Design of an Aquifer Storage and Recovery system

CEGM2006: Subsurface storage for water, energy and climate

Justin van Beek & David Haasnoot

Delft University of Technology

TU Delft

Abstract

Aquifer Storage and Recovery (ASR) systems represent a crucial solution for augmenting water resources, particularly in the context of drinking water supply. This report delves into the design and operational aspects of an ASR system specifically for drinking water storage, with a targeted extraction volume of 40,000 m^3 during peak demand periods (July and August). Through a meticulous examination of comparable systems worldwide, various factors influencing system efficiency are explored, including hydraulic conductivity, injection-extraction rates, and recovery efficiencies.

The document outlines a comprehensive methodology for modeling and optimizing ASR systems, with a focus on multi-layered groundwater flow simulations. Sensitivity analyses reveal the profound impact of parameters such as hydraulic conductivity and porosity on system performance. Notably, lower hydraulic conductivity facilitates the retention of freshwater near the well, enhancing recovery efficiencies per cycle. Conversely, higher porosity enables greater storage capacity but may lead to increased dispersion of injected water. The amount of layers controls the smoothness of the results.

Insights from the sensitivity analyses guide the formulation of strategies to optimize injection schemes and meet extraction targets. Adjustments to injection volumes and well radii and/or the addition of wells are proposed to ensure compliance with pressure constraints while maximizing extraction efficiency over time. Moreover, considerations of longitudinal dispersivity underscore its role in governing the spread of injected water within the aquifer, influencing both system efficiency and recovery rates.

The findings suggest that a balanced combination of hydraulic conductivity, porosity, and injection-extraction strategies is crucial to achieving optimal ASR system performance. Notably, the proposed methodologies offer practical guidelines for ASR system design and implementation, emphasizing sustainability, resilience, and long-term viability. By leveraging empirical data and modeling insights, drinking water companies can effectively address water scarcity challenges and fortify water infrastructure against future uncertainties. This was all done in a theoretical framework with uncertainties about a lot involving the system.

Overall, this report provides a nuanced understanding of ASR system dynamics and offers actionable recommendations for stakeholders involved in water resource management. Through strategic planning and adaptive management, ASR systems can serve as cornerstone solutions in ensuring reliable drinking water supply for communities worldwide.

Contents

Abstract **ii**

1 Introduction **1**

2 Method **2**
2.1 Comparable systems 2
2.2 Guidelines and rules of thumb 4
2.2.1 Maximum injection rate 4
2.2.2 Maximum allowed specific discharge 5
2.2.3 Maximum soil compaction 6
2.2.4 Dispersivity 7

3 Modelling steps and results **8**
3.1 Model one year 8
3.2 Repeat for 10 years 9
3.3 Adjust injection volume yearly 9
3.4 Parameter sensitivity 9
3.5 Adjusting injection scheme 14

4 Conclusion and discussion **16**

References **17**

A Source Code **18**

1 Introduction

Large-scale Aquifer Storage and Recovery (ASR) systems represent artificially engineered or enhanced natural setups designed to capture rainwater and gather it for subsequent injection into aquifers. The primary goal is to store freshwater when there is an excess, and later utilize it during a deficit. This is mostly done for agricultural irrigation, but in this case is explored for drinking water supply. These systems are instrumental in enhancing the overall quantity of available water. Furthermore, the cost-effectiveness of these systems stems from their efficient utilization of space. By effectively harnessing the aquifer's storage potential, the drinking water company aims to extract 40,000 m^3 of drinking water during peak demand periods (Dillon et al., 2006).

Their importance for the future of sustainable water supply is crucial. So the need to devise a strategic ASR system for storing drinking water is great. The significance of implementing an ASR system lies in its capacity to provide a reliable reservoir for drinking water during critical summer months, particularly July and August. As climate variations and population growth amplify the strain on traditional water sources, the ASR system emerges as a crucial solution.

