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# Improved Knowledge on Water Bearing Fractures and Groundwater Flow Using Ground Source Investigations

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## ABSTRACT

The undisturbed temperature profile measured before a thermal response test (TRT) and the recovery temperature profile measured after a test can be used as a valuable complement to the results from a thermal response test. The temperature profiles are also useful to detect water bearing fractures and groundwater flow (Liebel et al. 2012 and Holmberg et al. 2018). Water passing through fractures in boreholes can be observed as local temperature changes in the recovery temperature profiles. Data from laboratory measurements from several rock types in the larger Oslo area (Ramstad et al. 2014) and several unaffected TRTs gives a good knowledge of the expected thermal conductivity of the bedrock. Groundwater flow, however, may affect the results from a TRT leading to a considerably higher effective thermal conductivity as compared to the expected value for the rock based on its mineral composition and layering.

In the present paper, temperature profiles measured before and after 60 TRTs in Norway are systemized, analyzed and presented. The temperature profiles are combined with site geology and topography in an attempt to quantify the presence and explain the flow of groundwater through fractures in the bedrock. The data shows that there is a relation between high water yield of the boreholes and groundwater flow. In about 50 % of the cases the groundwater is stagnant and is not detectable in a TRT or in the temperature profile. The prerequisites for groundwater flow are, a hydraulic gradient e.g. as induced by topography and minimum a moderate water yield of the borehole, thus a water bearing fracture system. The groundwater flow can either be perpendicular to the well and vertically between two fracture zones with different hydraulic gradient. In cases where differences in the hydraulic gradient causes a vertical groundwater flow, it is expected that the drilling of several energy wells equalizes the hydraulic gradient in the area and reduces the groundwater flow. This method and knowledge from ground source investigations can also be considered as a useful supplement to understand other hydrogeological applications, e.g. drinking water supply, underground infrastructures, tunnels etc. in urban areas.

## 1. INTRODUCTION

Temperature profile measurements using a temperature probe are an easy and cheap method to measure the vertical temperature in boreholes. The measurements are routinely performed before and after a thermal response test (TRT). The information given from the temperature profiles is an important complement to the test results from the TRT (Liebel 2012) and can be used both as a quality assurance of the test results and for documentation of the ground source heat pump (GSHP) installation (Holmberg et al. 2018).

Groundwater flow can enhance the performance of the boreholes and thus the results given from a TRT. This shows as an unrealistically high effective thermal conductivity of the ground, compared to the expected value for the mineralogical composition of the rock as measured in laboratory (Ramstad et al.2014). In most cases, the contribution from the groundwater flow is little and can be assumed to be negligible. The recovery temperature profile measured after a TRT is useful to detect water bearing fractures and groundwater flow (Sanner 2007 and Liebel 2011). Water passing through fractures in the test borehole can be observed as local temperature changes in the temperature profile. The recovery temperature profile is therefore a good indicator to the reliability of the test results.

In the present paper, temperature profiles measured before and after 60 TRTs are systemized, analyzed and presented. The TRTs are performed in commercial GSHP projects in Norway and have been analyzed by Asplan Viak AS. The position of the boreholes is indicated with blue markers in figure 1. The boreholes range between about 50 to 500 m depth with most of the boreholes being in the range of 200 to 300 m.

The aim with the paper is to present data from the temperature profiles and some conclusions drawn from the study. Thereby contributing to a better understanding of groundwater flow in boreholes and water bearing fractures in crystalline bedrock. The general conclusions from the study are presented together with selected illustrative cases. The paper also illustrates the value of systematic collection of information from commercial GSHP projects as a statistical basis for a deeper understanding of the mechanisms of groundwater flow in fracture systems in crystalline bedrock. The knowledge given from the results can be important for the general understanding og groundwater flow in boreholes and in the subsurface, which can be useful for other hydrogeological applications.

