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Groundwater Circulation Wells for Geothermal Use: Preliminary Results of the Project Integralsonde Type II

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ABSTRACT

Groundwater heat pump (GWHP) systems are a widespread technique to provide buildings with heating and cooling. Most open loop shallow GWHPs are doublet systems which consist of two wells, one for extraction and one for reinjection of groundwater. Hence, there has to be enough space to set up such a system.

Shallow groundwater circulation wells (GCW) are an alternative. These open loop low-enthalpy shallow geothermal energy systems extract and inject groundwater in the same well via two filter screens at different depths. GCWs also demand less space, but so far there are only few installations. Our aim is to investigate the efficiency of those systems, their influence on groundwater chemistry and microbiology and evaluate their long-term productivity. These are the main research goals of the research project "Integralsonde type II" (01LY1507B /BMBF, KMU-innovativ). GCWs for geothermal use and their impact on groundwater quality are investigated at several sites in the quaternary main aquifer (Saalian age) in the Berlin (Germany) area. For the system studied, groundwater is extracted at the lower filter screen and pumped to a GWHP where the thermal energy is utilized for cooling or heating of the building and then re-injected via the upper well screen. The temperature gradient between extracted and injected groundwater is around 3 K. Since the groundwater circulates in the same aquifer which is used for drinking water production, it is crucial to avoid any negative impacts on groundwater. To reduce clogging, mineral precipitation, and dissolution, or physical processes such as particle mobilization, degassing, and flocculation, it is critical to prevent mixing of different hydrochemical zones. Especially the presence of high contents of ferrous iron and manganese are usually exclusion criteria for the installation of open geothermal groundwater systems. We monitored both newly installed as well as running GCWs by sampling groundwater from the well and nearby groundwater observation wells. Major anions and cations, especially ferrous iron, manganese and sulfate as redox sensitive parameters, as well as physicochemical parameters for redox zone determination were analyzed. To monitor changes within microbial community, DNA from groundwater samples was extracted and used for quantitative real-time PCR applying primers for iron-reducers, -oxidizers and sulfate-reducing bacteria. Our preliminary results showed that the redox zones in the vicinity of a newly installed GCW remained stable if groundwater was pumped in intermittent intervals. Continuous pumping over weeks changed the bacterial community of the produced water. A groundwater circulation well could therefore be a potential alternative for groundwater otherwise not suitable for open geothermal systems.

1. INTRODUCTION

Groundwater circulation wells are originally known for their use in groundwater remediation (Scholz 2000; Mohrlok, et al. 2002, Johnson and Simon 2007). In the 1990s - 2000 they were used for pump-and-treat remediation of contaminated groundwater, pumping the contaminated groundwater to the surface, cleaning and re-injecting it into the aquifer. The system was rediscovered for its use for geothermal energy production (Xu and Rybach 2005). Other open systems, like doublets, consist of two separate wells for extraction and injection of groundwater. GCWs need only one well for extraction and injection and are therefore a space-saving alternative, especially in densely populated areas.

Open shallow geothermal systems are highly energy efficient and considered to be environmentally friendly (Lo Russo, et al. 2012). Still, the number of newly installed open systems are far below those of closed systems (Rode, et al. 2015). Since groundwater is directly used as a heat carrier fluid, there are several requirements regarding groundwater quality, for example low iron and manganese contents to prevent clogging (VDI 2010). Possible impacts and processes of open shallow geothermal energy systems have been reviewed by Hähnlein, et al. (2013).

Doublet systems and their impact have been described in several publications (e.g. Brons, et al. 1991, Bonte 2013, Possemiers, et al. 2016), but GCWs and their impact on groundwater quality has not been examined scientifically yet (Zeng, et al. 2017). One of the most common and crucial impediments for the operation of shallow, open loop geothermal systems is well aging through clogging of filter screens due to iron hydroxide precipitations (Hähnlein, et al. 2013, García-Gil, et al. 2016, Possemiers, et al. 2016) accelerated by microorganisms. Clogging as a technical problem leads to system productivity losses with increasing operation time. To avoid this negative effect, there are several recommendations for threshold concentrations in groundwater for iron and manganese concentrations, e.g. UMBW (2009) $c(Fe_{total}) < 0.1$ mg/l and $c(Mn_{total}) < 0.05$ mg/l.

