, direct push injection logging was performed before well installation to collect information on the subsurface vertical variations in hydraulic conductivity. During injection logging water is injected through a screen at the tip of the probe at selected depths (here in 0.5 m depth intervals) while the injection rate and injection pressure are measured. Relative hydraulic conductivity, a parameter that can be closely related to absolute hydraulic conductivity (see Lessoff et al., 2010; Vienken et al., 2012), is calculated as a function of flow rate, water pressure in the injection tubing at different injection rates, and system parameters. For detailed information on the direct push injection logger and interpretation routine see Dietrich et al. (2008).

During tracer testing, the combination of salt tracer testing and direct push electrical conductivity profiling has the capability of providing temporal snapshots of the tracer distribution over depth, as the presence of the salt tracer leads to a strong increase in electrical conductivity (see experimental laboratory data in Fig. 1).

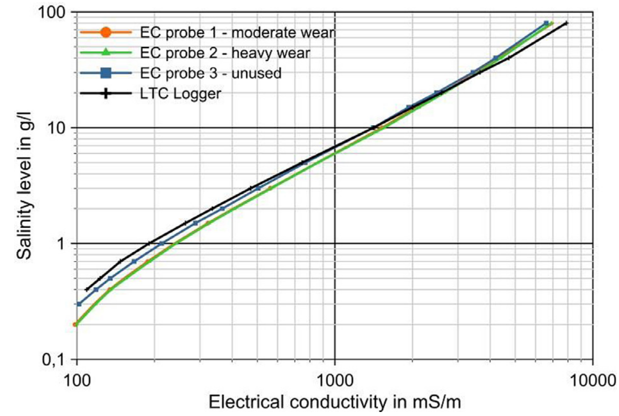

Fig. 1. Laboratory measurements of water salinity and electrical conductivity with Geoprobe SC 500 electrical conductivity probes with different mechanical wear; reference measurements made with standard ground water level, temperature, and electrical conductivity logger (LTC).

While the electrical conductivity probe is pushed into the subsurface, an electrical current is applied to the ground and the applied current as well as the resulting voltage is measured, see Christy et al. (1994) , Sellwood et al. (2005), McCall et al. (2006). An increase in subsurface electrical conductivity can be related to an increase of clay mineral content, or, as in this study, by free ions of the salt tracer in the ground water. Direct push electrical conductivity profiling was performed using Geoprobe SC 500 probes that were operated in Wenner configuration.

3. Application at the Tagliamento River

The test site at the banks of the Tagliamento River is built up by highly permeable open-framework gravels as well as bimodal gravels as part of the sedimentary braided river deposits that show strong contrasts in hydraulic conductivity on meter scale (Huber and Huggenberger, 2016). The site was chosen, as the sedimentary architecture (e.g. trough structures), highly permeable sediments, and the variable hydraulic gradient represent challenging conditions that may be faced in the field. Direct push profiling and pneumatic slug testing results that were collected during a field campaign at the site in 2014 indicated the presence of highly permeable sedimentary deposits, but it was unclear whether direct push profiling results reflected actual aquifer permeability or were merely restricted by measurement resolution.

To assess the hydraulic regime, two consecutive tracer tests with identical set-up were conducted during March 18th and 19th, 2015. Tracer test 1 aimed at deriving a first understanding of the local ground water flow direction and velocity. The collected data were then employed to determine the position and depth intervals of the monitoring wells for tracer test 2. Tracer test 2 was performed to obtain tracer breakthrough curves. In addition, direct push high resolution vertical electrical conductivity logging was used to collect additional information of the tracer distribution over depth. In the following we will provide an overview of the tracer tests and the main results of the investigation.