In crystalline rock, groundwater flow is dependent on the hydraulic gradient (topography driven flow) and the presence of fractures (pathways for the water) in the rock. In boreholes, the presence of fractures and connectivity to fracture systems can be indicated by the water yield of the boreholes. Boreholes with low water yield have little connectivity. The absence of groundwater flow in these boreholes can also be seen in the recovery temperature profiles.

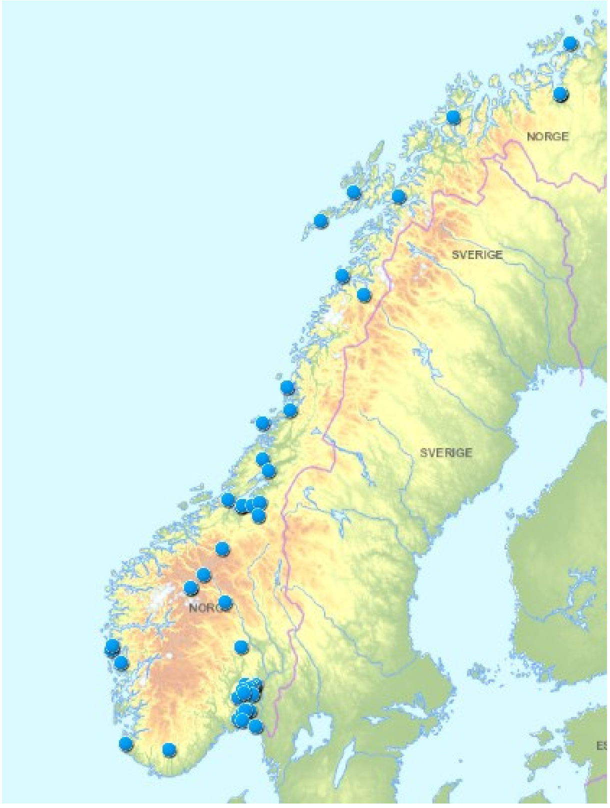


**Figure 1: Location of the test boreholes studied in the paper.**

## METHODOLOGY

The temperature measurements presented in the present paper are derived from a series of GSHP projects involving several companies and with different temperature probes. While the measurements are expected to be influenced by the different operators, the temperature profiles are accurate enough to determine the undisturbed temperature of the borehole and to identify factors that are of importance for the BHE sizing and the interpretation of the TRT results.

The temperature profiles are measured inside one of the collector pipes with a probe, commonly of the type 110 from hydrotechnik GMBH. Such temperature probes have an accuracy of <0.1 K and a resolution of 0.1 K. This is a manual procedure were the value is noted for each 5$^{th}$ to 10$^{th}$ meter, at each step, the probe is held still until the temperature has stabilized. For a 250 m borehole, this takes about 30 - 40 minutes. Measurements are either performed from top to bottom, or from bottom to top. Provided that care is taken when performing the measurements, both measurement directions give the same results. When measuring from bottom to top, the probe is first lowered to the bottom of the borehole and then held still a few minutes until the temperature has stabilized before starting the measurements. This measurement direction is often more practical since it distributes the work involved with winding up the temperature probe.

Undisturbed temperature profiles are measured after the borehole has rested a minimum of 3 days after the drilling is completed, in most cases the profile is measured after 5 to 7 days. When measuring the temperature profile there should not be any drilling in the area near to the borehole as this can disturb the measurements.

The temperature profiles after the TRT (recovery profiles) are measured while the temperature in the borehole is recovering. To avoid the rapid temperature changes directly after the TRT, the temperature should be measured after a few hours (Heiko et al. 2011). Due to practical considerations, the temperature profile is usually measured about 1- 5 hours after the heating period of the TRT is finished.

For most cases, temperature measurements with a 5 to 10 m resolution is enough to capture effects such as groundwater flow in a 200 – 300 m borehole. For short boreholes (e.g. 50 m) is it natural to use a shorter measurement interval of about 2 m.

