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Assessment of seasonal aquifer thermal energy storage as a groundwater ecosystem service for the Brussels-Capital Region: combining groundwater flow, and heat and reactive transport modeling

Christian Anibas[a,]*, Janik Kukral[a], Mathias Possemiers[b], Marijke Huysmans[a,c]

[a]*Vrije Universiteit Brussel (VUB), Department of Hydrology and Hydraulic Engineering, Pleinlaan 2, 1050 Elsene, Belgium*
[b]*AGT nv., Kontichsesteenweg 38, 2630 Aartselaar, Belgium*
[c]*KU Leuven, Department of Earth and Environmental Sciences, Celestijnenlaan 200E, 3001 Leuven, Belgium*

Abstract

Seasonal aquifer thermal energy storage and recovery (ATES) help urbanized areas to contribute to their energy demands. We assess the potential of ATES in the Brussels-Capital Region, Belgium with groundwater flow, heat and reactive transport models. Situated in the phreatic Brussels Sand aquifer, they indicate that ATES systems are unfeasible for hydraulic conductivities of $4.2e^{-6}$ ms^{-1}. At low groundwater flow velocities however, ATES are feasible for hydraulic conductivities of $1.4e^{-4}$ ms^{-1}. Iron(hydr)oxide precipitation during ATES operation is investigated with reactive transport models. To avoid well clogging groundwater should be pumped only from above or below the aquifers redox boundary.

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Keywords: ATES; groundwater modeling; heat transport; reactive transport; Belgium

* Corresponding author. Tel.: +32-2-629-3635; fax: +32-2-629-3022.
E-mail address: canibas@vub.ac.be

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1. Introduction

Urban areas have a very high energy demand, and therefore place added pressures on ecosystems, the atmosphere, soils and water resources [1]. In the light of global warming, urbanization and an evolving energy system, it is important to let urbanized areas contribute to their own energy demands. One option is to make use of urban aquifers as an ecosystem service. Seasonal aquifer thermal energy storage and recovery (ATES) can assist to more efficiently distribute the used energy between production and demand [2]. This may lead to a decrease in primary energy consumption [1, 3].

ATES, also referred as groundwater heat pumps, are technical systems where a groundwater body acts as a temporal (i.e. seasonal) storage of thermal energy [4]. A typical ATES system consists of one or more wells for the cyclic extraction and the injection of groundwater. During summer, relative cool groundwater is extracted from one well (referred as cold well). At the surface the thermal energy stored in the water is used to cool a building. By this process the water is warmed up before it is injected into the warm well. During winter, the direction of flow reverses, water is now extracted from the warm well. Via the heat pumps and/or heat exchangers the thermal energy is used to heat the building. The cooled groundwater is consequently injected into the cold well. During the next summer, the described cycle starts over again. Most ATES systems operate with small temperature differences of $\Delta T<15°C$ between warm and cold wells; warm wells remain at around 20-25°C while cold wells are limited to ca. 3-5°C. ATES systems are especially suitable for urban areas where office buildings, schools, hospitals and shopping malls have a high demand for heating and cooling power.

The numbers of ATES systems are increasing, further growth is expected in the future. The Netherlands are a leading country in ATES application, where the number of ATES systems has grown from around 30 installations in 1995 to 200 in 2000 and more than 2000 in 2012 [5]. Significant growth rates are also reported in other European countries like Switzerland, Sweden, Germany and in the US [6-8].In some regions they are widespread enough to have recognizable energetic and economic influence. This stimulates scientific investigations on the potential, limitations and recognized problems of ATES operation.

Belgium does not yet make efficient use of its shallow geothermal resources. Both the applied geothermal capacity (i.e. ≈ 20 times less than in the Netherlands) and the growth rate are moderate. The northern region of Belgium, Flanders, facilitates the majority of the countries ATES systems with about 20 large systems (>250 kW) operational in 2011. This is much less than the Netherlands, but a growing interest for ATES is nevertheless indicated. Especially in urbanized areas like the Brussels-Capital Region where a considerable potential for ATES systems exists.