These limitations and the complexity of clogging processes as well as keeping a shallow open-loop system oxygen-free might be the reasons why shallow open loop systems are still rare in the urban area of Berlin (Germany). With iron concentration of 2.97 mg/l ± 4.61 mg/l and maximum values up to 52.1 mg/l (Senatsverwaltung für Stadtentwicklung und Wohnen Berlin 2006), Berlin groundwater seems to be not suitable for the operation of open, shallow systems especially due to potential clogging at reinjection screens.

Biotic processes in open geothermal systems in Berlin (Germany) have been analyzed by Lerm, et al. (2011), Vetter, et al. (2012), Eggerichs, et al. (2014), Eggerichs, et al. (2015), and Opel, et al. (2014). These studies showed that microbial activity is highly site-specific, depending on the local community of microorganisms, on the amount and reactivity of organic material available, and on the operation of the geothermal system. Our aim is to investigate the efficiency of GCWs, their influence on groundwater chemistry and microbiology and evaluate their long-term productivity within the urban area of Berlin, Germany.

2. SYSTEM DESCRIPTION

Groundwater circulation wells (GCWs) for heating and cooling as the investigated type „Integralsonde“ (developed and installed by Geo-En Energy Technologies GmbH, Berlin, Germany) consist of a single well with two filter screens which are hydraulically decoupled. The system can be used in porous aquifers with a sufficient thickness of the permeable layer. Groundwater is pumped via the lower filter screen to a heat pump where heat or cooling energy is extracted and used for heating and cooling of buildings. Simultaneously the water is directly re-injected via return flow into the aquifer via the upper filter screen. Between the extraction (lower) and the re-injection (upper) filter screen a vertically directed pressure difference is developed resulting in the formation of a groundwater circulation cell. The injected water flows in bended tracks to the extraction well (Figure 1)

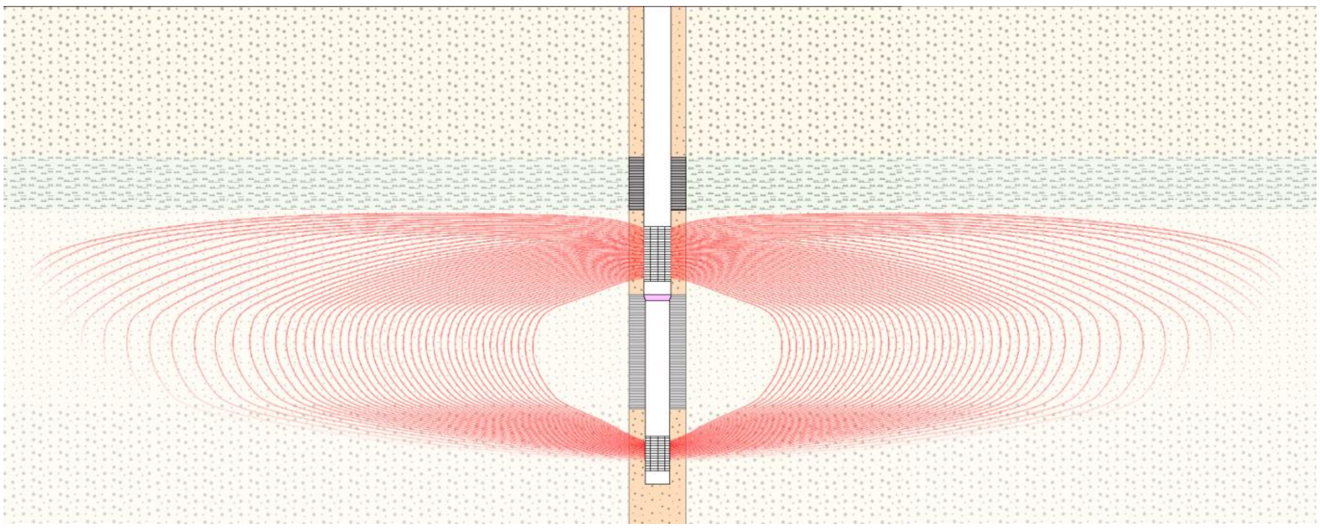

Figure 1: Modeled circulation cell of re-injected groundwater from upper filter screen to lower filter screen. The depicted GCW is located at Berlin-Southwest site at pumping rate 8.6 m³/h without groundwater flow with FeFlow 6.1. The vertical expansion of the circulation cell is 40 m assuming a continuous pumping time of more than 100 days. Real operation cycles are less than four hours per day.

