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Research papers

Conceptualization of flow and transport in a limestone aquifer by multiple dedicated hydraulic and tracer tests

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ABSTRACT

Limestone aquifers are of great interest as a drinking water resource in many countries. They often have a complex crushed and fractured geology, which makes the analysis and description of flow and transport processes in such aquifers a challenging task. In this study, the solute transport behavior including fracture-matrix interaction in hydrogeological units of a limestone aquifer in eastern Denmark was characterized by designing, conducting and interpreting six depth-specific tracer tests involving natural- and forced-gradient conditions with multiple tracers representing different diffusion properties. To determine flow parameters, the tracer tests were complemented by a comprehensive set of depth-specific borehole and hydraulic tests.

Based on the tests, a new and stronger conceptual understanding was developed for the different aquifer units. The investigated limestone aquifer is composed of a glacially crushed unit and two fractured units, with calcarenitic and bryozoan limestone of similar hydraulic properties. Hydraulic tests revealed that the crushed unit has a lower hydraulic conductivity than the fractured limestone units, likely due to the crushed conditions with small limestone clusters and small-aperture fractures potentially filled with fine material.

In the fractured limestone units, a distinct preferential flow and primary transport along major horizontal fractures was inferred from the tracer tests under forced-gradient conditions. The dominant horizontal fractures were identified on impeller flow logs and appear connected between wells, having an extent of up to several hundred meters. Connectivity between the aquifer units was investigated with a long-term pumping test and tracer tests, revealing restricted vertical flow and transport. A very pronounced hydraulic conductivity contrast between major fractures and matrix could also be inferred from the borehole and hydraulic tests, which is consistent with the findings from the tracer tests. The difference in the matrix diffusion behavior of the simultaneously injected tracers and a long tailing in the breakthrough curves revealed that matrix diffusion has a strong influence on the solute transport in the fractured limestone.

1. Introduction

Limestone aquifers are important drinking water resources in many countries such as the UK, the USA and Niger (Ireson et al., 2009; Marella and Berndt, 2005; Qian et al., 2014). In Denmark, about one third of the water supply is based on groundwater from limestone aquifers (Vangkilde-Pedersen et al., 2011). Limestone aquifers in densely populated areas are vulnerable to contamination from diffuse and points sources due to heavy water abstraction, complex flow fields and low contaminant attenuation capacity (Aisopou et al., 2015; Levi et al., 2014). Therefore, knowledge on the hydrogeology and the flow and transport behavior in such aquifers is essential for groundwater resource management, risk assessment and remediation of contaminated sites. However, knowledge of transport in limestone aquifers is limited and difficult to acquire, particularly in fractured aquifers (Klepikova et al., 2014).

The flow field and the transport pathways in limestone aquifers can be very complex, as limestone is a very heterogeneous geological setting (Williams et al., 2006). Limestone often contains chert layers and nodules, may be weathered, crushed or fractured, and may contain fault zones due to geological activity (Jakobsen et al., 2017; Odling et al., 2013). In areas with glacial activity, the upper unit of the limestone often consists of distinct zones with different properties, e.g. reworked limestone mixed with till and sand, crushed or fractured limestone units

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(Jakobsen and Klitten, 1999), while deeper parts comprise intact geological units with a low fracture density (Jakobsen et al., 1993). Fractured units of limestone aquifers often exhibit a dual-continuum nature (Hartmann et al., 2007; Price et al., 1993): fast flow in a network of fractures dominates the advective transport in the aquifer, while the long-term fate of solutes is strongly influenced by matrix diffusion, sorption and degradation processes (Bottrell et al., 2010; Jardine et al., 1999; Witthuser et al., 2003).

Hydraulic characterization of limestone aquifers can include several traditional and more novel methods. Pumping tests and slug tests are commonly used for determining hydraulic conductivity and specific storage capacity values for all kinds of aquifers, including limestone aquifers (Ackerer and Delay, 2010; Butler et al., 2009; Kruseman and de Ridder, 1990; Macdonald and Allen, 2001). More recently, advanced characterization methods have been developed (Berkowitz, 2002; Neuman, 2005), including transmissivity profiling with FLUTe liners (Broholm et al., 2016; Keller, 2016), passive flux meters (Klammler et al., 2016), geophysical methods, optical and acoustical televiewer imaging (Maurice et al., 2012), impeller flow logging (Basiricò et al., 2015; Butler et al., 2009; Paillet, 1998), hydraulic tomography (Illman, 2013; Sanchez-León et al., 2015; Trottier et al., 2014), cross-borehole tests and thermal methods (Pehme et al., 2014; Somogyvári et al., 2016). However, some of the methods like FLUTe transmissivity profiling or optical televiewers require open boreholes. The borehole walls in fractured limestone and particularly in crushed limestone may be unstable and thus casings and well screens are installed to prevent borehole collapse (Odling et al., 2013). These installations restrict the choice of hydraulic and geologic characterization methods.

