Chapter 7

Summary and synthesis
7.1 Introduction

In this chapter I will summarize the outcomes of this PhD thesis and discuss what these can mean for drinking water production. Next, guidelines for water quality monitoring at shallow geothermal energy (SGE) systems will be proposed. Following this, the current policy for SGE systems in relation to groundwater protection will be reflected upon, and a suggestion is made which type of systems could be allowed in which environments without compromising the usability of groundwater as a resource for drinking water production. Last, the perspectives for future research based on the outcomes of this thesis will be given.

7.2 Summary of thesis research

Chapter 2: Shallow geothermal energy: A review of impacts on groundwater quality and policy in the Netherlands and European Union

In chapter 2, a review is presented on the effects that SGE systems can impose on groundwater quality and the risks this can pose for drinking water production. Four categories of effects by SGE on groundwater quality were distinguished: 1) hydrological, 2) thermal, 3) chemical, and 4) microbial impacts. This thesis focuses on the latter two. A literature survey on the chemical and microbial effects of SGE showed that most published research on SGE technology focused on operational aspects such as well clogging and thermal efficiency, whereas the impacts on water quality in relation to other users, notably drinking water production, has been limited addressed in research. Particular gaps in knowledge exist on: i) the effect of low temperature SGE systems (<25ºC) based on field data, ii) the fate of trace metals at elevated temperatures in SGE systems, and iii) the impact of temperature changes on the microbial communities, redox processes, and hydrochemistry.

The policy survey presented in this chapter showed that regulation and research on the potential impacts of SGE on groundwater resources in many countries lags behind technological developments and the rate of deployment of this renewable energy source. This situation has improved in the Netherlands with the establishment of the Order in Council (AMvB) on SGE as of July 2013. The lack of a clear and scientifically underpinned risk management strategy implies that potentially unwanted risks might currently be taken at vulnerable locations such as near public supply well fields, whilst at other sites the application of SGE is avoided without proper reasons. Cross-sectoral subsurface planning is required to minimize negative conflicts between SGE and other subsurface interests.

Chapter 3: A field and modeling study of the impacts of aquifer thermal energy storage on groundwater quality.

In chapter 3 data from an aquifer thermal energy storage (ATES) system located 570 m from a public supply well field were used to investigate the impacts on groundwater quality. These data showed that groundwater circulation by the ATES system influenced groundwater quality.
by introducing shallow groundwater with a different chemical composition at greater depth, and vice versa. Numerical groundwater flow and solute transport modeling confirmed that this physical mixing process can explain the observed changes in groundwater quality. Because a large fraction of the water injected in the ATES wells in one season drifted away before it could be recovered in the next, it was not possible to analyze the effect of the temperature change on groundwater quality. This was the main reason to add laboratory experiments to this research.

Microbiological data showed that groundwater sampled from the ATES system contained bacteria that with standard culture tests are characterized as fecal indicator bacteria. Molecular identification however showed that most of these organisms were not related to a fecal contamination and possibly naturally present in the aquifer. Two samples contained the fecal bacteria *C. perfringens* but its presence was not linked to ATES operation and may be a relic of well construction. The presence of *C. perfringens* did not form a hygienic risk because of the sufficient travel time between the ATES wells and the public supply well field.

**Chapter 4: Temperature-induced impacts on mobility of arsenic and other trace elements**

In chapter 4, a laboratory column testing setup was used to assess the impacts of temperature on water quality at 5°C (cold storage), 11 °C (ambient temperature), 25 °C (maximum allowed regular SGE), and 60 °C (high temperature heat storage). Column tests were performed on anoxic, reactive, unconsolidated sandy sediments cored from a fluvial aquifer (Sterksel formation). This formation is widely used for drinking water production and SGE in the Netherlands.

The results showed that at 5°C no effects on water quality were observed compared to the reference of 11°C (in situ temperature). At 25°C, As concentrations were significantly increased and at 60°C, significant increases were observed in dissolved organic carbon (DOC), P, K, Si, As, Mo, V, B, and F concentrations. These elements should therefore be included in water quality monitoring programs of SGE projects. No consistent temperature effects were observed for Ba, Co, Cu, Ni, Pb, Zn, Eu, Ho, Sb, Sc, Yb, Ga, La, and Th, all of which were present in the sediment. The temperature-induced chemical effects were hypothesized to be caused by (incongruent) dissolution of silicate minerals (K and Si), desorption from, and potentially reductive dissolution of, iron oxides (As, B, Mo, V, and possibly P and DOC), and mineralization of sedimentary organic matter (DOC and P).

