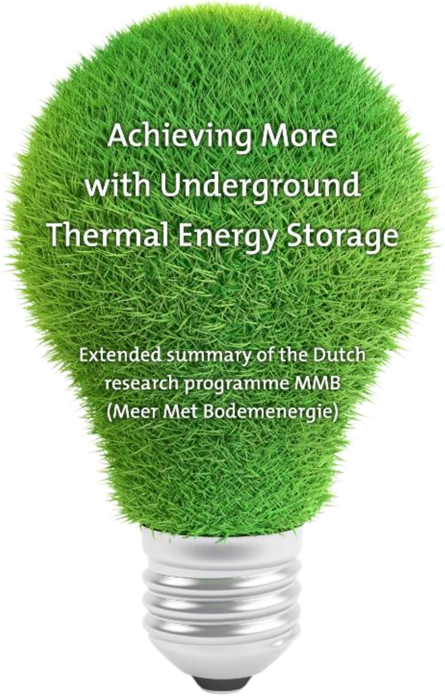
Aquifer Thermal Energy Storage in the Netherlands, a research programme

(2010-2012)

Extended English summary of a report by the Dutch research programme MMB (Meer Met Bodemenergie)



Achieving More with Underground Thermal Energy Storage

Extended summary of the Dutch research programme MMB (Meer Met Bodemenergie)

This is a translation of an extended summary of the results of the joint research programme *Achieving More with Underground Thermal Energy Storage (UTES)*(“Meer met bodemenergie”) that was carried out by Bioclear, Deltares, IF Technology and Wageningen University Research (WUR).

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Date

Dutch publication: June 2012
English translation: July 2018
English edit: January 2019

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1. Introduction

Underground Thermal Energy Storage (UTES) is a technology that is widely used for the sustainable heating and cooling of buildings in the Netherlands (see Figure 1). Its application is encouraged by the Dutch government, as expressed in the Underground Energy Storage Decree that has been in force since 2013. The two-year research programme *Achieving More with Underground Energy Storage (Meer Met Bodemenergie), in this translation referred to as "the programme")* filled a number of knowledge gaps with regards to Underground Thermal Energy Storage. This was felt to be desirable by all of those involved, since there are still a number of uncertainties relating to the effects of the technology on the subsurface (soil & groundwater quality). The programme was organised in a series of work packages.

The research was carried out by four main groups (Bioclear, Deltares, IF Technology and Wageningen University and Research Centre (WUR)). The programme was funded by 35 participants, including both government and commercial partners. The most important questions which the programme provides answers to are:

- *What are the hydrological, thermal, microbiological and chemical effects of Underground Thermal Energy Storage (UTES) on the soil system?*
- *What are the range of technical options for sustainably integrating UTES in the water-energy chain? Is it possible to achieve multiple goals simultaneously by making smart combinations?*

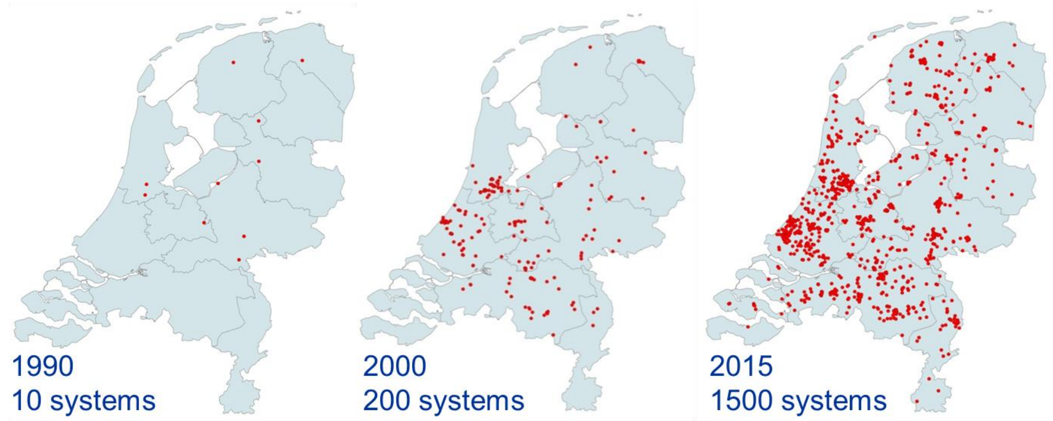

Figure 1: Development of Aquifer Thermal Energy Storage systems in the Netherlands

1.1 The basic working principle of ATES & BTES

The basic principle of Aquifer Thermal Energy Storage (ATES) involves using the subsurface to overcome the seasonal discrepancy between the availability of and demand for thermal energy in the built environment. Buildings in temperate climates generally have a surplus of heat in summer and a shortage in winter. Where groundwater is present in sandy layers (aquifers) of sufficient thickness and hydraulic conductivity, thermal energy can be stored in and extracted from the subsurface. An ATES system consists of two wells – one to extract groundwater and one to store it or do both. The system operates by changing the groundwater temperature using a heat exchanger that is connected to a building (Figure 2).

Buildings can be efficiently cooled during summer using groundwater from the cold well. This water, which is heated to about 14-18°C, is simultaneously stored via the warm well, which is then used for heating in the following winter season. This cooling requires nothing other than the low-temperature groundwater stored in the previous winter season; this is called free cooling. When, during the summer season the temperature of the cold well rises above approximately 10°C, this free cooling is no longer possible; the heat pump, which is always required for space heating during winter, is then used as a back-up cooling machine. During winter, groundwater is extracted from the warm well. The heat pump boosts the temperature to the level required to heat the associated building, which is approx. 40°C. While heating the building, this heat pump also cools the pumped groundwater to between 5-8°C, which is stored via the cold well. Balancing the seasonal storage and extraction of thermal energy is essential for sustaining long-term use of the subsurface for thermal aquifer storage. ATES reduces the net consumption of fossil energy for heating and cooling buildings. On average, applying ATES reduces primary energy consumption for heating and cooling of buildings by 50% but, in order to sustain subsurface energy storage, it is essential to balance seasonal storage and extraction of thermal energy. These techniques are applied in buildings of virtually any type, but the most common applications of ATES are in larger office and utility buildings.

There are various types of ATES concepts, the most common being 1) doublets, where the warm and cold well are separated horizontally and 2) monowells, where the warm and cold well screens are placed above each other in a single borehole. Monowells are mostly used when there is less energy demand, i.e. for smaller buildings, but the vertical screen arrangement requires a thick aquifer to allow for enough space between the screens to prevent short-circuit flow.

Another familiar UTES system for small buildings is Borehole Thermal Energy Storage (BTES). Such system consists of a number of closed tubes that contains a transport fluid, usually glycol or water with an additive to improve its thermal properties. By pumping the fluid around, thermal energy is extracted from or stored in the subsurface using thermal conduction only. This limits the extent of their thermal influence on the subsurface. This research focuses on open systems (ATES), as they are most commonly installed under large buildings and, therefore, require explicit use of much of the subsurface space below urban areas – especially city centres.

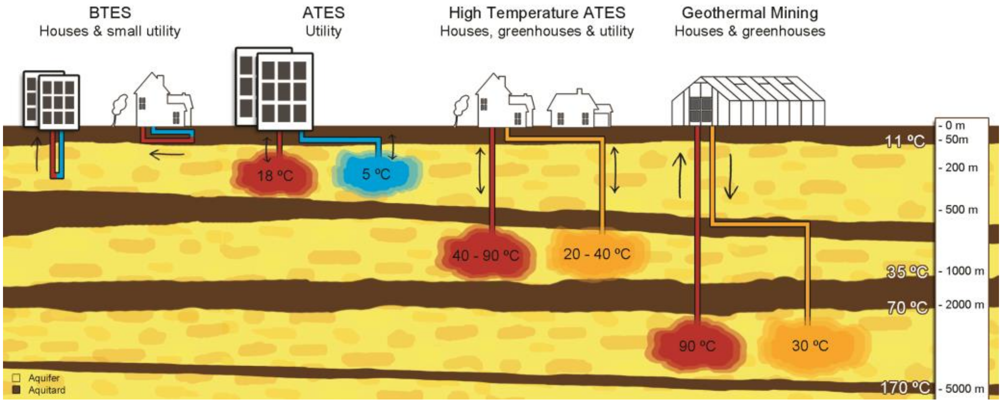

Figure 2: Various types of geothermal energy systems

1.2 Reading guide

This document provides a synopsis of the programme and each of its 11 chapters is an outline of one of the 11 research reports. More details on each subject can be found in the individual research reports (available in Dutch); the aim of this summary is to offer a clear overview of the research that was conducted and the results.

Chapter 2 relates to the first work package in the programme, describing the main issues relating to policy, and how the results of this research can be used to develop policy. Chapter 3 summarises current knowledge on ATES systems; it’s based on research that was carried out before the programme started and it identifies the knowledge gaps that still need to be investigated. Chapter 4 examines the impact of ATES systems on the geochemistry and biology of the subsurface, based on the results of experiments carried out at nine locations. Chapter 5 describes the results from modelling three existing ATES systems that were investigated as part of the programme. Chapter 6 provides an overview of high-temperature ATES systems, a relatively new technique that has not yet been widely applied. Chapter 7 focuses on the issue of ATES mutual interference, which is expected to occur in areas with a growing number of systems and could potentially reduce the systems’ efficiency. Chapter 8 is about the autonomous development of soil temperature. This has to do with the changes in soil temperature that will occur independently of ATES systems as a result of climate change and urbanisation; this provides important input on discussions about policy change that relate to the energy balance in ATES systems. Chapter 9 reviews the possible impact of ATES systems on soil contaminants, while Chapter 10 examines the potential of combining ATES systems with soil remediation. Chapter 11 is related to the implementation of ATES systems within a regional groundwater management approach. Finally, Chapter 12 explores the wide range of opportunities and possibilities of using ATES in combination with other functions. The three main concepts described in this summary are industrial residual heat storage, irrigation water for greenhouses and process water.

2. Underground Thermal Energy Storage policy

2.1. Connecting research results with aspects of policy

Work package 1 was the main part of the research programme. Fundamental to this work package is the link between research results and policy development. During working sessions with the participants and researchers, the programme-related policy themes were determined (see Table 1).

Table 1: Policy issues related to the programme

Policy issue	Relevance
Infiltration temperature	There is currently insufficient knowledge of the influence of the infiltration temperature on the soil and groundwater quality.
ATES and soil remediation	The presence of contaminants is impeding the implementation of ATES, while it also offers opportunities for combining ATES with other (soil) functions.
Energy balance	The usefulness and necessity of the energy balance is not well substantiated. In addition, the current requirements for energy balance are often not met in practice.
Mutual interaction with ATES	There is insufficient knowledge about the risks of interference between open systems.

The participants also indicated how the research results can be used to develop policy . This can be done in three steps:

1. The results can contribute to developing area and function-oriented policy, so that sustainable use of the subsurface is guaranteed (by the government);
2. The research results of the programme should be used to review the current Dutch policy framework (especially the Water Act and the Soil Protection Act);
3. The research results should provide advice to the government on developing area and function-oriented policy for the subsoil (within the programme).

For the research results, see Chapters 3 to 6 in this summary and the individual research reports (in Dutch). The ways in which the research results can be translated into policy development are categorised below per policy theme.

2.2. Infiltration temperature

In Dutch provincial regulations, a maximum infiltration temperature of 25°C is applied for open systems. An exception to this is the province of South Holland, where a maximum infiltration temperature of 30°C is allowed. According to the new Soil Energy Decree it is possible to deviate from this general rule if there are good reasons for doing so.

The current policy (maximum infiltration temperature = 25°C) applies to ATES that are used both in residential and in non-residential buildings. However, in for example industry and agriculture, much heat needs to be ‘destroyed’ within the current policy framework. For this reason, in areas where a great deal of residual heat and/or agriculture is present, deviating from this maximum infiltration temperature (and the provincial regulation) is desirable from an energy point of view. The new Underground Thermal Energy Storage Decree thus provides for this.

From the measurement data presented in Reports 3 & 4. it appears that changes in water quality are measured at the location with infiltration temperatures < 30°C. However, these are probably mainly due to the mixing of vertically stratified aquifers. In this temperature range, the effects of mixing are greater than those of temperature alone. Possible direct temperature effects are masked by mixing. This provides a good justification for supplementing field research with laboratory research. Column tests carried out by KWR/VU indicate that when you heat groundwater from 11ºC to 25ºC and to 60ºC, organic matter is mobilised and arsenic is released. The mobilisation of organic matter is very low at 25ºC and significant at 60ºC, which is consistent with the laboratory tests carried out within the programme and the results of previous research (Brons et al., 1991). The explanation for the mobilisation of arsenic in the laboratory tests carried out by KWR/VU was desorption of iron hydroxides. In the field measurements carried out within the programme for programmes with higher storage temperatures, no mobilisation of arsenic was detected, with the exception of at the Zwammerdam location. However, water treatment with hydrochloric acid was applied to Zwammerdam's high-temperature storage, which was used within the programme as a possible explanation for the mobilisation of arsenic. However, it cannot be ruled out that high temperatures in the past (> 80 ºC in the warm well) played a role too.

The results of the research by the programme are generally in line with those produced by KWR/VU. In field measurements, up to 20ºC, it is mainly the effects of mixing that can be seen. From the column tests carried out at KWR, sulphate reduction appears to have been highly temperature-dependent throughout the entire range between 5 and 60 degrees (tests carried out at 5, 12, 25 and 60ºC). This shows the temperature dependence of microbiological activity. An increase in arsenic values was also measured at 25ºC; presumably the result of a changing equilibrium with iron hydroxides, a process that is also described in the literature and that can also be expected for other elements that bind to iron hydroxides. This process will then be limited to the warm well. When the water cools down again, part of the arsenic is likely to be bound again. KWR/VU intend to carry out more tests to further investigate this aspect. It may also be the explanation for the differences between the laboratory tests carried out by KWR/VU (where mobilisation of arsenic was found) and the results of field measurements of the programme (where no – or hardly any – mobilisation of arsenic was found). If that is the case, then this effect would appear to occur especially in the early stages.

If no other and/or vulnerable activities are present within the groundwater, the results of the programme justify the consideration of additional policy. We therefore recommend that the Dutch provinces should allow pilot options for ATES at higher temperatures. This means that they a) designate areas within their province where this can be allowed, and b) establish requirements that apply for such initiatives. Such preconditions would make permits for HT-ATES pilots possible, which in turn can help to fill in the current gaps in knowledge.

2.3. ATES and soil remediation

Contaminated sites prevent both area development and the application of ATES. This is why there is a need for programmes combining open systems and remediation of contaminated groundwater. A question that emerges here is: which combination concept can best be applied? In addition, there is insufficient insight into the actual contribution of an ATES to a soil remediation programme. These two topics were examined in the programme.

