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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).

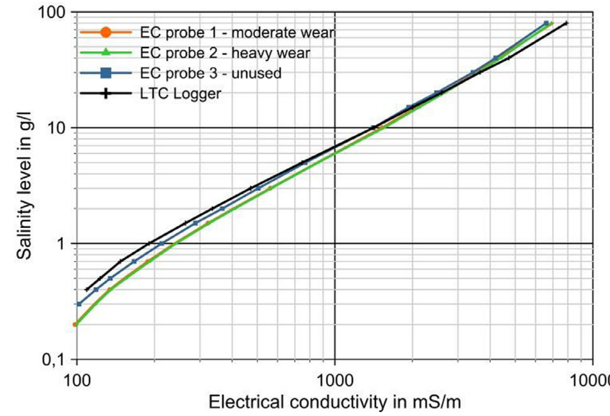

Fig. 1. Laboratory measurements of water salinity and electrical conductivity with Geoprobe SC 500 electrical conductivity probes with different mechanical wear; reference measurements made with standard ground water level, temperature, and electrical conductivity logger (LTC).

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