INVESTIGATION METHODS FOR CONTAMINATED FRACTURED AQUIFER

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ABSTRACT

Investigations of contaminated aquifers are often too much concentrated on the plume itself. However, for any kind of remediation scheme fundamental knowledge is required. Especially the investigation of fractured aquifers needs a more detailed investigation, due to the extremely high variability of the fracture system. This paper will present a combination of investigation tools that was used for the determination of the fracture system in a Buntsandstein aquifer in south-western Germany that is contaminated by fuel and chlorinated hydrocarbons (CHC). The tools used were core drilling, geophysical logging incl. sonic logs, fluid logging, packer tests and pumping tests. The target of the investigation was to develop a detail model of the aquifer before implementation of a remediation scheme.

KEYWORDS: Fractured aquifer, investigation methods, hydrogeological tools

INTRODUCTION

In a hard rock aquifer open fractures as well as bedding planes or faults give place to preferential flow paths for ground water, contaminants in solution, and free product. Depending on the hydraulic gradient, the fluid velocities within these open features can be many orders of magnitude bigger than in primary aquifers. The distribution of the fractured network is generally highly heterogeneous and varies from site to site even within a particular rock type. Additionally, vertical anisotropy effects can be enhanced by the presence of open bedding planes or diminished by open vertical features.

Furthermore, the hard rock itself is often able to store ground water, contaminants in solution, or free product. In this case it is described as matrix. The storage ability of the matrix is due to either pores like in sandstone or small fractures or fissures as in granite.

Due to these complexities, it is always necessary to investigate each particular site to assure the success of any remediation scheme. The investigations on site should be able to determine:

- Lithology and regional structural geology
- Governing flow conditions (matrix or preferential flow)
- Storage capacity and hydraulic conductivity of the matrix
- Size, distribution, connectivity, and hydraulic conductivity of preferential flow path features
- Horizontal and vertical hydraulic gradient

In this paper a field case is presented as an example of the way to proceed in the investigation of a polluted fractured aquifer.

THE FIELD SITE

The geology of the site consists of silicified medium- to fine-grained sandstone layers of approx. 30 m thickness (middle series of Buntsandstein). These layers are concordant underlain by clayey fine-to medium-grained sandstone of the lower series of Buntsandstein. The transient zone in between consists of approx. 30 m of sandstone with intercalated thin layers (1 – 2 cm) of clayey siltstone and layers (5 – 30 cm) of fanglomeratic debris and is considered as an aquitard. The ground water level in the area is 7 – 14 m below surface.

The found contaminants are fuel and CHC. The plumes spread some 700 m length by 300 m wide and have been mapped using approx. 100 boreholes of various depth and set ups. In these boreholes, the fuel has been found up to a depth of 50 m and CHC up to a depth of 100 m.

METHODOLOGY APPLIED

The goal of this project was the determination of the local flow conditions in the area for the development of a remediation scheme. Different investigation methods were applied as follows:

- **Core drilling** was used to inspect the matrix, bedding planes and fractures, as well as precipitation. Furthermore, it allowed sampling for the determination of the matrix porosity using laboratory tests
- **Packer tests** were used for ground water sampling at predefined depths. The analysis should give an idea of the vertical distribution of the water quality. Additionally, the tests were performed to check on vertical hydraulic contact between the different test intervals. Furthermore, this tool allows the investigation of flow conditions of certain features as bedding planes

- **Geophysical logging** includes caliper, fluid temperature, fluid salinity, gamma-ray, resistivity, neutron-neutron, flow-meter, and borehole scanning. Caliper logging was used to correct the other logging data. Fluid temperature and salinity allowed the identification of through-flow features within the borehole. Gamma-ray and resistivity helped to map the clay content in the different layers within the borehole. Neutron-neutron logging was performed to estimate the total matrix porosity. The water strikes within the borehole were identified among other using flow-meter tests. The borehole scanning was used to characterised the fracture system.
- **Salt dilution tests** were performed to first establish the vertical flow dynamic within the borehole and secondly to identify the preferential flow path features
- **Step-drawdown tests** were done to identify inflow losses (skin effects) that occur during dewatering of preferential flow path features. Furthermore, they are a tool used for the identification of the features conductivity (infinite or finite) as well as the matrix conductivity
- **Long-term pumping tests** will be used to determine the aquifer parameters (transmissivity T and storage coefficient S), double porosity effects, long-term storage behavior, as well as removal capacity of contaminants using active pump and treat measures. This tests have not been performed yet
- **Diffusion sampler bags** are thought as a tool for a detailed mapping of horizontal through-flow of contaminants in a certain vertical interval of the aquifer. This test has not yet been performed

RESULTS

All above described tools were used to determine the flow situations in various boreholes drilled within the contaminated area.

