Assessing the quantitative potential of seasonal aquifer thermal energy storage and recovery in the Brussels-Capital Region using combined 3D- groundwater flow, heat and reactive transport modelling

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ABSTRACT

In an evolving energy system it is important that urbanized areas contribute to their own energy demands. The availability of renewable energy sources often does not coincide with demand and production. An attractive manner to store energy is to facilitate urban aquifers for seasonal aquifer thermal energy storage and recovery (ATES). ATES can improve environmental quality in urban areas and decrease primary energy consumption In this study, we investigate the potential of ATES for the Brussels Sand Formation, a phreatic aquifer up to 70 m thick located in the Brussels-Capital Region, Belgium. Distributed groundwater flow and heat transport models are applied on representative pilot sites to quantify the potential of ATES. The process of well clogging by iron hydroxide precipitation, which can be an important problem in ATES operation is addressed with reactive transport models. Distributed models can provide feasibility maps, which help to establish guidelines for future subsurface planning in an urban area. Different model scenarios show that only for low hydraulic conductivities of $4.2e^{-6}$ ms^{-1} that the hydraulic and thermal output is insufficient for ATES systems. For a high hydraulic conductivity scenario ($1.4e^{-4}$ ms^{-1}) the potential output of ATES is satisfactory, as long as the groundwater flow velocity does not exceed $5e^{-4}ms^{-1}$. The reactive transport model shows that to avoid well clogging, groundwater should be pumped only from above or below the aquifers redox boundary.

1. INTRODUCTION

Urban areas have high energy demands and therefore put pressures on their ecosystems, atmosphere, soils and water resources (Vienken et al. 2015). In the light of global change, with a trend towards urbanization and an evolving energy system, it is important that urbanized areas contribute to their own energy demands. One option is to make use of urban groundwater systems as an ecosystem service (Bonte et al., 2011). Seasonal aquifer thermal energy storage and recovery (ATES) helps to more efficiently distribute energy between times of production and demand. This may lead to a considerable decrease in primary energy consumption and related emissions (e.g. Zuurbier et al., 2013, Vienken et al. 2015).

1.1 ATES principle

ATES, also referred as groundwater heat pumps, are technical installations for the geothermal exploitation of the shallow subsurface (<100 m below surface). ATES are open loop systems where a groundwater body acts as a temporal storage for thermal energy (Possemiers, 2014). A typical ATES system (Fig. 1) consists of one or more wells to pump and inject groundwater. By facilitating the heat capacity of both groundwater and the soil/rock matrix of the aquifer, the pumped water is used for cooling or heating a building. At the so-called ‘cold well’ relative cool groundwater is pumped during summer, and is used for cooling by means of heat exchangers and/or heat pumps. By this process the water is warmed up and consequently injected into the so-called ‘warm well’. During winter the direction of flow reverses and water is pumped from the ‘warm well’ to be used as heating. Resultantly, the now cooled groundwater is injected into the ‘cold well’. In the next summer, the direction of flow is reversed again, restarting the described cycle. In autumn and spring the ATES system is inactive.

Most ATES systems operate with only small temperature differences ($\Delta T<15°C$) between ‘warm’ and ‘cold’ wells. Dependent on the local climatic conditions, warm wells remain at around 20-25°C while cold wells are limited to ca. 3-5°C. To run ATES systems economically certain pumping rates and thermal capacities of the subsurface are required. The volume of the aquifer, along with its hydraulic and thermal conductivities are primary design parameters. In case a suitable aquifer is exploited, common ATES can provide substantial heating and cooling power for office buildings, district heating systems, schools, hospitals or shopping malls, hence users that have high energy demands.