3.1. Tracer test 1

50 kg of sodium chloride were dissolved in approximately 240 l of river water (resulting in a concentration of 208 g/l) and injected in three injection pulses with an injection rate of 5.3 l/min during tracer test 1. The duration of each infiltration pulse was 15 min with two breaks of 8 and 9 min between pulse injections to refill the injection tank. The direct push injection logging results indicate highly permeable sediments with only minor variations in the

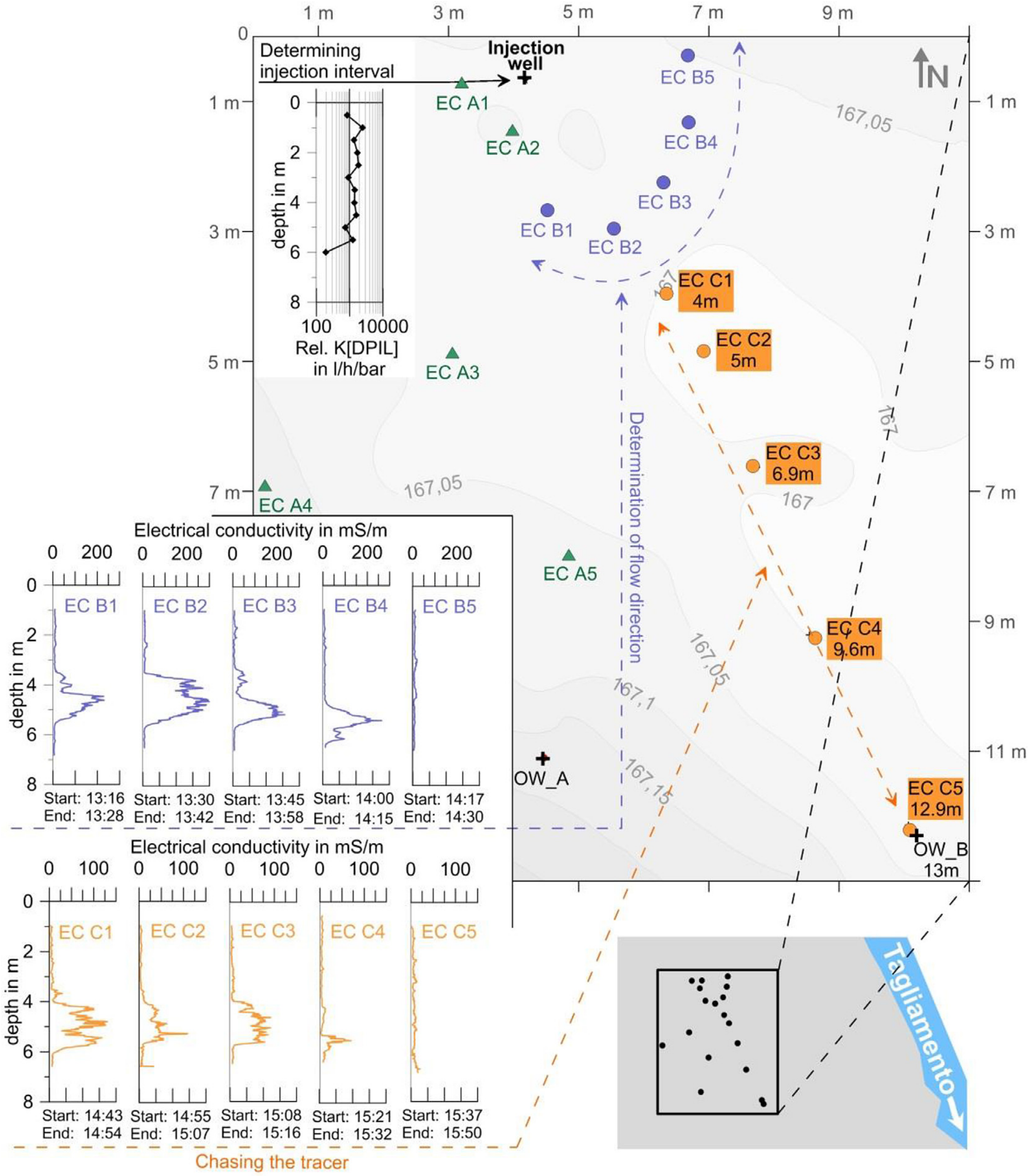

Fig. 2. Overview of the position and relevant results of the direct push hydrogeological and electrical conductivity profiling as well as position of observation wells (OW) during tracer test 1. Map isolines represent ground elevation in meter above mean sea level.