The first borehole (Bh I) was core drilled to a depth of 100 m below surface. After drilling completion, double packer tests were performed aimed to analyse the ground water quality in different intervals along the depth. The samples were taken after stabilisation of the electrical conductivity. In average, each packer test was performed with an extraction rate of 0.5 to 1.5 l/s over a period of 30 to 60 minutes.

It was found that salinity (3–4 mS/cm) and content of contamination do not vary significantly along the borehole depth (0.2 to 0.4 mg/l BTEX and 0.01 to 0.03 mg/l CHC), but this contradicts the vertical piezometric head distribution measured in the borehole. The salt dilution test performed in the open borehole showed a strong vertical downwards directed flow. An inflow of about 3 l/s takes place over the upper 30 m. This water leaves the borehole along the lower 70 m.

Considering that the drilling works lasted 4 days and the packer tests took place on the fifth day, it can be calculated that approximately 10^6 l of contaminated water flew downwards along the borehole into the lower part of the aquifer. A volume of water of 5000 l was extracted during each of the 5 packer tests performed in the lower 70 m of the borehole. Due to the fact that only a total of 25 000 l of the infiltrated water were recovered during this tests, it is clear why the water quality does not differ significantly along the depth of the borehole although a strong difference in the piezometric heads has been measured.

Following the results obtained in this borehole, the drilling and packer tests procedures were changed. The core drilling was then performed in 9 m intervals, each of them followed by a single packer test. This new procedure showed the presence of at least 7 different aquifers, which were showed by both, strong differentiated water salinity and piezometric heads. Additionally, it was found that the fuel contamination appears only in the upper part (18 m) of borehole Bh II apparently underlain by the CHC contamination, which was found from 28 to 45 m (Figure 1). However, the increased values of BTEX at depth of 38 to 45 m is not plausible and could be a result of leakage during a break over 4 days. During this period contaminated water infiltrated from upper level into the bottom of the open hole due to the naturally downwards directed gradient, which is indicated by the dilution test (Figure 1).

In order to set up a fuel remediation scheme based on pump and treat an area of 80 000 m^2 needed to be investigated more in detail. For this purpose, further 11 shallow boreholes (up to 20 m) were core drilled. Five of these boreholes are characterised by low yields (0.2 to 0.7 l/s) while the other 7 have yields of approx. 2–3 l/s. Which is the result of the heterogeneous distribution of open bedding planes as shown in two typical examples.

All boreholes with higher yields have a characteristic flow distribution as described below. Figure 2 shows the lithology encountered in a typical borehole of this group (Bh III) as well as the results of the caliper, gamma-ray and resistivity, fluid temperature and salinity. Figure 3 presents the flow-meter and salt dilution test results.

Up to 8 m depth the caliper log only shows the contact between 2 stand pipes at 4 m below surface. Further down, some changes in the borehole diameters appear at depths of 11.5 m, 13.5 m, 14.5m, and 15 m. Final borehole depth is 20 m. These diameter changes can be correlated with features indicated in the borehole scanning. The diameter change at 11.5 m below surface can be correlated with a peak in the gamma-ray log and a clay layer in the lithological log.

The resistivity log was measured only from 12.5 m up to 19 m, due to the probe dimensions. A constant lower resistivity from 12.5 m to 15 m correlates with an increase in the gamma-ray activity. From 15 m up to 17.5 m, the resistivity increases permanently up to a maximum of 280 Ωm to decrease again further down. This change correlates with the change in the gamma-ray.

The fluid salinity log shows gradient changes at 10.5 m, 11.5 m, 13.5 m, 14.5 m, 15 m,

