CityChlor

The combination of aquifer thermal energy storage (ATES) and groundwater remediation

Tackling urban soil and groundwater contamination caused by chlorinated solvents

Investing in Opportunities
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Summary
This document describes the possibilities and obstacles for aquifer thermal energy storage (ATES) combined with groundwater remediation in Flanders. The study shows that about 50% of the surface area of Flanders is suitable for a certain groundwater energy system. The effects of a GWE system on groundwater contamination are due to mixing and hydraulic head variations rather than to temperature variations. Model calculations are performed for a hypothetical case where a plume of chlorinated solvents is combined with various forms of GWE systems.

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0 SUMMARY

The European project 'Citychlor' (www.citychlor.eu) is a transnational cooperation project that aims to improve the quality and minimize the pollution of soil and groundwater by developing an integrated approach to tackle the threats caused by contamination with chlorinated solvents in urban areas. Within the context of CityChlor, this project is performed in order to examine the potential for combining aquifer thermal energy storage (ATES) with groundwater remediation.

A map was developed indicating regions in Flanders suitable for developing a significant GWE-system. The suitable area ***encloses about 50% of the total area.*** For some regions only small residential systems are applicable, for other regions large GWE-systems may be installed and operated.

Although specific literature on the combination of GWE and groundwater remediation seems to be very scarce, relatively many studies are available on the effects of temperature on the physical, chemical and biological behaviour of pollutants in subsurface environments. In the relevant temperature interval for the current study, biological and geochemical reaction rates will however only slightly be affected. Especially the groundwater flushing and mixing effect caused by the GWE-system will be relevant in the context of remediation.

Groundwater and reactive solute modelling are necessary to predict the behaviour of the groundwater pollution when GWE-systems are active. Feflow, Modflow or equivalent other models are available. Since temperature effects are limited (for the systems described here), it is not important to model them. The groundwater flow and mass-transport effects produced by the GWE-system, however, are very important. Some hypothetical modelling examples of relevant combinations of groundwater remediation and "ordinary" GWE systems operating in PCE-polluted areas in Flemish aquifers are presented. The model results, although very preliminary, show large spreading effects caused by pumping and reinjection, especially for mobile partial dechlorination products such as dichloroethenes and vinyl chloride. In later work, a real field pilot should be executed and carefully monitored. These monitoring results should be used to calibrate model input data.

For known polluted locations, it is currently not strictly forbidden, but yet not evident to install and operate a GWE-system. There is a tendency to prohibit GWE-systems as they are considered to disturb or cause additional migration, thus worsening the pollution situation. The combination of groundwater remediation with energy production causes an environmental as well as economical benefit. Combining both remediation and energy production refocuses the project from an environmental cost to an environmental benefit (or at least a lower cost). In ideal cases, the implementation of a GWE-system could render a groundwater remediation project more economically feasible.

It is advised to create a suitable framework for the implementation of combined remediation and energy systems defining the allowed boundary conditions. Most combined approaches have a certain impact on the migration of subsurface pollutants which must be addressed in the legal context or existing Codes of Good Practice. In that way, the development of renewable geothermal heating and cooling can be offered maximum possibilities in respect to the environmental circumstances.

1 INTRODUCTION

Energy from groundwater

The average energy bill in Europe is severely influenced (almost for 50%) by costs related to heating and cooling of houses/buildings (Fig. 1). Heating and cooling are mostly realised by fossil fuel consumption. Reduction of the energy bill – thus the environmental impact – can be realized if sustainable, renewable alternatives can be found. The search for 'green' energy is – mostly – a search for 'green electricity'. The possibilities of using 'green heat' are often overlooked, albeit its great promise, especially **geothermal energy**.

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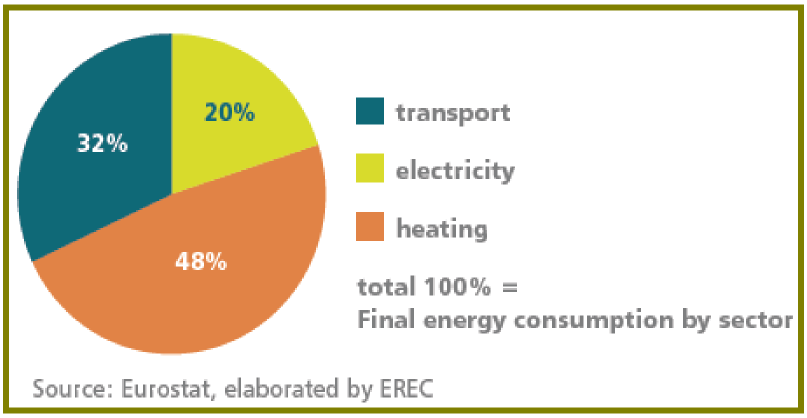

Figure 1. *Average energy bill in Europe – contribution of transport, electricity consumption and heating/cooling*

Shallow geothermal systems are the most obvious choice since they are applicable in both small and large installations, via ground-coupled heat pump systems and energy storage projects. This type of technology can – in term – significantly contribute to meet European climate goals, as was demonstrated in a recent study of VITO for VEA (Desmedt et al, 2009).

Shallow geothermal energy systems can be used for underground energy storage. They are typically limited to depths of 200 m below ground level (bgl), and can be subdivided into several categories; two mayor classes are (i) *heat-withdrawal systems* and (ii) *energy storage systems*. The first type of systems utilizes the natural, constant temperature of the subsoil for above-ground heating applications. Best known are ground-coupled heat pump systems that extract heat from the subsoil. A heat pump transfers heat from a lower (12°C) to a higher temperature level (35-45°C). This is realized at high yield, i.e. the heat increase that is realized equals on average four times the (electrical) energy consumption of the heat pump. Heat can be extracted from groundwater (open systems with re-injection) or by vertical or horizontal closed looped piping (closed systems).

In underground energy storage systems, thermal energy is being stored during summer (cooling of building), to be re-used during winter for the heating of the same building.

Energy storage systems make use of the same basic technologies as in heat-withdrawal systems, but better utilize the heat *storage capacity* of the subsoil.

Systems using pumped groundwater are called **groundwater energy systems (GWE)**, including **aquifer thermal energy storage or ATES**. Vertical closed-loop heat exchangers are called **borehole thermal energy storage systems (BTES).**

Soil and groundwater pollution

'Preventing new contamination and remediating historical soil and groundwater contamination' are the main objectives of the Decree for soil remediation and soil protection, established on 27 October 2006 (prior version: 1995). In the Flemish Soil Decree a remediation obligation rests on the operator or the owner of the land where the pollution entered the soil. OVAM, the Public Waste Agency for Flanders (www.ovam.be) is supervising the execution of this decree. Since its introduction in 1995, roughly 5000 soil remediation projects have been executed, of which more than half involved groundwater abstraction.

The presence of any kind of soil or groundwater pollution thus far caused the dismissal of potential geothermal projects at the specific sites, in 99% of all cases. However, geothermal projects may potentially fortuitously be combined with soil and groundwater remediation.

In the current document the results are described of a study performed by Terra Energy and VITO, by order of OVAM, to investigate (i) the current state-of-the-art of GWE-systems in Flanders (§2.1), (ii) the suitability of the subsoil to install GWE-systems in Flanders (regional applicability; §2.2), (iii) existing literature on the effects of GWE on (polluted) groundwater systems; §2.3), (iv) a hypothetical case-study, using a mathematical model (§2.4), and (v) the economical aspects of GWE combined with remediation (§2.5).

This study more specifically focuses on ATES as a (more complex) application of the basic technology of pumping groundwater for heat withdrawal, followed by water re-injection into the same aquifer. Systems using groundwater discharge (into sewer, surface waters) after heat extraction are being regarded as inferior to re-injection systems, generally spoken, although partial discharge (after purification) can be considered when ATES is combined with groundwater remediation.

This study has been performed within the context of the European project 'Citychlor' (www.citychlor.eu). CityChlor is a transnational cooperation project that aims to improve the quality and minimize the pollution of soil and groundwater by developing an **integrated approach** to tackle the threats caused by contamination with **chlorinated solvents** in urban areas.

2 RESULTS

2.1 Overview of aquifer thermal energy systems

Groundwater energy systems (called GWE-systems including aquifer thermal energy storage or ATES) can be classified in many ways according to the specific criterium that is used. In this paragraph an overview of different classifications is used in order to describe the existing/possible ATES systems. Afterwards, the different GWE-systems are subdivided into groups that are relevant within the theme of this study, namely the combination of ATES and groundwater remediation. All members of each group can then be treated more or less equal in the course of the study.

2.1.1 Classification by well operation

GWE-systems are composed of (an) extraction well(s) and injection well(s). This not merely technically allows to store energy in the subsurface; it is one of the conditions to obtain an installation permit for the system (see further). All water that is pumped must be returned to the same hydrogeological system (aquifer). This can be technically realized in two ways:

- In a so-called *unidirectional system*, groundwater is continuously being pumped up from the same well(s) and returned into another (set of) (re-injection) well(s). The natural groundwater temperature of the extracted water is continuously used for either heating (during winter) or cooling (during summer). The reinjection well(s) receive(s) cooled (during winter) or heated water (during summer). Groundwater flow is always from injection well towards extraction well, hence the name 'unidirectional'.
- Alternatively, GWE systems can be part-time pumping or re-injecting groundwater in the same well(s). This is the so-called *bi-directional system* (the groundwater flow direction is reversed after switching between wells from injection-mode to re-injection mode. The switching frequency, in general, is half-yearly. In this way an ATES can be realized in which stored heat or cold in the subsurface, can be recuperated.

Figure 2 schematically shows both system types. Uni- and bidirectional systems fundamentally differ in hydraulic and thermal characteristics, which obviously will have important implications for the design of the concurrent groundwater remediation.

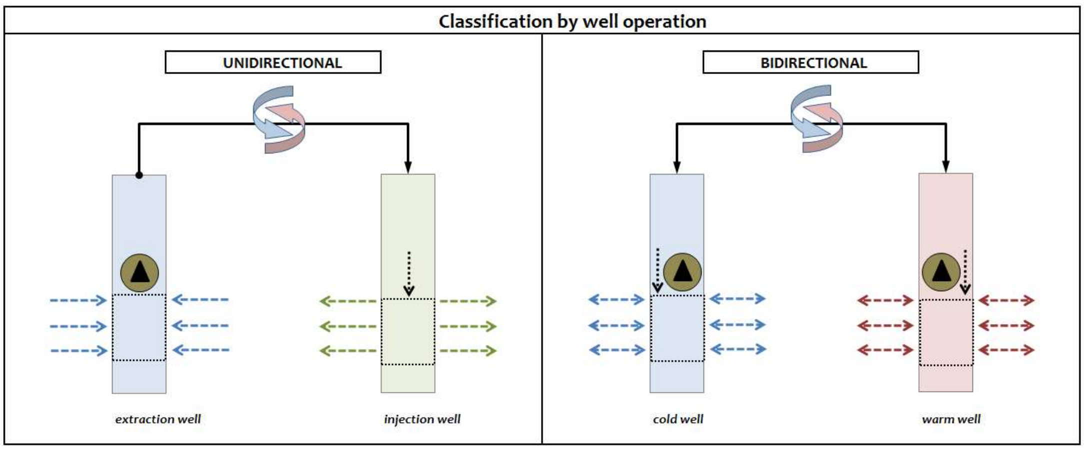

Figure 2. *Classification of GWE-systems by well operation*

2.1.2 Classification by well configuration

The abstraction and reinjection of groundwater mostly involves at least two wells, although abstraction and reinjection can –in principle – be applied in just one well (Fig. 3). In the latter case, a so-called single-well is installed, composed of two screened intervals at different depths but within the same aquifer system (provided that the aquifer thickness is sufficiently large).

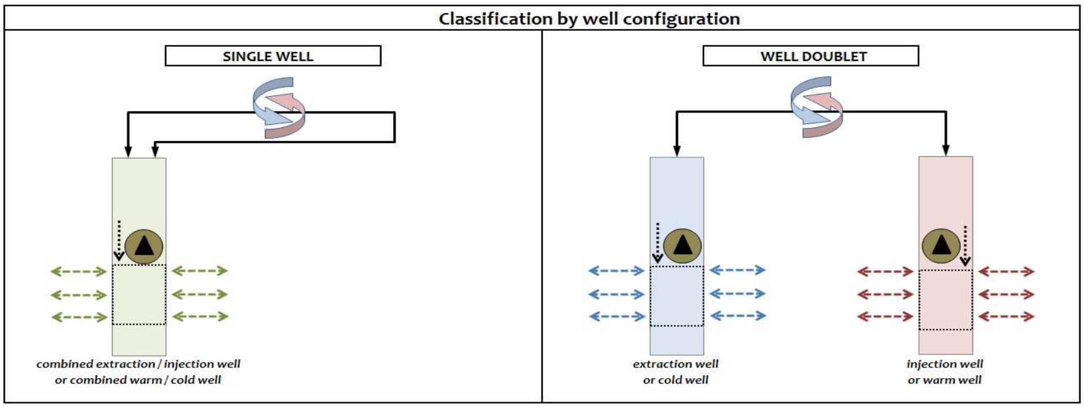

Figure 3. *Classification by well configuration*

A single well system has limitations, since extracted water and reinjected water should not intermix in the subsurface (mixing would negatively influence the energetics of the system). This implies that single-well type systems are best suited for smaller installations using smaller groundwater abstraction/reinjection rates. In practice, such systems are only used with rates up to 10 m^3/h, in the Kempen-region (with relatively deep aquifers).

2.1.3 Classification by flow rate / power

GWE-systems can also be subdivided according to their size. At the one hand, typical small, private systems with groundwater rates ranging between 1 and 8 m^3/h and thermal capacity up to 50 kW. Small GWE-systems are not always the evident choice since the minimal technical equipment requirement represents costs that are sometimes higher than what can be considered as 'economically feasible'.

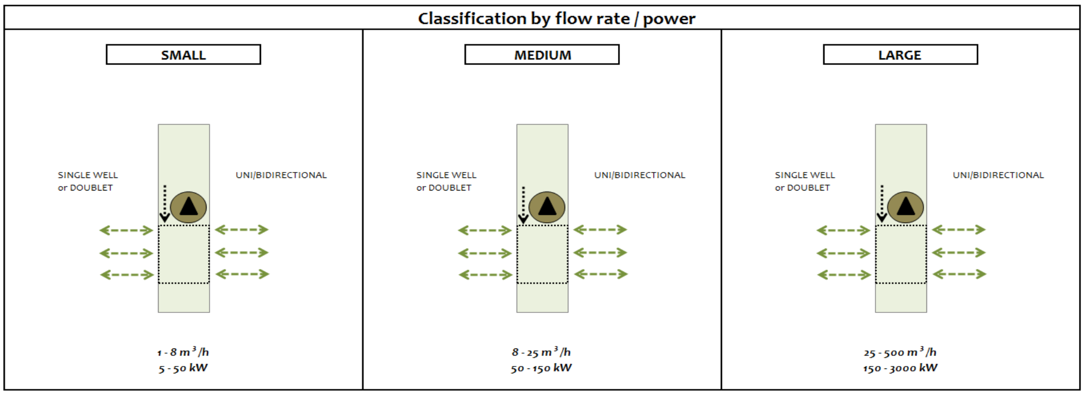

Figure 4. *Classification by flow rate / power*

A medium-sized installation has a flow rate between 8 and 25 m^3/h and power between 50 and 150 kW. This class represents the most promising GWE-system class, also from the point of view of possible combination with groundwater clean-up. Middle-sized GWE are typically installed in offices, industrial buildings, SMEs, apartment blocks, etc. Large GWE systems have rates up to 100 m^3/h and more, with typical power range of 150-3000 kW. Such large installations are typically suitable for hospitals, large buildings, etc. (Fig. 4).

2.1.4 Classification by application

Implementations of a GWE-system can be very diverse. For each application with a thermal requirement for heating as well as cooling, an individual design is necessary. Three types of applications are distinguishable: private (houses), industrial and tertiary systems. Single family systems are simple and small installations. For industry, mostly larger projects are common, with an emphasis on cooling. In the tertiary sector, mostly medium to large size systems are installed, typically with a seasonal and balanced energy requirement profile (both heating and cooling).

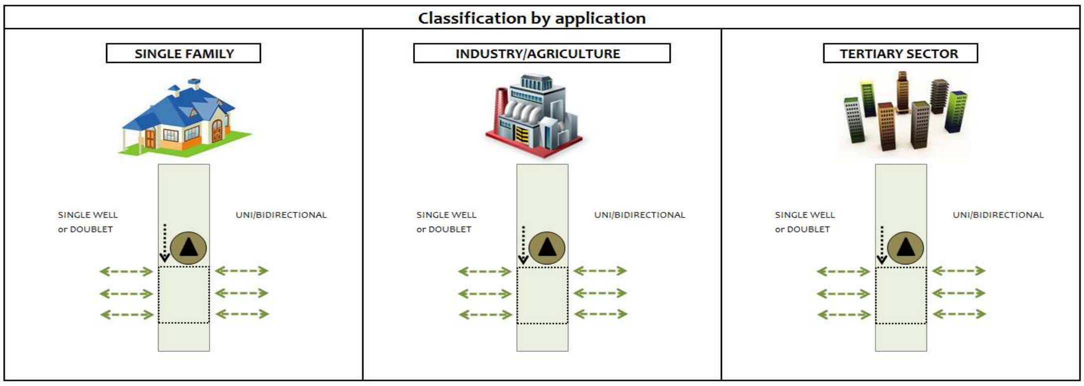

Figure 5. *Classification by application*

2.1.5 Classification by well temperature range

Regardless the specific application type, GWE-systems can be classed by temperature range.

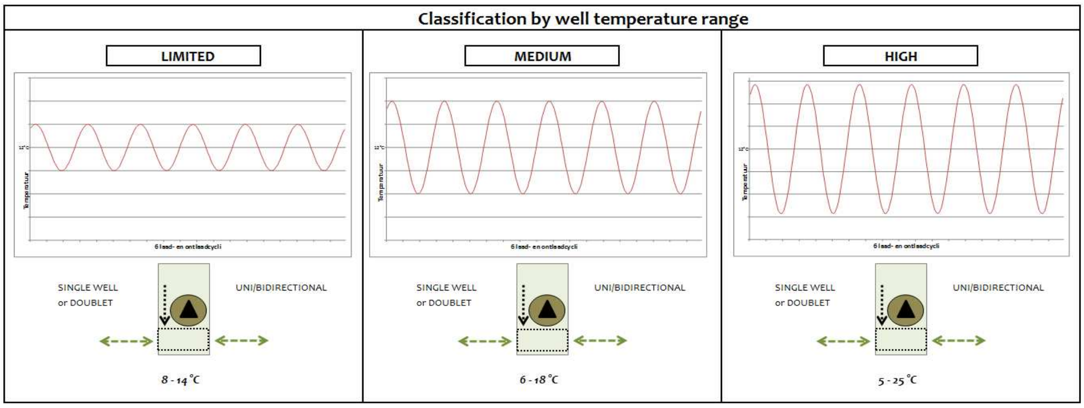

Figure 6. *Classification by well temperature*

Small temperature differences between wells mostly lead to energetically less efficient applications due to the related smaller heating/cooling capacity. In order to be energetically efficient, a minimal temperature gradient of 2 to 3°C is necessary; otherwise the pumping energy consumption would be too high. Typically, the cost-effectiveness of a GWE-system will increase with increasing temperature difference between the wells. However, groundwater temperatures above 25°C are not permitted (licence restrictions). The classification of systems based on temperature range therefore are 8-14°C / 6-18°C and 5-25°C (Fig. 6).

2.1.6 Classification by well depth

A GWE-system can be installed at varying depths below ground level (bgl). Both phreatic (not-confined), confined (aquifer below an impermeable layer) and semi-confined aquifers can be exploited (Fig. 7). The choice of depth of wells in a GWE-system is strongly dependent of the respective depths of layers in the geological formations at the specific site. Most common are depths between 20 and 200 m bgl. A more shallow system is more susceptible to well clogging because of the higher oxygen levels in shallow groundwater.

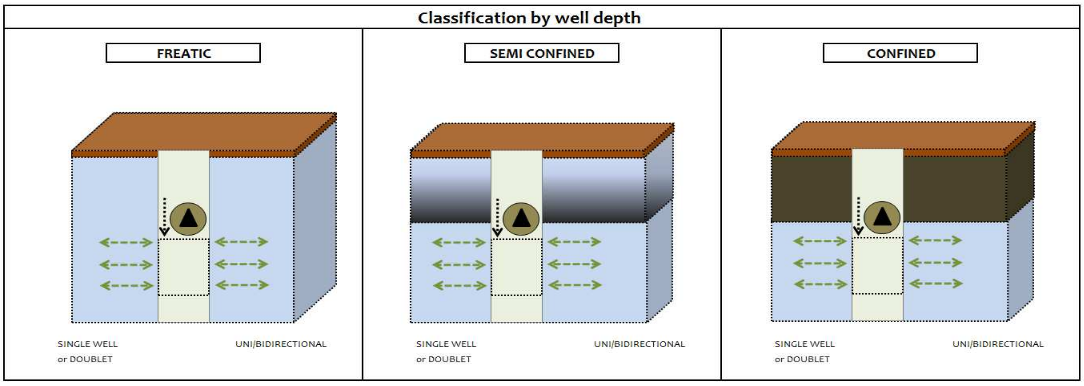

Figure 7. *Classification by well depth*

2.1.7 Classification by quality level

Among GWE systems, the quality of used materials, equipment and safety devices can be used to classify them. Three quality levels may be distinguished: basic, standard and tailor made (Fig. 8).

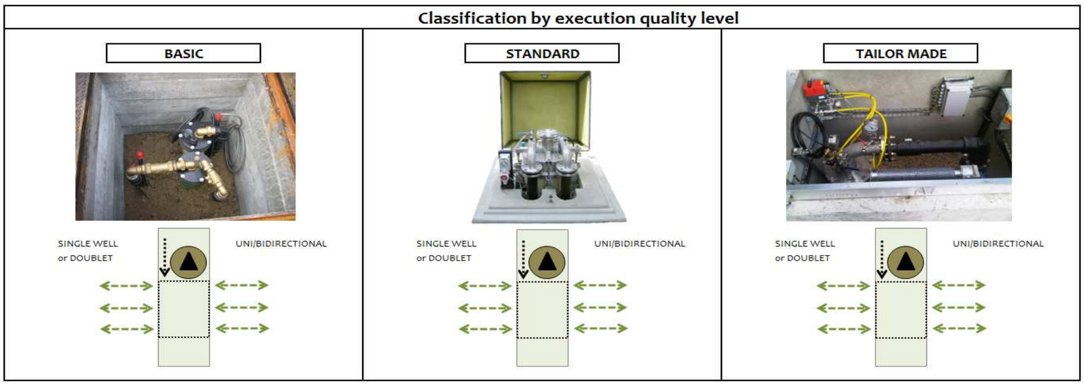

Figure 8. *Classification by quality level*

Small installations are generally 'basic', using mostly PVC and some basic facilities for level and pressure control and maintenance. The 'standard' installations are build out of a standardised well head (in inox) and some more sophisticated options regarding control and maintenance. Tailor-made installations are fully assembled on-site, using top materials and mostly equipped with extensive monitoring, safety and alarm systems for all relevant parameters.