Despite this increase, the presence of ATES systems in Belgium concerns public drinking water companies and environmental regulators about their potential impact on groundwater quality. The aquifer presented in this paper is prone to well clogging because of iron(hydr)oxide precipitation [9]. To date, ATES suitability in the Brussels-Capital Region was only based on geology [10], where only a relative small fraction of the subsurface meets the conditions for ATES (i.e. the presence of relatively thick, geologically and geochemically homogeneous aquifers). This former study, however, did not take into account the hydrology, heterogeneity, or varying saturated thickness of the aquifer; nor were groundwater flow velocities or the induced hydraulic head changes due to ATES operation included. Detailed coupled groundwater flow and heat transport models are therefore needed. The general objective of this research project is to assess the potential and the risks of ATES as an ecosystem service for the Brussels-Capital Region in Belgium in a modeling study. The presented framework applies coupled numerical groundwater flow, heat transport and reactive transport models. This allows for the suitability of the aquifer for ATES to be investigated and potential risks, like well clogging, to be addressed.

2. Hydrogeology of the Brussels Sand Formation

The Brussels-Capital Region has a pronounced topography, where the region east of the Zenne River is covered by an elevated plain which is intersected by several streams and their alluvial lowlands (Fig. 1). A VITO [10] report concluded that the Brussels Sand Formation has a good potential for ATES systems. This formation is present in the eastern part of the Brussels-Capital Region, its western limit is the Zenne River valley. The Brussels-Capital Region is crossed from southwest to the northeast also by smaller streams, including the Woluwe River. They eventually discharge into the Zenne River (Fig.1). The Woluwe River cuts into the relative thick layers of the Brussels Sand Formation, which together with the very similar Lede Sand Formation form an up to 70 m thick phreatic aquifer in the Brussels-Capital Region, called the Brussels Sand aquifer. While the maximum saturated thicknesses are found on top of the elevated plain, the Brussels Sand aquifer reaches saturated thicknesses of around 40 m along both banks of the Woluwe River (Fig.1). Close to the river the saturated thickness of the Brussels Sand aquifer is insufficient (<20m) for an effective ATES system.

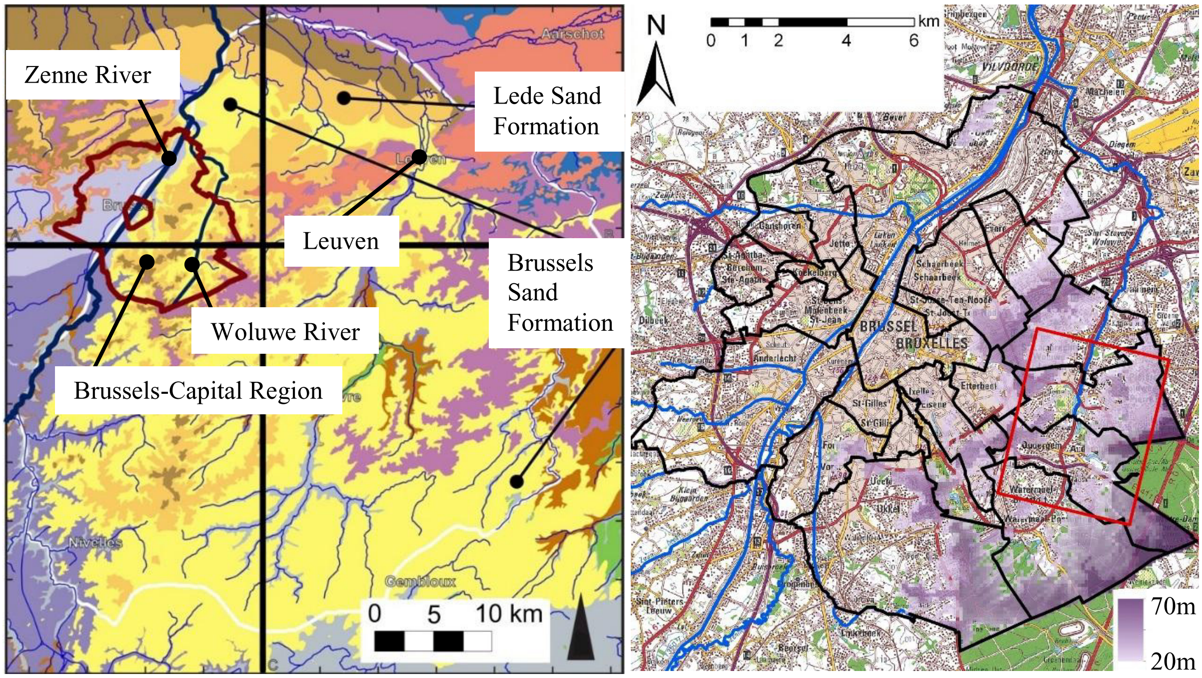

Fig. 1. Left subplot: the Brussels Sand Formation and the very similar Lede Sand formation (both in yellow) contain the Brussels Sand aquifer, which is interesting for the application of ATES in Central Belgium. The presented scenario for the reactive transport model is situated in Leuven. Right subplot: this paper focuses on the Woluwe River valley (i.e. the Woluwe pilot site as a red rectangle), a tributary of the Zenne River. In the area the saturated thicknesses reach 70 m. Below 20 m however the saturated thickness is insufficient for ATES systems.