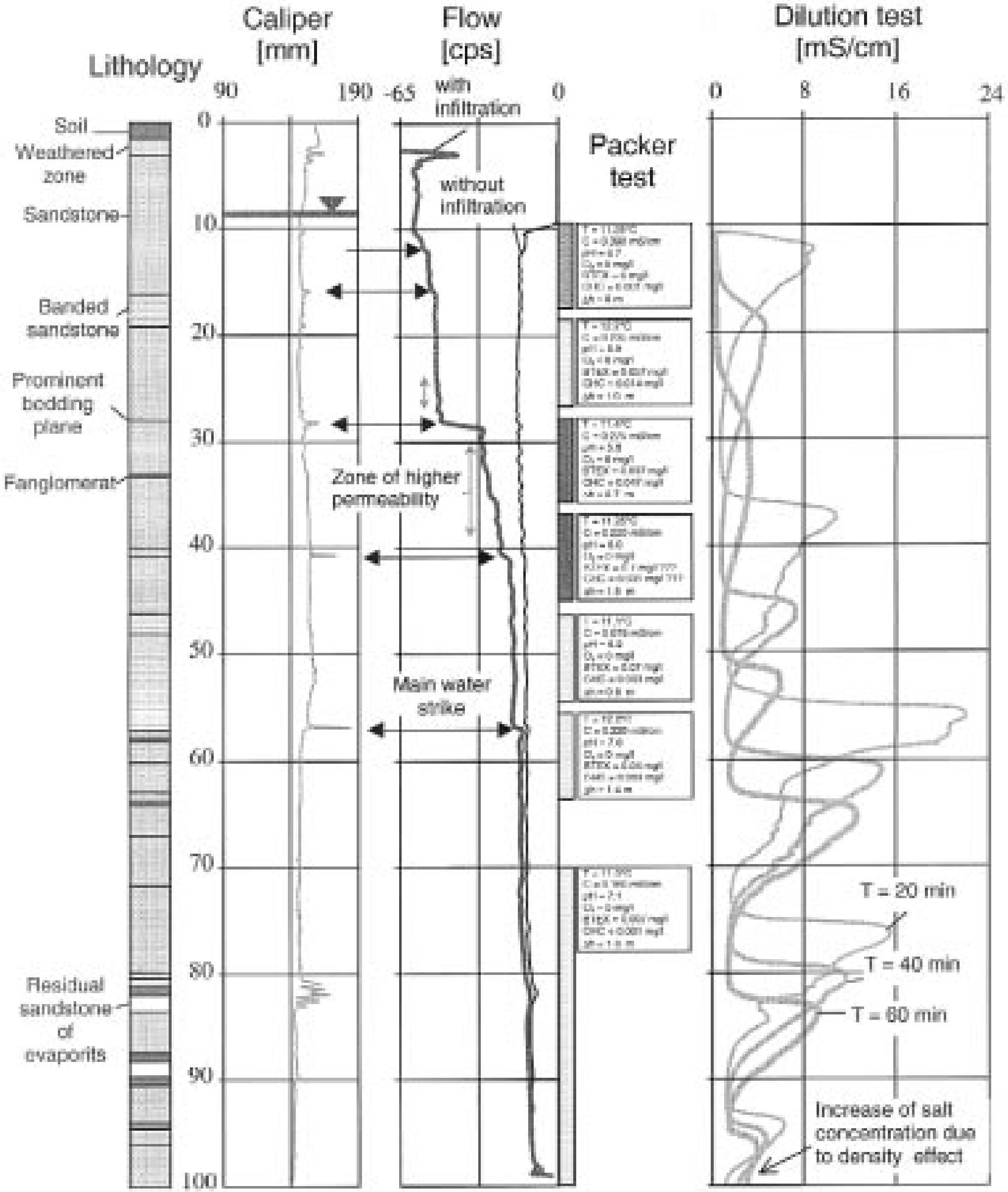


Figure 1. Selected drilling and testing logs applied to borehole Bh II. Prominent bedding plains are identified by caliper log. Main water strikes with infiltration are shown in flow-meter log. These strikes correspond to the caliper log results of prominent bedding plains. Vertical gradient is indicated by the dilution test. The chemistry and contamination content of the packer test samples indicate clearly separated aquifer zones (Δh = pressure difference between test interval and water pressure above packer).