The measurements are presented without any kind of post processing or corrections, e.g. as suggested in Raymond et al. 2016 for the rise of the collector fluid due to the added volume of the temperature probe. The TRTs are usually performed following the guidelines established by the Swedish Geoenergycentrum (2015) and with a heating period of 72 hours. Test results are analyzed according to Gehlin (2002) and Signorelli (2004 and 2007).

The test boreholes and the corresponding temperature profiles were systemized according to the water yield as indicated by the drillers log and the presence of groundwater flow as indicated by the temperature profiles. The water yield noted in the drillers log is not indicative of the long-term capacity of the boreholes which would have to be tested by a long-term test pumping. The position of the boreholes has been cross referenced with the geology at the sites as mapped by the Geological Survey of Norway. The hydraulic gradient near the boreholes has been estimated based on topographic profiles derived from laser data (hoydedata.no), i.e. it has been assumed that the hydraulic gradient follows the topographic gradient.

## INTERPRETATION OF TEMPERATURE PROFILES

Measured temperature profiles before and after TRTs in two separate test boreholes are shown in figure 2. There is no sign of groundwater flow in either of the temperature profiles in the figure to the left. And while there is no sign of groundwater flow in the undisturbed temperature profile for the right figure, the recovery temperature profile measured after the TRT clearly indicates that there is water flowing into the borehole. In the following parts of the paper, the focus will be on the recovery temperature profiles (indicated by red in figure 2).

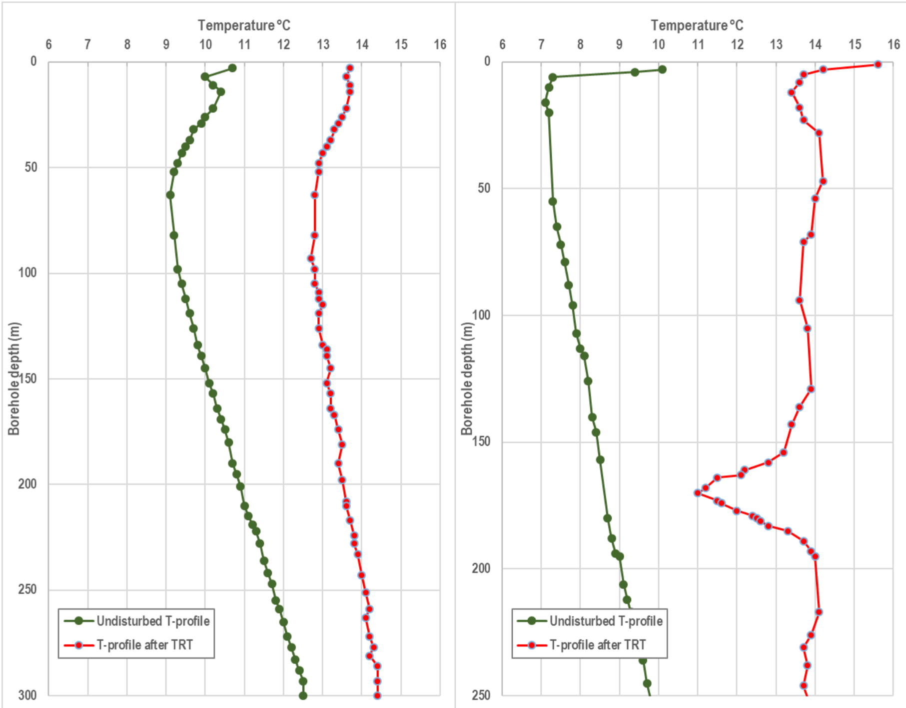


**Figure 2: Temperature profiles measured before and after a TRTs in two test boreholes, left figure is without groundwater flow and right figure is with groundwater flow showing in the recovery temperature profile.**

## RESULTS

A continuous groundwater flow that intersects the borehole shows as a distinct feature in the recovery temperature profiles. It can, however, be difficult to distinguish and quantify the influence from the groundwater on the effective thermal conductivity of the borehole as tested with a TRT, especially when the contribution is modest. In some cases, the influence of groundwater is rather clear as it leads to unrealistically high values of effective thermal conductivity.