**Chapter 5: Temperature-induced impacts on redox processes and microbial communities**

Next, the column setup was used in chapter 5 to investigate the impacts on redox processes and the associated microbial community. Both hydrochemical and molecular data showed that a temperature increase from 11°C (in-situ) to 25°C caused a shift from iron-reducing to sulfate-reducing and methanogenic conditions. A thermodynamic analysis showed that the shift from iron- to sulfate-reducing conditions can be explained by a shift in microbial competition, with sulfate reducers becoming more efficient at utilizing substrates than iron reducers.
A further temperature increase (>45ºC) resulted in the emergence of a thermophilic microbial community capable of fermentation and sulfate-reduction, but not of iron-reduction and methanogenesis. Two distinct maxima, of similar order of magnitude (5x10^{-10} M s^{-1}), were observed in sulfate-reduction rates at 40ºC and 70ºC. Thermophilic sulfate reduction, however, had a higher activation energy (100-160 kJ mol^{-1}) than mesophilic sulfate reduction (30-60 kJ mol^{-1}), which is probably due to a trade-off between enzyme stability and activity with thermostable enzymes being less efficient catalysts requiring higher activation energies. These results reveal that, while sulfate reducing functionality can withstand a substantial temperature rise, other key biochemical processes appear more sensitive to a temperature change.

Chapter 6: Reactive hydrochemical modeling to explain and quantify impacts of shallow geothermal energy on groundwater quality.

In chapter 6, the data collected with the laboratory column experiments were used to develop and calibrate a hydrogeochemical reactive transport model (PHREEQC) simulating the thermally induced water quality changes. The model included temperature-dependent surface complexation and cation-exchange, dissolution of K-feldspar, and mineralization of organic matter via sulfate-reduction, and methanogenesis. Optimization results combined with literature data revealed that surface complexation of (oxy)anions is consistently exothermic and their sorption decreases with temperature, whereas surface complexation of cations is endothermic and cation sorption increases with temperature.

The calibrated model was applied to simulate arsenic and boron mobility in several hypothetical aquifer thermal energy storage systems using a simple yet powerful mirrored axi-symmetrical grid. Results showed the system mobilizes arsenic and boron towards the fringe of the warm water plume and the center of the cold water plume where these solutes become resorbed. This transient re-distribution of trace metals causes their aqueous concentrations in the cold and warm groundwater plumes to gradually approach similar elevated levels, with a final concentration depending on the average temperature over the warm and cold groundwater zones.

7.3 Translating hydrochemical effects to impacts on drinking water production

After having summarizing the principal hydrochemical effects, the next step is to discuss what these could imply for drinking water production. The first process discussed is the physical mixing of different water qualities by an ATES system changing the natural water quality zoning in the aquifer, re-distributing electron acceptors and potentially impacting on local redox conditions (chapter 3). The effect of these processes on a drinking water pumping station depend on (the depth distribution of) the aquifer's reactivity and buffering capacity, and the well screen depth of both the pumping station and ATES system. In a worst case scenario a contaminant is brought to greater depth where sediment has a relatively high conductivity and low chemical buffering
capacity. This could cause a contaminant to reach a pumping station faster and at higher concentrations. In a best case scenario, the pumping station has a well screen setting causing it already to have problems with the contaminant and the ATES system causes a dilution of the contaminant to levels below maximum allowable concentrations. Because the effects of ATES-induced mixing in the capture zone of a pumping station are likely in many cases unknown, and often highly uncertain, the establishment of ATES near a public water supply station will often interfere with the precautionary principle applied in groundwater protection zones. A complicating factor to assessing the impacts of ATES induced mixing is that the groundwater quality depth profile itself is a transient feature (Broers and van der Grift 2004) resulting in a transient water quality at pumping stations (Mendizabal et al. 2012). And although the concentrations of some contaminants such as nitrate may be decreasing over recent years (Visser et al. 2007) the occurrence of others like pharmaceuticals may be increasing (Bound and Voulvoulis 2005).