2.1.8 Classification by operation modus

GWE-systems can be operated in a variety of modes. One option is to maximally utilize the naturally available thermal energy in the subsoil ('direct use'). The natural groundwater temperature is directly used for heating or cooling. In heating mode, the aquifer will cool down, in cooling mode it will be heating up. The aquifer thus solely acts as a heat or cold source. In most cases however, a heat pump is used that will increase the temperature of the extracted water to a suitable range (35 - 45°C) for heating. In cooling applications, a condenser (cooling machine or reversible heat pump) will be used that will transfer the excess heat to the subsoil. The latter application is referred to as 'no direct use'. An intermediate operating mode is a combination of direct and indirect use of the subsoil. In most applications, the heating mode will involve a heat pump and the cooling mode a free natural cooling via the subsoil. Most GWE-systems applicable in Flanders (small to large) make use of the latter operation mode, called 'semi-direct use' (Fig. 9).

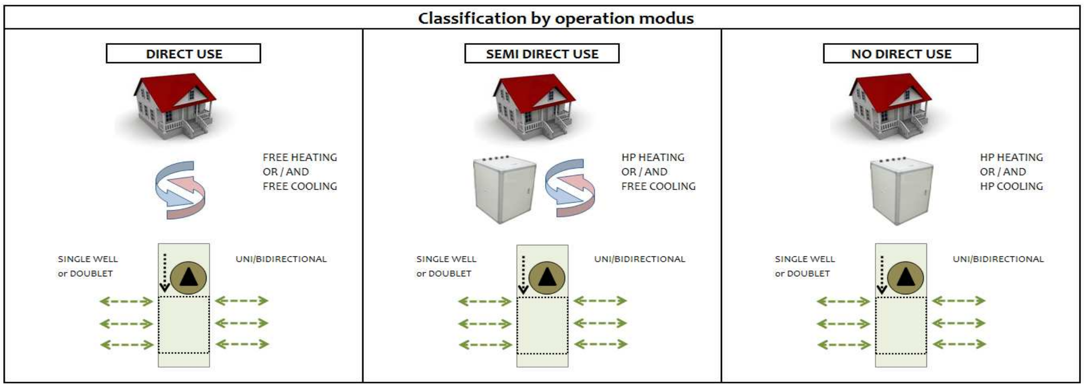

Figure 9. *Classification by operation modus*

2.1.9 Classification by thermal balancing

GWE-systems abstract thermal energy from the subsoil, making both use of the natural soil temperature and the thermal storage capacity of the aquifer. Small private systems are mostly meant for sustainable heating using a heat pump. Such systems are 'mainly heating'. Potential use in summer for cooling is possible but of minor importance. Such systems will result in an average cooling down of the subsoil (negative energy balance). The long term impact of the system for the immediate environment will be small for small GWE-systems. For larger systems however (> 50 kW), the natural regeneration to original temperatures may be insufficient to control the cooling effect in the long run. The opposite modus ('mainly cooling'), is less often used (Fig. 10). A typical example is industrial process-cooling using groundwater. The size of such applications is mostly too large, implying a (undesirable) long-term heating effect of the subsoil. In most cases (medium and large sized GWE-systems), active thermal balancing is necessary to make sure the system does not have a structural thermal impact on the subsoil.

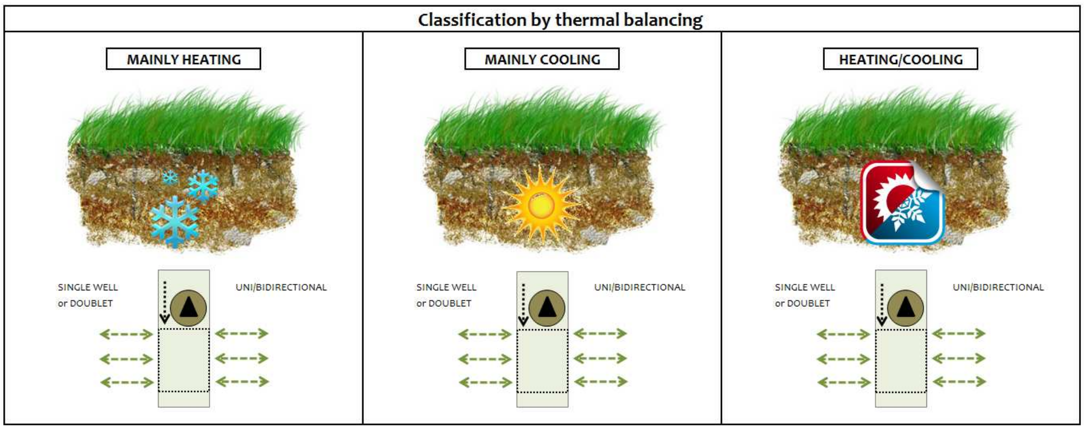

Figure 10. *Classification by thermal balancing*

This implies that the extracted amount of heat within the systems zone of influence is kept (on average) equal to the injected amount of heat. This aspect in the design of GWE-systems is very important. Control tools that enable to tune the system to thermal balance should be part of the system in order to guarantee the thermal equilibrium of the subsoil.

2.1.10 Relevance in the project context

Not all of the above mentioned criteria regarding the subdivision and types of GWE-systems are relevant in the context of the current project. Moreover, some systems may be combined since they imply a mutual treatment or have a comparable impact on the environment.

This leads to the following relevant general classification of GWE-systems:

- Phreatic aquifer systems;
- With a sufficient thickness to enable adequate pumping rates;
- Minimal quality level, using pressure control and source protection;
- Groundwater temperatures within the range 5 - 25 °C;
- Compulsory thermal balancing for systems with capacity > 50 kW;
- Rates and capacities between small (5 kW ; 1 m3/h) to very large (5 MW ; 1000 m3/h)

Confined aquifer GWE-systems are not relevant in this study, because such aquifers are mostly not polluted; instead the installment of a GWE-system may lead to a risk of polluting the aquifer (if e.g. DNAPL chlorinated solvents are present in the aquifer situated above the impermeable layer). All systems that do not comply with minimal quality levels should not be considered e.g. systems without pressure maintenance or systems that create too high or too low temperatures.

2.1.11 Selected research systems

Seven different GWE-systems and applications may be selected for potential combination with groundwater remediation (Table 1 and Table 2 summarize their typical characteristics).

Table 1. *Overview of GWE-systems that are relevant for simultaneous groundwater remediation (1)*

n°	*name*	*typical application*	*well configuration*	*well operation*	*groundwater flow*	*thermal power*	*yearly groundwater displacement*	*temperature well or filter 1*	*temperature well or filter 2*
1	coldstorage/rercirculation - small - 2 wells	typical single family HP installation	1 extraction / 1 injection well	unidirectional	1 - 8 m^3/h	5 - 50 kW	2000 - 15000 m^3/y	5 - 9°C	11 - 12°C
2	coldstorage/rercirculation - small - 1 well	typical single family HP installation	1 combined extract/inject well	unidirectional	1 - 8 m^3/h	5 - 50 kW	2000 - 15000 m^3/y	5 - 9°C	11 - 12°C
3	coldstorage/rercirculation - large - 2 wells	industrial cooling installation	1 extraction / 1 injection well	unidirectional	25 - 100 m^3/h	100 - 1500 kW	30000 - 500000 m^3/y	5 - 20°C	11 - 12°C
4	cold/heatstorage - small - 1 well	typical single family HP installation	1 combined extract/inject well	bidirectional	1 - 8 m^3/h	5 - 50 kW	2000 - 15000 m^3/y	5 - 10°C	14 - 20°C
5	cold/heatstorage - small - 2 wells	typical villa with swimming pool, small enterprise installation	1 extraction / 1 injection well	bidirectional	5 - 15 m^3/h	30 - 75 kW	5000 - 30000 m3/y	5 - 10°C	14 - 20°C
6	cold/heatstorage - medium - 2 wells	typical tertiary sector installation (small offices, showroooms, warehouses,...)	1 extraction / 1 injection well	bidirectional	10 - 25 m3/h	50 - 150 kW	15000 - 75000 m^3/y	5 - 10°C	14 - 20°C
7	cold/heatstorage - large - 2 wells	typical tertiary sector installation (offices, hospitals, ...)	1,2,3 extraction / 1,2,3 injection wells	bidirectional	25 - 100 m3/h	150 - 800 kW	50000 - 300000 m^3/y	5 - 10°C	14 - 20°C

Table 2. *Overview of GWE-systems that are relevant for simultaneous groundwater remediation (2)*

n°	*name*	*balancing*	*remark*	*typical filter length*	*typical depth*	*typical well distance*	*summer operation*	*winter operation*
1	**coldstorage/rercirculation - small - 2 wells**	no real thermal balance, natural regeneration required	extraction well is warmer then injection well ; no real energy storage	10 m in both wells	30 - 150 m	10 m	direct cooling by using natural groundwater temperature for floor or air cooling, without operating heat pump	use of heat pump, heat extraction from groundwater, injection temp < extraction temp
2	**coldstorage/rercirculation - small - 1 well**	no real thermal balance, natural regeneration required	typical installation with 2 filters on different depths in 1 well	10 m at different depths in 1 well	30 - 150 m	0 m (only 1 well)	direct cooling by using natural groundwater temperature for floor or air cooling, without operating heat pump	use of heat pump, heat extraction from groundwater, injection temp < extraction temp
3	**coldstorage/rercirculation - large - 2 wells**	regeneration required, balancing with cooling tower	no real cold & warm well, injection at high t° (summer) and low t° (winter)	30 - 50 m in both wells	30 - 150 m	150 m	direct cooling by using natural groundwater temperature for industrial cooling process	use of direct cooling by using natural groundwater temperature for industrial cooling process + storage of cold with cooling tower
4	**cold/heatstorage - small - 1 well**	regeneration by using heat and cold (direct free cooling, heating with heat pump)	real bidirectional pumping from cold to warm well according to energy demand from application	10 m at different depths in 1 well	60 - 150 m	0 m (only 1 well)	direct cooling by using natural groundwater temperature for cooling, without operating heat pump, injection temp > extraction temp	use of heat pump, heat extraction from groundwater, injection temp < extraction temp, creation of cold and warm zone in vertical direction
5	**cold/heatstorage - small - 2 wells**	regeneration by using heat and cold (direct free cooling, heating with heat pump)	real bidirectional pumping from cold to warm well according to energy demand from application	10 - 20 m in both wells	30 - 150 m	30 m	direct cooling by using natural groundwater temperature for cooling, without operating heat pump, injection temp > extraction temp	use of heat pump, heat extraction from groundwater, injection temp < extraction temp
6	**cold/heatstorage - medium - 2 wells**	regeneration by using heat and cold (direct free cooling, heating with heat pump)	real bidirectional pumping from cold to warm well according to energy demand from application	10 - 30 m in both wells	30 - 150 m	50 m	direct cooling by using natural groundwater temperature for cooling, without operating heat pump, injection temp > extraction temp	use of heat pump, heat extraction from groundwater, injection temp < extraction temp
7	**cold/heatstorage - large - 2 wells**	regeneration by using heat and cold (direct free cooling, heating with heat pump)	real bidirectional pumping from cold to warm well according to energy demand from application	30 - 50 m in both wells	30 - 150 m	100 m	direct cooling by using natural groundwater temperature for cooling, without operating heat pump, injection temp > extraction temp	use of heat pump, heat extraction from groundwater, injection temp < extraction temp

These seven systems were finally further grouped in three types, each requiring a clearly different strategy, approach and feasibility testing, within the context of this project:

1) ***Bidirectional operated well pair(s)***
2) ***Unidirectional operated well pair(s)***
3) ***Single well***

Within each type system, a number of fixed and variable parameters can be selected:

- Aquifer location and thickness, quality level and thermal balancing requirements are preset;
- Pumping rates, temperatures, well location and well interdistances can be varied to investigate the consequences for the groundwater system.

2.2 Geographical suitability analysis

An important step in this study is the evaluation of the regional suitability of the subsoil for installing well-working GWE-systems. It is obvious that one can only consider combining remediation with GWE in areas were GWE-systems are technically feasible.

011In an early feasibility study (Patyn et al, 1999) an indicative map for Flanders was already developed (Fig. 11). This map dates from a period when the first GWE-systems were installed in Flanders. At that time, only systems requiring high discharges (> 25 m³/h) were considered, and in such a way, this map is not relevant for GWE-systems that can be combined with groundwater remediation.

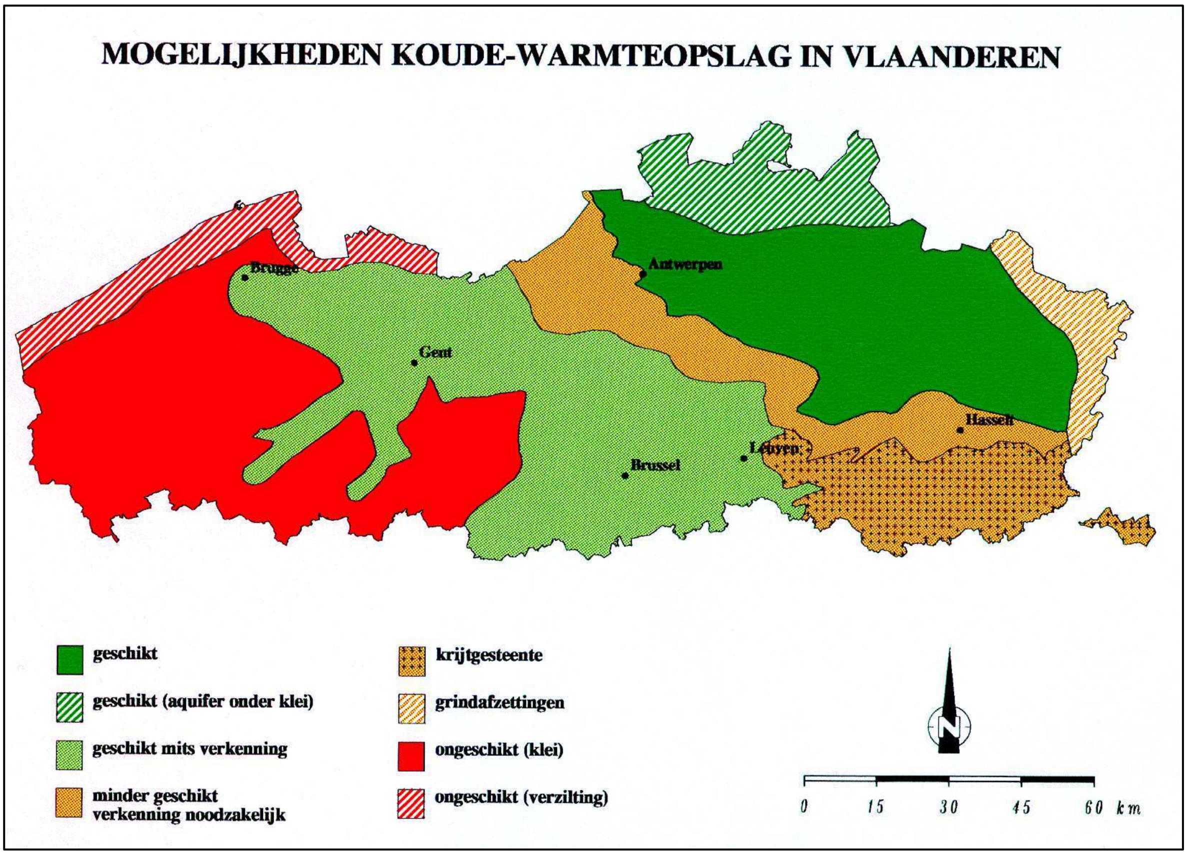

Figure 11. *'Old' regional GWE-system suitability map (VITO, 1997). Dark green (full or dashed): suitable. Light green: potential suitable (needs site-specific evaluation); other: less or not suitable.*

During long periods groundwater extraction for energy purposes (esp. cooling) has been associated with discharge of huge volumes slightly thermally influenced water. Currently, such an inappropriate use of a valuable resource is no longer permitted. This makes that even small systems require a combined pumping- and injection system. Partly due to evolution of technology (and new variants such as unidirectional well systems) and standardization of methods and system components smaller systems become more relevant and profitable. This evolution is not represented in the available map (Fig. 11). Opportunities for combined GWE-systems with remediation are found suitable for smaller systems, as remediation discharge larger than 25 m³/h is not considered as standard practice. A second relevant change concerns the increased insight over the years regarding applicability of GWE-systems in Flanders. Thanks to the experience gathered in projects and geological survey (test drillings, pump tests), knowledge on the Flemish shallow geology highly improved. Finally, the map must be compared with the known locations of contaminants thus ensuring the potential of combined GWE-systems with remediation.

2.2.1 Use of GWE systems

The drawing of a map which indicates suitable areas for combined energy production and sanitation starts with the defining of the geographical zones where GWE-systems can be exploited in a feasible way. Contamination of soil and groundwater does not occur in confined aquifers. Therefore only GWE-systems in the phreatic groundwater are relevant.

Shallow filters may cause a lot of hydrological problems (injection-wells !) and because oxygenated groundwater can cause precipitation of e.g. rust and well clogging, installation of shallow filters is to be avoided. As a rule the first 20 m are not used to install GWE-systems. Therefore GWE-systems require a minimum thickness of the phreatic reservoir for small as well as for large GWE-systems. A minimum thickness of 25-30 m is needed for rather small flow rates of 3 to 5 m³/h in case of residential applications. For the large (industrial) GWE-systems, with a flow rate up to 100 m³/h, phreatic layers of 100 m are required.

The former ATES map of fig 11 was compiled with the boundary condition that a feasible ATES-system needed at least 25 m³/h. Due to technological - and economic - evolutions, GWE-systems are currently significantly smaller. This is also taken into account into the new map.

2.2.2 Remediation zones

In order to define the suitable zones for combining energy production with sanitation, the polluted areas should be drawn on the map of Flanders. However, it’s clear that possible polluted zones are widely spread all over the country (see figure 12) and that there is a significant potential for a combined system development. Pollution is related to industrial activity. With the development the so-called brownfields, Sustainable projects and renewable energy systems are to looked for despite hostile circumstances as contaminated soils. GWE-installations are certainly sustainable projects that can be combined with the problematic nature of brownfields. In that way a twofold objective is reached : a renewable energy system and a sanitation of soil and groundwater.

However, the type of pollution is important in order to evaluate the risk for spreading the contamination. The mobility of contaminants in the soil increases with the solubility of the substances and decreases with the degree of adhesion to soil particles. The biggest part of the soil contamination is limited to the upper five meters of the soil. GWE-systems are applied in water bearing layers or aquifers at much higher depths (> 15 m). In these layers are particularly volatile chlorinated hydrocarbons (VOCl) found and to a lesser extent volatile aromatic hydrocarbons (BTEXN). These mobile contaminations form a pollution plume. Dependant on groundwater velocity, the composition of the soil and contamination properties a smaller or larger plume will occur. Contamination with a higher density than water will sink into the soil relatively quickly. The pollution can move around unpredictably in low permeable layers causing an erratic distribution pattern.

When defining most relevant zones for combining GWE-systems with groundwater sanitation, focus on the mobile contaminants should be made (like VOCl, BTEXN, …). Currently, maps on specific locations of those mobile contamination are not available, but experience has taught that thousands of locations can be found throughout the region of Flanders (source : OVAM).

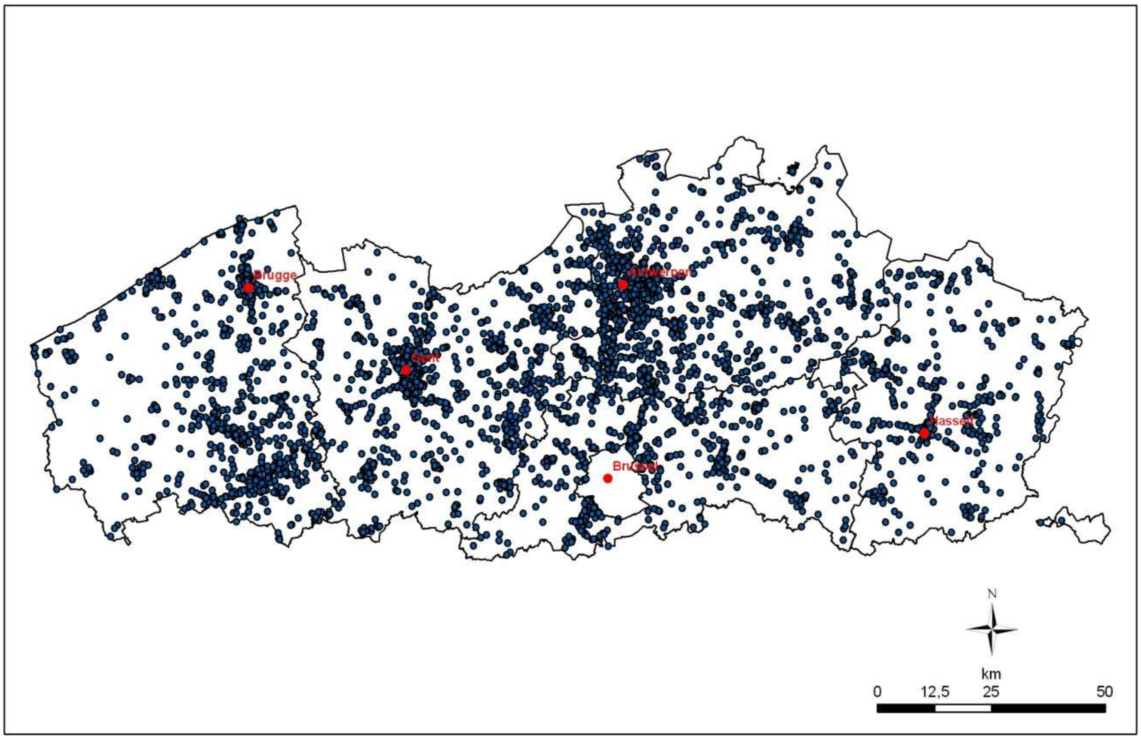

Figure 12. *Known sites contaminated with chlorinated solvents.*

2.2.3 Cartography

As GWE-system development is related to the presence of suitable aquifers, the starting point will be a study of the available maps of Tertiary deposits in Flanders (see figure 13). This map gives a good overview where phreatic GWE-systems can be installed. Phreatic aquifers are also exposed to contamination risks from surface sources. Many pollutants are classified as mobile (chlorinated solvents, BTEX, MTBE,…).