The water yield of the studied test boreholes varies between a minimum of <50 l/h and a maximum of 100 $m^3$/h. The boreholes were divided into three groups depending on the water yield noted in the drillers log. This short-time water yield is measured just after completed drilling and is done by emptying the borehole by air-pressure and by measuring the time of naturally re-filling the borehole with groundwater.

Figure 3 shows that 50 % of the studied boreholes had a high-water yield (>1000 l/h) after drilling, 33 % of the boreholes had a median high-water yield (50 – 1000 l/h) and 11 % had low or negligible water yield (<50 l/h). 5 % of the studied cases had no information on the water yield. The results from TRTs (figure 3) indicate that in 22 % of the cases, the performance of the boreholes (as measured by the effective thermal conductivity of the rock) were clearly affected by groundwater flow, in additionally 15 % of the cases the results might have been affected by groundwater flow. TRT results affected by groundwater were predominantly found amongst the boreholes that were characterized with a high-water yield (figure 4). Only in three cases were boreholes with medium high-water yield affected. Most of the tests (63,3 %) were, however, not affected by groundwater.

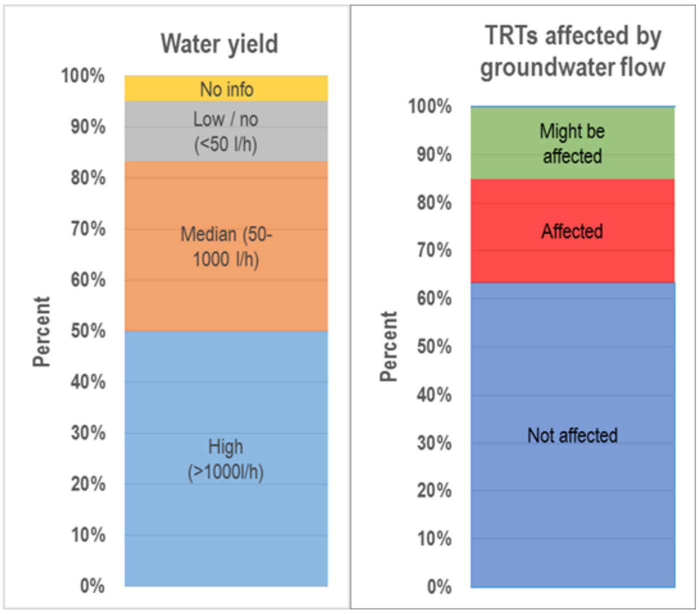


**Figure 3: Distribution of logged water yield in the TRT test boreholes (left) and TRTs affected by groundwater flow (right).**

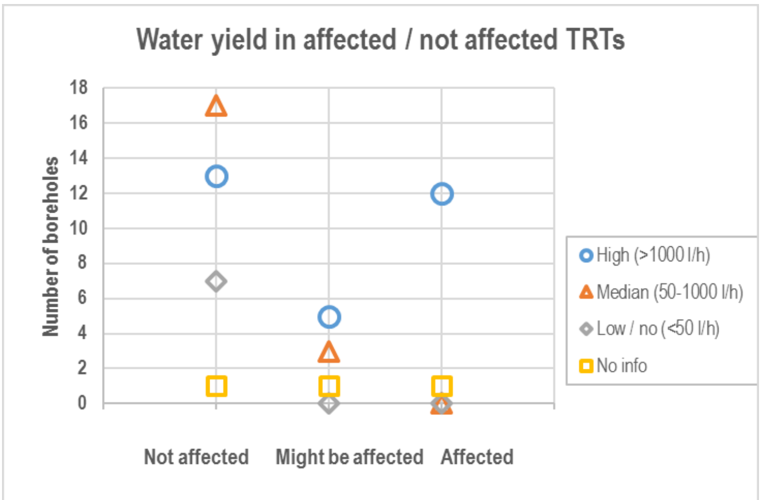


**Figure 4: Distribution of logged water yield for the TRT test boreholes, divided into categories of *not affected, might be affected* and *affected* by groundwater flow during TRT.**