In chapter 4, various species were shown to be increasingly mobile under elevated temperatures. Because most SGE systems operate at temperatures up to around 16°C, far below the maximum allowed temperature of 25°C (which was also used in our experiments), effects will be smaller for most systems. The results of surface complexation modeling combined with data from the literature (chapter 6) suggest that sorption of (oxy)anion forming species (arsenic, boron, carbonate, phosphate, silica) is consistently exothermic and decreases with temperature, but cation sorption is endothermic (calcium, magnesium, heavy metals) and increases with temperature. This implies that for typical heavy metals, an opposite effect may be expected compared to arsenic and that their mobility decreases with temperature which was to a certain extent confirmed by chapter 6, as sediments containing heavy metals such as lead and zinc, did not leach these elements upon a temperature increase.

A complicating factor, however, is that the combination of temperature induced desorption with mixing of groundwater by ATES, can result in mobilization of As (or other anionic trace elements) to parts of the aquifer layers with a lower sorption capacity resulting in a net shift of arsenic from the sorbed to aqueous phase. In the Netherlands, several public supply well fields abstract raw water with As concentrations above the maximum permissible concentration of drinking water (10 \text{ug L}^{-1}). These levels (up to 70 \text{ug L}^{-1}) are in general easily removed through rapid sand filtration thanks to accompanying high Fe\textsuperscript{2+} concentrations (Stuyfzand et al. 2006). When however arsenic desorbs due to a temperature increase, the Fe\textsuperscript{2+} concentration will not increase along with it, unless reductive dissolution of iron oxides occurs as well. This combined behavior was shown in chapter 5, but occurred only at the lower temperatures for one of the sediments tested. If iron-reduction occurs concomitantly with sulfate-reduction, precipitation of iron-sulfides may also sequester arsenic that is thermally desorbed. The combination of stable iron oxides and thermally desorbing arsenic is thus possibly more problematic, and could necessitate an additional treatment step, for example, coagulation with FeCl\textsubscript{3} (Hering et al. 1997). For heavy metals, the effect could again be the opposite, leading to an increase in net sorption in the aquifer and an improvement in water quality.
A second water quality parameter observed to increase with temperature, was the DOC concentration. This can cause color problems in drinking water which may necessitate a discoloration treatment step (such as oxidation) of the water abstracted (Wallage et al. 2006). An advanced oxidation step can however cause problems with toxic disinfection by-products (Von Gunten 2003). An important notion that was inferred in chapter 5 and also observed elsewhere (Evans et al. 2005, Xu and Saiers 2010) is, that DOC mobilized at higher temperatures is relatively recalcitrant and thus less easily removed in water treatment. On the up-side, it is also less likely to cause well clogging in SGE systems. A final relevant aspect to the increasing DOC concentrations is that humic substances constituting the bulk of DOC can form complexes with trace elements, causing them to remain mobile and not to become resorbed with decreasing temperature outside the direct zone of influence of the ATES system (Cao et al. 1995).

The increasing mineralization rate of sedimentary organic matter (SOM) at temperatures > 25°C is likely to lead to a reduction of the buffering capacity of the aquifer. SOM is particularly important for the sorption and retardation of hydrophobic organic micro-pollutants (Appelo and Postma 2005). The associated promotion of sulfate-reduction following the fermentation of SOM described in chapter 5 however, can lead to the formation of iron sulfides, which sequester thermally mobilized anionic trace elements. This has a positive impact on groundwater quality (and is in fact also used for remediation of groundwater with high arsenic concentrations (Beaulieu and Ramirez 2013).

### 7.4 Groundwater quality monitoring near SGE systems

A next step is to derive meaningful monitoring requirements for those locations where SGE systems are planned at some distance from sites where groundwater is extracted for other uses. Table 7-1 provides a comprehensive proposal for monitoring at these sites, and provides a key to the relevant processes and sections in this thesis which address them. Also shown is a number of monitoring parameters, required for operational aspects to complete this overview. A site dependent selection can be made from this table, based on vulnerability of other groundwater uses and anticipated relevant processes.

