Interaction between multiple ATES systems

Analysis of thermal and geohydrologic performance

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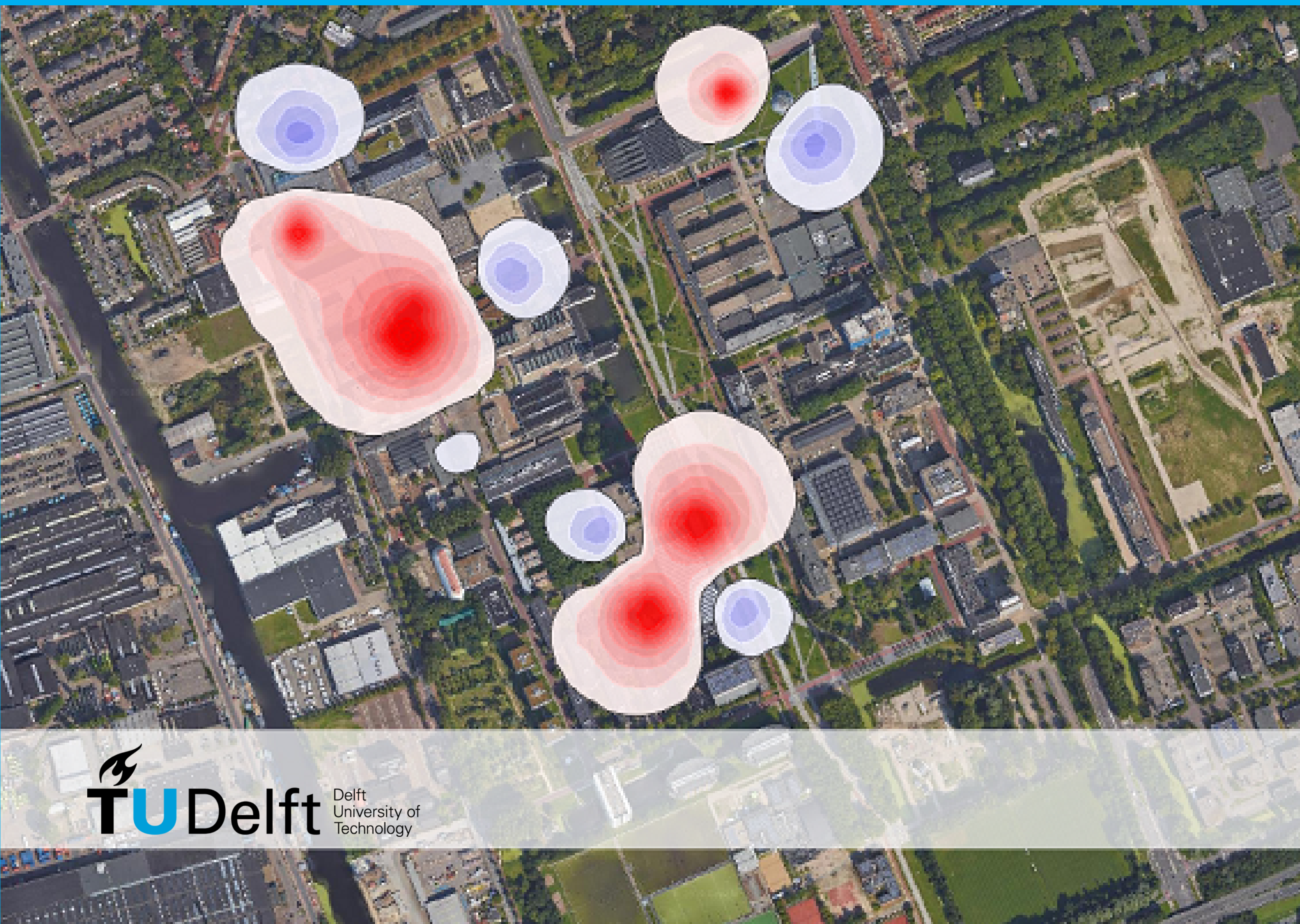

TU Delft Delft University of Technology

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by

R. Duijff

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TU Delft

Preface

This research is the result of my graduation work for the Master of Science Water Management at the Delft University of Technology and is performed in collaboration with Campus Real Estate of the Delft University of Technology.

This research enabled me to gain in depth knowledge about an interesting technology that can provide thermal energy to the built environment. Providing thermal energy to buildings has a large share in our total energy demand. In order to make our energy production more sustainable, more attention should be given to alternative heating technologies. I am therefore grateful that I could gain insight in this technique and I hope to apply this knowledge in the future. I hope this research will help with the successful implementation of aquifer thermal energy storage systems in areas where many ATES systems are installed.

I want to thank the members of my graduation committee. Without their help and feedback I could not have achieved the same results. I want to express special gratitude to Martin Bloemendal as my daily supervisor at the Delft Technical University. You were able to provide constructive feedback without guiding me in a certain direction with this research. I feel this greatly improved my end results while the research is still my own product. I also want to thank Anne Medema for consulting me on the case study. Our collaboration gave me a broad view of the operation of aquifer thermal energy storage systems in practice. This combined with the theoretical insights helped me to gain a more complete understanding of aquifer thermal energy storage. Furthermore, I want to thank Mark Bakker. During our meetings your questions helped re-evaluate my steps which led to a better research. Although we only met a couple times I also want to thank Phil Phardon. Your insights helped me to improve the final result, especially the discussion and conclusions.

Furthermore, I want to thank my parents for helping me reach this point in my education and Mies for all her support.

I hope you enjoy reading this research.

R. Duijff
Delft, October 2019

Abstract

Aquifer thermal energy storage (ATES) is an energy efficient technique to provide sustainable thermal energy to buildings in a temperate climate. Around 40% of worldwide energy is used for heating and cooling, which is mainly provided by burning fossil fuels. Because of the negative effects of burning fossil fuels, alternatives like ATES are needed. The principle of ATES is to temporary store thermal energy in aquifers in a warm and cold well in order to use this thermal energy for heating and cooling in the next season.

ATES is an increasingly popular approach to meet heating and cooling demand, especially in the Netherlands. Because the available subsurface space is limited, congestion problems can occur in areas with high ATES density. In these areas a conflict of interests exists between private parties who want to achieve maximum efficiency by avoiding negative influence of other systems, and the public interest to maximize the amount of thermal energy stored in the aquifer. Current policy is aimed at protecting the interests of private parties by applying large safety margins which limits the amount of systems that is placed in a certain area. Another problem with ATES systems is to achieve thermal balance to prevent cooling or heating of the subsurface. Therefore regeneration is needed to balance the system. Extra energy is required for this regeneration, reducing the performance of the system.

A proposed solution for these problems is to reduce the distance between wells of the same temperature. One thermal zone is formed which is advantageous for the efficiency of individual wells. Because wells are placed closer together more systems are installed in a certain area. Accepting imbalance in individual systems can be accepted in this approach, provided that thermal balance is met for a group of systems. This can prevent the regeneration of wells.
The main goal of this research is to quantify the change in performance of ATES systems when their thermal zones are connected. The performance parameters are the thermal recovery efficiency and the pumping energy of the groundwater system. A model study is used to gain insight in the effect of connecting ATES systems. The results from this study are then applied to asses a case study.

The main findings of this research are as follows: Connecting the thermal zones of wells of the same temperature increases the thermal recovery efficiency of individual systems. For average systems with a storage volume of 250.000 m^3/year this increase is around 8-20%. Systems with a small storage volume have the highest increase in thermal recovery efficiency, around 15-40% for systems with a storage volume of 50.000 m^3/year. The main factor determining the increase in thermal recovery is the reduced ratio between the area of the thermal zone and the volume of the thermal zone, also called the A/V value.
The drawdown in the wells increases when thermal zones are connected and wells of the same temperature are both injecting or extracting. This leads to extra energy needed for pumping. The combined effect of increased thermal recovery efficiency and the increase in pumping energy is positive when a small distance between wells of the same temperature is taken. The distance between wells of the same temperature should be small, around 0.5 times the thermal radius of the wells. Thermal zones are connected while the extra pumping energy is limited. The distance between wells of opposite temperature should be larger than 3 times the thermal radius of the wells to avoid negative effects of mutual interaction.

Imbalance could be accepted for individual systems if balance is required for a group of systems. Thermal energy is exchanged between wells of the same temperature if their thermal zones are connected, avoiding the need for regeneration. Ambient groundwater flow can be used to transport thermal energy between wells of the same temperature, if the wells injecting a larger volume are placed upstream.

Due to the positive effect on thermal recovery efficiency and the imbalance of the system, it is found that placing wells of the same temperature together will increase system performance. Because of the reduced distance more systems can be placed in a certain area. Therefore this approach is suitable to maximize individual efficiency and store as much energy as possible.

Contents

Nomenclature

Acronyms

Acronym	Description
ATES	Aquifer Thermal Energy Storage
COP	Coefficient Of Performance

Variables

Symbol	Description	Unit
α	Dispersivity tensor	m
ΔT	Temperature difference	K
η_V	Volume recovery ratio	unit
$\eta_{th,norm}$	Thermal recovery efficiency normalised to volume recovery ratio	unit
η_{th}	Thermal recovery efficiency	%
μ	Dynamic viscosity	$kg/m/s$
μ_0	Dynamic viscosity at reference concentration and temperature	$kg/m/s$
∇	Gradient is x, y and z direction	-
ϕ_m	Diffusive mass flux	$kg/m^2/d$
ϕ_q	Local heat flux	W/m^2
ρ_0	Water density at the reference temperature and concentration	kg/m^3
ρ_b	Bulk density of the soil	kg/m^3
ρ_f	Density of the fluid	kg/m^3
ρ_s	Density of the solid	kg/m^3
θ	Porosity of the soil	-
R_{th}	Thermal radius	m
A	Area of the thermal zone	m^2
B_E	Energy balance	-
B_V	Volume balance	-
C	Concentration of the solute	kg/m^3
c_w	Volumetric heat capacity of water; $4.2E+06$	$J/m^3/K$
c_{aq}	Volumetric heat capacity of saturated porous medium; $2.8E+06$	$J/m^3/K$
$c_{P,fluid}$	Specific heat capacity fluid	$J/kg/K$
$c_{P,solid}$	Specific heat capacity solid	$J/kg/K$
D_m	Molecular difffusion coefficient	m^2/d
$D_{m,temp}$	Thermal distribution factor	m^3/kg
E	Energy	J
E_{system}	Energy input needed for ATES systems for well pumps, heat pumps etc.	J
F_{MI}	Factor describing change in thermal recovery efficiency due to mutual interaction	-
H	Thicknes of the aquifer	m
h	Hydraulic head	m
h_0	Hydraulic head in terms of the reference fluid at reference concentration and temperature	m
k	Hydraulic conductivity	m/d
K_0	Hydraulic conductivity tensor of the material saturated with the reference fluid	m/d
K_d	Distribution coefficient	unit
$K_{d,temp}$	Thermal conduction	m^2/d
$k_{T,bulk}$	Bulk thermal conductivity	W/m/K
k_{Tfluid}	Thermal conductivity solid	W/m/K
k_{Tsolid}	Thermal conductivity fluid	W/m/K
k_T	Thermal conductivity	W/m/K
L	Well screen length	m
Q	Discharge	m^3/day

q	Specific discharge of sinks and sources	m/d
r	Distance from well	m
S_s	Specific storage of the porous material	m^{-1}
T	Temperature	°C / K
t	Time	days
T_s	Transmissivity of the soil	m
V_s	Seasonal storage volume	m^3
W	Volumetric flux per unit volume	d^{-1}
z	Elevation head	unit

Sub- and superscripts

Symbol	**Description**
$()_{all}$	All wells
$()_{amb}$	Ambient
$()_{cool}$	Cooling
$()_c$	Cold
$()_{extr}$	Extracted
$()_{heat}$	Heating
$()_{ind}$	Individual well
$()_{inf}$	Infiltrated
$()_s$	Source or sink
$()_w$	Warm

1
Introduction

1.1. Sustainable thermal energy with ATES

Aquifer thermal energy storage (ATES) is a form of seasonal thermal energy storage. The main reason for the implementation of seasonal storage of thermal energy is to provide sustainable thermal energy for heating and cooling of buildings. The thermal energy is currently provided by burning fossil fuels which leads to the emission of greenhouse gasses and rising of the average global temperature.
Heating and cooling accounts for a large part of the worldwide energy consumption. Estimations vary between 40% for the Netherlands (Harmsen and Harmelink, 2007) (Bloemendal and Hartog, 2018) and 50% (REN21, 2017) worldwide.

If heating and cooling is made more sustainable, a large amount of greenhouse gas emissions is prevented. First the demand for thermal energy should be reduced, for example by installing better insulation for buildings and optimal building design. Sustainable technologies are needed to provide thermal energy. This correspond to the policy of the Dutch government to reduce the fossil fuel consumption for heating of buildings (Ministerie van Economische Zaken, 2016).

One sustainable option to provide thermal energy is aquifer thermal energy storage (ATES). It is applied in temperate climates where both heating and cooling is needed throughout the year (Bloemendal et al., 2015). In these climates a seasonal offset exists between supply and demand of thermal energy. Heating capacity is abundant in the summer while it is needed in the winter. Cooling capacity is available in winter and is needed in the summer. ATES systems overcome this problem by temporary storing thermal energy in aquifers so it can be used later. In the next season thermal energy is extracted and used for low temperature heating and high temperature cooling.

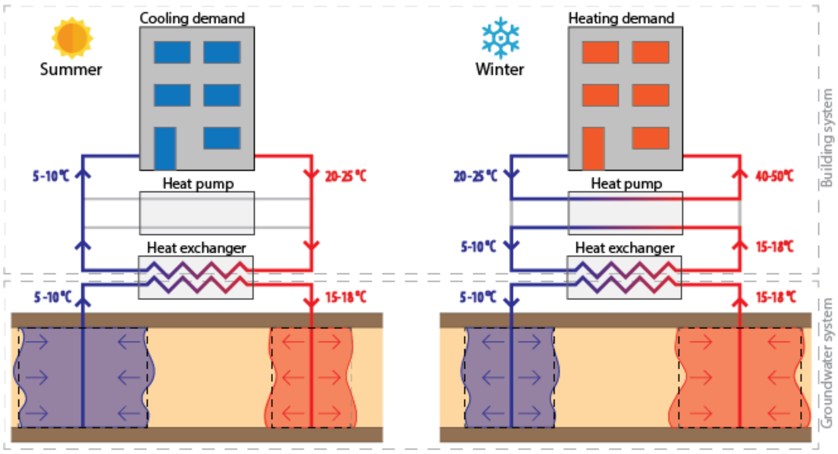

Figure 1.1: Basic working principle of ATES systems. In summer direct cooling is used. In winter a heat pump is needed to provide sufficiently high temperatures for heating.

ATES systems operate by seasonal storage of warm and cold water in aquifers in two separate wells. The most common form is a doublet. The warm and cold wells are placed in the same aquifer with sufficient distance between wells, see Figure 1.1. The systems are called open because they infiltrate water in the aquifer to extract it in the next season. In the warm well water is stored at 12-25°C and in the cold well water is stored at 6-12°C. Due to the high heat capacity of water ($4.2*10^6 J/kg/K$) a large amount of thermal energy is stored despite the small difference in temperature. These systems are called low temperature ATES systems (LT-ATES), which represents 99% of all ATES systems. In summer cold water is extracted for cooling of the building. A heat exchanger is used to transport thermal energy from the groundwater system to the building system. The heated groundwater is then infiltrated in the warm well. During winter the flow is reversed. Warm water is extracted and used to heat the building, often in combination with a heat pump because building heating systems cannot operate on the low temperatures of the warm well.
The system requires some external energy for the operation of the well pumps and the heat pump. The energy needed for operation is small compared to the amount of thermal energy delivered an ATES system. If electricity from sustainable sources like solar panels is used for the well- and heat pumps, no greenhouse gasses are produced in the utilisation of ATES, making it a sustainable option to provide heating and cooling.

1.2. Suboptimal use of ATES potential

Besides being a sustainable option, ATES is also cost effective compared to fossil fuels. Therefore many ATES systems have been constructed. In the Netherlands around 2500 open systems are in operation according to Fleuchaus et al. (2018). This is around 85% of all systems operational worldwide. Although the number of systems has grown considerably over time, some problems regarding ATES are present today including congestion of the subsurface and imbalance in systems. These problems are discussed in the next paragraphs.

The first problem is the suboptimal use of available aquifer space. In some urban areas the amount of ATES systems has grown to congestion levels (Bloemendal et al., 2018). The congestion is partly caused by the amount of ATES systems in a particular area. The congestion is further increased by the current planning and permitting approach, which requires large distances between wells. The recovery of stored thermal energy needs to be as high as possible. Therefore the aim of the local authorities is to protect the interests of existing systems against negative effects of interaction between warm and cold wells. As a result, large safety margins are applied regarding the distance between the wells. The distance depends on the radius of the thermal zone. In general a distance of three times this radius is required between systems (NVOE, 2006), see Figure 1.2 a.
Besides safety margins, ATES systems on average use less than 50% of their permitted capacity (Bloemendal et al., 2018) to cover uncertainties in the design, leading to even larger distances between wells.
While this approach maximizes efficiency of individual wells, it limits the maximum number of systems in a certain area. Fewer buildings can install ATES systems reducing economic potential of ATES and limiting savings on greenhouse gas emissions. This indicates a misalignment between the private interests of optimizing individual system performance and the public interest of storing as much thermal energy in the subsurface as possible. The aquifers where the ATES systems are placed can therefore be considered a common-pool resource with a natural limit for sustainable exploitation (Jaxa-Rozen et al., 2015).
Besides suboptimal use in the horizontal plane, the available aquifer thickness is also used suboptimal. In some cases only a part of the available aquifer thickness is used. The screen length of the well does not always penetrate the whole aquifer. During the design a certain ratio between the screen length and the thermal radius is taken into account to limit losses (Bloemendal and Hartog, 2018). The screen length is also limited to reduce installation cost. Finally the total storage volume is limited by the pumping capacity and the amount of thermal energy required by the buildings. All these factors lead to well screens that do not fully penetrate the aquifer, leading to suboptimal use of the underground.

Another problem is the imbalance in individual systems. Buildings can have an dominant heating or cooling demand over the year. If there is a structural excess need for heating or cooling for a longer period of time, the warm or cold well keeps growing while the other is depleted every season. This is called imbalance in the system. To prevent unsustainable use of the aquifer, thermal balance is often required to prevent the aquifers from heating up or cooling down. Imbalance in the systems could be mitigated by regeneration of heat or cold from other sources. This increases both energy consumption and operational cost (Bozkaya and Zeiler, 2018).

1.3. Connecting thermal zones of ATES systems

The problems mentioned earlier are summarized in a goal for the utilisation of ATES systems. The goal is to store as much thermal energy as possible in the aquifers, while the efficiency of individual systems is sufficiently large.
Several possibilities exist for optimizing the utilisation of available subsurface space and to improve individual performance of ATES systems. One possibility is to apply larger temperature differences between the wells which leads to the storage of more thermal energy in a smaller volume of soil (Lieten et al., 2012).
Another option is to keep the distance between wells of the same temperature small, as illustrated in Figure 1.2 b and c. This can lead to lower losses to the surroundings and therefore to a better recovery of thermal energy. Because wells are placed close together, more systems can be placed in a certain area. Placement of wells of the same temperature can lead to clusters of wells of the same temperature (Figure 1.2b). Using ATES planning wells of the same temperature can also be placed in lanes (Sommer et al., 2015), see Figure 1.2c.
Another option is to require the use of systems with a large storage volume. Several buildings are connected to one large system. Like placing wells of the same temperature together, this would increase the recovery of thermal energy because losses are lower for larger systems. The radius of the thermal zone does not increase linearly with system volume, so more thermal energy can be stored in a certain area. Requiring the use of large systems can also lead to the use of the whole aquifer thickness. It would however complicate applying ATES for individual building owners.

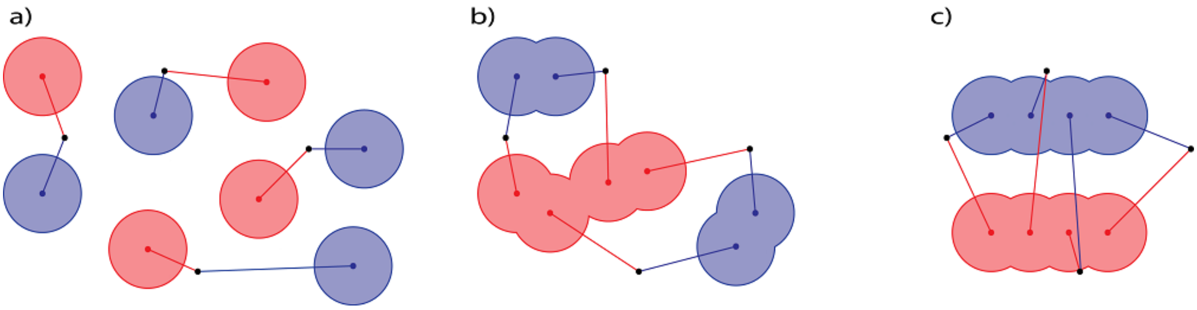

Figure 1.2: Arrangement of wells of four ATES systems. a) Random placement with a distance of $3R_{th}$ between wells. b) Random placement with a distance of $3R_{th}$ between wells of opposite temperature and $1R_{th}$ between wells of the same temperature, leading to clusters of the same temperature. c) Placement in lanes with a distance of $3R_{th}$ between wells of opposite temperature and $1R_{th}$ between wells of the same temperature.

This research focuses on the effect of placing wells of the same temperature together. The placement of wells of the same temperature together can have a positive effect on the recovery of thermal energy. Bakr et al. (2013) observed both increase and decrease in efficiencies of ATES systems due to mutual interaction, with a positive effect when wells of the same temperature are placed close together. The reduced distance also increases the total amount of thermal energy that is stored in a certain area. Individual building owners will be responsible for their individual ATES systems while the thermal zones are connected. This approach leads to extra investment cost compared to the case that several buildings are connected to one big system. It is however easier to implement because a partnership regarding responsibility for the system is not needed. Therefore this approach is taken more often in practice.

Currently individual ATES systems have to operate under thermal and volumetric balance (Lieten et al., 2012). If the thermal zones of several wells are combined, it is expected that imbalance could be tolerated for individual systems, while balance is required for a group of systems. Thermal energy is exchanged between wells of the same temperature. Warm water can be transported from a building with a larger cooling demand to a building with a larger heating demand, while the cold water is transported from the building with a larger heating demand to the building with larger cooling demand. This approach avoids regeneration of the wells which leads to a lower energy consumption and reduced investment and operation cost.

1.4. Goal of research

Placing wells of the same temperature together is already applied in practice. Research focused on the effect of this concept on geohydrologic and thermal performance is however still limited. The goal of this research is to assess the geohydrologic and thermal effects of applying the concepts for connecting ATES systems and identify a generic design and planning approach. This leads to the main research question:
How does connecting the thermal zones of ATES systems affect performance of individual ATES systems?

To answer the main research question the following questions will be answered:

- *How does the thermal performance of individual ATES systems change when the thermal zones of ATES systems are connected underground?*
- *Can imbalance in individual systems be accepted when the thermal zones of ATES systems are connected?*
- *Can more systems be implemented in a certain area by connecting the thermal zones of ATES systems?*
- *How does the geohydrologic performance of individual ATES systems change when the thermal zones of ATES systems are connected?*

1.5. Approach

The research questions will be answered using a generic approach and a case study. The generic approach takes into account characteristics of Dutch ATES systems. For the case study some individual cases at the TU Delft campus area are assessed.
In Chapter 2 the characteristics of ATES systems are described. The current situation in the Netherlands is explained in addition to the characteristics of the case study site. Finally the current literature on connecting ATES systems is described. Chapter 3 contains the methods and materials used in this study. The research approach is presented and the assessment framework is described. Chapters 4 and 5 contain the results of the generic and the case study, followed by the discussion and conclusions in Chapters 6 and 7.

2
Literature study

This literature study summarises the current research on ATES systems. The history of research on ATES is briefly covered to show why low temperature ATES is mostly applied. Several ATES characteristics which are important for this research are described. Next the characteristics of ATES and the case study area are given. Lastly the current research on interaction between multiple ATES systems is explained.

2.1. History of ATES research

Research on ATES systems started around 1960. In this part the development according to Fleuchaus et al. (2018) is summarised.

The first known application of ATES was in China. Groundwater was used to meet industrial cooling demand. To reduce land subsidence due to long term pumping of groundwater, artificial recharge was implemented. Research indicated that the water temperature was preserved for several months in the aquifer. Eventually these systems were forced to stop operating due to their unsustainable design. Especially clogging of wells and heat exchangers were among the encountered problems as well as imbalance of the systems due to the constant addition of thermal energy to the subsurface.