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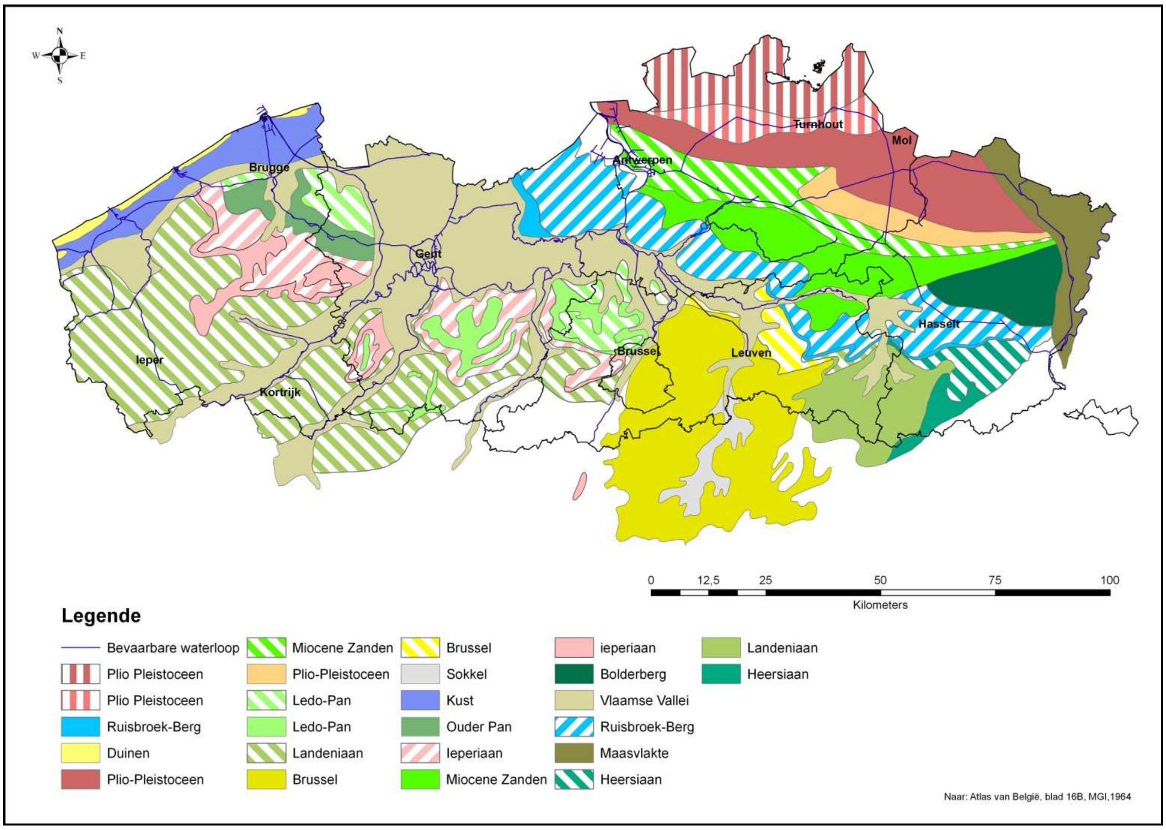

Figure 13. *Tertiary map of Flanders*

The type (unidirectional/bidirectional) or size (from a few m^3/h up to 100 m^3/h) of GWE-systems is important as the major condition is the presence of a phreatic aquifer with a thickness of at least 25 to 30 m. In such cases, it is possible to install a small GWE-system that can provide energy for a small-scale ground source heat pump system. When developing large scale HP systems, an increased thickness of the phreatic aquifer is required (up to 100 m). As a result, figure 14 shows the suitable zones for developing a significant GWE-system. For some regions this can only be a small residential system while for other localities a large GWE-system (providing energy to big office building, hospital, industry,…) is possible.

Figure 11 shows the geographical distribution for the development of large GWE-systems. The combination of large GWE-systems ($Q > 25$ m^3/h or $P > 150$ kW) with sanitation activities is only possible in the dark green area, exp. The Campine region. But, since soil pollution is not limited to specific regions, the areas suitable for the installation of GWE-systems in polluted soils are represented on Fig. 14.

Figure 14 is based upon a map that specifies the possibility of aquifers - both confined as well as unconfined - for installing industrial GWE-sytems. This map conforms to the index of the topographic map. This map that was made for the former AMINAL-administration (Patyn et al, 1999) summarizes experience on the exploitation of aquifers. The capacity of an aquifer for water collection depends mainly on the transmissivity [saturated thickness times permeability] and his extent. To assess the capability of a water bearing formation, we prefer the known specific capacity (m^3/h/m) which is an integral parameter, mostly found through experience. Neogene formations in the Campine region (e.g. Mol) have a capacity

s_p up to 10 m³/h/m, which means that lowering the piezometric level with 1 m, may yield a discharge of 10 m³/h. On the other hand, s_p of the heterogeneous quaternary sand of the Flemish Valley (region : Menen, thickness 20 m) is about 1 m³/h/m.

It was specified already that concerning GWE-systems and remediation, only phreatic reservoirs are to be considered, since contamination of confined aquifers is very unlikely. Because of this, Figure 14 reflects mainly the expert appraisal on the capacity of phreatic aquifers and the possible combination with remediation.

The white areas are suitable for small and larger GWE-systems. ***They enclose about 50% of the total area.*** On this scale it is not possible to give more details on the local hydrogeology or to investigate the presence of contamination in detail.

Industrial areas with a high thermal energy need and a risk for soil contamination or already existing contamination are coloured in purple. Although some are situated in a "good" area (region of Antwerp-LO), only small GWE-systems can be installed because of the limited capacity of the phreatic reservoir.

The blue, grey and green zones are not or less appropriate for the installation of even small GWE-systems.

The light blue areas show the protection zones for drinking water extraction, these zone are not suitable for GWE-systems nor industrial development.

Along the coast possible salinisation of the phreatic reservoir should result in a prohibition of installing GWE-systems : pumping even modest volumes will cause a displacement of the salt/fresh water interface. Once this interface is coned up, it is extremely difficult or even impossible to restore the former situation.

In the grey zones there is only a very thin phreatic aquifer, and a classic GWE-system cannot be installed in this areas :

- North province of Antwerp : outcrop of the Campine Clay (still exploited in the region Turnhout-Malle for the fabrication of bricks)
- Western part of Flanders (Ieper-region) outcrop of clay of Kortrijk Formation (KoMo, KoAa)
- Very thin phreatic layer in the hilly country south of Kortrijk : presence of Kortrijk-clay (KoAa) or sliding surfaces on other clay layers ; the relief and the geological structure doesn't allow any injection.
- Eastern part : formation of Hannut and Heers consist of hardrock (sandstone) marls or clay. Those sediments are not appropriate for GWE-systems.
- In many places of the central part (Flemish Valley) : the phreatic layer is not deep enough (< 20 m). Areas where the phreatic layer is known to be heterogeneous or very deep are also marked unsuitable.

The classification on fig. 14 might be a too rough estimate, esp. for the central part. It should be advised to examine the actual cases.

Anyhow, each project on GWE-systems or sanitation needs an examination of the particular situation. Laconically one could say : there are as much combinations of hydrogeology, energy requirements and pollution as there are applications.

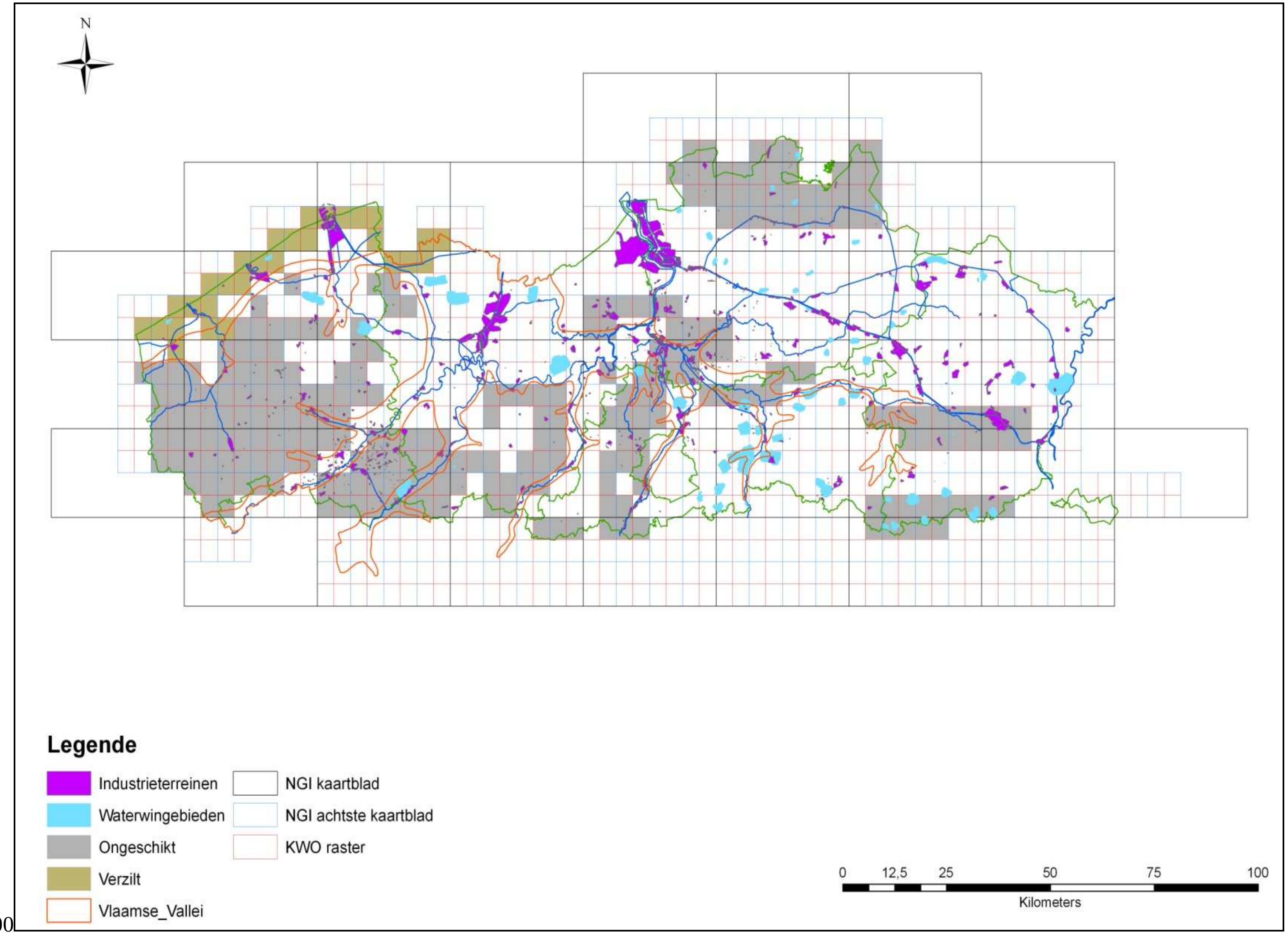

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Figure 14. *Updated suitability map for GWE systems in Flanders*

2.3 Screening of relevant literature

In this research project, existing literature has been screened (existing research reports and descriptions of applications of groundwater remediation combined with subsurface energy storage, scientific journals, and websites of US-EPA, Senternovem (now Agentschap NL),….). More specifically, information was summarized about (i) pollution types for which a combination with subsurface energy storage may be relevant; (ii) general information on the effects of variable temperature and increased water fluxes in the subsoil on the physical-chemical (adsorption/desorption, hydrolysis, chemical reduction,…) and biological processes (aerobic/anaerobic degradation) in the aquifer system.

Other important aspects include the sensitivity of the subsurface energy storage system to decreased permeability (*fouling),* especially when a combination is attempted with in-situ groundwater remediation through bioremediation (introduction of e.g. an organic substrate to the aquifer to stimulate in-situ anaerobic biodegradation).

The long-term effects are especially important as well as effects of subsurface energy storage in general. For this reason a suitable commercially available modelling tool (FeFlow 6.1), was selected and tested to study several realistic field scenarios of a combination of groundwater remediation of chlorinated aliphatic hydrocarbons (CAHs) and subsurface energy storage.

Finally, a brief investigation is included to policy-technical, legislative and juridical aspects (specific for the Flemish situation) of subsurface energy systems in general and more specifically when combined with groundwater remediation.

2.3.1 Existing research reports

Three recent studies are available in The Netherlands: the manual ‘*Handleiding Boeg’* (Verburg et al., 2010); ‘*De mogelijke risico’s van warmte- en koudeopslag voor de grondwaterkwaliteit*’ (van Beelen et at, 2011) and the document ‘*Meer met bodemenergie’* (Van Oostrom et al., 2011). The latter study contains an extensive literature overview about subsurface energy storage, including a separate chapter on the possibility of combining it with soil & groundwater remediation (chapter 11). A number of other specific subjects regarding the combination of GWE and remediation were elaborated in the same study as separate chapters: effects of temperature variations on the physical behavior of pollutants (chapter 12), biological degradation of pollutants (chapter 13) and regional groundwater (chapter 14).

Van Oostrom et al. (2011) list the following potential combination concepts for GWE and groundwater remediation:

- Purifying a *fraction* of the pumped (polluted) groundwater from the GWE system, and disposal or re-use of that water;
- Hydraulic control of the pollution by the GWE (recirculation) system;
- Stimulation of natural degradation of the pollution by the forced increased subsurface groundwater (delivering electron acceptors or donors to the micro-organisms responsible for the degradation of the pollution);
- Stimulation of the natural degradation rate by the temperature effects caused by the GWE system;

- Stimulation of natural degradation by the subsurface addition of nutrients and/or organic substrates;
- Backfilling GWE wells with reactive materials or mixtures (e.g. zero-valent iron; activated carbon,…) or the use of subsurface aeration (sparging, hydrogen peroxide or "slow-release" oxygen sources such as Ca-peroxide).

2.3.2 Groundwater mixing effect caused by the GWE-system

GWE systems are generally installed in deeper aquifer regions (typically in the range 20-150 m bgl). Groundwater contaminations mostly occur in more shallow soil layers (0-20 m bgl), suggesting that a combination of GWE with groundwater remediation is not trivial. Instead, the mixing effect caused by the GWE-system may lead to direct (migration) risks, also taking the generally high pumping rates into account. Dissolved contaminants will be distributed over the full soil volume within the zone of influence of the GWE-system.

In such cases, the GWE system may still be workable within a containment-strategy, although careful modelling is required for each specific case (see further). In the case of DNAPLs (such as chlorinated solvents), pollutions may have reached larger depths (20-100 m bgl). Especially for those cases, combination between remediation and GWE are relevant.

If the deeper groundwater at the site is salty, the GWE-system can cause mixing of salt water with the more shallow fresh water. The mixing of groundwater of – more generally – different physic-chemical quality (pH, redox potential, dissolved minerals,...), the mixing effect of GWE-systems will cause several undesired effects, such as precipitation of minerals (e.q. metal sulphides, carbonates, oxides,...), biomass fouling or gas fouling (N_2, CH_4, CO_2) (Van Oostrom et al., 2011). Changes in redox potentials due to groundwater mixing may also cause pH-changes (e.g. formation of sulphuric acid due to oxidation of metal sulphides). This, in turn can lead to mobilisation of heavy metals. Such effects are however not unique for GWE-systems, in fact they are known in 'common' groundwater remediation projects involving Pump&Treat or in-situ bioremediation (Code of Good Practice "Pump&Treat", OVAM, 2002; Code of Good Practice "anaerobic bioremediation of chlorinated solvents", OVAM, 2007).

2.3.3 Physical and chemical effects of subsoil temperature variations

DNAPL migration as a liquid will be enhanced by increasing temperatures (due to a decrease of viscosity and density). Aydin et al. (2011) showed that within the temperature range of 10 to 40°C, small variations in the system temperature can strongly influence the solubilization, mobilization and stability of the multiphase system.

DNAPL dissolution rates, into the groundwater, will by itself be increased by increasing temperatures. The daughter product solubilities (VC and cDCE) however will decrease. Temperature will also affect *sequestration* of cis-DCE and VC within DNAPL source zones (Ramsburg et al., 2010). Also the adsorption-desorption rates of organic pollutants to the soil matrix (thus their retardation in the aquifer) will be affected by variations in temperature.
In the report of Van Oostrom et al. (2011) it is stated that a temperature increase by 50°C will increase chlorinated solvent fugacity (equilibrium concentration in the gas phase at constant water phase concentration), by one order of magnitude.

An increase of groundwater temperature will generally lead to higher solubility of most minerals (e.g. calcium sulphates, silicates,…). However, for some minerals the opposite is true. E.g. calcite (Ca-carbonate) will precipitate at higher water temperatures (> 40°C). In their geochemical modelling study on the effects of varying temperatures (10–50 °C) in an aquifer system, Palmer and Cherry (1984) demonstrated that within that temperature range, significant reductions of porosity and permeability can be expected. However, **within the normal temperature range of most modern GWE-systems (8-20°C), it may be assumed that the temperature effects will have no or only a small impact on the chemistry of the groundwater**.

2.3.4 Effect of temperature on chemical and biological degradation rates of pollutants

Several recent studies can be found that study the effect of temperature on chemical or biological degradation rates. Kalimuthu et al. (2011) studied the effectiveness of biodegradation of **PCE** by *Bacillus* sp. strain JSK1 under variable pH, substrate and temperature conditions. The maximum degradation rate was observed at pH 7.5 and 30 °C.

A temperature dependent degradation rate is observed for a variety of pollutant types. For instance, Kookana et al. (2010) found that the half-life of the pesticide **atrazine** in surface soils at subtropical sites ranges from 11 to 21 days, which is 2 to 3 times faster than sites located in colder climates. Similar observations are available for **PAH's** (Viamajala et al., 2007). Biodegradation rates of PAHs are typically low at mesophilic conditions and it is believed that the kinetics of degradation are controlled by PAH solubility and mass transfer rates. Solubility tests for phenanthrene, fluorene and fluoranthene in the range of 20-60°C showed a significant increase in the equilibrium solubility concentration and of the rate of dissolution of these polycyclic aromatic hydrocarbons (PAHs) with increasing temperature. Soluble PAH's are relevant in this study, since they may be present at larger depths at creosote-impacted sites.

Chang et al. (2011) compared the rate and extents of biodegradation of other **petroleum hydrocarbons** at variable site temperatures (1–10 °C) and constant temperatures (6°C). Under the variable site temperature conditions biodegradation rate constants of semi- and non-volatile hydrocarbon fractions were enhanced by over a factor of two. Although this study involved an ex-situ pilot-scale landfarming experiment, which is not directly comparable to an in-situ (water-saturated) environment, a rate increase factor of about two agrees to the Arrhenius equation:

$$k_T = A \cdot \exp\left(\frac{E_a}{R \cdot T} \right)$$

or

$$\ln(k_T) = \frac{-E_a}{R \cdot T} + \ln(A)$$

With Ea the activation energy (mol/J), A the frequency factor (day^{-1}); k_T the first order rate (day^{-1}); T the absolute temperature (K) and R the ideal gas constant (8.314 J/mol·K). Plotting ln(kT) against 1/T should yield a straight line.

Lai and Lo (2007) not only studied the effect of temperature (in the range 10 - 23°C) on the dechlorination rates of **trichloroethylene** (TCE) and **tetrachloroethylene** (PCE) by zero-valent iron (Fe-0), but also the effect of the seepage velocity. In a series of laboratory column tests at seepage velocities ranging from 31 to 1,884 m/year at 10°C, they found that increasing the seepage velocity in that range resulted in a 7 to 9-fold increase in the normalized dechlorination rate constants of TCE and PCE, respectively. Raising the groundwater temperature from 10 to 23°C at a given seepage velocity only resulted in 2.7 and 1.1 times increases in the degradation rates of TCE and PCE.

In situ chemical oxidation (ISCO), e.g. using persulfate ($S_2O_8^{2-}$) requires activation, so rates will increase with temperature. Waldemer et al. (2007) determined the kinetics and products of chlorinated ethene oxidation with heat-activated persulfate and compared them to the temperature dependence of other degradation pathways. The kinetics of chlorinated ethene disappearance were pseudo-first-order for 1-2 half-lives, and the resulting rate constants-measured from 30 to 70°C fitted the Arrhenius equation. This temperature range is however higher than the normal temperature range for GWE-systems.

Another common groundwater pollutant, that may be relevant within this study, is **MTBE** (and its degradation product TBA). Greenwood et al. (2007) demonstrate that the optimal biodegradation temperature ranges from 15°C to 30°C, while becoming ineffective at 0°C. First order mineralization rate constants of TBA at 5°C, 15°C and 25°C were 2.86 ± 0.05, 3.31 ± 0.03, 5.60 ± 0.14 y-1, respectively. Temperature had a statistically significant effect on the mineralization rates and was modelled using the Arrhenius equation with frequency factor (A) and activation energy (Ea) of 154 day^{-1} and 23,006 mol/J, respectively.

Fletcher et al. (2011) measured anaerobic dechlorination rates of PCE to ethane in laboratory experiments in relation to varying temperatures. The PCE-dechlorinating consortia produced ethene when incubated at temperatures of 30°C, but vinyl chloride (VC) accumulated when cultures were incubated at larger temperatures, i.e. 35° or 40°C. Cultures incubated at 40°C for less than 49 days resumed VC dechlorination following cooling; however, incubation at 45°C resulted in complete loss of dechlorination activity. In general, such elevated temperatures will however not be reached in modern GWE-systems.

2.3.5 Design guidelines for GWE-systems in relation to groundwater quality

Proper design of GWE-systems implies consideration on specific aspects of groundwater quality in order to avoid negative aspects like precipitation of undesired substances, clogging or well cracks and soil bursts.