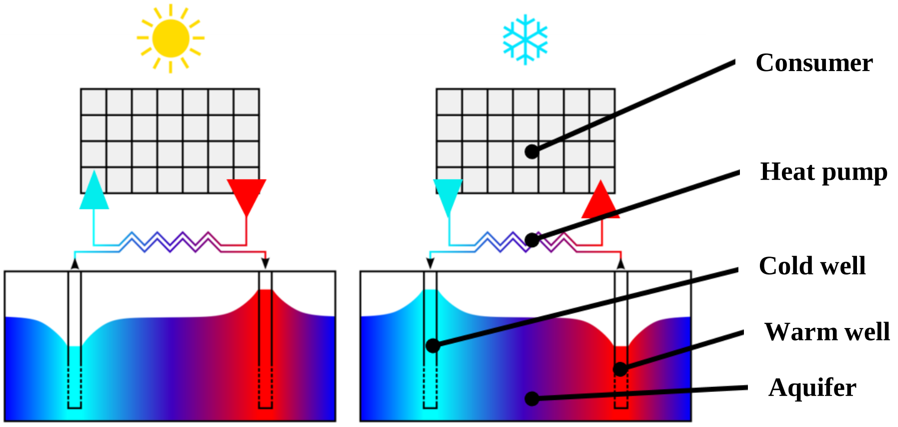

Figure 1: Working principle of ATES: In summer (left subplot) groundwater is pumped from the aquifer (i.e. 'cold well') and by means of a heat exchanger, a building is cooled. Through this process the water is warmed up and injected into the aquifer at the 'warm well'. In winter (right subplot) the flow direction is reversed and the water from the 'warm well' is pumped to heat the building. The cooled groundwater is then injected into the 'cold well'. In summer, the flow direction is again changed and the cool water from the 'cold well' is re-used. This process creates a cycle of seasonal thermal energy storage and recovery (based on Possemiers, 2014).

2. ATES IN BELGIUM

Since more than a decade the number of ATES systems is increasing, for many countries strong growth rates are expected in the future. However, several challenges related to their practical application remain. A widespread application of ATES will not only have recognizable influences on the hydrology and the ecology of the used aquifer, but also for the energy distribution system and energy economics. In turn this stimulates modelling studies on the potential for, and limitations (e.g. well clogging) of ATES operation (e.g. Possemiers, 2014).

Seen from a hydrogeological perspective, the evolution from a single or a few ATES systems to its application on a much greater scale poses several scientific and engineering challenges:

- Are ATES installations economically viable and technically reliable in heterogeneous aquifers (e.g. in aquifers with varying redox conditions and/or sedimentary structure)?

- The currently accepted favourable conditions for ATES are met only in small fractions of the subsurface (i.e. the presence of relatively thick, and geologically and geochemically homogeneous aquifers). Research indicates (Sommer et al., 2015) that these parameters do not necessarily represent the technological or economical optimum. Hence these optimums need to be adequately assessed for a specific aquifer.

- The increasing number of ATES systems in Belgium concerns public drinking water companies and environmental regulators about their environmental impact (e.g. on groundwater quality). What are the possible impacts of ATES systems, and how can they be managed or avoided?

In Europe, the Netherlands are a leading nation in ATES application, where the number of ATES systems has strongly grown from around 30 installations in 1995 to 200 in 2000 and more than 2000 in 2012 (Bonte, 2013). Significant growth rates are also reported from many countries around the globe, including Switzerland, Sweden, Germany and the US (Self et al., 2013). Compared to these, Belgium does not yet make efficient use of its geothermal resources. Both the installed thermal capacity (only ≈ 5% of the Netherlands) and the growth rate are relatively low. With about 20 large systems of >250 kW thermal power, the northern region of Flanders facilitates the majority of Belgium's ATES systems. The hydrogeology and the high concentration of population and economic activity indicate a considerable potential for ATES systems in Belgium. Hence a growing demand is expected, especially in highly urbanized areas such as the Brussels-Capital Region.

3. METHODOLOGY

A decade ago, VITO (2007) constructed a geothermal suitability map covering the Brussels-Capital Region. The Brussels Sands aquifer is indicated as a potential ATES site. This assessment is based purely on geology and does not take into account hydrologic aspects such as the saturated thickness of the aquifer, the apparent groundwater flow velocities, or the induced hydraulic head changes due to ATES operation. However, these processes are prominent limiting factors for ATES systems. In order to take these aspects and the above mentioned challenges into account, groundwater flow and heat transport models are needed.

