A FIVE SPOT WELL CLUSTER FOR HYDRAULIC AND THERMAL TOMOGRAPHY
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ABSTRACT
We present a five spot groundwater well arrangement for investigating hydraulic and thermal conditions in the subsurface. The experimental facility is located on the North-campus of the University of Göttingen/Germany. In 2008, one well was drilled next to a geothermal borehole heat exchanger, both reaching a depth of 80[m] in a clay stone formation. In summer/autumn of 2012 four additional boreholes were drilled down to the same depth to get a spatially splayed test site in a 5-spot arrangement. At one borehole the core was taken, in addition to geophysical borehole measurements performed in all boreholes.

One unique feature of the site is the relatively small distance of the wells from 1.5[m] to 6[m], which is important for several kinds of aspired subsurface heat transport experiments. All five wells are constructed equally. The casing is divided into 9 full cased and 9 slotted parts to achieve and investigate connections to different geological strata. The wells are equipped with a comprehensive system of temperature measurement devices. A chain of 27 pt1000 resistance thermometers, an optical fiber cable for spatially highly resolved temperature measurements and an actively heated cable are installed in the filling grout of each hole. This measurement system can optionally be adapted by a chain of mobile thermometers with a relative resolution of 0.3[mK] for operation inside the well casing.

The efficiency of using the subsurface as a heat source (or sink) is tightly dependent on the thermal conductivity. This parameter is usually estimated by a thermal response test (TRT). The state of the art evaluation of such a test is based on simplifying assumptions. The result is the mean thermal conductivity in a very small surrounding of the borehole. In heterogeneous environments, the real thermal conductivity might locally deviate strongly from the estimated mean value or it might change significantly in a distance, which is not covered by the TRT. Such an erroneous assessment of the thermal parameters may lead to over- or underestimations regarding the borehole depth necessary for a required energy extraction.

Another important subject is the possible domination of subsurface heat transport by advective processes resulting from groundwater flow or convective processes as product of unstable heat stratifications. This may also have a major influence on estimated parameters in thermal response tests (i.e. WITTE, 2001; CHIASSON & HELLSTRÖM, 2003).

The high number of open questions in the field of determining thermal properties of the subsurface led us to create an experimental test site that is suitable for various kinds of subsurface heat transport experiments.

THE FIVE SPOT CLUSTER
We constructed a five spot cluster of wells for hydraulic and thermal tests. This test site is located on the property of the Georg-August University in Göttingen, Germany. It resides close to the GZG (Geowissenschaftliches Zentrum der Universität Göttingen). Important requirements for the cluster are

- short distances because of the long travel time of thermal signals,
- depths comparable to usual shallow geothermal systems,
- a reasonable geometrical arrangement to get 3D information about signal spreading and subsurface properties,
- a preferably inhomogeneous property distribution to have the chance of testing new methods under different situations.
Figure 1 shows a sketch of the arrangement. The five spot consists of an existing well (West) and four new drilled wells (North, East, South, Middle). The distances between the wells are notably short. We avoided subsurface contact of the boreholes by an adaptive drilling approach with measurement of lateral deviation after every drilling. Each new borehole was drilled at a position suitable to the deviations of the already existing boreholes. The red arrows in Figure 1 indicate the maximal lateral deviation of the boreholes.

Additionally to the inclination measurements, extensive borehole geophysical measurements were accomplished by the LIAG (Leibniz Institute for Applied Geophysics, Hannover). The measurements included televiewings (optical and acoustic), gamma ray spectroscopies with passive and active devices, caliper logs, dual laterologs, DIP and more. The information gained from these recordings will be used for modeling the site and correlating further experimental results.

Borehole North was performed as core drilling. Examples of the cores are shown in Figure 2. The cores will be used for several further analyses. We will arrange experimental determinations of key parameters of the core samples, e.g. thermal, electrical and hydraulic conductivities. This information will be a reference point for further in-situ experiments.

**Well Configuration**

The five wells of the arrangement reach to a depth of 78[m]. They are equally configured with alternating permeable and impermeable screens (Figure 3). The permeable screens consist of 3[m] slotted PE pipe sections that are filled up with filter gravel overlapping 1[m]. The impermeable screens are full cased PE pipes filled up with high dense clay that is heavy enough to sink down fast and trusty blinding the gap between the pipe and the subsurface. This configuration achieves hydraulic connection to different geological strata.

**Figure 1:** Arrangement of the five spot well cluster. Red arrows mark the max. horizontal deviation of the drillings.

**Figure 2:** Core samples of the northern well, sampled between 24[m] and 32[m].

**Figure 3:** Sketch of the well construction. All five wells are constructed equally in this way.
The surface construction (Figure 4) consists of concrete rings with hydraulic top covers providing room for experimental equipment and easy access to the wells.

Figure 4: Surface construction of the well cluster

The four new drilled wells are extensively equipped with independent thermal measurement systems. Every well features 27 resistance thermometers \((pt1000)\) that are fixed at the PE pipe and distributed uniformly, always two elements within a filter screen and one element within the impermeable screen. The resistance thermometers form the backbone of the thermal measurement equipment since they are the most reliable system.