Re-injected cooled water reaches in situ aquifer temperature through heat convection in the aquifer. When reaching the extraction filter the groundwater is heated up again and ready to use for heating purposes. Depending on hydraulic conductivity of the aquifer, the vertical distance between the filter screens, capacity of the circulation well (flow combined with temperature difference between flow and return) and operation time, the circulated water is cooled down during a heating period.

An intermediate change between heating and cooling operation is possible. The alternating operation of heating and cooling of buildings leads to a balanced aquifer temperature with only a few Kelvin fluctuation within annual cycles.

3. MATERIAL AND METHODS

Within this project three sites in and near Berlin with groundwater circulation wells have been monitored. We focused on hydrochemical and microbiological interactions between the system and the aquifer. Sampling of groundwater was conducted before installion of a new system as well as for running systems in weekly up to monthly intervals. Physicochemical parameters (specific electric conductivity EC [µS/cm], dissolved oxygen [mg/L], redox potential E_H [mV] and pH), as well as anion and cation concentrations and dissolved organic carbon [ppm] in the flow water and return water were analyzed.

Changes in microbial diversity in groundwater and process water were investigated. Gene number copies of eubacteria, iron-oxidizer *Gallionella spp.*, iron-reducer *Rhodoferax sp.* and *Geothrix sp.* and the sulfate reducing bacterium *Desulfovibrio vulgaris* were determined in all samples from groundwater circulation- and monitoring wells by quantitative real-time PCR (qPCR) analysis of the 16S rRNA genes.

3.1 Operational data

The operating data (pressure, temperature, flow, circulated water volume in total, circulated water volume for flow and return, respectively) for every site are logged at minute intervals to compare changes in hydrochemistry to operational switches. Groundwater temperatures at Berlin-Southwest site vary between 9 – 12 °C at 60 m below ground level.

3.2 Site description

At Berlin-Southwest site both filter screens are located in the unconfined main aquifer of Berlin, which is of Saalian age. The aquifer consists of sand and gravel, which is also the aquifer used for drinking water production (Limberg and Thierbach 1997). The upper and lower filter screens are located in 52 – 56 m and 67.4-69.9 m respectively. Above the upper filter screen a 4 m thick clay lense was locally encountered with an unknown lateral extension. The aquifer belongs to the Teltow plateau with water levels up to 20 m below ground level. A groundwater observation well in 7 m distance of the GCW was sampled to compare the composition of groundwater within the aquifer with the groundwater from the circulation well. The groundwater observation well is screened between 61 and 62 m below ground level. The GCW was brought into service in March 2016 and sampled weekly until August 2016. From January 2017 on it was sampled monthly. Between August 2016 and January 2017 sampling was not possible since there was no access to the GCW.

4. RESULTS

4.1 Hydrochemistry

At Berlin-Southwest site we were able to monitor the hydrochemical changes of groundwater quality since the beginning of a newly installed groundwater GCW for geothermal use. Before installation of the GCW, the groundwater at 44 m and 70 m showed Fe_{total} concentrations of 1.9 and 0.23 mg/L. After installation, but before operation of the GCW, the Fe_{total} concentration was measured to be 3.9 mg/L.

Operation of the GCW in Berlin-Southwest started in March 2016 with a continuous pumping test over 5 days. Accidentially, oxygen entered the aquifer for five days during the pumping test and caused $Fe(OH)_3$ precipitations at the filter screens. The GCW was fixed on March 18, 2016 and from then on no oxygen entered the GCW anymore. A low redox potential of 50 mV E_H and vanishing $Fe(OH)_3$ precipitations three months after regular operation was observed. Most likely the precipitation was dissolved as ferrous iron and the circulated water became clear again (see Fig. 2). Ferrous iron concentration after one year of operation was 3.5 mg/L.

Dissolved manganese concentrations showed a slight decrease after oxygen entry in March 2016 from 0.22 mg/L to 0.15 mg/L, possibly due to precipitation as manganese oxide. After maintenance stable manganese concentrations of 0.28 mg/L were observed. Under continuous operation of ten days during a pumping test in August 2016, manganese concentration increased to 0.6 mg/L. Fe_{total} concentrations varied between 3.3 – 3.6 mg/L during the pumping test (Fig. 2). Nitrate concentrations fluctuate between 0 and 1.7 mg/L and increased slightly at the end of the pumping test to 2.1 mg/L.

The concentrations of total iron, manganese and nitrate in the nearby groundwater observation well were comparable to those measured in the GCW at the start of GCW operation and were almost identical after the pumping test in August 2016.