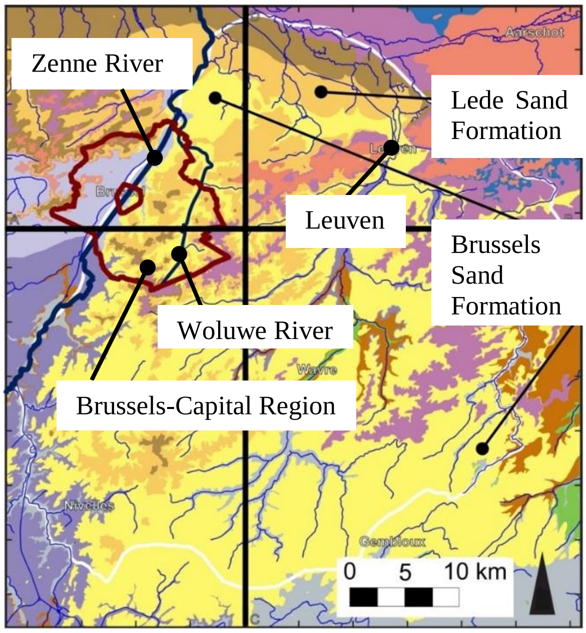

Figure 2: The Brussels Sand Formation and the very similar Lede Sand formation (both in yellow) are interesting for the application of ATES in and around the Brussels-Capital Region (red frames). Within the Brussels-Capital Region the Brussels Sand Formation is present east of the Zenne River (thick blue line), which flows from S to N. The research focuses on the Woluwe River valley, a right sided tributary of the Zenne River (based on Peeters, 2014).

Based on these criteria, the potential of ATES as an ecosystem service for the Brussels-Capital Region in Belgium is assessed. Coupled numerical groundwater flow, heat transport models and reactive transport models are built and applied to delineate suitable sites for future ATES development. This models can also be facilitated to investigate environmental impacts of ATES systems, including their thermal and geochemical impacts (e.g. well clogging), possible effects of groundwater pollution, interferences of ATES systems with competing water uses (e.g. groundwater extraction sites), other ATES installations or subsurface structures. Overall, these models can assist in the formulation of practical recommendations for optimal subsurface planning.

3.1. Hydrogeology of the Brussels Sand Formation

An important groundwater bearing hydrogeological unit within the Brussels-Capital Region is the Brussels Sands Formation. Together with the very similar Lede Sands Formation they form an up to 70 m thick aquifer (Brussels Sands aquifer). The Brussels Sands are shallow tidal sand deposits of the Eocene, occurring in an approximately 120 km long and 40 km wide SSW-NNE oriented zone in central Belgium (Fig.2). These sands fill an embayment which ended in the Eocene North Sea. The Brussels Sands are considered heterogeneous, consisting of unconsolidated quartz sands with variable percentages of feldspar, flint, glauconite and lime. Because of the presence of lime, the groundwater of the Brussels Sands aquifer is of $CaHCO_3$ type. Anthropogenic activity lets the shallow parts of the aquifer suffer from increasing concentrations of nitrate, chloride and sulphate (Peeters, 2010). Hydraulic conductivity values are variable, but generally high. Values between 4.2e^{-6} ms^{-1} and 1.4e^{-4} ms^{-1} have been reported. Since the Brussels Sands aquifer is heterogeneous, different model scenarios were created, covering different hydraulic conductivities and hence also groundwater flow velocities. The average thermal parameters are described with a thermal conductivity of 2.4 WmK^{-1}, a volumetric heat capacity of 2550 Jm^{-3}K^{-1} and a bulk density of 1610 kgm^{-3} (Peeters, 2010; Possemiers, 2012).

3.2. Coupled groundwater flow, heat and reactive transport models

Distributed groundwater flow and heat transport models are built in ‘Processing MODFLOW 8.0’ (PMWIN), a widely used, powerful platform for MODFLOW (Zheng and Wang, 1999) processing and visualization. While MODFLOW calculates groundwater head distributions, groundwater flow velocities and groundwater drawdown around ATES wells, MT3DMS is used to simulate the associated heat transport. PHREEQC-2 (Parkhurst and Appelo, 1999) is used for the reactive transport modelling part. PHT3D (Prommer and Post, 2010) couples MT3DMS for the simulation of three-dimensional advective-dispersive multi-component transport with the geochemical model PHREEQC-2 for the quantification of reactive processes.

Input data for this research was collected in collaboration with public and private partners including ‘Bruxelles Environnement/Leefmillieu Brussel’ (BIM), the environmental agency of the Brussels-Capital Region, and the consulting firms AGT nv. and Iftech nv., respectively. Hydrogeologic data is also gathered from public databases like the ‘Databank Ondergrond Vlaanderen’ (dov.vlaanderen.be).

3.3. Pilot sites

A coupled groundwater flow, heat transport and reactive transport model covering the whole Brussels-Capital Region is not practicable. Hence, with respect to their delineation, the models are kept simple and reasonably small to reduce calculation times. The methodology for this research is therefore based on specific pilot sites, which cover limited but representative parts of the Brussels Sands.