The multifaceted objectives of this report encompass not only the design intricacies of the ASR system but also the development of injection-extraction schedules, waste minimization strategies, and compliance with critical pressure and velocity guidelines found in chapter 2. Equally crucial is ensuring the longevity of the ASR system, with a targeted operational span of at least 10 years. Acknowledging the inherent uncertainties in hydrogeological dynamics, this report will delve into a comprehensive discussion of potential challenges, fostering adaptive strategies to address unforeseen circumstances which can be found in chapter 2. Overall, this report provides a road map for the drinking water company to implement an ASR system that not only meets extraction targets but also fortifies water infrastructure against the uncertainties of the future.

2 Method

As mentioned in the introduction a storage system for drinking water needs to be designed. This system and design needs to hold the following important parameters:

- The drinking water company needs to extract a total of 40,000 m^3 of drinking water during the summer months of July and August.
- A time schedule for injection, extraction and, if necessary storage.
- The waste of injected drinking water needs to be as small as possible.
- The system needs to meet the guidelines for injection pressure and maximum velocity during extraction.
- The ASR system can function for at least 10 years with possibly a start-up year when the extracted volume is smaller.

The current situation of the aquifer is as presented in figure 2.1 in this figure the important parameters given are visualised in black. In grey the parameters found in literature are shown. These are likely to have the parameters in the given range. To accurately model the processes in the system, a multi-layered model is required.

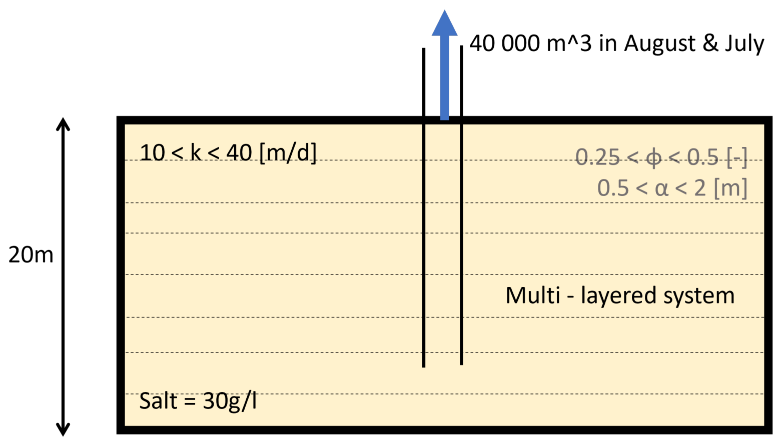


Figure 2.1: Overview situation aquifer

2.1. Comparable systems

Around the world quite a few aquifer storage and recovery systems exist, all with very different aspects and characteristics. Pirnie describes a system operating in Florida which extracts 100 times more water from the subsurface as the system in this research, highlighting the differences in the systems (2011).

Anotger paper provides an overview of several systems that are located all over the globe as seen in figure 2.2 (Ward, Simmons, Dillon, and Pavelic, 2009. This is used as a reference for this research.

Table 6
Parameters from field sites.