With regard to groundwater quality, mainly three aspects (in correspondence and addition with chapter 2.3.2) are of major importance :

- Redox barrier
- Fresh / salt water interface
- Gas content

The redox barrier is mainly important for phreatic groundwater layers, thus of great importance in relation to this study. The redox barrier is the borderline between oxygenated or nitrate containing and ferriferous groundwater. When oxygenated (or nitrate containing) and ferriferous groundwater are intensively mixed, iron oxide will be formed. At GWE-systems mixing can occur in case that groundwater filters are located in the different types of groundwater or if the redox barrier is pulled down into the filter element. Flocculation of iron oxide can occur which can result in a well blockage. In order to avoid this negative effect, the filter element should be located entirely in an environment of homogeneous water quality, at sufficient distance of the redox barrier. In practice, the filter elements are typically located as deep as possible in one specific groundwater layer.

The fresh / salt water interface can be present in a phreatic as well as a confined groundwater layer. It means that groundwater quality (concerning chloride content) switches from fresh over brackish to even salt water. Salinisation is of course a typical problem near the Belgian coast line, as specified in the geographical suitability analysis.

Knowledge on the gas content of groundwater is of importance in relation to the pressure handling in the groundwater circuit. The pressure ought to be high enough to keep gases dissolved in solution at groundwater transport through the groundwater circuit at all times. If pressure becomes too low, degassing can occur. Infiltration of degassed groundwater will clog the source filter immediately.

Every GWE-system design implies the execution of a groundwater analysis in order to define the correct boundary conditions (ion balance, chloride content, gas content, redox potential, PH, conductivity, …). In addition, geo(hydro)logical characteristics are analysed : sediment depth analysis, sediment grain size, temperature, porosity, permeability, heat capacity, dispersion coefficient, natural groundwater flow, neighbouring extractions,…

All this data is used in a simulation tool in order to calculate all geohydrological influences (temperature, hydraulic head, flow changes, thermal and hydrological radius, soil settlements,…) based on the energy profile of the specific application, as described in several reports : KIWA (2000), Driscoll, F.G. (1989), Kobus et al, (1976), Olsthoorn, T.N. (1982). Based on maximum flow rate, load duration curve, aquifer thickness and clogging potential the velocity on the borehole wall can be calculated as one of the mayor design parameters. Afterwards, the main design parameters of a GWE-system can be fixed :

- well orientation;
- minimum well distance;
- well diameter;
- filter location and length;
- minimum circuit pressure;
- injection pressure;
- drilling technology;

Specific guidelines in relation to this matter is available in “NVOE Richtlijnen Ondergrondse Energieopslag, nov 2006”. A more broad requirements list concerning general GWE-system quality, design demands, assessments and checklists was drawn up by KIWA (KC 114, 2005).

IF Technology et al. (2006) described more in detail the theoretics of particles clogging, specific design guidelines, operation and monitoring instructions and well regeneration. The report offers a very good resume on more than 25 studies on the matter (e.g. K. van Beek et al (2005), M. Juhazs Holterman et al (2004), J. Prins (2003), B.R. de Zwart et al (2005)).This work resulted in an overview of 37 guidelines on design, monitoring and regeneration issues.

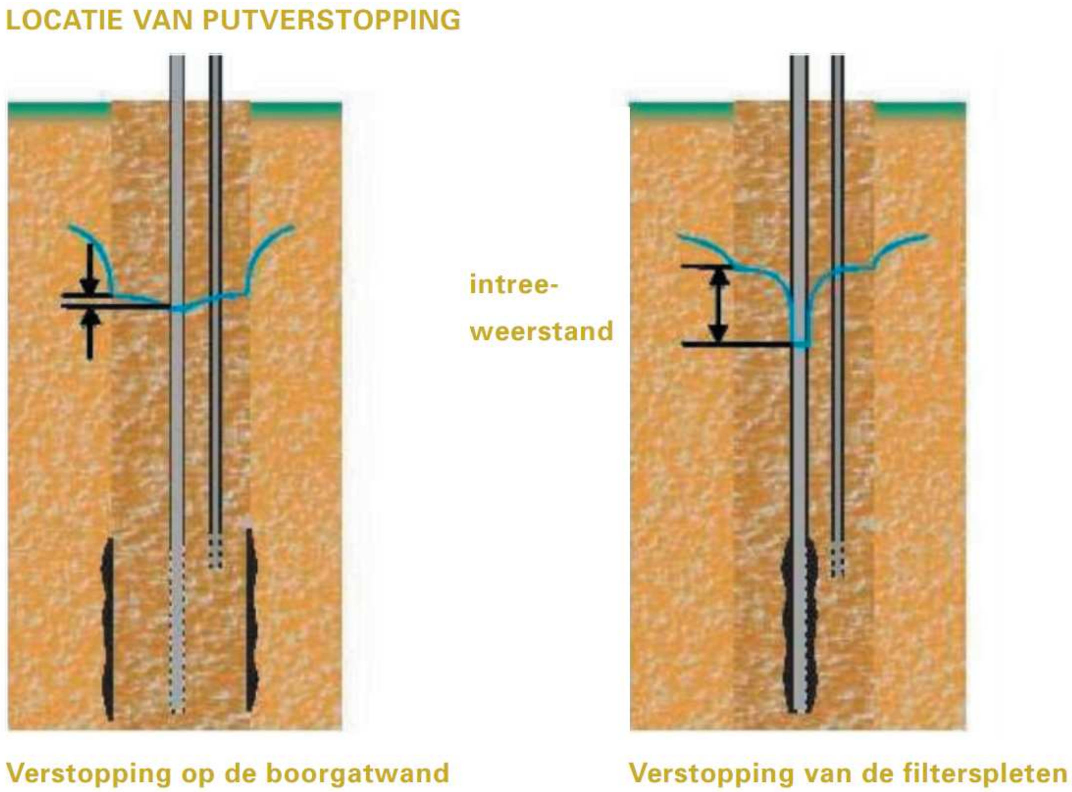


Figure 15. *Typical clogging phenomena and locations in groundwater pumping wells*

A specific situation occurs when ‘normal’ groundwater quality is influenced by pollution. Pollutions can be mobile (e.g. chlorinated hydrocarbons) or immobile (e.g. heavy metals). Especially, the mobile pollutions can be spread widely (as well as in distance as in depth). In relation to GWE-systems, pollutions in a radius of 250 to 300 meter need to be analysed. For very mobile pollutions, this range should be extended up to 500 to 1000 meter.

Chemical or biological well clogging is on the other hand a relevant issue when GWE-systems and sanitation are combined. These processes and how to evaluate and prevent them are not ‘unique’ or ‘more pronounced’ for a combined GWE-remediation system than for a ‘regular’ remediation system (without GWE).

Biologically-induced clogging can occur in aquifer systems after injection of organic substrates (e.g. to induce anaerobic bioremediation of chlorinated solvents; OVAM, 2007). In specific cases (groundwater rich in sulphate and iron), excessive precipitation of iron sulfides can occur. This should be accounted for in the design of the system (pilot feasibility tests and modeling of the radius of influence). The zone of influence of the injected substrate should be such that it does not cause extra clogging problems in the GWE wells and system.

Another potential remediation technology that may likely be well-combinable with GWE is zero-valent iron, e.g. as a reactive barrier located in-between GWE wells. This is further illustrated in the theoretical modeling example described hereafter. The installation of such barriers may however also lead to chemical clogging and changes in pH of the groundwater downstream of such barriers (see: OVAM, 2005).

2.3.6 Conclusions on literature

Although specific literature on the combination of GWE and groundwater remediation seems to be very scarce, relatively many studies are available on the effects of temperature on the physical, chemical and biological behaviour of pollutants in subsurface environments. In the relevant temperature interval for the current study, biological and geochemical reaction rates will however only slightly be affected. Especially the groundwater flushing and mixing effect caused by the GWE-system will be relevant in the context of remediation.

When combining energy production with sanitation, the design of GWE-systems can be made according to the classical guidelines and calculation methods. An adapted design might be necessary according to the more complex content of the groundwater, but basic principles stay the same with some extra attention to e.g. well clogging. Yet, more detailed and complex simulation activities with specialized tools are necessary in order to analyse the impact of the GWE-system on the pollution, concerning the exact groundwater transport pattern and the complex reaction with the contaminants. Furthermore, a thorough follow-up of the system is required with more observation wells and an intensified monitoring.

2.4 Modelling of GWE-systems and groundwater remediation

2.4.1 Introduction

The above-mentioned Dutch studies (Verburg et al. (2010) and Van Oostrom et al. (2011) do not include a thorough discussion on the modelling requirements in the design of a GWE-system. Either or not combined with groundwater remediation, for each individual application, the development of a mathematical model is essential to be able to predict all aspects and implications of the system in the long run (both physical, chemical and biological). Only a holistic modelling approach will be able to evaluate the overall effect of the GWE-system, because of the high complexity of the system.

The model should be able to give a reliable insight into:
i) the natural groundwater flow and the forced flow created by the abstraction and reinjection of groundwater;
ii) the transport of dissolved pollutants in the complex flow field;
iii) chemical and biological degradation processes, increased by increased temperatures and flow rates (mixing effect).

Thermal effects and thermal zone of influence, including changes in density resulting from it, are also relevant for the design of GWE-systems. The effect of changing temperatures on remediation is however limited (for the type of GWE-systems described here), as described earlier.

We evaluated the **FeFlow 6.1 modelling software** (Diersch H-JG, 2009). This code uses a finite element approach to simultaneously calculate the overall behaviour of the GWE and groundwater system: groundwater flow, heat flow, mass transport of dissolved contaminants including chemical and biological transformations in the subsoil.

An extensive number of relevant information about this modelling tool can be found on the following website: http://www.feflow.info/manuals.html.

In "White papers – Vol.4", a complete example is included on the sequential and non-sequential degradation of chlorinated solvents under variable aerobic-anaerobic conditions (paragraph 1.9; page 49 and further).

In the next paragraph, a practical example of a realistic GWE system is elaborated in FeFlow 6.1, in which several potential remediation scenarios are included, assuming that the location is contaminated with perchloroethylene (PCE), e.g. as a result of former drycleaning activities.

Other modelling tools, such as the more extensively used Modflow and its reactive transport modules, are also applicable but recent versions do not allow temperature gradients to be modelled.

2.4.2 Application to a hypothetical site contaminated by chlorinated solvents

The GWE system is installed in the Campine region (phreatic Diest aquifer with average hydraulic conductivity of K = 6 m/d). The total aquifer thickness is 30 m with an average effective porosity of 0.25. Hydraulic gradient: 1‰ (1m per km), from West to East.

A pollution source zone is assumed to be present in the aquifer, containing PCE-NAPL (residual) in a cylindrical soil volume with radius of 4 m. The upper part (0-8 m below groundwater level) is assumed to contain a residual NAPL volume of 0.1% of the total pore volume. The lower 2 m of the contamination zone contains a higher residual NAPL concentration (sinking layer): 0.5% of the total pore volume. In summary, a total pollutant mass (PCE) is assumed of 164 kg of residual PCE in the upper part of the aquifer and 205 kg of sinking layer PCE in the lowest part of the aquifer.

Simulation scenarios

1. *Reference scenario*: groundwater pollution evolution (simulation time: 50 years) without any actions (GWE nor remediation);
2. *GWE with hydraulic containment scenario*: installation of a unidirectional doublet system with following characteristics:
    - Two pumping wells with depths of 30 m and screen length 10 m (installed between 20 – 30m bgl); the distance between these two wells is 50 m.
    - The downstream well (eastern well) is operated as pumping well; the upstream well (western well) as reinjection well;
    - Flow rate of the pumping well: 15 m^3/h (30,000 m^3/year);
    - Operation: 50% of total duration in heating-mode and the other half of the time in cooling-mode. The total temperature difference dT = 5K;

    The first 20 years of the simulation are identical to the reference scenario (GWE-system inactive); the next 30 years the GWE system is active. In order to obtain hydraulic containment, not the full pumped volume is reinjected into the reinjection well, but only 90% (27,000 m^3/year). The volume difference is assumed to be purified on-site and disposed off (e.g. in sewer or surface water). Reinjection of purified (aerated!) water is not considered, to avoid additional clogging risks.

3. *Unidirectional GWE with in-situ reactive zone scenario.* This includes a doublet system installed with following characteristics:
    - 2 wells with lengths of 30m and screen length 10m, installed between 20 and 30m bgl. The distance between both wells is 50 m.
    - The flow rate is 15 m^3/h (30,000 m^3/year) and is operated in 50% heating and 50% cooling-mode with dT = 5K;
    - A reactive wall with chemical or biological reduction potential for chlorinated ethenes is assumed to be present in the plume zone at the start of the full modelling period of 50 years;
    - The first 20 years of the modelling period the GWE is inactive; after 20 years the system is switched on and remains active until the end of the modeling period.
    - The downstream well (in the pollution plume) is being operated as extraction well and reinjection of the same volume (without purification) occurs in the upstream well;
4. *Bidirectional GWE without hydraulic containment.* The doublet system that will be simulated has the following characteristics:
    - 2 wells with depths of 30 m bgl and filter length of 10m (installed between 20 – 30m bgl) and a distance between wells of 50 m;
    - The flow rate is 15 m^3/h (30,000 m^3/year) in 50% heating and 50% cooling-mode with dT = 5K;
    - Pumping of 15,000 m^3/year; 50% of the time from the warm to the cold well and the other 50% of the time from the cold to the warm well;
    - The pollution source is present in the centre between the wells;
    - Total simulation time is 50 years; the GWE system is activated after 20 years.

More information (location of wells, reactive zone etc.) is given in the following paragraphs and figures.

The modelled scenarios are purely hypothetical examples of potentially relevant combinations of groundwater remediation and “ordinary” GWE systems operated in PCE-polluted areas. In later work, a real field pilot should be executed and carefully monitored. These monitoring results can then be used to evaluate and calibrate the modelling results.

2.4.3 Modelling results

(a) Reference scenario

Figure 16 shows the model area (2000 x 2000m), hydraulic heads and grid cells. A PCE source was incorporated into the model as described above. Standard degradation kinetics (consecutive dehalogenation through halorespiration in the sequence PCE → TCE → DCE → VC → ethene) were applied, as described in the FeFlow White papers – Vol.4 (paragraph 1.9; page 49). Further details on the input parameters are given in Table 3.

Table 3. *Overview of additional input parameters*

Longitudinal dispersivity	Transversal dispersivity	Total porosity	Effective porosity		Sorption coefficient	Decay rate Reference scenario	Decay rate Reactive zone(*)
(m)	(m)	(-)	(-)		(-)	(s^{-1})	(s^{-1})
5	0.5	0.3	0.25	**PCE**	7,8	3,47E-07	3,47E-07
				TCE	0,82	1,04E-06	1,00E-04
				DCE	0,424	1,04E-07	1,00E-05
				VC	0,13	0,00E+00	5,00E-06
				ETHENE	0	0,00E+00	0,00E+00

(*) reactive zone as defined in scenario 3

In the reference scenario (input parameters as described), the model predicts a pollution situation (50 years after introduction of the PCE NAPL) as depicted in figure 17.

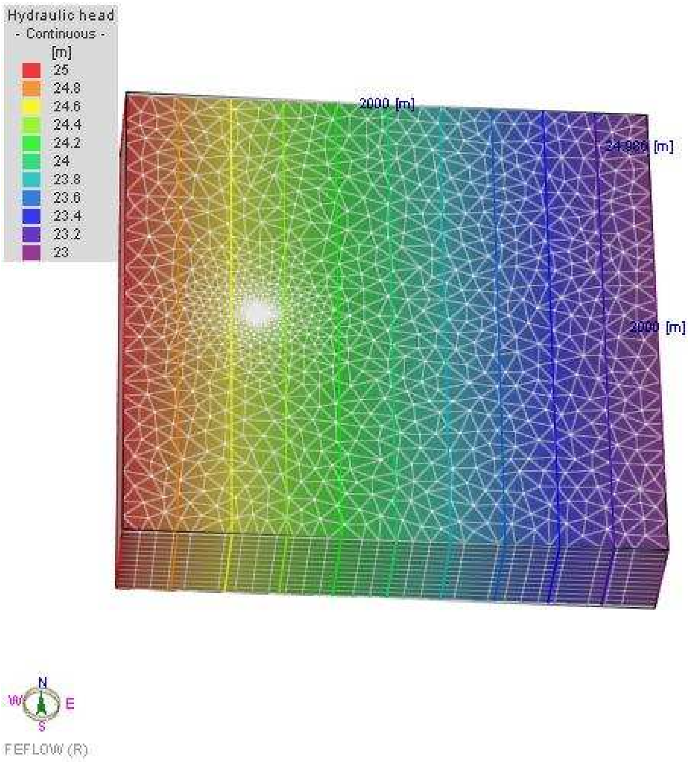


Figure 16. *Model area with natural hydraulic head conditions (reference scenario without operational GWE system)*

Figures 18-20 show the degradation product plumes after the specified simulation time (overall depth). With the set of input parameters used, mostly VC, being the most mobile of the chlorinated ethenes, formed a large contaminant plume (anaerobic conditions with natural dechlorination stopping largely at VC). Figure 21 shows vertical sections of the pollutant plumes of PCE, TCE, DCE and VC in the reference scenario after 50 years (no action).

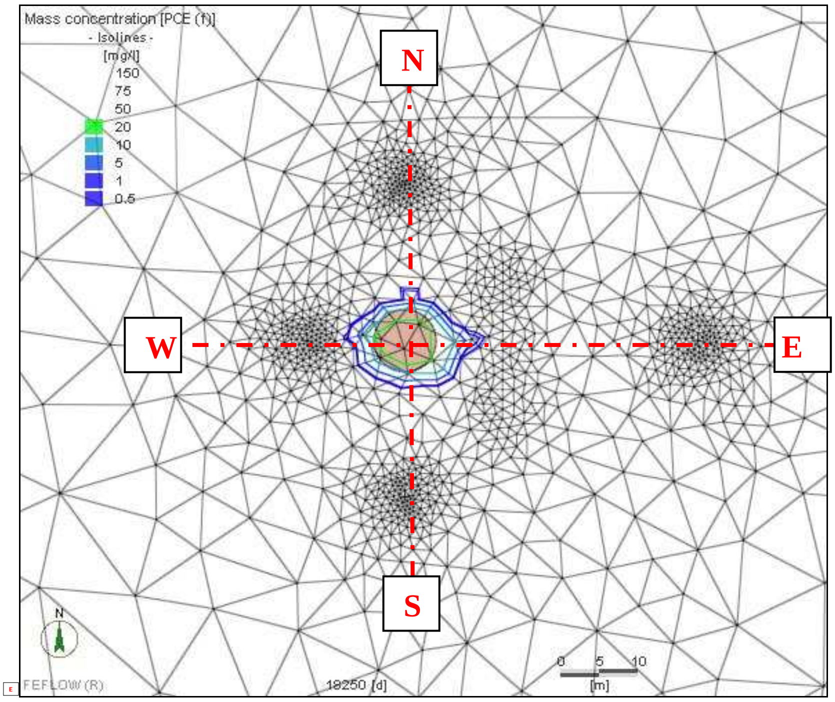


Figure 17. *Model area (zoomed, top-view) with PCE contamination source area (orange circle) and groundwater PCE concentration contours after 50 years (reference scenario: no action)*

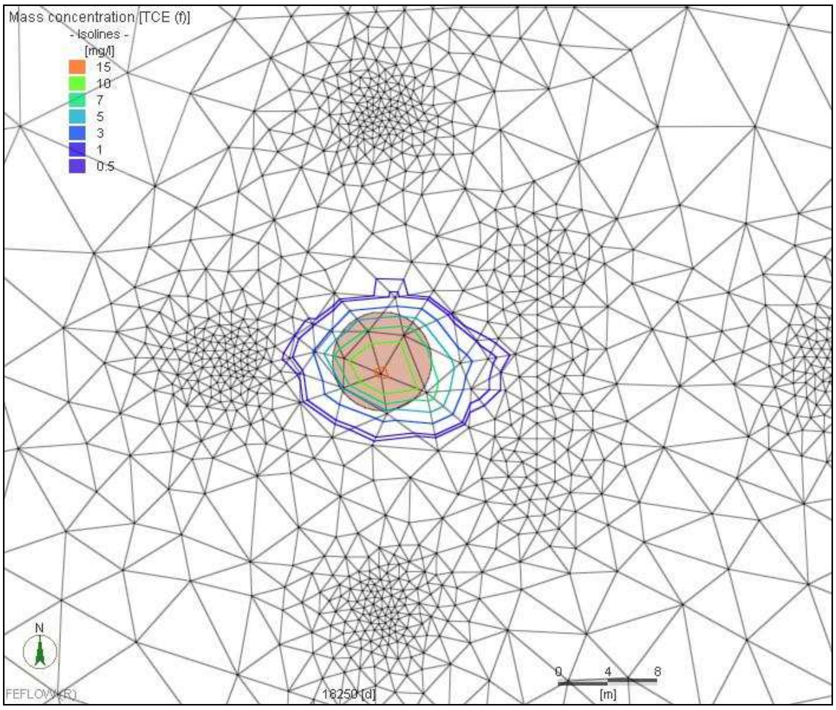


Figure 18. *Model area (zoomed, top-view) with PCE degradation product TCE concentration contours after 50 years (reference scenario)*

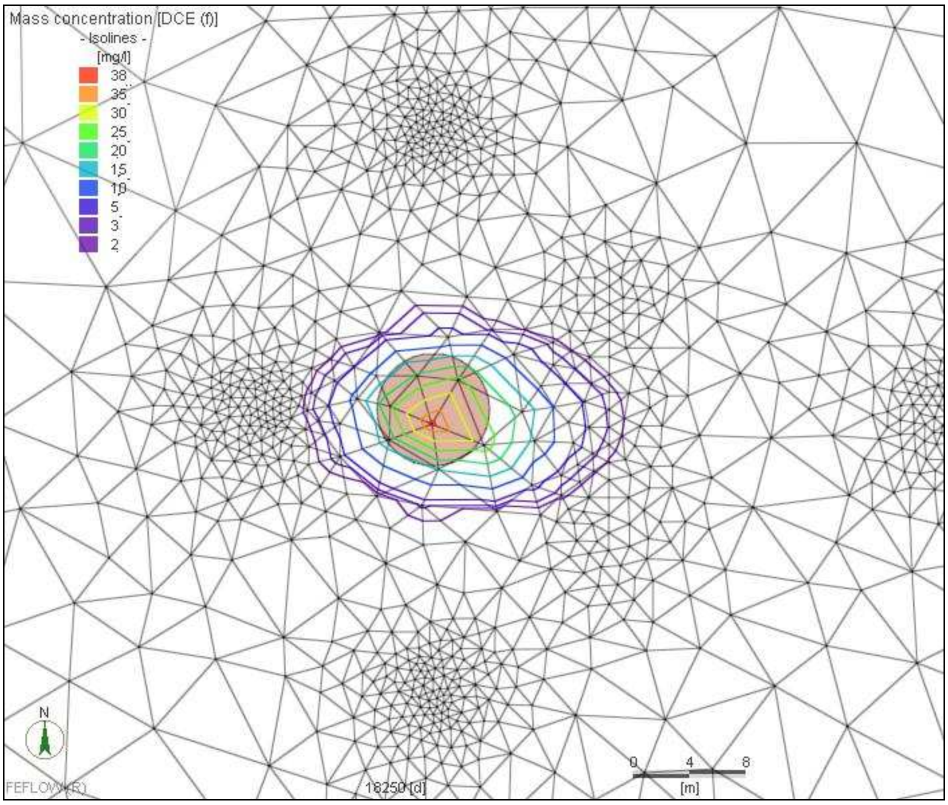


Figure 19. *Model area (zoomed, top-view) with PCE degradation product DCE concentration contours after 50 years (reference scenario)*

