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Diagnosing Encrustation Problems in Open-loop Groundwater Heat Pump Systems in Melhus, Norway

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ABSTRACT

Groundwater in unconsolidated sediments represents a local and renewable energy resource. Utilizing the groundwater as an energy source for open-loop ground source heat pumps offers the possibility of cost-effective heating and cooling of buildings. Still the method is not utilized to its full potential. However, in the town of Melhus, Norway the method is widely used, with currently nine plants operating. All the plants have experienced incrustation problems, with iron oxides as the major incrustation product. This paper includes groundwater chemical data from seven of these plants.

The groundwater is anoxic and with a relatively low pH, leading to metal dissolution. When the water enters the system, mixing of different water qualities, contact with the atmosphere and CO_2 degassing may occur. This will lead to oxygenation and a pH increase respectively, consequently triggering oxidation leading to insoluble oxides precipitating. The possible presence of iron related bacteria catalyze oxidation. These problems may be accompanied with mechanical incrustations, caused by sedimentation of suspended solids in the groundwater. With time, these precipitations will encrust and clog parts of the system, e.g. well screens and heat exchangers, leading to a decreased water extraction and heat transfer capacity.

Results from field measurements and lab analysis of water samples in seven open loop systems in Melhus suggest that the water in the open-loop system is oversaturated with regards to iron oxides. High iron concentrations (> 3 mg/l) lead to oversaturation, despite a low dissolved oxygen content (≤ 0,05 mg/l). This matches data on incrustation type from video inspection of wells and mineralogical analysis of the incrustation material. However, data on oxygenation pathways, CO_2 degassing, microbiology and suspended solids in the systems must be retrieved to fully diagnose the incrustation problems in Melhus.

1. INTRODUCTION

Groundwater is a local, cost-effective and renewable energy resource for heating and cooling of buildings. Yet the energy resource is not much utilized (Hoekstra et al., 2016). By use of an *open-loop groundwater heat pump system* (*open-loop GWHP system*) the solar energy stored in the soil can be extracted in the wintertime, while excess heat can be stored in the soil during warmer periods. During colder periods, the open-loop system comprises, see Figure 1, water extraction from a *production well* by use of a submersible pump. The water is then lead through pipes to a *heat exchanger* connected to a *heat pump* where heat is extracted from the groundwater and temperature is lifted to a level useful for the consumer. Finally, the colder water is transported back to the groundwater reservoir through an injection well, or alternatively discharged via the local sewage system (Banks, 2012).

Despite the advantages of the open-loop system, operating the systems may be challenging. One of the challenges is the *incrustation* of the systems by various compounds initially dissolved or suspended in the water phase. This leads to *clogging* of wells, pumps, pipes and heat exchangers, and consequently a decreased water and heat extraction capacity, leading to increased operational and maintenance costs. In the study area, the town of Melhus, Norway, incrustations in the open-loop systems are of major concern, and hence the main focus of this article.

There are three major incrustation types, with various subdivisions (Bakema, 2001; Houben and Treskatis, 2007):

- Chemical incrustations, caused by changes in chemical equilibrium when groundwater is moved from the aquifer to the open-loop system, e.g.
  - Iron and manganese (hydr)oxides, caused by mixing of oxygen rich and iron/manganese rich waters in the wells or oxygenation due to leaky seals in the open-loop system, leading to iron and manganese oxidation. Iron oxidation by oxygen is described with the equation (Houben, 2004)

    $$4Fe^{2+} + O_2 + 10H_2O = 4Fe(OH)_3 + 8H^+ \quad (1)$$

    where Fe^{2+} is ferrous iron, O_2 is oxygen, H_2O is water, $Fe(OH)_3$ is ferric (hydr-)oxide and H^+ is hydron.
  - Carbonates, typically calcium or iron carbonates, precipitated due to a pH increase caused by CO_2 degassing, mediated by a temperature increase and/or pressure decrease
- Biological incrustations, caused by naturally occurring bacteria in the groundwater, e.g.
  - Iron related bacteria (IRB) gaining energy from oxidation of iron and manganese, leading to iron and manganese oxides
  - Sulfate-reducing bacteria (SRB) gaining energy from reduction of sulfate, leading to incrustation of iron sulfides
  - Slimes consisting of a variety of bacteria and their secrete, leading to biofilms/bioclogging
- Mechanical incrustations, caused by sedimentation of suspended solids, e.g.