permeability distribution in the upper 5.5 m, see Fig. 2. Hence, the tracer was injected in a shallow depth between 3 and 4 m below ground surface in a direct push installed 2″ PVC well. To quantify maximum tracer velocity, the direct push electrical conductivity probe was pushed down to 3.5 m below ground surface at approximately 0.75 m from the injection well (location EC A1, Fig. 2) in the direction of presumed ground water flow direction and kept in logging mode at this particular depth during tracer injection. After the tracer injection had ended, no tracer was detected at position ECA1. Five electrical conductivity profiles (EC A1–AC5, Fig. 2) were performed at different distances to the injection well in the direction of presumed ground water flow. The tracer signal could only be detected at position EC A2 (see Fig. 2) that is located in close proximity to the injection well. Hence, five additional electrical conductivity profiles (see Fig. 2 EC B1–B5) were measured in a hemi-circle 2.5 m distanced from the injection well to determine tracer flow direction. The five electrical conductivity profiles were conducted within a time span of 74 min; respectively 137–211 min after tracer injection had ended.

The strongest electrical conductivity increase was observed at position EC B2, leading to an estimated main tracer propagation in SSE direction, i.e. almost parallel to the bank of the Tagliamento River at the test site. To obtain an understanding of ground water flow velocities and to install a monitoring well ahead of tracer arrival, five electrical conductivity logs (see Fig. 2, logs EC C1–C5) were performed along the identified main tracer direction at a distance of 4 m, 5 m, 6.9 m, 9.6 m, and 12.9 m downstream of the injection well. Despite the increasing distance to the injection well and rapid direct push measurements, high ground water velocities led to a chase to get ahead of the tracer. At 12.9 m distance from the injection well only a very weak increase in electrical conductivity was recorded 291 min after the injection. A ground water observation well (OW B, see Fig. 2) was subsequently installed 13 m distanced from the injection well with a screened inter-