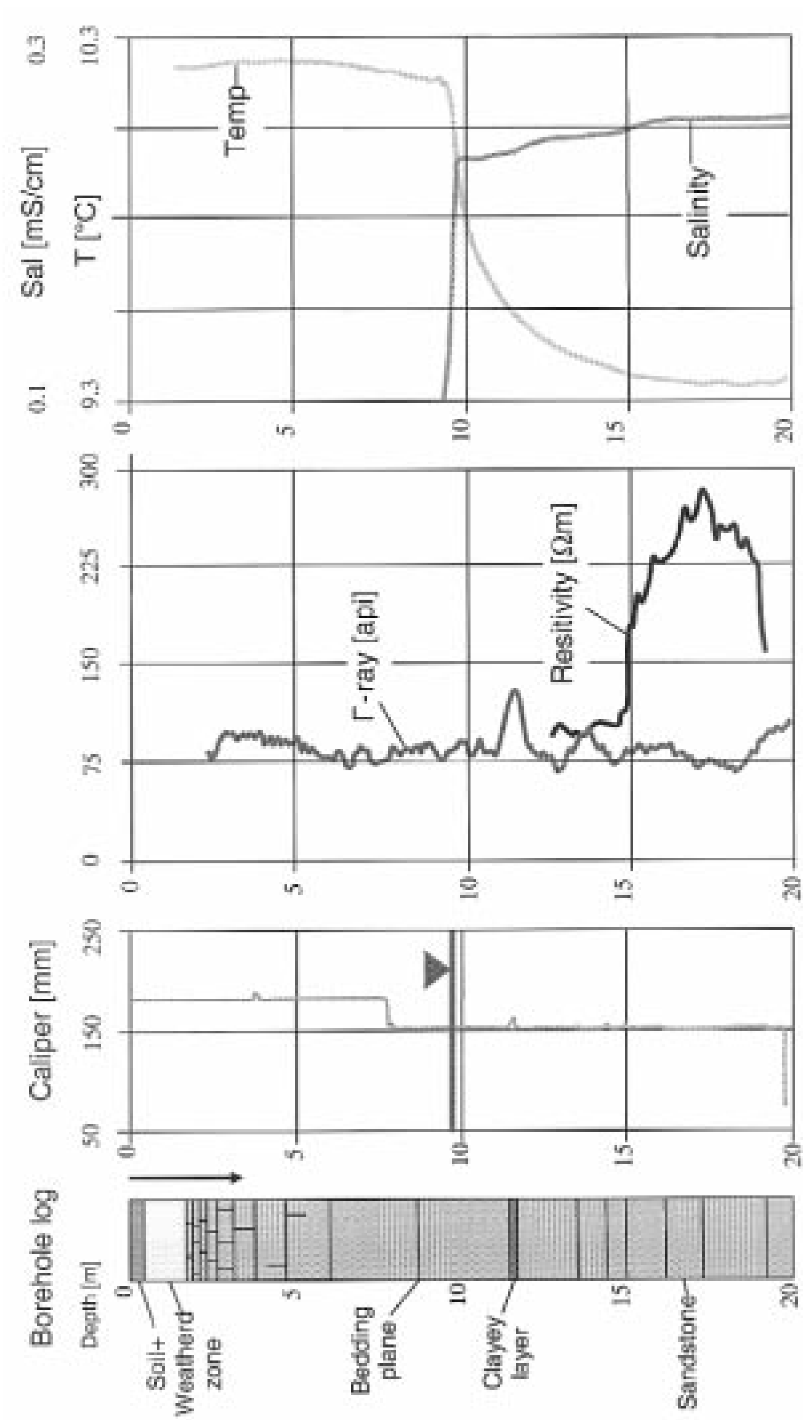


Figure 2. Selected drilling and testing logs applied to borehole Bh III.