The physicochemical parameters pH and dissolved oxygen remained stable at 7.4 and 0.09 mg/L oxygen, whereas the electric conductivity rose continuously from 954 µS/cm at the beginning of operation to 1016 µS/cm during the tracer test in August 2016. The well is operated according to heating or cooling requirements in the building. This leads to non steady-state pumping operation and quickly changing phases of operation.

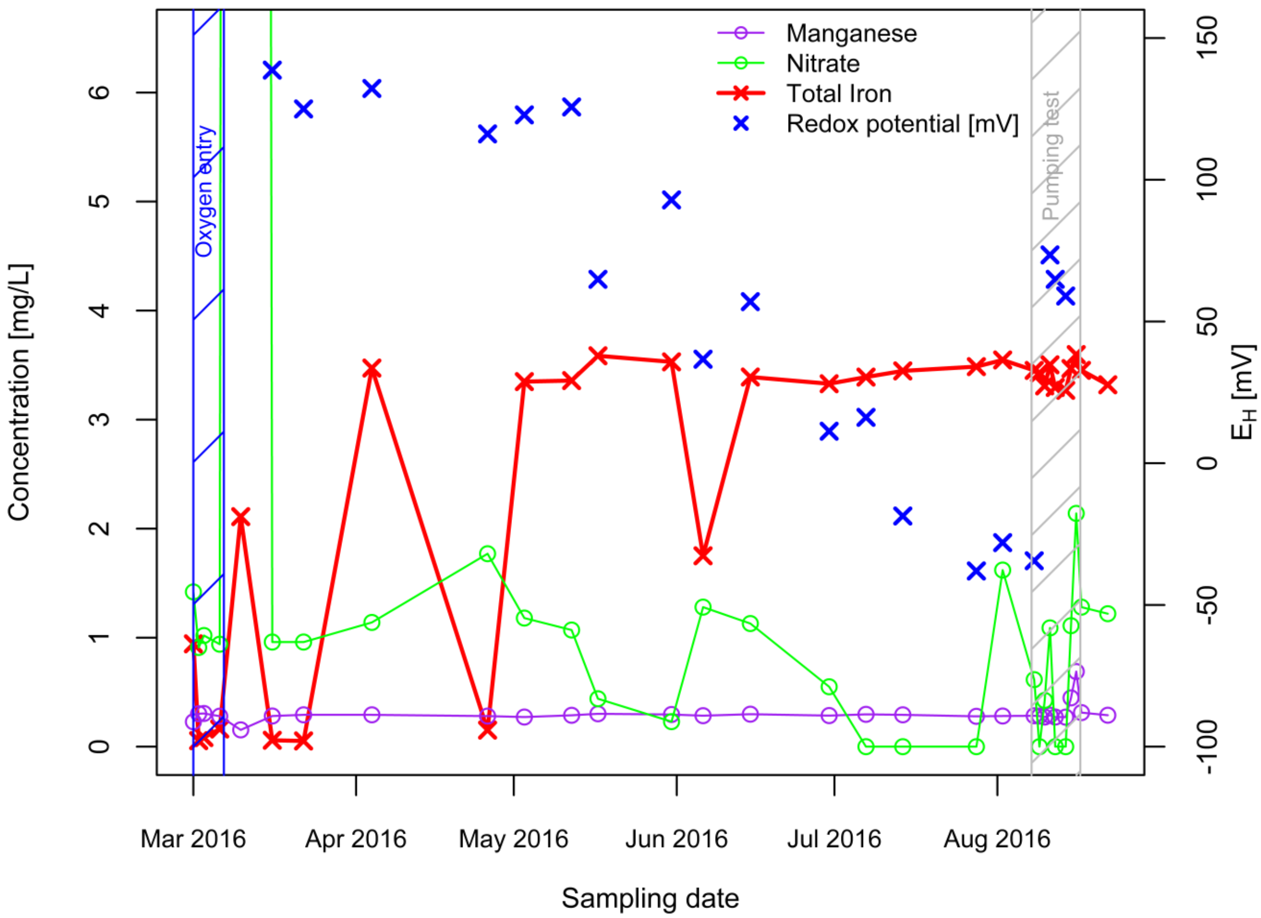

Figure 2: Long-term course of redox-sensitive parameters at Berlin-Southwest site between start of operation in March 2016 and end of tracer test in August 2016. Oxygen entered the system accidentially for 5 days in continuous operation in March 2016. A pumping test was conducted in August 2016 for 10 days.

4.2 Microbiology

Flow water and the nearby groundwater monitoring well are sampled to determine changes in microbial diversity.