In the 1970's more theoretical research on ATES was conducted. The focus of this research was on the storage under high temperatures (HT-ATES). Practical experience revealed several operational problems. These problems included the scaling and clogging of wells and heat exchangers, corrosion of wells, buoyancy flow and thermal breakthrough, imbalance between stored heat and cold and the swelling of clay materials (Fleuchaus et al., 2018). Research in the years after proved that most problems are avoided by pre-investigation and operational management. Because less problems were encountered at lower storage temperatures, focus shifted to low temperature ATES (LT-ATES) with temperatures below 40 °C. Scientific focus shifted towards optimization of individual ATES systems, focused on the influence of ambient groundwater flow, buoyancy flow, dispersion, aquifer heterogeneity and building integration (Fleuchaus et al., 2018). Consensus is reached on many of the engineering problems for individual systems, leading to increasing implementation of the technology.

2.2. ATES characteristics

Working principle

ATES systems operate by seasonal storage of thermal energy in aquifers in two separate wells. The warm well stores water of 12-25°C and the cold well stores water of 6-12°C. In summer cold water is extracted for cooling of the building. A heat exchanger is used to transfer the thermal energy from the groundwater system to the building system. The heated water is then stored in the warm well. In winter the flow is reversed. Warm water is extracted and used to heat the building, often in combination with a heat pump because building heating systems cannot operate on the low temperatures of the warm well.

Conditions for ATES

Application of ATES systems requires several conditions (Bloemendal et al., 2015). Firstly a suitable aquifer with sufficient water is needed to temporary store thermal energy. Secondly the buildings should have an heating and cooling demand over the year, because ATES systems operate in equilibrium. Therefore temperate climates with a seasonal offset between supply and demand of thermal energy are suited for the application of ATES systems.

Thermal radius

When water is infiltrated in the aquifer it is assumed that the infiltrated water is stored in the shape of a cylinder. The diameter of this cylinder is called the hydraulic radius. When the water is infiltrated the thermal energy is stored in both the water and the soil particles in the aquifer. Thermal energy is exchanged between the water and the soil particles. The water at the edge of the hydraulic radius will adjust to the temperature of the ground. Therefore the transport of heat is retarded compared to the water transport. This leads to a smaller zone where the temperature is equal to the temperature of the well, also called the thermal zone. The radius of the thermal zone is called the thermal radius, defined by Equation 2.1.

$$R_{th} = \sqrt{\frac{V_s c_w}{c_{aq} \pi L}} \tag{2.1}$$

with R_{th} the thermal radius [m], V the seasonal storage volume $[m^3]$, c_w the heat capacity of water $[J/m^3/K]$, c_s volumetric heat capacity of saturated porous medium $[J/m^3/K]$, L the well screen length [m] and n the porosity of the soil [-].

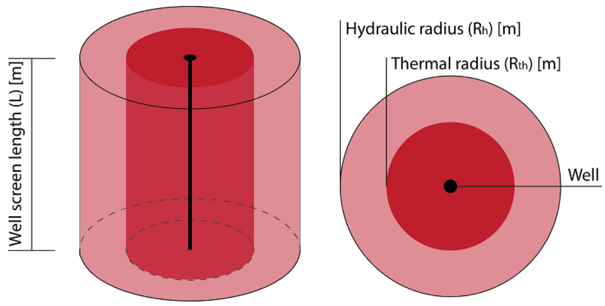

Figure 2.1: Cylinders representing the hydraulic radius (R_h) of water around the well and the thermal radius (R_{th}) of the thermal zone around the well. The height of the cylinder is the wells screen length L.

Temperature range

The temperature difference between the warm and cold well for ATES systems depend on several conditions. The temperature of the warm well is limited by problems occurring at high temperatures (> 40 °C) like scaling or corrosion (Fleuchaus et al., 2018) of wells and energy losses due to buoyancy (van Lopik et al., 2016). The maximum temperature is limited by current policy in the Netherlands based on the problems occurring at higher temperatures as described in Section 2.1. The injection temperature of the warm well depends on the characteristics of the building heating system, because for cooling no heat pump is used.
The temperature of the cold storage is limited by the freezing point of water (0 °C) and current policy (5 °C) to prevent freezing of water in the system (Lieten et al., 2012). In heating mode a heat pump is often used. The set point of the heat pump determines the injection temperature of the cold well and is therefore more constant.

Building system

A heat pump is needed because the temperature of the warm well is not sufficiently high to heat a building. Heat pumps transport heat from a low temperature region to a high temperature region, in this case the warm water from the heat exchanger and the building heating system respectively. Energy in the form of work is needed for the transport of thermal energy. The work is done by a compressor. A common parameter to assess the performance of a heat pump is the coefficient of performance (COP). This is the ratio between the delivered thermal energy by the heat pump and the energy consumed by the compressor. Because thermal energy is extracted from the water in the groundwatersystem, the temperature of the water decreases. This water is stored in the cold well. The water in the building system is heated to operating temperatures of 35

- 45°C. This water is used in low temperature heating systems inside the building. These systems consist mostly of floor or wall heating. These low temperature heating systems differ from conventional systems whose temperature is in the range of 70-90 °C.

External energy
While ATES system provide sustainable thermal energy, still some energy is needed for the pumps and the heat pump. For the whole system the COP is also used, expressed as the ratio between delivered thermal energy and the energy consumption of the well pumps and heat pump. More common is to determine the COP over a whole season, also called the seasonal performance factor (SPF) (Gao et al., 2017).

Losses and the thermal recovery efficiency
Not all energy stored in the aquifer is recaptured. Different processes contribute to the losses in the system. Due to ambient groundwater flow some of the thermal energy is transported away from the well.
At the edges of the thermal front losses to the surroundings occur. Due to a temperature difference heat is lost to the surroundings by conduction. Because the soil is never homogeneous on a small scale due to varying pore structure, losses due to differences in particle velocity occur. This process is called dispersion. Bloemendal and Hartog (2018) found that conduction losses dominate dispersion losses.
In case the distance between the wells of opposite temperature is not sufficiently large, mutual interaction between the warm and cold well can lead to losses. Mixing of the warm and cold water leads to a zone which temperature is equal to the average temperature of the two wells, which is often the ambient groundwater temperature. The warm water will cool down in this zone, while the cold water is heated up. This leads to losses in both wells.
Due to the losses not all energy is recaptured from the subsurface. This is expressed by the thermal recovery efficiency (η_{th}), the percentage of the thermal energy that is injected in the aquifer that is extracted in the next period. The thermal energy injected and extracted is calculated with respect to the natural temperature of the aquifer.
Over time efficiency of ATES systems increase (Doughty et al., 1982) because the soil is adjusted to the temperature of both wells. In the first cycles a large part of the thermal energy is used to adjust the temperature of the soil. A part of this energy cannot be extracted. In the next cycle the temperature of the soil is closer to the temperature of the well, leading to lower losses.

Volume and shape of the wells
The volume and shape of the thermal zone influence the thermal recovery efficiency. Losses occur at the boundary of the thermal zone. Minimizing the area of this boundary minimizes the losses. Therefore the ratio between the area of the thermal zone and the volume of the thermal zone (A/V) should be minimal.
Bloemendal and Hartog (2018) found that systems with a large storage volume have a high thermal recovery efficiency due to a low A/V value, which leads to a high efficiency. Figure 2.2 shows the relationship between well screen length and A/V for different storage volumes. An optimal well screen length exists where A/V is minimal. The minimal A/V value is small for systems with a large storage volume and is less sensitive to the well screen length. A lower A/V leads to a higher efficiency, as shown in figure 2.3. The efficiency increases linearly with decreasing A/V values under similar conditions. The different relation found in different studies is due to difference in parameters and model set-up.

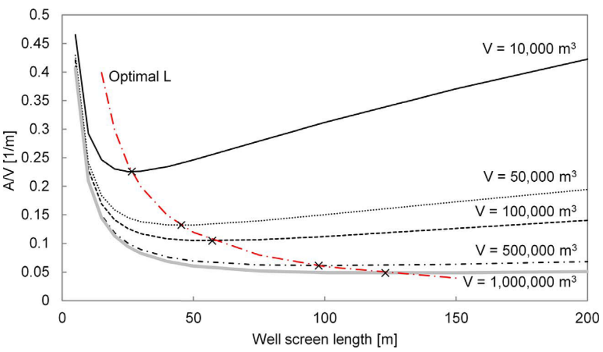

Figure 2.2: Relationship between the well screen length and the A/V value for different well sizes (Bloemendal and Hartog, 2018).

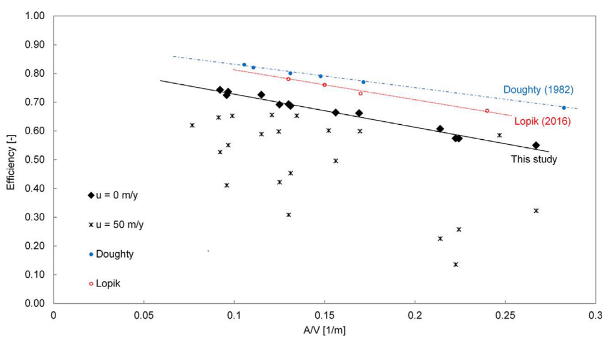

Figure 2.3: Relationship between the A/V value and the thermal recovery efficiency (Bloemendal and Hartog, 2018).

Minimizing the A/V ratio leads to an optimal ratio between the well screen length and the thermal radius (L/R_{th}). The thermal radius is the theoretical radius of the thermal zone in the aquifer and is defined by Equation 2.1. Wells with a large L/R_{th} value are shaped like a long cylinder, while wells with a small L/R_{th} value are shaped like a disk.vBloemendal and Hartog (2018) found an optimal ratio of 2 based on minimizing the area of the thermal zone. Doughty et al. (1982) found a different value by taking into account the different mechanisms for losses towards the confining layers and losses towards the surrounding aquifer. The value found in this research is $L/R_{th} = 1.5$, although this optimum was flat.
The A/V and L/R_{th} value for different well volumes and well screen length is presented in Figure 2.4

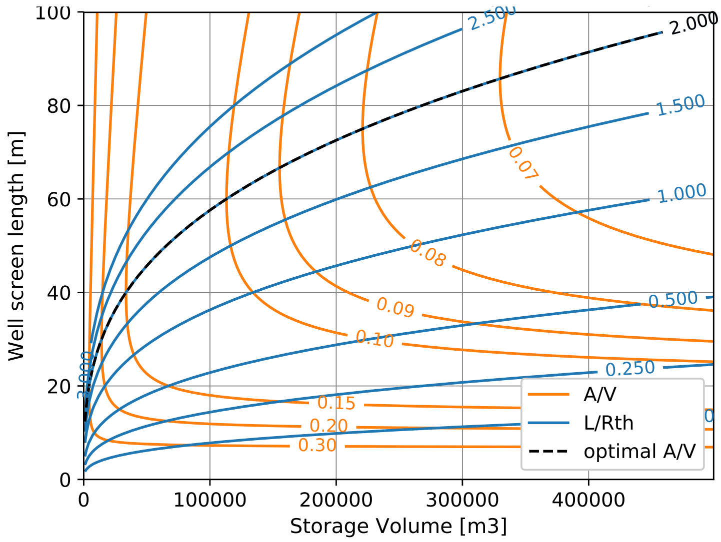

Figure 2.4: Values of A/V and L/R_{th} for different storage volumes and well screen length.

Thermal and volumetric balance
Every ATES system has to achieve thermal and volumetric balance in order to prevent heating or cooling of the soil. Volumetric balance means that the injected and extracted volume are equal. Equal flow does not guarantee equal amounts of energy, because the temperature difference between the aquifer and the injected water can differ. Therefore the energy balance or thermal balance is used.
When the volumetric balance is large, thermal breakthrough can occur. This happens when the system is not in equilibrium. The warm or cold well will grow in volume. This will continue until the water of one well is withdrawn at the other well. This is called thermal breakthrough, it has a large negative influence on system performance. Therefore both the volume of water and thermal energy stored in the wells should be equal over larger periods of time. When imbalance is present, one of the wells should be regenerated. This is often done with dry coolers or cooling towers when extra cooling capacity is needed. When extra heating capacity is needed solar heaters or thermal energy from surface water can be considered.
Research regarding the balance of ATES systems is limited. The energy balance ratio (eq 3.24) of ATES systems in the Netherlands is on average -0.02 for all systems. For individual systems the energy balance ratio varies between 0.22 and -0.22 for individual systems (Willemsen, 2016). This means that overall the balance is met while unbalance can occur in individual systems. The energy balance ratio per year depends on the variation in weather over the season. A strong correlation is found between the amount of thermal balance and the yearly temperature.

ATES systems in groundwater flow
In many aquifers the groundwater is flowing due to difference in hydraulic heads. The flow of ambient groundwater poses problems for the utilization of ATES. The movement of the water leads to displacement of the injected water, and therefore displacement of thermal energy. During extraction the well is unable to extract a part of the injected energy.
Groundwater flow in the Netherlands range between 0 - 200 m/year. With an ambient groundwater flow above 25 m/year, advection losses are dominant over conduction losses (Bloemendal and Olsthoorn, 2018). The extra losses lead to a decrease of the efficiency of the wells.
One option to mitigate the effect of ambient groundwater flow is to limit the well screen length of the wells.

Bloemendal and Olsthoorn (2018) found an optimum value for L/R_{th} of 0.5 for systems experiencing high ambient groundwater flow. Another option is to apply multiple doublets in the direction of the ambient groundwater flow. In this case the upstream wells can infiltrate the water. After displacement by the ambient groundwater flow, the water is extracted downstream by the extraction wells. The distance between the wells depends on the ambient groundwater flow. An optimal distance of 0.4 times the ambient groundwater flow was found. The pumping scheme determines the distribution of extracted volume over the two wells. Some water is extracted at the injection wells during peak demand. Large systems or systems with high ambient groundwater flow should minimize the amount of water extracted at the infiltration well.

2.3. ATES in the Netherlands

A large number of systems has been installed in the Netherlands. Currently around 2500 open systems are in operation in the Netherlands according to Fleuchaus et al. (2018), around 85% of all systems operational worldwide.

The preconditions for ATES are very favourable in the Netherlands (Bloemendal et al., 2015). Almost every part of the subsurface in the Netherlands is suitable for ATES (Technology, 2006). Generally thick aquifers consisting of sand at a depth of 70-200 m are present. These aquifers have a high permeability with low ambient groundwater flow. The combination of thick aquifers and high permeability enables wells to discharge large quantities of water. The low ambient groundwater flow leads to higher efficiencies for individual wells (Bloemendal and Olsthoorn, 2018) because no water is transported away from the well.
The Netherlands has a moderate climate. Buildings have both cooling and heating demand. The average temperature in the Netherlands is around 10 °C (KNMI, 2018) with a large deviation in summer and winter. The mismatch between supply and demand of thermal energy makes seasonal storage an interesting option. Current policy and acceptance in the Netherlands contributes to the success of ATES. The process of applying for a permit is generally short, around two months (Fleuchaus et al., 2018). Current policy is aimed at protection of individual systems, guaranteeing system performance over longer periods of time. Therefore a minimal distance of $3R_{th}$ between wells is applied (NVOE, 2006). ATES is accepted as a sustainable and economic way to supply thermal energy. Therefore ATES is considered as a suitable technology for new energy systems.

ATES is mainly applied at office buildings and large utility buildings. These buildings have both a large cooling demand and heating demand. A certain scale is needed to implement ATES economically. For smaller buildings investment cost like well drilling are relatively high. Furthermore the thermal recovery efficiency is higher for larger storage volumes. Therefore most ATES systems are installed for larger buildings, visualised in Figure 2.5. ATES could be applied at smaller buildings when a large systems is installed in combination with a low temperature heating network but this approach is not common practice.

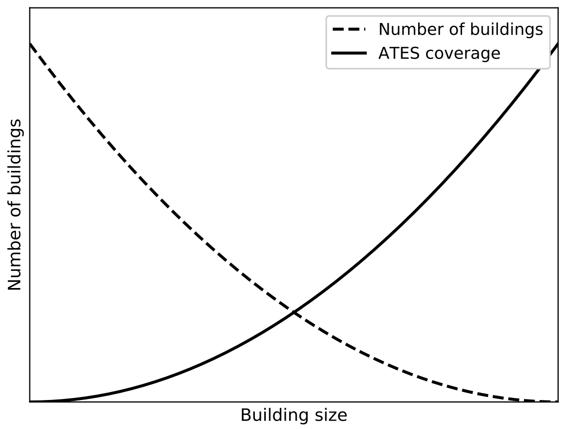

Figure 2.5: The reversed relation between building size and ATES coverage.

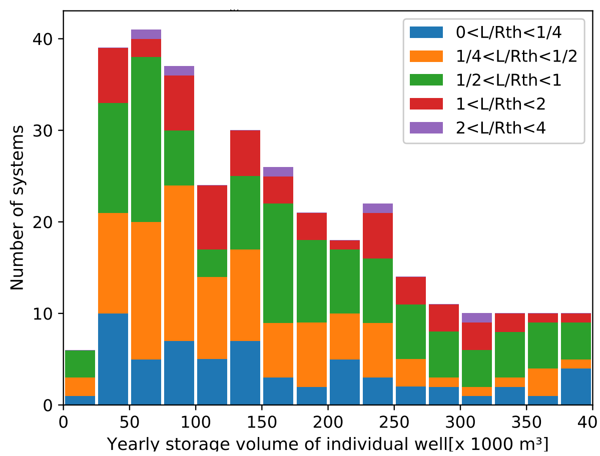

Figure 2.6: System size and L/Rth-ratio for systems in the Netherlands (Bloemendal and Hartog, 2018)

The distribution of storage volume and shape (L/R_{th} values) of systems in the Netherlands with volumes between 0 – 400.000 m^3/year is presented in Figure 2.6. The data represents around 15% of all systems in the Netherlands. Additionally, 62 systems with a storage volume larger than 400.000 m^3/year were found. This figure is based on well size data obtained by Bloemendal and Hartog (2018). In this research the average storage volume was 244.000 m^3/year. The L/Rth-ratio is generally between 0.25 and 1.

2.4. ATES in case study area

For the case study the campus area of the Delft university of technology (TU Delft) is considered. In this area a large number of ATES systems is already in use, see Figure 2.7. The systems are used to meet heating and cooling demand of large utility buildings. Many systems are already operational, but plans are made for the construction of even more systems. Due to the many systems planned in the area, an ATES plan was made to guide future well placement in a checker-board configuration. The goal of this plan is to avoid negative effects of mutual interaction between wells of opposite temperature and to facilitate as much systems as possible. The checker-board was chosen over lanes because of concerns regarding changes in water level in the aquifer. Due to the low ambient groundwater flow this configuration is possible. The placement of systems within the checker-board will lead to clusters of wells of the same temperature. The thermal zones will be connected if the wells are placed close together. It is therefore of importance for the TU Delft to know how the placement of wells can improve the system performance.

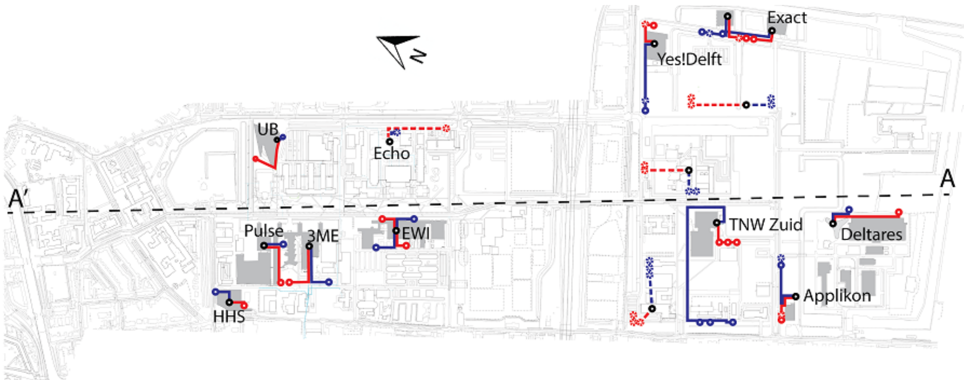

Figure 2.7: Systems currently in operation at the TU Delft campus area and planned systems (dashed). The red circles are warm wells, the blue circles cold wells. Cross section of the subsurface lithology is taken at intersection A-A'

Table 2.1: Characteristics of ATES systems in the TU Delft campus area based on measurement data during the start of operation until January 2019.

System	Volume	B_V	T_{ic}	T_{iw}
3M	14.500	0.2	9.4	15.2
3ME	56.000	-0.24	8.3	15.4
Applicon	16.000	0.14	7.0	15.0
Exact	38.000	-0.06	9.8	13.8
EWI	171.000	0.21	6.0	17.0
Haagse Hogeschool	Unknown			
Pulse*	50.000	0	8	15
TNW Zuid	149.000	0.24	7.0	17.0
UB	39.500	-0.02	7.8	17.2
Yes!Delft	44.000	-0.3	7.0	17.0

*based on design

The characteristics of current systems is described in Table 2.1. A total of 10 systems are in operation in the TU Delft campus area. The system of Deltares is situated just outside the campus area. System size varies between 14.500 $m^3/year$ to 149.000 $m^3/year$. Balance varies for the different systems but neither positive or negative imbalance is dominant. The temperature range is between 7 and 9.4 for the cold well and between 13.8 and 17.2 for the warm well. Some of the systems are placed close together. Both the warm wells and the cold wells of Exact and 3M are clustered. The warm wells of 3ME and Pulse are also placed together. The TNW

Zuid system has three wells for one system due to the high discharges. This system uses both aquifer 2A and 2B. In Appendix G the thermal zones at the TU Delft campus area are shown.

The subsurface lithology in the case study area consists of several layers. Figure 2.8 shows the soil layers at the TU Delft in cross section A-A' as shown in Figure 2.7. The model of the underground is taken from the database REGIS II (TNO, 2019b). The first aquifer is used for considerably groundwater extraction 2 km north of the study area. This extraction leads to considerable groundwater flow in the first aquifer. This extraction will be reduced over the following years.
The second aquifer is locally divided by a confining clay layer which extends around 1 km to the north. ATES systems are mainly placed in the top layer of aquifer 2. In this case referred to as aquifer 2A. The aquifer has an average thickness of 30 meter and lies between -40 to -70 N.A.P. The flow in the second aquifer due to the flow in the upper layer is approximately 5 m/s in NNW direction based on the contour lines in TNO (2019a).

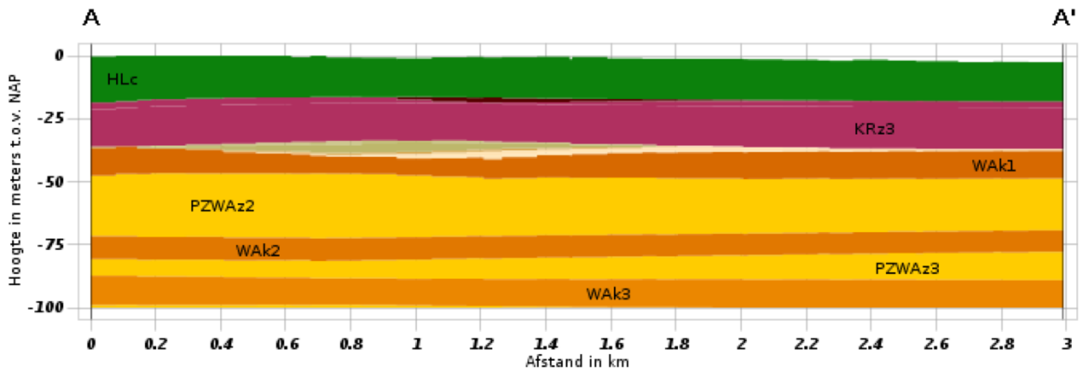

Figure 2.8: Subsurface lithology of the TU Delft campus area over cross section A-A'. The bright yellow layers PZWAz2 and PZWAz3 make up the second sandy layer which is locally divided by a clay layer.

2.5. Background and literature review on the connection of thermal zones

The high number of ATES systems in the Netherlands also leads to problems. In Chapter 1 the current problems with ATES in congested areas is described. Connecting individual ATES systems is proposed as a solution to these problems. This approach provides advantages for the total amount of thermal energy stored in an area and on the performance of individual systems. It could also have advantages by allowing imbalance in individual systems.