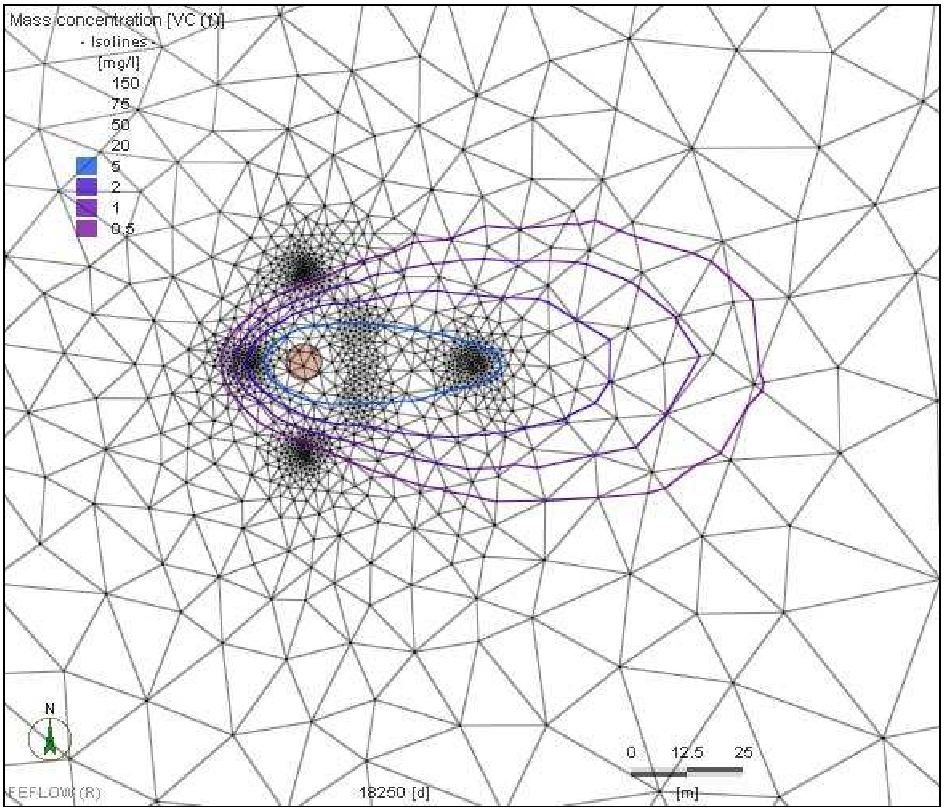


Figure 20. *Model area (zoomed, top-view) with PCE degradation product VC concentration contours after 50 years (reference scenario)*

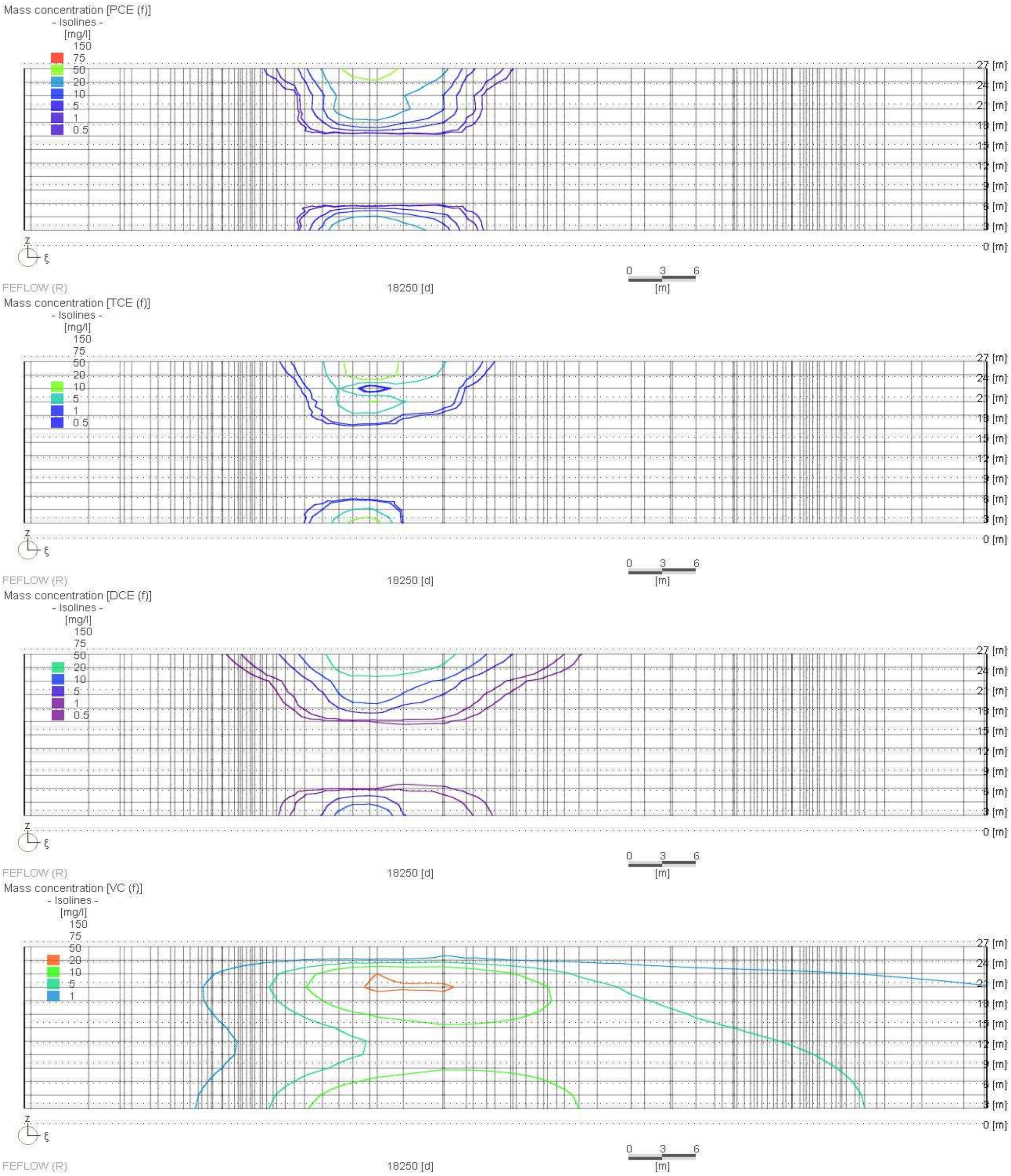


Figure 21. *West-East cross sections (as indicated in fig. 17) of the PCE and daughter products TCE, DCE and VC groundwater concentrations (reference scenario: no action; situation after 50 years). 0m: bottom of the aquifer; 27 m: top of the aquifer (= groundwater level).*

(b) GWE with hydraulic containment scenario

The GWE system has a substantial influence on the hydraulic heads in the model area. Figure 22 shows the groundwater flow pattern (situation at the end of the simulation period; backward path lines. In a backward analysis the pathway is calculated in reversed order, i.e. starting from the endpoint (e.g. a well) to the origin, along a flowline).

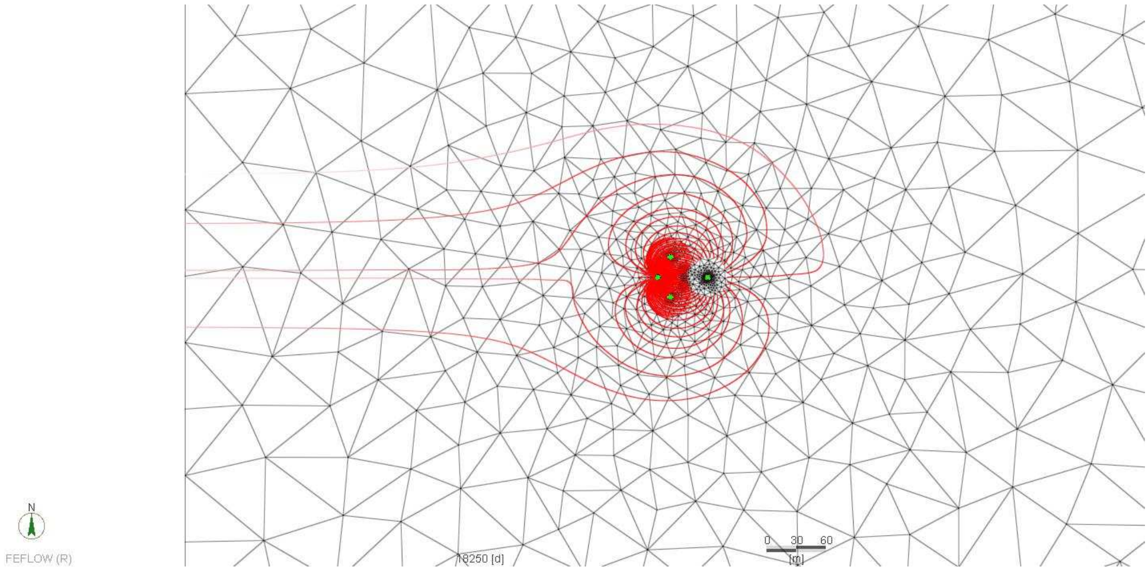


Figure 22. *Groundwater pathlines at the end of the simulation period (50 years). A significant 'back-flow' is observed due to the reinjection (opposite to the natural groundwater flow direction)*

The model predicts a final temperature distribution (after 30 years of operation of the GWE system) in the aquifer as shown in figure 23. The temperature is lowest near the reinjection well. The overall temperature difference is however limited (< 10°C).

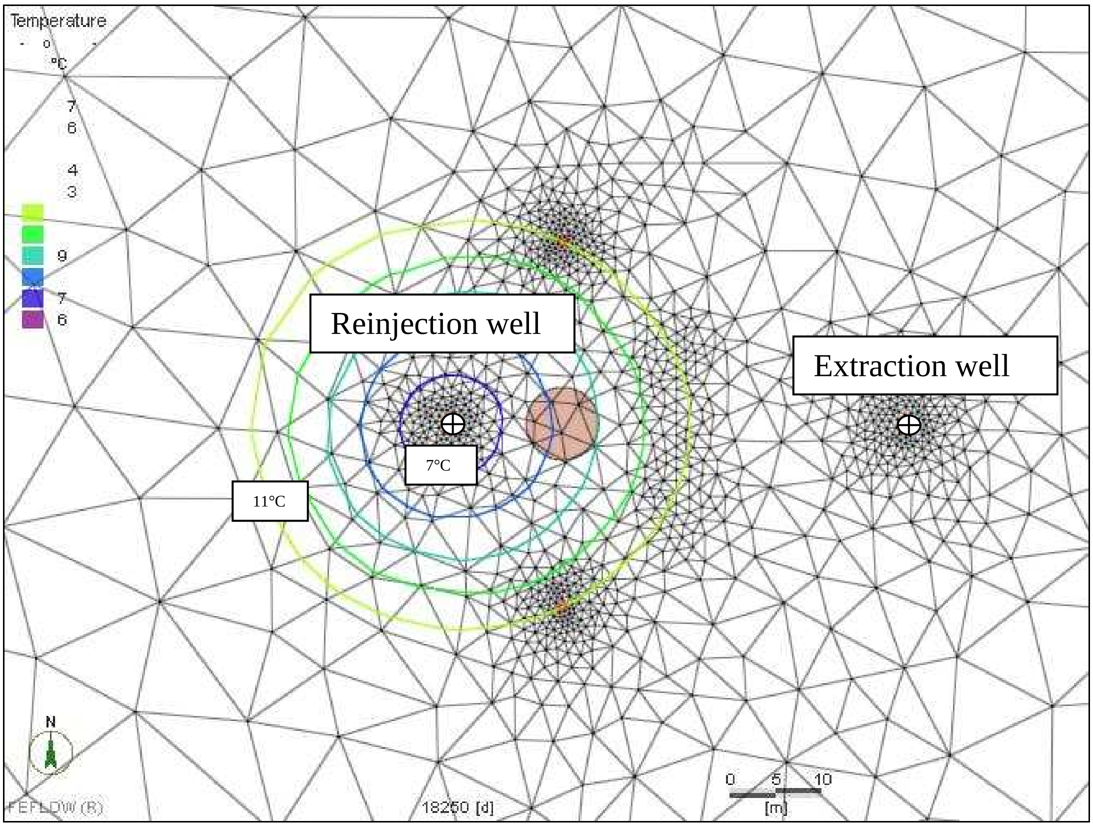


Figure 23. *Temperature isolines of the groundwater at the end of the total simulation time (50 years) – GWE with groundwater containment*

The modelled pollutant migration in the West-East transect through the GWE-wells (cross sections) is shown in figures 24-27.

PCE migration in the groundwater is rather limited, owing to its higher sorption characteristics and its conversion to TCE. The same holds for TCE. The modelled migration for DCE is more pronounced, due to its lower sorption characteristics. VC is the most mobile component, and – more importantly – in the current scenario it is assumed to be recalcitrant (not further degraded). This leads to a worst-case migration result (figure 27).

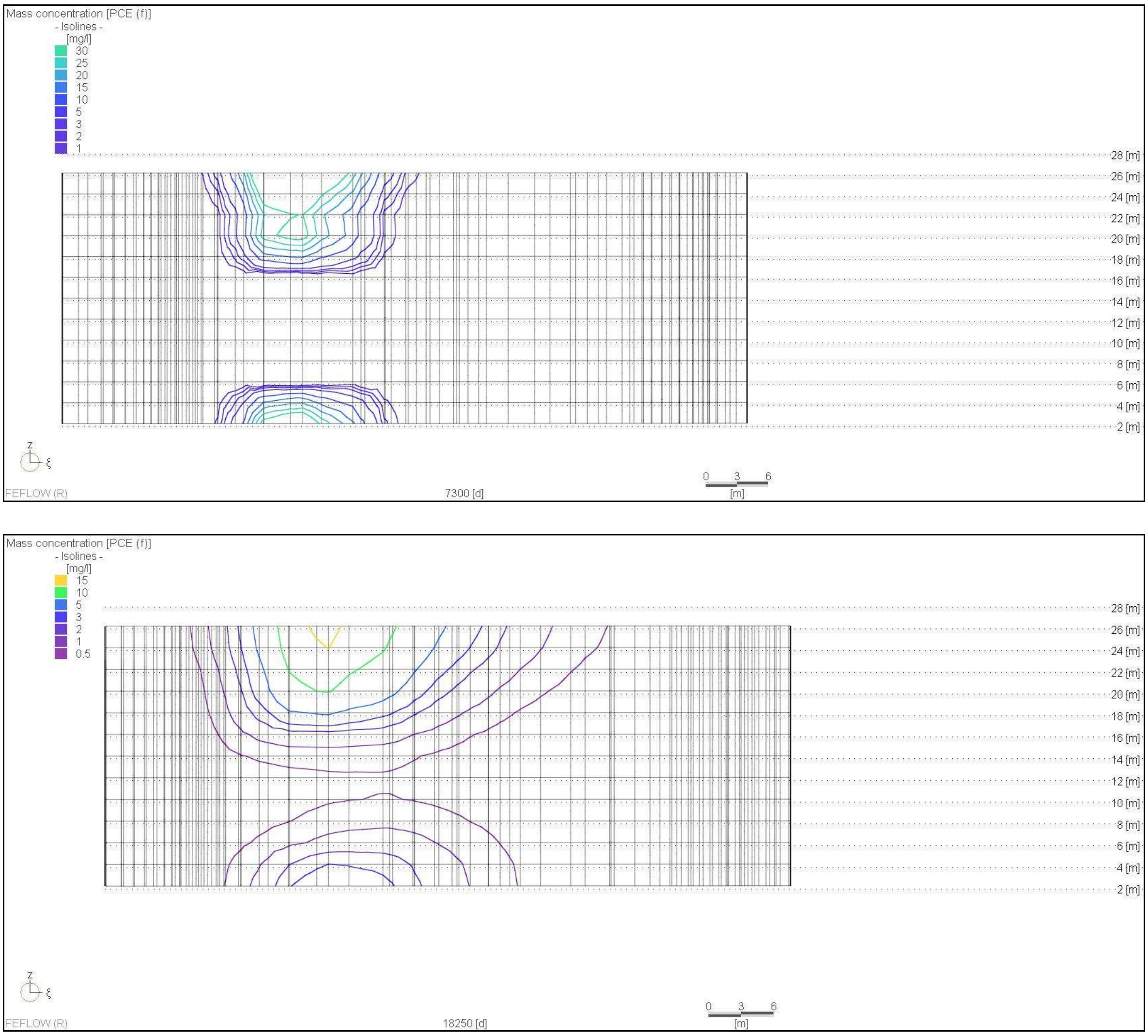
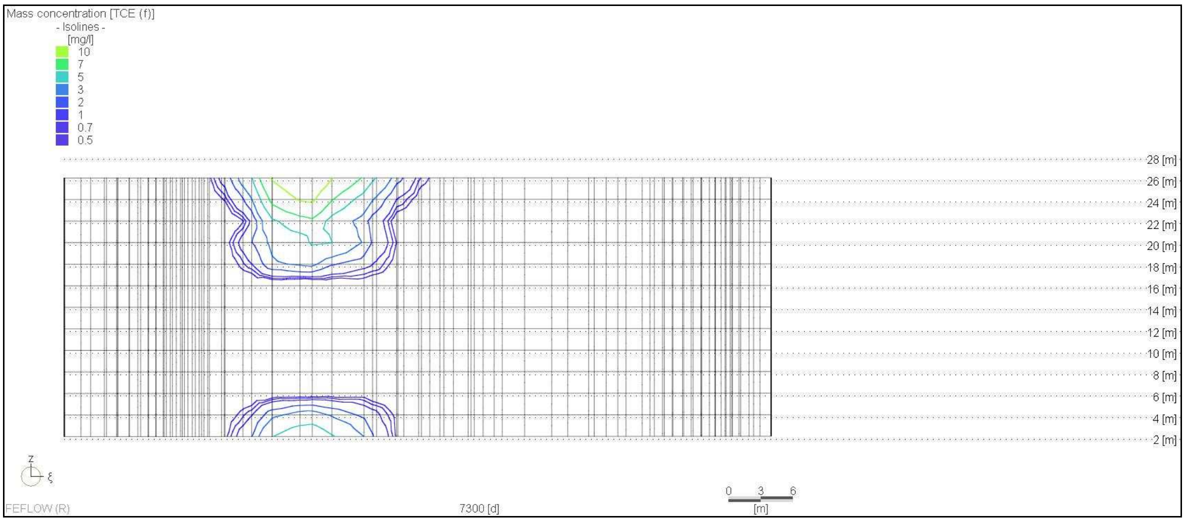


Figure 24. *West-East cross-sectional view of PCE groundwater concentration isolines at the start of the GWE-system (top) and at the end of the simulation period (50 years) (below) – GWE with groundwater containment*



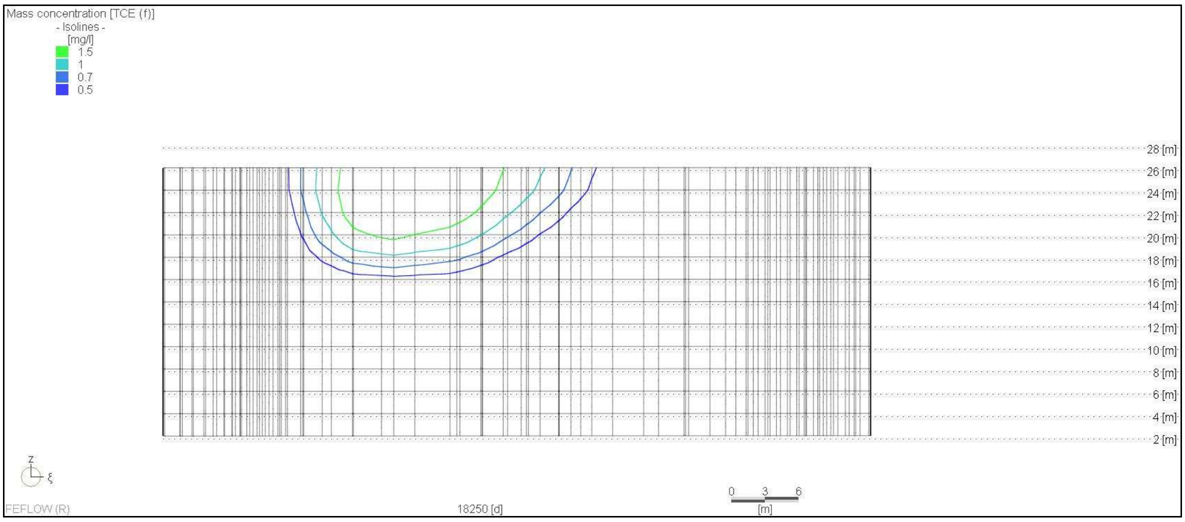


Figure 25. *West-East cross-sectional view of TCE groundwater concentration isolines at the start of the GWE-system (top) and at the end of the simulation period (50 years) (below) – GWE with groundwater containment*