The programme results show that the conditions under which degradation occurs can be improved by applying ATES. In particular mixing and dilution contribute to this. It is not known whether these improved degradation conditions result in an increase in degradation and whether these effects will continue in the long term. It is also unclear to what extent these effects are representative of other locations or circumstances. It is therefore important to carry out new measurements at other locations. Mixing and dilution imply an increase in the spread of the contamination to the environment (horizontal direction) and/or in depth (vertical direction). Dispersion of contaminants to the environment can be reduced by the smart positioning of open systems (example Strijp-S).

There are currently no general rules that could determine in which situation and under which circumstances ATES systems have an effect on contaminant removal and how large this effect might be. The remediation potential of ATES needs to be investigated in a site-specific context by assessing the biodegradation potential (e.g. the presence of required bacteria, redox conditions, the presence of electron donor/electron acceptor) and the groundwater flow.

In general, among the various systems, the recirculation system is the best way to control contamination. If substances are added to the system to promote biodegradation, a recirculation system or an energetically more favourable triplet is the system of choice, because of the better predictability of the flow paths. The triplet has the additional advantage that the relatively regular flow patterns are combined with a warm well in which the natural degradation of pollutants can be stimulated.

The legal framework under which the combining remediation and ATES systems falls is the Dutch Soil Protection Act (Wbb). The Wbb is currently being amended. It offers potential for a regional approach to large-scale contamination sites. Such an approach presents good opportunities for dealing with pollution in combination with installing ATES systems in a responsible manner. It opens up opportunities because it allows for the interpretation of how a (possibly) desired quality improvement can be achieved in a larger area, rather than preventing the spread of individual cases of contamination. Also, in regional groundwater management, a broader application of water flows is considered and integration and consideration of multiple aspects (at different levels) takes place. In practice, many applications for licences for ATES are rejected due to the chance of contamination being displaced. In this way, energy saving and CO_2 emission reduction is blocked. Currently, a lot of hard work is being done to encourage and facilitate regional groundwater management, to foster customised rules which would allow activities that cannot be allowed under the standard regulation. We recommend actively sharing knowledge and experience gained in regional groundwater management with all relevant parties.

2.4. Energy balance

In order to guarantee sustainable use of subsurface space and to prevent continuous heating or cooling of the subsurface, the policy adopted is to balance the amount of extracted cold and heat within certain limits. For each province, the allowed energy balance deviation varies between 15% in the first five years and 10% after ten years, while closing the balance at least once every two years. The energy balance requirement will be included in the Soil Energy Decree.

From the "Research Criteria for the Energy Assessment of ATES" document, it appears that the energy balance is only one of the factors that determine the subsurface use of space. The other factors that play a role are building envelope & use, climate conditions, the quality of management and groundwater flow. Meeting the energy balance requirement can be done in two ways:

1. The missing part of energy balance in the aquifer can be obtained by regeneration facilities (e.g. dry coolers to get extra cooling capacity, or solar collectors to get extra heat). This is why correcting the imbalance may lead to higher energy use, which reduces the intended energy saving and emission reduction, while at the same time increasing costs.

2. The main demand is partly covered by conventional installations, so that the net demand for the aquifer is in balance: this is easier to accomplish than covering the complete heat and cold demand with ATES, in combination with regeneration for repairing the energy balance. This way, the balance requirement can result in less use of ATES.

Because maintaining an energy balance does not ensure that the intended goal – namely the guarantee of a sustainable aquifer use of space and preventing the continuous heating or cooling of the subsurface – is achieved, and because an energy balance is technically and financially complex, we propose that the current set of requirements should be reviewed.

We advise all those involved to discuss this. The discussion should cover the ways in which the underground use of space for ATES and the possible effects of the temperature can best be dealt with. This discussion should also influence the Soil Energy Decree, where the 'effective use of the subsurface' still needs to be implemented. The aim is to arrive at a set of rules and parameters that lead to the common goal i.e. the efficient use of the subsurface and the efficient functioning of ATES systems, without the subsurface being continuously heated or cooled down. We recommend abandoning the current requirements and developing alternative requirements.

2.5. Mutual interaction between ATES systems

Various working sessions with the programme participants showed that it is expected that interference in busy areas will increase with the considerable growth in the number of ATES systems. Policy makers and managers of ATES view mutual interaction as undesirable if it reduces the efficiency of systems or leads to an increase in the impact on other (vulnerable) interests in the subsurface. To gain more insight into this, the programme participants investigated the influence of mutual interaction among open systems on their efficiency and on the environment.

This study shows that the efficiency of ATES systems will not necessarily suffer much from mutual interaction, as long as the permit application takes the surrounding systems into account. In fact, when the ATES wells are placed ‘smartly’ relative to each other, efficiency can be increased. This means that, under certain physical conditions (suitable groundwater flow rate & direction and homogeneous aquifers), wells can be placed closer together. In addition, periodically reconsidering the permitted storage volume (as a result of the actual pumped water quantity and future energy requirements) can help prevent unnecessary claims on the subsurface space.

In areas where a large number of systems are present or expected, extra attention is needed to prevent mutual interaction. The current implementation of the Soil Energy Decree already takes this into account. This allows the local authority to designate so-called “ambition” areas. Separate regulations can be drawn up for these areas.

Even outside ambition areas extra attention can be paid to, for instance, flexibility and customised well positioning, such as reducing the distance between the cold and warm wells, so that optimal use of ATES can be achieved. With regard to the issue of mutual interaction and optimal use of subsurface space, the following actions are recommended:

1. Designate busy areas as ambition areas and develop additional policy for these areas.
2. Local authorities should have an active attitude with regard to evaluating Water Act licences.
3. Further investigate actual mutual interactions. Do this on a thermal, hydrological and financial level. Based on this information, criteria can be drawn up for assessing interference: when does interference occur, and how can we best deal with this?

3. Literature review

3.1. Overview of existing knowledge and research questions related to Underground Thermal Energy Storage

In this review we explore the available knowledge on a number of aspects of ATES systems, their various effects, and the possibility of combining ATES with soil remediation. For a number of aspects, a global consensus has already been reached on how ATES affects the groundwater system. There are many more aspects, however, that need to be further investigated.

The direct influence of thermal storage systems on the subsurface can be split into two categories: hydrological and thermal effects, including derived effects as a result of both types.

Hydrological effects are the result of groundwater extraction and infiltration. This has an effect on the hydraulic head in the soil layer used by the ATES system and can also affect the head in other soil layers. As a consequence of these changes in head, groundwater flow in the vicinity of the system is influenced. In addition, mixing of water from different depths takes place. These direct impacts may give rise to secondary impacts, such as soil settlements and displacement of water quality interfaces.

Thermal effects are the result of the goal of thermal storage itself: storing heat and/or cold. In the immediate vicinity of ATES systems, the temperature is influenced. These changes in temperature can affect the chemical and microbiological composition of the groundwater, while large changes in temperature can cause groundwater flow induced by differences in density.

When combining heat and cold storage with remediation, there are hydrological and thermal effects that can contribute to the degradation of contaminants, but also to the spreading of pollutants. In the case of high-temperature storage and/or combining ATES with remediation, it may be necessary or desirable for substances to be added to the water; note that these substances can have additional effects on the subsurface.

Closed systems (BTES) only have a temperature effect and no direct flow effect (unless variable density flow arises due to large temperature differences). The subjects of this chapter do not specifically indicate whether a particular effect occurs only in ATES or BTES situations; however, it is clear that if an effect is solely or mainly due to temperature changes, then it also applies to BTES. More information relating to BTES and specific issues are described in Report 10 (in Dutch).

3.2. Hydrological effects

In the application of ATES systems, groundwater is extracted and, after being heated or cooled down, it is returned to the same aquifer. This extraction and infiltration of groundwater causes changes in the hydraulic head, which can affect the direction and speed of groundwater flow within the aquifer, and possibly even between aquifers; this means that the hydraulic head (or groundwater level) can also be affected in other aquifers.

The changes in hydraulic head and groundwater level are the direct hydrological effects of the application of ATES systems, while indirect effects include soil settlements and displacement of water-quality limits. Below you can read which stakeholders or processes can be influenced by the various effects:

Hydraulic head changes:

- Other groundwater uses in the vicinity (for example drinking water, other ATES systems, industrial extraction or temporarily dewatering/lowering the groundwater level).
- Underground infrastructural works, which have been designed based on a certain regime of hydraulic head.

Groundwater level changes:

- Construction (flooding or groundwater shortage)
- Agriculture (water damage or drought damage)
- Nature/ecology (desiccation/watering)
- Archaeological values (reducing groundwater level can be harmful)

- Other groundwater users
- Underground infrastructure.

Soil settlements:

- Buildings and infrastructure.

Displacement of water-quality limits:

- Groundwater contamination
- Freshwater/saltwater transitions.

In assessing these effects, the background effects are also important. These are independent effects that are likely to occur without ATES systems.

Because the extracted groundwater in ATES systems is simultaneously returned to the same soil layer, the volume reduction from extraction is partially compensated by the increase in volume from infiltration. At a greater distance, the effect of the extraction is virtually the same as the effect of the infiltration, resulting in a small net effect. This means that the area influenced is often relatively small for ATES systems (up to a few hundred metres), compared with extractions of comparable magnitude where no return of extracted water takes place (such as for extractions for drinking water, where effects can reach up to several kilometres).

The hydraulic head and groundwater level changes caused by ATES can be easily predicted with existing hydrology knowledge, provided that the soil properties and the extraction-infiltration pattern of the system are known. In order to avoid underestimation of the expected effects, in practice the worst-case assumptions of soil properties and extraction-infiltration pattern are used.

The most important remaining research question relates to the interaction between systems. If the concentration of ATES systems is growing in a certain area, hydrological interaction will increase. The question is what does this mean for the combined hydrological effects, and what will the influence of the new ATES systems on the previously applied systems be? To what extent can undesirable effects occur with a larger concentration of ATES systems? To what extent should requirements be imposed on the design of thermal storage systems in order to achieve optimal use of the subsurface? In the programme these questions are addressed by modelling various scenarios.

3.3. Soil mechanical impacts

If a load is applied to the surface, the underlying soil layers can be compressed in a process called settling or subsidence. The excessive load can be caused by extra weight at ground level, such as the weight of a tractor driving over soft ground, or the weight of a sand layer applied. A decrease in the hydraulic head or groundwater level can also create an additional load and therefore cause settling.

The extent to which settling occurs depends not only on the extra load, but also on the soil's sensitivity to settling and the thickness of the soil layer. For example, clay and peat soils are much more sensitive to settling than sand and gravel soils. The extent to which the soil layer has been weighed down in the past – the so-called pre-load – is also important. The loads from the past have caused a certain amount of compression, and as long as the new load does not exceed the maximum load from the past, the soil layer will not be further compressed.

As a result of pre-load, the soil layers are hardly – if at all – susceptible to settling, in much of the Netherlands. In the northern half of the country, the layers of soil before the penultimate Ice Age were strongly compressed by hundreds of metres of thick ice. In the southeast, soil layers that were once on the surface have disappeared due to erosion, thus reducing the surface load. In addition, the older layers (Pleistocene or older) that are on the surface have undergone more than 10,000 years of groundwater level fluctuations (also during the period when the sea level was more than 100 metres lower), so that the groundwater level will not fall under the minimum level in the past in the near future. This is why settling is only to be expected in areas with relatively young deposits (Holocene age) in the west and north of the country and in river areas.

Soil settling is relevant to ATES, as they can cause damage to buildings and infrastructure. They are especially harmful when there are large differences in settlement from place to place; if the settlement is even, it does not cause any damage, unless very large. Settlement at greater depths is 'damped' by the overlying layers. Settlement at ground level is thus divided over a larger area and is much smaller and more uniform than settlement at depth. In the case of shallow ATES systems, the probability of variations at ground level is much higher, because hardly any damping can take place.

As far as is known, no damage has ever occurred in practice as a result of settlement due to ATES. However, there are at least 10 ATES programmes known in the Netherlands where the calculated settlement has been a reason for ground level monitoring to be required.

Settlement does not only occur as a result of ATES systems. The expected independent ground subsidence and swelling in the Netherlands for the period up to 2050 was inventoried in 1997 by Rijkswaterstaat. There are three main reasons for the ground subsidence (or swelling) in the Netherlands:

- Settling and oxidation as a result of drainage in clay and peat areas will lead to a soil subsidence of 10 to 70 cm in 2050 in the areas concerned.
- Natural gas extraction in Groningen and Friesland will lead to subsidence between 25 and 36 cm in the period up to 2050.
- Tectonic movements of the earth's crust will lead to an increase of up to 5 cm in the southeast and a maximum reduction in 5 cm in the northwest in the period up to 2050.

Settlements due to hydraulic head changes can be easily predicted with calculations based on empirical formulas. However, much less is recorded in the scientific literature and observed in practice about settlement that can be expected as a result of temperature changes: with large changes in temperature in the soil, thermal settling can occur due to the expansion or shrinkage of soil particles. In laboratory tests, a linear relationship for elastic stress formation has been found in the temperature range from 0 to 80°C, both for clay and for sand. Settlements of up to 0.0014% /°C occurred for sand and 0.03% /°C for clay, while measurements in practice seem to indicate that the actual effects are smaller.

An open research question is how the settling measured in existing ATES systems relates to the calculated settling (with specific consideration of the high-temperature heat storage systems in connection with thermal settlement). Height measurements of surface level that have been carried out on existing programmes can be used for this purpose. Since settling could only occur in a small number of specific situations, research on this subject is not included in the programme’s research plan.

3.4. Salinisation

Salinisation occurs in areas with saline groundwater as a result of two main causes: large-scale pumping for the polders, and an increase in groundwater extraction. There is a great deal of knowledge about salinisation. The key question is under what conditions (geology, freshwater – saltwater distribution in the subsurface, extraction regime) and to what extent will an ATES system influence the fresh–brackish–salt distribution of the groundwater. An important derived question is what will the (cumulative) effect of several ATES systems be on salinisation of the groundwater system.

There is a quite clear picture of the risks of salinisation caused by water extractions and where in the Netherlands these risks occur. Within the regions, however, it has not yet been determined where the risks are higher. It is expected that injection of water through ATES systems will have a dampening effect on salinisation, although there has been little research on this effect. It is unclear when salinisation of the groundwater system is regarded as undesirable and no standard has been established.

Extraction creates a risk of salinisation. Even if no groundwater is extracted (as in ATES systems, where the extraction is balanced out by infiltration) the freshwater supply might be reduced by mixing. In the west and north of the Netherlands, the fresh-saline interface of the groundwater is very shallow and the risk of salinisation caused by ATES is greater than in the rest of the country.

The possible reduction in the freshwater supply depends on the geohydrological situation (the geological structure and the degree of hydraulic permeability), the current freshwater-saltwater situation and its development history, the extraction rate, the degree of water balance or imbalance and the type of ATES system.