Recovery temperature profiles were missing in 7 of the cases, these were, however, included in the study since they were clearly affected by groundwater flow and had high water yield. In the remaining 53 boreholes, groundwater flow could be observed in 47 % of the temperature profiles (figure 5).

Recovery temperature profiles with appearing water inlets, and TRTs affected and might affected by groundwater flow, can not be observed in any of the boreholes with little or negligible water yield (figure 4 and figure 5). Appearance of water inlets can be seen in the recovery temperature profiles for 8 out of 20 (40 %) of the boreholes with median high-water yield, but only 3 of these boreholes had TRT-results that might have been affected by groundwater flow (figure 6). 16 out of 23 (69,5 %) of the boreholes with high water yield also had recovery temperature profiles with appearing water inlets, and this number is probably higher due to the 7 boreholes without temperature profiles (figure 7). In 93 % of the cases where the TRT results were or might have been affected by groundwater flow also the recovery temperature profiles were affected.

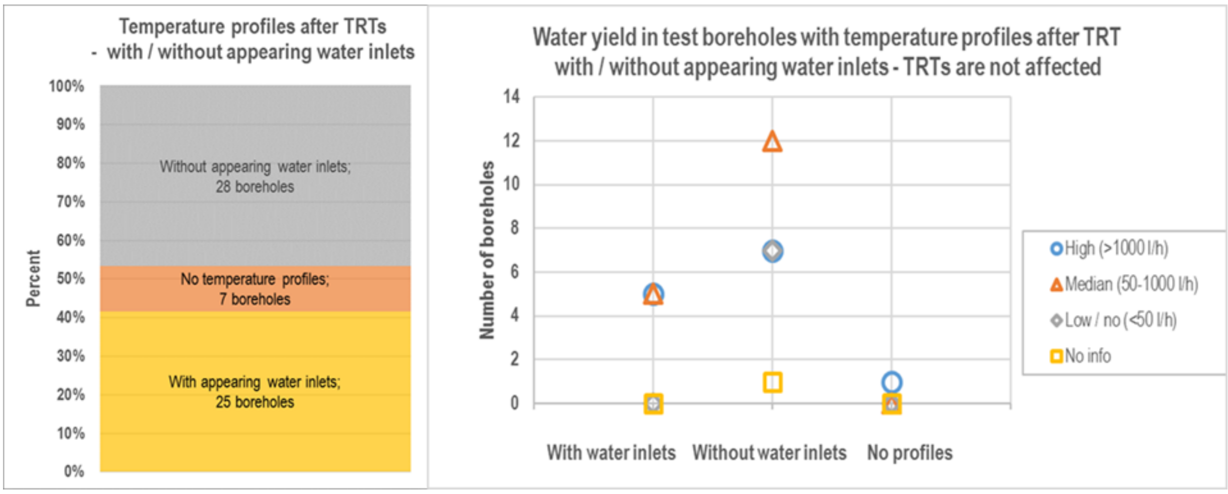


**Figure 5: Recovery temperature profiles and the presence of appearing water inlets (left), water yield and appearing water inlets on the temperature profiles after TRTs not affected by groundwater flow (right).**