- Sedimentation in the gravel pack outside the production well screen
- Sand production, due to improper well screen dimensions or too high entrance velocities, leading to suspended solids entering the system and sedimentation in the pumps, pipes and injection wells

Especially, the problems associated with iron and manganese incrustations are challenging. These incrustations mature and become less soluble with time, making well rehabilitations, e.g. brushing, jetting, steaming, chemicals additives, less effective. In worst case this leads to a permanent well productivity decrease and abandoning of the wells (Houben and Treskatis, 2007). Thus, incrustations should be discovered and rehabilitated at an early stage.

Incrustations are essentially detected as a decrease in specific capacity, i.e. pumping rate (l/s) divided by drawdown (m), in the wells (Bakema, 2001) and increasing pressure loss through components, e.g. heat exchangers (Bott, 1995). Consequently, monitoring flow rate and pressure at different locations in the systems may reveal incrustations problems (Gjengedal, 2019). To distinguish between chemical and mechanical incrustations, van Beek et al. (2009) suggest monitoring pressure both inside the well and in the gravel pack surrounding it. The former is associated with pressure losses in the well screen, while the latter primarily leads to losses in the gravel pack.

Furthermore, chemical analysis of the groundwater may reveal incrustation potential. Water samples analyzed for cations and anions and field measurements of pH, alkalinity (Alk), dissolved oxygen (DO), oxidation-reduction potential (ORP) and electrical conductivity (EC) can be used to determine which compounds are oversaturated and likely to precipitate (Houben and Treskatis, 2007). It may also be used to identify kinetics of e.g. iron oxidation, following the rate law (Stumm and Lee, 1961)

$$r = k\ [Fe^{2+}]\ [O_2(aq)]\ [OH^-]^2 \quad (2)$$

where r is the oxidation rate (mol/l/min), k is the rate constant ($l^3\ mol^{-3}\ min^{-1}$), $[Fe^{2+}]$ is the iron concentration (mol/l), $[O_2(aq)]$ is the dissolved oxygen concentration (mol/l) and $[OH^-]$ is the hydroxide concentration (mol/l). Equation 2, adjusted for the auto-catalytic effect of iron oxidation by iron oxides (Tamura et al., 1976), can be used to estimate rate of iron oxide incrustation in well systems (Applin and Zhao, 1989; Houben, 2004). The kinetics are affected by the presence of microorganisms, e.g. IRB bacteria. To examine the risk of microbial impact on the oxidation kinetics, a diagram indicating preferred habitat (pH, DO) of two common IRB bacteria can be utilized (Eggerichs et al., 2014). Biological Activity Reaction Tests (BART) and turbidity measurements are two alternative methods to determine microbial presence (Cullimore, 2008). Microbiological lab methods are more precise, and more costly, measures to identify bacteria. Risk and rate of mechanical incrustations can be examined by means of the Membrane Filter Index (MFI), indicating how easily the groundwater flows through a filter membrane (Buik and Willemsen, 2002).

Mineralogical analysis of incrustation material by e.g. X-Ray Diffraction (XRD) can be used to identify incrustation material and maturation (Sung and Morgan, 1980; Houben, 2003), while Scanning Electron Microscopy (SEM) can be used to visually detect iron related bacteria (Banfield and Zhang, 2001). Alternatively, the incrustations can, to some extent, be visually categorized by relatively inexpensive video inspection of the wells (Houben and Treskatis, 2007). Field observations of odor, gas bubble formation, color and suspended solids in the discharged groundwater may also give valuable information regarding potential incrustations (Bakema, 2001).

The objective of this article is to identify what can be inferred about incrustations from available data in the study area of Melhus, and what data is needed to fully diagnose this “open-loop system patient”.