Salinisation is an almost irreversible process: once it has occurred, the groundwater system will not recover quickly (at least not within decades). If the mixing of fresh and saline water takes place in an ATES system, the freshwater supply will usually decrease. The use of ATES in aquifers with a transition from fresh to saline groundwater is therefore usually not permitted, unless it can be demonstrated that no adverse effects are likely to occur.

A modelling study in Flevoland shows that the damping effect of infiltration on salinisation is significant; a recirculation system has a greater salinisation effect at the same flow rate and under the same geohydrological conditions compared to a doublet system. However, it is not known how the configuration (design and management) affects the possible salinisation of a thermal storage system; this relates, among other things, to well distances, water balance or imbalance and flow rates.

Water quality measurements were included in the programme's research programme. Based on this data, it can be assessed whether the pumped groundwater at the pilot programme location in question is more saline than in the reference tube, which may indicate salinization. Past measurements will also be used for this. In addition, the influence of ATES on salinisation will be investigated using models, both for a few individual ATES programmes and for combining several ATES systems.

3.5. Changes in temperature due to ATES

There is considerable knowledge about heat transfer and density flow in the subsoil. Changes in temperature resulting from ATES systems can therefore be easily predicted if the subsurface properties are known at the relevant location. However, these properties are subject to uncertainty. Combining this theoretical knowledge with an uncertainty analysis plus measurements from practice should provide more information about their importance.

The greatest uncertainty in predicting temperature effects lies in the pattern of use of the ATES system. In practice, the infiltration temperatures and the displaced water quantities often deviate from the design values. In order to ensure that the Water Act permit conditions are complied with, the volumes of water and infiltration temperatures are often presented as larger when applying for the permit application; thermal effects are therefore smaller in practice than those calculated for the permit. However, for systems with an energy imbalance, larger thermal effects can occur, because the volume stored in the warm or cold well increases every year.

One of the greatest physical uncertainties that might have a thermal influence is the soil structure of the subsurface. Model calculations often assume a homogeneous soil structure, while in practice there is a greater or lesser degree of heterogeneity. Relatively little research has been done on the influence of this heterogeneity on the distribution of heat and cold in the subsurface and the efficiency of ATES systems. It is possible that the infiltration and extraction largely compensate for each other, but the question as to whether heterogeneity will have a significant impact on the output and possible interference within a single ATES and between several ATES systems cannot be answered with certainty. It should be noted that the sensitivity of the ATES efficiency to soil heterogeneity mainly depends on the distance(s) between the cold and warm well(s).

Differences in density and viscosity caused by large temperature differences can lead to groundwater flow and thus have an impact on thermal impact of an ATES system. For currently installed systems, where there are only a few degrees of temperature differences, these effects can be ignored. In the case of ATES systems with large temperature differences (an order of magnitude of tens of degrees difference), this effect should be considered.

From the literature it appears that the influence of temperature on the specific heat capacity (c_p) of liquids and solids is very small. Since the average value for the heat capacity of sand and clay is the same, the influence of heterogeneity on the distribution of the heat capacity in the subsurface is limited. The thermal conductivity (k_T) seems to be independent of temperature and density and its value is different for the different soil types. Both parameters influence thermal impact of an ATES system. Much can be found about these parameters in literature, but not much seems to be known about putting this theory into practice.

The research (according to the research programme) is:

- Modelling the influence of heterogeneity on the efficiency of one ATES system and on possible mutual interaction between systems
- Measuring soil temperature profiles close to the selected pilot locations, investigating the influence of the physical parameters on thermal effects, and modelling thermal impact of a practical example with comparison to the measurements
- Modelling the temperature gradient in the subsurface after the termination of an ATES system
- Investigating thermal losses in practice and the effect on large-scale application
- Performing an analysis of existing soil temperature measurements (possibly supplemented with new measurements) in areas that have not been influenced by ATES systems (associated with ‘background’ effects on the soil temperature).

Additional questions related to this chapter:

- Examining the sensitivity of the overall efficiency of ATES systems to the extraction temperature
- To what extent and when is an energy balance useful/necessary?

3.6. Past temperature changes

Changes in temperature that occur as a result of ATES systems are often in the order of a few degrees compared with the original soil temperature. In heat storage programmes, the difference with the natural soil temperature is often much greater. In order to be able to put the influence of stored temperatures and energy quantities into perspective, it is important to also investigate changes in temperature in the subsurface that occur independently of ATES.

The temperature in the substrate depends on many factors. Most of these factors are stable over time. This applies, for example, to the heat flux from the earth's core and the heat capacity of the soil layers.

In the Netherlands, changes in temperature in the subsurface caused by deep soil heat extraction are currently insignificant. Changes in temperature mainly occur due to alterations on the surface, such as changes to the surface temperature (for example due to climate change or changes in changes in land use) and water management (for example the creation of polders).

The earth's surface temperature is an important precondition for the subsurface temperature. The subsurface reacts slowly to temperature changes: the daily temperature cycle is therefore evident only in the upper metre of the subsurface and the annual temperature cycle only up to approximately 15 m deep. Deeper than 20 m (where ATES systems are placed) only the influences of long-term changes in temperature are noticeable, such as climate change or changes in land use. As the effects of changes in temperature on the surface work slowly through to deeper levels, insight can be gained into long-term trends in the average surface temperature based on soil temperature measurements.

The long-term average temperature on the surface is determined not only by the climate, but also by land use. For example, it is known that the average temperature in forest areas is about 1.5°C lower than in agricultural areas. ATES is mainly used in urban areas. Various studies have shown that the air temperature in a city in the Netherlands can be up to 2.5°C higher than in the surrounding non-urban area. Research has shown that this effect is also noticeable in the subsurface. The extent of this urban "heat island" effect in the Netherlands has yet to be investigated.

The groundwater flow also influences the temperature distribution in the subsurface. It is expected that large-scale groundwater extraction for water management – in low-lying polders in particular – will affect the soil temperature, not only because it generates groundwater flow, but also because of the change in the average surface temperature caused by the drainage. The extent of this influence has, to our knowledge, not been investigated.

Within the programme, the soil temperature development that has taken place in the past 50 years will be recorded, as well as developments that can be expected in the next 30 years. Because ATES is mainly used in urban areas, quantification of the heating of the subsurface in urban areas independently of ATES is particularly relevant. For example, a net cooling effect due to an ATES system could completely or partially compensate for this heating of the subsurface.

3.7. The effects of geochemical changes in the soil

The extent to which geochemical processes can lead to a significant change in groundwater quality depends on the ATES system (e.g. through temperature differences) and the biogeochemical properties of the groundwater system (e.g. redox states). The effects of temperature differences on the groundwater quality depend on the ATES system used, but many of the other geochemical processes that can occur in ATES are already known from research on, for instance, the behaviour of contaminants, or groundwater quality for drinking water production. For ATES, research has been conducted on the relationship between chemistry and temperature, especially at higher temperatures (> 50°C), focusing on the precipitation of calcium carbonate ($CaCO_3$) and silica (SiO_2), reactions that can cause well clogging. In addition to Calcium (Ca) and Silicon (Si), other macrochemical parameters are usually also investigated. Apart from this effect of temperature on the mineral balance, there is also an effect of temperature on the rate at which geochemical reactions occur and the extent to which substances absorb aquifer sediment. These last two effects have until now been ignored in the research on the effects of ATES.

In addition to the direct effect of temperature on geochemical processes within an ATES system, the following physical and geochemical processes in particular influence the groundwater quality:

- mixing
- variation in gas pressure
- aquifer/groundwater interaction
- interaction with groundwater outside the ATES system.

These processes are not specific to ATES but may be important for the change in expected groundwater quality. The effects on the groundwater are expected to increase with stronger concentration gradients (e.g. pH or redox), or when the aquifer sediment is more heterogeneous and more reactive.

The effects on the geochemical quality of groundwater can – depending on the process and the location – take place at specific times and places within the ATES system. That is why it is important that the location and timing of the monitoring are tuned as much as possible to where and when the effects can be expected during the injection cycles. Based on the literature, there seems to be hardly any effect on the macro-chemistry of the groundwater due to changes in temperature in low-temperature ATES systems (<25°C). However, the effect on trace elements has remained not been covered in the literature. In order to take the effect of changes in temperature into account, the high-temperature (HT) systems are particularly expected to provide insight into which processes are most susceptible to them.

At low temperatures, it is mainly through mixing that effects can be expected, especially when there is a strong vertical variation in the original groundwater composition. In addition to the mixing of different groundwater qualities inside the extraction well, mixing also takes place along the edges of the injected water volumes. This is caused by the gradients between the mixed groundwater within the ATES system, which has changed composition, and the groundwater outside the ATES system. It is expected that during injections, stronger deviations for mineral equilibriums and larger redox contrasts may occur between mixed groundwater and aquifer sediment.

The most important knowledge gaps in geochemistry are as follows:

- The influence of ATES on trace elements has not yet been sufficiently investigated. Within the programme, measurements are carried out in the pilot programmes, whereby the trace elements will also be analysed.
- Mixing groundwater at different depths can give rise to reactions between the mixed water and the soil material, especially if there is strong vertical variation of the groundwater quality. This aspect has remained ignored until now and was not considered within the programme research plan.

3.8. Changes in the microbiology of the subsurface

The soil ecology is responsible for various soil functions that are important to people and the environment. The soil ecology has, among other things, a buffering effect on restoring natural conditions and a purifying effect on anthropogenic substances and pathogens (decomposition of pollutants). Influencing soil ecology through heat storage may have consequences for these functions and it is therefore a social issue that should be investigated.

Our literature review shows that an increase in temperature rarely results in an increase in the total number of micro-organisms in the groundwater. The main reason for this is that in the deep groundwater, under normally prevailing conditions, there is no or hardly any assimilable organic carbon that micro-organisms need in order to grow. In cases, however, that nutrients are supplied by the groundwater, the number of micro-organisms can increase. Competition arises between the various types of micro-organisms, as those that are adapted to the circumstances will survive better and niches will occur.

The composition of microbial populations in groundwater can therefore be influenced by a change in temperature and groundwater mixing caused by ATES systems. The effect of these changes has yet to be thoroughly investigated. So far, microbiological research of soils and groundwater focuses mainly on indicating the presence of specific groups and species of micro-organisms. In some studies, the focus is also on detection of specific soil functions (nitrate reduction, iron oxidation, etc.). The programme research will focus on monitoring changes in soil functions and microbial composition, both in the field and at the laboratory (degradation tests and column tests).

No increase in pathogens has so far been observed in any the ATES programmes that have been monitored. Faecal organisms such as E. coli have been found at a single location, but not in excessively increased numbers. In fact, it appears that the pathogens in ATES systems can even decrease. Pathogens that do not occur naturally in the subsurface have little chance of survival, as they are insufficiently adapted to the conditions and are outcompeted by the naturally occurring micro-organisms.

If ATES systems are placed outside of groundwater protection areas (zones in which groundwater requires at least 25 years of travel time to reach the extraction well) there is no risk with regard to pathogens. Already after a residence time of about 60 days, the pathogens in the soil are outcompeted or deactivated. The maximum found residence time of pathogens was found to increase to 12 to 24 months in unfavourable circumstances.

Even though ATES systems do not cause an increase in pathogens (as far we know), it is important to do more research on this subject, as ATES systems will inevitably be placed near drinking water sources in the future. In the programme, research is therefore carried out on the presence and proliferation of pathogenic micro-organisms as a result of the effects caused by the operation of an ATES installation. No research has been carried out into the presence and proliferation of viruses, but this has been done in the research carried out by KWR.

Further research is required to determine the indirect effects of ATES systems on the soil ecology; the effect of temperature on the release of assimilable organic carbon and nutrients, as well as the effect of groundwater mixing on soil ecology, have been examined in field and lab tests.

3.9. Guidelines for ATES in practice

Guidelines, protocols and legal requirements concerning the design and realisation of UTES systems are defined in the Water Act permit. These guidelines and regulations are intended to ensure good-quality systems and to prevent or limit adverse environmental effects. The most important guidelines and protocols are:

- <u>NVOE guidelines:</u> Intended to guarantee the quality of design, realisation, management and termination of ATES systems. This system was set up by the players in the UTES market. There is no obligation to follow these guidelines.

  - SIKB protocol "Mechanical Drilling": Intended to guarantee the quality of ground drilling. As of 2011. all drilling companies must be certified on the basis of this protocol.

In addition, a process has been set in motion within the context of the ATES Cooperation Programme in order to achieve integral and legally anchored quality assurance of all aspects of ATES. Not only the drilling, but also other aspects are discussed, such as energy efficiency.

To obtain a Water Act permit for an ATES system, the national and provincial policy must be complied with. Requirements are set for the construction of an ATES system, the measurements to be performed and reported, conditions during use and the termination of the system. Some of these guidelines are in line with the NVOE guidelines and the SIKB protocol. Other important requirements are:

- An ATES system must meet an energy balance over a specified period of time. Net heating or cooling of the substrate is not permitted.
- The infiltration temperature is a minimum of 5°C and a maximum of 25°C (30°C in South Holland).
- ATES may not be used in some provinces in certain deep aquifers.

These latter requirements create limitations for ATES systems and are thus under discussion. Restoring an energy balance can lead to higher energy consumption and result in extra investment costs.

Storing heat at high temperatures can severely limit the energy consumption of the heat pump or even make the heat pump unnecessary. An increase in the maximum infiltration temperature can further improve the sustainability of ATES systems and provide additional energy savings. The main drawback, however, is the possible adverse influence of the high temperatures on soil and groundwater. In the programme the effects of higher infiltration temperatures are investigated by conducting laboratory tests and measurements on existing high-temperature systems.

The restricted aquifers are in many cases suitable for ATES. If other aquifers cannot be used or are not suitable, this constraint prevents the application of an ATES system, even though it would be possible. The revocation of these restrictions would thus be beneficial for ATES. The main objection to this revocation is the possible negative influence on the groundwater quality. The necessity of restricting certain aquifers is being investigated indirectly in the programme by gathering additional knowledge about the effects of ATES on groundwater quality.

The starting point of the current policy is that the first party to have a licence has the first right. However, it is becoming increasingly common that new ATES initiatives are being hindered by existing ATES systems. In connection with this, the question is whether and when control on the subsurface is necessary in order to arrive at a fair and optimal use of the underground space. A possible solution is area plans.

Research relating to the available underground space on the one hand, and the required underground space (for the full application of ATES) on the other, can provide insight into the areas for which these questions are important. At present, a guideline on masterplans is made by SKB together with a consortium of consultancy firms. This provides guidelines that define under which conditions a masterplan should be made and how.