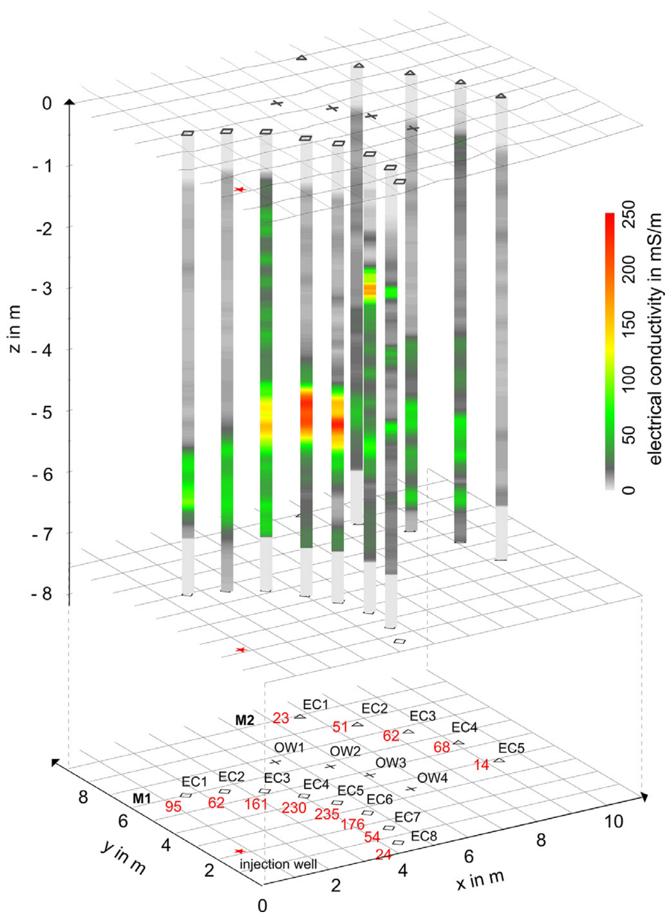

Fig. 3. Layout of the tracer test 2 with location of the injection well, observation wells (OW), as well as position and results of the direct push electrical conductivity profiling. Red numbers refer to maximum measured electrical conductivity values in mS/m. Outer logs M1_EC8 and M2_EC1 are not depicted for figure clarity as no increase in electrical conductivity due to the presence of a tracer was observed. Logs were measured in the following sequence: M1= EC4, EC5, EC6, EC7, EC8, EC3, EC1, and EC2; M2= EC3, EC5, EC1, EC2, and EC4.

val between 3 and 6 m below ground surface and equipped with level, temperature and conductivity (LTC) data loggers (recording hydraulic head, temperature, and electrical conductivity in ten-minute intervals) at 3.5 m, 4.5 m, and 5.5 m below ground surface. A slight increase of electrical conductivity was observed 405 min after start of the tracer injection. An effective tracer velocity of 1.9 m/h was estimated based on the first arrival time after tracer injection had started.

3.2. Tracer test 2

Based on the results of the first tracer test four 1″ ground water monitoring wells spaced 1 m apart and screened 3–6 m below ground surface were installed 6 m downstream of the injection well (see Fig. 3). Tracer testing was conducted in the same way as the first test with 50 kg of sodium chloride dissolved in 240 l of river water and injected between 3 and 4 m below ground surface. Three LTC loggers were installed in the two central monitoring wells at 3.5 m, 4.5 m, and 5.5 m below ground surface and two LTC loggers were installed at 4.5 m and 5.5 m below ground surface in the outer wells. Similar to tracer test 1 temperature, head, and electrical conductivity were logged every ten minutes. In addition, direct push electrical conductivity profiling was conducted along two control planes 4 m and 9 m downstream of the injection well. Direct push logging was performed to obtain a better understanding of the spatial distribution of the tracer and to identify preferential flow paths in the subsurface.

Eight electrical conductivity profiles with spacing of 1 m were performed at the first monitoring plane; see Fig. 3 M1_EC1–EC8, during a time span of 167 min (i.e. 125–292 min after the start of tracer test 2). Out of these eight profiles, the central two profiles showed overall strongest tracer response. A moving average of 10 measurement points was used for the data analysis of the direct push electrical conductivity measurements. This was done to bring together the initial predetermined software vertical data resolution of 1.5 cm and the 6.5 cm vertical measurement coverage corresponding to the electrode spacing at the direct push probe. The main tracer response in these two logs was measured between 4.0 m and 5.3 m below ground surface with a maximum value of 235 mS/m. Five electrical conductivity profiles were measured on the second monitoring plane (M2_EC1–EC5, see Fig. 3) during a time span of 90 min, i.e. 296–386 min after the start of tracer test 2. The electrical conductivity profiling results at this control plane indicate that (a) the main response signal is captured at depths between 5.3 and 6.4 m and (b) a partitioning of the tracer plume into two additional depth zones between 4.2 m and 5 m as well as 6.6 m and 7.1 m (Fig. 3).