The monitoring locations can be a filter set in the annulus of the ATES well, a tap point of the ATES wells, or a dedicated monitoring well located at some distance from the ATES well or BTES borehole. Note that for ATES systems, it is important to have a good understanding of the dynamics of the systems. Common monitoring pitfalls are:

- When monitoring water quality at the ‘warm’ well at the end of summer, one may expect to sample the maximum effect of heat storage. The warm well at the end of summer however contains recently injected water from the cold well, and if there is some bell drift in the cold bubble, it will contain groundwater hardly influenced by ATES. Timing of sampling events of groundwater in the ATES well, should thus be based on the warm or cold water bubble size, the velocity of bell drift, and the flow through the system.
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- The redistribution of trace elements in an ATES system and resorption should be considered when monitoring for these solutes. Modeling in chapter 6 showed that with progressing cycles, concentrations in cold and warm wells will become similar and a reference well outside the zone of influence should be used to determine the net effect of the system.

- Locations of monitoring wells are often based on the anticipated design circulation volume of the ATES system which are often much smaller than actual volumes. This causes monitoring wells to be situated outside the zone of influence.

- ATES system temperature readings should be used with caution as sensors may be located above ground. The best method is to take a submersible temperature sensor and take readings at the depth of the filter from where the groundwater sample is taken.

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Table 7-1  Groundwater quality monitoring guidelines for SGE systems

<table>
<thead>
<tr>
<th>Group</th>
<th>Parameter</th>
<th>Reason and further reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field parameters</td>
<td>pH, Electrical conductivity, temperature (down hole), dissolved oxygen (DO)</td>
<td>Monitor mixing of different water qualities and thermal impacts (chapter 3).</td>
</tr>
<tr>
<td>Macro parameters</td>
<td>Cl, SO$_4$, alkalinity, NO$_3$, NH$_4$, Ca, Mg, Na, K</td>
<td>Quality assurance of analyses (electrical balance, also used for many other aspects discussed below).</td>
</tr>
<tr>
<td>(toxic) trace elements</td>
<td>As, Mo, V, B, Cr, Be and F or a complete ICP-MS scan</td>
<td>Mobilization due to desorption or reductive dissolution (chapter 4).</td>
</tr>
<tr>
<td>Redox parameters</td>
<td>Fe, SO$_4$, NO$_3$, NH$_4$, CH$_4$, DOC, PO$_4$</td>
<td>Monitor changing redox processes (chapter 5).</td>
</tr>
<tr>
<td>Contaminants present in ATES influence area</td>
<td>Depends on type of contaminants present. Broad standard packages can be used such PAH, BTEX, VOCl$^a$</td>
<td>Monitor spreading of contaminants by increased flow velocities (briefly discussed in chapter 2, and Zuurbier et al. (2013b))</td>
</tr>
<tr>
<td>Pathogens</td>
<td>E-coli + molecular confirmation</td>
<td>Assure system is not open to microbial contamination</td>
</tr>
</tbody>
</table>

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Operational aspects

- Carbonate scaling: Ca, Mg, alkalinity, pH, temp, Fe, DOC
  - Prevent precipitation of carbonates (T>30°C) (Griffioen and Appelo (1993))

- Iron precipitation: Fe, Mn, pH, temp, DO and NO$_3$
  - Prevent iron precipitation (Houben and Trestakis (2007))

- Iron sulphides scaling: Fe, SO$_4$, pH, HS$^-$
  - Prevent iron sulfide scaling due to SO$_4$ reducing conditions (briefly discussed in chapter 5, see also (Brons 1992))

- Gas pressure: Partial pressures of CH$_4$, N$_2$, CO$_2$
  - Prevent degassing and gas bubble clogging or intrusion of oxygen

- Corrosion: SO$_4$, Cl
  - Prevent anaerobic corrosion (briefly discussed in chapter 5, see (Brons 1992, Lerm et al. 2013))

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$a$: PAH: polycyclic aromatic hydrocarbons, BTEX: benzene toluene ethylbenzene and xylene, VOCl: Volatile Chlorinated Organic Compounds
7.5 Policy perspectives

With the recently introduced legislation on shallow geothermal energy (the Order in Council on shallow geothermal energy, here abbreviated as the AMvB, corresponding to the generally used Dutch abbreviation), a new legal framework is introduced in the Netherlands as of July 2013. The rules for groundwater protection zones are not addressed in this AMvB and remain secured under the national Environment protection act (abbreviated under the generally used term Wm). The Wm directs provincial authorities to define groundwater protection areas in which rules apply to protect groundwater quality for drinking water production.