3.10. Well clogging

Due to the long life of ATES systems, it is very important to ensure that well clogging is kept to a minimum. According to research from 2008, 5-10% of ATES systems in the Netherlands are currently affected by this problem. There are various causes of well clogging, as explained below. In most cases it can be solved quickly – serious problems with clogging rarely arise. However, in view of the expected increase in the number of systems in the years ahead and the arrival of new players in the market (who have less knowledge and experience), well clogging remains an important point that needs attention. In addition, the combining ATES and remediation will involve increased risks of clogging, as water qualities are mixed more frequently.

Well congestion by particles is likely to happen to a greater or lesser extent in every ATES system. This type of clogging has been studied extensively in the context of the Business-oriented Technological Cooperation Programme (*Bedrijfsgerichte Technologische Samenwerkingsprogramma* - BTS). The most important conclusion is that particle congestion can be limited with frequent switching. In addition, it can be controlled by preventive maintenance of the wells.

Chemical/biological well clogging usually occurs by mixing water with different compositions. The most common chemical/biological clogging in ATES systems is caused by iron oxides and hydroxides. Preventing the mixing of different water types is the most obvious solution. This means that the preliminary investigation requires attention to the quality of groundwater.

Considering the combining ATES with remediation, the risk of well clogging increases considerably, due to greater differences in water quality and increased levels of degradable substances. Since there is hardly any experience on this combination, it is unknown if and when prevention or control of this problem is feasible. In the context of an SKB study into the combining ATES with remediation in Apeldoorn, possible solutions have been proposed to limit the occurrence of clogging or to keep the problem under control. In addition, a design was made of a pilot installation for a first programme with associated facilities that enable further research.

At high-temperature heat storage, clogging may occur due to precipitation of carbonates. In this case, water treatment may be necessary to prevent this.

Another issue is gas clogging, which can be effectively prevented by ensuring that the water remains under sufficient pressure. If there is high gas pressure in shallow groundwater, maintaining sufficient pressure cannot always be guaranteed, and therefore it is preferable to use energy storage in a deeper aquifer. Degassing is also possible, but not desirable if methane (which is a strong greenhouse gas) ends up in the atmosphere.

Finally, thermal well clogging and clogging due to clay swelling usually do not play a significant role.

In conclusion, the main research question that is important for the functioning of wells in practice involves combining ATES and remediation: to what extent will congestion occur, can the clogging problem be prevented or controlled, and how can this be implemented? Based on additional literature research and practical data both from remediation systems and ATES systems in contaminated groundwater, an inventory was made (within the programme) of the effects that can occur and what counter-measures are possible.

3.11. BTES

The previous chapters mainly focus on open ATES systems. This chapter specifically describes Borehole Thermal Energy Storage (BTES) systems. These are closed systems, where water flows in a tube that forms a loop in the ground, without coming into contact with the groundwater.

Various legal requirements apply to BTES. In provincial environmental regulations and in the Keur (a decree containing regulations that water boards may impose to protect dams, waterways and associated works), restriction areas have been determined for the application of BTES. A permit in the context of the Environmental Management Act applies to systems larger than 1.5 kW, and the Soil Protection Act has provisions that specify taking care of the soil. Because no groundwater is extracted or infiltrated, no Water Act permit is required.

The current policy for BTES does not include testing of the effects of these systems, and moreover, there is currently no registration of the systems. As a result, there is little insight into developing the number of systems and their effects. The latest information on numbers relates to 2007: according to the estimate of Statistics Netherlands, 20.000 drill holes for soil heat exchanger existed in the Netherlands in that year.

For BTES systems, attention needs to be paid to the following risks:

- Sealing of pierced clay layers (which work as natural barriers that can separate groundwater with varying qualities and, among other things, impede the spread of pollutants to other aquifers).
- Leakage of substances foreign to the soil, such as glycol, which is often used as the circulation fluid in the tubes.
- Adverse thermal impact on existing ATES.
- The decommissioning of the systems is not subjected to any rules.
- Placing BTES systems too close together will result in systems that are likely to influence each other.
- Freezing of the soil in the case of excessive cooling.

The sealing of drilled resistance layers should be carried out from 2011 onwards according to the "Mechanical Drilling Protocol", with which this risk is legally covered. With the arrival of the Soil Protection Board (at the time when the programme was carried out, it was scheduled for 2012), a mandatory notification or licence obligation will come into force for BTES systems, so that more insight can be gained into the developments.

Although the risk of leakage is small, it cannot be ruled out. Various measures can be taken to eliminate or minimise the risks:

- Carrying out extensive tests at the realisation of the programme to detect leakage
- Applying leak detection systems
- Setting preconditions concerning the materials to be used (for example, durability of the pipes and filling of the borehole with poorly permeable material)
- Setting boundary conditions for the fluids circulating in the BTES tubes (for example, not allowing certain additives that can be harmful).

The various measures have consequences for the systems to a greater or lesser extent and thus influence both the feasibility (costs) and the environmental effects (for example, if a certain measure reduces the energy efficiency per loop, and thus requires more boreholes). It is therefore important to make a proper assessment between the consequences of the measures and the effects that are prevented or limited.

The question as to how the soil can be restored after deactivation of a BTES system has not yet been answered. Replacing the fluids used with clean water is clearly only a partial solution; however, it is important to ensure that a correct discharge is released.

In summary, the following research questions remain:

- What requirements should be set to limit the risks of leakage of circulation fluids, and what are the consequences of these requirements?
- How can interference between a BTES system and other existing BTES or ATES systems be prevented?
- How should the deactivation of BTES systems be dealt with?

In addition to identifying the risks related to the use of antifreeze in BTES systems (existing knowledge on this topic is in the literature review), the programme research programme does not include any additional research specifically designed for BTES systems.

3.12. Options for combining ATES and soil remediation

Since an ATES system may not cause displacement of groundwater contamination, installations in contaminated areas are designed a way that no interaction with the pollutants will occur. Due to the growing demand for ATES systems, however, the pressure to allow their installation in contaminated aquifers is increasing. Such ’combination concepts’ could deliver a win-win situation, as it would become possible to apply ATES systems in areas where this was not allowed in the past and at the same time open up new opportunities for soil remediation.

Much information is available about ATES and soil remediation separately, but knowledge about the combining both techniques is scarce. The only example from practice is the Sanergy programme in Eindhoven, where an ATES system is used to control and clean up contamination. Since Sanergy had recently started at the time the programme was conducted, it was still unknown what the results of the combination concept would be.

In addition, combination concepts have been elaborated in the scientific literature for various contaminated sites within the Netherlands. Elaborating these concepts often includes one or more of the following elements:

- partially purifying and discharging groundwater from the ATES system
- controlling pollution through a smart groundwater recirculation system
- increasing natural degradation by groundwater transport
- increasing natural degradation by heating the soil
- stimulating natural degradation with the addition of auxiliary substances.

In addition to the above options, the reactivity around ATES wells and/or underground aeration (also known as underground de-ironation or Vyredox) may be of interest. In both techniques, an active zone around the ATES wells is constructed, in which chemical or biological degradation of the contamination can take place.

In elaborating the above concepts it appears that the flow rates of ATES systems are often much greater than those applied for remediation. This means that the above-ground purification of the total volume of pumped water is unaffordable, and conversely, supplying cold and heat from the water that is released during remediation is not profitable. However, an intermediate solution can be chosen, where a small part of the extracted groundwater would be purified and discharged.

ATES systems are usually placed in deep soil layers (20 – 150 metres below ground level), while groundwater contaminations are often found in shallower soil layers (0 - 20 m b.g.l.), which means that, On the one hand, the combination with ATES is more difficult to make, and on the other hand, differences in groundwater quality result in greater risks. However, contamination – often chlorinated hydrocarbons – can also be found at greater depths (20 - 100 m b.g.l.), in which case combinations are worth considering. An important point of attention when combining ATES and remediation is the increased risk of clogging.

To compensate for the shortage of practical experience in combination concepts, lab and practical tests are carried out in the programme, investigating the effectiveness and sustainability of this idea. Furthermore, the available knowledge is bundled and developed in combination with concepts that can serve as a practical basis for future programmes. In the elaborated concepts, attention is paid to the financial and environmental performance.

3.13. Effects of changes in temperature on the physical properties of contaminants

The behaviour of contaminants changes with temperature. In order to be able to predict this behaviour, attention should be paid to the effects of changes in temperature on the physical properties of the most common contaminants BTEX and VOCl. The volatility, solubility and spreading behaviour of these contaminants are temperature-dependent.

The following applies to VOCl: with an increase in temperature of 50°C, the equilibrium concentration in the gas phase (with constant concentration in the aqueous phase) becomes ten times larger, and VOCl therefore shifts faster to the gas phase. For benzene and naphthalene, the equilibrium concentration increases with approximately a factor of six for the same temperature increase.

For PCE and TCE, the maximum solubility remains stable from 0 to 60°C and increases exponentially at higher temperatures. For p-xylene – one of the components of BTEXN – the solubility increases exponentially with temperature, starting from 25°C. No such relationship is known about the other components of BTEXN.

With VOCl in pure product form, there is a chance that at higher temperatures, it will accelerate to greater depth.

The effects of temperature on the physical properties of the contaminants are negligible in most ATES systems, as the temperature differences that occur are only a few degrees.

High-temperature ATES systems, however, are expected to have a significant influence. The effect of high-temperature ATES on the spreading of VOCl is still unknown.

Remediation techniques based on heating of the soil include electro-reclamation and steam extraction. With these techniques, the soil is heated up to 100°C, making the contamination more mobile or causing part of the contamination to evaporate. The effects of these techniques can possibly be compared with the effects of high-temperature ATES systems on contamination.

Before a high-temperature ATES system can be placed in an area with VOCl, more research will need to be carried out into their spreading behaviour at these temperatures. In the programme, solute transport models are used to visualise the effect of an ATES system on VOCl. In elaborating the combination concepts, the extent to which these physical effects can also be (temporarily) used for accelerated removal of contaminants is examined.

3.14. Biological degradation of contaminants

In order to develop combination concepts, it is important to know the criteria for biological degradation of contaminants to occur. The focus is on the two most common and mobile groundwater pollutants: chlorinated ethenes (PCE, TCE, DCE and VC) and BTEXN.

Tetrachloroethene (PCE) and trichloroethene (TCE) can be degraded by means of anaerobic reductive dechlorination, via DCE (dichloroethene) and VC (vinyl chloride), to the harmless degradation products ethylene and/or ethane. For reductive dechlorination to occur, the following conditions should be met simultaneously in the soil:

- greatly reduced redox conditions (preferably methanogenic)
- sufficient electron donors
- presence of the specific micro-organisms that can break down VOCl.

Cis-DCE and VC can also be degraded via aerobic or anaerobic oxidation. Anaerobic oxidation is of particular interest, because this type of degradation can take place under soil conditions that often also prevail in the highly permeable aquifers in which ATES systems are installed. The maximum proven rate of conversion of anaerobic oxidation is very low compared to the rates that can be reached with aerobic degradation or anaerobic reductive dechlorination. Little is known about the anaerobic oxidation process.

Under aerobic conditions, TCE, CIS and VC can be co-metabolised in the presence of co-substrates such as toluene, propane or methane.

Volatile aromatics such as benzene, toluene, ethylbenzene, xylenes and naphthalene (better known as BTEXN) can be rapidly degraded to carbon dioxide and water under aerobic conditions. The degradation of BTEXN is also possible under anaerobic conditions but it is usually much slower. Anaerobic degradation of benzene and naphthalene does not appear to occur in all cases and is sometimes very slow. The anaerobic degradation of benzene can also be influenced by the presence of TEX; degradation of benzene and naphthalene occurs only after TEX has been degraded.

Research has shown that the optimum temperature for biodegradation is around 10-30°C. From a study in which the degradation of VOCl via anaerobic reductive dechlorination at different temperatures was investigated, the degradation of DCE appeared to stagnate at temperatures lower than 4 - 10°C. At a temperature higher than 60°C, TCE was no longer degraded, and at 40 to 50°C, the degradation of DCE and VC stagnated. From the results of an electrobioreclamation decontamination, in which the soil temperature was raised to 40°C, increases in the first-order degradation constants were observed, with a factor of four for VC and a factor of 100 for PCE. The contamination that was adsorbed by organic material was also found to be released more quickly.

Taking all ATES installations together, the energy balance is almost closed at the national level, as many systems have correspondingly large warm and cold zones. It may be that the degradation is stimulated in the warm well, but the degradation rate decreases in the cold well. The net impact of this on biodegradation is unknown.

Little practical knowledge is available about the effect of ATES on the degradation rate of VOCl and BTEX. No field tests have been carried out, and in the few laboratory tests that have been conducted, the biological processes were only followed briefly. By means of field and lab measurements, the programme specifically focuses on these biological degradation processes. More about this can be found in Report 11 (in Dutch).

3.15. Regional groundwater management

In many urban and industrial areas in the Netherlands, soil and groundwater have been contaminated on a large scale by various business activities. In practice, it has been proved difficult to effectively tackle areas with large-scale deeper soil and groundwater contaminations in the context of the Soil Protection Act. On the one hand, it is difficult to visualise the nature and extent of the contamination, and the cause of it is often not traceable or no longer liable. On the other hand, the (social) costs for a complete clean up appear to be extremely high, while often there is no high motivation to tackle deeper groundwater contaminations quickly. At the same time, the need to use the deeper subsurface for multiple functions is rapidly increasing, and groundwater contamination hinders developing these new user functions. There are also risks, especially in the long term, for sustainable land use and for the quality of groundwater and surface water resources. This is the reason that in the past 10 years, various players have investigated the potential for addressing the large-scale groundwater pollution in an regionally-oriented way.

There are in total three ways in which ATES can have a beneficial effect on the pollution load in deep groundwater. The first is through stimulating the natural degradation of contaminants by raising the soil temperature. The second way involves pumping (polluted) groundwater, which could be beneficial for the natural degradation by mixing of contaminants, auxiliary substances and bacteria. Finally, a third way is that ATES systems could be used in order to track and control groundwater contamination. In the Netherlands, the concept of regional groundwater management is applied in a number of areas (including Rotterdam, Het Gooi, Utrecht Centre and Apeldoorn).

Regional groundwater management comprises a number of aspects that deserve attention: technical, administrative, financial, organisational and spatial integration. Several important points of discussion have emerged from the pilot programmes that have been carried out. The first question is whether the identification of large-scale contaminated areas (where potential for regional groundwater management is offered) is complete. The favourable effect of ATES on groundwater contamination is still a hypothesis that should be further investigated. Modelling the contamination in such a setting requires adaptation of the existing approach and the model codes. The monitoring of the groundwater flow and the distribution of point sources and/or plumes should be well-justified, considering the physical system and the administrative boundaries. The measurement data should be assessed according to a clear and (nationally) accepted assessment framework, which is still missing.