The Brussels Sands Formation is a shallow tidal sand deposit of the Eocene, occurring in a 40 km wide SSW-NNE oriented zone in central Belgium. These sands fill an approximately 120 km long and 40 km wide embayment which ended in the Eocene North Sea. The Brussels Sand formation is considered heterogeneous, consisting of unconsolidated quartz sands with variable percentages of feldspar, flint, glauconite and lime [11]. Because of the presence of lime, the groundwater in the aquifer is of $CaHCO_3$ type. The shallow parts of the aquifer suffer from increasing concentrations of nitrate, chloride and sulfate because of anthropogenic activity [12, 13]. Hydraulic conductivity values are variable but generally high. Values between $4.2e^{-6}$ ms^{-1} and $1.4e^{-4}$ ms^{-1} have been reported. The average thermal parameters are described with a thermal conductivity of 2.4 WmK^{-1}, a volumetric heat capacity of 2550 $Jm^{-3}K^{-1}$ with a bulk density of 1610 kgm^{-3} [12, 13, 14].

3. Methodology

The methodology for this research is based on pilot sites, covering areas of 10-20 km^2 within the Brussels-Capital Region (Fig.1), for which the coupled groundwater flow, heat and reactive transport models were developed. The models were then run for different model scenarios. Literature and data was collected in collaboration with public and private institutions like ‘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 was gathered from the 'Databank Ondergrond Vlaanderen' (dov.vlaanderen.be). A GIS system was used to classify and analyze spatial data (Fig.1). To choose interesting pilot sites, the following factors were taken into account: (i) the abundance of the Brussels Sand formation, (ii) the availability of piezometric data, (iii) information from earlier projects, and (iv) the potential for future urban development. With its pronounced topography, the urban environment and the relative scarcity of piezometric measurements, the Brussels-Capital Region is a complex environment for groundwater modeling.

Distributed groundwater flow and heat transport models were built in 'Processing MODFLOW 8.0' (PMWIN), a widely used, powerful platform for MODFLOW [15] 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. The geochemical model PHREEQC-2 [16] was used for the reactive transport modeling part. PHT3D [17] couples MT3DMS for the simulation of three-dimensional advective-dispersive multi-component transport with PHREEQC-2 for the quantification of reactive processes.