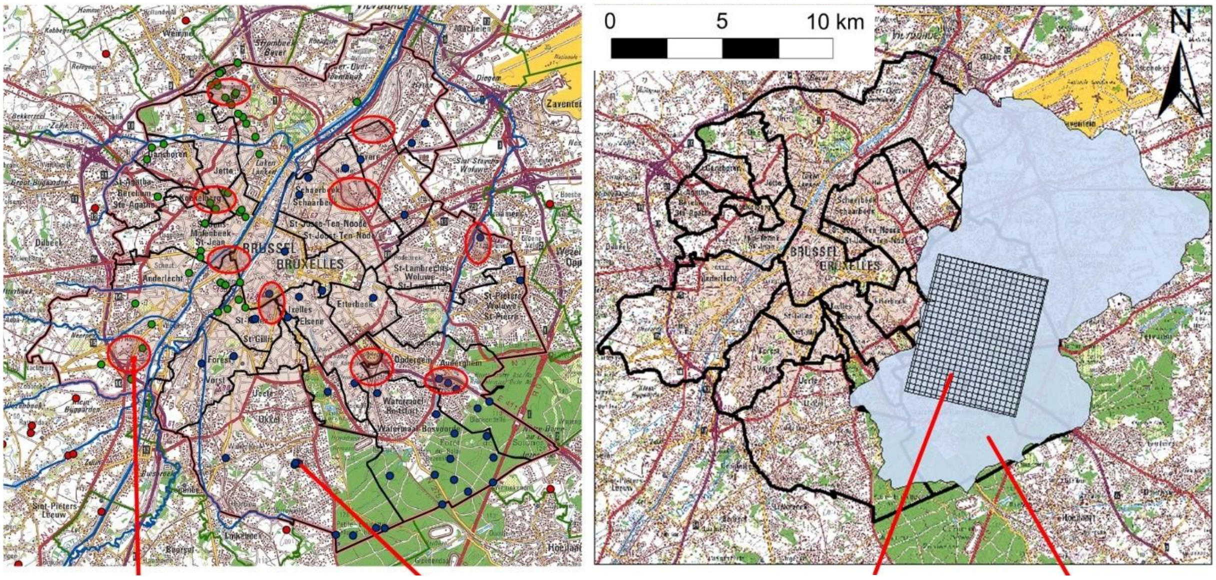

Figure 3: Interesting pilot sites in the Brussels-Capital Region are indicated by red circles (left subplot). The sites have been chosen according to the abundance of available piezometric data (dots), the abundance of the Brussels Sands (see also Fig. 2), and results from former groundwater research. The right subplot shows the model grid of the Woluwe pilot site (size 4000x5000 m) located in the Woluwe River catchment (blue area).

The pilot sites (Fig.3) are set up as rectangles of about 5000x4000 m (covering 10-20 km^2) where the longer side is aligned to the predominant groundwater flow direction. The pilot sites are established according to (i) the occurrence of the Brussels Sands, (ii) sufficient piezometric data, and if possible, (iii) where information from earlier projects was available (i.e. already existing groundwater models). For the groundwater flow only the aquifers like the Brussels Sands aquifer are of importance, for the heat transport however also the underlying aquitards are taken into account. A cell size of 10 m was chosen for the models. It can be assumed that, at a depth of 10 to 20 m, the groundwater temperature is slightly above the mean annual temperature (Domenico and Schwartz, 1998), thus the groundwater temperature is assumed to be at 12°C. Temperatures of 16°C and 8°C were assigned at the 'warm' and 'cold well', respectively.

In this publication, we present a pilot site situated in the Woluwe River Catchment for the groundwater flow and heat transport model (Fig.3). The Woluwe River is, after the Zenne River, the second biggest river within the Brussels-Capital Region. It flows in a NNE direction (Figs. 2 and 3) and cuts into the relative thick layers of the Brussels Sands. The Brussels-Capital Region has a pronounced topography. Along both sides of the river the Brussels Sands reach saturated thicknesses of around 40 m. Close to the river however, the saturated thickness of the Brussels Sands is insufficient (<20m) for an effective ATES, while deep groundwater tables reduce the saturated thickness on top of the plateau.

The results for the reactive transport model are adopted from Possemiers et al. (2016), which investigated an ATES site in Leuven, Belgium (Fig. 2). Both the Woluwe and the Leuven site are located in the Brussels Sands, hence we assume that their results are complementary. For the Woluwe pilot site, an average saturated thickness of the Brussels sands of 33 m was calculated. This value was used for the groundwater and heat transport models and is fairly similar to the respective value of 37 m in Possemiers et al. (2016).