Fiber optic cables were embedded in the filling grout as loops. They will be used for laser temperature measurements that are based on Raman scattering and run time measurements of the laser beam. This new technique provides temperature measurements to a spatial resolution of 1[m] with accuracy to within ±1[K] at a resolution of 0.01[K]. These fiber optic cables are placed within all five wells of the 5-spot.

Additionally, a complete system for enhanced geothermal thermal response tests (eTRTs) is installed in the four newly drilled wells. These cables consist of a fiber optic cable and a copper wire that can be used as an electric heater.

The thermal measurement equipment is completed with a mobile useable high resolved thermometer with a relative resolution of 0.3[mK]. This thermometer is equipped with up to three elements in arbitrary distances and can be placed in the well pipes in various depths as needed.

**First Pumping Test Results**

The conventional pumping tests with fully penetrating wells cannot provide hydraulic parameters that are differentiated into vertical profiles. The parameters determined by a common pumping test are not an arithmetic mean, but a spatially integrated physical average that is caused through the radial flow process (PTAK et al., 1996).

In order to estimate the vertical changes of hydraulic parameters, we planned cross-well multi-level pumping tests, implementing a tomographic array along a straight line between a pumping well and four observation wells (HU, 2011). The distances between the pumping well and the observation wells are shown in Figure 1. During the pumping test, the water was partially pumped out of the pumping well (Middle) with an internal tube diameter (ID) of 1.94[cm] by employing double packer system with a screened interval of 5[m] (topmost interval, see Figure 3). The observation interval is also 5 m, separated also with double packer system. This design allows the measurement of water level changes at different depths of the aquifer.

For this study we carried out a pumping test, through which the pumping interval and observation intervals are the first screen intervals in each well at the same depth. The pressure changes in the pumping well, as well as in the observation wells were recorded at a frequency of 4 Hz (one record every 0.25 second) with the pressure transducer (PDCR 35/D-8070) connected to a data logger (Campbell Scientific® CR 3000).

For the analytical evaluation of pumping tests, the straight line method from COOPER & JACOB (1946), as well as the method from THEIS (1935) were used. The results are listed in Table 1.

**Table 1: Results of pumping tests in the topmost screen**

<table>
<thead>
<tr>
<th></th>
<th>Middle</th>
<th>North</th>
<th>East</th>
<th>South</th>
<th>West</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K,[m/s])</td>
<td>3×10^{-4}</td>
<td>5×10^{-4}</td>
<td>3×10^{-4}</td>
<td>4×10^{-4}</td>
<td>5×10^{-4}</td>
</tr>
<tr>
<td>(S_r,[m^3])</td>
<td>4×10^{-3}</td>
<td>2×10^{-3}</td>
<td>1×10^{-3}</td>
<td>6×10^{-3}</td>
<td></td>
</tr>
</tbody>
</table>

The analytically evaluated \(K\) values do not show large changes in different wells. This was not surprising because pumping tests often reflect the integral behavior throughout the whole area of investigation. Besides that, the values determined by analytical methods are often dominated by the highly permeable zone of the aquifer (DIEH et al., 2010; HU, 2011), which means that the pumping test results reflect the hydraulic properties of the highly permeable zones within the aquifer.

The evaluated \(S_r\) values, in contrast, show higher differences depending on the measurement position. Particularly at the observation well East a substantially faster reaction time is observed, resulting in a significantly smaller storage term. This might indicate a connection (possibly a fracture) between the pumping well and well East. However, also the drilling process may have had an effect on the formation changes of the aquifer, which leads to a sudden change of storage parameter. With further aquifer characterization based on hydraulic tomography, combined with geophysical measurement, we will be able to answer such questions and finally “see into the aquifer”.
OUTLOOK

The five spot well cluster provides possibilities for a wide range of hydraulic and thermal experiments. There are multiple options to utilize one or more wells for pressure or thermal signals and the remaining boreholes as observation points. The screening layout of the wells allows obtaining depth dependent data and parameter values. Tests for the characterization of the hydraulic conditions have just started, which will be followed by thermal experiments.

In this study, the start of the hydraulic characterization can be reported only. The evaluation of the first pumping test based on analytical solutions is presented. In near future, series of pumping tests will be performed. For every pumping test and every pumping interval, the pressure changes in the different depths of the observation wells will be recorded. By varying the pumping interval, a large number of drawdown curves can be recorded for the further aquifer characterization based on hydraulic tomography (e.g. HU, 2011), in order to achieve a resolved 3D aquifer reconstruction.

The detailed information about the hydraulic characteristics of the cluster is important for the planned thermal tests. We will use this knowledge for the identification of advective heat transport in various layers of the subsurface. A detailed understanding of the geothermal processes at a representative site (as the Göttingen site seems to be) will also help concerning the further development of methods for the characterization of geothermal reservoirs in general and concerning the optimized layout of geothermal heat production facilities.

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REFERENCES