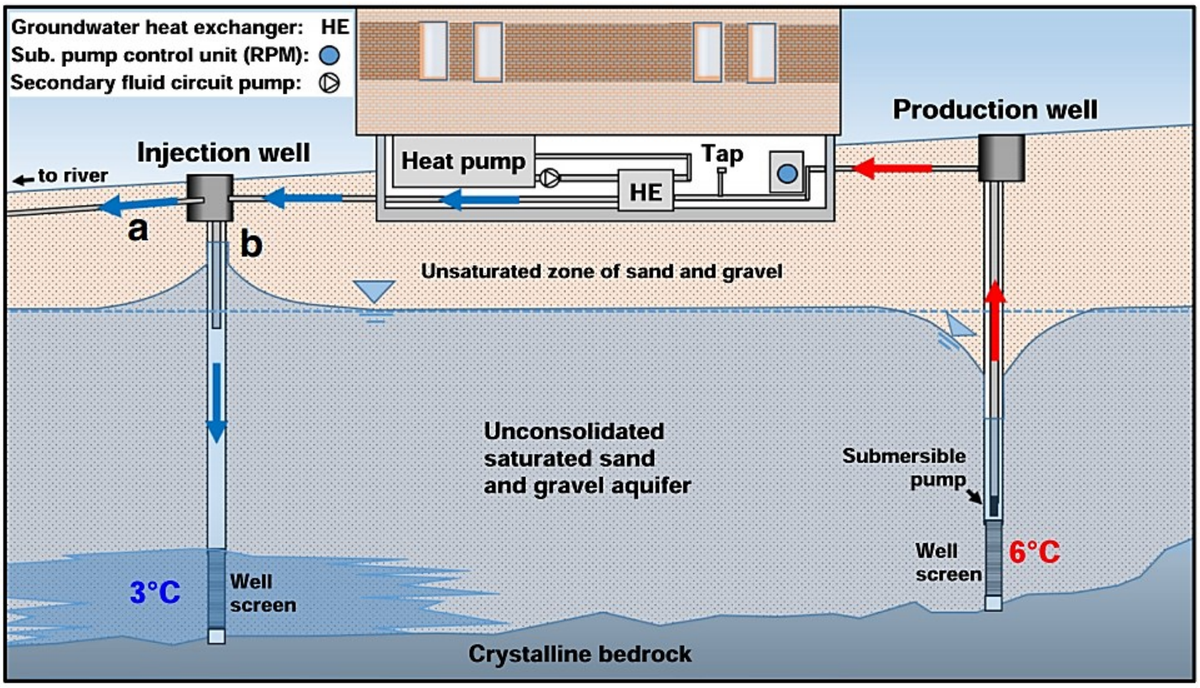

Figure 1: Typical set-up of the open-loop ground source heat pump systems in Melhus, with two configurations: a) discharge run-off to the local drainage system, and b) reinjection through an injection well (Gjengedal et al., 2019).

2. STUDY AREA

Melhus town, is located 20 km south of Trondheim, in Mid-Norway, see Figure 2. The area has favourable conditions for open-loop systems due to a thick layer of coarse glaciofluvial deposits hydraulically connected with the river Gaula (Ganerød and Ramstad, 2016). There are currently nine open-loop systems operating in the town center, supplying heating and cooling to apartments, nursing homes, schools and offices. The systems have experienced extensive iron incrustations (Riise, 2015). Partly because of these challenges, the *ORMEL project* ("*Optimal utilization of groundwater resources for heating and cooling in Melhus and Elverum*") started in 2015. As part of the project, Brøste (2017) and Gjengedal et al. (2019) have further documented the problems. A sequel of the project, ORMEL 2, was initiated in 2018, with increasing focus on iron and manganese incrustations.