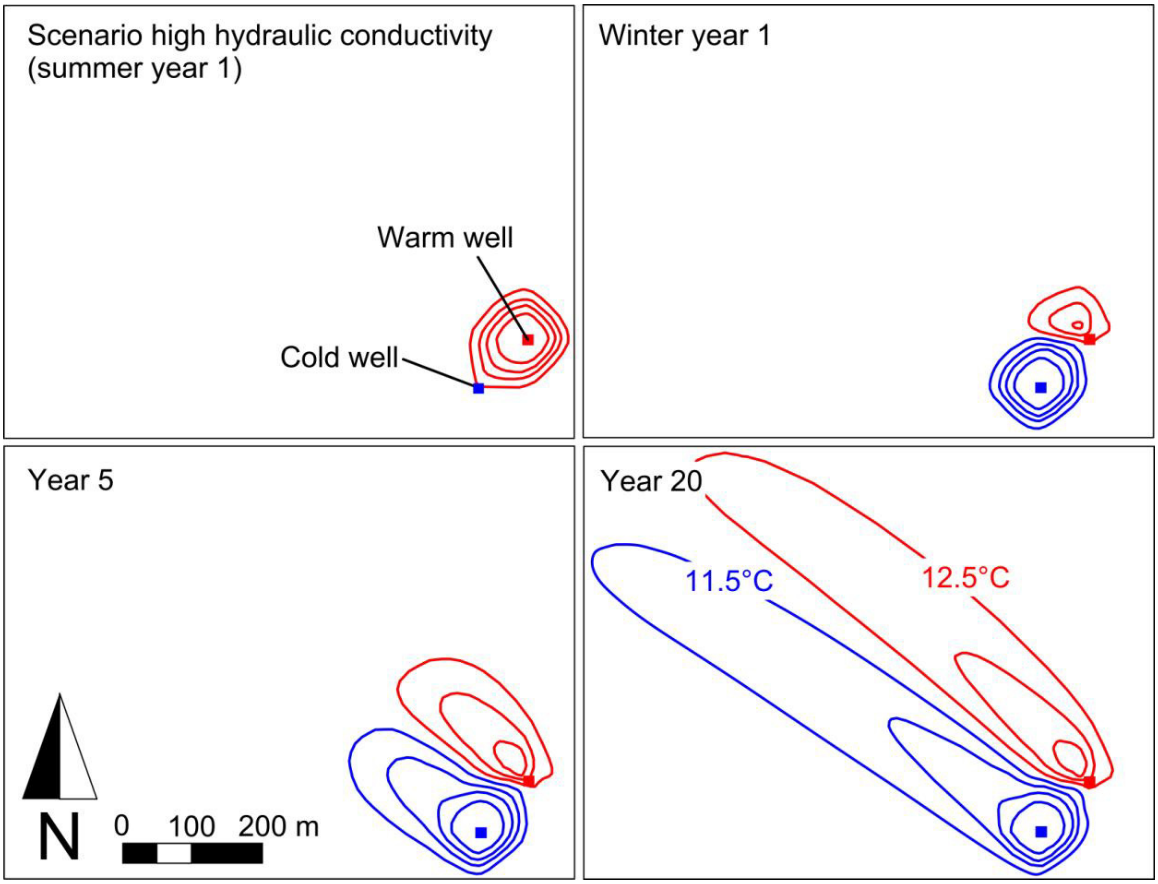

Fig. 2. Development of the heat plume of two ATES wells in a time of 20 years assuming a scenario of a high hydraulic conductivity of $1.4e^{-4}$ ms^{-1}. This scenario leads to groundwater flow velocities of up to $5e^{-4}$ ms^{-1}, and a drift of the heat plume of several hundred meters downstream. The isothermal lines indicate temperature differences of 1°C.

4. Results

For the groundwater flow and heat transport model we present results from a pilot site situated in the Woluwe River catchment (Fig.1). The results for the reactive transport model are adopted from Possemiers et al. [9], which investigated an ATES site in Leuven, Belgium. Both the Woluwe and the Leuven site are located in the Brussels

Sand aquifer, 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. [9].

The saturated thicknesses and hydrologic parameters of the Brussels Sand aquifer were assessed with GIS tools (Fig.1). Here the influence of variable hydraulic conductivity on the performance of ATES is presented. For a scenario with low hydraulic conductivity (i.e. $4.2e^{-6}$ ms^{-1}; temperatures of 16°C and 8°C were assigned at the warm and cold well, respectively), the groundwater flow velocity was found negligible. Low groundwater flow velocities are positive for ATES operation, because the stored heat is not moving out of the injection/pumping zone. However, the achieved pumping rate is with 7.2 m^3h^{-1} fairly low, even with a drawdown of 9 m. Hence, this is not a very practicable setting; ATES systems in this scenario are probably not economic. The technical performance could be improved with the installation of well fields. In the scenario with a high hydraulic conductivity (i.e. $1.4e^{-4}$ ms^{-1}), as shown in Fig. 2 ATES systems perform very differently. Very high pumping rates of 180 m^3h^{-1} are possible with a drawdown of 7.5 m, enough to serve any present ATES system. However, because of the pronounced topography of the Brussels-Capital Region, groundwater flow velocities can reach $5e^{-4}$ ms^{-1}. This means that after 20 years of operation the ATES heat plume extends several 100 m downstream (Fig.2). This is limiting the thermal efficiency of the ATES system to 80%. This reduction in thermal efficiency is not substantial, ATES systems in this scenario however, should preferably be built in zones with flow velocities $<5e^{-4}$ ms^{-1}.