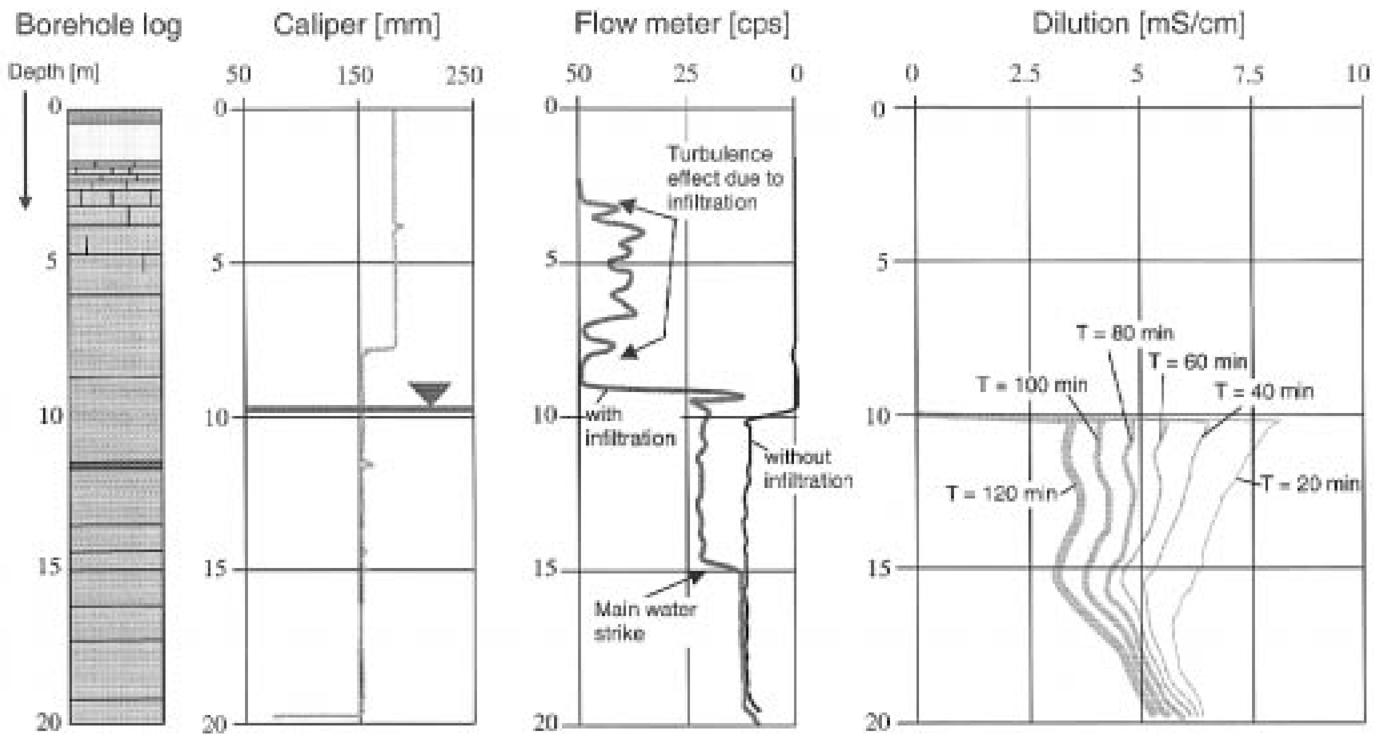


Figure 3. Selected drilling and testing logs applied to borehole Bh III.

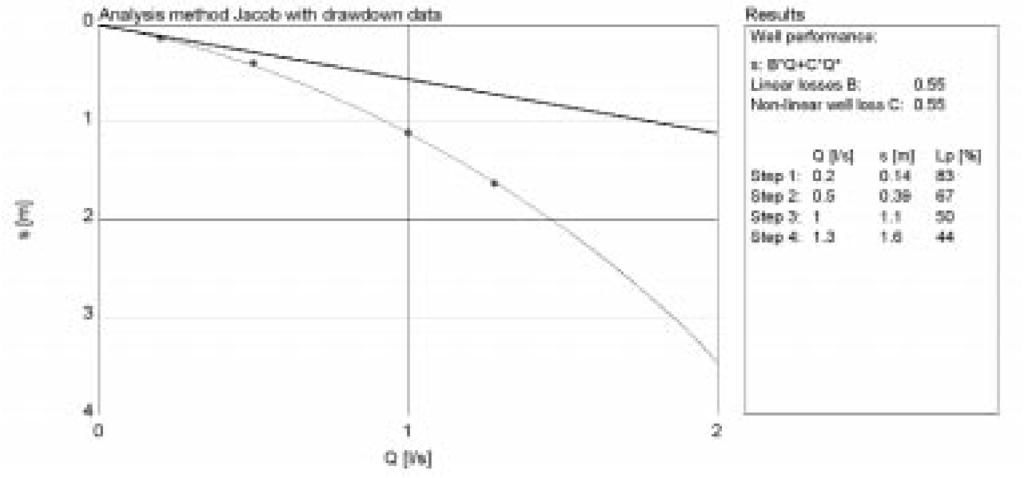
and 16 m, which correlate with the caliper log and borehole scanning results. The temperature curve, although superposed to the cooling effects from air to water temperature, correlates with the fluid salinity log.

The flow-meter log shows a sudden change at 14.5 m, which indicates the main water strike and correlates with the above presented results and the borehole scanning.

The salt dilution test results indicate a horizontal flow direction that collaborates to dilute the front with time in the upper part of the borehole. The highest velocities are seen from 10 to 12 m, further down the velocity decreases to a lower value and remains constant from 12 to 16 m. The velocity decreases rapidly up to 17.5 m and remains constant in the lower 2.5 m.