5. RESULTS

To simulate the cyclic nature of ATES systems a transient groundwater flow model of the pilot site is necessary. With its pronounced topography, the urban environment and the relatively scarcity of hydrologic measurements the Brussels-Capital Region is a complex environment for groundwater modelling. The piezometric data within the Brussels-Capital Region is clustered and spatially heterogeneous, limiting the quality of groundwater models and the possibility to create complex small-scaled models. Based on the experiences of this research the piezometric network in the Brussels-Capitol Region can be modified in the future to allow for optimal ATES modelling.

A scenario with low hydraulic conductivity in the Brussels Sands of $4.2e^{-6}$ ms^{-1} leads to a negligible groundwater flow velocity. This is usually favourable for ATES application because no heat stored in the aquifer is moving away from the well. But even with a drawdown of 9 m, which is not practicable in an urban environment, the pumping rate is only 7.2 m^3h^{-1}. Hence this setup is most probably insufficient for the economic exploitation of ATES systems. However, with the installation of a well field this limitation may be overcome.

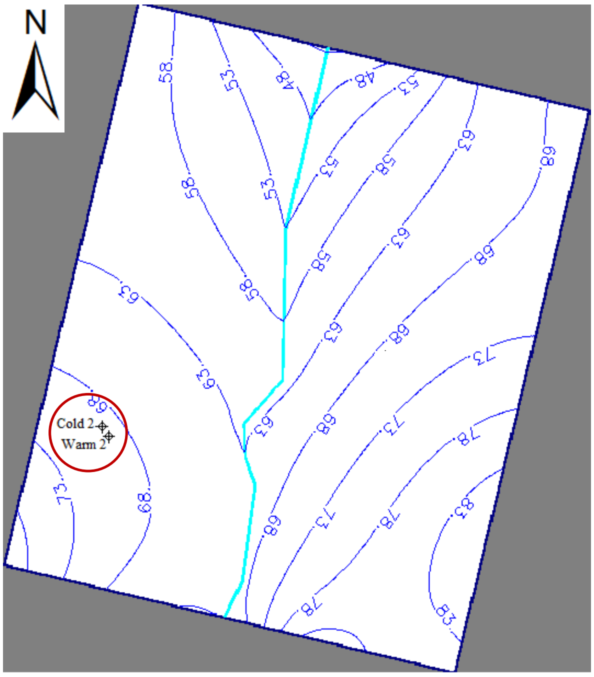

Figure 4: Modelled groundwater head distribution (in metres above sea level) of the Woluwe pilot site. The Woluwe River crosses the model area from South to the North. The Brussels Sands are assumed to have a uniform hydraulic conductivity of 1.4e^{-4} ms^{-1}. An ATES system is indicated by two wells with a distance of 100 m (red circle).

Figure 4 shows a scenario with a high hydraulic conductivity of 1.4e^{-4} ms^{-1}. These conditions are all in all favourable for ATES systems, because, according to the model, a very high pumping rate of 180 m^{3}h^{-1} with a drawdown of 7.5 m can be achieved. This is 25 times greater than the low conductivity case. However, the high conductivity leads to groundwater flow velocities of around 3e^{-4}ms^{-1}, displacing the heat plume several hundred metres downstream after 20 years (Fig. 5). This process transports a significant amount of energy away from the wells and thus limits the thermal efficiency to 80%. Most locations in the Brussels Sands however have lower flow velocities and lower hydraulic conductivities, hence efficient ATES systems can be conceived also with considerably lower values than in this second case.

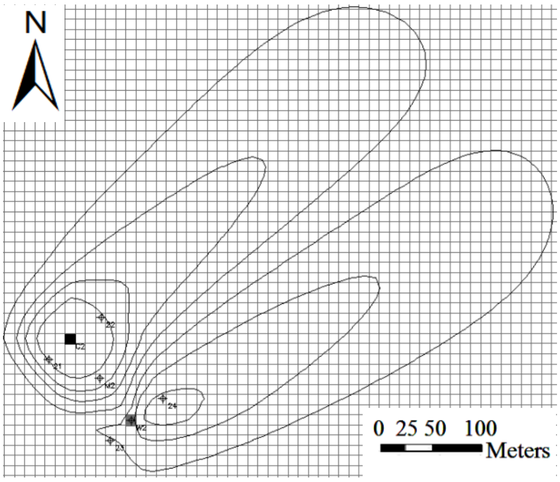

Figure 5: Heat plume after 20 years of ATES operation. Scenario of high hydraulic conductivity and a flow velocity of approx. 3e^{-4} ms^{-1} from south west to north east (see also Fig. 4). The solid lines are temperature contours in degrees C. Although the water cooled or heated with 1˚C moves about 700m downstream, the area of strong thermal influence remains relatively small.