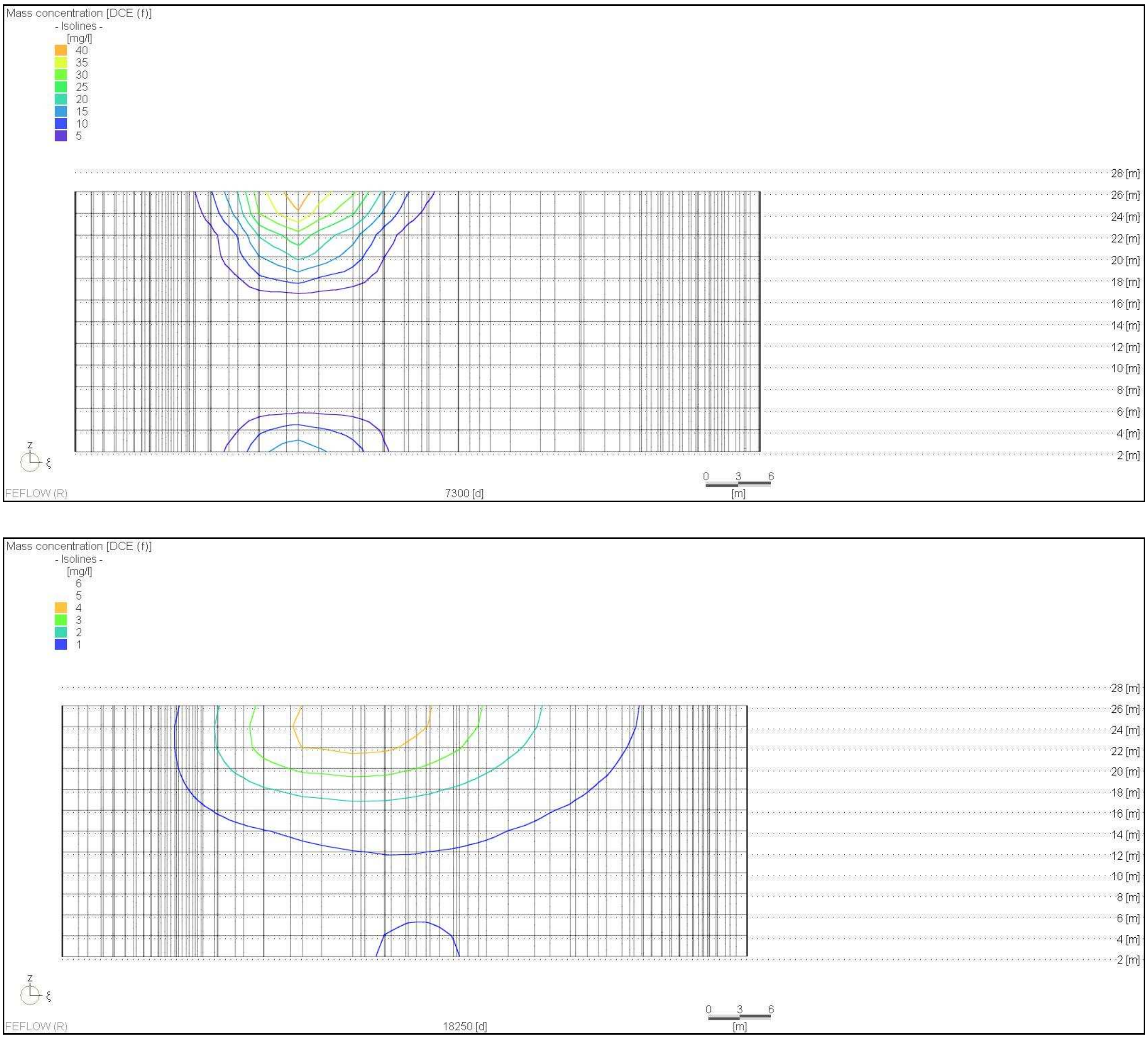
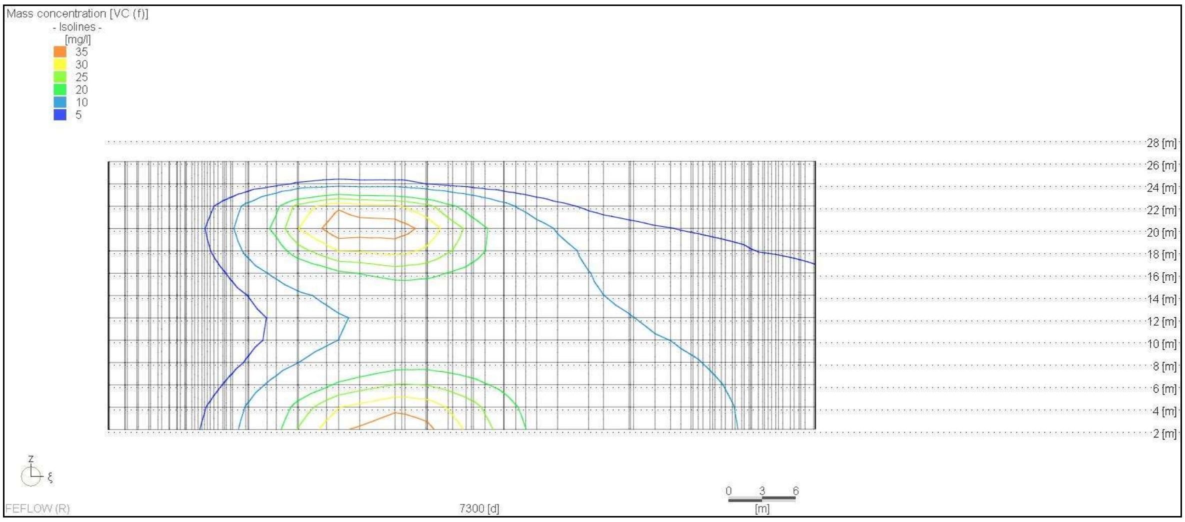


Figure 26. *West-East cross-sectional view of DCE groundwater concentration isolines at the start of the GWE-system (top) and at the end of the simulation period (50 years) (below) – GWE with groundwater containment*



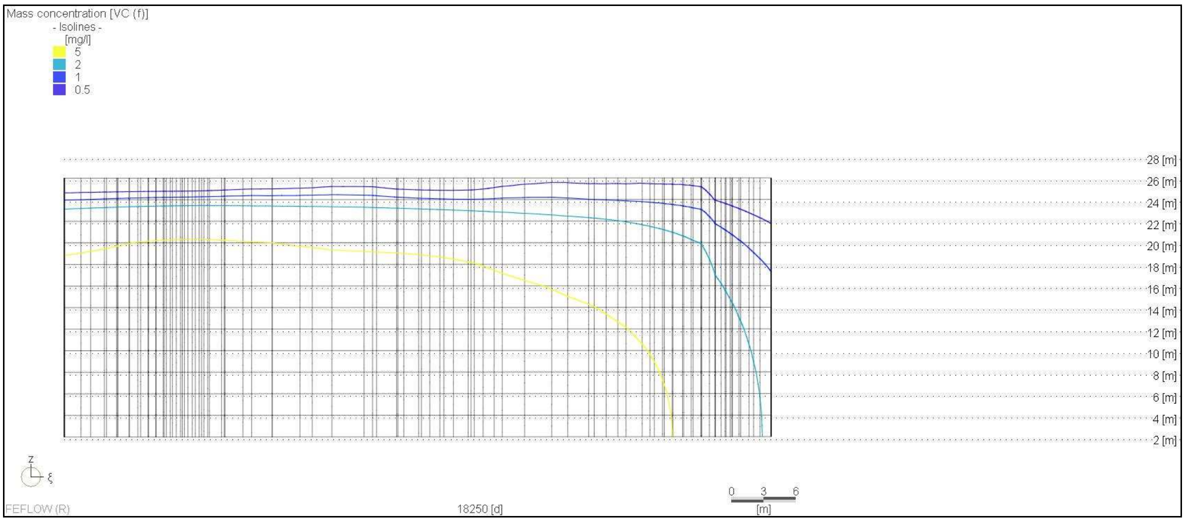


Figure 27. *West-East cross-sectional view of VC groundwater concentration isolines at the start of the GWE-system (top) and at the end of the simulation period (50 years) (below) – GWE with groundwater containment*

Scenario conclusions:

1. Even though only 90% of the pumped volume in the GWE system is reinjected in the injection well, instead of 100%, the system causes undesired migration of the pollution in westerly direction (opposite to the natural groundwater flow). This is especially the case for the more mobile daughter compounds DCE and vinyl chloride.
2. The system does however – according to the model - provide adequate hydraulic containment in easterly direction.
3. The simulated large spreading of VC in this scenario is –obviously – also mainly attributable to the assumed zero degradation rate of vinyl chloride. The “real” degradation rate is site-specific and should be measured in the field and/or in lab-scale tests.
4. The highest groundwater flow rates are created in the lowest 10 m of the aquifer (because the GWE-well system is screened at this depth. The increased groundwater flow lead to lower daughter compound concentrations at that depth as compared to the concentrations near the groundwater table.

(c) Unidirectional GWE with in-situ reactive zone scenario

Figure 28 shows the location of the model-reactive zone (the orange circle represents the PCE-source zone). In this example, the reactive barrier consists of zero-valent iron that can chemically reduce chlorinated ethenes to ethyn, ethene and/or ethane. As described earlier,

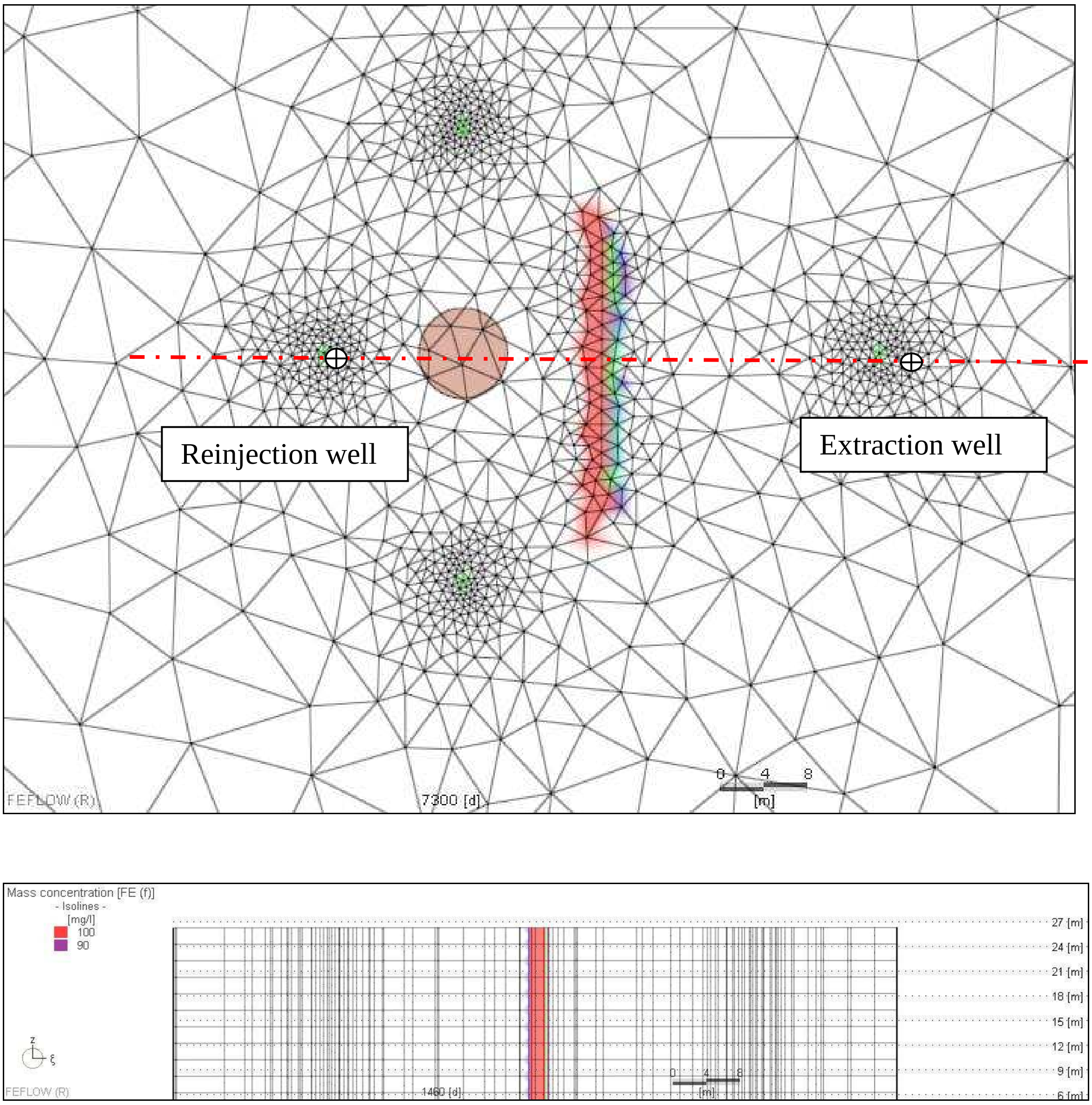


Figure 28. *Location (in red) of the assumed reactive barrier between the unidirectional GWE-wells. Model cells for which the increased CAH-degradation rates were defined are indicated in red. The PCE-source area is the orange circle. Above: top-view; below: cross-sectional view in West-East direction.*

The high pumping rates of the GWE-system obviously produce similar hydraulic effects (fig. 29) as in the previous scenario (since the pumping rates are similar). The same holds for the temperature effects (results not shown).

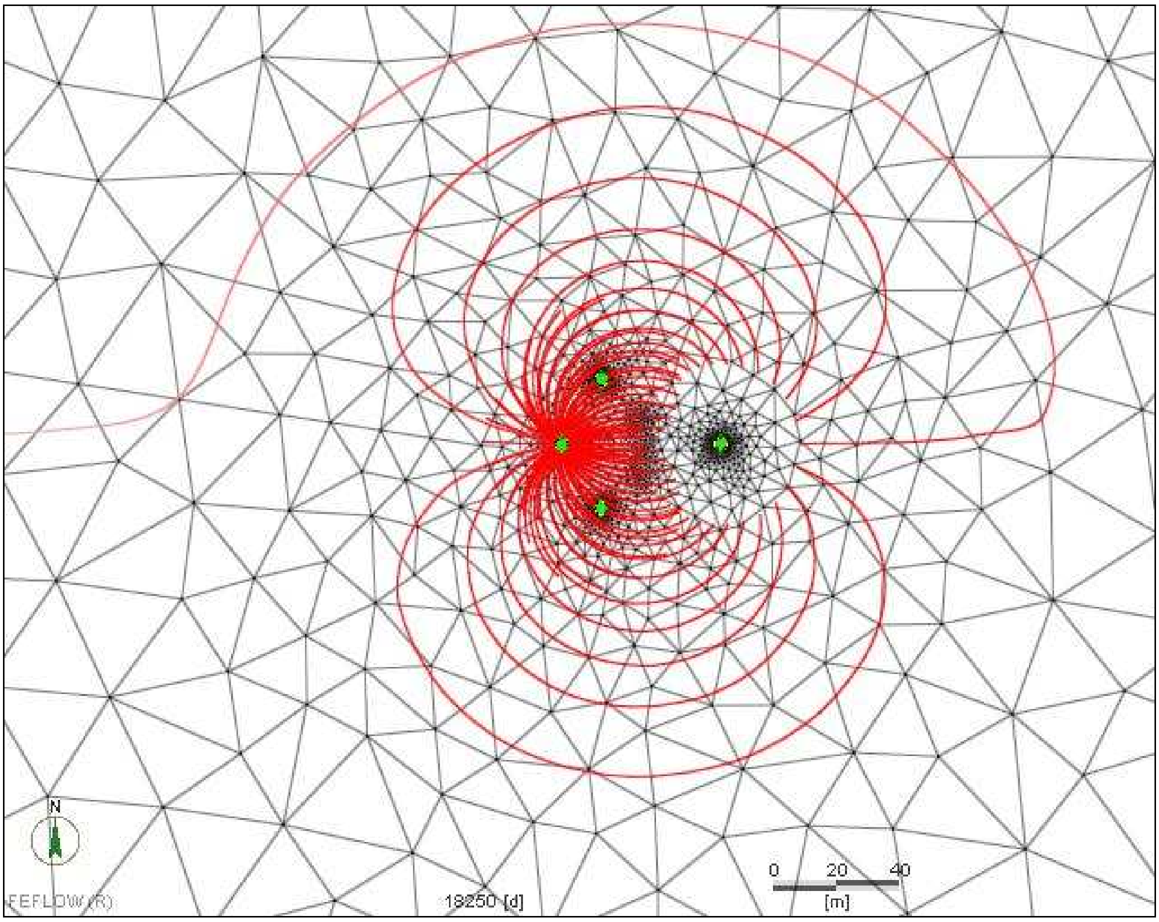


Figure 29. *Groundwater pathline pattern at the end of the simulation period (50 years).*

The modeling results (top-view and W-E cross sections on the hypothetical line through the GWE-pumping wells) for the expected migration of PCE dechlorination products DCE and VC are shown in figures 30 and 31. Results for PCE and TCE are not shown (they are approximately equal to the observed migration in the 10%-P&T scenario).

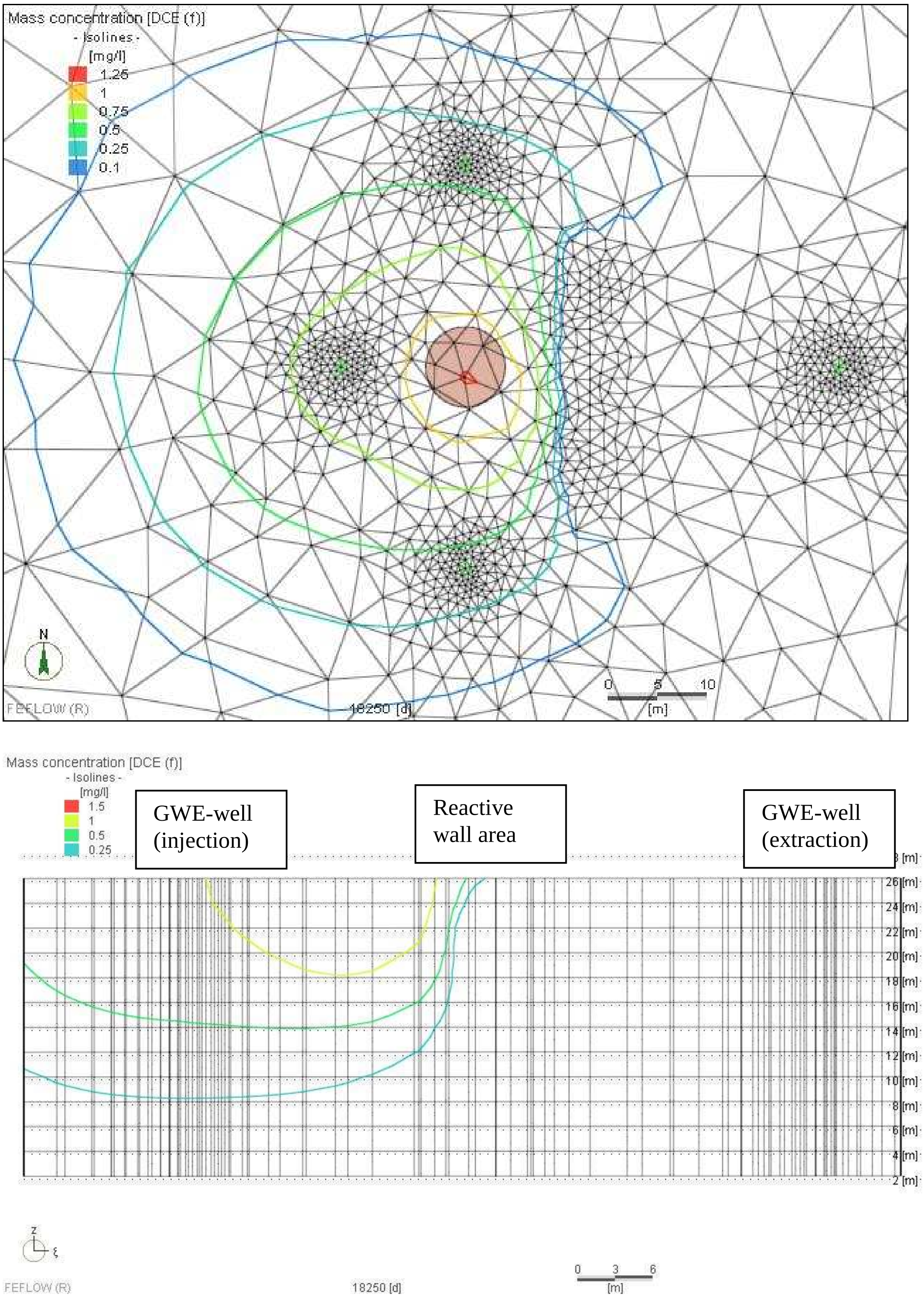


Figure 30. *Top view (above) and West-East cross-sectional view (below) of simulated DCE groundwater concentration isolines at the end of the simulation period (50 years) – Reactive wall scenario.*

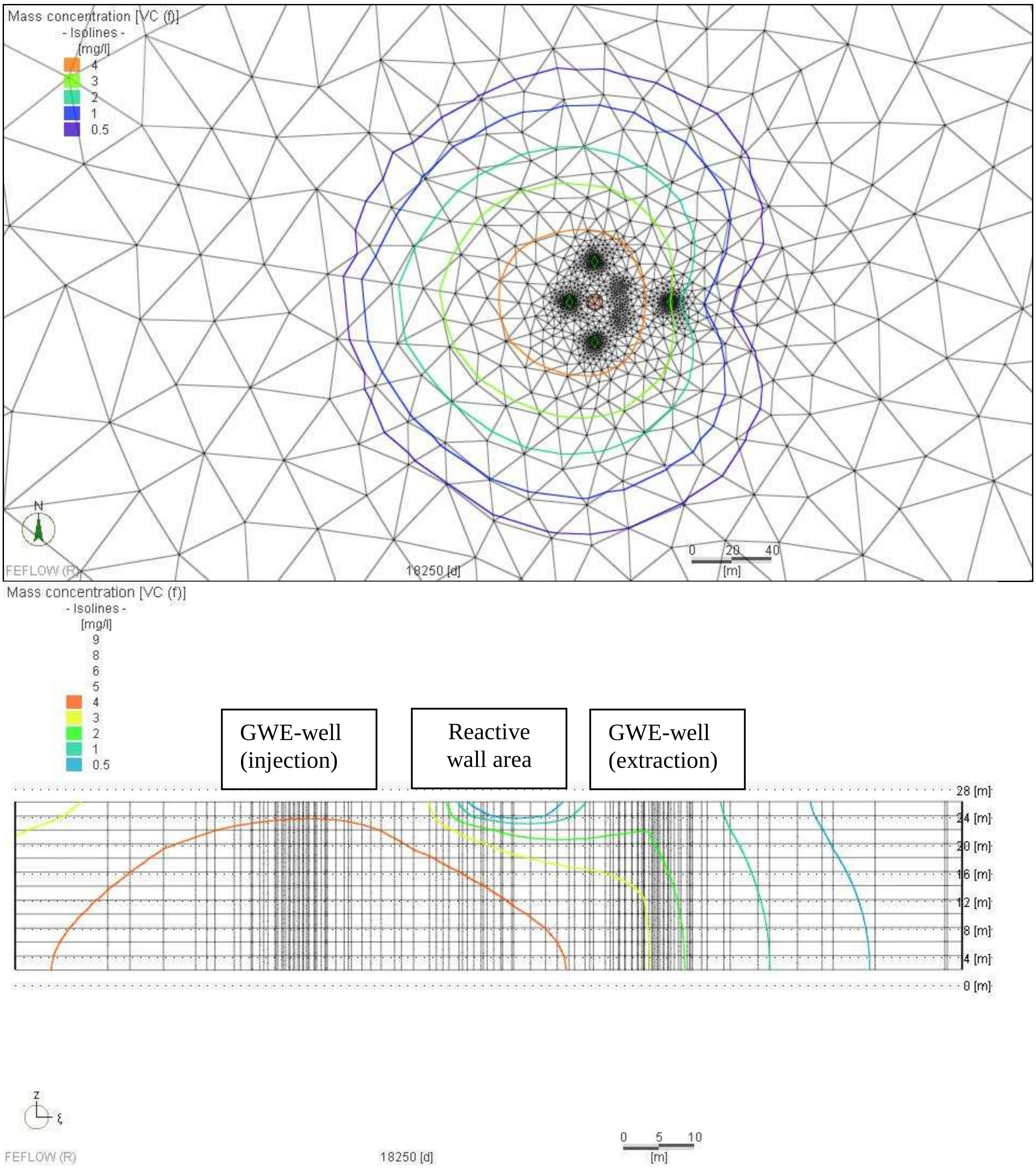


Figure 31. *Top view (above) and West-East cross-sectional view (below) of simulated VC groundwater concentration isolines at the end of the simulation period (50 years)*– Reactive wall scenario.