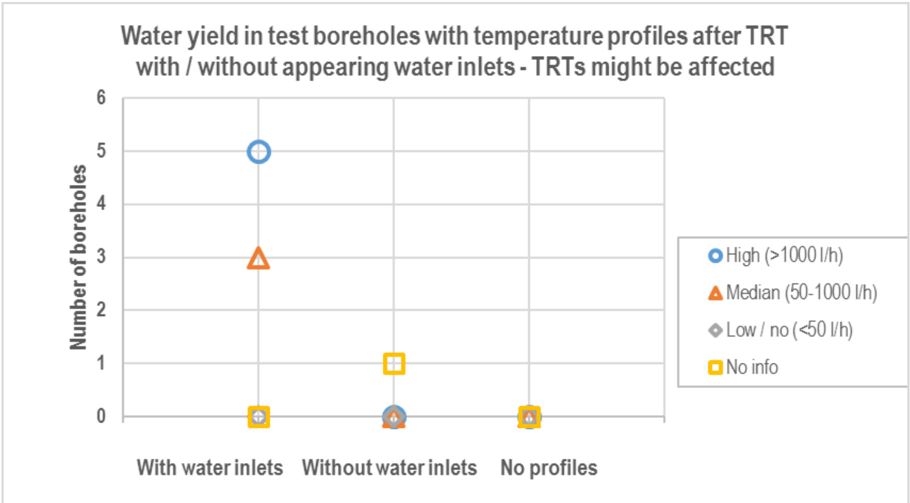


**Figure 6: Water yield and appearing water inlets on the temperature profiles after TRTs that might be affected of groundwater flow.**

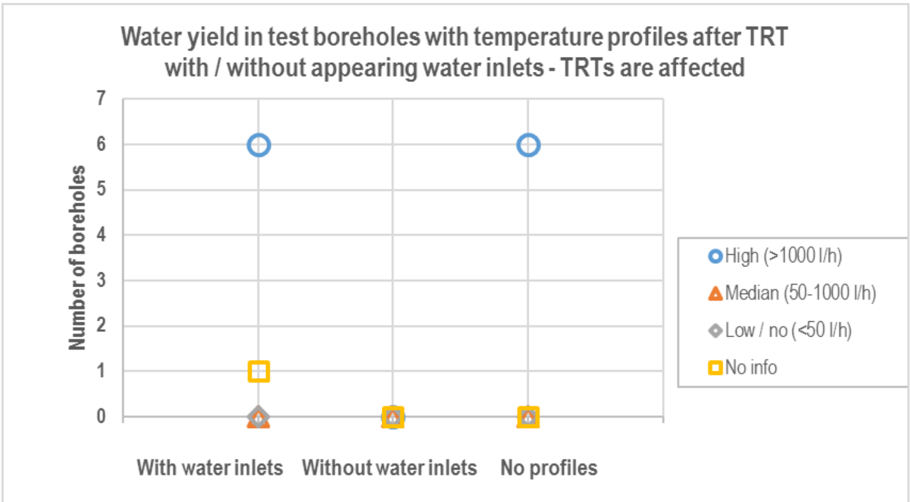


**Figure 7: Water yield and appearing water inlets on the temperature profiles after TRTs affected by groundwater flow.**

### Geology and topography

While the groundwater flow is related to the hydraulic gradient and the presence of fractures through the crystalline rock, no clear relationship was seen between the site-specific geology and the presence of groundwater flow. Although some rock types such as rhomb porphyry tend to give a high-water yield, rocks such as granites and gneisses are present both in boreholes with none and with high water yield.

The topography varies significantly between the different borehole sites, with some of the boreholes situated in valleys surrounded by steep hillsides and some in a flat terrain. Since groundwater flow through fractures in the rock is topography driven, is intuitive that there should be a relationship between the topography at the sites and the observed groundwater flow. The influence of topography was studied using the assumption that the hydraulic gradient (driving potential for the groundwater) is closely related to the topographic gradient. The topographic gradient was then calculated for several selected cases based on topographic profiles derived from laser data (høydedata.no). Preliminary results indicate that boreholes located near steep terrain and with a high-water yield tend to be affected by groundwater flow, the results are however not unambiguous and also boreholes located in a near flat terrain and with a significant water yield can be affected. The presence of water conducting fractures and a high yield seems to be the most important factors.