In regional groundwater management, the initiators, policy makers and consultants paid particular attention to the legal and aspects of policy, and less to the organisational and financial aspects. The SKB framework also identified which areas would potentially qualify for a regionally-oriented approach. The following questions need to be answered:

- How will the range of tasks of area managers be defined? Which powers will they receive? Which (financial) resources will he or she have access to? What can be expected for the 'polluters' in the area?
- How reliable are the cost models used, on the basis of which the financial budget of the regional approach is calculated?
- When and how is it determined whether the intended objectives of the regional approach are met? More concretely: how is monitoring conducted, and how will the local authority test it? What level of protection is used against possible threats within and outside the area?

Little is known about the technical and spatial implications of applying ATES systems in large-scale contaminated areas. Many of the standing technical questions focus, On the one hand, on facilitating the use of the (contaminated) subsoil for ATES, and on the other hand, on using the potentially managing and remediating function of ATES systems.

The programme has addressed the technical questions; more on this can be found in the full 3rd report (in Dutch). Related to the use of ATES in regional groundwater management, the programme has addressed the following questions:

- Is it realistic to expect that ATES in a large-scale contaminated area can substantially contribute to the improving groundwater quality?
- Does ATES offer an opportunity to control the pollution load?
- Which technical, process and policy issues are there? What criteria should be used?
- How can groundwater monitoring be optimally used?

3.16. Ways of combining ATES with other applications

Pumping large quantities of groundwater, and adding or extracting thermal energy, offer potential starting points for combinations with other processes in the water cycle and energy management. The many examples of new possibilities that have been found can be divided into two categories. The first category is related to (relatively) new areas of application of ATES (e.g. ATES in greenhouse agriculture, livestock, or preventing roads and runways from icing) and new ways to capture heat or cold (e.g. use of surface water, asphalt, sewage/wastewater, or semi-closed greenhouses). The second category is related to areas of application that do not involve thermal energy, such as the combining ATES with remediation, fire extinguishing or (drinking) water extraction.

In the full report (in Dutch), an overview was made of the various innovative applications of combining ATES with other processes in the Netherlands. In addition, a number of examples are given of how these can be applied in practice, but all the examples are still only in concept stage. Most innovative combinations relate to the production and use of renewable energy. The conclusion is that ATES can be applied in many situations, but that ultimately few innovative 'win-win situations' have been created with orientations other than energy, although there may well be opportunities for this in the future. The fourth report includes further identification of – and elaboration on – promising concepts that could, in principle, be applied in certain areas or circumstances.

4. The effects of UTES systems on the geochemistry and biology of the soil

4.1. Results of measurements at pilot locations and lab tests

By the application of geothermal storage systems, changes are made to the existing soil and groundwater management. These changes can be due to the temperature differences and/or the pumping and infiltration of water (which leads to the mixing of water with varying compositions), and they can have an effect on the chemical and (micro)biological composition and quality of groundwater and the soil structure.

In order to determine what happens when applying ATES systems in practice, physical, chemical and biological measurements were carried out at nine pilot locations. These locations include different types of UTES systems including a closed system, doublet systems, a single well system (monowell), a recirculation system in uncontaminated groundwater, and a recirculation and a doublet system in groundwater contaminated with chlorinated hydrocarbons (VOCl).

In terms of the expected geochemical effects, changes in the gradients of chloride (fresh-saline water mixing), pH, hardness and redox were examined. Regarding the expected effects on biology, changes in the quantity, composition, functioning and biodiversity of micro-organisms in the groundwater were examined. In addition, physical measurements were carried out to determine actual temperatures and the occurrence of, for example, density currents. In addition to pilot field measurements, lab tests were also conducted to provide more insight into the effects of temperature.

In open systems, it is often assumed that the temperature difference is an important - if not the most important - parameter that influences the chemical and microbiological composition of the groundwater. However, in the open systems that have been studied, it appears that the mixing of water as a result of extraction and infiltration is the most determining factor. This mixing can take place in a number of ways, such as the extraction of groundwater with varying compositions, which are mixed and then returned to the aquifer. This effect is particularly important in the first year and/or in the case of an imbalance in the annual quantities of pumped water. Mixing water with different chloride contents and hardness profiles has been found to be the most common case at the pilot locations.

In terms of the temperature effects on geochemistry, both an elaboration on a theoretical basis and site measurements were performed. The speed of geochemical and biological reactions increases by a factor of 2 to 3 when the temperature is increased from 10°C to 20°C. For ATES systems, the reaction rates are thus lower in the cold well and higher in the warm well, compared to the rates in the natural groundwater temperature. The greater the changes in temperature, the greater the changes in the reaction rates. However, in UTES systems with an energy balance, approximately the same amount of warming and cooling occurs. As a result of this, the net effect on the reaction rates is small. The temperature differences, therefore, only have a minor influence on the geochemical water quality of the systems studied in the programme.

Based on theoretical framework for temperatures lower than 20°C, there are no significant temperature effects to expect on a 20-year time scale. The water quality changes that can be expected based on the mineral balance for calcium carbonate correspond well with the field observations at the Heuvelgalerie location.

In the lab tests, no effects on the population and functioning of the micro-organisms occurred at a temperature of 18°C. Some effects on the activity of the micro-organisms were observed at 30°C. In the field, these effects were not found within the measured temperature range (between 11°C and 35°C). The measured quantities and compositions of the bacteria both inside and outside of the ATES system fall within the total natural variation in Dutch soils. These values mainly depend on the sampled location.

At temperatures higher than 30°C, changes in the composition of the microbiological population were found. In the lab tests, it appeared that the functions of micro-organisms remained intact. This corresponds to theoretical expectations; at this temperature, another group of micro-organisms has a selective advantage. This means that the specific types of micro-organisms that perform the different functions can change depending on the temperature, and at this temperature, the functions are taken over by the new species. In field tests, within the measured temperature range (up to 39°C at Beijum, which was the location with the hottest temperatures) biodiversity neither increased or decreased due to temperature. This is important for the resilience of the microbiological system.

At the pilot sites, zero or very low numbers of potential pathogens of the Enterobacteroceae group or E. coli bacteria were found, indicating that there is no contact with sewage water or contaminated shallow groundwater at these locations. Legionella pneumophila was not found at any of the sampled locations, whereas Clostridium perfringens was only found in very low numbers in one sample at the Beijum location. These measurements confirm earlier observations that Legionella does not survive well under the conditions on which ATES systems work, and that no high-risk quantities of Clostridium perfringens have been found at the locations investigated.

At a number of locations (Heuvelgalerie, Hederakwekerij Luttelgeest, Beijum and Zwammerdam) there was density-driven groundwater flow as a result of temperature differences. Differences in density due to differences in salt concentration also led to density-driven flow at the Beijum location (storage of 60°C).

In conclusion, the mixing effects are especially relevant in the overall effect of a low-temperature ATES system. The intensity of the effects depends on the quality of the mixed water quantities. The extent to which these effects are acceptable depends on the magnitude of the effects, as well as the objectives for using water. The results from this report are thus starting points for further processing of policy implications, for example in regional groundwater management.

5. Modelling UTES systems

Effects of UTES systems on the immediate environment – Modelling individual programmes

The fifth report describes the results from modelling three existing ATES systems that were investigated as part of the programme. These consist of one recirculation system (located at Hederakwekerij van den Berg in Luttelgeest), one high-temperature heat storage system (located at de Bruggen in Zwammerdam), and one energy storage system (located at de Uithof in Utrecht). The aim of the modelling these systems is to gain insight into the reliability of the predicted hydrological and thermal effects, the causes of possible deviations, and possible improvements that could increase the reliability of the predictions.

5.1. Modelling hydrological effects

The reliability of the predicted effects

The hydrological effects were modelled for two locations and these were compared with the measurements taken. For both locations, the hydrological effects predicted during the permit application are greater than or equal to the effects that follow from the measurements. This corresponds to the outcome of Reports 3+4 (the full reports are available in Dutch), in which the results of the measurements were compared with the predicted effects of the permit application for several research locations. This conclusion is a logical consequence of the often-used worst-case approach: in the hydrological calculations conducted for the application, the input parameters are often chosen unfavourably (e.g. a low estimation of the average permeability), in order to ensure that the actual effects will not be greater than those predicted.

Many of the input parameters (e.g. permeability, heterogeneity, use pattern) are rather uncertain, which means that there is also a degree of uncertainty in the outcomes of the model. More interpretation to this can be given by translating these uncertainties into a determination of the bandwidth of the expected effects. This can be done by using a Monte-Carlo simulation to calculate the probability of occurrence of a certain effect. For example, the hydrological area of influence can be determined based on a probability (e.g. 90%) that the actual effect is smaller than or equal to the presented effects. It is recommended to use such an approach in future research programmes. For regular permit applications, the sensitivity analysis described here is not convenient, in connection with the large amount of work that it requires; a worst-case approach is sufficient in these cases.

Schematisation in time

In the calculation of the hydrological effects, a variety of ways can be chosen for time schematisation, ranging from a stationary calculation based on the maximum flow, to a non-stationary calculation based on average flow rates over a certain period (e.g. weeks or even the entire season). A stationary calculation has the advantage that an equilibrium situation is calculated; this is why the actual effects will never exceed the calculated ones – provided that the input parameters are correct. The disadvantage of this approach is that slow-acting effects can be significantly overestimated. On the other hand, a calculation based on the seasonal average displacement provides a good estimation of the seasonal average of the expected effects but underestimates the maximum effects that can be expected.

As the pattern of use is not known in advance, and yet a good indication of the maximum expected effects needs to be given, a worst-case approach is often chosen. For example, in the study of the effects for the permit application for the system in de Uithof, a non-stationary calculation was chosen, for which the maximum flow rate was calculated for a consecutive period of three weeks. The results of the calculations for this system almost corresponded to the results of a stationary calculation. It should be noted that this system is in an aquifer confined by separating layers; in the case of a phreatic aquifer, it would take longer for the maximum effects to be reached.

5.2. Modelling the thermal impact

The reliability of the predicted effects

As with the hydrological effects, the reliability of the predicted thermal impact depends on the reliability of the input parameters of the model. This is related to the use pattern of the system (quantities of pumped water, extraction and infiltration temperatures and time variation), the properties of the system (e.g. locations of wells, filter lengths and depths) and the properties of the subsurface (e.g. heterogeneity, permeability).

The model schematisation can also be important. For example, in order to properly calculate the effects of density-driven groundwater flow, a three-dimensional thermal transport system is required. In ATES systems, where temperatures are usually low (<25°C), density flow is negligible and two-dimensional models are sufficient. Only if there are high infiltration temperatures (<20°C) and in combination with high permeability (>40 m/d) would a three-dimensional groundwater model offer improved accuracy. For high-temperature heat storage systems (>25°C), a three-dimensional model is recommended under all circumstances.

The measurements taken at different programmes (Luttelgeest and Utrecht) show that at certain depths, the infiltration water diffuses faster than at other depths across the filter trajectory. This is due to some soil layers having relatively high permeability. This heterogeneity is usually impossible to estimate in advance and is therefore not included in the model calculations; homogeneous soil layers are usually assumed in thermal models, resulting in some inaccuracies in the distribution of heat and cold in the subsurface.

Research has been carried out into the effects of heterogeneity on the storage efficiency of ATES systems. The results have shown that, although some heterogeneity influences the temperature distribution in the subsurface during the storage cycle, the influence on the storage efficiency is relatively small. A prerequisite for this is that the distance between the warm and cold wells is large enough (in accordance with NVOE guidelines) for short-circuit/round pumping to be prevented. Under highly heterogeneous conditions, there will indeed be a noticeable adverse effect on the storage efficiency. This conclusion applied not only to interference between the warm and cold well of a system, but also to interference between neighbouring ATES systems.

At the high-temperature heat storage system of Zwammerdam, soil temperature measurements were carried out 8 years after the system was shut down and the measured temperatures were compared with model calculations. The calculated “extinction” of the temperature at the warm well (140 – 150 m b.g.l.) and just above the storage corresponds well with the measurements. Closer to the surface, the difference between the calculations and the measurements rises to 3°C at a depth of 65m, but this was considered to be a small difference compared to the originally stored temperatures (>80°C). It was concluded that the extinction of the temperature can be reasonably easily predicted with a thermal model.

Schematisation in time

When applying for a permit in the context of the Water Act, calculations are usually conducted using fixed water quantities and infiltration temperatures per season, whereby an energy balance is the starting point. In practice, the pumped water quantities and infiltration temperatures are different every season and there is usually no energy balance on an annual basis.

For the system in Utrecht, the variation of thermal influence area has been calculated based on the actual water displacements and infiltration temperatures at the end of winter and at the end of summer, for the period 2003 to 2010. Although thermal effects vary every year, thermal influence area remains broadly in line with that of the permit application. The fact that this is the case for the system in Utrecht, is probably the result of the regional energy balance that is referred to here. In the case of a large imbalance, for example a surplus of heat in the soil, the warm bubble becomes clearly larger than the cold bubble. It can be concluded that the actual area of thermal influence will correspond to the calculated area, if the requirement of a (nearly) closed energy balance is met in practice, and there is no strong heterogeneity in the soil.

6. High-temperature heat storage

Knowledge overview and practical measurements on high-temperature storage systems

Work package 6 is related to high-temperature heat storage. Rising energy prices and increasing concern for CO_2 emissions have brought high-temperature heat storage systems in the spotlight. The residual heat that is available during summer, when temperatures are high, can be temporarily stored to be used for heating purposes during winter; it has been found that the subsurface can be used as a medium for this heat storage, which has resulted in a large growth of high-temperature (HT) ATES systems.

6.1. Benefits

High-temperature ATES has a number of important advantages over low-temperature ATES. The user’s heating system needs a certain minimum temperature to provide sufficient heating capacity. At low-temperature ATES, the stored heat can only be used to pre-heat the ventilation air in a building and enhancement is required to further raise the temperature (e.g. with high-efficiency boilers). Nowadays, heat pumps are mostly used for this purpose. These heat pumps are relatively energy-efficient compared to boilers; however, they still use a great deal of electricity. By storing heat at high temperatures, the use of the heat pump can be minimised or even become unnecessary. This way, the energy saving is significantly improved compared to low-temperature ATES. In addition to the energy benefits, the temperature difference between the warm and cold well at high-temperature ATES is also much greater, so that more energy can be supplied with the same quantities of water.

If in the summer, sources of (residual) heat are available, and in the winter the heat demand is greater than the supply, then high-temperature storage is an attractive option. Energy sources that qualify for this purpose are residual heat (e.g. from industrial processes, waste incineration or electricity generation) and renewable heat (e.g. from deep UTES or solar energy). Urban heating networks can also be connected to storage systems to level the net heat demand: store heat when the demand is low (overcapacity of heat production), and supply when the demand is high.

6.2. Application in practice

In spite of these advantages, however, HT heat storage is hardly ever applied. More than 99% of the ATES systems in the Netherlands are "low-temperature systems". There have only been two programmes with storage temperatures higher than 80°C (in Utrecht and Zwammerdam), and both are no longer in use, for different reasons: in Utrecht, the heating installations of the building were not properly matched to the heat storage system, and in Zwammerdam, the heat demand turned out to be considerably lower than expecting, rendering the system economically unprofitable. Technically, however, both systems were fully functional.