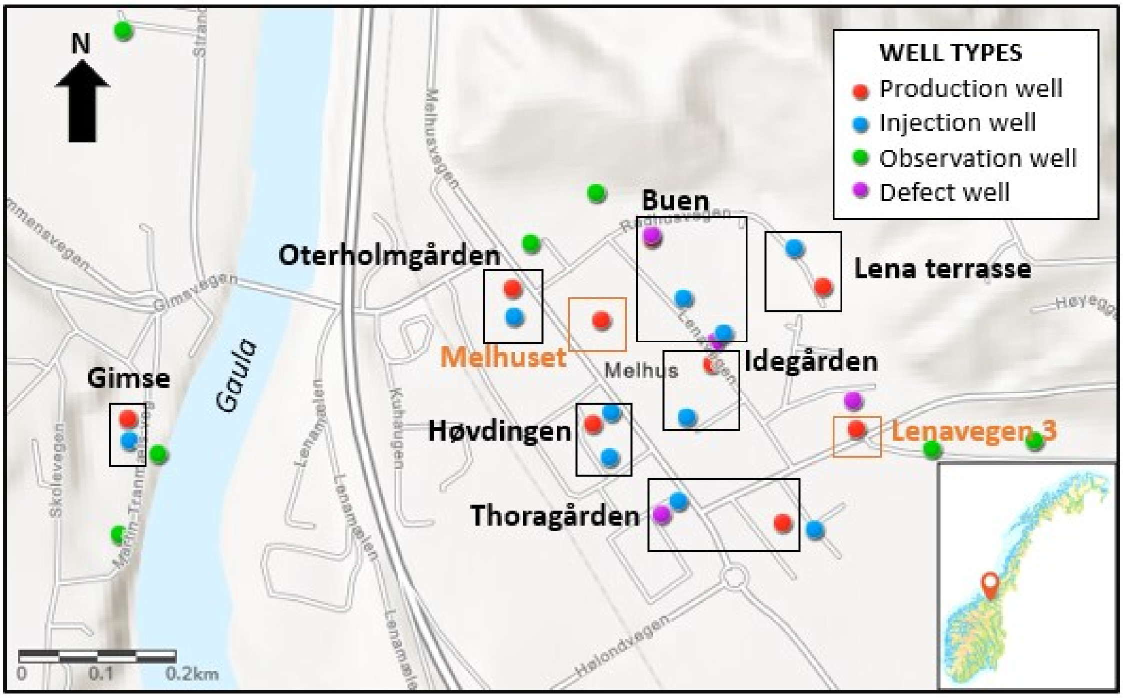

Figure 2: Map of Melhus town, with indicated location of open-loop systems with injection wells (black letters) and discharge to the local drainage system (orange letters) (Modified from Holmberg, 2018).

The open-loop systems in Melhus extract water from the same aquifer consisting of unconsolidated gravel. The thickness and depth of the gravel layer varies across Melhus (Førde, 2015). Consequently, the well dimensions in the systems differ, see Table 1. The submersible pumps of the systems are placed just above the well screen top in the production wells. Most of the plants operate at a constant pumping rate Q (except Lena terrasse), see Table 1, meaning the heat transfer in the heat exchanger is dependent on the temperature alteration. Typically, this alteration is 3-4 °C (Gjengedal et al., 2019).

Plant	Year of construction	Well depth (m)	Well screen depth (m)	Q (l/s)
Lenavegen 3	1999	p: 43	p: 39,5-43	15,5
Idegården	2008	p: 60 i: 65,5	p: 46-60 i: 56,5-65,5	6,5
Lena terrasse	2003, 2014*	p: 35 i: 36,5	p: 30-35 i: 23,9-33,9	7-17
Melhuset	1999	-	-	4
Buen	2013	p: 41,5 i1: 33 i2: 48,5	p: 33,5-41,5 i1: 31-33 i2: 40-48	8
Gimse	2009	p: 32,1 i: -	p: 17,1-32,1 i: w/o screen	6,5
Thoragården	2013	p: 86 i: 83,7	p: 72,9-77,9 i: 79,5-83	14
Høvdingen	2015	p: 69 i1: 65,5 i2: 60	p: 66-69 i1: 62-65 i2: 57-60	-
Oterholmgården	2010	p: - i: 28,9	p: - i: 25,4-28,9	-

Table 1: Basic information about construction, dimensions and operation of the open-loop systems in Melhus. Black letters indicate reinjection systems, orange letters indicate systems with discharge to local drainage system, p = production well, i = infiltration well and Q = pumping rate. * = reconstruction of open-loop system Data from (Holmberg, 2018).