Scenario (reactive wall) conclusions:

1. Under the defined conditions, the reactive wall has a remedial effect on the pollution concentrations but the pumping/recirculation effect was more important, especially in the lower part of the aquifer (where GWE-screens are installed). The reinjection caused an undesired migration of the pollution in western direction (opposite to the natural groundwater flow), as was also the case in the 10% P&T scenario.
2. Especially for VC the model predicts extensive spreading, notwithstanding the defined degradation kinetics in the subsurface reactive wall area. The model predictions are highly dependent of the defined degradation kinetics. Since this modelling exercise is kept purely hypothetical, no further calibration to ‘real’ field measurements can be performed. Later pilot studies are necessary to calibrate model input parameters.
3. The highest groundwater flow rates are created in the lowest 10 m of the aquifer (because the GWE-well system is installed at this depth).
4. The pumping/reinjection rate of about 300 m³/d causes a large hydrodynamical disturbance in the defined setting. This is because of the relatively small distance between the two wells and the small phreatic aquifer thickness (30 m).
5. The reactive wall seems too short (flowlines are passing the wall as is visible in figure 29).

(d) Bidirectional GWE without hydraulic containment

Figure 32 shows the typical hydraulic pattern caused by a bidirectional GWE-system.

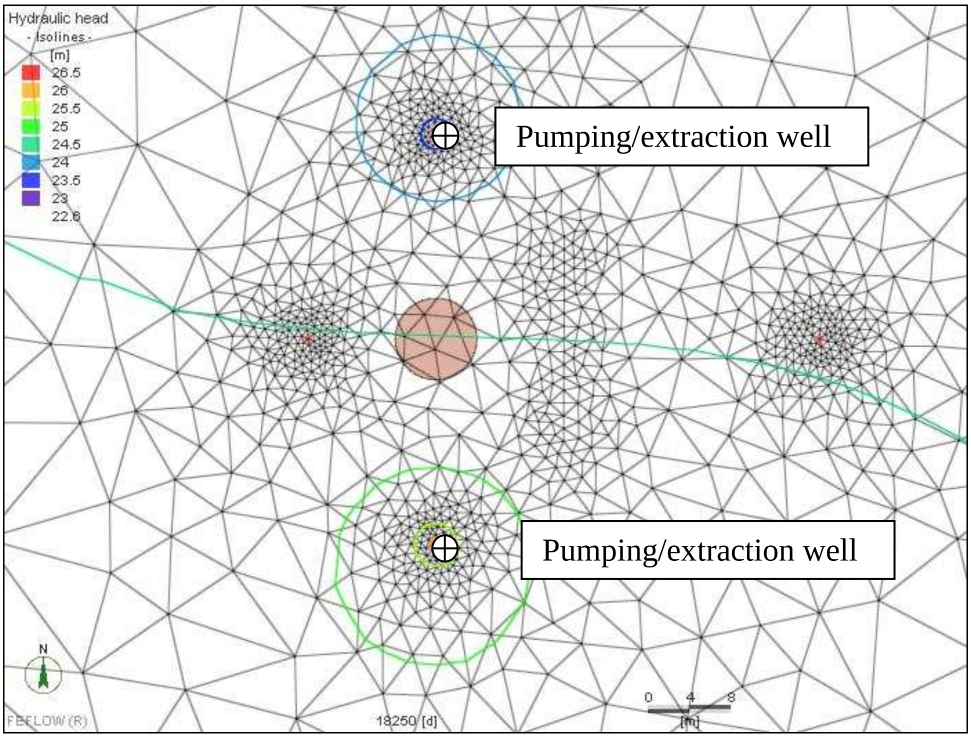


Figure 32. *Hydraulic heads at the end of the simulation period (50 years) – bidirectional scenario*

The bidirectional system creates, according to the model, looped groundwater flow patterns (figure 33), perpendicular to the natural groundwater flow direction. The temperature gradients created (fig. 34) are more pronounced than in the unidirectional scenarios, but overall temperature differences remain relatively small (<10°C).

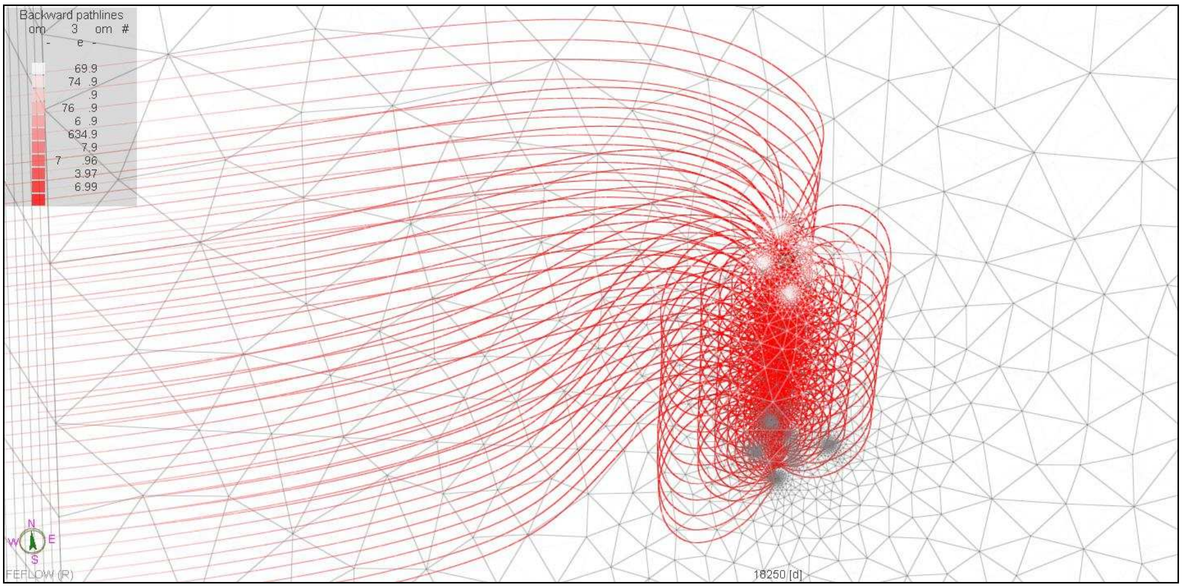


Figure 33. *Simulated groundwater pathlines (pattern obtained at the end of the simulation period) – bidirectional scenario.*

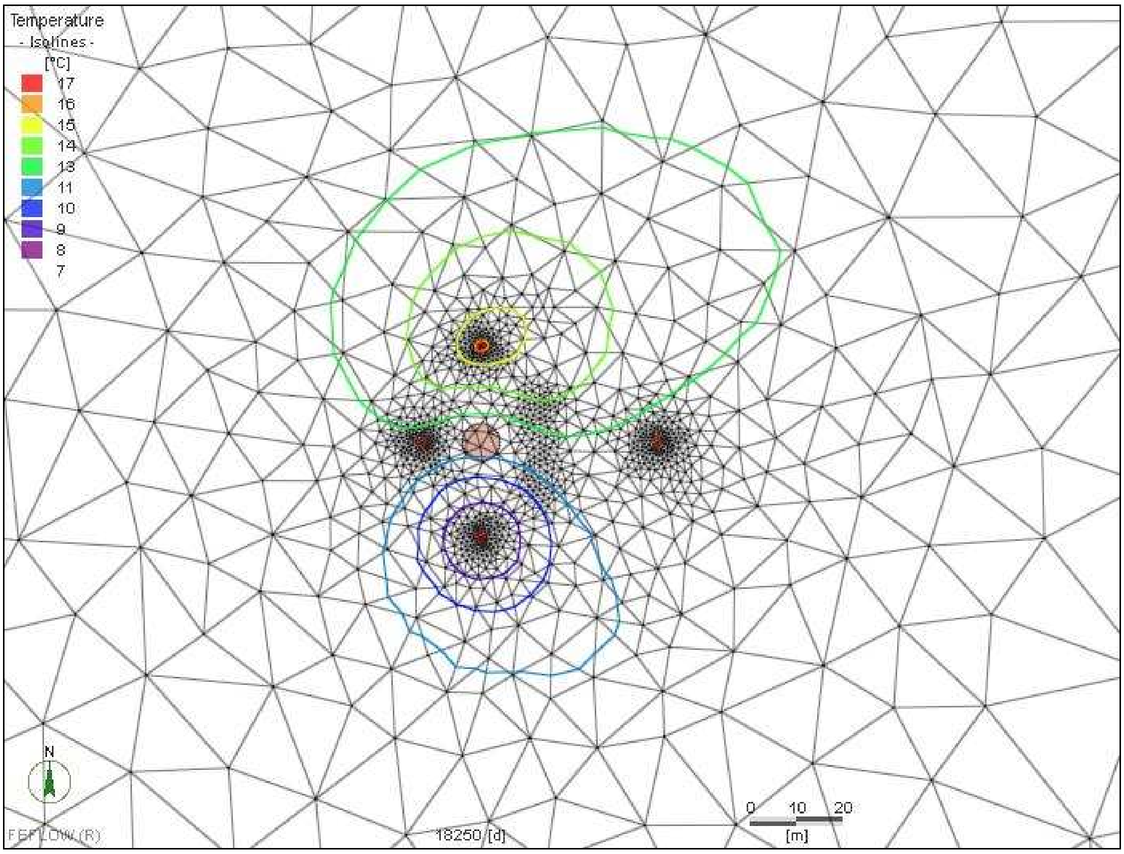


Figure 34. *Temperature isolines of the groundwater at the end of the simulation period (50 y) – bidirectional scenario.*

The bidirectional pumping as defined in this scenario causes – according to the model - a more pronounced North-South migration component, even for the less mobile PCE and TCE (Figures 35 -37).

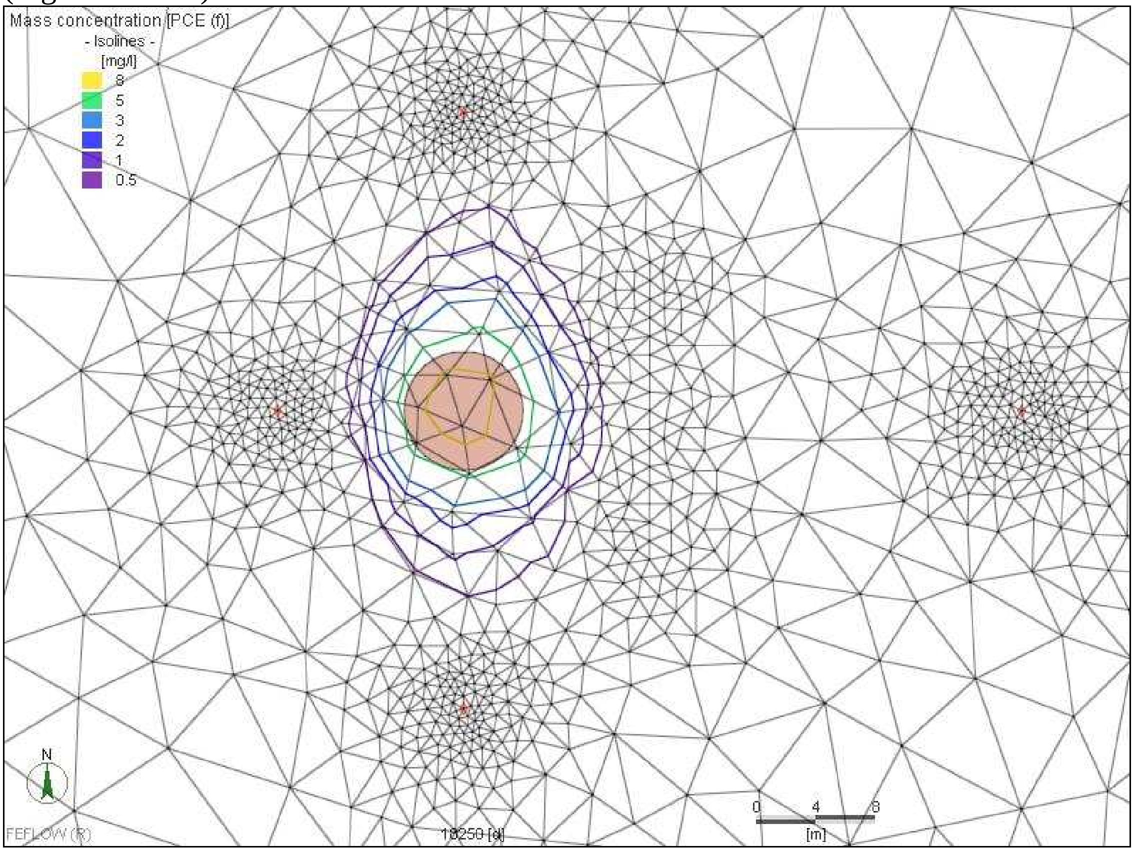


Figure 35. *Top-view of* ***PCE*** *groundwater concentration isolines at the end of the total simulation period (50 y) – bidirectional scenario.*

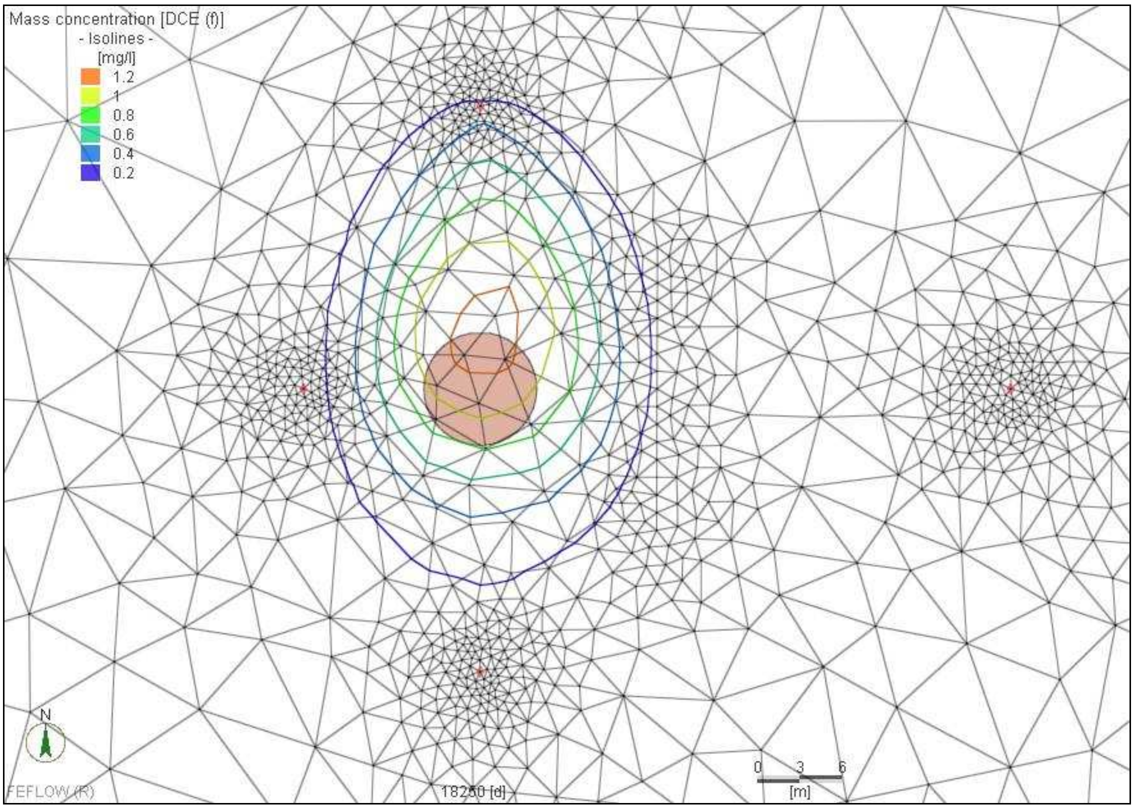


Figure 36. *Top-view of* ***DCE*** *groundwater concentration isolines at the end of the total simulation period (50 y) – bidirectional scenario.*

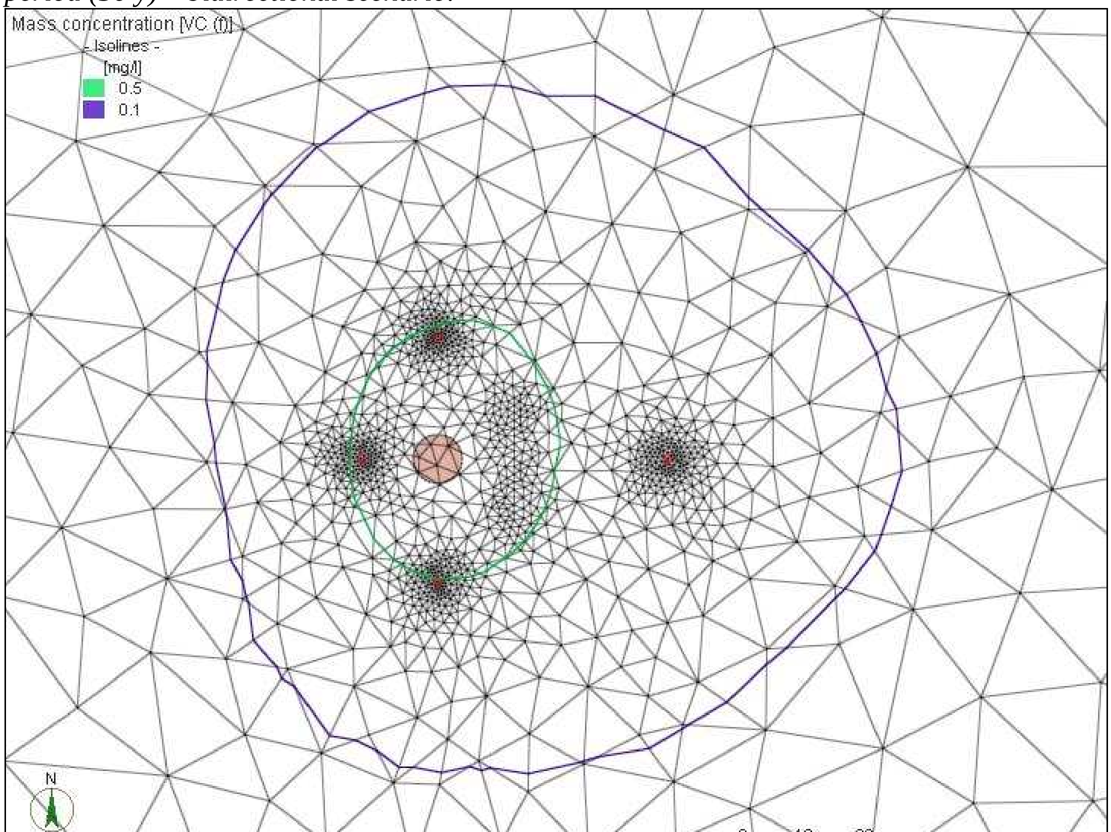


Figure 37. *Top-view of* ***VC*** *groundwater concentration isolines at the end of the total simulation period (50 y) – bidirectional scenario.*

Scenario (bidirectional)conclusion
The doublet system produces a N-S/S-N groundwater flow perpendicular to the natural W-E flow, and is reversed twice per year. It caused, as expected, lateral pollution migration (with respect to the natural groundwater flow direction, broadening the plume in the North-South direction). This was obviously problematic for the mobile daughter compounds DCE and especially VC. For PCE and TCE, no "breakthrough" was observed (the 6-month switching frequency period between injection and extraction well seemingly was short enough to prevent PCE/TCE from reaching the GWE wells, preventing direct "transfer" of pollution between well locations).

2.4.4 Conclusions on modelling

Groundwater and reactive solute modelling are necessary to predict the behaviour of the groundwater pollution when GWE-systems are active.

It is not necessary to use Feflow as a modelling tool, Modflow or equivalent other models can be equally adequate. Temperature gradients can however not be modelled with current versions of Modflow. Since the temperature effects are limited (in the context of groundwater remediation), it is not important to model them. The groundwater flow and mass-transport effects produced by the GWE-system, however, are of utmost importance.

The illustrated scenarios are hypothetical examples of relevant combinations of groundwater remediation and "ordinary" GWE systems operating in PCE-polluted areas in Flemish aquifers.

The model results, although very preliminary, show the large spreading effects pumping and reinjection can cause, especially in the case of the mobile partial dechlorination products DCE and VC.

In later work, a real field pilot should be executed and carefully monitored (technical details on how this field pilot should be designed, constructed, and monitored fall beyond the current study). The pilot should be modelled and calibrated with the monitoring data. To avoid numerical dispersion, special attention should also be devoted to the grid-cell definition, not only in the vicinity of the wells and the pollution area, but for the whole area where contamination can be expected.

2.5 Policy-technical, legislative and juridical aspects

The installation of a GWE-system is subject to the application for an environmental permit. Specific items in relation to GWE-systems are added to the Vlarem regulations.