When implementing ATES in congested areas the misalignment between private and public interests has to be taken into account. Private parties want to optimize individual system performance by avoiding negative effects of mutual interaction while the public interest is to store as much thermal energy as possible.
Existing literature mainly focuses on avoiding the negative effects of mutual interaction. Mutual interaction is defined as the combination of effects of multiple wells where the thermal and geohydrologic effects are reinforced or cancelled. van Oostrom and Bakr (2012) describe how mutual interaction is often seen as negative by policy makers because of the focus on decreased thermal efficiency and suboptimal system performance. Mutual interaction could also have a positive effect if the efficiency of individual wells increases or if problems with groundwater are mitigated. This approach is often neglected in current literature.
Sommer et al. (2015) showed that positive effects of mutual interaction can increase thermal recovery efficiency by placing wells of the same temperature in lanes. By placing wells of the same temperature in lanes, one thermal front is created with a small surface area. Because losses occur at the boundary of the thermal front, a smaller area of the thermal front limits the losses. The aim of the research is to maximize the total amount of energy stored in a certain area. He showed that allowing a certain decrease in efficiency due to mutual interaction between wells of different temperatures maximizes the amount of thermal energy stored. Between 30 and 40% more energy could be provided compared to the case where all negative effects of mutual interaction is avoided. Therefore negative effects of mutual interaction can be accepted if the goal is to maximize total energy storage. The research of Sommer et al. (2015) found optimal distances between wells of 2.8-3.3 R_{th} between lanes and 0.41-0.56 R_{th} for wells in a lane.
The placement of wells of the same size in lanes is however not sufficient for practical use because practical

limitations like varying well size were not taken into account (Bloemendal et al., 2018). It could even lead to lower application of ATES because the first systems are placed at suboptimal locations. Bloemendal et al. (2018) therefore propose a stepwise policy approach depending on the allocated aquifer space in a certain area. Self planning using certain design rules is proposed at first. After a certain threshold is reached ATES planning can be implemented.
By using simple design rules, mutual interaction could increase thermal recovery efficiency of individual systems if the location of other wells is taken into account. Bakr et al. (2013) found positive and negative mutual interaction for wells in the area of Den Haag. There was no ATES planning in this area. By reducing the required distance between wells of the same temperature clusters were formed, see Figure 2.9. The change of system efficiency due to interaction found by Bakr et al. (2013) is presented in Figure 2.10. Overall most wells had higher thermal recovery efficiencies due to positive effects connecting thermal zones. The positive effects of mutual interaction is caused by creating thermal zones with bigger volumes with lower A/V values. Therefore losses to the surroundings and to thermal zones with different temperature are lower, leading to higher efficiencies.

Figure 2.9: Temperature of the thermal zones of systems in Den Haag (Bakr et al., 2013).

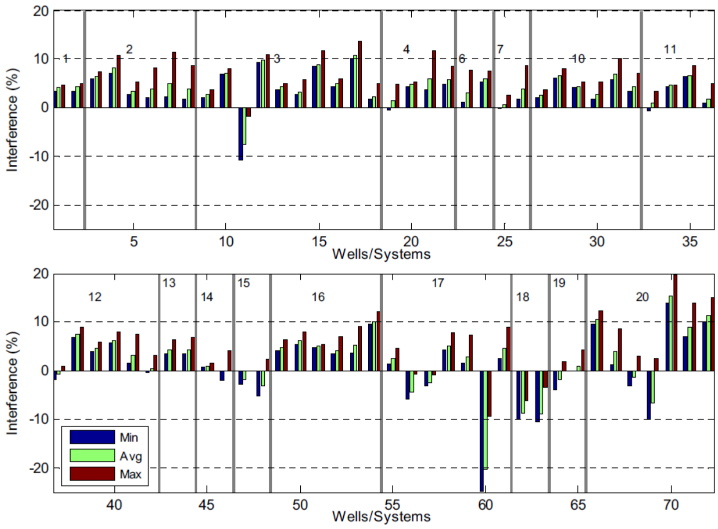

Figure 2.10: Effects of mutual interaction on thermal recovery efficiency in Den Haag (Bakr et al., 2013). A positive interference means the efficiency of the individual well is increased due to the presence of the other wells.

A method to quantify the effects of mutual interaction in a model study was proposed.The efficiency of the well assuming no other wells are present is used as a base case. The efficiency of the well with other wells present is calculated and the change in thermal recovery efficiency is calculated. This parameter is called interference in this research and is expressed as a percentage.
This study assess the effects of mutual interaction in a case study area with fixed well position. It does not

vary these positions to find optimal distances between wells. No research is currently focused on optimizing thermal recovery efficiency using the positive effects of mutual interaction.

Effect on imbalance

When thermal zones are connected imbalance in individual systems can be accepted, provided that balance is required for a group of systems. In this case heat and cold are transported between wells.

In the Netherlands, systems have to operate under thermal equilibrium to avoid temperature changes of the subsurface in order to protect future interests. In many cases regeneration of the cold or warm well is needed to guarantee balance of the system. Regeneration often leads to higher costs and a higher external energy consumption of the system. Research currently focuses on ways to optimize regeneration technologies, or to find alternative regeneration technologies. Combining systems with opposite imbalance to avoid regeneration is not considered in current literature.

Current research on the transport of heat in aquifers is currently limited. The Master Thesis of Jiang (2017) proved heat could be transported in aquifers using injection and extraction wells in combination with protection wells. The focus was on the efficiency of transport of high temperature water from a source to a sink. It did not consider transport of excess heat between wells in a group of ATES systems.

Effect on head during pumping

Placing wells with the same temperature together can have a positive effect on the thermal recovery efficiency and could allow for some imbalance in individual systems. The placement of wells together also has an influence on the head in the aquifer. Due to pumping at the well the head in the aquifer is lowered near the well. The drawdown at the well depends on the discharge of the well and on the transmissivity of the aquifer. Due to the drawdown at the well a gradient exists in the aquifer, leading to flow towards the well. The opposite effect occurs when the well is infiltrating.

When multiple wells are present in an aquifer the effects on the head of multiple wells is added using superposition. The total effect on the head is the combined effect of individual wells. In case that one well is extracting and one well is infiltrating, the effect on the head of individual wells is mitigated. This is shown in Figure 2.11. The red lines represent the individual effect on the head. The green line represents the effect of both wells on the head. In this case the drawdown at the well is reduced.

In the case that both wells are extracting or infiltrating the change in the head in increased, see Figure 2.12.

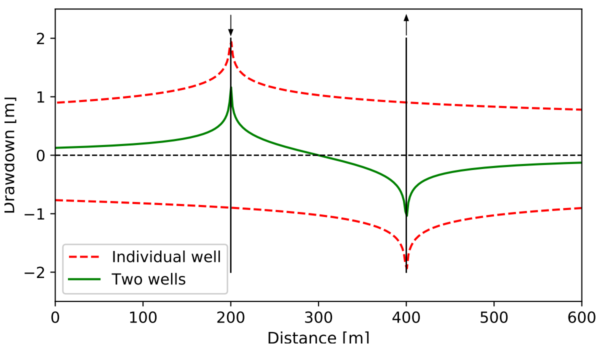

Figure 2.11: Example of the change of the head in the aquifer due to the combined effect of two wells with opposite discharge.

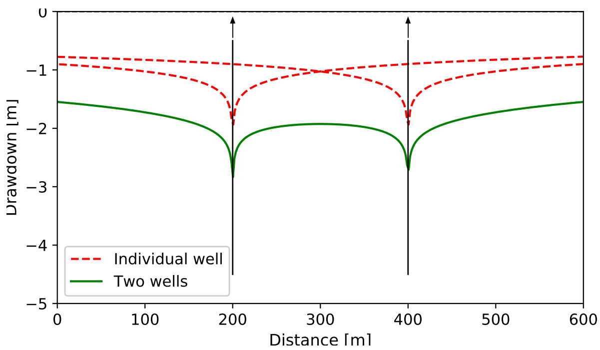

Figure 2.12: Example of the change of the head in the aquifer due to the combined effect of two wells with the same discharge.

The change in the head has an influence on many aspects of ATES design. Wells of the same temperature extract or infiltrate in the same seasons, while wells of different temperature always operate in opposite direction.

Placing two wells with the same temperature near each other will lead to a larger drawdown at the wells. This increases the amount of energy needed for pumping. Wells have a certain maximum injection pressure to avoid bursting of confining layers. Placing wells of the same temperature together increases the injection pressure in each well. Lastly changes in pressure can lead to changes in consolidation of the soil.

Because of of the mentioned aspects it is important to know how placing wells near each other influences the head in the aquifer. Two wells within one system will have a positive influence while two wells of the same temperature of different systems will have a negative influence.

3

Methods and materials

In the methods and materials the research approach is explained. In order to answer the research question as stated in Chapter 1 this research is split into a generic and a case study. The generic study will give insight in which parameters determine whether connecting ATES system leads to better system performance. The case study is used to gain insight in system performance under real circumstances. The governing processes of groundwater flow and heat transport are described as wells as the simulation tools. In the last part the parameters used to assess system performance are explained.

3.1. Research approach generic study

In the generic study three main subjects are distinguished. First the effect on the thermal recovery efficiency is assessed. The in the second section the effect of imbalance is assessed. The last part explains the effects of connecting ATES systems on the geohydrologic performance.

3.1.1. Effect on thermal recovery efficiency

Two wells

First the distance between two wells is varied between 0 and 4 times the thermal radius . The change in recovery efficiency is assessed for every distance. In this case both the effect of two wells of the same temperature and two wells with opposite temperature is taken into account. The size and shape of the wells are constant in this simulation. The storage volume is 250.000 m^3, which is an average size for system in the Netherlands according to Bloemendal and Hartog (2018). This volume is injected in one season and extracted in the next season. The flow is distributed over the year by a sine function, so that the total volume is equal to the storage volume. The shape is determined by the ratio between the screen length and the thermal radius (L/R_{th}). In this case a ratio of 1.35 is taken. The temperature of the cold wells is 7 ^oC and the temperature of the warm well is 17 ^oC, representing common temperatures for ATES systems in the Netherlands. Fully penetrating well screens are used with an aquifer with a thickness of 60 meter. The aquifer is confined with confining layers of 20 m to take into account losses to the confining layers. The effect of well distance is assessed using the ratio for the change in recovery efficiency as described in Section 3.5, Equation 3.16. It shows how much the thermal recovery efficiency is changed due the to interaction with other wells.

Figure 3.1: Definition of distance between wells of the same temperature (D_s) and the distance between wells of opposite temperature (D_o)

Two doublets

ATES operates by using a doublet. Therefore the wells of opposite temperature are always present at a limited distance. In the next part the influence of placing another doublet near the first doublet is taken into account. The thermal recovery efficiency of the warm well of the first system is calculated. The efficiency is calculated

taking into account a certain distance between the wells of the same temperature (D_s) and a certain distance between wells of opposite temperature (D_o). The efficiency is compared to the efficiency of the warm well of system 1, assuming the other wells are not present. This results in a ratio describing the change in recovery efficiency as defined in Section 3.5, Equation 3.16.
This process is repeated for different values of D_o and D_s to show the effect of different combinations of the distance on the thermal recovery efficiency. The value for D_o is varied between 0 and 4 and the value for D_s is varied between 0 and 5.5 times the thermal radius.

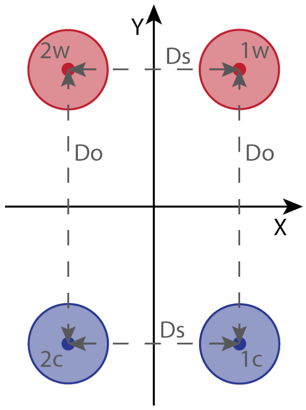

Figure 3.2: Definition of distance between wells of the same temperature (D_s) and distance between wells of opposite temperature ()D_o) for two doublets.

Storage volume and system shape
Secondly the storage volume, representing the size of the well, and the L/R_{th} value is changed to determine the effect of storage volume and shape of the thermal zone on the maximum change in thermal recovery efficiency. The wells are placed close together because the maximum effect is expected when the distance between wells of the same temperature is minimal. For the L/R_th values between 0.25 and 4 are taken into account. The optimal value of L/R_{th} is 2 based on minimizing the surface area over volume ratio (Bloemendal and Hartog, 2018). Doughty et al. (1982) found an optimum of 1.5 because the losses to the confining layers are different than the losses to the rest of the aquifer. This optimum was however flat, so a L/R_{th} between 1 and 4 should be acceptable. Bloemendal and Hartog (2018) found that many systems have lower values of L/R_{th} because of limiting aquifer thickness or due to the appliance of shorter screen to reduce drilling costs. The storage volume is varied between 0 and 350.000 m^3 based on storage volumes in the Netherlands (Bloemendal and Hartog, 2018).
Finally 12 combinations of storage volume and L/R_{th} values are taken and the distance between the wells is varied as described in Figure 3.2. The distance taken are $D_s = 1-3R_{th}$ and $D_o = 2.5-5R_{th}$ to reduce computation time. The values for L/R_{th} are 0.25, 0.5, 1 and 2. The volume are 50.000, 100.000 and 200.000 $m^3/year$.

For all systems the recovery efficiency and the theoretical A/V value is calculated, both in the individual and combined case. The these parameters are plotted together to see the relationship between A/V and the efficiency.

3.1.2. Effect on head in well

To asses the geohydrologic performance the drawdown at the well is taken into account. This is an indication for the head in the rest of the aquifer. Analytical methods are used to calculate the drawdown at the wells. Analytical methods are suitable because the objects only consist of wells in a theoretical finite aquifer without other objects. A finite difference method would need a grid at the well with a grid size equal to the diameter of the well. This would require a very small grid. Also boundary conditions need to be specified in the case of a finite difference method.
The following approach is taken to asses the effect of placing wells together. First the drawdown of the wells is calculated, assuming one system is in operation with a certain distance between the wells of opposite temperature. The same system characteristics as in Section 3.1.1 are taken. It is assumed that the diameter of the well is 0.3 meter and that the discharge is equally distributed over the season.

Another system is placed at a certain distance between wells of the same temperature. The drawdown in the wells of the first system is calculated and the increase in drawdown is calculated. The distance between wells of the same temperature (Ds) is varied between 0 and 4 Rth and the distance between wells of the different temperature is varied between 0 and 5.5 Rth.

The exact value of the drawdown of the well depends on aquifer properties like hydraulic conductivity and aquifer thickness and on the discharge from the well. The change in the drawdown does however not depend on aquifer properties or discharge, see Equation 3.3.
The increase in drawdown will have a negative effect on system performance because well pumps need more energy to extract and infiltrate the groundwater. The pumping energy is needed to overcome the change in drawdown in both the injection and extraction well and to overcome losses in the pipes and heat exchanger. The change in pumping energy due to the connection of thermal zones will have a negative effect of the system performance while the change in thermal recovery efficiency could have a positive effect. The combined effect is assessed by subtracting the increase in pumping energy (expressed as a factor) from the change in the thermal recovery efficiency. This is done for the various combinations of the distances between wells.
It is assumed that the efficiency of the pump is the same for different heads. Furthermore a well radius of 0.3 meter and constant losses in the pipe system of 20 meter is assumed.

3.1.3. Effect on imbalance

Connecting thermal zones could provide advantages for systems under imbalance. In the case that two systems have an opposite imbalance, energy can be exchanged between the systems without the need for pipes. Therefore the amount of energy transported between the wells is important in this case. The following approach is taken to assess the effect of placing systems with opposite imbalance together.

Effect of systems with imbalance placed together

First the general effects of placing systems with a certain imbalance together is assessed. Again a system with a certain storage volume (250.000 m^3) and shape (L/R_{th} = 1.35)is chosen. The distance between wells are $D_s = 1.5R_{th}$ and $D_o = 5R_{th}$. The thermal radius is calculated based on this average storage volume. A certain volumetric balance is chosen based on average values of thermal imbalance in the Netherlands (Willemsen, 2016). In this case a volumetric imbalance is chosen because a thermal imbalance is needs an iterative modelling approach. The volumetric balance is 0.15 for system 1 and -0.15 for system 2. Based on the storage volume and the volumetric imbalance the flow in each season is calculated. A sine wave function is used for the distribution of the flow over the season. The simulation time is 20 years because it is expected that some time is needed before the water from one well reaches the other well. The time step is 10 days.
The efficiency of the wells in system 1 are calculated. System 2 is not considered because the results for system 2 will be the same as system 1 due to symmetry . The thermal recovery efficiency is influenced by the imbalance of the system. In this case the warm well of system 1 injects more water than it extracts, leading to a low efficiency. Therefore the efficiency is normalized to the amount of water extracted at the well, see equation 3.21. The normalized efficiency provides information about the difference between the injection and extraction temperature with respect to the ambient groundwater temperature. The amount of energy extracted at each well is calculated to see if exchange of energy takes place. To visualise the processes the temperature in the aquifer is plotted. A conservative tracer is injected in the warm well of system 1 to see how the water moves in the aquifer.

Distance between wells

Secondly the effect of the distance between wells is assessed. Wells of the same temperature have to exchange energy. Therefore the distance between wells of opposite temperature (Do) is kept constant at five times the average thermal radius of both wells, while the distance between wells of the same temperature is varied. The distances considered in this research are shown in Figure 3.4.
The effect of the distance on the thermal recovery efficiency, the normalized recovery and the extra amount of energy extracted after 20 years of operation is displayed as a function of the distance between the wells.
The same is done for varying distance between wells of opposite temperature (D_o). In this case the distance between wells of the same temperature is taken at $D_s = 1.5R_{th}$. Evaluation of all combinations of D_o and D_s on the effect of imbalance like is done in Section 3.1.1 is not done in this case because simulation times are considerably longer.

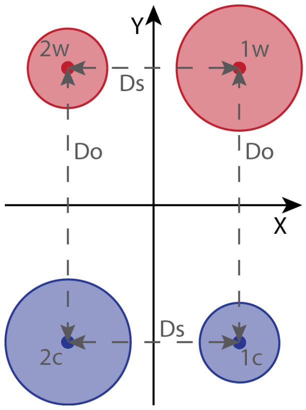

Figure 3.3: Definition of D_s and D_o between two doublets for two systems under imbalance

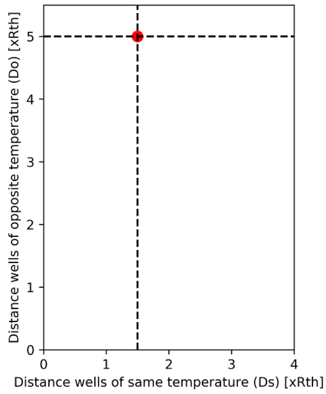

Figure 3.4: Combinations of distance D_o and D_s taken into account for the effects of imbalance.

Amount of imbalance

The effect of the degree of imbalance is taken into account.The distance between wells is kept constant at $D_o = 1.5R_{th}$ and $D_s = 5.0R_{th}$, see Figure 3.4. The degree of imbalance is varied between $B_V = 0$ and $B_V = 0.3$. The change in the thermal recovery efficiency is calculated and compared to the case where only one system is present.

Groundwater flow

Another aspect is the effect of ambient groundwater flow on the performance of ATES for systems with imbalance. Ambient groundwater flow transports water and therefore thermal energy away from the wells. In the case of imbalance the ambient groundwater flow could have a positive effect on the performance off the wells. Wells with a larger injected volume are placed upstream. The surplus of thermal energy is transported by the ambient groundwater flow to the wells that extract more water. This way the transport of thermal energy from wells with an energy surplus to the wells with an energy deficit enhanced due to the ambient groundwater flow. The new configuration is more complex and is shown in Figure 3.5. In this case it is assumed that the wells are placed in the direction of the flow. The effect of ambient groundwater flow in other directions is not taken into account. The velocity of the ambient groundwater flow is varied between 0 and 200 m/year. This range represents the values for the groundwater flow in the Netherlands (Bloemendal and Olsthoorn, 2018). The effect on the efficiency of both wells is assessed.

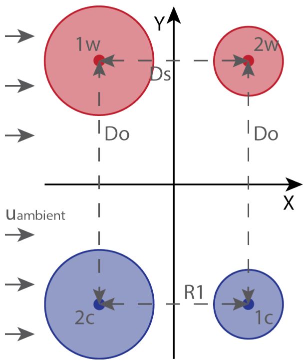

Figure 3.5: Placement of wells in case of ambient groundwater flow. The wells that infiltrate a larger volume are placed upstream, wells that extract a larger volume are placed downstream.

3.2. Research approach case study

The case study is split in two parts. The case Exact and 3M mainly looks into the effect on the thermal performance of connected systems. For the case Echo and Schoemakerstraat the focus is on the effect of imbalance when systems are connected.

3.2.1. Exact and 3M

The fist case considers the systems of Exact and 3M. These systems are small and both the warm and cold wells are placed close together. It can therefore be expected that connecting the thermal zones of these systems could lead to a better system performance due to the connection of the thermal zones. The system of Exact is constructed four years before the system of 3M. Therefore we could expect a deviation from the trend of the yearly efficiency of Exact over time due to the presence of the new system of 3M.
Monitoring data is available for both systems. The following approach is therefore taken. First the current performance of both systems is analysed based on monitoring data. Based on these data several model parameters are determined. The model parameters are used to model the theoretical performance of the systems. The expected performance of the system is then compared to the model results.

First the monitoring data is used to assess system performance and to determine the model parameters. The available monitoring data are the absolute value of the flow in the system, the pressure in the warm well and the pressure in the cold well (expressed in kPa or mwc) and the temperature in both wells. The data is available at 8 minute intervals and is obtained from Lift monitoring system. Because the flow was available in absolute values, the direction of flow had to be determined based on the pressure difference between the two wells. In case the pressure was higher in the cold well, it is assumed that the cold well was injecting and the warm well was extracting. This assumption is valid as the natural gradient in the aquifer is small. The injected and extracted energy could then be calculated per time step using Equation 3.17 – 3.20. The normalized efficiency can then be calculated for every year using Equation 3.16 and 3.21.

The model parameters determined are the injected and extracted volume at each well and the injection temperature at each well. The injected and extracted volumes are determined based on the direction of flow, the flow in the system and the interval time between measurements. The injection temperature is calculated by rewriting Equation 3.18 and 3.19 or 3.20 in order to calculate the average infiltration temperature. The ambient groundwater temperature is determined based on measurements from test drills in the area and verified based on the extracted water at Exact during the first extraction. The hydraulic conductivity and the thickness of the aquifer are obtained from the database REGIS II (TNO, 2019b).
Besides the real distance between the wells, another configuration is modelled with a shorter distance between the cold well to see whether this has effect on the expected efficiencies.

The model is run using the model parameters. It is assumed that the average yearly infiltration and extraction is distributed as a sine wave function.

3.2.2. Echo and Schoemakerstraat

The case of Echo and Schoemakerstraat considers two systems currently in the planning phase. This case is interesting because both systems will have a large volumetric and thermal imbalance. Schoemakerstraat is built for housing and has a dominant heating demand. This leads to the infiltration of more cold water over time, cooling down the subsurface. Under current legislation cooling down of the subsurface is allowed. In the current configuration the cold well is placed upstream of the warm well. Combined with the imbalance this could lead to thermal breakthrough between the wells.
The new building of Echo will be used by the university and is expected to have a dominant cooling demand. Due to legal requirements no excess warm water can be infiltrated in the subsurface. Echo will therefore use dry coolers to regenerate the cold well during winter.
Connecting the thermal zones underground could prevent the need for Echo to regenerate the cold well while preventing thermal breakthrough in the wells of Schoemakerstraat by exchanging energy between wells of the same temperature.

The effect of connecting the thermal zones of systems under imbalance is assessed by a model study. The design parameters for both systems are used as well as local soil characteristics. Echo is designed with a

storage volume of 50.000 mm^3/year for both wells in the case of regeneration of the cold well. In case regeneration is not applied it is assumed 31.879 m^3 is extracted from the cold well. The infiltration temperature of the cold well is 7 ^{o}C, the infiltration temperature of the warm well is 15 ^{o}C. The whole system infiltrates in aquifer 2A.
Schoemakerstraat has a design extraction of 114.000 m^3/year from the warm well and 62.000 m^3/year from the cold well. The infiltration temperature of the cold well is 8 ^{o}C, the infiltration temperature in the warm well 16 ^{o}C. Both aquifer 2A and 2B will be used by the system. It is assumed for this case that the discharge is equally split over the filter screen length in both aquifers, which is 12 meters for aquifer 2A and 13 meter for aquifer 2B (Buro Bron, 2018). Therefore 54.720 m^{3}is extracted form the warm well every year and 29.760 m^3/year from the cold well.

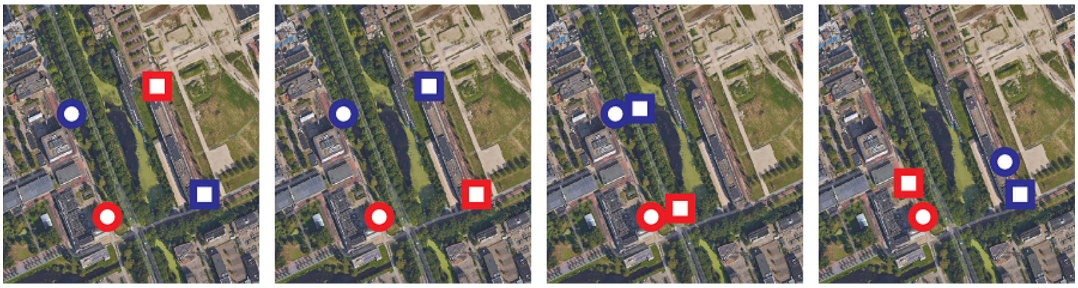

Figure 3.6: Configurations of wells of Echo (circles) and Schoemakerstraat (squares) for configuration 1-4, displayed from left to right.