Figure 8 shows recovery temperature profiles in two boreholes that are both located near steep terrain, the corresponding topographic profiles are shown in the figure to the right. Profile 1 corresponds to a borehole with a high-water yield and is clearly affected by groundwater flow, the TRT resulted in a high effective thermal conductivity of 11 W / m·K which is clearly unrealistic, the geology at the site is mapped as sandstone. Profile 2 which corresponds to a borehole with medium water yield (50 - 500 l/h) show no sign of groundwater flow despite being in a steep terrain, in this case the TRT resulted in an effective thermal conductivity of 3 W / m·K which is as expected for the geology at the site (dioritic and granitic gneiss).

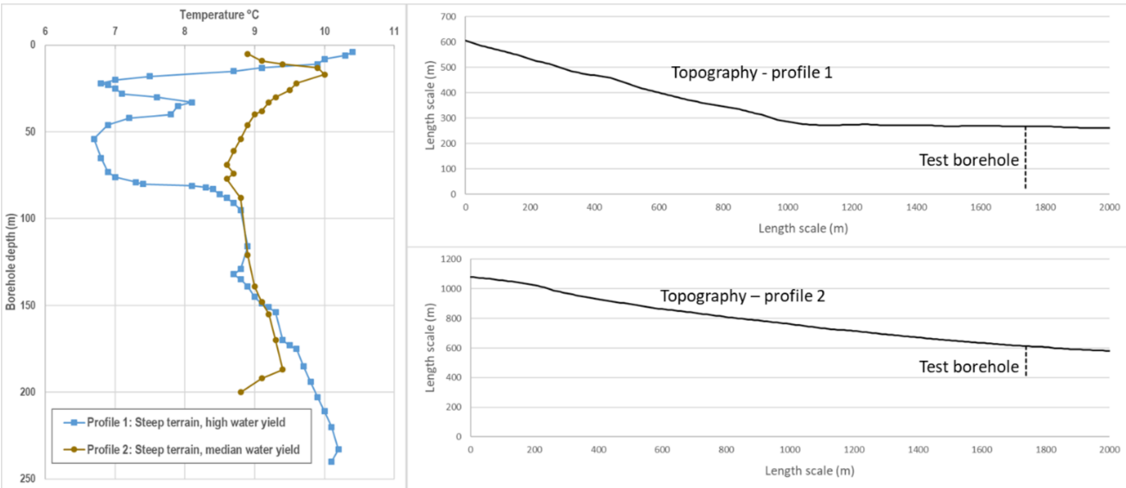


**Figure 8: Recovery temperature profiles measured in boreholes with high water yield and with medium water yield. Both boreholes are located near steep terrain as shown by the topography profiles.**

The results from the study also shows that boreholes having a significant water yield not necessarily needs to be affected by the groundwater. As an example, two separate TRT tests were performed in southern Norway in test boreholes that both had a significant water yield of about 60 $m^3/h$ respective 22.5 $m^3/h$ and were situated in a near flat terrain (figure 9). Both TRTs resulted in low values of effective thermal conductivity (2,2 W / m·K and 2,4 W / m·K) that are in range of the expected values for the present geology (monzonite and rhomb porphyry). The recovery temperature profiles are shown in figure 9. In the test borehole with the highest water yield a single major fracture zone was observed at about 140 m, and this coincides with the temperature change shown in the figure. In the other borehole, the water bearing fractures were distributed throughout the borehole and no major temperature change can be seen in the temperature profile. The low or negligible contribution from the groundwater on the TRT results in these boreholes indicates that the groundwater in these boreholes must be stagnant or near stagnant. As the temperature change induced by the TRT also can cause potential for movement (convection) in the water, it is not unexpected that the lager fracture zone shows in the temperature profile.