In addition to high-temperature systems, there are some medium temperature systems in the Netherlands with storage temperatures of 30 to 60°C. As far as is known, only one high-temperature ATES system is active worldwide: The Reichstag in Berlin, where heat at 70°C is stored. In addition, several medium and high-temperature BTES systems are known, in which mainly solar heat is stored (including the Beijum programme in Groningen).

6.3. Issues

The prevalent explanation for the limited number of HT-ATES programmes is that they are technically more complex than low-temperature programmes. In the past, many problems occurred during experiments and pilot programmes of HT- ATES. The main problems were:

- Low efficiency of storage or usage
- Pit clogging due to carbonates precipitation
- Corrosion of materials

It is clear that the technical problems encountered in cold storage or low-temperature heat storage are much smaller than those associated with high-temperature heat storage. The research that has been subsequently carried out has shown that the problems encountered can be solved (Snijders, 2000). To prevent low efficiency of storage, aquifers of low permeability should be used. Also, water treatment methods have been developed to prevent minerals precipitation (Sanner, 1999; Drijver, 2011a). Finally, corrosion can be avoided when using the proper corrosion-resistant materials. All these solutions, however, have disadvantages related to costs: lower permeability leads to lower capacity per well and thus higher investment costs, water treatment entails higher installation costs, and the corrosion-resistant materials required are more expensive than the standard materials used.

Also from a legal aspect, high-temperature heat storage is controvertible for a number of reasons. Firstly, the infiltration temperature is higher than allowed. Secondly, the requirement of an energy balance cannot be met, as there is always net heat loss. Finally, the water quality effects are relatively large, not only because of the large temperature differences, but also as a result of the necessary water treatment. High-temperature storage is therefore only possible by deviating from the policy, in the form of pilot programmes. An (integral) assessment will need to be made per programme on the basis of the advantages and disadvantages.

One of the most important aspects that play a role in practice is the extent to which changes in temperature are also noticeable in overlying aquifers. In order to avoid exceeding the temperature limit, the thickness of the separating layer should be at least 20 to 30 m. An inventory of performed calculations in HT-ATES programmes indicates that the resistance of the separating layer is also crucial. For a large-scale programme in the province of Zuid-Holland (storage temperature 84°C) the temperature in the overlying aquifer was calculated for 20 years of heat storage for various resistance values. The separating layer was 45 m thick in this case. At a (very low) resistance value of 500 d, the temperature would rise to about 40°C, and with a resistance of 2.500 d, the temperature remained just below 25°C.

High-temperature heat storage is still a relatively new technique, and because of all the mentioned complications, it has hardly been applied on a commercial scale. However, several systems that are well-functioning from a technical aspect have already been realised.

6.4. Suitable aquifers

As the water stored has a significantly higher temperature and therefore a lower density than the groundwater, it tends to flow to the upper part of the aquifer. This process can have major negative consequences for storage efficiency. The extent to which this process occurs depends mainly on the aquifer's permeability and the temperature difference between the stored water and the groundwater.

The permeability values for which the heat losses will increase rapidly have been investigated for various circumstances. The maximum permeability for each case can be used to select aquifers that are suitable for application of HT-ATES. Table 2 shows that aquifers of low permeability need to be selected. The disadvantage of these moderately permeable aquifers is that the current design standards indicate low flow rates per source, which adversely affects the economic feasibility of programmes. The question now is to what extent these existing design standards apply to this type of aquifers, and whether this offers prospects for higher flow rates per source.

Table 2: Maximum horizontal permeability in m/d for seasonal storage of high-temperature heat. With higher permeability, heat losses increase rapidly.

Storage temperature [°C]	**k_a^h at H=10 m with k_a^h/k_a^v =**			**k_a^h at H=25 m with k_a^h/k_a^v =**			**k_a^h bij H=50 m with k_a^h/k_a^v =**		
	2	**5**	**10**	**2**	**5**	**10**	**2**	**5**	**10**
30	11	18	25	28	44	62	56	88	124
50	2.8	4.4	6.2	6.9	11	15	14	22	31
70	1.2	1.9	2.7	3.0	4.8	6.7	6.0	9.5	13
90	0.7	1.0	1.5	1.7	2.6	3.7	3.3	5.2	7.4

k_a^h = horizontal permeability [m/d]; H = aquifer thickness [m]; k_a^v = vertical permeability [m/d]

7. Mutual interaction between ATES systems

Effects of Underground Thermal Energy Storage systems on their environment – modelling large-scale integration in urban areas

Report 7 deals with the issue of interference between open ATES systems. As already mentioned in Chapter 1 interference is expected to occur in busy areas and become even more pronounced with the large growth in the number of systems, which policy makers and managers of ATES view as undesirable. The important question, relating to licensing of ATES systems, is whether the interaction between neighbouring systems lowers the efficiency.

For the determination of interference, a comparison is therefore often made between the (theoretical) functioning of a single ATES installation and of several ATES installations. In practice, however, it is not always the case that a system independently achieves the efficiency that has been predicted in the design, and also interference is not the only factor that can reduce the output. This is why it becomes quite difficult to accurately quantify the effect of mutual interaction in advance.

The study area of work package 7 is The Hague, an area where interference is expected to occur due to the large amount of ATES installations. The research had two objectives:

- To evaluate the (theoretical) energy efficiency of the ATES installations
- To determine whether noticeable regional effects can occur, as a result of the accumulation of small effects per system

Simulations were carried out to determine whether interference occurs in The Hague centre and which parameters are decisive for its occurrence. For this purpose, the number of systems, flow rates, and temperatures of the injection water used in the simulations, varied within a range of values. Negative interaction occurs only at four out of the 76 system locations included in the simulation, so in general it can be concluded from the simulations that there is no large-scale negative interference. Given the fact that The Hague centre is one of the busiest areas of the Netherlands with respect to ATES, this outcome is a contra-indication to the presence of large-scale interference in the Netherlands. Obviously, the current design rules have sufficiently prevented negative effects on existing ATES installations. However, it is not known to the authors to what extent initiatives for new ATES installations were stranded due to the presence of an existing system, and whether a different arrangement of the systems by means of a masterplan could have led to a greater utilisation of the underground capacity.

The above conclusion is of course based on the assumptions made during the simulations. The most important ones were:

- Systems have a volume and energy balance – although a few scenarios were also simulated, in which there were different degrees of energy imbalance from year to year, but the balance was closing over a period of 10 years.
- Systems do not pump more water than the design quantity.
- A locally homogeneous substrate was assumed.
- The design flow rate (equivalent to two-thirds of the licensed flow) was used in the calculations.

According to the scenario calculations, the recovery efficiency per system is more than sufficient (80-90%) in this area, which means that the existing density of systems – if their arrangement is according to the designs – will not be a problem. The largest differences in outcomes between the scenarios occur when changing the assumptions relating to the injection temperature or the flow rate. The energy efficiency even seems to increase very slightly as more systems are simulated in the area (positive interference).

The simulations show that when the hydraulic head in the aquifer is influenced by the superposition of multiple ATES wells, the systems lead to a smaller area of influence, compared to those of individual systems. The large margin between the average water volume to be pumped according to the design, and the maximum water volume that can be pumped according to the permit, means that no negative interference has been found in the simulations (with the exception of a few locations), but it may also lead to a too large claim on subsurface space. This can make the implementation of future systems more difficult or even impossible. Policy should take this into account and a statement should be required on how to deal with those margins (avoiding negative interference, versus accommodating more ATES systems).

Focusing on interference only, without including the stand-alone efficiency of a system (or of a single source of a system), can lead to a legally explainable approach (the neighbour is not allowed to cause damage), but does not lead to an area-based optimisation in energy saving (how does interference relate to possible inefficiencies?).

With regard to developing a methodology to better simulate interference in practice, the following recommendations are made:

- The determination of a flow pattern is an important step that should be taken, in order to be able to count on possible future interference, in situations where the flow rate cannot be determined afterwards or in advance.
- It is necessary to properly determine a definition of underground efficiency and the influence of the extraction and injection temperatures on achieving sufficient energy savings.

The effects on the quality of groundwater as a result of the presence of several systems in an area have not been investigated. This could include cumulative effects on salinisation, or the spreading of contaminants. More information on this can be found in Chapter 11 of this extensive summary and in the full 11th report (in Dutch).

8. Autonomous development of soil temperature

Chapter 8 is a study on the autonomous development of soil temperature that was carried out within the programme . The full report (in Dutch) contains an analysis of the extent of thermal influence of climate change and urbanisation on soil temperature. The results of the research can be used as input for the policy discussion and are most important for the policy with regard to the energy balance in thermal storage systems.

Thermal changes in soil temperature can be the result of climate change, urbanisation, and heat/cold storage.

- Climate change: Due to the growth of the greenhouse effect, the average air temperature in the Netherlands has increased by approximately 1.7°C since 1900 and is expected to increase further in the future. This warming is also noticeable in the soil temperature.
- Urbanisation: Urbanisation creates an effect called 'urban heat island' (UHI). A UHI is the phenomenon in which the air temperature in an urban area is higher than in the surrounding rural area. The most important causes of the UHI are the absorption of sunlight by the dark-coloured materials that prevail in cities, the obstruction of radiation due to buildings, the relatively low wind speeds, and the heat produced by human activities (e.g. heating, transport, etc.).
- Heat/cold storage: In the immediate vicinity of ATES wells, the soil temperature is influenced – there is a temperature reduction near cold wells and an increase near warm wells. In cases of energy balance, the amount of heat that remains in the soil is equal to the amount of cold, and no net heating or cooling takes place. In cases of energy imbalance, an ATES will cool the soil with a net heat extraction or heat it with a net cold extraction.

In this chapter we investigate the autonomous development of soil temperature of the subsurface that has occurred since 1900 and that can still be expected in the period up to 2040. A distinction has been made between rural areas, where only climate change plays a role, and urban areas, where the UHI effect is also important. The consequences of these changes in temperature for the chemical and microbiological quality of the groundwater are discussed in Reports 2 and 3 & 4. In order to estimate the influence, information is needed about the extent of temperature development and the course over time. Figure 3 shows the moving average of air temperature in De Bilt for periods of 5, 10, 20 and 30 years. The red lines in the graph indicate the predictions according to the KNMI climate scenarios of 2006: an increase in temperature (minimum 0.9°C and maximum 2.5°C) by 2050 compared to 1990. The dashed line provides the starting point for the calculations of this report: it is assumed that the temperature increase that has taken place since the mid-1970s is the same as the maximum KNMI climate scenario (the moving averages indicate that the increase until 2010 follows the maximum scenario). Figure 3 shows an increase in temperature of 1.7°C between 2010 and 2040. Year 1900 was chosen as the starting point, because the increase in air temperature due to climate change started at that time (based on temperature measurements in De Bilt).

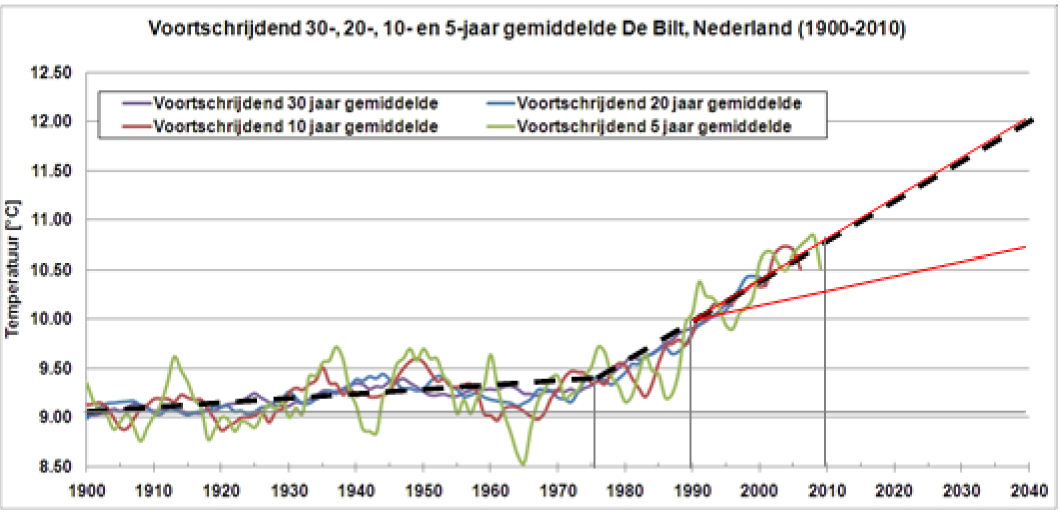

Figure 3: 5, 10, 20 and 30-year averages of the temperature in De Bilt. The red lines show the bandwidth of the predicted increase in temperature from the KNMI climate scenarios of 2006 (increase in relation to the temperatures of 1990). The dashed line indicates the schematisation of the increase in temperature that has been used for the calculations in this report.

(Temperatuur = temperature ; voortschrijdend 30-jaar gemiddeld = total 30 years average)

In addition to climate change, the magnitude of the UHI effect is also important in urban areas. Using soil temperature measurements inside and outside of urban areas, the effect is estimated at 1 to 3°C, depending on the size and building density of the city, as well as the location within the city (suburbs or centre). No information has been found about the course the UHI effect over time. This report assumes that the magnitude of the effect has been linear from 1900 until now and that this trend will continue in the future to the same extent. Table 3 shows the chosen starting points for the calculations.

Table 3: Starting points of autonomous soil temperature development calculations

Period	**Changes in temperature due to climate change [ºC/year]**	**UHI 1 ºC in 2010 [ºC/year]**	**UHI 3 ºC in 2010 [ºC/year]**	**Climate change + UHI 1 ºC [ºC/year]**	**Climate change + UHI 3 ºC [ºC/year]**
1900-1975	0.0045	0.0091	0.0273	0.0136	0.0318
1976-2010	0.035	0.0091	0.0273	0.0479	0.0661
2010-2040	0.035	0.0091	0.0273	0.0479	0.0661
Total 1900-2010	1.7 ºC	1.0 ºC	3.0 ºC	2.7 ºC	4.7 ºC
Total 1900-2040	2.86 ºC	1.27 ºC	3.82 ºC	4.13 ºC	6.68 ºC

8.1. Results

Using the figures in Table 3, a number of scenarios have been calculated for the periods of 1900-2010 and 1900-2040. where both the individual effects (only climate change or only UHI effect) are shown, as well the combined effect. Figure 4 shows the results of the calculations compared to the starting situation in 1900 (dashed line). The results are in line with expectations based on measurements, both in the programme research and in other studies conducted in the Netherlands.