These logs show a horizontal flow situation with a main water strike (bedding plane) at a depth of 14.5 m. Evidence of the main water strike are shown mainly in the flow-meter log, but also indicated in the caliper and fluid salinity and temperature logs as well as in the borehole scanning results. However, the highest velocities in the salt dilution test results are shown in the upper saturated part of the borehole. This log also shows the horizontal character of the through-flow.

Following the Jacob method, the well efficiency can be calculated to approx. 50% for a rate of 1 l/s (Figure 4). The recovery data of the step-drawdown test allowed the estimation of the matrix transmissivity according to the Theis Method. The value was calculated to 0.002 m^2/s taking into account the data of the radial flow phase (Figure 5).



Results

Well performance:

s: B*Q+C*Q²
Linear losses B: 0.55
Non-linear well loss C: 0.55

	Q [l/s]	s [m]	Lp [%]
Step 1:	0.2	0.14	83
Step 2:	0.5	0.39	67
Step 3:	1	1.1	50
Step 4:	1.3	1.6	44

Figure 4. Well performance of borehole Bh III. The available drawdown above the main water strike was approx. 5 m (see flow meter diagram of Fig. 3). At a discharge rate of 1.3 l/s a drawdown of approx. 1.6 m was observed. A sustainable yield of about 2 l/s for a drawdown of 3.5 m seems to be realistic for the borehole.

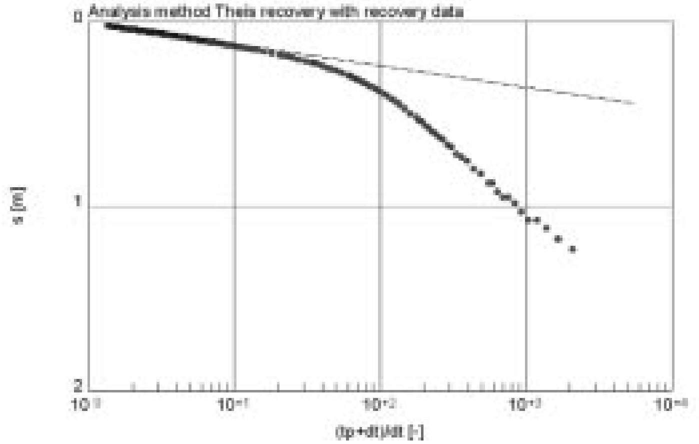


Figure 5. The recovery curve of borehole Bh III shows the influence of the open bedding plane and the well bore storage effect. The straight line analysis after Theis for the data of the radial flow phase (at late time) give a transmissivity of approx. T = 0.002 $m^?/s$.

The boreholes with lower yield have flow characteristics as described for the following borehole Bh IV. Figure 6 shows the lithology encountered in the borehole as well as the results of the caliper, fluid temperature and salinity, flow-meter, and salt dilution test results.

Up to 8 m depth the caliper log only shows 2 contacts between stand pipes at 2 and 5 m below surface, respectively. Further down, some changes in the borehole diameters appear at depths of 8.5 m, 9 m, 9.4 m, 11.7 m, 13.9m , 15 m, 15.7 m, 16.2 m, and 17.9 m. Final borehole depth is 21.5 m.

The fluid salinity log (Figure 6) shows a slightly gradual decrease from 13.5 m down to the bottom of the borehole. No significant changes in the fluid temperature were recorded, except for the cooling effects from air to water temperature, and correlates with the fluid salinity log.

The flow-meter log shows a gradual decrease of the velocity from the water level to the bottom of the borehole.

The salt dilution test results show water infiltration from the unsaturated zone into the borehole. This fresh water presses the salt front in the vertical direction. Furthermore, there is a horizontal inflow within the borehole that can be seen in the upper part of the log. Additionally, due to the very low horizontal through-flow within the borehole, there is a density effect at the bottom of the borehole from 19 m downwards.

These logs show a typical infiltration profile of a relatively homogeneous porous matrix. There are no clear indications of preferential flow paths, although in this case there as much indications for changes in the borehole diameter as in the first case.