In the observation wells, tracer arrival and part of the tracer breakthrough was captured by LTC loggers in the two central observation wells OW_2 and OW_3 (see Fig. 4). The strongest signal is recorded at well OW_2 with a maximum value of 552 mS/m at 5.4 m below ground surface. The LTC loggers installed at 4.4 m and 3.5 m depth did not record any clear tracer signals. In contrast, lower electrical conductivity values were measured at well OW_3. However, distinct responses of up to 254 mS/m were measured in 4.4 m depth and a response of up to 357 mS/m was measured in 5.4 m depth. These measurements are in good agreement with the electrical conductivity profiles that indicated a partitioning of the tracer plume. Similar to tracer test 1, a downward dipping of the tracer was observed in the direct push electrical conductivity data from the depth of tracer injection (3–4 m below ground surface) to the main tracer signal measured between 4.0 and 5.3 m below ground surface at the first monitoring plane and to the main tracer signal measured between 5.4 and 6.6 m below ground surface at the second monitoring plane. High maximum tracer velocities can be deduced based on first arrival times of the tracer in the observation wells. In OW_2 a first increase in electrical conductivity was measured only 36 min after the injection had started, leading to an estimated maximum tracer velocity of 10 m/h. In OW_3 the first increase in electrical conductivity was measured 66 min after the injection had started, leading to a maximum tracer velocity of 5.5 m/h.

4. Discussion

During a first site reconnaissance, it was observed that the river water level was significantly above the water level of two adjacent ponds and that all the water levels showed similar temporal fluctuations indicating a hydraulic connection. These observations suggested the infiltration of the Tagliamento River water into the ground water body. A local ground water flow direction roughly perpendicular to the river bank was hypothesized and the tracer test was planned accordingly. However, results of the electrical conductivity profiling that was performed within the first hours after tracer injection revealed a local ground water flow direction almost parallel to the river bank at the test field (see Fig. 2). The strong influence of the regional ground water flow could explain the discrepancy between the hypothesized and the observed local ground water flow direction. This is a typical example of how a wrong assessment of the hydraulic regime can impact

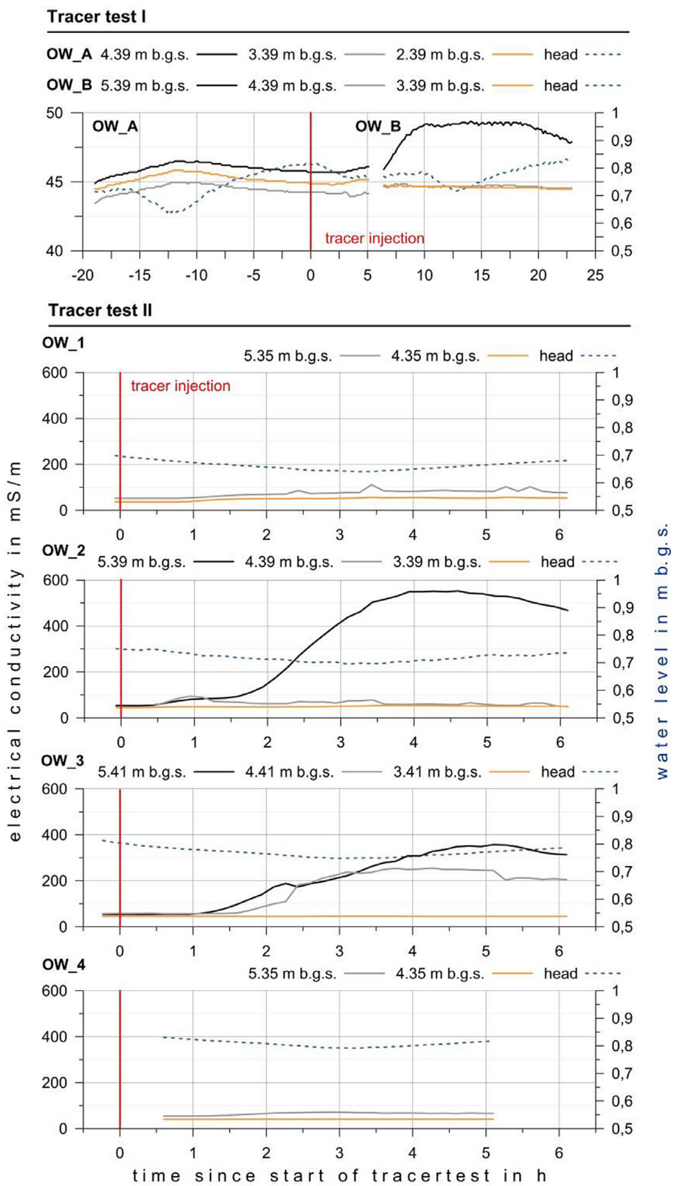

Fig. 4. Overview of the results of electrical conductivity monitoring at the observation wells during tracer test 1 and tracer test 2. During tracer test 1 LTC loggers from observation well A were placed in the new observation well B after main tracer direction was determined.