Tracer tests have been commonly used to determine parameters characterizing the transport behavior (porosity, matrix diffusion, dispersion) and connectivity in limestone aquifers (Bottrell et al., 2010; Hartmann et al., 2007) and other fractured aquifers. These tests can be performed as single-well or multiple-wells tests, and with chemical species or heat as tracer (Doro et al., 2015; Somogyvári et al., 2016; Wagner et al., 2014). A single-well dilution test (Maurice et al., 2011; West and Odling, 2007) is a relatively simple and inexpensive method to identify high-flow zones within a borehole. Another kind of single-well test is a push-pull test (Becker and Shapiro, 2003), where the same well is used for tracer injection and extraction. Multiple-well tracer tests can be subdivided in natural-gradient (Bottrell et al., 2010; Jardine et al., 1999; LeBlanc et al., 1991; Ptak and Teutsch, 1994) and forced-gradient tracer tests (Hartmann et al., 2007; Jakobsen et al., 1993; Lloyd et al., 1996; Riley et al., 2001; Sanchez-León et al., 2015; Witthuser et al., 2003). Forced-gradient tracer tests establish a hydraulic gradient by pumping (and possibly by injecting), and have the advantage that the tracer breakthrough happens much faster than for natural gradient tracer tests. They also provide a well-defined flow field and tracer recovery is usually high. A well-defined flow field is particularly useful for fractured limestone aquifers, as it helps to reduce tracer loss and tracer occurrence at unexpected locations (Bottrell et al., 2010). A forced-gradient in a fractured medium caused by pumping may, however, activate additional flow paths compared to natural gradient conditions, as discussed by Butler et al. (2009).

Only a few fully analyzed tracer tests in limestone aquifers have been reported in the literature. Amongst those, the tests of the eastern England Chalk are particularly notable (Black and Kipp, 1983; Bottrell et al., 2010; Hartmann et al., 2007; Maurice et al., 2012; Riley et al., 2001). Hartmann et al. (2007) performed a comprehensive forced-gradient tracer test study in a fractured limestone aquifer, using single fluorescent tracers for each injection. They mention the occurrence of a weathered, ‘putty’ chalk layer, in which the boreholes were cased. The injection and pumped intervals of the boreholes had a length of 46–55 m, all in the fractured limestone aquifer, and different aquifer units were not distinguished. Bottrell et al. (2010) conducted lab and field tracer tests in a Chalk aquifer contaminated with hydrocarbons. The tracer tests were originally planned under forced-gradient conditions. However, the pumping rate could not be kept constant throughout the field experiment, hence the tracers were also monitored under natural gradient conditions after the initial pumping. Riley et al. (2001) present the results of an extensive tracer test study in Lincolnshire limestone using a borehole array for forced-gradient tracer tests with fluorescent and ionic tracers. They simultaneously applied multiple tracers and observed species-dependent tracer breakthrough behavior in lab column tests, but not when the tracer mixture was applied under field conditions. Jakobsen et al. (1993) present a forced-gradient tracer test applying lithium as tracer, while monitoring in five pumped intervals in a borehole located in the same unit of a fractured bryozoan limestone aquifer. They obtained tracer breakthrough curves showing fast tracer arrival and long tailings.

The results show that most of the presented tracer tests consider the limestone as a single aquifer unit. However, in many cases the upper limestone has different properties (Hartmann et al., 2007; Jakobsen and Klitten, 1999), for instance because of glacial activity, resulting in different flow and transport behavior. The upper limestone units are particularly important for contaminants infiltrating from diffuse or point sources because their transport and fate will be highly depending on flow patterns and properties of these units. In most previous field studies in limestone, a single tracer was injected at the same time and location in limestone. However, the simultaneous injection of a mixture of tracers with different properties can provide additional information about the flow and transport processes in the aquifer, particularly about matrix diffusion, as reported in Jardine et al. (1999) for fractured shale bedrock and in Somogyvari and Bayer (2017) in the context of hydraulic tomography.

The aim of this paper is to enhance the conceptual understanding of flow and solute transport in limestone aquifers with a focus on different aquifer units, involving crushed formations, fractures, and a low permeability matrix. This is an important step towards a better understanding of contaminant behavior, risk assessment and design of remedial actions in limestone aquifers. The site investigation techniques applied in this study involve a combination of tracer tests, borehole tests and hydraulic aquifer tests (pumping tests, slug tests etc.) to determine fracture-matrix interaction and matrix-diffusion behavior at the intermediate site scale (meters to a tens of meters). Two types of tracer tests were developed, where the first involved the simultaneous injection of multiple tracers with different diffusion coefficients in one borehole. The second involved injection of a tracer prior to pumping under natural-gradient conditions and subsequent monitoring at a pumping well under forced-gradient conditions. A novel feature of these hydraulic aquifer and tracer tests is that they were conducted in wells screened at different depths so as to obtain dedicated information about the main units in the upper weathered part of a limestone aquifer. The study was conducted in an aquifer consisting of an upper calcarenitic limestone and a lower bryozoan limestone at a field site situated in the eastern part of Zealand, Denmark (Fig. 1a).

2. Description of the field site

A comprehensive field study was conducted in a limestone aquifer at the Akacievej site in Fløng, about 30 km west of Copenhagen (Fig. 1a). The study of the site was motivated by the history and the current status as a contaminated site. The operation of a dry cleaning facility at the Akacievej site and a fire in 1975 had caused a spill of PCE and the development of a 400–500 m long PCE plume in the limestone aquifer (Fig. 1b), posing a risk to the groundwater resource. The site is not far from the abstraction wells of a local waterworks (Fløng), located ca. 700 m north of the Akacievej site, however with the current pumping rate the waterworks is not affected by the contamination. In 2006, the most contaminated soil (upper 6 m of the glacial deposits on top of the limestone aquifer) was removed and a pump-and-treat system was installed to establish hydraulic control of the contamination in the source zone and to limit further contaminant leaching and plume