Several configurations are modelled to see the effect of well placement, see Figure 3.6. In the first configuration the wells are placed at the locations proposed by current plans. In this configuration the checker-board configuration of the TU Delft is further extended outside the campus area. With the wells in configuration 1, two separate models are used. In the first (1a) it is assumed Echo will operate under volumetric balance. In the second (1b) case it is assumed Echo will extracts more water from the cold well. In the second configuration the warm and cold well of Schoemakerstraat are switched. The distance between wells of the same temperature is 5.5 times the thermal radius. In the third configuration the wells of Schoemakerstraat are placed at a distance of 1.0 times the thermal radius from the wells of Echo. In the last configuration the wells are placed in lanes in the flow of the ambient groundwater flow. The wells with a larger infiltrated volume are placed upstream of the wells with a larger extracted volume.

3.3. Governing processes

In order to determine the thermal and geohydrologic effects of ATES several processes are important. In this section the processes regarding groundwater flow and heat transport are explained.

Groundwater flow

ATES systems operate by extracting groundwater from one well and simultaneously infiltrating the groundwater in the other well. Pumping influences the hydraulic head at the wells which leads to flow in the aquifer. The three-dimensional movement of groundwater trough porous material is described by the partial-differential equation 3.1 (Harbaugh, 2005). Here the flow is calculated based on gradients in x,y and z direction, discharge at the sources or sinks and the storage in the aquifer.

$$\frac{\partial}{\partial x}\left(k_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t} \tag{3.1}$$

This is rewritten into:

$$\nabla(K\nabla h)=S_s\frac{\partial h}{\partial t}-W \tag{3.2}$$

with k$_{xx}$, k$_{yy}$ and k$_{zz}$ the hydraulic conductivity along the x, y and z axes [m/d]; h the hydraulic head [m]; W the the volumetric flux per unit volume, representing sources and/or sinks of water, [d^{-1}]; S$_s$ the specific storage of the porous material [m^{-1}]; t the time [d] and ∇ the gradient is x, y and z direction; k the hydraulic conductivity[m/d].

The analytic solution for the head around the a well in an infinite confined aquifer is given by:

$$h = \frac{Q}{2\pi kH} \ln r \tag{3.3}$$

with h the head [m]; Q the discharge [m^3/day], k the hydraulic conductivity of the soil [m/d], H the thickness of the aquifer [m], and r the distance from the well [m]
When multiple wells are considered the effect of individual wells is added using the principle of superposition. In the case of two wells with opposite discharge this leads to the equation:

$$h = \sum \frac{Q_i}{2\pi kH} \ln r_i \qquad \sum Q_i = 0 \tag{3.4}$$

with Q_i the discharge of well i (positive for extraction, negative for injection) [m^3/d]; and r_i the distance to well i [m]

Heat transport
The transport of heat is described by advection, conduction, diffusion and dispersion. Advection is the transport of heat by bulk motion. In this case water is used as a transport medium. Dispersion describes the uneven flow due to the heterogeneity of the soil matrix. Conduction is the transport of heat due to collisions between molecules in both the water and the soil. Energy is transported by conduction from a high temperature region to a low temperature region. Diffusion is the transport of water molecules due to random collisions. Diffusion leads to a transport of energy from high temperature to low temperature regions.

Heat is mainly transported to and from the well by advection. Water is infiltrated into the aquifer and extracted in the following season. Transport of this water leads to the transport of heat. Heterogeneity of the soil leads to uneven transport of heat at the local level. This process is called dispersion.
During infiltration the water flows into the aquifer, which has a different temperature than the infiltrated water. Due to conduction the thermal energy is distributed over the water/soil matrix. The soil matrix will adjust to the temperature of the infiltrated water. At the hydraulic front the infiltrated water will adjust to the initial temperature of the soil matrix, which is equal to the ambient groundwater temperature. The thermal front will therefore move slower from the well and is called retarded with respect to the hydraulic front.
Conduction also transports heat away from the thermal front. Heat loss therefore occur at the boundary of the thermal zone. Bloemendal and Hartog (2018) proves heat losses are dominated by conduction. The transport of heat depends on the temperature gradient. The transport of heat due to conduction is described by Fourier's law for heat transport:

$$\phi_q = -k_T \nabla T \tag{3.5}$$

with ϕ_q the local heat flux [W/m^2]; k_t the material thermal conductivity [W/m/K]; T the temperature [K].

In the soil the heat is distributed over the soil and the water. Soil and water have different heat capacities. An average heat capacity is used for the aquifer using the porosity, the density of the soil and the water and the heat capacity of soil and water. The thermal conductivity of the soil and water differs as well. Therefore the bulk thermal conductivity k_{Tbulk} is used. k_{Tbulk} is calculated using the arithmetic mean (Equation 3.6) or geometric mean (Equation 3.7). The value used for the bulk thermal conductivity is given in Table 3.1

$$k_{Tbulk} = \theta \cdot k_{Tfluid} + (1-\theta)\, k_{Tsolid} \tag{3.6}$$

$$k_{Tbulk} = k_{Tfluid}^{\theta} \cdot k_{Tsolid}^{1-\theta} \tag{3.7}$$

The heat transport equation for heat transport in a porous medium is described by Equation 3.8 (Langevin et al., 2008).

$$\left(1 + \frac{1-\theta}{\theta} \frac{\rho_s}{\rho_f} \frac{c_{Psolid}}{c_{Pfluid}}\right) \frac{\partial(\theta T)}{\partial t} = \nabla \cdot \left[\theta \cdot \left(\frac{k_{Tbulk}}{\theta \rho_f c_{Pfluid}} + \alpha \frac{q}{\theta}\right) \cdot \nabla T\right] - \nabla \cdot (qT) - q_s' T_s \tag{3.8}$$

with θ the porosity of the soild [-]; ρ_s the density of the solid [kg/m^3]; ρ_f the density of the fluid [kg/m^3]; c_{Psolid} the specific heat capacity of the solid [J/kg/K]; c_{Pfluid} the specific heat capacity of water [J/kg/K]; k_{Tbulk} the bulk thermal conductivity of the aquifer material [W/m^2]; α the dispersivity tensor [m]; q the specific discharge [m/d]; q_s the specific discharge of sources or sinks [m/d]; T the temperature [°C]; T_s the temperature of sources or sinks [°C]

3.4. Simulation tools

The processes described in Section 3.3 are solved using numerical methods. Numerical methods more suitable for modelling heat transport in aquifers because they are capable of solving both the flow and heat transport equation. The effects of temperature on viscosity and density are taken into account. Numerical methods consists of a large number of simple equations, making them suitable to be solved by computer software. In this section the software used for solving the numerical methods is described. Furthermore, the characteristics of the model used in this study are given.

3.4.1. Software

The selected software to model the transport of heat is SEAWAT, which combines MODFLOW and MT3DMS. It is designed to simulate three-dimensional, variable density groundwater flow and multi-species transport (Langevin et al., 2008). It can also be used to simulate the transport of heat by treating heat as one of the solute species. Python is used as an interface to construct input files and to process SEAWAT output using the flopy package (Bakker et al., 2016). The code used for pre- and postprocessing is written by M. Bloemendal and M. Jaxa Rozen based on code developed by T. Oolsthoorn. This code is adjusted for this study. The input parameters in python are written in an excel file. In this thesis SEAWAT version 4, MODFLOW version 1.18.01 and MT3DMS version 5.20 are used.

MODFLOW

MODFLOW is a computer program that uses the finite difference method to solve the three dimensional groundwater flow equation on a rectangular finite difference grid (Harbaugh et al., 2000). It is written in FORTRAN and has a modular structure. The code is free and publicly available. MODFLOW is able to simulate groundwater flow in multi-layer aquifer systems. The grid is adjustable in the horizontal plane, but each layer consists of the same grid. The partial differential equation describing ground water flow (Equation 3.1) is solved by MODFLOW. For this study MODFLOW 2005 is used.

MT3DMS

MT3DMS is designed to simulate solute transport. It is a modular three-dimensional multi-species transport model. MT3DMS simulates advection, dispersion, sorption and reaction of solute species in the groundwater (Langevin et al., 2008). The solute transport equation solved by MT3DMS is Equation 3.9. It expresses the rate of change of concentration. To account for sorption of species to the soil material, a species-specific retardation factor is used. This retardation factor is multiplied with the rate of change.

$$\left(1+\frac{\rho_b K_d}{\theta}\right)\frac{\partial(\theta C)}{\partial t}=\nabla\cdot\left[\theta\left(D_m+\alpha\frac{q}{\theta}\right)\cdot\nabla C\right]-\nabla\cdot\left(qC\right)-q_s'C_s \tag{3.9}$$

with ρ_b the bulk density of the soil $[kg/m^3]$; K_d the distribution coefficient $[m^3/kg]$; θ the porosity [-]; C the concentration of the solute $[kg/m^3]$; t the time [d] D_m the molecular diffusion coefficient $[m^2/d]$; α the dispersivity tensor[m]; q the specific discharge [m/d] q_s the specific discharge of sinks and sources [m/d] C_s the sink or source concentration $[kg/m^3]$.

In this thesis the focus is on the simulation of heat transport in the soil. It is possible to simulate the transport of heat with MT3DMS because the mathematical description of heat transport is identical to the mathematical description of solute transport. This is shown by comparing the conductive heat transport described by Fourier's law (Equation 3.5) with Fick's law of diffusion (Equation 3.10)

$$\phi_m=-D_m\nabla C \tag{3.10}$$

with ϕ_m the diffusive mass flux $[kg/m^2/d]$.

Heat transport can therefore be simulated with MT3DMS. The diffusion of particles is replaced by conduction of temperature the the aquifer. The sorption of solutes to the soils is replaces by heat transport between the water and the soil. Advection and the dispersion are mathematically the same in the equation. In order to use MT3DMS to simulate heat transport Equation 3.8 should be rewritten using the thermal conduction K_{dtemp} $[m^2/d]$, the thermal distribution factor D_{mtemp} $[m^3/kg]$ and the bulk density of the soil ρ_b $[kg/m^3]$.

$$K_{dtemp}=\frac{c_{Psolid}}{\rho c_{Pfluid}} \tag{3.11}$$

$$D_{mtemp} = \frac{k_{Tbulk}}{\theta \rho c_{Pfluid}} \tag{3.12}$$

$$\rho_b = \rho_s (1-\theta) \tag{3.13}$$

Using these parameters equation 3.8 are rewritten into:

$$\left(1 + \frac{\rho_b K_{dtemp}}{\theta}\right)\frac{\partial(\theta T)}{\partial t} = \nabla \cdot \left[\theta\left(D_{mtemp} + \alpha \frac{q}{\theta}\right)\cdot \nabla T\right] - \nabla \cdot (qT) - q_s' T_s \tag{3.14}$$

Equation 3.14 is mathematically similar to Equation 3.9. Therefore heat transport can be modelled in MT3DMS as a species of solute transport. In this case the distribution coefficient K_d is replaced by the thermal distribution factor K_{dtemp}. The molecular diffusion coefficient D_m is replaced by the thermal conductivity D_{mtemp}.

SEAWAT

SEAWAT combines MODFLOW and MT3DMS to calculate the flow and heat transport at every time step. It is designed to simulate three-dimensional, variable density groundwater flow and multi-species transport (Langevin et al., 2008). It includes the effect of viscosity changes with temperature, difference in density. The flow equation used in SEAWAT is given in Equation 3.15 (Langevin et al., 2008).

$$\nabla \cdot \left[\rho_f \frac{\mu_0}{\mu} K_0 \left(\nabla h_0 + \frac{\rho_f - \rho_0}{\rho_0}\nabla z\right)\right] = \rho_f S_{s,0}\frac{\partial h_0}{\partial t} + \theta \frac{\partial \rho_f}{\partial C}\frac{\partial C}{\partial t} - \rho_s q_s' \tag{3.15}$$

with ρ_f the fluid density $[kg/m^3]$; μ_0 the dynamic viscosity at reference concentration and temperature $[kg/m/s]$; μ the dynamic viscosity $[kg/m/s]$; K_0 the hydraulic conductivity tensor of the material saturated with the reference fluid [m/d]; h_0 the hydraulic head measured in terms of the reference fluid at reference concentration and temperature [m]; ρ_0 the water density at the reference temperature and concentration $[kg/m^3]$; z the elevation head [m]; $S_{s,0}$ the specific storage $[m^{-1}]$; t the time [d] and ρ_s density of source or sink $[kg/m^3]$.

3.4.2. Model generic approach

Besides the characteristics of the model itself the mathematical approach and the model parameters have to be specified. These model parameters consist of normal parameters like fluid density, the layout of the grid, choice of the time step, initial conditions, boundary conditions and parameters describing the wells. The choice of these parameters are described in the following section.

Mathematical approach

The Preconditioned Conjugate Gradient (PCG) package is used to solve the numerical equations This is the most commonly used solver package because it is fast and does not require excessive memory.

Parameters

In the model the following parameters are specified. In the model several other parameters are calculated based on these parameters. The porosity assumed to be 0.3. It is only used for the calculation of the other parameters. For the different layers the porosity is specified in the model. The thermal conductivity is based on saturated sand and saturated clay. The heat capacity of soil is based on quartz sand.

Table 3.1: Model parameters used in this research.

Parameter	Symbol	Value	Formula	Unit
Porosity	θ	0.3		[-]
Specific storage	S_s	1e-5		$[m^{-1}]$
Thermal conductivity soil	$K_{T,s}$	3		[W/m/K]
Thermal conductivity clay	$K_{T,c}$	1		[W/m/K]
Thermal conductivity water	$K_{T,water}$	0.58		[W/m/K]
Heat capacity soil	$C_{p,s}$	710		[J/kg/K]
Heat capacity water	$C_{T,w}$	4183		[J/kg/K]
Density soil	ρ_s	2640		$[kg/m^3]$
Density water	ρ_w	1000		$[kg/m^3]$
Calculated parameter	Symbol	Value	Formula	Unit
Thermal conductivity aquifer	$k_{T,aq}$		$k_{T,s} * (1-n) + k_{T,w} * n$	W/m/K
Thermal conductivity aquitard	$k_{T,aqt}$		$k_{T,c} * (1-n) + k_{T,w} * n$	W/m/K
Bulk density soil	ρ_b		$\rho_s * (1-n) + \rho_w * n$	$[kg/m^3]$
Specific heat capacity aquifer	C_b		$C_{p,s} * \rho_s * (1-n) + C_{p,w} * \rho_w * n$	[J/kg/K]
Thermal distribution coefficient???	K_{dist}		$C_{p,s}/\rho_w/C_{p,w}$	$[kg/m^3]$

Grid

The three dimensional groundwater flow equation is calculated using a finite difference grid. In this study multiple wells are considered. Therefore a rectangular grid is required. The default option to increase grid size exponentially between wells is not suitable for this study because the thermal interaction between the wells is of interest. Therefore a constant grid is used with a length and width of 400 meters determined by the systems with the largest thermal radius and the largest distance between wells so that the theoretical thermal radius of both wells is within the constant grid. Inside this constant grid the grid size is constant at 4 meters. This discretization is within the minimum level of detail of 5 m to model the temperature field around ATES wells (Sommer et al., 2014). A finer grid would lead to a limited accuracy increase but also leads to a long runtime for the model. This has to be avoided because many configurations are taken into account in this study, which makes the modelling process time consuming. Using this configuration the Courant number is below 0.86 within the area around the wells.
Around the constant grid the grid size increases exponentially to 150 meters. The total length of this part is 1000 m on all sides to diminish effects of boundary conditions. The grid is presented in Figure 3.7.
The height of the grid cells is 5 meters everywhere. A homogeneous confined aquifer is considered. Therefore the flow is expected to be equally distributed over the depth of the aquifer. Therefore the layers are a bit coarse. The confining layers are 20 meters thick.

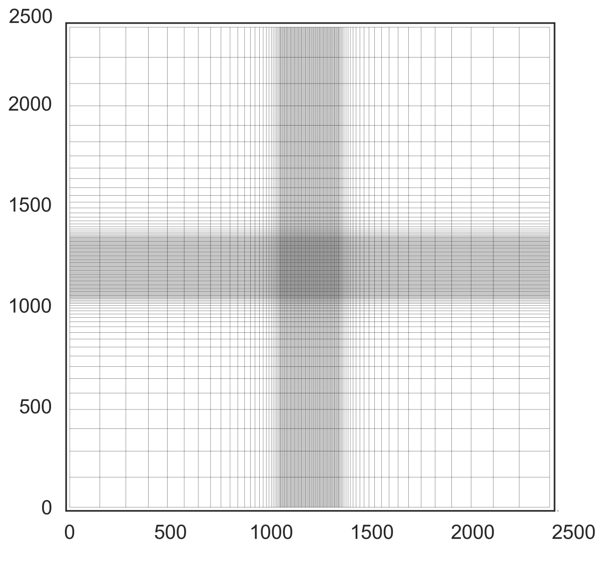

Figure 3.7: The rectangular grid used in the generic approach. The grid is constant in the middle for 400 m and increases in size exponentially towards the edges of the model.

Time step

The time step is determined by balancing accuracy and calculation time. In this study the difference between simulation results are more important than the actual thermal efficiency. Many configurations have to be modelled to gain insight in the performance of the system. Therefore a time step of 30 days is used in this study, although for some configurations a smaller time step is taken when short term effects are more important. The results did not differ much for cases where a smaller time step of 10 days was taken.

The system is started in the winter and a total run length of 5 years is chosen. This is done because efficiency is very low in the first years because the groundwater is not adjusted to the well temperature. After 5 years 90% of the final thermal recovery efficiency is reached (Sommer et al., 2013). The final efficiency is not necessary because the increase of thermal recovery efficiency is more important than the exact value of the thermal recovery efficiency.

Initial and boundary conditions

In this case a groundwater temperature of 12 °C is assumed. This value is suitable for the Dutch case. The head is initially zero everywhere in the aquifer.

The boundary conditions are determined by the initial conditions. At the edges of the model the initial temperature and initial pressure head is maintained. Sufficient distance between the wells and the edge of the model is needed to guarantee the influence of the boundary conditions can be neglected.

Wells

The volumetric balance is assumed to be zero, unless explicitly indicated otherwise . This means that exactly the same volume is injected and extracted from the cold and the warm well.

Density

Effect of solutes and temperature on the fluid density is taken into account by SEAWAT. Differences in density can lead to buoyancy which affects the performance of the wells. Fresh water has the highest density at 4 degree ^oC and decreases as temperature increases. The relationship between the temperature and water density in non-linear, see Figure 3.8 based on data from EngineeringToolbox (2003).

SEAWAT only considers a linear relationship between water temperature and water density. Therefore a linear relation has to be assumed in the model. In this study only low temperature ATES systems are considered. Therefore the temperature density relationship between 5 and 25 degrees is most important. The tangent of the graph in this part has a slope of around -0.14 kg/m^3/K. This value is used in the model.

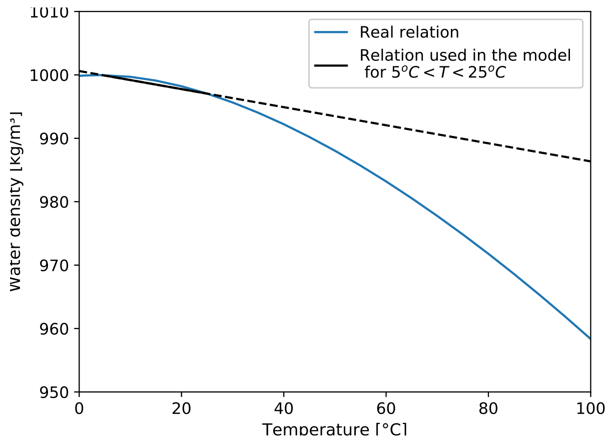

Figure 3.8: Relationship between water temperature and water density. MODFLOW uses a linear relationship which is shown with a black line.

The effect of solute concentration on the density of the fluid is not taken into account in this study.

3.4.3. Model case study

The modelling approach of the model study is almost the same as the modelling approach of the generic study. The same mathematical approach and the same parameters are used. The runtime is 20 years because transport of energy in the aquifer between wells is expected to take a longer time. The time step is also shorter to see the effects of imbalance during one season. The time step used is 10 days

3.5. Assessment framework

The thermal and geohydrologic performance of the systems are assessed based on several criteria. The criteria are listed below.

Thermal recovery efficiency

One of the most important parameters to assess the performance of an ATES system is the thermal recovery efficiency (η_T). This is the percentage of the thermal energy injected in the subsurface that is extracted from the subsurface in the next season. A 100 % recovery efficiency means all energy stored in a previous cycle is extracted. The yearly thermal recovery efficiency is calculated using Equation 3.16.

The thermal energy is measured with respect to the ambient groundwater level. Both energy used for heating and energy used for cooling is regarded as thermal energy. Therefore the definition of the ΔT is equal but negative for cold wells.

$$\eta_{th} = \frac{E_{extr}}{E_{inf}} 100\% \tag{3.16}$$

$$E_{extr} = \int (Q_{extr} c_w \Delta T) dt \tag{3.17}$$

$$E_{inf} = \int (Q_{inf} c_w \Delta T) dt \tag{3.18}$$

For the warm well:

$$\Delta T_w = T - T_{amb} \tag{3.19}$$

For the cold well:

$$\Delta T_c = -(T - T_{amb}) \tag{3.20}$$

Normalized thermal recovery efficiency

In case of volumetric imbalance the definition of the thermal recovery efficiency is less useful because the extracted and infiltrated volumes are not the same. Therefore the recovery efficiency can be normalised by dividing the thermal recovery efficiency η_T by the volume recovery ratio (η_V) of the well.

$$\eta_{\text{th,norm}} = \frac{\eta_{th}}{\eta_V}, \qquad \eta_V = \frac{V_{\text{extr}}}{V_{\text{inf}}} \tag{3.21}$$

Change in thermal recovery efficiency

In this thesis the thermal interaction between wells is of key interest. To quantify the effect on thermal recovery efficiency a similar approach as proposed by Bakr et al. (2013) is followed. The change in thermal recovery efficiency due to the influence of other wells is calculated, expressed by F$_M I$. First the thermal recovery efficiency of one wells is calculated, assuming no other wells are present. Then the thermal recovery efficiency of the same well is calculated, assuming that the other wells are present. The change in thermal recovery efficiency is calculated and expressed as a factor to avoid confusion between the thermal recovery efficiency and the change of thermal recovery efficiency due to interaction with other wells.

If F_{MI} is above 1 the presence of another well has a positive influence on the thermal recovery efficiency of the well. If the F_{MI} is below 1 the presence of other wells has a negative influence on the thermal recovery efficiency. In the case that the F_{MI} is below 0 thermal breakthrough from another well occurs. In this thesis the term change in recovery efficiency is used.

$$F_{MI} = \frac{\eta_{th,all} - \eta_{th,ind}}{\eta_{th,ind}} + 1 \tag{3.22}$$

with F$_{MI}$ factor describing change in thermal recovery efficiency due to mutual interaction [-]; $\eta_{T,all}$ the thermal recovery efficiency of the wells with all other wells in operation [%] and $\eta_{T,ind}$ the thermal recovery efficiency of the individual well with all other wells turned off [%].

Coefficient of performance

The coefficient of performance is another important parameter. The goal of the ATES system is to provide thermal energy temporary stored in the aquifer. Some additional energy is needed for the well pumps, heat pump, regeneration and other parts of the installation. To give an indication about the ratio between the provided thermal energy and the total energy needed for operation the coefficient of performance (COP) is defined in Equation 3.23 as the thermal energy extracted from a source divided by the external energy supplied to the system. In this case we are only interested in the groundwater system and the transport network. Therefore only the pumping energy is considered in the calculation of the COP. Energy requirements for heat pump and regeneration are not taken into account. When the COP is calculated over a whole year for all system components, the COP is also called the seasonal performance factor or SPF.

$$\eta_{COP} = \frac{\sum E_{extr}}{\sum E_{system}} \tag{3.23}$$

Thermal- and energy balance

The energy balance of the system is important to guarantee sustainable use of the subsurface. Thermal balance (energy balance ratio or B_E) is defined by the difference between the amount of energy extracted in cooling and heating modes, normalised by the total extracted energy (Equation 3.24). An B_E of 0 indicates a balanced system. Negative B_E indicates a prevailing heating demand of the system which means the subsurface is cooling down. A positive B_E indicates a prevailing cooling demand of the system which means the subsurface is heating up. The value of B_E is between -1 and 1. Another parameter to describe imbalance is the volumetric balance, equation 3.25. It is calculated in the same way as the energy balance but takes into account the injected and extracted volume instead of energy.

$$B_E = \frac{\sum E_{cool}^{extr} - \sum E_{heat}^{extr}}{\sum E_{cool}^{extr} + \sum E_{heat}^{extr}} \tag{3.24}$$

$$B_V = \frac{\sum V_{cool}^{extr} - \sum V_{heat}^{extr}}{\sum V_{cool}^{extr} + \sum V_{heat}^{extr}} \tag{3.25}$$

L/Rth and A/V

The parameters L/R_{th} and A/V are important parameters. L/R_{th} gives an indication of the shape of the thermal zone. It is calculated by dividing the well screen length L by the thermal radius R_{th}, described by Equation 2.1.