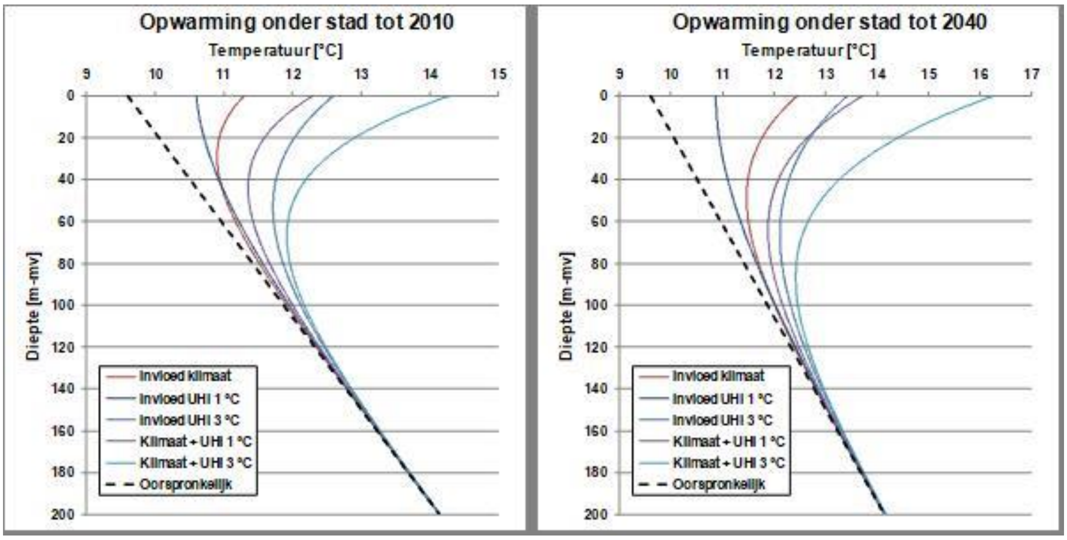

Figure 4: Calculated temperature in the subsurface under urban area in 2010 (left) and 2040 (right). Before 1900 (indicated as a dashed line) it is assumed that climate change and/or urbanisation have no effect on the soil temperature. Comparison with ATES effects.

(Diepte = depth ; Opwarming onder de stad tot = Increase in temperature below the city till ; Invloed = influence ; klimaat = climate ; oorspronkelijk = original)

Depending on the chosen scenario, the increase in surface temperature varies between 1 and 7°C. The increase in soil temperature decreases rapidly in depth and is negligible at a depth of 150 m. In ATES systems, the temperature difference between the extracted and infiltrated water is an average of 4.3°C. Taking some temperature losses in the soil into account, the difference between the average temperatures in the warm and cold well will be approximately 5°C. The temperature of the warm well is thus about 2.5°C higher than the natural groundwater temperature. According to the calculations, an autonomous temperature development of 2.5°C is possible up to a depth of 40m (scenario for 2040 with the maximum UHI effect). In many cases, ATES systems are deeper than 40m and the local changes in temperature due to ATES will be greater than those of the autonomous temperature development.

The temperature effects of ATES can also be compared with those of autonomous soil temperature development at the level of an area. Calculations for the centre of The Hague, which is one of the areas with the highest density of ATES systems in the Netherlands, show that the expected net influence of ATES is smaller than the influence of autonomous temperature development at the same depth (20 – 60m below the surface). The calculated influence of ATES is an (area) average temperature change of -0.02°C per year when assuming an energy balance or imbalance of -10% (cold surplus), and +0.01°C per year when assuming energy a balance or imbalance of + 5% (heat surplus).

8.2. Energy balance (and imbalance)

An energy balance requirement applies to ATES systems in the current policy, meaning that the amount of heat disposed to the soil must balance the amount extracted over a specified (long-term) period. This requirement has consequences on the design and operation of ATES systems and is therefore under discussion. At present, DWA and IF are conducting research on behalf of SKB into the usefulness and necessity of this energy balance. The autonomous temperature development of the soil indicates that an overall energy imbalance is present even without ATES, or with ATES that have a perfect energy balance. After all, the soil is heated by climate change and urbanisation.

8.3. Consequences for the applicability of BTES

From the calculations it follows that the autonomous temperature development of the subsurface is highly dependent on the depth (see Figure 4). The increase in temperature is concentrated in the upper 50 to 100 metres of the subsurface and will only be noticeable in the very long term (hundreds to thousands of years) at greater depths. In the case of ATES systems located in deeper aquifers, autonomous temperature development does not play any significant role.

Closed systems (BTES) are almost always installed in the top 100 metres of the ground and therefore are most influenced by autonomous temperature development. Since BTES systems are more often used for heating, the increase in temperature in the soil is usually beneficial for the operation.

The calculations made indicate that the total soil temperature development in urban areas over the period 2010-2040 will vary from 0.9 to 1.5°C. at 20m of depth and 0.15 to 0.3°C. at 100m of depth. Although an increase in temperature of more than 1°C is considerable, this increase has no noticeable consequences for the applicability or functioning of ATES systems, which is confirmed by the presence of ATES systems in aquifers with very different natural temperatures (between 9 and 14 ºC).

Recirculation systems can be sensitive to changes in the natural groundwater temperature. Warming makes the pumped water less suitable for cooling purposes in these systems: to achieve the same cooling capacity, higher temperature will often require a higher flow rate.

8.4. Beneficial use of accumulated warming

For the heating of the subsurface shown in Figure 4, the high heating capacity requires a large amount of energy. The amount of energy added to the soil and the amount that will be added in the future due to the rising surface temperature can easily be calculated and compared with the energy demand of buildings. This comparison is relevant for ATES systems, since they can be used not only to store but also to extract energy from the soil. If the objective is for the soil temperature to remain the same, it would probably be possible to make use of ATES to compensate for the effect of autonomous warming by applying net heat extraction from the soil. This would mean that the ATES system would be deliberately operated in imbalance. It is therefore important to have an insight into the relationships between the heating and cooling demand of buildings (which can be supplied by ATES systems) and the energy absorbed by the soil as a result of autonomous warming. In Table 4. the calculated autonomous warming of the subsurface is converted to GWh per year.

Table 4: Calculated amount of energy absorbed by the as a result of climate change and UHI.

Warming	**1900-2010**	**2010-2040**	**1900-2040**	**1900-2010**	**2010-2040**	**1900-2040**
(Climate change/ UHI)	**GWh/km^2**	**GWh/km^2**	**GWh/km^2**	**GWh/km^2 /year**	**GWh/km^2 /year**	**GWh/km^2 /year**
Climate change	33	35	68	0.3	1.2	0.5
Climate change + UHI + 1 °C	61	47	108	0.6	1.6	0.8
Climate change + UHI +2 °C	89.5	59.5	149	0.8	2.0	1.1
Climate change + UHI +3 °C	118	72	190	1.1	2.4	1.4

The heat use on the surface has been mapped by NL Agency (http://agentschapnl.kaartenbalie.nl). The heat potential that can be supplied with ATES from the subsurface is also available (Figure 5)

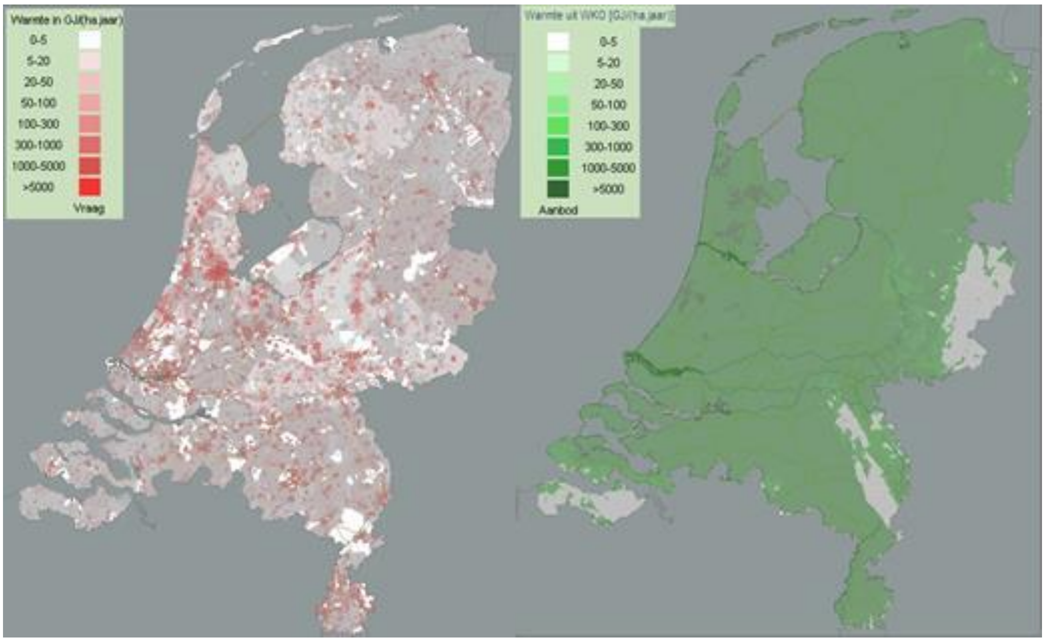

Figure 5: Left: Map showing the heat demand per hectare (excluding industry). The annual energy demand varies from 0-20 GJ/ha in the countryside to > 5000 GJ/ha in the cities. Right: Potential amount of heat that can be supplied with ATES in the Netherlands. This potential supply ranges from 0-500 GJ/ha per year in the east to > 5000 GJ/ha per year in the west of the country (Source: http://agentschapnl.kaartenbalie.nl). Only the heat demand is known; no data is available on the cooling demand.

For the rural area the heat demand is 0 – 0.6 GWh/km² per year. The warming of the subsurface here is almost exclusively the result of climate change and amounts to 1.2 GWh/km² per year. In the rural area, the heating of the soil is therefore greater than the heat demand. Even if the total heat demand on of all buildings (excluding industry) was supplied by heat extraction coming from the top 50 to 100m of the subsurface, there would still be a net heating of the subsurface on an area level.

The largest part of urban areas has an energy demand of between 1.000 and 2.000 GJ /ha/year, which corresponds to 28 – 56 GWh/km²/year, or 830 – 1.670 GWh/km² over the period 2010-2040. The total surface warming in the period 2010-2040 amounts to 50 – 70 GWh/km² and corresponds to approximately 5% of the heat demand in the same period. In the period 1900-2010 another 60 – 120 GWh/km² of "heat supply" was built up (about 7% of the heat demand of 2010-2040).

Based on the Statistics Netherlands data for 2009, approx. 0.4% of the total heat demand from households, non-residential construction and agriculture was supplied in 2009 with shallow UTES systems. The annual autonomous warming of the subsurface in urban areas was therefore about 12.5 times larger in 2009 than the heat supply with ATES. Since most of the ATES systems not only extract heat but also store it, it can be concluded that the warming of the subsurface in cities will be greater than the net heat extraction by ATES in the coming decades (even if ambitious growth targets for ATES are met).

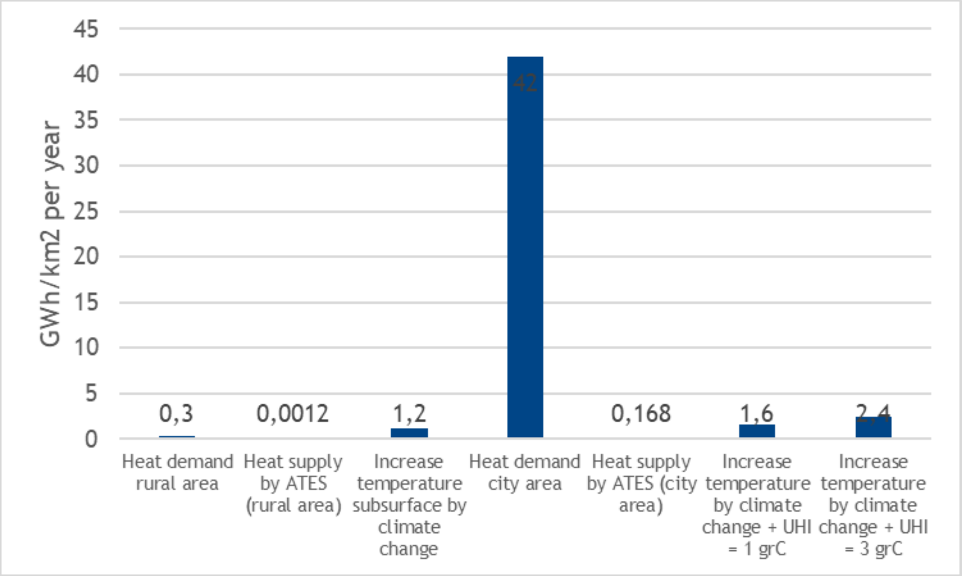

Figure 6: Relations between the annual heating of the subsoil under the influence of climate change and urbanisation and on the other hand the average heat demand in rural and urban areas, respectively the current average heat supply by thermal storage in rural and urban areas.

9. Effects on remediation

Effects of ATES combined with soil remediation – result measurements at pilot locations and lab tests

Due to the large number of contaminated sites in the Netherlands, the increasing use of ATES systems means that they are more likely to be installed in or near a contaminated area. There is therefore an increasing need for insight into the mutual effect between ATES systems and soil contamination. The effect of ATES systems is double: effect due to changes in temperature and effect due to mixing.

This report describes the interpretation of possible effects of heat and cold storage systems on soil contaminants. To assess these effects, data from field monitoring was used, at two contaminated locations where ATES systems are active; these were in Utrecht Centrum and at Strijp-S in Eindhoven. At the Strijp-S location not all monitoring wells had been influenced yet, so it was only possible to draw preliminary conclusions. In addition, laboratory tests were carried out based on the data from Strijp-S, aiming to determine the effect of temperature on the degradation of VOCl and the composition of the microbiological populations.

9.1. Temperature effect on degradation of contamination

The temperature change due to the ATES systems was too low at both research locations (only a few degrees in Utrecht Centrum and even less at Strijp-S). No clear effect of the temperature could be detected – the observed effects in the field were therefore caused only by the mixing effects.

The conditions during the lab tests may have led to stimulation of microaerophilic degradation, probably due to the introduction of oxygen. Micro-aerophilic degradation performed better at lower than at higher temperatures (30°C); the reason for this was not investigated further. No reductive degradation potential was present in these samples (no Dehalococcoides bacterium was detected). In the field, reductive dechlorination appears to be the primary degradation process at Strijp-S.

9.2. Mixing effect on degradation of contamination

At the Utrecht Centrum location, the geochemical composition of the groundwater is quite homogeneous. It is plausible that the groundwater has been homogenised by the ATES system during its period of use (20 years). Mixing of pollutants and carbon source (electron donor) has little effect here, partly because the organic matter content is low by nature. Because the main part of the contamination is on the upstream side of the ATES system, the ATES has not contributed significantly to the spreading of the contamination. Some degradation occurs at this location, both at the ATES filters and at some distance therefrom. There are no clear indications that the ATES has directly stimulated the degradation, but there are indications that bacteria are displaced by the groundwater circulation. The presence of these bacteria can have a positive effect on the degradation of VOCl, if the other conditions for degradation are favourable.