2. METHODS AND MATERIALS

The encrustation problems in the nine open-loop systems operating in Melhus town has been investigated by various methods in the wells (production, injection and observation) and machinery rooms (heat exchanger rooms). This includes field measurements of water quality parameters, hereunder machinery room measurements of iron and manganese concentration with Portable colorimeter pHotoFlex Ph (WTW), visual titrimetric alkalinity with MColortest (Merck), pH with SenTix 980 sensor (WTW), dissolved oxygen with FDO 925 optical sensor (WTW), electrical conductivity with TetraCon 925/C sensor (WTW), and oxidation-reduction potential with SenTix ORP 900 (WTW). The latter four parameters were measured in a customized transparent *flow-through cell* connected to a tap in the groundwater pipes, see Figure 3. Typical tap location is indicated in Figure 1. Furthermore, field observations were noted, including incrustations material color, smell and visual observation of bubble formation and sedimentation in flow-through cell. Water samples were taken from the earlier mentioned taps. Later, they were analyzed for cations and anions by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Ion Chromatography in the chemical lab of the Department of Chemistry (NTNU). Video inspection of wells to determine extent and type of encrustations were also part of the investigations. To distinguish incrustation types, XRD and SEM analysis of the encrustation material from pipes and heat exchangers were conducted in the mineralogical lab of the Department of Geoscience and Petroleum (NTNU). Groundwater flow rate in the pipes measured by mechanical and ultrasonic, PTFM 1.0 (Greyline Instruments), flow meters were available from janitor logs and unpublished material by Sondre Gjengedal, PhD candidate at NTNU. Drawdown in the systems measured by manometers and Divers (van Essen instruments) were also retrieved, in addition to rehabilitation and reconstruction intervals.

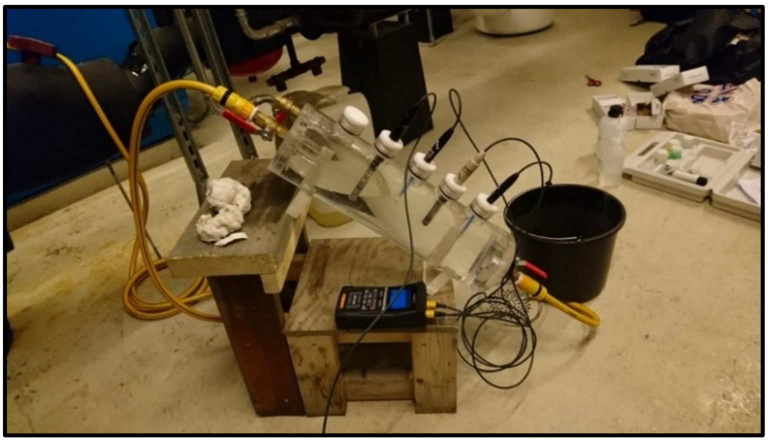

Figure 3: Flow-through cell operated in a machinery room of an open-loop system in Melhus. The groundwater is led from a tap in the groundwater pipe, see Figure 1, and through the cell where pH, dissolved oxygen, electrical conductivity and oxidation-reduction potential is measured.

3. RESULTS

The most significant data collected from seven of the open-loop systems is displayed in Table 2.