The A/V is also important because minimizing the A/V value minimizes losses to the surroundings. The A/V value is calculated with equation 3.26.

$$\frac{A}{V} = \frac{2\pi R_{th}^2 + 2\pi R_{th} L}{\pi R_{th}^2 L} = \frac{2}{L} + \frac{2}{R_{th}} \tag{3.26}$$

Head in the well

Changes in groundwater level are taken into account in this study. Transport of heat by water can have influence on the groundwater level and the hydrostatic pressure in the aquifer. In many cases changes in groundwater level are restricted to prevent several problems. Therefore these values are part of the assessment framework.

$$h = \sum \frac{Q_i}{2\pi T} \ln r_i, \qquad \sum Q_i = 0 \tag{3.27}$$

4 Results generic study

4.1. Increase in thermal recovery efficiency

4.1.1. Mutual interaction between two wells

In order to calculate the effect of placing wells together, two wells wit a storage volume of 250.000 m^3 and an L/R_{th} value of 1.35 are placed together. The distance D between the wells is expressed as a function of the thermal radius of the wells. In this case the thermal radius is 45 m. The effect of the well distance on the change in thermal recovery efficiency is given in Figure 4.1.
The red line indicates a decrease in thermal recovery efficiency due to placing two wells with of opposite temperature together. The decrease in efficiency confirms the negative effects of mutual interaction as placing wells of different temperature together results in an extreme decrease in thermal recovery efficiency. In this case the maximum decrease in efficiency is a factor -1.5 when a cold and warm well are placed at the same place. The cause of this extreme decrease is breakthrough of water between the wells, as shown in Figure 4.3 for D=0.1 R_{th} and D=0.5R_{th}. Wells in a doublet always operate in opposite direction. If placed close together the water will flow directly from the infiltrating well into the extracting well. This leads to a negative efficiency of the extracting well, leading to a factor for the change in recovery efficiency below 0.
Increasing the distance between wells with a different temperature prevents thermal breakthrough. The efficiency however is still lower because at the boundary between the warm and cold storage energy is transported due to conduction which leads to cooling of the warm water and heating of the cold water. This is shown in Figure 4.3, at D =1 R_{th},D=2R_{th} and D=3R_{th} . The influence becomes insignificant when the wells are 5R_{th} from each other. The change in thermal recovery efficiency for two wells with different temperature is exponentially convergent from -1.5 at 0R_{th} to 1 around 5R_{th}.

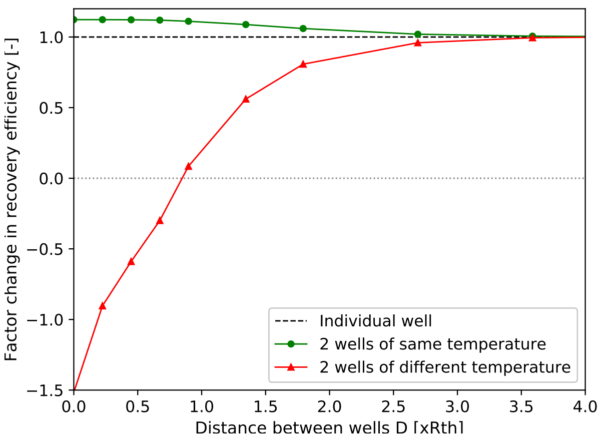

Figure 4.1: Effect of distance between two wells on the change in recovery efficiency for wells with a volume V=125000 m³ and L/Rth=1.35

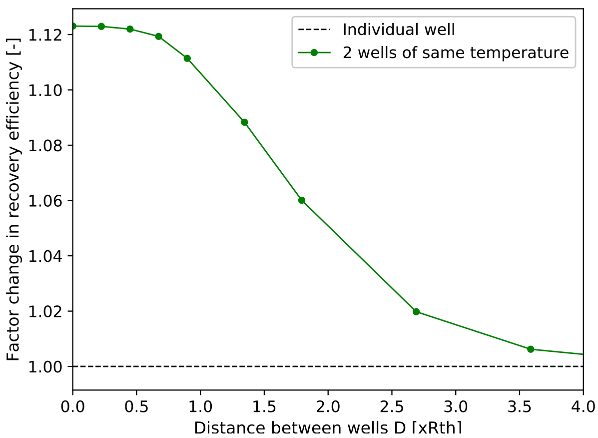

Figure 4.2: Focus on positive effect on the change in recovery efficiency for wells with a volume V=125000 m³ and L/Rth=1.35

The positive change in thermal recovery efficiency is small compared to the negative effect. This is expected because the positive effect of placing wells together is achieved due to the reduced area of the thermal zone compared to the total volume. A smaller A/V ratio leads to a higher efficiency (Bloemendal and Hartog, 2018).
The positive change in thermal recovery efficiency is shown separately in Figure 4.2. In the case of a yearly storage of 250.000 m^3 and a L/R_{th}value of 1.35 the maximum change in thermal recovery efficiency factor is 1.12 (12 % increase). The factor stays around 1.12 until a distance of $0.5R_{th}$. In this range the thermal zones of the wells is regarded as one big thermal zone of a well with twice the volume, see the left image for D=$0.1R_{th}$ in Figure 4.3. At a distance larger than $0.5R_{th}$ the change in thermal recovery efficiency decreases. The combined thermal zone becomes an ellipse (D=$0.5R_{th}$ and D=$1R_{th}$ on the left). The area of this shape is larger than the area of a cylinder. Therefore more losses occur at the boundaries and which leads to lower thermal recovery efficiencies. With increasing distance the thermal zones of the wells are separated until the change in thermal recovery efficiency is zero.

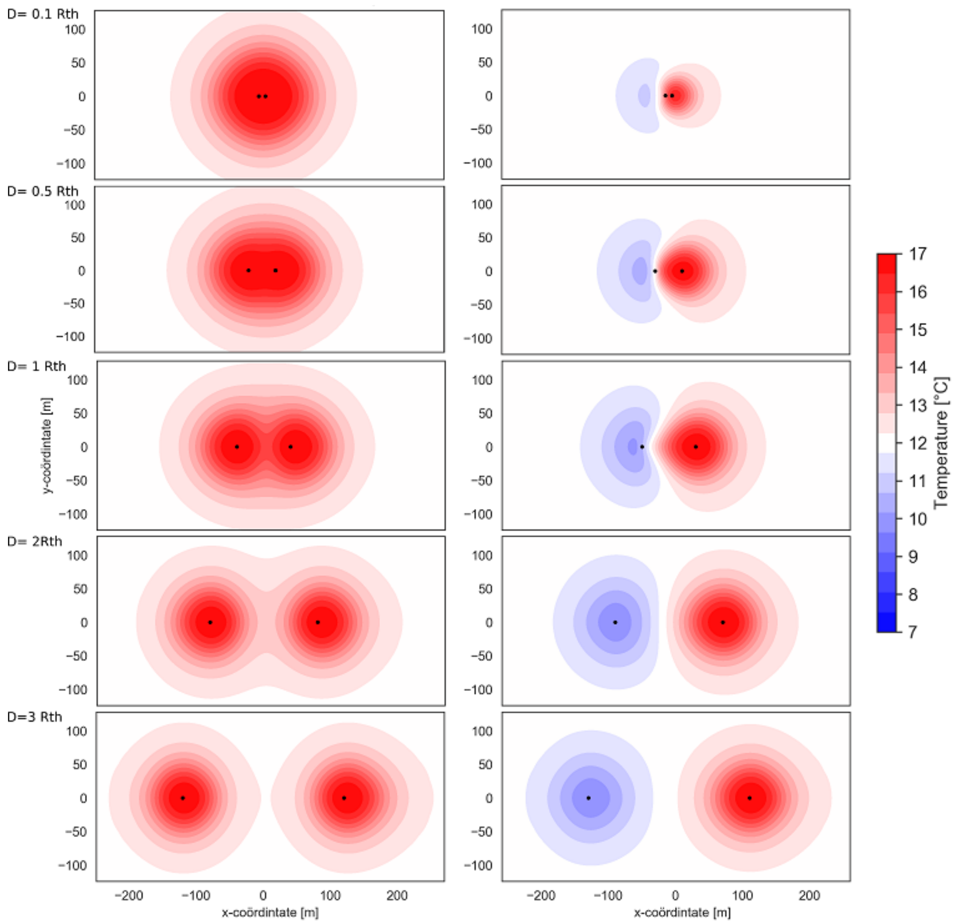

Figure 4.3: Visualisation of the thermal zone after 5 years at the end of the summer for 2 warm wells (left column) and for 1 warm and 1 cold well (right column) for different distances between the wells, expressed in terms of the thermal radius.

4.1.2. Mutual interaction between two doublets

The previous results presented in Figure 4.1 and Figure 4.2 only considered two wells. Only the effect of two wells of the same temperature or the effect of two wells with different temperature is taken into account. In practice ATES systems are constructed as a doublet. In the next part two doublets are considered to take into account the combined effect of wells of the same temperature and wells with a different temperature. The distance between wells of the same temperature (D_S) is varied as well as the distance between wells with a different temperature (D_O), see Figure 3.2. For each configuration the thermal recovery efficiency is calculated and compared to the case where no other wells are present to calculate the change in thermal recovery efficiency.

The results of these calculations are presented in Figure 4.4. The negative effects of mutual interaction are clearly present when wells of different temperature are placed closer than $D_O = 2.5R_{th}$ from each other. The distance D_S between wells of the same temperature has a minor influence when well of opposite temperature are placed close together. The efficiency is slightly lower when the wells of the same temperature are also placed near each other. This is likely because the thermal radius of the combined wells is larger than the thermal radius of individual wells. Doubling the volume by combining well leads to an increase of $\sqrt{2}$ in the thermal radius of the combined thermal zone. Therefore more distance is needed between the warm wells and cold wells to avoid negative effects of mutual interaction.
Some configurations lead to an increase of thermal efficiency. The boundary between increase and decrease of thermal recovery efficiency is visualised by the black line. Because this increase is small compared to the decrease, a separate scale for the positive change in efficiency is presented in Figure 4.4.
Between $D_O = 2.5R_{th}$ and $D_O = 4.5R_{th}$ the efficiency is increased if wells of the same temperature are placed close to each other. The optimal distance D_S varies between 0-1.5 R_{th}. This optimum is likely because when D_s is zero one thermal zone with a large thermal radius is formed, which comes into contact with the large thermal zone of the opposite temperature. When D_s is to large the thermal zones are not connected, leading to lower efficiencies.
When D_O is larger than $4.5R_{th}$ the influence of wells with a different temperature can be neglected. The change in thermal recovery efficiency only depends on D_S and has the same increase in recovery efficiency as seen in Figure 4.2. The maximum increase in efficiency is around 12 % in this case. It is achieved when wells of the same temperature are placed as close together as possible.

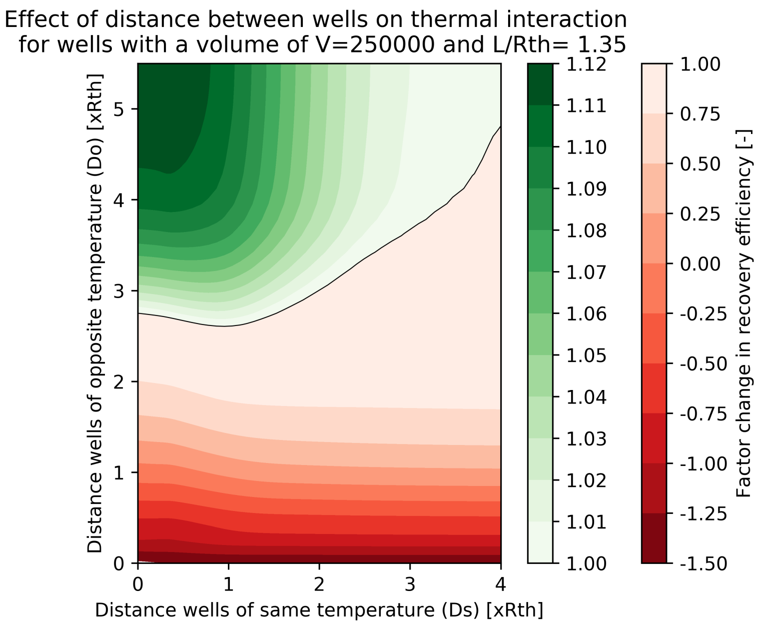

Figure 4.4: Relationship between distance between wells and the change and change in thermal recovery efficiency of individual wells, expressed as a factor. A value of 1 means no change in thermal recovery efficiency (black line), a factor larger than 1 means an increase in efficiency (green) and a factor below 1 means a decrease in efficiency (red).

4.1.3. Influence of storage volume and shape of thermal zone on maximum increase recovery efficiency

So far the effect of distance between wells has been studied. The storage volume and the shape of the thermal zone are expected to have an influence on the change in thermal recovery efficiency because they influence the A/V value. The shape of the well is defined by the ratio between the screen length L and the thermal radius R_{th}.

In this part the maximum increase in thermal recovery efficiency is calculated using varying volumes and L/R_{th} values. First the efficiency of one well with a certain volume and L/R_{th} is calculated, see Figure 4.5. The depth of the aquifer is the same as the screen length which is calculated using the volume and L/R_{th}. Then the efficiency is calculated for the case two wells with the same characteristics are placed together really close to each other. The distance should be small because it is expected that this will lead to the highest increase in efficiency. The results of various combinations of storage volume and L/R_{th}-values on the maximum change in thermal recovery efficiency is presented in Figure 4.6.

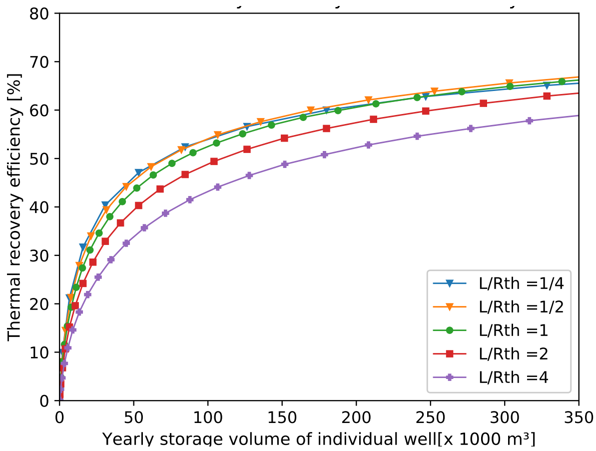

Figure 4.5: Relationship between storage volume and shape of the thermal zone and the thermal recovery efficiency of 1 well after 5 years.

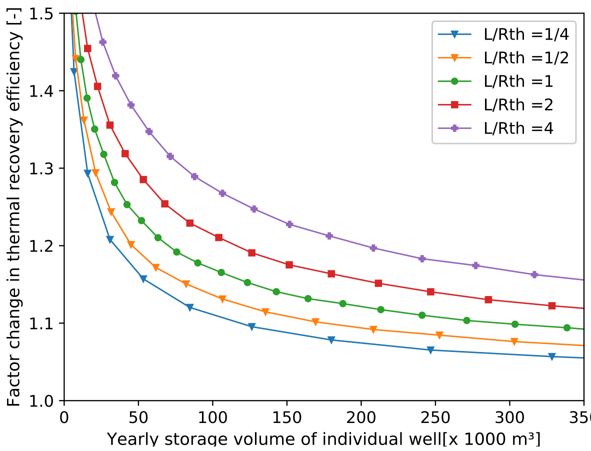

Figure 4.6: Maximum value of the increase in thermal recovery efficiency, expressed as a factor, due to connecting the thermal zones of two wells of the same temperature for different volumes and L/Rth-ratios.

Figure 4.5 shows larger systems have a higher efficiency than smaller systems. Systems with larger storage generally have a smaller A/V ratio which leads to lower losses (Bloemendal and Hartog, 2018) . The A/V ratio decreases with a smaller rate as the volume increases, therefore the efficiency increases with a smaller rate. The efficiency is higher when the L/R_{th} value is closer to 1.5.

Systems with large storage volumes have a small increase in thermal recovery efficiency, see Figure 4.6. Therefore connecting thermal zones of the same temperature is more advantageous for systems with a small storage volume because the initial efficiency is low for individual systems.

Systems with higher L/R_{th} values have a higher increase in recovery efficiency. Wells with a high L/R_{th} mainly lose energy at the side of the thermal zone and less at the edge between the aquifer and the confining layers. These systems have more advantage of placing another well nearby, because the area at the sides is reduced. Systems with a small L/R_{th} loose to the surrounding aquifer, and little to confining layers. The effect of placing wells near each other is limited.

It is concluded that systems with a small volume and high L/R_{th} value have the most advantages from combining ATES systems.

4.1.4. Distance between wells for different storage volumes and shape of thermal zone

The storage volume and and L/R_{th} have an influence of the maximum increase in thermal recovery efficiency, as shown in the previous part. The effect of distance between two wells of the same temperature is assessed for 12 configurations of storage volume and L/Rth values. The same approach as seen in Figure 4.2 is taken. The results are presented in Figure 4.6.
The results are consistent with the results obtained in the previous section. Small storage volumes and large L/R_{th} values have the highest increase in thermal recovery efficiency when wells are placed together.
Distance between wells has the largest effect on small storage volumes. The positive effect of placing wells of the same temperature together decreases faster with increasing distance for small systems. The values are relatively constant for distances between 0 and 0.5 R_{th}.

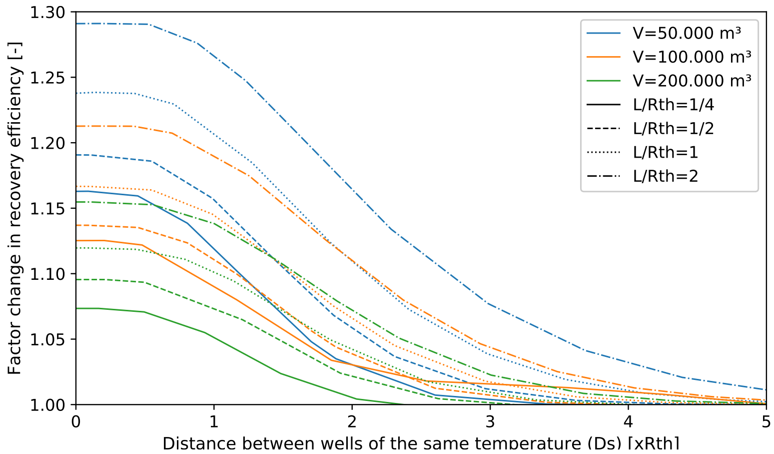

Figure 4.7: Influence of distance on the change in thermal recovery efficiency,expressed as a factor, for different storage volumes and L/R_{th} values.

The effect of storage volume and L/R_{th} values for different distances between wells is given in appendix C. The results are presented similarly to Figure 4.4 for different combinations of storage volume and L/R_{th} values. The largest increase is found for systems with a small storage volume and a high L/R_{th} value. Although the maximum increase varies for different configuration, the range of D_o and D_s where the change in recovery efficiency is positive is approximately the same. When the distance between wells of opposite temperature (D_o) is larger than $3R_{th}$ and the distance between wells of the same temperature (D_s) is limited, a positive effect was found for all configurations. The distance D_o where the maximum increase is found differs per configuration. Systems with a large storage volume and a low L/R_{th} value obtain the maximum increase when $D_o = 3R_{th}$. A low storage volume and large L/R_{th} value means the distance should be increased to around $D_o = 5.0R_{th}$ to obtain the maximum increase. The L/R_{th} value seems to be most dominant.

4.1.5. Increase in thermal recovery efficiency in relation to A/V values

For the systems described in Section 4.1.3 the A/V value of the thermal zones and the efficiency are calculated for the individual and combined case. The results are given in Figure 4.8. As shown in previous research the efficiency increases with decreasing A/V value. Besides the A/V value, the shape of the thermal zone is of influence of the thermal recovery efficiency. The shape is defined by the L/R_{th} value. Systems with a low L/R_{th} value achieve a high efficiency for the same A/V value. The relationship between A/V and efficiency is approximated as linear for systems with the same L/R_{th} value and for small A/V values.
The change in system efficiency and A/V value due to connecting thermal zones is presented by the dotted black line between points. All systems have a decrease in A/V and an increase of the thermal recovery efficiency. The largest reduction in A/V and the highest increase in efficiency is found in systems with a high A/V in the individual case. Systems with a small A/V have a low reduction in A/V (see figure 2.4) and therefore a small increase in thermal recovery efficiency. Systems with a large L/R_{th} have a large decrease in A/V because wells are connected side to side. This large decrease in A/V leads to a large increase in efficiency. At large A/V values the relation between A/V and efficiency is not linear and converges towards zero, see appendix D.

The same approach was taken for the systems shown in appendix C. In this case 12 systems with different volumes and shapes are considered. A/V and efficiency for individual and combined systems are calculated. The distance between wells of opposite temperature is 5 R_{th}. The results are shown in Figure 4.9. Connecting the wells of two systems leads to a lower A/V and a higher efficiency. Overall the efficiency increases with A/V value. For a certain well size there is however an optimal A/V value with a maximum efficiency. This optimum is at a slightly higher A/V than the minimum A/V. This is likely due to difference in losses to the surrounding aquifer and the losses to the confining layers, leading to an optimum L/Rth lower than 2 as found in other studies. This lower L/Rth leads to a higher A/V as shown in Figure 2.4.

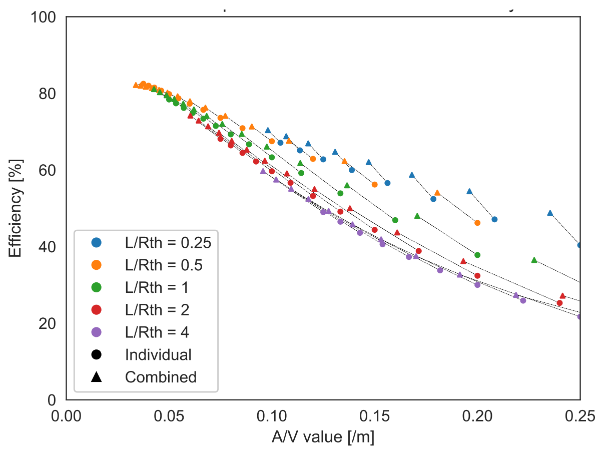

Figure 4.8: The A/V value compared to the the thermal recovery efficiency for different storage volume and storage shape. The dotted lines show the decrease in A/V and increase in efficiency when the thermal zones are combined.

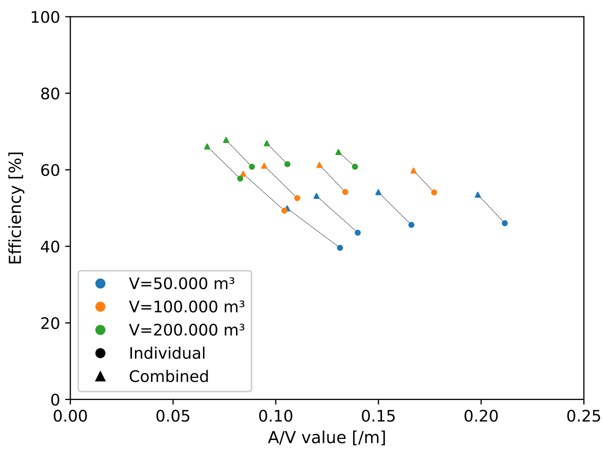

Figure 4.9: The A/V value compared the the thermal recovery efficiency for 12 configurations of V and L/Rth.

4.2. Effect on head in well

Placing multiple wells together results in change in the head in the aquifer and the drawdown at the well. In the previous section it was shown that wells of the same temperature should be placed close together to increase efficiency. Because wells of the same temperature generally inject and extract at the same time, it is expected that placing these wells close together effects the drawdown at the wells which negatively influences the required pumping energy.

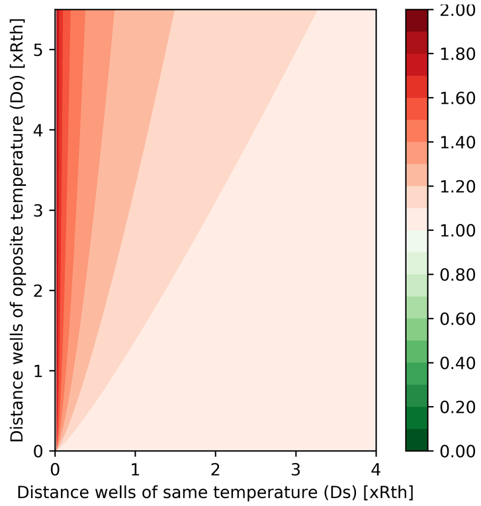

Figure 4.10: Change of the drawdown at the warm well of system 1 due to the presence of the other doublet, expressed as a factor.