SITE	Bolivar	Jandakot	Willunga	East Bay	Kingswood 1	Kingswood 2	Charleston
Primary source	Pavelic et al. (2006)	Rattray et al. (2005)	Sibenaler et al. (2002)	Tognolini et al. (2005)	Barry et al. (2007)	Barry et al. (2007)	Petkewich et al. (2004)
Parameters							
K_x (m/day)	3	43.2	4.2	50	2.9	0.46	8
I	0.002	0.00006	0.01	0.002	0.007	0.007	0.0005
K_z (m/day)	0.3	43.2*	4.2*	50*	2.9*	0.46*	0.8
$C_{injectant}$ (mg/L)	1270	180	920	50	15	15	100
$C_{ambient}$ (mg/L)	2010	2700	1100	500	2500	2500	4000
β_L (m)	2	20	50	5	0.17†	0.15†	0.5
V (m^3)	248000	40600	26200	95200	3.4	3	7010
B (m)	50	37	18	27	11.7	10.9	8
$t_{injection}$ (d)	265	10	56	20	0.16	1.4	43
$t_{storage}$ (d)	111	109	13	19	3	5	99
$t_{recovery}$ (d)	121	42	58	16	0.004	0.02	61
ε	0.45	0.3 (est)	0.3 (est)	0.25	0.3 (est)	0.3 (est)	0.3
$x_{i,upstream}$	54.5	31.4	36.1	61.6	0.51	0.50	28.0
Dimensionless numbers							
R_{TV}	0.027	0.032	0.050	0.12	0.40	0.11	0.047
R_{DISP}	0.037	0.64	1.38	0.081	0.33	0.30	0.018
M	0.0032	0.14	0.0073	0.044	0.0092	0.013	0.020
R_{ST}	0.00065	1.04	0.00032	0.0085	2.27	0.59	0.0073
R_{ASR}	0.068	1.85	1.44	0.26	3.00	1.01	0.092
f at:							
Start	1	0.28	1.1	0.99	0.81	0.99	0.99
Middle	0.81	0.64	0.52	0.45	–	–	0.69
End	–	0.36	0.32	–	–	–	0.24

Figure 2.2: Parameters of several aquifer storage and recovery systems (Ward, Simmons, Dillon, and Pavelic, 2009)

In figure 2.2, the factor 'f' corresponds to a recover efficiency in some way. This efficiency is calculated via the correlation in equation 2.1. In this correlation the efficiency is the mixing fraction and is defined as the proportion of injected water contained in the recovered water at time t during recovery. ($f = 1$ if the extracted water is completely fresh, $f = 0$ if the extracted water is entirely brackish)

$$f(t) = \frac{C_{ambient} - C_{well}(t)}{C_{ambient} - C_{injected}} \qquad \text{(Ward et al., 2009)} \qquad (2.1)$$

From the report and figure one can conclude:

- Efficient injection and recovery is achieved by aquifers with moderate to high hydraulic conductivity
- A suitable hydraulic gradient will ensure effective movement of water in and out of the aquifer
- The recover efficiency increases with an increasing rate between injection time and extraction rate.
- The Charleston system as described in the figure has the most overlapping factors with the system discussed in this report

2.2. Guidelines and rules of thumb

The goal is to let this system operate at it most efficient way to achieve this some guidelines are applied. These guidelines hold indications for the injection rate, the maximum specific discharge between wells and maximum soil compaction due to the extraction of water from a layer. The following correlations are used respectively.

2.2.1. Maximum injection rate

The maximum injection rate controls the amount of value that is pumped into the aquifer. It is optimized to achieve the highest recover efficiency and to keep the aquifer stable. The maximum injection rate is important, because if it was too high it could cause:

- Over-pressurization of the aquifer which could in the end lead to fracturing or compaction of the aquifer.
- Clogging of flow paths due to the damage to the internal structure of the aquifer.
- Changes in groundwater flow patterns could be induced which causes water to flow away from the aquifer and increase heads in surrounding areas.
- Other legal issues, for example the displacement of contaminants or other particles in the water to an area where those aren't allowed.

The maximum injection rate is determined via the empirical relation shown in equation 2.2:

$$Q_{in} = \frac{2\pi kD(h_{in} - h_0)}{ln(\frac{\sqrt{kDc}}{r_{well}})} \qquad \text{(Van Dooren and Zuurbier, 2020)} \qquad (2.2)$$

With:

k	hydraulic conductivity of aquifer ($\frac{m}{d}$)
D	thickness of aquifer (m)
c	hydraulic resistance of confining layer (d)
r_{well}	well radius (m)
h_{in}	infiltration head (m + land surface)
h_0	natural hydraulic head in aquifer (m + land surface)

k =	10 - 50 ($\frac{m}{d}$)
D =	20 (m)
c =	1000 (d)
r_{well} =	0.2 (m)
Δh =	4 (m + land surface)