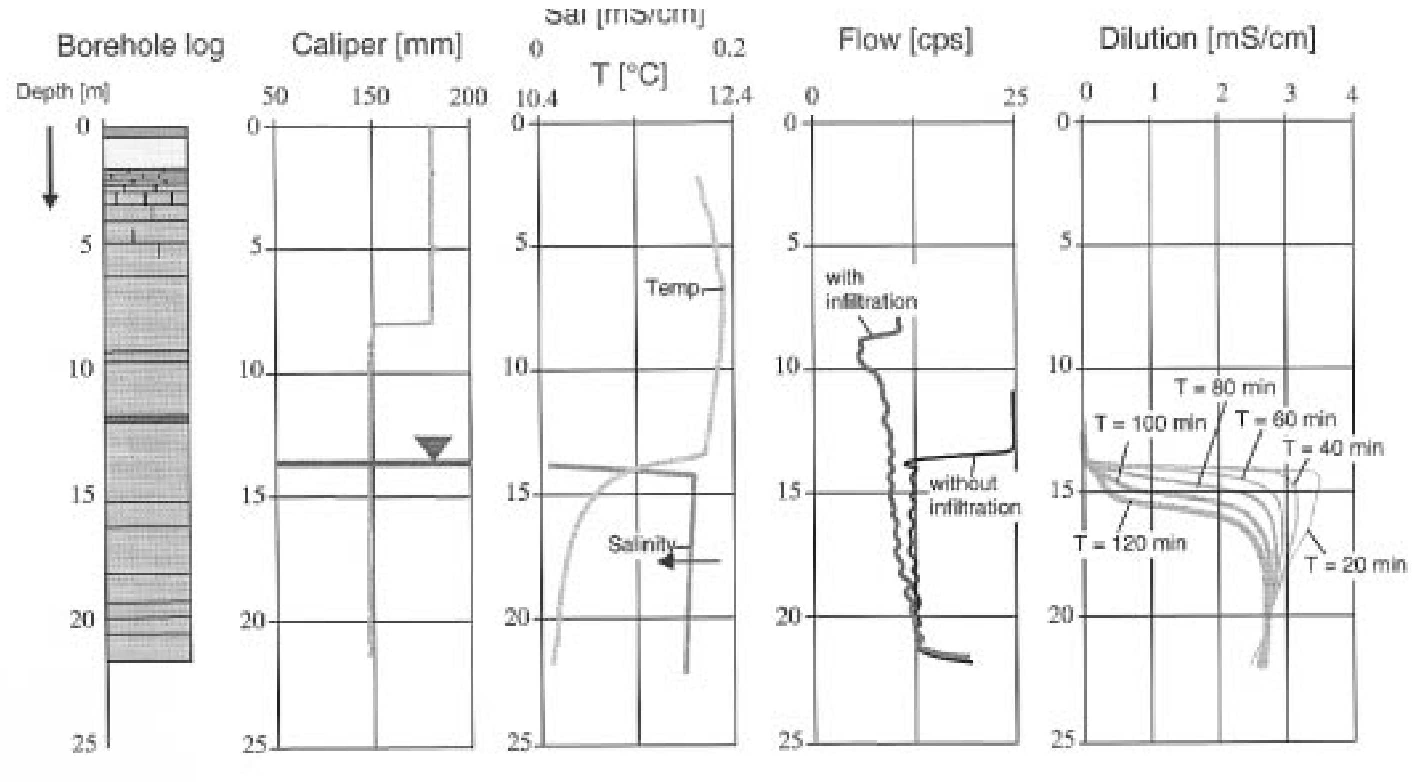
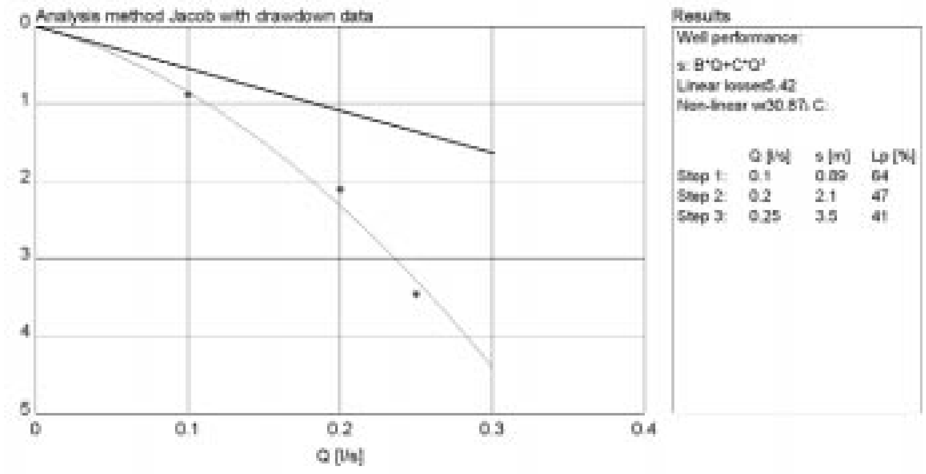


Figure 6. Selected drilling and testing logs applied to borehole Bh IV.