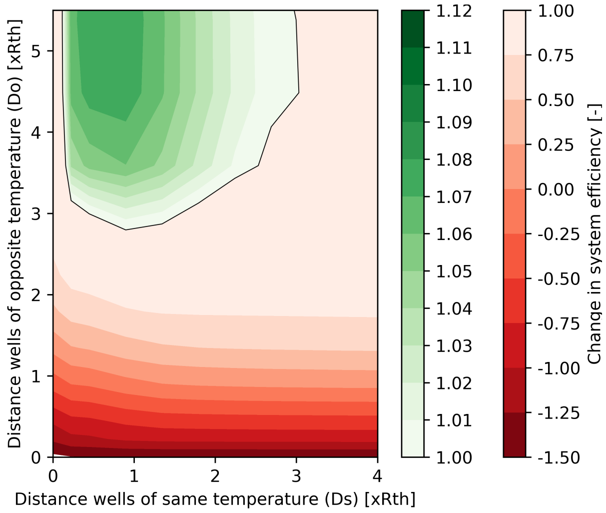

Figure 4.11: Combined effect of change in recovery efficiency and the change in pumping energy at the warm well of system 1 due to the presence of the other doublet, expressed as a factor.

The effect of distance between wells on the change in the drawdown is given in Figure 4.10. The factor indicates the change in drawdown in the well due to the presence of the other doublet. A factor above 1 means the absolute drawdown increases. The injecting well needs a higher head to infiltrate the same discharge. The well extracting has a lower head. An increase of the absolute drawdown is seen as negative because more more pumping energy is required. Therefore, values higher than 1 are displayed in red.
The figure shows the influence of placing a second doublet near the first doublet. This leads to a negative effect because the well with the same discharge is closer than the well with the opposite discharge. Placing wells of the same temperature close to each other leads to a large increase in the drawdown. The effect reduces exponentially with increasing distance between the wells (D_s). The distance between wells of opposite temperature (D_o) has a smaller influence. A larger distance leads to a larger increase in the drawdown.

The change in the drawdown leads to an increase of the required pumping energy. If the negative effect due to increased pumping energy is subtracted from the positive effect of mutual interaction, Figure 4.11 is obtained. Compared to Figure 4.4 the increase is somewhat lower. Increase in total system performance is however still positive if the distance between systems is chosen right. A certain distance between wells of the same temperature is needed. This distance is small because the increase in drawdown increases exponentially with reducing distance between wells. A distance of 0.5 times the thermal radius seems to be best in this case.

4.3. Effect on imbalance

In this section the results of connecting thermal zones of systems under imbalance is presented. System 1 has a prevailing cooling demand, leading to growth of the warm well over time. System 2 is placed near system 1 as presented in Figure 3.3 and has a prevailing heating demand, leading to growth of the cold well. First the results of placing systems with an opposite imbalance are presented. The effect of the distance between wells is considered as well as the effect of the degree of imbalance, the effect of the volume of the wells and the effect of ambient groundwater flow.

4.3.1. Effect of placing systems with imbalance next to each other

Placing systems with opposite imbalance together has a large influence on system performance. In Figure 4.12 the efficiency of the wells in system 1 is shown. Overall the efficiency grows over the first years. The efficiency of the warm well is low because only a part of the injected volume is extracted in the next season. It is showed that the efficiency of the warm well is higher in the individual case. In de individual case the warm zone keeps growing, improving the efficiency over the years. In the combined case the warm water is extracted by the warm well of system 2. Therefore the warm zone does not keep growing as in the individual case. In the individual case the efficiency of the cold well decreases after some years. This is likely due to the growth of the warm well, heating up the cold water near the cold well. This is showed in Appendix E, Figure E.2 and E.4.
The efficiency of the cold well is much higher in the combined case. The cold well receives thermal energy from the cold well of system 2. The efficiency is even higher than 100 %, which can only happen if energy is supplied from the outside of system 1. The increase in efficiency is due to 3 processes: Firstly transport from the cold well of system 2 to the cold well of system 1 due to the opposite imbalance of the systems. The second process that contributes to the increased efficiency is the connection of the thermal zones of the cold wells, leading to less losses to the surroundings as explained earlier. This effect is however small. The last process is the limited growth of the warm well of system 1, leading to lower losses because the warm well of system 1 does not keep growing, which would lead to higher losses at the cold well.

Because the warm well only extracts a part of the injected volume, the efficiency is very low for the warm well of system 1. Therefore the normalized efficiency is given in Figure 4.13 as is calculated in equation 3.21. The warm well has a higher efficiency than the cold wells when the volumetric imbalance is taken into account.

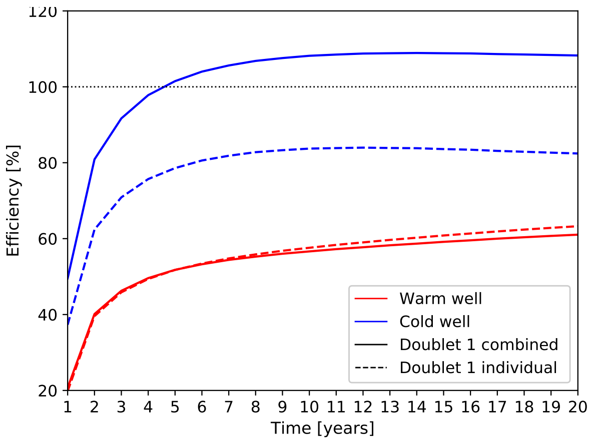

Figure 4.12: Efficiency in year 20 of system 1 for the combined and individual case.

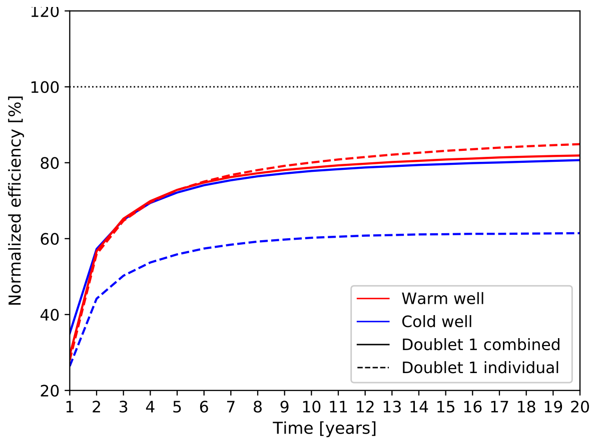

Figure 4.13: Efficiency normalized to the volumetric balance

Another way to look at the thermal performance is to look a the amount of energy extracted each year. The amount of energy extracted and injected in each year is shown in Figure 4.14. The dotted line represents the injected energy in each season. The energy injected in the warm well is higher than the amount of energy injected in the cold well due to the imbalance. In the combined case the cold well can extract more energy than was injected in the cold well. The extra amount of energy is supplied by the cold well of system 2. This shows that energy is exchanged between systems with opposite imbalance. In this case the amount of energy extracted from the cold well is around 30 % higher if you compare the combined case to the individual case.

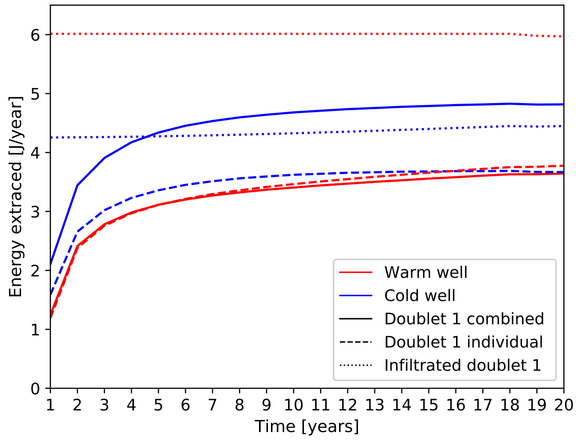

Figure 4.14: Amount of energy infiltrated and extracted at system 1 for the combined and individual case.

Visualisation of the flow from the well with a higher injected volume than extracted volume provides insight in the spread of water of the wells under imbalance. A conservative tracer was modelled to inject in the warm well of system 1. The results for a distance of $D_s = 0.5R_{th}$ and $D_o = 5R_{th}$ can be seen in Figures 4.15 and 4.16, representing the concentration of the tracer at the end of summer and the end of winter respectively after 20 years of operation. The gradient observed in the concentration is likely due to numerical diffusion.

During summer , the warm wells of system 1 and system 2 are both injecting. Therefore the water from the warm well of system 1 is pushed away from the warm well of system 2. This is shown by the white area on the left of the warm well of system 1. The discharge of the warm well of system 2 is however lower. Therefore the water from system 1 is somewhat closer to system 2. The water from system 1 flows around the water infiltrated by system 2. Because the cold well of system 1 is extracting during summer, the water tends to flow towards the cold well of system 1. Because of the imbalance water wants to flow from the warm well to the cold well. In Appendix E the result for the individual doublet is given in Figure E.6. Compared to the individual case less water flows from the warm well of system 1 to the cold well of system 1.
During winter time the flow in the wells is reversed. The warm wells are extracting water while the cold wells infiltrate water. Therefore the water from the warm well of system 1 is displaced by the water from the cold well of system 1. The warm well of system 2 is extracting more than the warm well of system 1. This leads to a flow of water injected by the warm well of system 1 towards the warm well of system 2. This flow leads to a net transport of energy from the warm well of system 1 towards the warm well of system 2.

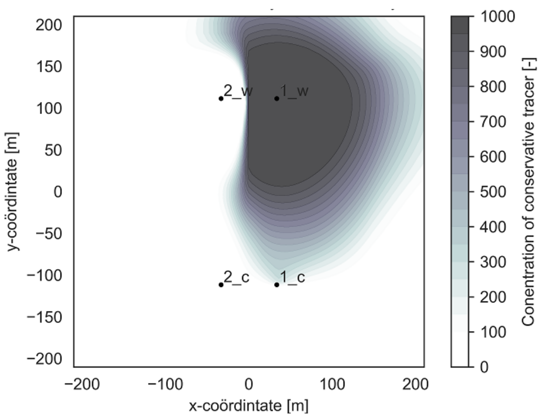

Figure 4.15: Spread conservative tracer at the end of summer in year 20.

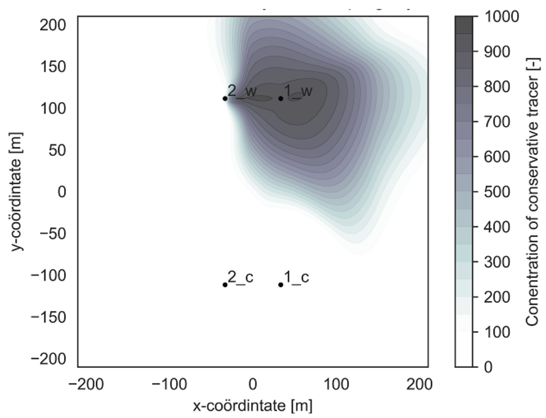

Figure 4.16: Spread conservative tracer at the end of winter in year 20

4.3.2. Effect of distance between systems

The effect of placing wells with opposite wells together reduces with increasing distance between wells of the same temperature. In this case the distance between wells of the same temperature (D_s) is varied between 0 and $6R_{th}$ while the distance between wells of opposite temperature (D_o) is kept constant at $5R_{th}$.

The effect of the distance between wells on the thermal recovery efficiency is presented in Figure 4.17. The cold well has a large increase in the amount of energy that is extracted at the cold well and therefore on the thermal recovery efficiency. In this case the factor is around 1.32 which represents an increase of 32 %. A larger distance leads to a lower increase. The effect is significant until around 6 R_{th}. Compared to the effect of connecting thermal zones without imbalance, as presented in Figure 4.1, the effect on the thermal recovery efficiency is significant for larger distances between the wells.

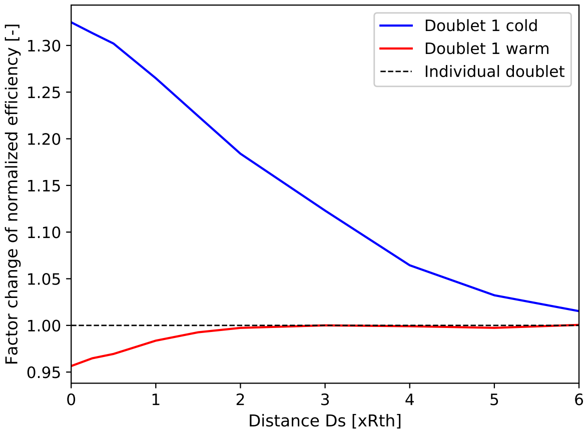

Figure 4.17: Change in normalized efficiency expressed as a factor for varying distance between wells of the same temperature (D_s) and a set distance between wells of opposite temperature of $D_o = 5R_{th}$ for two systems with an imbalance of $B_V = 0.15$

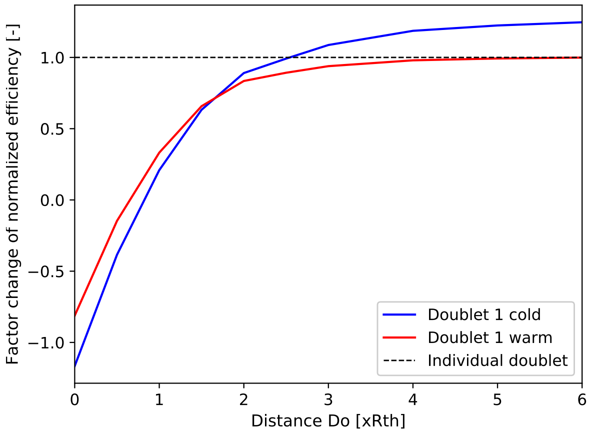

Figure 4.18: Change in normalized efficiency expressed as a factor for constant distance between wells of opposite temperature ($D_o = 1.5R_{th}$) and a varying distance between wells of opposite temperature of D_s for two systems with an imbalance of $B_V = 0.15$

4.3.3. Effect of the degree of imbalance

The amount of imbalance has a large influence on the recovery efficiency of the wells. It is expected that systems with a larger imbalance will transport more thermal energy to the other well, therefore the thermal recovery efficiency will increase more for larger values of the volumetric imbalance. This is presented in Figure 4.19. In this case the distance between wells is constant at $D_s = 1.5R_{th}$ and $D_o = 5.0R_{th}$.

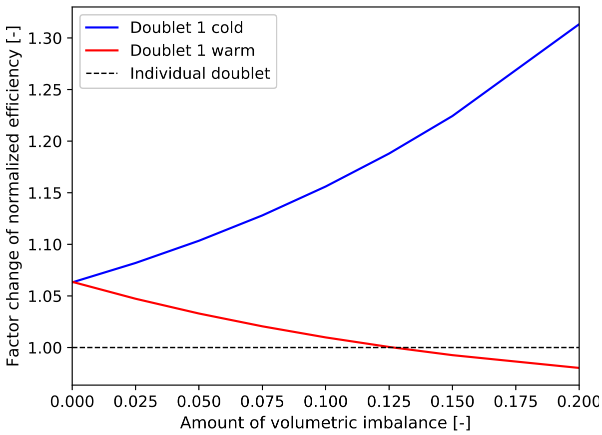

Figure 4.19: Effect of the degree of imbalance on the change in recovery efficiency.

When there is no imbalance in the system, both wells of system 1 will have a slightly higher efficiency. This is due to the positive effects of mutual interaction as described in Section 4.1. With growing imbalance

the efficiency of the cold well of system 1 increases due the transport of thermal energy from the cold well of system 2 to the cold well of system 1. The rate at which the efficiency increases becomes larger for a larger imbalance. This means that a larger fraction of the excess energy is extracted at the cold well.
The efficiency of the warm well of system 1 decreases because energy is transported to the warm well of system 2. When the volumetric imbalance is 0.125 the negative effect of the transport of heat equals the positive effect of mutual interaction between wells. At this point the warm well of system 1 has the same efficiency as in the case where only system 1 is present. When the volumetric imbalance becomes larger the efficiency decreases even further, although the decrease becomes smaller for a larger imbalance.
The negative effect on the warm well of system 1 is much smaller than the positive effect on the cold wells of system 1. This means that placing two systems with opposite imbalance together has a positive effect on the overall performance of the systems.

4.3.4. Effect of ambient groundwater flow

The results of ambient groundwater flow on a system is given in Figure 4.20. This system has a volume of 250.000 m^3, an L/R_{th} value of 1.35 and a distance between wells of $D_s = 0.2, 0.5, 1.5 R_{th}$ and $D_o = 5R_{th}$. The configuration in Figure 3.5 is used.

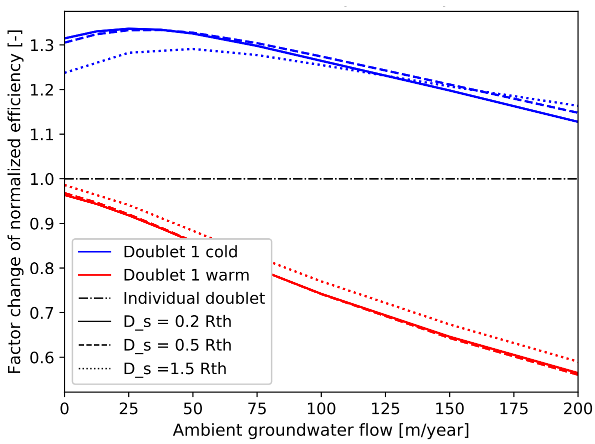

Figure 4.20: Effect of ambient groundwater flow on the change in recovery efficiency for different distance between wells of the same temperature.

The efficiency of the downstream of both systems is increased by ambient groundwater flow. For this case an optimum exist for the velocity of the groundwater flow. When no flow is present the energy can only be transported by pumping of the wells. Ambient groundwater flow transports energy from the well witch injects a larger volume to the well that extracts a larger volume. A larger ambient groundwater flow leads to more transport of thermal energy to the other well. When the flow becomes too large, the injected water and the thermal energy is transported with a larger velocity. The water passes the well downstream and is therefore not recovered by the well. This leads to a lower increase in efficiency for larger ambient groundwater flow.
In practice the ambient groundwater flow is known. In that case an optimal distance between wells of the same temperature exists where the increase in thermal recovery is highest, see Figure 4.20. This distance becomes larger for higher ambient groundwater flow velocities.

5

Results case study

5.1. Exact and 3M

Based on the monitoring data the current performance of Exact and 3M is determined as described in Section 3.2.1. The calculated normalized efficiency is presented in Figure 5.1. From the figure it can be seen that the normalized thermal recovery efficiency is high, ranging from 60 % to 90 % after the start up period. Taking into account the small size of both systems the efficiency is not expected to be that high. Based on the generic study it can be expected that Exact will perform better once 3M starts operating after 4 years of operation. This can however not be derived from the real data.
Using the monitoring data several model parameters could be determined. The injected and extracted volume as well as the injected temperature is determined for each well. The ambient groundwater temperature was 12 ^oC based on test drills and initial temperature of extracted water. In Table 5.1 the model parameters are summarized.

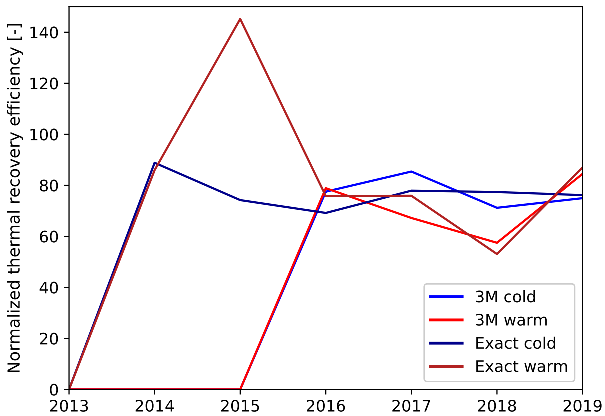

Figure 5.1: η_{norm} of the warm and cold wells over time for the 3M and Exact system based on monitoring data.

Table 5.1: Model parameters determined by data analysis of the Exact and 3M system.

System	Injected $[m^3/year]$	Extracted $[m^3/year]$	$T_{inj}[^oC]$	$T_{amb}[^oC]$
Exact cold	35,635	40,434	9.77	12
Exact warm	40,434	35,635	13.84	12
3M cold	17,536	11,569	9.39	12
3M warm	11,569	17,536	15.02	12

The results of the model are presented in Figure 5.2 and 5.3. In Figure 5.2 the normalized efficiency of Exact and 3M is shown over a period of 20 years. The dashed line represents the efficiency of the systems in the case that the other system would not be present. The dotted line represents the second configuration, where the cold well of 3M is placed closer towards the cold well of Exact.

It can be seen that the highest efficiency is achieved at Exact, especially the warm well. This is because Exact infiltrates more warm water than it is extracting, leading to a buffer of warm water around the warm well. The storage volume of Exact is also higher, leading to a lower A/V value and therefore to lower losses to the surroundings. Exact has a small advantage of connection of the thermal zones. Although the efficiency of the Exact system is still increasing before 3M starts, a clear deviation from the trend is visible. Due to the operation of 3M, the normalized recovery efficiency is 1.13 times higher for the cold well and 1.17 times higher for the warm well, see Figure 5.3
The efficiency of 3M without the presence of Exact is very low because of the low storage volume, which leads to a high A/V ratio and lower efficiency. The efficiency of the warm well is even lower because at the end of the season ambient groundwater is extracted due to the imbalance of 3M. Due to the small size of 3M, connection of the thermal zones leads to a large increase in the normalized thermal recovery efficiency. Figure 5.3 shows that placing the wells of 3M near the wells of Exact leads to a large increase in efficiency during start up. The efficiency is generally lower in the fist years because the aquifer temperature needs to adjust to the water temperature. In this case the soil around the Exact wells is already adjusted to the temperature of the wells, see Figure 5.4. Because less thermal energy is needed to adjust the soil to the right temperature, the efficiency is increased considerably in the first years.
The long term increase of normalized thermal recovery efficiency of the cold well is 1.28 times higher than the efficiency of 3M operating individually. The efficiency of the warm well is 1.50 times higher. The large increase of the normalized efficiency is due to the low efficiency of the warm well in individual operation due to the imbalance.

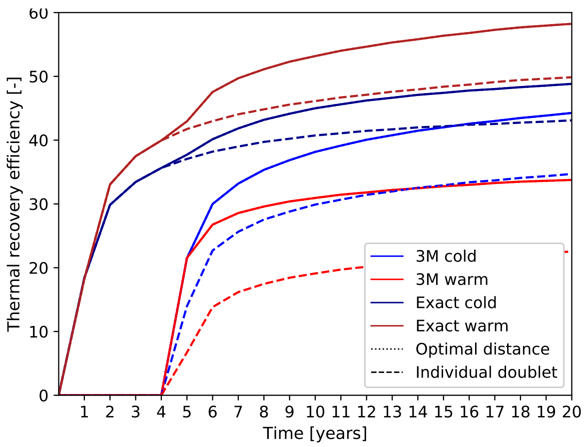

Figure 5.2: Normalized thermal recovery efficiency of the warm and cold wells over time based on the model.

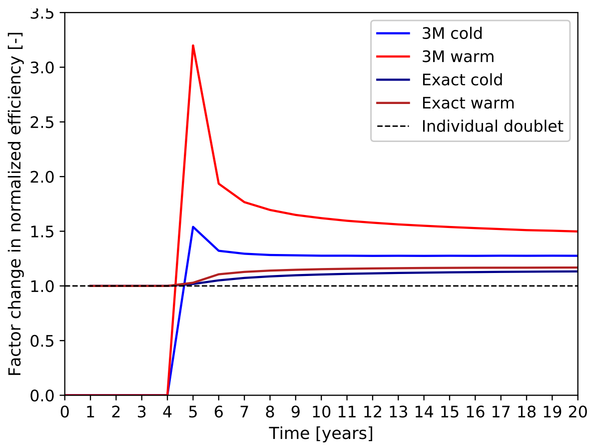

Figure 5.3: Factor for the change in normalized recovery efficiency due to the presence of the other doublet based on the model

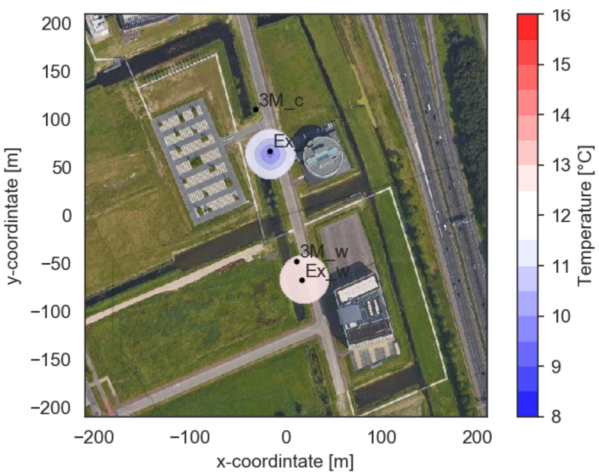

Figure 5.4: Thermal zones of Exact just before 3M starts operating.