Plant	Fe (mg/l)	Mn (mg/l)	NO3 (mg/l)	pH	Alk (mmol/l)	DO (mg/l)	EC (µS/cm)	T (°C)	Field observations	Incrustation type	Rehab-ilitation(s)
Lenavegen 3	3,56	0,53	0	7,3	4,7	0,04	2900	8,1	Sediments Gas bubbles	Iron oxide (?)	2013
Idegården	3,18	0,57	0	7,3	5,0	0,04	2450	9	-	-	2018
Lena terrasse	3,42	0,64	0	7,1	5,4	0,05	1716	5,2*	Gas bubbles	Iron oxide, Iron carbonate	2006, 2018, 2019
Melhuset	0,94	0,21	0	7,4	3,7	0,03	1582	8,1	-	Iron oxide	2014
Buen	3,43	0,61	0	7,2	5,1	0,03	2420	7,8*	Sediments	Mechanical, Manganese	2018
Gimse	1,40	0,14	0	7,2	3,3	0,03	533	5,8	Sediments	Iron oxide (?)	2018
Thoragården	0,20	0,03	0	8,1	5,0	0,03	3680	8,9	Sediments	Iron oxide	2014
Reference	*1)*	*1)*		*1)*	*1)*	*1)*	*1)*	*1)*	*1)*	*2,3,4)*	*2,3)*

Table 2: Selected data from seven open-loop plants in Melhus. Fe = iron concentration, Mn = manganese concentration, Alk = alkalinity, DO = dissolved oxygen concentration, EC = electrical conductivity, T = water temperature (before and *after heat exchanger). Incrustation type is determined from XRD, field observations and video inspection. Data from 1) investigations by main author (May-June 2019), 2) Riise (2015), 3) Sondre Gjengedal and 4) Brøste (2017).

4. ANALYSIS

According to Jurgens et al. (2009) the groundwater in the open-loop systems can be classified as anoxic (< 0,5 mg/l dissolved oxygen), with iron or sulfate reduction as the governing redox process. However, geochemical modelling with PHREEQC (Parkhurst and Appelo, 1999) shows that all the open-loop systems are oversaturated with respect to iron oxides (goethite, ferrihydrite and hematite) and iron carbonates (siderite), due to the high iron content. Some of the systems are also oversaturated with calcium and manganese carbonates. Accordingly, iron oxide incrustations can be expected in all the seven plants. This matches the data on incrustation types in the systems, see Table 2.

Eggerichs et al.'s (2014) diagram, see Figure 4a, displays oxidation rate kinetics at various dissolved oxygen concentrations and pH values based on experiments with purely chemical oxidation, and oxidation mediated by two of the most common iron related bacteria, *Gallionella* and *Leptothrix*. The plot of Melhus data in this diagram illustrates that the oxidation rates are expected to be small, except for in Thoragården. However, this diagram does not consider the high iron concentration, which based on Equation 2 will influence the kinetics; higher concentrations lead to faster kinetics.

As an initial assumption, the rate constant *k* is the same for all the open-loop systems. Based on literature it is assumed to be $1{,}2*10^{-16}$ (Davison and Seed, 1983, in Houben, 2004). The oxidation rates for the plants were then calculated from data in Table 2 inserted in Equation 2 and plotted against rehabilitation intervals (in million liters discharged water) based on average pumping rates Q and year of construction (see Table 1) and rehabilitations (see Table 2). The results are shown in Figure 4b and indicate an insignificant correlation between oxidation rate and rehabilitation interval. A reasonable assumption would be that there is a significant correlation between the two parameters. However, there are no convention on when to rehabilitate the plants in Melhus, e.g. percentage decrease in specific capacity. Thus, the rehabilitation intervals may not be a good indicator for how fast the capacity of the wells decrease.

Furthermore, field observations of sediments in the flow-through cell and gas bubble formation, may indicate mechanical incrustations and degassing respectively, but must be studied more thoroughly to be further described.