Following the Jacob method, the well efficiency can be calculated to approx. 40% for a rate of 0.25 l/s (Figure 7). The recovery data of the step-drawdown test allowed the estimation of the matrix transmissivity according to the Theis Method. The value was calculated to 0.0007 m^2/s taking into account the data of the radial flow phase (Figure 8).



s: B*Q+C*Q²
Linear losses5.42
Non-linear w30.87\ C:

	Q [l/s]	s [m]	Lp [%]
Step 1:	0.1	0.89	64
Step 2:	0.2	2.1	47
Step 3:	0.25	3.5	41

Figure 7. Well performance of borehole Bh IV. The available drawdown (head above the pump inlet depth) during the test was approx. 4.5 m, which is about 50% of the saturated zone of the borehole (compare Fig. 6). At a discharge rate of 0.25 l/s a drawdown of approx. 3.5 m was observed. A sustainable yield of only 0.3 l/s at a drawdown of 4.5 m seems to be realistic for this borehole.

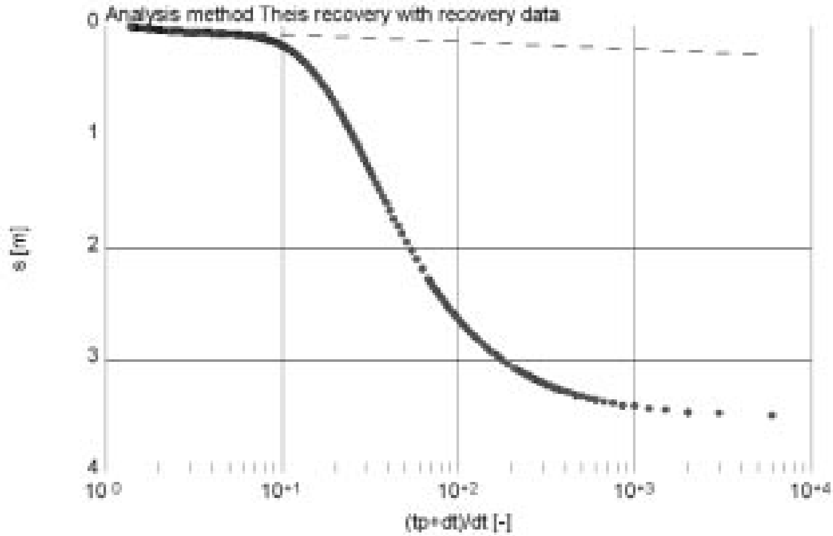


Figure 8. The recovery curve of borehole Bh IV shows a long well bore storage effect. The straight line analysis after Theis for the data of the radial flow phase (at late time) give a transmissivity of approximately T = 0.0007 m^2/s.

The differences in the matrix transmissivity obtained from the pumping tests can be explained by the presence of a preferential flow path feature in borehole Bh III. The estimated matrix transmissivity in this case is influenced by the transmissivity of the fracture, whose extension was not overcome by the cone of depression.

CONCLUSION AND RECOMMENDATIONS

The conclusions from this paper can be summarised as follows:

- To characterised the hydrogeology of a fractured aquifer, it is necessary to apply a series of investigation techniques
- All the techniques applied in this case study are all common available techniques
- The combination of interval drilling and single packer test turned out to be an excellent method to determine the vertical distribution of the contamination and to identify different aquifer systems
- Caliper, fluid temperature, salinity, and borehole scanning allowed to identify the position of preferential flow features, but from these data it is not possible to quantify the through-flow capacity
- The open borehole scanning helped to visualise the preferential flow path features in situ, which is hardly possible using the core (in this example bedding planes)
- The salt dilution tests turned out to be very important. The results allowed to clearly determine the vertical flow dynamic in a boreholes as well as the horizontal through-flow
- The flow-meter logs were useful to identify main water strikes
- The step-drawdown tests helped to define capacity of the borehole, the well efficiency, and in some cases the matrix hydraulic conductivity. Often they also confirm the presence of horizontal features, especially if they dewater during the test
- However, the results of the presented investigation demonstrates that any start of an investigation of an unknown aquifer must start with the determination of the vertical flow behaviour to avoid for instance unnecessary fail interpretation of the pollution depth
- In general, care must be taken while drilling monitoring or pumping wells because often the presence of vertical flow within these different aquifers could worsen the situation by leading contamination into unpolluted aquifers. It is therefore recommended that interval core drilling and single packer tests be used in the first borehole.

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