The configuration used for this correlation is shown in figure 2.3

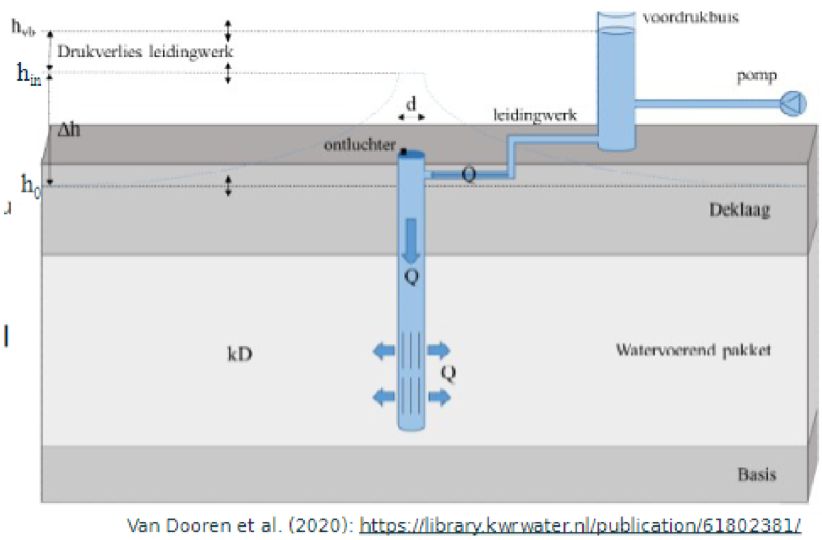


Figure 2.3: Figuration for correlation on maximum infiltration rate

2.2.2. Maximum allowed specific discharge

Specific discharge is the rate of groundwater flow per unit area and is influenced by factors such as hydraulic conductivity, aquifer thickness, and the hydraulic gradient. There will arise some issues if this discharge between two wells or within the aquifer is too large, so a maximum determined value is required. Issues that could arise are:

- With high flow rates, smaller particles can clog up the well screen. This reduces the ability to pump water out of the aquifer. The well then needs to be cleaned which is an expensive and time consuming processes.
- A specific discharge that is too high could lead to compaction of the surrounding rock or soil and this in its place leads to land subsidence.
- High specific discharge may indicate that the aquifer is being pumped or exploited at a rate exceeding its natural recharge capacity. This can lead to a decline in groundwater levels, potentially causing wells to go dry and impacting the sustainability of water supply.
- If the discharge is too high it could lead to water flowing from or to the aquifer. This may lead to increased discharge into rivers, streams or lakes. Wetlands (animals and plants), ecosystems and reservoirs could be destroyed in the process. This is not elaborated in this report, because the aquifer we use to analyse is theoretical framework and doesn't have any boundary conditions at his sides.

This specific discharge should therefor be limited. This limitation is evaluated using equation 2.3:

$$\begin{aligned} q_{max} &= \frac{\sqrt{k}}{30} \\ Q_{max} &= q_{max} * 2L\pi r_{well} \qquad \text{(Van Dooren and Zuurbier, 2020)} \end{aligned} \tag{2.3}$$

With:

k = horizontal hydraulic conductivity of aquifer ($\frac{m}{d}$)
L = screen length (m)
r_{well} = well radius (m)

The parameters are the same for this calculation as for the one in equation 2.2. Leading to the result shown in figure 2.4.

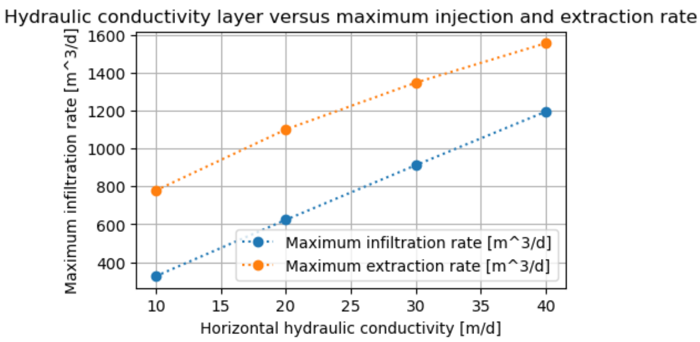


Figure 2.4: Horizontal hydraulic conductivity versus maximum injection and extraction rate