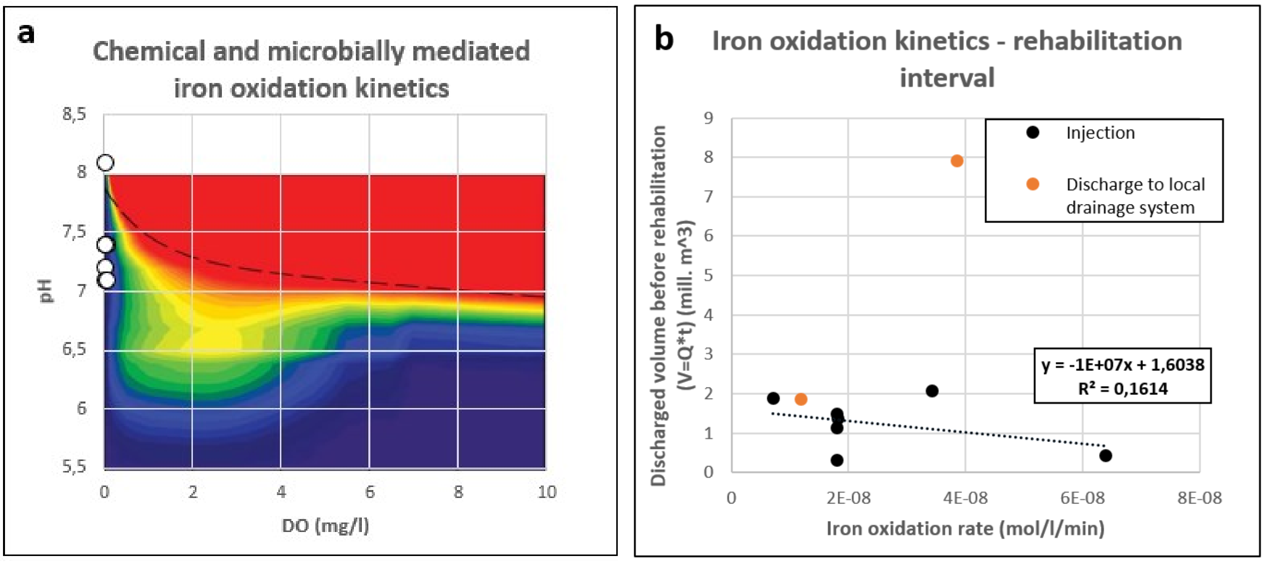

Figure 4: a) Chemical and microbially mediated iron oxidation kinetics. Red color = fast oxidation rate, blue = slow oxidation rate (not available data for pH > 8). White dots indicate measurements from Melhus (Modified from Eggerichs et al., 2014), b) Iron oxidation rate calculated for all plants with Equation 2 plotted against estimated rehabilitation interval (volume water pumped through system). The regression line is based on black dots (systems with injection wells).

4.1 What data are missing?

Analysis of the data indicate iron oxidation as the major incrustation problem. However, what causes this problem is yet not clear. Mixing of anoxic and oxic groundwater in the production wells is reported as a trigger for iron oxide incrustations (Bakema, 2001; Houben & Treskatis, 2007, van Beek et al., 2009). Due to the cone of depression around a pumped well, shallow oxic water may mix with deep anoxic water, if the well screen draws water from both sides of the oxic-anoxic horizon. Water chemical measurements in the machinery room can't distinguish between oxygen content derived from e.g. leaky seals or mixing in the well screen. *Diffusive Gradients in Thin films* (*DGT*), which is an in-situ method for measuring aqueous species concentration by use of diffusion through a thin film (Zhang and Davison, 1995), is a possible method to diagnose mixing problems. An example of deployment in groundwater wells is shown in Figure 5. Measuring iron concentrations vs. depth with a DGT array, while pumping from the same well, may reveal variations in iron concentrations with depth. This provides evidence to whether the well draws both oxic and anoxic water, and consequently evaluates the risk of mixing.

Alternatively, CO_2 degassing in the systems, leading to a pH increase may also cause iron oxidation. In addition, the pH has a much more pronounced effect on the oxidation kinetics than the oxygen content, see Equation 2. Therefore, it is an important parameter in iron oxidation. Investigating the CO_2 degassing requires continued measurements of pH and alkalinity, combined with data on pumping rate, pressure and temperature at various locations in the systems. Monitoring equipment and methods as described in

Gjengedal et al. (2019) would be able to monitor system performance as well as giving valuable data for degassing interpretation. On the other hand, the locations of the water taps in the machinery rooms are either placed on top, on the side or underneath the pipes. This may influence degassing detection with the flow-through cell.