tracer test design. By applying the novel tracer test concept, direct push high resolution vertical electrical conductivity profiling did not only provide critical information on the ground water flow direction but also provided valuable snapshots of the tracer distribution over depth to support understanding of the plume characteristics: based on first arrival times, maximum tracer velocities of 1.9 m/h were measured for tracer test 1 (observation well 13 m away from injection well) and 5.5–10 m/h for tracer test 2 (observation wells 6 m away from injection well). Differences in observed tracer velocities between tracer test 1 and 2 reveal a scale-dependent tracer propagation. Higher flow velocities during tracer test 2 may be explained by tracer movement along preferential flow paths. Plume separation that was clearly identified with the direct push electrical conductivity profiling support this finding.

It is interesting to note that, despite high flow velocities, results of the electrical conductivity profiling during tracer test 1 and 2 (first monitoring plane) clearly show a widening of the tracer plume to an approximate 80° angle spread downgradient from the injection well (see Figs. 2 and 3). In contrast, during tracer test 2, if tracer responses in the two central monitoring wells were the only available data, a much narrower plume would have been assumed. This demonstrates the significant gain in information when classical breakthrough curve measurements and electrical conductivity profiling are combined. Similarly, this also applies to the vertical partitioning of tracer that was clearly captured in the electrical conductivity profiling data but could not be inferred from ground water logger data.

Furthermore, a downgradient dipping of the tracer plume was observed. It cannot be excluded that the dipping motion of the tracer was density driven. However, Beinhorn et al. (2005) show in numerical simulations that density effects do not have significant impact on tracer plume development under high flow velocities. In consideration of the high advection rates and low downstream tracer concentration (a maximum level of 552 mS/m was measured in OW_2 which refers to a concentration of <4 g/l sodium chloride, see Fig. 1), we presume that tracer distribution is governed by dipping sedimentological structures. Results of a GPR survey that was conducted before the tracer experiment additionally support this assumption, as GPR data indicate sedimentary structures dipping parallel to the main tracer direction (see Fig. 5) in the area of tracer injection.

Characterization of the plume geometry was possible due to centimeter scale vertical resolution and rapid nature of the direct push electrical conductivity profiling. Detection of these plume features based on conventional breakthrough curve measurements would have required enormous efforts regarding the number of monitoring wells, sampling intervals, and sampling frequency. In contrast, the direct push equipment was easily moved around to cover the test site of approximately 140 m^2 (see Fig. 2). The necessary time to measure one vertical electrical conductivity profile including probe recovery was approximately 15 min. Moreover, rapid direct push-based installation of small diameter observation wells in combination with real time data transmission during electrical conductivity profiling allows on-site decision making and adaptive well positioning on-the-fly. These are clear advantages of this tracer test concept over existing approaches that are especially beneficial when subsurface heterogeneity, anisotropy of the ground water flow field or dynamic hydraulic regime limit conventional tracer test application. In this study we solely focus on a qualitative analysis of the obtained electrical conductivity data. Incorporation of profiling data into a flow and transport model can potentially provide further insight into the flow and transport behavior. However, it is important to note that the acquired profiling information represents temporal and spatial snapshots of the tracer distribution over depth that is only valid at the position and at the exact time of logging; latter one is important given the high tracer velocities at the test site.