An improvement for groundwater protection in a broader sense (so outside groundwater protection zones) with the introduction of the AMvB SGE, is that both closed and open loop systems are now required to be registered with the authorities (respectively municipalities and provinces). Furthermore, a training and certification system is established to educate drilling companies aiming to assure high quality work be delivered which also strengthens groundwater protection, for example by strictly following guidelines on resealing of perforated aquitards. Regulatory enforcement by the responsible authorities will be required to secure that these protocols are followed. The effort required to get the permit for an ATES system has decreased as the previously required, extensive impact assessment report is no longer required and the processing time has decreased from >6 months to 8 weeks. In many areas in the Netherlands (especially the west), ATES systems are realized in deep saline aquifers where historically no other users are present, justifying this less restrictive legislation. A complicating factor here is however that the horticultural sector in this area is increasingly using the subsurface for storage of fresh water (Zuurbier et al. 2013a). This highlights the need to broaden policies dealing with the subsurface balancing interests of all subsurface users as discussed in chapter 2.

An important aspect of the new SGE legislative framework is that it explicitly gives local authorities the possibility for allowing higher maximum re-injection temperatures than the default threshold levels of 25°C and 30°C for open and closed loop systems, respectively. Also, the provincial authorities can decide on whether SGE could be allowed in groundwater protection zones. The possibility of higher temperatures was already present in previous legislation (the Water Act), but the AMvB specifically states that a temperature above the ‘default’ maximum injection temperature is allowed and can result in higher efficiencies of systems and many provinces are now investigating how and where to allow high temperature heat storage (e.g. the province of Gelderland as discussed in Zaadnoordijk et al. (2013)). The decision on whether SGE could be allowed within groundwater protection zones also basically remains with the provincial authorities who regulate groundwater protection zones. It is noted that there is not a strict prohibition of SGE within protection zones (which already led to a number of ATES systems in groundwater protection zones shown in Figure 1-3). On the basis of the results of this thesis, a suggestion is made how these rules could be interpreted for different groundwater regions in the Netherlands (Table 7-2).
In regions where restrictions apply for drinking water protection (region I and II, Table 7-2),
the precautionary principle should generally prevail. Only in extraordinary cases an SGE system
should be feasible. An example could be a planned closure of a pumping station, or if the benefits
of allowing SGE are such that it would compensate for potential adverse effects for the water
supply. It is unlikely that the benefits of an individual SGE system (for a building or group of
buildings) could outweigh the interest of water supply of a city or region. So this option could
only be feasible in a regional context where heat and water supply are considered together.

Under the current rules, SGE systems can be established outside the protection zone, which
can still be part of the capture zone of a PSWF (region III). In these cases, it would be desirable to
have a proper impact assessment. Currently, applications for SGE systems are handled whenever
a license application arrives at the regulating authority. And given the shortened handling times
for license approvals, it may be become hard to carry out a proper impact assessment. A more
thorough risk assessment in the capture zones may be possible if an ex ante evaluation of the
impacts of SGE in the capture zone are combined with the broader water quality risk assessment
carried out for the so-called protected area dossier (Gebiedsdossiers), a tool resulting from the
EU Water Framework directive for protection of drinking water resources. Currently, this dossier
mainly focuses on water quality threats from land surface (fertilizers, pesticides, sewers and point
or diffuse pollution plumes).

The application of higher temperature SGE seems only warranted in deep saline aquifers
(region VI). Saline aquifers do not provide groundwater that can easily be used for drinking water
production, at least not using a ‘basic water treatment’, as described in the EU Water Framework
directive. It is noted that the definition of a ‘basic’ water treatment differs regionally and by source
water, but for groundwater aeration, rapid sand filtration and, if required, a disinfection step
can be considered as basic steps (Wuijts and Rijswick 2007). Shallow saline groundwater bodies
(zone V) are less suitable as the impacts of higher temperature SGE can more easily dissipate into
surface waters, and thus form a risk for aquatic ecology and recreational use of these waters.
Table 7-2 Policy on SGE in the Netherlands: current situation and perspectives for refinements