2.5.1 General

When groundwater is pumped an injected back into a closed system :
Vlarem I section 53.6 : Drilling of groundwater wells and groundwater extraction used for GWE-systems, including pumping back with a pumped flow rate of
- less than 30,000 m^3/year : class 2 permit
- at least 30,000 m^3/year : class 1 permit

When not a closed system is concerned (if not all of the pumped groundwater is reinjected) :
Vlarem I section 53.8 : Drilling of groundwater wells and groundwater extraction, other than those referred to in section 53.1 to 53.7n with a pumped flow rate of

- less than 500 m^3/year : class 3 permit
- 500 to 30,000 m^3/year : class 2 permit
- 30,000 m^3/year or more : class 1 permit

Vlarem I section 3.4 : The discharge of waste water and cooling water :

- less than 2 m^3/h (for water without hazardous substances according to annex 2c of Vlarem I) : class 3 permit
- less than 2 m^3/h (for water with hazardous substances according to annex 2c of Vlarem I) : class 2 permit
- between 2 - 100 m^3/h : class 2 permit
- at least 100 m^3/h : class 1 permit

2.5.2 Environmental conditions

The relevant sections of Vlarem II are sections 5.53 and 5.3. The most relevant passages are reproduced below and summarized.

Vlarem II section 5.53.6.2.1 : GWE-systems are prohibited in a protection zone of type I or type II of groundwater extraction for public water supply. To see whether this section applies for a specific area the website with web address http://dov.vlaanderen.be can be consulted. It is allowed to install a GWE-system in protection zone of type III.

Vlarem II section 5.53.2 : The extraction and infiltration filters must be located in the same aquifer as no different aquifers may be interconnected. The same aquifer means that there is both physical (no separating layer between) and chemical (fresh and salt water or iron-rich and iron-poor water) resemblance. For that reason, clay stops at the height of the separating layers are necessary or cementation between the inserted pipes and the borehole wall is required. In addition, for each groundwater extraction filter a monitoring pipe in the relevant water bearing layer is required.

Vlarem II section 5.53.3 : A flow meter must be installed so that the pumped volume can be aggregated. The equipment must meet specific technical requirements. At least two flow meters are installed, so the net pumped volume can be determined, as a result of the difference between the withdrawn and reinjected flow rate. The meter positions are registrated every month (or every year according to specific requirements made by permit services).

Vlarem II section 5.53.4 : The installation of measuring wells is mandatory :

- for groundwater extractions from phreatic aquifers :
    - one monitoring well for each amount of 200.000 m^3/year licensed flow rate (for permit between 30.000 to 1.000.000 m^3/year);
    - one monitoring well for each amount of 500.000 m^3/year licensed flow rate (for permit over 1.000.000 m^3/year);
- for groundwater extractions from confined aquifers :
    - one monitoring well for permit between 30.000 to 500.000 m^3/year;
    - one monitoring well for each amount of 500.000 m^3/year licensed flow rate with maximum of 3 (for permit over 500.000 m^3/year);

The location of the monitoring wells is to be defined in dialogue with an accredited environmental expert in the discipline of groundwater. The well must be located in the drawdown cone of the groundwater extraction.

Yearly, the groundwater operator needs to report the pumped volumes, the measured groundwater levels and the results of groundwater analysis. The analysis requires information on ion balance, PH, temperature, conductivity, hardness, oxygen content and alkalinity.

2.5.3 Levies

Groundwater extractions used for GWE-systems are exempt from charges provided that the groundwater flow is returned in the same aquifer (as stated in Vlarem II – 5.53.2). In order to obtain an exemption on taxes on the extraction of groundwater, it's necessary that two flow meters and a monitoring well are present. There is an exemption only on the (vast) portion that is injected back into the same aquifer from which it is withdrawn. If the groundwater drain (in order to purge wells for maintenance) or effective consumed water volume is less than 500 m^3/year, there is no charge. If the annual effective consumption is greater than 500 m^3/year, there is a tax on the use of groundwater.

2.5.4 Permit barriers

The installation of GWE-systems is not strictly forbidden in Flanders when a groundwater pollution is present. Yet in practice, when it's known that a site is polluted, the integration of a GWE-system will never be implemented but on the contrary the system will not be implemented. Main argumentation is the fact the in every case there is a danger for spreading the pollution when using a GWE-system which needs to be avoided. In those cases, the only options are to remediate to site or to maintain a status quo. In many cases, the second option will be valid when the seriousness of the pollution is considered as marginal. When severity is an issue, the guidelines for the permit are drawn up by OVAM and custom defined measures ought to be taken according to the specific situation. Until now, only actions are permitted that lead to a significant decrease in time of the pollution by remediations like "pump and treat", it's not evident to allow spreading the pollution. It can be useful to allow GWE-systems in certain situations as they provide also long term benefit to the pollution itself.

2.5.5 Conclusions on the legal part

As long as there is no knowledge on pollution of a site, the current environmental allowance conditions are aimed at maintaining the groundwater quality and temperature balance and avoiding the waste of valuable groundwater. There is no limit on using GWE-systems, even though if there is a pollution present which isn't known. There is no obligation on examining or proving that a certain site is pollution free. In that regard, there is no limitation on using GWE-systems.

For known polluted locations, it is currently not strictly forbidden but yet not evident to install and exploit a GWE-system. For reasons of environmental safety, the installation of GWE-systems will be prohibited as they are considered as disturbing or spreading and yet worsening the problem of pollution. A distinction can be made between remediated and non-remediated sites. When remediation is applied, some types of geothermal energy use can currently be applied but within certain limited applications. When remediation is not applied, the polluted area remains untouched (neither a solving action to the remediation nor an energy application). In both cases, a framework needs to be established within which the rules are set for installing and exploiting a GWE-system on a polluted site. This can cause benefit for both the types of known polluted locations by creating possibilities for using renewable energy and reducing remediation costs.

Current legislation is intended to control either energetic applications (subscribed in Vlarem, advised by VMM) or polluted zones (tailor-made approach defined by OVAM). A legislative framework needs to formulate an answer to the question how GWE-systems can be developed in polluted areas, combining guidelines from both VMM and OVAM. This can be organized by creating a code of good practice with specific formulated conditions on installation, operation and monitoring. Several boundary conditions need to be defined on groundwater displacement, temperature differences, pollution movements, area specific approaches,…

2.6 Economical factors

The application of GWE-systems brings benefits for the user and the society. Main benefit for the society concerns the reduced environmental impact for producing heating and cooling in comparison with traditional technologies. Primary energy savings and CO_2 emission reductions of ≈ 30 - 50 % on the heating production with a ground source heat pump system compared with gas or oil fired boilers can be expected. For cooling purposes and the use of free geothermal cooling, primary energy savings and CO_2 emission reductions can go up to ≈ 80 - 90 % due to the very energy intensive electricity consumption of traditional compression cooling compared to GWE-pumping systems. Main benefit for the user / owner of the energy system concerns the energy saving potential with typical cost savings of ≈ 5 - 50 % on heating and ≈ 80 - 90 % on cooling. As ground source heat pump systems are responsible for a shift from gas or oil driven heating to electricity driven heating with high efficiency, the variability in effective savings on heating is large depending on the specific energy prices. Typically the ratio between the electricity price and the gas (or oil) price is important. The higher the ratio, the smaller the cost savings. In extreme conditions, it is possible that a high performance ground source heat pump system is more expensive than a gas boiler. In these circumstances, it’s possible to use a gas fired heat pump system, actual present on the market. The lower the ratio electricity/gas price, the greater the cost savings.

2.6.1 Overview GSHP market in Belgium

EurObserv’ER carried out a study on the evolution of the European ground source heat pump (GSHP) market (report 09/2011). For the second year on a row, the European market in 2010 shrank (by 2,9 % in 2010), less than 104.000 units were installed (107.000 units in 2009), see Fig. 38 (** preliminary values).

Figure 38. *Yearly installed numbers of GSHP systems in Europe*

In total, over 1 million GSHP's are in operation in Europe. The market differentiation of the heat pump technologies in Europe is shown in the figure below. About 22% of the heat pump market is related to ground source systems, with a vast majority of brine-water systems. Within the brine-water heat pump market, most systems are vertical loop or BTES systems.

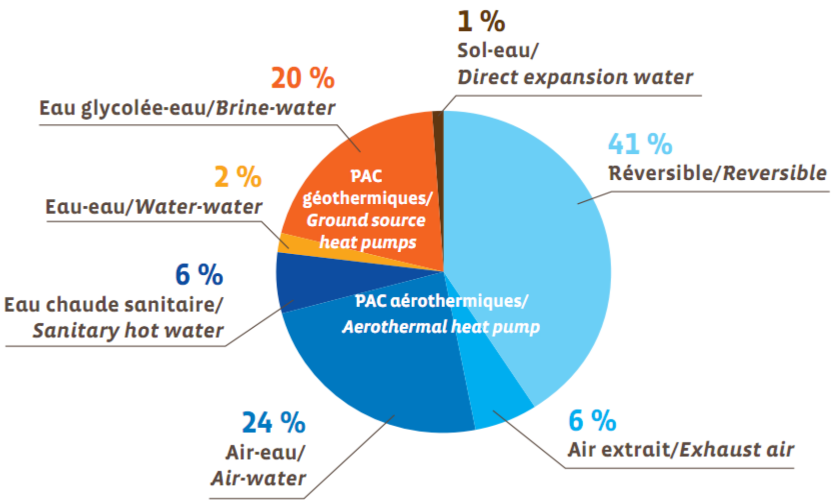


Figure 39. *European heat pump market differentiation*

A full overview of the number of installed ground source heat pumps for each EU country is given in the table below, with Belgium located on position 13. In Europe, also Switserland and Norway (as non EU members) have significant higher heat pump capacity in comparison to Belgium, so this brings Belgium to position 15 just before southern (no heating necessary) and eastern countries. For 2010, it's estimated that 1249 units were installed with total capacity of 15 MW. Due to slower market development in the past, Belgium still has a growing heat pump market in comparison to most of the other European countries.

Table 4*. Overview installed ground source heat pumps in Europe (2009 and 2010)*

	2009			2010**		
	Nombre/ *Number*	Puissance/ *Capacity (MWth)*	Énergie renouvelable capturée/*Renewable energy captured (ktoe)*	Nombre/ *Number*	Puissance/ *Capacity (MWth)*	Énergie renouvelable capturée/*Renewable energy captured (ktoe)*
Sweden	348 636	3 702,0	784,8	378 311	4 005,0	867,8
Germany	179 634	2 250,5	293,5	205 150	2 570,1	335,2
Finland	52 355	967,8	194,2	60 246	1 113,0	223,3
France	139 688	1 536,6	200,4	151 938	1671,3	218,0
Austria	55 292	618,8	68,4	61 808	729,5	80,1
Netherlands	24 657	633,0	63,6	29 306	745,0	74,9
Denmark	20 000	160,0	40,6	20 000	160,0	40,6
Poland	15 200	202,2	26,4	19 320	257,0	33,5
United Kingdom	14 330	186,3	24,3	18 390	239,1	31,2
Ireland	11 444	196,1	25,6	11 658	202,7	26,4
Czech Republic	11 127	174,0	20,5	13 349	197,0	24,4
Italy	12 000	231,0	23,0	12 357	231,0	23,0
Belgium	11 836	142,0	18,5	13 085	157,0	20,5
Estonia	5 422	78,0	15,6	6 382	91,8	18,4
Slovenia	3 849	43,3	7,4	3 948	54,8	9,5
Lithuania	1 865	34,5	6,9	2 221	41,5	8,3
Bulgaria	543	20,6	6,8	543	20,6	6,8
Greece	350	50,0	6,4	350	50,0	6,4
Slovakia	1 845	23,5	3,6	2 000	25,7	3,9
Hungary	3 030	26,0	1,7	4 030	43,0	3,1
Romania	n.a.	5,5	0,7	n.a.	5,5	0,7
Latvia	20	0,3	0,1	20	0,3	0,1
Portugal	24	0,3	0,0	24	0,3	0,0
Total EU 27	**913 147**	**11 282,2**	**1 833,1**	**1 014 436**	**12 611,1**	**2 056,0**

This brings total installed GSHP capacity on 157 MW thermal energy in Belgium. With a total number of 13085 units installed, the average GSHP unit accounts for 12 kW of produced heat.

An increase with about 20 MW is expected to be realized in 2011 with ≈ 1400 GSHP units (brings Belgian total to 177 MW). Most of these units (95 %) are installed in residential housing (≈ 1330 GSHP units). About 20% of these units are equipped with horizontal loops, 5% are groundwater systems and approx. 75% are brine-water (vertical loop) systems. The vast majority of these systems in installed in Flanders (about 85 %). It can be concluded that the number of GWE systems in Flanders accounts for about 60 systems in 2011. This number is growing each year (although European market decreased slightly).

The market of residential heat pumps (with small GWE systems) is responsible for about 50 installations in 2011. In total, about 615 GWE systems are into operation in Flanders (total installed number).

Terra Energy and VITO performed a market search in relation to the market of non residential heat pumps is growing slowly but surely. Non residential heat pumps have a capacity of at least 50 kW, these medium to big size GWE systems are known as ATES systems (Aquifer Thermal Energy Systems). These systems are typically described as UTES systems as the vast majority (99%) of these installations operate for heating and cooling (and not only heating like most of the residential 'vertical loop' systems). About 130 units are installed in Belgium up to now with ≈ 45 units in 2011 only. They can be divided in two types with 33% ATES+HP systems and 67% BTES+HP systems. Non residential ATES coupled GSHP systems account for 43 units (total installed number), coupled to 35 ATES well systems (with about 10 new systems in 2011 only). Half of these installations are medium size well systems with a capacity between 5 – 15 m^3/h, used in small offices or SME's (garages, shops,..), and equipped as unidirectional well systems without real heat storage. The other systems concern big ATES systems (30 – 200 m^3/h) used in big offices, hospitals,… Medium non residential ATES systems have a capacity of 175 kW thermal power and a flow rate of 25 m^3/h and are constructed as doublets (one cold and one warm well). Total installed ATES capacity is calculated as 6220 kW, or an installed GSHP capacity of 7720 kW heating power (good for 4,3 % of total Belgian GSHP capacity with only 35 ATES systems). In total these non residential ATES systems produce yearly 37,2 TJ of heat and 19,6 TJ of cold.

This brings total number of non residential BTES coupled GSHP to 87 units (coupled to 65 BTES fields). The mean power of these BTES systems is 120 kW (≠ HP capacity), with an average of 35 boreholes to a depth of 105 m (3675 m average total borehole length, typical double U-tubes). Total installed BTES capacity is calculated as 7360 kW, or an installed GSHP capacity of 9720 kW heating power (good for 5,5 % of total Belgian GSHP capacity with only 65 BTES fields). In total these non residential BTES systems produce yearly 49,9 TJ of heat and 26,3 TJ of cold. The market for BTES (ditto for ATES) systems is boosted by public projects in health care sector with 30 large BTES fields in hospitals and rest homes. Another 36 BTES fields are used in order to heat and cool offices (as well public as private). Only a few other systems are installed in schools, agriculture, industry and collective housing.

As conclusion, the market of GWE systems is growing steady but surely although total market volume is rather limited. For 2011, 60 new systems (mainly small residential) were installed. For the next years, market development will go on, it's expected to have about 150 new GWE-systems each year by 2015.

2.6.2 Financial parameters

An analysis of the economical impact of the implementation of GWE-systems can be made when examining two typical cases, a small residential unidirectional (only or mainly heating) and a medium to large bidirectional (heating and cooling) GWE-system.

A small residential system contains a small groundwater flow rate, with a typical value of 3 m^3/h, and a heat pump with a capacity of 12 kW. A medium size system has a capacity of 25 m^3/h and a heat pump of 175 kW. A large size system has a capacity of 100 m^3/h and a heat pump of 700 kW.

Table 5. *Financial parameters small GWE system*

Case 1 – small residential system	
GWE system flow rate	3 m^3/h
Investment GWE+HP system	~ 25.000 €
Extra investment cost (compared to traditional systems)	~ 17.500 €
Energy savings	~ 850 €
Simple payback time (without incentives)	~ 20 year
Simple payback time (with incentives)	~ 15 year
Dynamic payback time	~ 12 year

For small systems, the benefit is mainly determined by the savings on heating. Cooling benefits are of minor importance as the need for cooling is limited or even absent in most residential applications. Simple payback times of 20 years are realistic without incentives. Due to various subsidies (as a bonus or tax reduction), it's possible to reduce simple payback time to 15 year. Dynamic payback time also takes into account interest rates, inflation and energy price increases. A dynamic payback time of 12 year can be reached.

Table 6. *Financial parameters medium GWE system*

Case 2 – medium SME system	
GWE system flow rate	25 m^3/h
Investment GWE+HP system	~ 250.000 €
Extra investment cost (compared to traditional systems)	~ 160.000 €
Energy savings	~ 13.500 €
Simple payback time (without incentives)	~ 12 year
Simple payback time (with incentives)	~ 9,5 year
Dynamic payback time	~ 7,5 year

Medium size systems can benefit from savings on heating and cooling. There is still a rather big investment necessary in relation to the delivered energy amount on heating and cooling. Nevertheless, acceptable payback times of 9 year (simple payback with subsidy) to 7,5 year (dynamic payback time) are possible.

Table 7. *Financial parameters large GWE system*

Case 2 – large SME system	
GWE system flow rate	100 m^3/h
Investment GWE+HP system	~ 550.000 €
Extra investment cost (compared to traditional systems)	~ 275.000 €
Energy savings	~ 35.000 €
Simple payback time (without incentives)	~ 8 year
Simple payback time (with incentives)	~ 6 year
Dynamic payback time	~ 4,5 year

The best economical figures can be reached with a large GWE-system with very acceptable payback times of 8 years (simple payback without subsidy) to 4,5 years (dynamic payback with support).

An analysis of the cost aspect of a groundwater remediation system shows a very big variability depending on the specific situation of the type of pollution, the way of treatment and the duration of the operations. When combining remediation with energy captation, the cost aspect will differ even more according to the applied energy system on the specific pollution situation. This offers a palet of many different solutions for combining energy with remediation with wide cost range, very dependent on the local situation (also regarding the energy application).

2.6.3 Economical conclusions

The elimination of an existing soil contamination is irrevocably linked to a significant bill for the site owner or the society. This cost is some sort of 'necessary evil' in order to control, limit and/or reduce environmental impact of human presence and activity for future generations. The environmental benefit is thereby related to a certain financial cost which will lead to a tendency of avoiding this cost if it isn't strictly necessary.

On the other hand, GWE-systems offer a solution for our dependency on fossil fuels for heating and cooling combined with renewable electricity production (sun, wind, water or biomass), the fossil fuel consumption drops to zero by operating GWE-systems with renewable electricity. GWE-systems offer a major impact on the overall energy bill for heating and cooling, as the most important part of our average total energy cost.

The combination of groundwater remediation with energy production causes an environmental as well as economical benefit. The environmental impact is dual by removing groundwater pollution as well as avoiding air pollution (by limiting greenhouse gas emissions). The economical benefit of developing GWE-systems is depending on local geological circumstances and therefore geographical defined. At some locations, these systems show poor economical feasibility, this is also the case at some less convenient combinations of GWE-systems with remediation. It's difficult to define the exact conditions for a good combination, this should be examined project dependant. This calls for the execution of extended modeling work in order to proof impact of the combined approach. This modeling work will cause an extra cost in project preparation, estimated as a few weeks of simulation work by a geohydrologic specialist. The economical benefit is also dual by reducing environmental cost (e.g. future CO_2 taxation) and the limitation of the energy bill. Combining both remediation and energy production transfers the project from an environmental cost to an environmental benefit (or at least a lower or limited cost). It can be stated that, in the best circumstances, the implementation of a GWE-system makes a groundwater remediation project economical feasible. This allows a faster and better approach and handling of the polluted areas in Flanders. It concerns an integral instead of an individual approach with optimal effect on environment and cost.

Main point of attention regards the definition of a suitable framework for the implementation of these systems defining the allowed boundary conditions. Some combined approaches have no impact at all on the pollution itself e.g. a classical pump and treat with additional groundwater energy production system. Most combined approaches (for remediation and energy production) have a certain (from small to substantially) impact on the spread of the pollution which should be allowed by legislation. This asks for the establishment of a specific working group for the definition of a suitable approach on the creation of an adapted legal framework. See chapter 2.5 for further details.

3 CONCLUSIONS

Groundwater energy systems can be classified in many ways according to the specific criterium that is used. Three types, each requiring a clearly different strategy, approach and feasibility testing, are considered within the context of this project namely bi-directionally operated well pair(s), unidirectional operated well pair(s) and single wells.

A map is drawn showing the suitable zones in Flanders for developing a significant GWE-system. For some regions this can only be a small residential system while for other localities a large GWE-system (providing energy to big office building, hospital, industry,…) is possible.

Although specific literature on the combination of GWE and groundwater remediation seems to be very scarce, relatively many studies are available on the effects of temperature on the physical, chemical and biological behaviour of pollutants in subsurface environments. In the relevant temperature interval for the current study, biological and geochemical reaction rates will however only slightly be affected. Especially the groundwater flushing and mixing effect caused by the GWE-system will be relevant in the context of remediation.

Groundwater and reactive solute modelling are necessary in order to predict the behaviour of the groundwater pollution when GWE-systems are active. The most important parameters concern groundwater flow and mass transport effects produced by the GWE-system. The illustrated scenarios are hypothetical examples of relevant combinations of groundwater remediation and “ordinary” GWE systems operating in PCE-polluted areas in Flemish aquifers. The model results show the large spreading effects caused by pumping and reinjection, especially for mobile partial dechlorination products. In later work and in addition to modelling work, a real field pilot should be executed and carefully monitored. These monitoring results should be used to calibrate model input data.

For known polluted locations, it is currently not strictly forbidden but yet not evident to install and exploit a GWE-system. There is a tendency to prohibit the use of GWE-systems as they are considered as disturbing or spreading and yet worsening the problem of pollution. The combination of groundwater remediation with energy production causes an environmental as well as economical benefit (when geological boundary conditions are suitable). Combining both remediation and energy production transfers the project from an environmental cost to an environmental benefit (or at least a lower or limited cost). It can be stated that, in the best circumstances (but not in every case), the implementation of a GWE-system makes a groundwater remediation project economical feasible. It concerns an integral instead of an individual approach with optimal effect on environment and cost.

It’s advised to create a suitable framework for the implementation of combined remediation and energy systems defining the allowed boundary conditions. Most combined approaches have a certain impact on the spread of the pollution which is not foreseen (or considered as a gap) in current legal context. Experience from different competence centers (such as OVAM and VMM) should be combined in order to establish an adapted legislation.

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