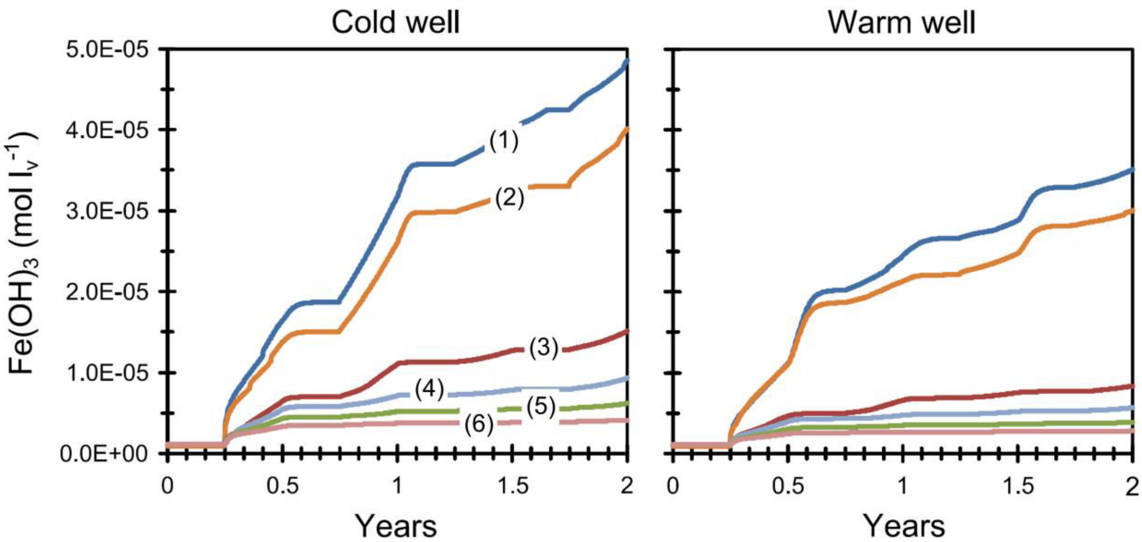

Fig. 3. Evolution of iron(hydr)oxide concentration around a cold and warm well in different scenarios. (1) Reference scenario. (2) The flow rate is reduced by factor two. (3) Shorter well screens of 10 m instead of 15 m. The redox boundary is now 2 m below the well screens bottom. (4) Same well screen positions as (3), but flow rate is reduced by factor two. (5) Shorter well screens (10 m) and positioned 3 m higher, so that the redox boundary is 5 m below the well screen bottoms. (6) Same well screen positions as (5), but flow rate is reduced by factor two (modified from [9]).

Beside the hydrologic limitations, the presence of a redox boundary in the Brussels Sand aquifer may also limit the long time performance of ATES due to well clogging with iron(hydr)oxides. In order to examine possible measures to decrease the iron(hydr)oxide precipitation in and around the wells, figure 3 shows results of the reactive transport model PHT3D after 2 years of ATES operation [9]. The reference scenario is described by a 15 m long ATES well filter which extends over both the oxidized and the reduced (3 m) part of the Brussels Sand aquifer. The reference scenario shows the least favorable condition for iron(hydr)oxide precipitation. When both water from oxidized and the reduced parts of the aquifer are mixed is the chance for precipitation high. The other scenarios all show lower precipitation rates. The flow rate has only a relative small influence. Increasing distances of the well screen from the redox boundary reduce the risks of well clogging. The presented results should not be viewed quantitatively, since temperature dependences of the geochemical reaction rates are not taken into account in this study.

5. Conclusions and possible applications in the Brussels-Capital Region

In a modeling study the potential of ATES as an ecosystem service for the Brussels-Capital Region, Belgium is assessed quantitatively, with special attention of the Brussels Sand aquifer. The presented framework uses coupled numerical groundwater flow, heat and reactive transport models. Quantitative model results consequently will allow for the calculation of possible savings in fossil fuel and electrical energy consumption, reductions of CO_2 emissions and atmospheric pollution achieved by ATES. They also allow setting up practical guidelines, management tools and legal regulations for subsurface and spatial planning. Groundwater measurement networks can be adjusted to better serve the needs of ATES development.

The groundwater and heat transport model suggests that the Brussels Sand aquifer in the Brussels-Capital Region has the potential for ATES installations. Different scenarios for hydraulic conductivity were tested to address the heterogeneity of the aquifer. Locations with low hydraulic conductivities (i.e. $4.2e^{-6}$ ms^{-1}) have only a limited potential for ATES installations. For the highest published hydraulic conductivities (i.e. $1.4e^{-4}$ ms^{-1}) very high pumping rates can be achieved, but high hydraulic conductivities often coincide with high groundwater flow velocities. In such cases the heat plume is moved downstream of the wells which reduces the thermal efficiency to 80%. Because of the high thermal output power of this scenario, 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 $<5e^{-4}$ ms^{-1}. The reactive transport model shows that well screens should be placed in a way that mixing of oxic and reduced water during the pumping process is avoided. This can be achieved to place the ATES well screen more than 2 m away from the redox boundary.

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