Figures 6 and 7 show results of the reactive transport model PHT3D after 20 years of ATES operation (Possemiers et al., 2016). In Fig. 6 it is visible that most $Fe(OH)_3$ precipitation occurs close to the well screens. The concentrations are higher in the reduced part of the aquifer, with highest $Fe(OH)_3$ concentrations just below the redox boundary (Fig.7). Further away from the redox boundary the concentrations reduce quickly. During ATES operation, Fe(2) and O(0) are consumed (Fig.6); Fe(2) strongly decreases around the reduced part of the well screen, while for the O(0) this is the oxidized part of the aquifer. The precipitation rate of $Fe(OH)_3$ is highest during the initial start-up of the ATES system (Fig. 7), but still occurs after 20 years of operation. After 3 years already half of the total precipitation has occurred. The highest concentration of $Fe(OH)_3$ occurs around the 'cold well'. For the initial injection into the 'warm well' the $Fe(OH)_3$ concentration at the 'cold well' is lower and closer to those of the warm well.

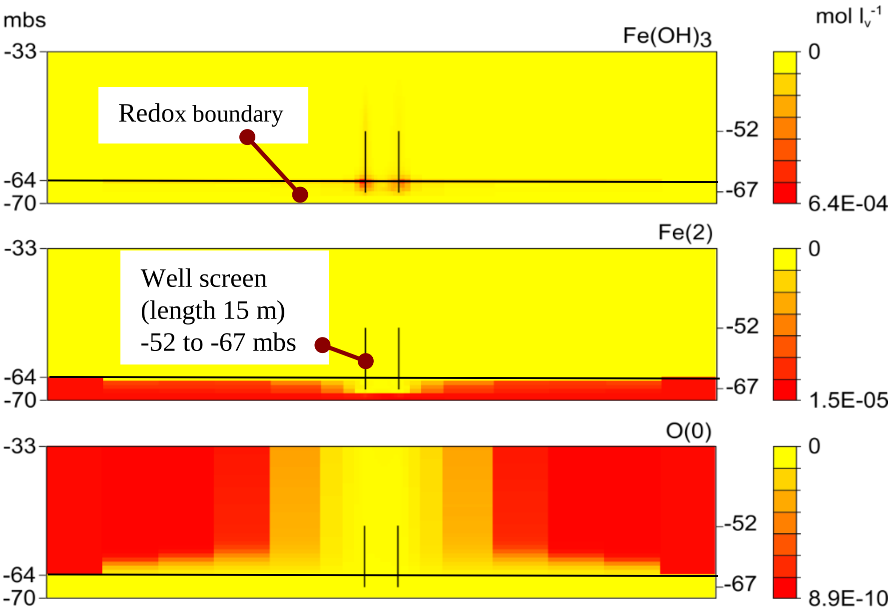

Figure 6: Reactive transport modelling of ATES wells in the Brussels Sands in Leuven. Modelled $Fe(OH)_3$, Fe(2), O(0) and pyrite concentration around the ATES wells after 20 years of operation. The black vertical lines show the position of the ATES well screens, while the horizontal line indicates the redox boundary. mbs stands for metres below surface (modified from Possemiers et al., 2016).