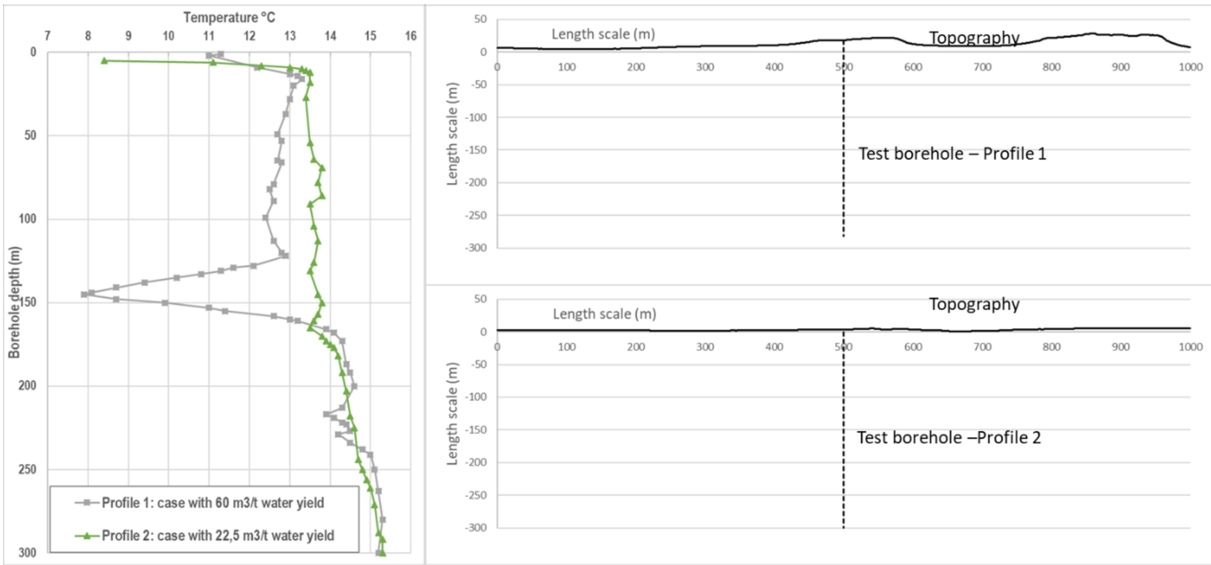


**Figure 9: Temperature profiles measured after TRTs in two boreholes with significant water yield of 60 $m^3$/h respective 22.5 $m^3$/h. Analysis of the TRT results show that the test was unaffected by groundwater flow.**

## CONCLUSION AND DISCUSSION

Categorization of TRT results and information derived from commercial GSHP projects can prove useful to enhance the knowledge of groundwater flow in water bearing fractures in crystalline rock. The strength of the method is the amount of data generated by the measurements. While the short-term water yield of the boreholes from the drillers log is a rough estimate, there is a relation between the estimated water yield and observed groundwater flow in the temperature profiles, i.e. temperature profiles are more likely to show indications of groundwater flow in boreholes with high water yield.

In addition, TRT results from test boreholes with a high-water yield are more likely to be affected by the groundwater flow. In almost all cases where the TRT results were affected by groundwater flow, the groundwater also affected the recovery temperature profiles. Recovery temperature profiles are therefore a good indicator of the reliability of TRT results.

Preliminary results show that boreholes located near steep terrain and with a high-water yield tend to be affected by groundwater flow, the results are, however, not unambiguous and will have to be studied further with a more extensive GIS- analysis. Boreholes with significant water yield and none or negligible influence on the TRT results shows that the groundwater, especially in flat terrain also can be stagnant or near stagnant.

Optionally the test boreholes should be studied more extensively with e.g. test pumping and temperature measurements using DTS (Acuna 2013). For most cases this is not possible due to the commercial nature of the projects which dictates a limited time frame and budget. Automated temperature measurements might be good approach to increase the repeatability and quality of the manual temperature profile measurements

## ACKNOWLEDGEMENT

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