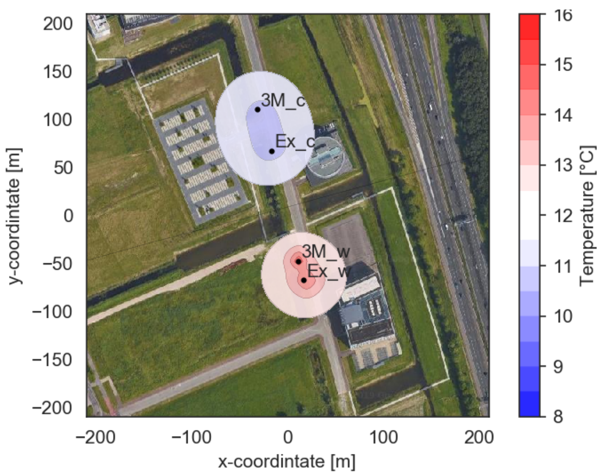

Figure 5.5: Thermal zones of Exact and 3M in the spring of year 20.

When comparing the modelled results to the data analysis it is shown that the real normalized efficiency is high compared to the predicted normalized efficiency. In the practice the efficiency of both systems in in the same range, while based on the model we might expect Exact to have a higher efficiency. The efficiency of the warm well of Exact is even higher than 100 %.

5.2. Echo and Schoemakerstraat

The efficiency of Echo and Schoemaker systems are determined for several well placement configurations as described in Section 3.2.2. The results are summarized in Table 5.2.

Table 5.2: Efficiency of the wells for different configurations in year 20 of simulation.

Normalized thermal recovery efficiency							
	Individual system		All systems				
Configuration	1a	1b	1a	1b	2	3	4
Echo cold	51.2	36.2	50.8	35.6	37.9	49.5	49.8
Echo warm	51.1	58.2	49.1	56.4	57.9	62.3	57.2
Schoemaker cold	62.6	62.6	61.5	61.0	62.0	66.5	63.0
Schoemaker warm	30.3	30.3	29.3	30.0	33.0	48.9	43.7

Echo has to achieve thermal balance due to current legislation. Therefore the efficiency is approximately the same for both wells in case 1a. Schoemakerstraat has a large imbalance, leading to a low efficiency of the warm well and a relatively high efficiency of the cold well when the system is operating individually.
For configuration 1b, 2, 3 and 4 it is assumed that Echo operates under imbalance, so energy could be exchanged between the systems. The base case for comparison is configuration 1b. In this configuration the wells are placed in a checker-board configuration. The imbalance in system 1b leads to a lower efficiency of the cold well and a higher efficiency of the warm well.
The normalized recovery efficiency is slightly higher when both systems operate individually for case 1a and 1b. The difference is however very small.
In configuration 2, switching wells of the Schoemakerstraat has a small positive effect on the normalized thermal recovery efficiency. The thermal zones are connected, see Figure 5.7, which leads to less losses to the surroundings. The distance between wells is still very large, around 5.5 $R_t h$. The effect is therefore limited.
Placing the wells of Schoemakerstraat at another location with a distance of $1.0Rth$ between wells of the same temperature in configuration 3 has a large advantage for the efficiency. The efficiency is increased for all wells. This is partly because the thermal zones are fully connected in this case, see Figure 5.8. The increase in efficiency is highest for Echo's cold well and Schoemakerstraat warm well, which extract more water than is injected. The large increase in efficiency is likely due to transport of thermal energy.
Placing the wells as is proposed in configuration 4 does not lead to better system performance. The distance between wells of opposite temperature is somewhat smaller for configuration 3. The distance is 5.5 R_{th} in configuration 3 and $4R_{th}$ in configuration 4. Therefore the losses between the systems will be higher. The positive effect of ambient groundwater flow is also small because of the low flow velocity of 5 m/year.

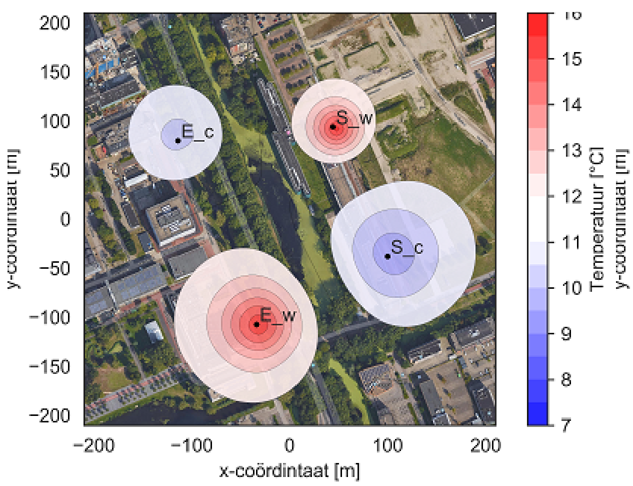

Figure 5.6: Temperature at the end of summer of year 20 for configuration 1b.

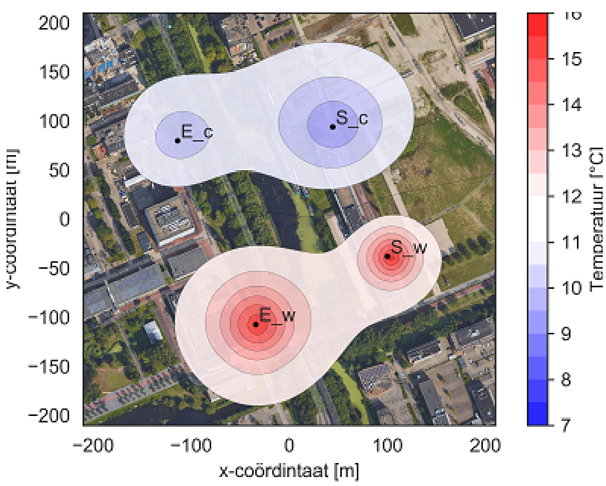

Figure 5.7: Temperature at the end of summer of year 20 for configuration 2.

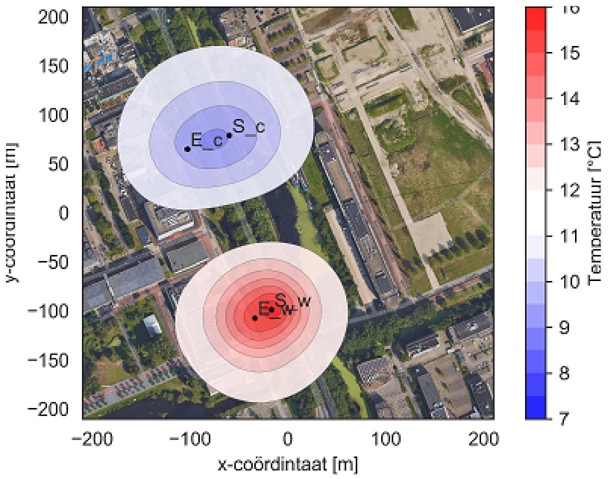

Figure 5.8: Temperature at the end of summer of year 20 for configuration 3.

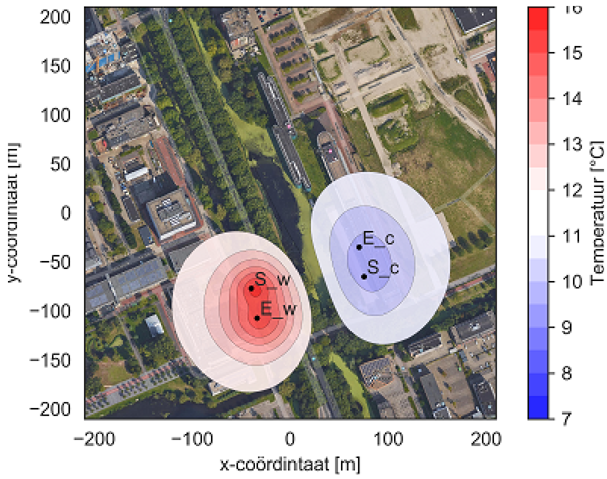

Figure 5.9: Temperature at the end of summer of year 20 for configuration 4.

6
Discussion

Several aspects of this research have to be taken into account to apply the results obtained in this research in practice. These considerations include the set-up of this research, the scope and some assumptions.

Model set up

Due to the setup of this research the results can differ in practice. As described in the Methods and Materials (Chapter 3) this research considers two doublets placed in a rectangular arrangement. The storage volume of the systems is equal as well as the imbalance if applied. The temperature of wells of the same temperature is equal and a sine wave function is used to distribute the storage volume over the seasons.

In practice there is much more uncertainty in the design of ATES systems and their spatial arrangement. The wells are not placed in a rectangular configuration and the thermal zones of more than two wells can be connected. The storage volume and balance is estimated during design but can differ due to uncertainty in system design and the variability in average temperature each season. The flow in the system depends on the weather and does not follow a sine wave function. The effect of these uncertainties on the results of this study are briefly elaborated.

It is unlikely that wells are placed in a rectangular arrangement. It can be the case that the thermal zones of two cold wells are connected, while the warm wells are connected to different clusters or are not clustered at all. It is expected that the arrangement does not influence the found results to a great extend as long as the distance between wells of the same temperature is small and the distance between wells of opposite temperature sufficiently large.
In practice more than two doublets can be placed in a certain area and therefore the thermal zones of multiple wells can be connected. As shown in this research, connecting the thermal zones of two wells leads to an increase of the thermal recovery efficiency. If the thermal zone of a third well is connected it is expected that the thermal recovery efficiency of the first two wells will increase. This increase will be smaller than the increase due to connecting the thermal zones of the first and second well. This can be reasonably expected based on the decrease in A/V. The decrease is large when two wells are connected and smaller when a third well is connected. The third well will have a large decrease in A/V due to the presence of two other wells. This leads to a high increase in the thermal recovery efficiency of the third well.

Assuming systems with the same storage volume is easier for interpretation of the results. In practice it is however unlikely that the storage volume of different systems is equal. In this research the distance between wells is expressed as the thermal radius, which depends on the storage volume. When systems with different storage volumes are placed, multiple thermal radii exist for the different wells. The choice which thermal radius is used influences the results of the research. One option is to use the average thermal radius of the two systems. A more conservative option is to use the thermal radius of the largest system.
Connecting thermal zones of systems with different storage volumes influences the change in thermal recovery efficiency. The system with the largest storage volume will have a lower increase in thermal recovery efficiency because the A/V is only slightly reduced. The system with the smallest storage volume will have

a high increase in thermal recovery efficiency because the A/V value is decreased significantly due to the presence of the other well.

Another aspect to take into account is proper operation of the system. This research found an increase in the performance of individual systems. It could even be beneficial if two systems with imbalance are placed together, provided that this imbalance is opposite. Connecting thermal zones can however become a problem if one of the systems starts extracting a larger volume than designed for, or starts infiltrating with a temperature closer to the ambient groundwater temperature. Imagine system A extracting more at the warm well. Because the thermal zones are combined, it will extract thermal energy injected by both system A and B. The warm well is depleted faster, negatively influencing system B while system A is positively affected. This is unfair because system A is malfunctioning. The same is the case when system A injects warm water with a lower temperature than system 2. Because the thermal zone is combined system B will extract water that is on average colder while the water at system A is on average warmer. This effects the efficiency of system B in a negative way. When thermal zones are connected, care must be taken that the the balance of the systems is met and that a certain infiltration temperature is reached.

The fact that building owners only use a part of the permitted storage volume further complicates the results of this research. It is found that on average 50% of the permitted volume is used (Willemsen, 2016),(Beernink et al., 2019). Therefore the thermal radius of the systems is smaller in practice than the thermal radius based on the permit. This will lead to larger distances between wells. Several options exist to mitigate this problem. Design guides could advice a smaller distance between wells of the same temperature, taking into account the smaller storage volumes in practice. Another option is to re-evaluate the permit every couple of years and adjust the permitted volume based on the real storage volumes plus a certain buffer for extreme years. This way the thermal radius of existing systems is known and new systems can be placed at the right distance.

Scope of research

This research is limited to the analysis of the performance of the groundwater system. The performance of the groundwater system is an important parameter to determine the performance of the whole system. An increase in performance in the groundwater system does however not lead to the same increase in performance of the overall system. In the next section the influence of the groundwater system on the overall system is described. A distinction is made between the system under heating and under cooling demand.

In the case of cooling, the performance of the overall system is expected to increase with a higher rate than the increase in thermal recovery efficiency of the groundwater system. In summer cooling is provided directly without the use of a heat pump. Direct cooling has a COP of around 40. Only when the temperature of the cold well is insufficient to cool, a heat pump is used. A higher thermal recovery efficiency means the water temperature in the cold well is on average lower. Therefore less water needs to be pumped in the groundwater system and the building system to provide the same amount of cooling. The flow is lower leading to lower dynamic losses. The reduced energy used in the system for the same amount of thermal energy leads to a higher coefficient of performance or COP, which increases more than the increase in thermal recovery efficiency.

The most important result of higher thermal recovery efficiency is that the water in the thermal zone is colder for a longer period of time. This has two large benefits: firstly it reduces the thermal energy that needs to be regenerated in winter. Regeneration of the wells has a COP of around 20, so avoiding regeneration leads to lower energy use of the system. Secondly it avoids the use of a heat pump at the end of the summer when the water temperature becomes to high for direct cooling. The energy demand of the heat pump is high, with a COP around 3. So avoiding the use of the heat pump for cooling will increase the performance considerably.

In the case of heating, the performance of the overall system is expected to increase with a lower rate than the increase in thermal recovery efficiency of the groundwater system. In winter heating is provided by using a heat pump which increases the temperature of the heating system, with a COP around 4. A higher thermal recovery efficiency leads to a higher temperature at the evaporator of the heat pump. This reduces the energy consumption of the heat pump but with a lower rate than the increase of the thermal recovery efficiency. Like in the case of cooling, a higher thermal recovery efficiency avoids the use of regeneration. This increases the performance of the system. The total effect is expected to be lower than the increase in thermal recovery efficiency.

7

Conclusions

7.1. Conclusions

This research quantified the effect of placing wells of the same temperature together. This approach solves the problem of interests between individual system owners who want individual ATES systems to have a large efficiency, and the public interest of storing as much energy in the limited available aquifer space. It is shown that this conflict in not present in the case of wells of the same temperature. This research proved that both the individual system performance and the amount of systems in a certain area can be increased by placing wells of the same temperature together and combining their thermal zones. Wells of opposite temperature should be placed at a large distance to avoid negative effects.

System performance

The main goal of this research is to quantify the change in performance of ATES systems when their thermal zones are connected. The performance of ATES systems is measured as the ability to extract thermal energy from the aquifer that was stored in the previous season, called the thermal recovery efficiency of the ATES wells. Another parameter to measure performance is the amount of pumping energy required, determined by the drawdown in the wells.

This research confirms that placing wells of the same temperature close together and connecting their thermal zones leads to an increase in thermal recovery efficiency of individual systems. A system with an average storage volume of 250.000 m^3 has an increase of thermal recovery efficiency between 8 and 20 percent, depending on the shape of the thermal zone.
The increase in recovery efficiency is due to a decrease in A/V when wells of the same temperature are connected. Lower A/V leads to lower losses and higher efficiencies. Systems with a low storage volume have a high A/V value which decreases significantly when wells are connected, leading to a high increase in efficiency. This is why connecting thermal zones is more advantageous for systems with a small storage volume. For example, systems with a small storage volume of 50.000 m^3 have an increase in thermal recovery efficiency between 15 and 40 percent.
The shape of the thermal zones, expressed as the L/Rth$value, alsohasaninfluence.SystemswithalargeL/R_{th}$ value have a large increase in thermal recovery efficiency.
Placing wells together also leads to an increase in pumping energy, which reduces system performance. This effect increases exponentially when the distance between wells of the same temperature is reduced. If a small distance between wells of the same temperature is taken, the combined effect of the increase in thermal recovery efficiency and the increase in pumping energy leads to an increase in overall system performance. The distance between wells of the same temperature should be 0.5 times the thermal radius. The distance between wells with opposite temperature should be larger than 3 times the thermal radius.

The case study also showed that connecting the thermal zone of a system with a small storage volume to the thermal zone of a system with a large storage volume is very advantageous for the small system. Connecting thermal zones also leads to fast start up of new systems because the aquifer temperature is already adjusted to the thermal zones of the other system.

Accepting imbalance in individual wells
When thermal zones of the same temperature are connected imbalance of individual systems should be accepted, provided that the energy balance of the combined system is met. Energy is exchanged between wells of the same temperature if their thermal zones are connected. Wells of the same temperature should be placed as close together as possible to exchange energy. The distance of 0.5 times the thermal radius should be applied.

Ambient groundwater flow can have a positive effect on the transport of energy between systems with imbalance, provided that the well injecting a larger volume is placed upstream of the wells that extract a larger volume. An optimal distance exists between wells of the same temperature. This distance increases with increasing ambient groundwater velocity.

7.2. Recommendations

Several recommendations are given based on this research. These recommendations are divided into recommendations for ATES planning and recommendations for future research.

Future research
Future research can improve the results found in this study. This research did not quantify the number of systems that could be placed in a certain area or the savings on greenhouse gas emissions. Furthermore only two systems in a rectangle configuration is taken into account. Agent based modelling can asses the effect of placing wells with the same temperature at a distance of 0.5 times the thermal radius apart, and wells of opposite temperature at a distance of 3 times the thermal radius. A more realistic view is obtained using agent based modelling which takes into account well placement in other configurations, placement of more than 2 wells in a cluster, the effect of different system size and different infiltration temperatures. The savings on greenhouse gasses for a certain area can be calculated to prove that placing systems closer together increases savings on greenhouse gas emissions.
This study is also limited to the performance of the groundwater system. The relationship between the performance of the groundwater system and the performance of the building system was not taken into account. Research focusing on the effect of the performance of the groundwater system on the building system is therefore necessary.
Cases could also provide information. To assess the effect of placing wells of the same temperature together in practice, it is preferred to have system operating for a long period. When a new systems is placed in the thermal zones of the old system, a deviation of the system efficiency could be measured. The extra pumping energy could also be measured to calculate the trade off between the advantage of increased thermal recovery efficiency and the disadvantage of increased pumping energy.

ATES planning
Spatial planning of ATES systems should cluster wells of the same temperature to increase system efficiency and to place more wells in a certain area. Currently a distance between wells of 3 times the thermal radius is applied for all wells. Design guides and planning approaches should distinguish between wells of the same temperature and wells of opposite temperature. The distance between wells of the same temperature should be 0.5 times the thermal radius and the distance between wells of opposite temperature 3 times the thermal radius or larger. In the planning of ATES systems it should be taken into account that small systems have a large increase in thermal recovery efficiency. Connecting the thermal zones should be prioritized for small systems.

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A
Overview of model runs

Table A.1: Overview of all model runs conducted in this research.

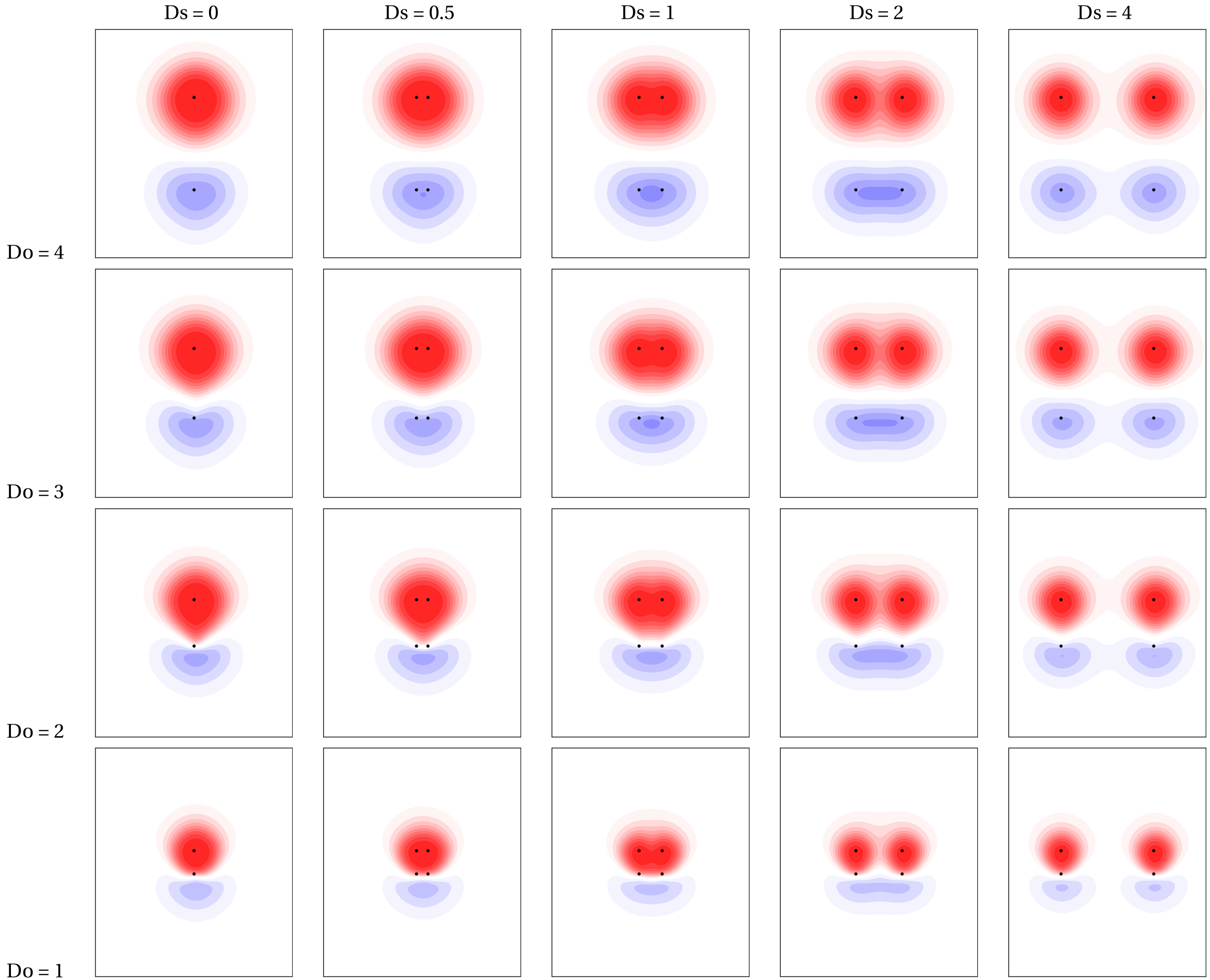
Generic			
Part	**Run**	**Description**	**Result**
Effect on thermal recovery efficiency	Distance between 2 wells with same temperature for 1 system	Distance between wells of same temperature (Ds) is varied for two system with V=250.000 m³ and L/Rth of 1.35. For every distance the efficiency is calculated and compared to the case the well is operating alone.	Effect of distance between wells of the same temperature on the increase in recovery efficiency
	Distance between 2 wells with opposite temperature for 1 system	Distance between wells of opposite temperature (Do) is varied for two system with V=250.000 m³ and L/Rth of 1.35. For every distance the efficiency is calculated and compared to the case the well is operating alone.	Effect of distance between wells of opposite temperature on the increase in recovery efficiency
	Distance between wells of 2 doublets	Distance between wells of opposite temperature (Do) and distance between wells of the same temperature (Ds) are varied for two doublets with V=250.000 m³ and L/Rth of 1.35 in a rectangular configuration. For every combination of Do and Ds the efficiency is calculated and compared to the case the well is operating alone.	Relationship between distance between wells (Do and Ds) on the increase in thermal recovery efficiency of individual wells, due to the combined effect of both wells of the same temperature and wells of opposite temperature.
	Different storage volume and shape	Two identical doublets are placed with a large distance between wells of opposite temperature and no distance between wells of the the same temperature. The storage volume is varied between 0 and 350.000 m³/year. The shape of the thermal zone, determined by the L/Rth value, is varied between 0.25 and 4. The efficiency is calculated and compared to the case when the well is operating alone.	Relationship between storage volume and efficiency of the well after 5 years and a relationship between storage volume and the increase in thermal recovery efficiency after 5 years, for different L/Rth values, assuming the thermal zones are fully connected.
Effect on drawdown	Distance between wells of 2 doublets	Distance between wells of opposite temperature (Do) and distance between wells of the same temperature (Ds) are varied for two doublets with V=250.000 m³ and L/Rth of 1.35 in a rectangular configuration. For every combination of Do and Ds the drawdown at one well is calculated and compared to the drawdown in the case one doublet is operating alone.	Relationship between the distance between wells (Do and Ds) on the increase in drawdown at the individual wells, due to effect of the placement of the other doublet.
Effect on imbalance	Effect of placing 2 doublet with imbalance together	Two average system with a storage volume of 250.000 m³ and L/Rth of 1.35 are used. Both systems have an equal but opposite volumetric imbalance of B_V = 0.15 and -0.15. The distance between wells of the same temperature is 1.5 R_{th} and the distance between wells of opposite temperature is 5 R_{th}. A sine wave function over 20 years is used to model the flow. The thermal recovery efficiency, the normalized thermal recovery efficiency and the amount of energy injected and extracted are calculated. A conservative tracer is used in the model to visualize the flow of water from one of the wells.	Showing that energy can be exchanged between two systems with opposite imbalance.