At the Strijp-S location, the operation of the ATES system has led to the spreading of pollutants, organic matter and hydrogen within the boundaries of the system. Mixing groundwater within the ATES system has resulted in a local increase in organic matter and hydrogen (electron donor), which probably led to more favourable redox conditions and growth of the dechlorinating bacteria. Where the favourable conditions prevail, degradation of VOCl will occur. In this location, bacteria were also spread by circulating groundwater. Since not all monitoring wells were influenced, it was unknown whether the proven degradation would spread over the rest of the site and whether the degradation capacity was sufficient to remove all contamination. If degradation continued to occur, this would have a favourable effect on the remediation efficiency. Follow-up monitoring should provide more insight into this.

The operationalisation of the Strijp-S system has led to the spreading of pollutants, organic matter and hydrogen within the boundaries of the system. Mixing groundwater within the ATES system has led locally (at the site of the affected monitoring wells) to an increase in organic matter and hydrogen (electron donor). This local increase in organic matter probably led to more favourable redox conditions and growth of the dechlorinating bacteria. Where such favourable conditions prevail, degradation of VOCl will occur. In this location, too, bacteria were spread by circulating groundwater. Since not all monitoring wells have been influenced, it is currently unknown whether the proven degradation (capacity) will spread over the rest of the site and whether the degradation capacity is sufficient to remove all contamination. If degradation occurs/continues to occur, this has a favourable effect on the remediation efficiency. Follow-up monitoring should provide more insight into this.

9.3. Influence of pollutants on the operation of ATES systems

No research has been carried out within the programme to determine the influence of pollutants on the operation of the ATES. However, from practical experience and literature it can be concluded that low VOCl concentrations do not adversely affect the functioning of an ATES system.

10. Ways of combining ATES with soil remediation

Overview of available techniques and new possibilities

10.1. Introduction

The increasing demand for UTES in the Netherlands is putting pressure on the use of underground space. On the one hand, this can lead to conflicting interests between the application of geothermal systems and the remediation and control of pollutants. On the other hand, this offers an opportunity to combine UTES and soil remediation. In the tenth report the fragmented knowledge in combination concepts has been brought together, expanded with practical observations and elaborated in promising combination concepts.

10.2. Remediation and management concepts involving soil energy

Groundwater remediation measures and energy storage are both dependent on the potential for the subsurface. The objectives – and usually also the technical basic principles of each technique – differ. Geothermal systems are designed for the reliable supply of sufficient and affordable heat and/or cold to the customers, while remediation measures are designed for the cost-effective management or removal of contaminants. These objectives can sometimes conflict. It is therefore important to determine which objective is primary when they are combined. This provides criteria for the choice of remediation methods and soil energy systems.

This survey provides an overview of available remediation methods and UTES systems. The potential combination concepts were tested against the following criteria:

- maintaining energy efficiency
- achieving the remediation objective

- cost efficiency
- long service life (no obstruction of well operation).

Based on the above criteria, 12 promising concepts have been selected that can be subdivided into four categories. In all of these concepts, the energy efficiency of the geothermal system is guaranteed, while the remediation efficiency differs per concept. The four categories are explained in this chapter.

1. Underground Thermal Energy Storage and control

A recirculation system is particularly suitable for controlling contamination. With this system, groundwater flow around the pollutant is controlled, and with a proper hydrological design, contamination can be limited by up to 80%. However, contamination is not actively removed, but – in cases of natural degradation – a system that controls the contamination has the advantage of offering more time for natural degradation to occur.

2. Underground Thermal Energy Storage and natural degradation

By applying a UTES system in an area where natural degradation occurs, the process may be accelerated. A UTES system can influence the natural degradation of pollutants in two ways: by increasing the groundwater dynamics, and by (locally) increasing the temperature.

- By circulating groundwater, substances that are already present in the aquifer (e.g. organic carbon and micro-organisms) are mixed to some extent. This allows a larger volume of the substrate to be suitable for natural degradation processes of, for example, VOCl or BTEX. However, the reverse can also occur: by pumping groundwater around, the locally favourable conditions for natural degradation can be negated.
- An increase in temperature leads to faster degradation. In practice, however, hardly any positive effect can be expected when there is an energy balance, as the degradation rates also decrease again when the temperature is reduced.

3. Underground Thermal Energy Storage within a reactive zone

If there are no favourable conditions for natural degradation, the creation of a reactive zone by adding auxiliary substances can be a solution for remediating the contamination.

In this study, the most suitable substances and application methods were made, considering the costs, current state of the art, and risks such as well clogging. Data from the literature, as well as lab tests, demonstrate that VOCl-degrading micro-organisms and ethanol can be used in or directly around the ATES wells to degrade VOCl without risk of well clogging. Chitin or (emulsified) plant oils can be installed as a reactive screen at a distance from the ATES wells to break down VOCl. The underground de-ironing technique can also be used, depending on the soil characteristics of the location, to break down BTEX as well as VC and CIS.

4. Underground Thermal Energy Storage and above-ground purification

If the contamination does not need to be completely removed, but full control is required, the water that is pumped up by the ATES system can be purified above ground. If the above-ground water is required for another use, for example brook restoration or process water, above-ground purification with a stripper can be a solution. If water is not needed above-ground, it should be infiltrated again. To make infiltration possible, it should be purified with a more expensive vacuum stripper, or with a nitrogen gas stripper. If the local WWTP still has capacity left over, it may be possible to think about discharging the contaminated water to a sewer.

Every combination concept appears to have several advantages and disadvantages, which means that no single most promising combination concept can be identified. To decide the most suitable combination concept for a specific location, the various concepts mentioned above will need to be weighed, considering above-ground use of water and objectives for remediation and energy efficiency. Next, it will be necessary to see whether the combination concept is more advantageous than the separate implementation of a geothermal system and a remediation technique. The cost estimates developed for a hypothetical case show that combining an ATES system and remediation can often be more cost-effective than separate processes.

11. Regional groundwater management

11.1. Integration of UTES into regional groundwater management – opportunities and issues

In this chapter, the deployment of ATES systems within a region-oriented approach and context is presented. The application of regional groundwater management is now much broader than just focusing on how to deal with contaminants. Although contaminants play an important role, and there should be careful consideration on how to handle them, they are not by definition the key factor influencing how regional groundwater management is implemented. This also depends strongly on the municipality or province involved.

The best way to apply ATES systems in contaminated areas is to adopt a broad integral approach within the context of regional groundwater management. A region-oriented approach involves taking into account different aspects, which are sometimes difficult to compare. Examples are the consideration of different types of sustainable energy, related climate aspects, economic aspects, above-ground and underground use of space, remediation, and risk management in terms of contamination.

When it comes to handling contaminants, the regional approach is risk-based. This means that the spread of contamination outside a specified area should be prevented, but contaminants may be allowed to move within this area without creating risks. As far as the improving groundwater quality and quantity is concerned, groundwater must, in any case, comply with the criteria required for the intended use. Additional requirements can be imposed by the local authority, for example for further improving the contamination situation.

In terms of ATES systems within a regional approach, a distinction can be made between non-contaminated areas, where a regional approach has been drawn up (but is still very limited), and contaminated areas where a regional approach is adopted to manage the contamination. This report points out that the application of ATES systems in both cases

– with and without contamination – offers opportunities as well as issues. The implementation of ATES in a specific region, while considering all related aspects, can be as diverse as the management objectives and the case-specific conditions of each region. This report therefore only reflects possible opportunities and attention points for regional management, for inspiration and nuancing.

Generally, it can be stated that application of ATES in non-contaminated areas within a regional context is feasible and offers opportunities for combination with other technologies. When groundwater extractions are already necessary in an area, these can be perfectly combined with energy extraction or climate control systems. The water quality does not play a very important role in this case.

If ATES is applied in a (possibly) contaminated area, the interaction between the ATES system and contamination does play an important role. Back to the criteria for a regional approach, the questions are to what extent ATES systems have a positive effect on the removal of contaminants, and to what extent they can reduce contamination-related risks. If in recent years, the impression was that ATES systems naturally lead to improving the contamination situation, this is unjustified.

For integrating ATES systems within areas with contaminated groundwater, implementation depends in particular on the management objectives that have been set, as well as on the location and case-specific technical factors. The objectives relating to desired quality and possible quality improvement are also very relevant: if a strong quality improvement is required, this places much higher demands on the soil system and on the integration of ATES systems.

On the other hand, other factors besides soil is related to also play a role in the choice of the regional approach. For example, the implementation of ATES fulfils the social need for more sustainable energy systems. By balancing these interests, not by sector, but integrally, the potential for a realistic interpretation is increased. From this perspective, the management objectives for groundwater quality are adjusted to the level to which acceptable risks, even in the long term, are not exceeded.

It has become clear that, in addition to the potential positive effects of the interaction between ATES and contamination, negative effects may occur. An example is the accelerated dissolution of DNAPL as a result of the increased dynamics induced by an ATES. Whether and to what extent these types of effects ultimately result in a net negative result, depends strongly on the biological degradation capacity in the soil. Although regional groundwater management is increasingly turning towards integrating various functions, the deliberate (partial) separation of functions should be carefully considered.

Before allowing the implementation of large-scale ATES systems in a contaminated area, a decision should be made that is strongly determined by the groundwater quality requirements imposed by the local authority. Report 11 indicates the relevant preliminary information that is required for this decision. Is quality improvement a difficult requirement? In that case, information about the potential DNAPL sensitivity of an area and the demonstrable presence of biological degradation potential is important. If the boundary of the region is wide and quality requirements are focused particularly on risks, certain parameters are much less relevant.

In order to make a thorough assessment in the context of integrating ATES systems into contaminated areas, it’s important to ask the following questions:

Question 1: Is it realistic to expect that ATES in a large-scale contaminated area can make a substantial contribution to improving groundwater quality?

The observed (positive) effects on one of the monitored contaminated sites show that changes in groundwater quality can occur, induced by changing dynamics due to pumping large volumes of groundwater. Bacterial numbers increased at this location and local changes in TOC were also observed. However, it’s not clear what the caused this effect and it cannot be concluded that it is a generic effect that can be expected in other locations. The expectation is that, if no ATES system was applied, the mixing and the observed effect would probably not occur. In other words, positive effects can be achieved by applying an ATES system, but follow-up monitoring is required to investigate whether these effects can be expected at other locations.

An important parameter when determining whether an ATES system can contribute to improving groundwater quality is the biodegradation capacity. In most areas for which the regional approach was developed, there was insufficient insight into this parameter. Lack of information on degradation makes it difficult to predict the effects of human interactions with the subsurface.

In summary, the ambition of accelerating the naturally occurring in-situ processes via ATES systems, and thus accelerating quality improvement, is somewhat overoptimistic. As explained, further monitoring should provide more insight into the cause of the positive trend that was found at one of the locations. Combinations of ATES systems with stimulated degradation could make an additional positive contribution.

Question 2: Does ATES offer an opportunity to control the contamination load? Which combinations with other underground or above-ground uses can be applied?

There appear to be good opportunities for controlling contamination or, more generally, reducing risks in a regional context. Currently the safest way to integrate ATES – or rather energy use – is to extract heat or cold from the withdrawn water, without re-injecting it for energy storage. This case forms a perfect match with regional groundwater management, but it is only feasible if the extracted water can be usefully utilised above ground. In many cases in inner-city areas selling the extracted water in large quantities can be difficult. Hence, it is expected that many doublets or recirculation systems will be used, where all the water will be infiltrated again. The application of these systems does not have a controlling effect in their normal form.

An interesting alternative option is to discharge a partial flow of the extracted water above ground. This creates a net withdrawal, which helps control the contamination. Another alternative that can be used is to mix the extracted contaminated water with clean water. If the ATES system is installed downstream of a contaminated area, this will lead to a reduction of toxic concentrations. As a result, concentrations in the downstream direction – e.g. towards a regional boundary – can be kept below a certain risk threshold value (for example an I or T value), and thus an ATES system can reduce risk.

12. Combinations with the water cycle

12.1. New applications of UTES in combination with concepts relating to the water cycle

The aim of this programme was to provide insight into the effects of the large-scale application of ATES systems on soil and groundwater. The results of the research can be used by the Dutch government to revise current policy relating to soil and groundwater (where necessary) and to stimulate developing applications and innovations in the science of UTES. Ultimately, this should be beneficial for the subsurface quality, both in terms of the climate and of society.

Work package 4 is the part of this programme that was designed to demonstrate the wide range of opportunities and the potential for using ATES in combination with other (soil) functions such as those described below. Some promising combinations were developed during a quick scan to gain insight into technical, legal and organisational requirements, financial feasibility, and environmental aspects.

Within this study, 17 areas were found in which it was possible to combine ATES with other functions. These are briefly described in this summary. The three most promising combinations are further elaborated below:

1. Industrial residual heat storage
2. Irrigation water for greenhouses
3. ATES and process water

12.2. Industrial residual heat storage

This concept involved storing residual heat at 45ºC from an industrial plant in the Botlek (near Rotterdam in the Netherlands). The customers for this heat lived on the other side of the Nieuwe Waterweg. Important considerations when designing such systems are the scale, the proximity of the energy source and delivery, as well as the way tap water is prepared. It is not legal to store medium-high temperatures (50 ºC) in the soil. In terms of management, however, it is important to consider whether storing higher temperatures outweighs the environmental advantages. Nevertheless, there are many opportunities for this concept, especially given the large volume of energy that is available at this temperature.

12.3. Irrigation water for greenhouses

The possibility of providing irrigation water using reverse osmosis has been investigated. The irrigation water thus produced is used in greenhouses, while the by-product (brine) is used for storing surplus heat in the soil. The advantage of this combination is that almost all the necessary tools are often already available. The disadvantage is that there is no energy balance and that the quality of the (brackish) groundwater is downgraded. These issues should be weighed against the benefits. The potential for this concept appears to be considerable, especially in the west of the Netherlands.

12.4. ATES and process water

There are many locations with substantial demand for cooling water where drinking water is currently being used (e.g. in hospitals with cooling towers). According to this concept, the water from the warm well of an ATES system is partially drained and used to supply the cooling towers. The great advantage of this is that no high-quality drinking water needs to be used as process water. In financial and environmental terms, such a combination is very interesting and, given the number of cooling towers in the Netherlands, it seems to have a great deal of potential. An important disadvantage, however, is that there is no volume and energy balance.

12.5. Conclusion

To exploit the potential of these combinations, their added value compared to legacy systems should be demonstrated through pilot programmes. In addition, changes in legislation will be needed, in particular relating to the temperature and the energy balance.