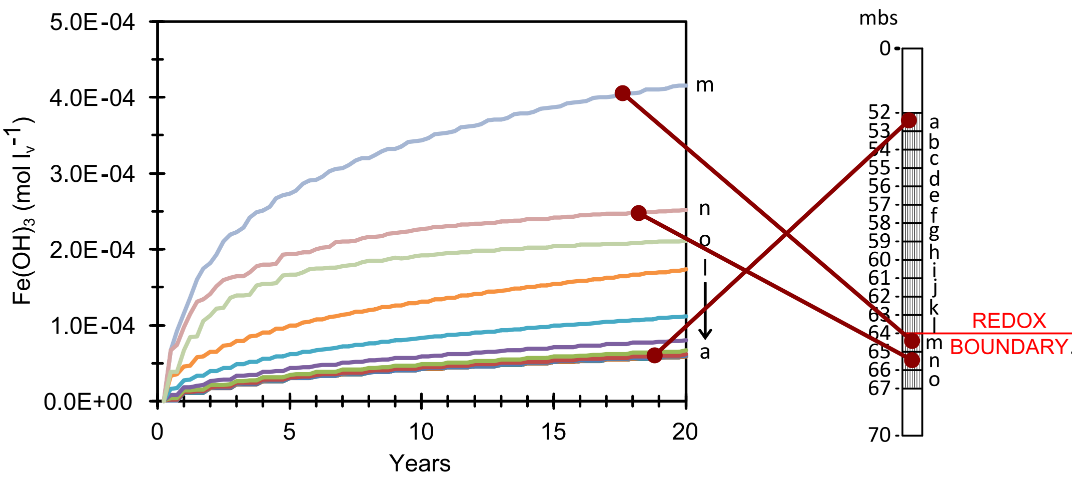

Figure 7: Reactive transport modelling of ATES wells in the Brussels Sands in Leuven. Modelled evolution of $Fe(OH)_3$ concentration in the well screen cells of the cold well: the highest concentrations occur just below the redox boundary. Both above and below the redox boundary reduces the concentration with increasing distance. mbs stands for metres below surface (modified from Possemiers et al., 2016).

The temperature dependence of the reaction rate of $Fe(OH)^+$, $Fe(OH)_2$ and other reactive substances is not taken into account in this research. Because of its limitations the results should not be viewed quantitatively. To date, avoiding the mixing of oxygen/nitrate rich water with iron rich water seems the best strategy to prevent well clogging. It is also advised to initially start ATES system in the summer season.

6. CONCLUSIONS AND POSSIBLE APPLICATIONS

In this modelling study, the potential of ATES as an ecosystem service for the Brussels-Capital Region, Belgium is assessed, with special attention to the Brussels Sands aquifer. Risks and disadvantages of ATES installation, like well clogging or thermal influences on the subsurface, were investigated. To cover the whole range of research questions coupled numerical groundwater flow, heat and reactive transport models are applied. The presented models allow quantifying effects of ATES systems on groundwater flow and interaction processes between ATES installations and competing groundwater usages. This helps in establishing practical guidelines, legal regulations and management tools for ATES modelling, design and management. In any case, an optimal subsurface planning should include the exploitation of geothermal resources like ATES in the Brussels-Capital Region.

It was found that the Brussels Sands in the Brussels-Capital Region have the potential for ATES installations. Different scenarios for hydraulic conductivity were tested to address the heterogeneity of the Brussels Sands. Locations with low hydraulic conductivities (i.e. $4.2e^{-6}$ ms^{-1}) have only a very limited potential for ATES installations. Although technically conceivable, with for example an ATES well field, it will probably not be economic. For the highest published hydraulic conductivities (i.e. $1.4e^{-4}$ ms^{-1}) on the other hand, very high pumping rates can be achieved. High hydraulic conductivities often coincide with high groundwater flow velocities. In such cases the heat plume is moved around 700 m downstream within 20 years of operation. The thermal efficiency is reduced to 80% by this process, but because the thermal output power of this scenario is high, this is only a minor disadvantage. With lower hydraulic conductivities the thermal efficiency is higher. Hence, efficient ATES systems can be conceived at locations with hydraulic conductivity values of $<1.4e^{-4}$ ms^{-1} and flow velocities of $<3e^{-4}$ ms^{-1}.

A limitation for the distributed models is the clustered and spatially heterogeneous availability of piezometric data within the Brussels-Capital Region. This limits accuracy and quality of complex small-scaled models. Such distributed models are needed to allow for the calculation of the potential energy savings and CO_2 reductions achieved by ATES in the Brussels-Capital Region. Based on this research the piezometric network in the Brussels-Capitol Region can be modified.

The risk of well clogging of ATES wells can be avoided by placing the well screen sufficiently far away from the redox interface. To know the exact position of this boundary prior to the well installation, an assessment of water quality variations at depth is necessary. Reactive transport modelling furthermore shows that starting the ATES systems initially with injecting water into the 'warm well' is minimizing $Fe(OH)_3$ precipitation. However, temperature dependences of the geochemical reaction rates are not taken into account in this study.

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