Microbiological investigations are not yet carried out in Melhus. The most viable methods of investigations are BART tests, visual inspection of SEM photos and turbidity measurements. The turbidity measurements may also indicate the risk of mechanical incrustations. Also, a Membrane Filter Index (MFI) procedure as described by Buik and Willemsen (2002) is an option to detect the latter incrustations type. van Beek et al.'s (2009) method to distinguish between chemical mixing and mechanical incrustation problems seems too costly as it involves the drilling of observation wells in the gravels packs of the pumping wells.

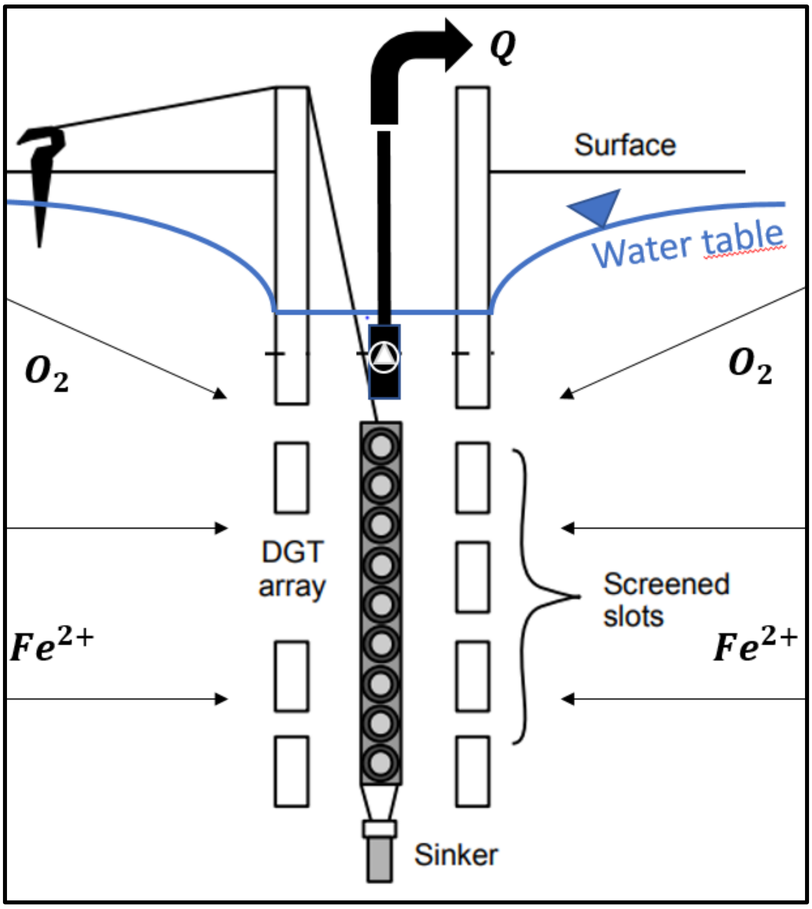

Figure 5: Principle of deploying Diffusive Gradients in Thin films (DGT) in groundwater wells. Every circle on the DGT array represents a unique measurement (Modified from Lucas, 2013).

5. CONCLUSIONS

The preliminary conclusions are:

- Small amounts of oxygen (≤ 0,05 mg/l) are enough to oxidize iron in the study area, but the oxidation trigger is yet unclear
- There is not enough evidence to reject the hypothesis that the iron oxidation is mediated by microbial activity
- Mechanical incrustations have occurred in the systems, but the mechanical incrustation potential of the groundwater is yet to be investigated
- The many types of problems, and their interrelation, make diagnosis of incrustation problems and potential difficult

Based on these conclusions the research focus will be continued measurement of water chemical parameters at regular intervals, investigating the possibility to use DGT to examine mixing risk in the production wells, kinetic experiments to further understand iron oxidation kinetics, investigate CO_2 degassing from pH, alkalinity and pressure measurements, and test methods to determine microbial presence and mechanical incrustation risk.

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