In this figure the maximum injection rate follows from equation 2.2 and the maximum extraction rate follows from equation 2.3 both varying with a range in hydraulic conductivity that in its place causes the head difference to change. As can be concluded from figure 2.4 that in the worst case ($k = 10[m/d]$) the maximum injection rate is 350 $\frac{m^3}{d}$. Given the inject period can last at most 303 days, the maximum amount to be injected is around 100 000 $\frac{m^3}{y}$, thus the systems must be more efficient than 40 percent in this case. During design of the system, it is important to check as this will vary based on the efficiency of the system.

The extraction rate however could become a problem for the system should the water be needed in a shorter period than 62 days. For instance, if a drought lasting 2 weeks in July requires a lot of water, the extraction rate will be exceeded. The maximum extraction rate in the worst case scenario is only 800 $\frac{m^3}{d}$.

If this extraction or injection rate is too low, a fairly easy change can be made in the radius of the extraction well. In the calculation shown this is 0.2m, increasing this to 0.3 or 0.4m will fix the problem for the worst case (where $k = 10[m/d]$). A smaller diameter well is of course cheaper.

2.2.3. Maximum soil compaction

The importance of the determination of the maximum soil compaction is great, because a large amount of compaction could lead to subsidence or decreasing of hydraulic conductivity. Subsidence in its place can cause mass damage to infrastructure and buildings at the surface. Decreasing of the hydraulic conductivity can lead to a decrease in the recover efficiency from the reservoir. The configuration used for this correlation is shown in figure 2.5. The primary compaction constant and secular compaction constant are determined in (Drijver, 2002).The pore pressure change follows from the head change in the well and surrounding area.

$$Z = d(\frac{1}{C_p} + \frac{log(t)}{C_s})ln(\frac{\phi + \frac{1}{2}d\phi}{\phi}) \quad \text{(Van Dooren and Zuurbier, 2020)} \quad (2.4)$$

With:

Z:	Soil compaction (m)
d:	Thickness of confining layer (m)
C_p:	Primary compaction constant (-)
C_s:	Secular compaction constant (-)
ϕ:	Pore pressure ($\frac{kN}{m^2}$)
$d\phi$:	Change of pore pressure ($\frac{kN}{m^2}$)
t:	time (days)

d =	10 (m)
C_p =	[7,10,30,140] (-)
C_s =	[80,110,500,1680] (-)
ϕ =	100 ($\frac{kN}{m^2}$)
$d\phi$ =	40 ($\frac{kN}{m^2}$)
t =	62 (days)

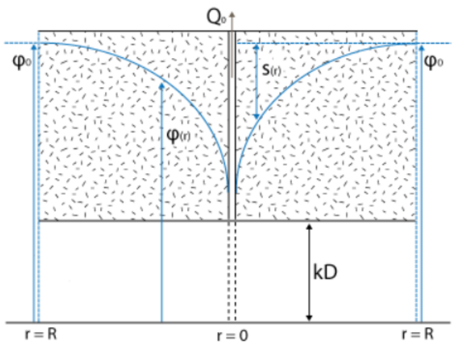


Figure 2.5: Figuration for maximum soil compaction

This all together leads to a compaction shown in figure 2.6. It is shown in this figure that the soil compaction increases for a lower value of the compaction coefficients, so in the worst case (sandy aquitards) will lead to a compaction of 0.16 m which is acceptable in most cases, but not with critical buildings, maybe some soil compaction need to be in place. This calculation is based on the head change for the average change in pore pressure, this will increase even further if the hydraulic conductivity of the aquifer is lower and the change in head is higher, so that should be taken into account if more knowledge is present about the exact hydraulic conductivity, this knowledge often is available after 1 cycle.