Between March and August 2016 weekly samples were taken to determine the gene copy numbers of the bacteria outlined above. Between March and April Eubacteria varied between 10^7 gene copies per ml and 10^5 gene copies per ml, whereas *Rhodoferax* and *Gallionella* gene copies were detected between 10^5 copies per ml and 10^3 gene copies per ml. *Geothrix sp.* were not detected at all. Between April and June 2016 Eubacteria remained relatively stable, but *Gallionella* declined continuously from 10^3 gene copies per ml until it was no longer detectable from July 2017 on.

Compared with declining redox potential measurements in Fig. 2 during that time and dissolved oxygen concentrations under 0.1 mg/l we assume that the entered oxygen was consumed through abiotic oxidation of ferrous iron to $Fe(OH)_3$ and biotic oxidation through *Gallionella sp*. After oxygen was consumed, *Rhodoferax* and *Geothrix* might have reduced $Fe(OH)_3$ to ferrous iron again. Iron precipitates were no longer visible in process water and ferrous iron contents in groundwater rose up to 3.5 mg/l.

During a 10 day pumping test in August 2018, Eubacteria remained stable at 10^5 gene copies per ml and *Rhofoferax* varied between 10^3 and 10^2 gene copies per ml. Geothrix spp. was detected during the pumping test with 10^1 gene copies per ml. Sulfate reducers were only detected at several days between 10^2 and 1 gene copies per ml.

Sampling of the groundwater observation well in 7 m distance to the GCW revealed gene copies of all analyzed bacteria present in native groundwater, but in lower abundance. *Gallionella sp.* was still detectable in July 2017 at the monitoring well, but not at the

GCW. Only during the pumping test all bacteria were detected in a 10^2 higher abundance in the monitoring well than in the GCW. The circulation cell might have reached the monitoring well and altered the bacterial community there.

We are interested whether anion and cation concentrations as well as physicochemical parameters and the bacteria match the assumption that both filter screens are located within the iron-reducing zone and how the intermittent vs. continuous operation of the GCW alters the groundwater quality.

5. DISCUSSION

According to VDI 2010 oxygen entry into open-loop geothermal systems operated in groundwater with low redox potential and iron and mangenese concentration should be avoided to prevent the precipitation of hydrated iron oxide and manganese oxide. Mixing of waters from different redox zones can have the same results leading to clogging of filter screens.

Even though there had been a massive oxygen input directly after start of operation of the GCW leading to precipitations at the upper filter screen (visible in camera inspection and in transparent parts of the pipe system), the precipitations dissolved when further oxygen input was stopped. The design of the GCW with both filter screens in the iron reducing zone of the aquifer combined with short pumping intervals led to a kind of "self-cleaning" of the filters and most likely to a reduction of $Fe(OH)_3$ to Fe^{2+}.

Results from analyzing the bacterial groundwater population detected by qPCR coinced very well since iron oxidizers dropped since inhibition of oxygen entry, until they were no longer detectable in June 2016. At the start of a pumping test at August 15, 2016, iron oxidizers were detected once with 100 gene copies/ml, probably due to oxygen entry through the installation of additional flow meters. Presence of iron reducers in higher concentrations and as different species support the reduction of already precipitated iron hydroxides. We assume that the low redox potential in combination with the occurrence of iron reducers led to a slight increase of Fe^{2+} concentration in the sampled groundwater.

Groundwater samples from the nearby groundwater observation well showed increasing similarities to the sampled groundwater of the GCW within months of operation. We conclude that the size of the circulation cell reaches the monitoring well which is in a distance of 7 m to the GCW. All bacterial genes were detected in higher abundance during the pumping test than at intermittent operation.

GCWs as the Integralsonde type are not operated in continuous operation at regular cooling or heating usage at the described site, and only running in several short intervals per day, dependent on heating and cooling demand in the building. Hence our findings showed that an intermittent operation is favorable to prevent clogging and maintained a low influence on local bacterial community in groundwater.

6. CONCLUSION

The prelimininary results of our study show that areas which have usually been excluded due to their high content of ferrous iron in groundwater, may be well-suited for geothermal energy production using GCWs. However, it is important to investigate the hydrochemical zones in the aquifer properly and design the GCW well according to the specific requirements of the site.

Our preliminary results show that redox zones in the vicinity of newly installed GCW remain stable if groundwater is pumped in intermittent intervals. Continuous pumping over weeks changes the bacterial community of the produced water.

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