Geoprobe SC 500 probes were used for the direct push electrical conductivity profiling in this study. Dehmut et al. (2015) reported about differences in obtained electrical conductivity values depending on the mechanical wear of direct push electrical conductivity probes based on numerical simulations. Results of comparative laboratory measurements indicate indeed small deviations in measured electrical conductivity between direct push soil electrical conductivity probes of different wear; all probes gave different readings than a calibrated ground water conductivity logger (Fig. 1). This uncertainty has to be considered and calibration routines can be adapted to meet the required accuracy if a quantitative interpretation of the electrical conductivity profiling results is envisaged. Lastly, as increases in electrical conductivity in the subsurface can be naturally caused by clay layers, salt bearing sediments or saline ground water, applicability of direct push needs to be tested on-site prior to experiments. In this study, electrical conductivity logs that were not influenced by the salt tracer did not

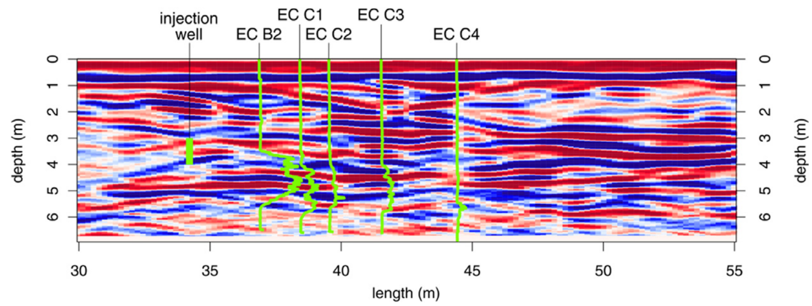

Fig. 5. GPR profile along the main tracer direction with results of the electrical conductivity profiling. Naming of logs refers to Fig. 2; red and blue colors representing relative signal amplitude. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

exceed a background value of approximately 20 mS/m which are typical values for non-cohesive material (see Sellwood et al., 2005; Vienken et al., 2012), while electrical conductivity of the ground water measured during an 18 h base line monitoring prior to tracer test 1 using 10 LTC loggers ranged between 37 and 58 mS/m with a mean electrical conductivity of 47 mS/m.

5. Conclusion and conceptual outlook

With this paper we present a novel tracer test concept that combines classical sodium chloride tracer testing with direct push vertical electrical conductivity profiling which allows adaption of the monitoring network and sampling strategies with on-site decision making during tracer testing. This tracer test concept was successfully applied under challenging site conditions with only scarce a priori information on the (hydro-)geological regime available beforehand. The following tasks were performed within only three consecutive days, whereby each tracer test (including installation of the monitoring wells) was conducted within one day:

i. Adaptive tracer tracking and reliable determination of the ground water flow direction.
ii. Adaptive installation of tracer observation wells in the main tracer plume direction for reliable breakthrough curve measurements with on-site decision making regarding screen length and depth.
iii. Direct push vertical electrical conductivity profiling provided temporal snapshots of tracer distribution over depth along two control planes.

Due to the flexibility of the mobile direct push equipment and vertical high resolution measurements of most of the available direct push sensor probes, detection of the tracer plume is guaranteed if the entire site is accessible for direct push profiling. Hence, the proposed tracer test concept strongly contributes to resolve the problem of a miss of the injected tracer that is not uncommon in hydrogeological practice (see Davis et al., 1985). Furthermore, direct push electrical conductivity profiling provided valuable information of the tracer distribution over depth. If electrical conductivity data are incorporated into a flow and transport model, this concept can serve to unravel the complexity of concentration distribution in the tracer plume in relation to the subsurface heterogeneity. If coupled with other direct push hydraulic tools, e.g. direct push permeameter (Butler et al., 2007), with built-in down-hole pressure transducers, this approach additionally allows depth distributed measurement of hydraulic conductivity and pressure head. Furthermore, this concept can also be efficiently applied to investigate ground water-surface water interactions as it is especially useful under highly dynamic conditions. Even at sites that do not favor the use of direct push electrical conductivity profiling (e.g. presence of saline groundwater) the test concept could be modified, e.g. using dye tracer testing in combination with soil color optical screening (see Hausmann et al., 2016).

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