Part	Run	Description	Result
Generic			
	Distance between wells	The distance between wells of the same temperature is varied between 0 and 4 times the thermal radius while the distance between wells of opposite temperature is kept constant at 5 times the thermal radius. The change in thermal recovery efficiency is calculated for every distance. The distance between wells of opposite temperature is also varied between 0 and 5.5 times the thermal radius. The same system characteristics are used as were used in the previous part.	Relationship between the distance of a well and the change in thermal recovery efficiency considering two systems with imbalance.
	Amount of imbalance	The same system characteristics as in the first part of imbalance are used. The imbalance in varied between B_V =0 and B_V =3. The change in thermal recovery efficiency is calculated for every distance.	Relationship between the degree of imbalance and the change in thermal recovery efficiency of the wells.
	Groundwater flow	The same system characteristics as in the first part of imbalance are used. Ambient groundwater flow is varied between 0 and 200 m/year. Wells of the same temperature are placed in the direction of the flow. The well injecting a larger volume is placed upstream of the well extracting a larger volume. For each value of the ambient groundwater flow the change in the normalized thermal recovery efficiency is calculated.	Relationship between the ambient groundwater flow and the change in thermal recovery efficiency. Optimal distance for a certain value of the ambient groundwater flow.
Case study			
Exact and 3M	Case study thermal recovery	Two small systems in case study area. One system starts 4 years before the other. Thermal recovery efficiency calculated based on monitoring data. Data used to model the expected performance.	Effect of connecting thermal zoned of real systems. Comparison between model performance and performance calculated based on monitoring data.
Echo and Schoemakerstraat	Case study imbalance	Two systems with opposite imbalance in case study area. Wells are placed in 4 configurations to facilitate the exchange of thermal energy.	Effect of placing wells with opposite imbalance together under real conditions, taking into account limitations to well placement due to buildings etcetera.

B

Thermal zones for different combinations of Do and Ds

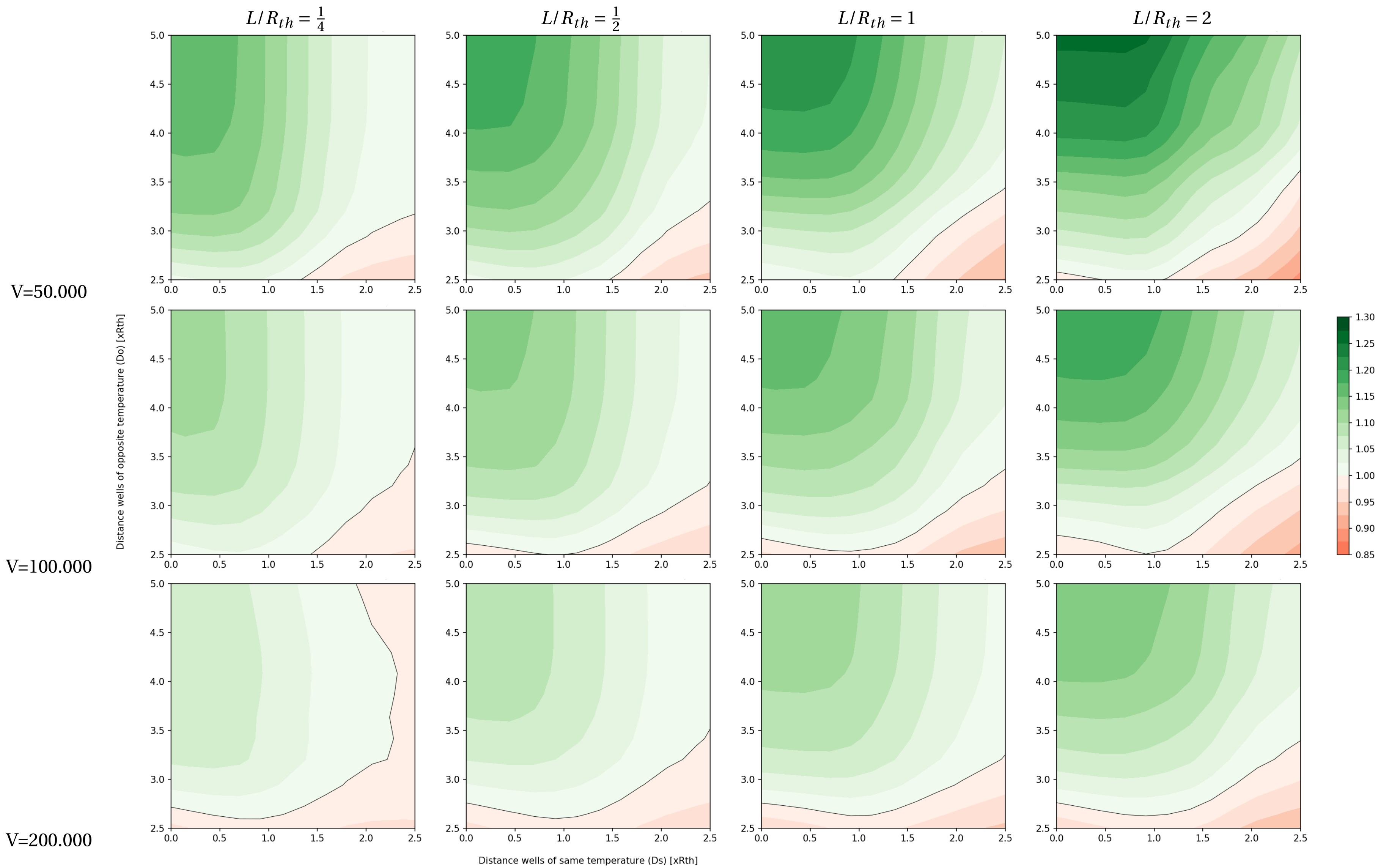
Table B.1: Plots of thermal zones for different combinations of distance between wells of opposite temperature (D_o) and of distance between wells of the same temperature (D_s), for a system with a storage volume of 250.000 m^3 and L/R_{th} of 1.35 at the end of summer.



C

Effect of volume and shape on change in thermal recovery efficiency

Table C.1: Relationship between the distance between wells (expressed in terms of the hydraulic radius) and the change in thermal recovery efficiency of individual wells, expressed as a factor. A factor of 1 means no change in thermal recovery efficiency, a factor larger than one means an increase in efficiency. The different figures represent different combinations of storage volume (V) and shape of wells (L/R_{th}).



D

Relationship A/V and thermal recovery efficiency

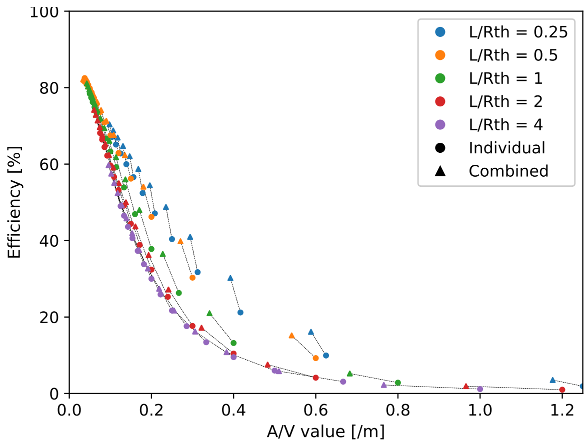


Figure D.1: The A/V value compared the the thermal recovery efficiency for a large range of A/V.

E
Imbalance

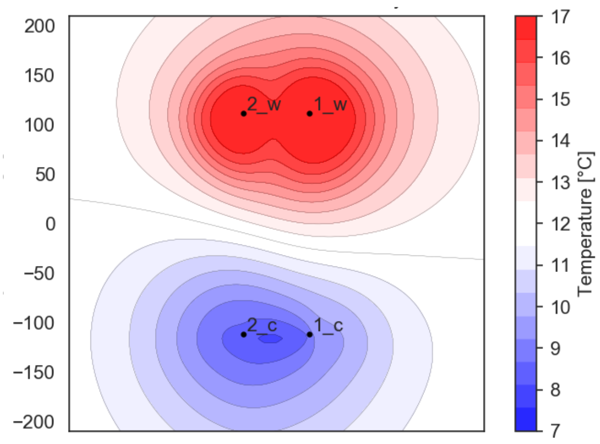


Figure E.1: Temperature in the aquifer at the end of summer of year 20 for 2 doublets.

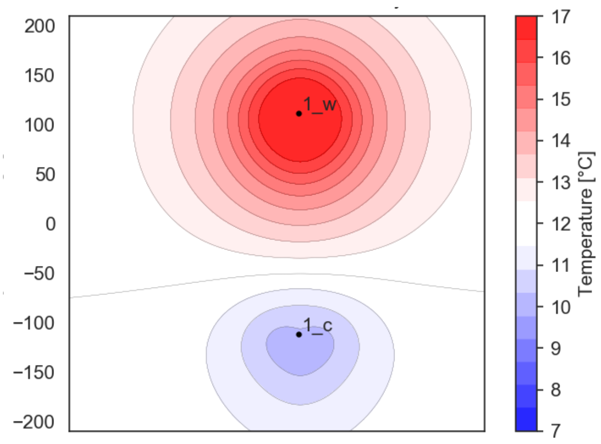


Figure E.2: Temperature in the aquifer at the end of summer of year 20 for 1 doublet.

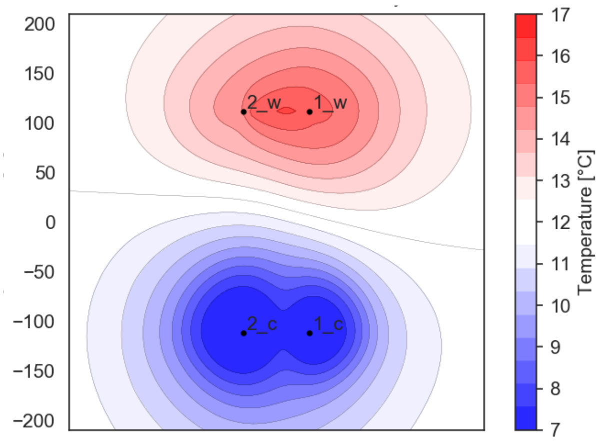


Figure E.3: Temperature in the aquifer at the end of winter of year 20 for 2 doublets.

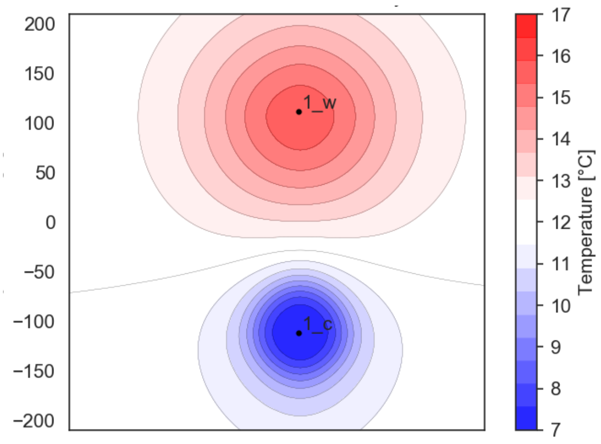


Figure E.4: Temperature in the aquifer at the end of winter of year 20 for 1 doublet.

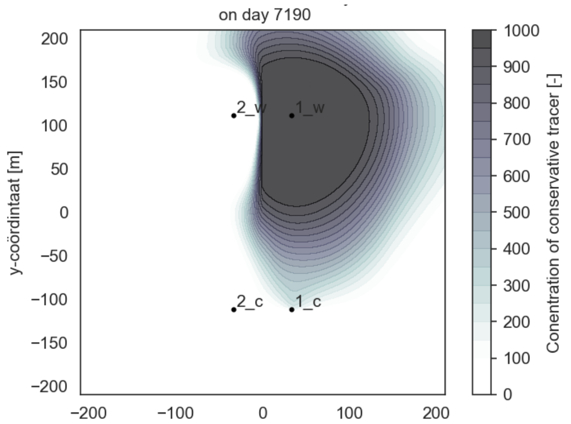


Figure E.5: Spreading of the conservative tracer at the end of summer of year 20 for 2 doublets.

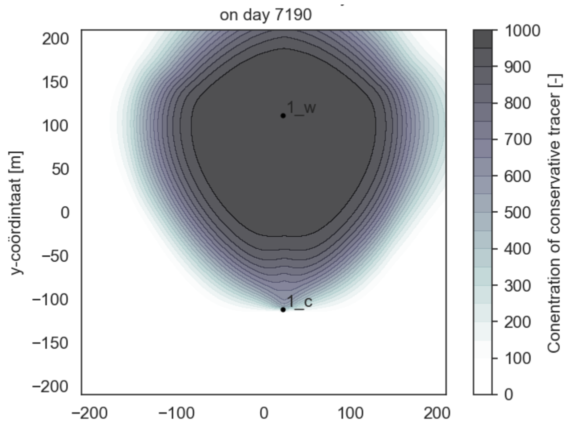


Figure E.6: Spreading of the conservative tracer at the end of summer of year 20 for 1 doublet.

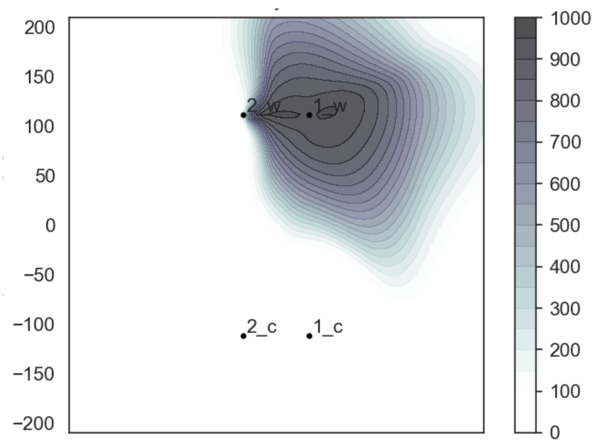


Figure E.7: Spreading of the conservative tracer at the end of winter of year 20 for 2 doublets.

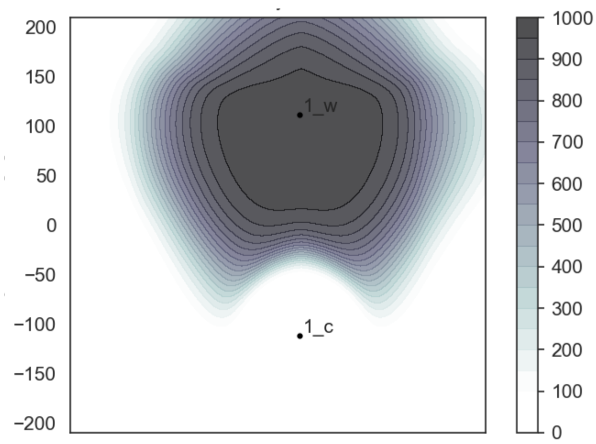


Figure E.8: Spreading of the conservative tracer at the end of winter of year 20 for 1 doublet.

F
Thermal zones case Echo

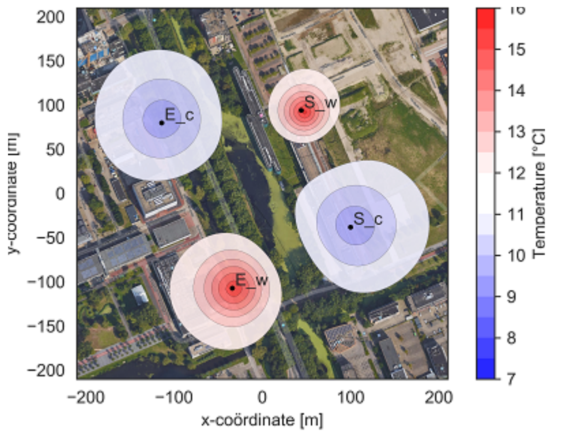


Figure F.1: Temperature at the end of summer of year 20 for configuration 1a.

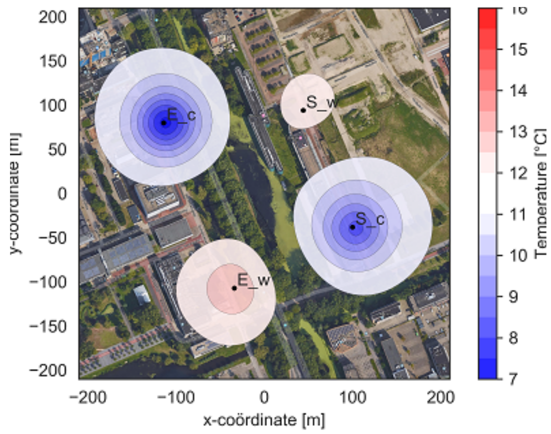


Figure F.2: Temperature at the end of winter of year 20 for configuration 1a.

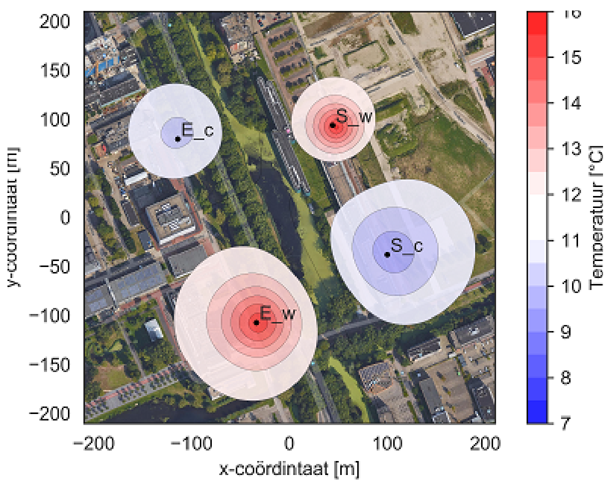


Figure F.3: Temperature at the end of summer of year 20 for configuration 1b.

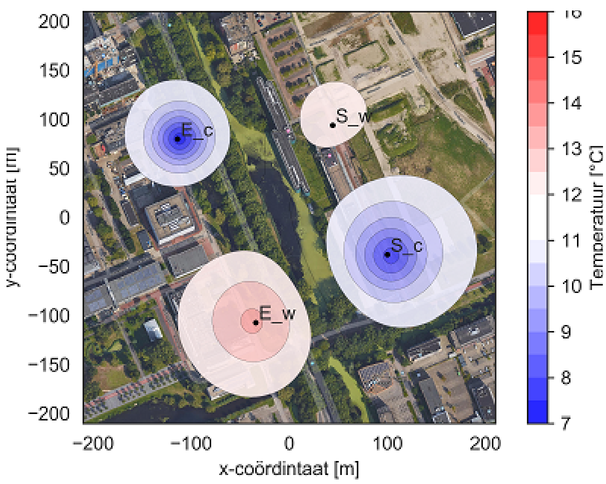


Figure F.4: Temperature at the end of winter of year 20 for configuration 1b.

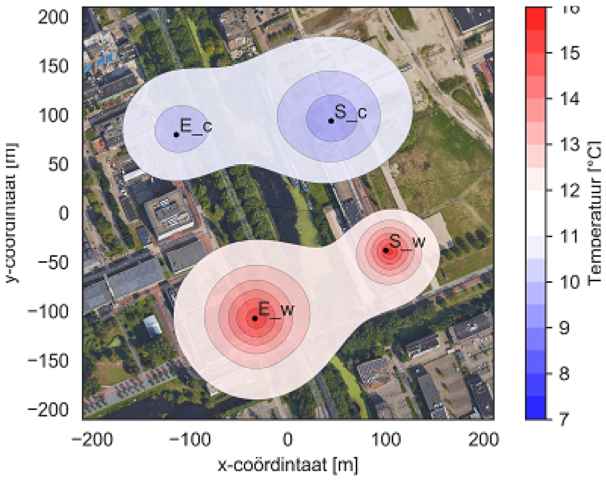


Figure F.5: Temperature at the end of summer of year 20 for configuration 2.

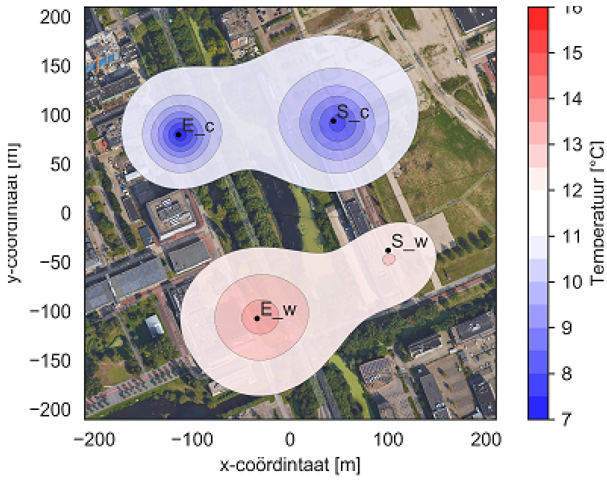


Figure F.6: Temperature at the end of winter of year 20 for configuration 2.

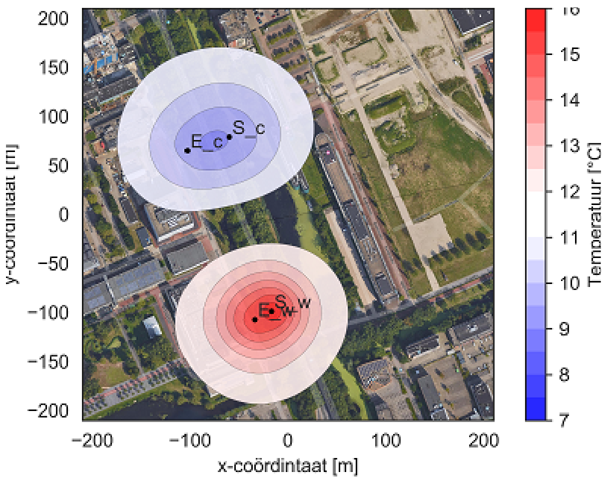


Figure F.7: Temperature at the end of summer of year 20 for configuration 3.

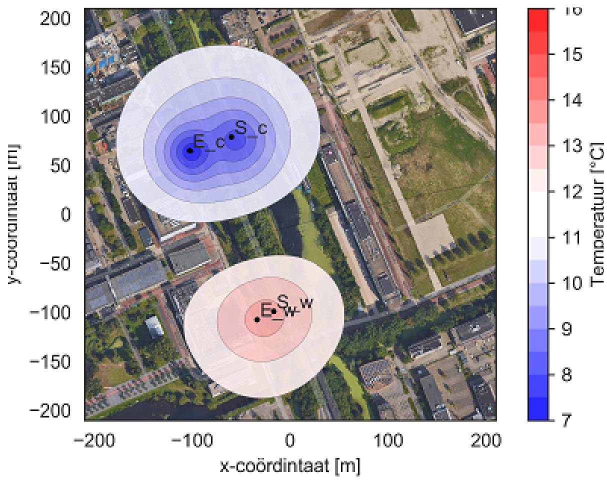


Figure F.8: Temperature at the end of winter of year 20 for configuration 3.

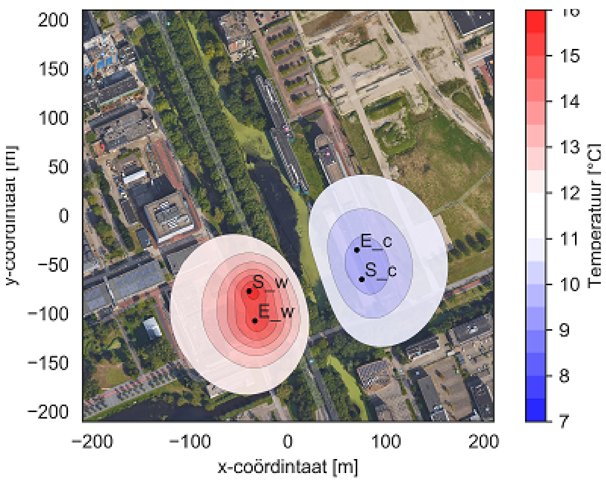


Figure F.9: Temperature at the end of summer of year 20 for configuration 4.

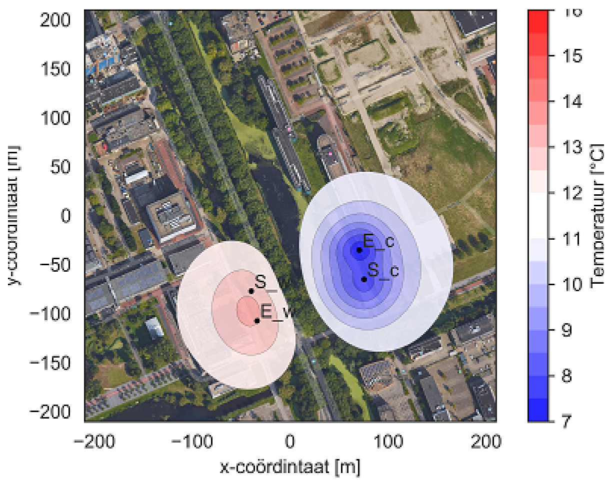


Figure F.10: Temperature at the end of winter of year 20 for configuration 4.

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G
Thermal zones TU Delft campus area

Figure G.1: Thermal zones of TU Delft campus area at the end of summer, based on average storage volumes of the wells after 20 years of operation.

Figure G.2: Thermal zones of TU Delft campus area at the end of winter, based on average storage volumes of the wells after 20 years of operation.