<table>
<thead>
<tr>
<th>Region</th>
<th>Current relevant legislation following from the AMvB and Wm</th>
<th>Suggested policy interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Groundwater abstraction region (generally 60 day zone)</td>
<td>Generally not allowed (often in ownership of water utility) (enforced under the Environmental protection act)</td>
<td>Precautionary principle prevails.</td>
</tr>
<tr>
<td>II. Groundwater protection zone (generally 25 year travel zone)</td>
<td>Generally not allowed (enforced under the Environmental protection act)</td>
<td>Precautionary principle prevails. Possible exceptions are well fields that are to be closed.</td>
</tr>
<tr>
<td>III. Capture zone, but outside protection zone</td>
<td>&lt;25°C re-injection temperature (open systems) and &lt;30°C for the circulation fluids (closed systems)</td>
<td>Authority may consult water utility or other consumptive water users. In case of vulnerable well fields, the water utility could protest against approval of the SGE system or could suggest it to operate at a reduced temperature regime.</td>
</tr>
<tr>
<td>IV. Other fresh groundwater bodies</td>
<td>Higher temperatures can be possible when this does not interfere with other uses. A heat balance is required (net cooling is sometimes allowed)</td>
<td>The requirements in the AMvB SGE are sufficient to address possible interferences with other groundwater users. High temperature heat storage is not advisable as temperature effects can propagate into surface water bodies. In these groundwater bodies high temperature heat storage could be allowed provided it does not increase the temperature in adjacent fresh aquifers.</td>
</tr>
<tr>
<td>V. Shallow saline groundwater bodies</td>
<td></td>
<td></td>
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<tr>
<td>VI. Deep saline groundwater bodies</td>
<td></td>
<td></td>
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</tbody>
</table>
7.6 Research perspectives

The last part of this thesis provides a short overview of relevant new research perspectives that follow from the results of this thesis:

- The strong temperature dependence of arsenic (and other oxyanions) mobility, also in the range up to 25°C, is important to consider especially when SGE is realized in aquifers used for drinking water production. A crucial next step is to validate the results of this study in field SGE systems (operating at 25°C or higher) in the Sterksel formation and to investigate the potential arsenic mobilization in other geological formations. It would be good to derive a more generic relationship between the geochemical reactivity of the Dutch geological formations (Gaans et al. 2011 and Griffioen et al. 2012) and the response of these to temperature increases. This would allow an efficient scaling up of the results found here, and facilitate an effective monitoring in sensitive areas.

- In this thesis, I have described the mixing effect that an ATES may have on the distribution of electron acceptors and redox processes in an aquifer on the one hand, and the thermal effects on trace element mobility and redox processes the other. I have described the combination of these two processes qualitatively in several chapters, but investigating this interaction in a more quantitative way is required to get a more thorough understanding of the impacts of ATES on groundwater quality. This could be achieved by detailed field monitoring, especially at some of the high temperature heat storage systems that are to be realized in the coming years, combined with reactive transport modeling. The reactive transport modeling framework presented in chapter 6 can provide a good starting point for this, but up-scaling to a full 3D model is required to assess the cumulative effects on downstream groundwater quality and impacts to other groundwater uses.

- The temperature dependence of sorption might also provide opportunities to optimize in- or ex-situ arsenic remediation systems. Arsenic is a common issue in aquifer storage and recovery (ASR) systems, where oxidation of pyrite causes the mobilization of arsenic (Wallis et al. 2011, Mirecki et al. 2012). During the storage phase of ASR, the arsenic concentration in the ASR injected water bubble is controlled by the equilibrium with arsenic sorbed to neo-formed iron hydroxides (Wallis et al. 2011). Combining heat storage with ASR could be a method of accelerating the removal of sorbed arsenic following pyrite oxidation and pre-conditioning the aquifer for storage of raw or drinking water. Cold water (having a relatively high dissolved oxygen concentration) effectively oxidizes pyrite releasing arsenic which is sorbed to neo-formed iron hydroxides. In the next season relatively warm water is injected which flushes arsenic from the sorbent. This causes an initial rapid flush with arsenic (which may be treated or disposed of), and not a long tail of elevated arsenic concentrations.

- Given the explicit policy freedom for high temperature heat storage, aiming to boost application of this technology, a wider understanding of the dynamics of thermophilic
sulfate reducing bacterial communities should be developed. It was shown in this thesis that these communities can develop in Dutch sediments, and in Germany Lerm et al. (2013) demonstrated that these can cause damage to these systems by anaerobic corrosion.