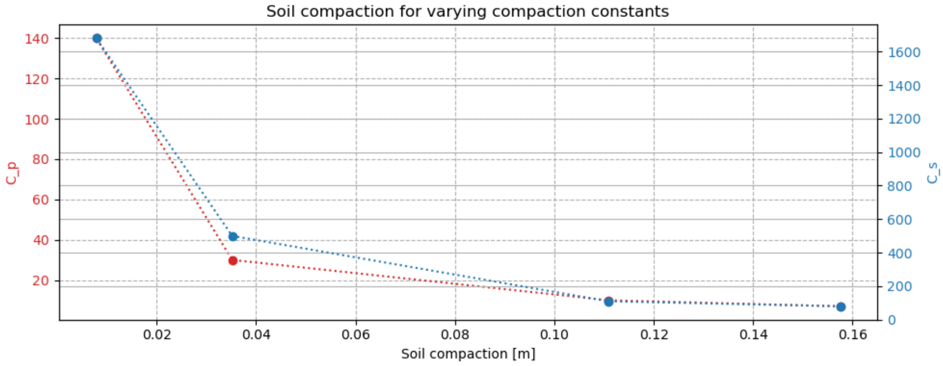


Figure 2.6: Soil compaction for varying compaction constants

2.2.4. Dispersivity

The dispersivity of an aquifer is a parameter that characterizes the spreading or dispersion of solutes as they move through the porous media of the aquifer. It is an important parameter in groundwater transport modeling. The dispersivity is typically denoted by the symbol α and is measured in units of length [m]. The dispersivity for this model is chosen upon the use of an external source (Ward et al., 2009) In this paper the dispersivity is displayed as an function of the scale of the reservoir. For a screen length of 20m the dispersivity falls in a certain range as indicated on figure 2.7. In this figure it is shown that the dispersivity varies from 0.2 m to 95 m for an intermediate accuracy and from 0.5 m to 2 m for an high accuracy. The dispersivity in the red circle is the range that is used in the model. Dispersivity is an empirical relation that is solely dependent on the length scale of the aquifer.

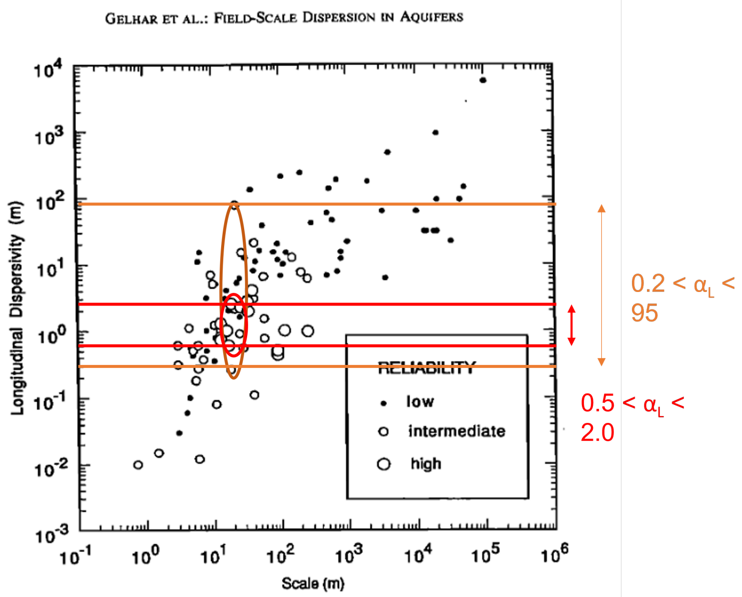


Figure 2.7: Dispersivity versus scale for different sites

3

Modelling steps and results

3.1. Model one year

To model the system a radial flow was used to reduce modeling complexity. This is a 2D model which mimics behavior of a radial system, but using the cell based approach of MODFLOW6. To achieve this, the porosity and hydraulic conductivity change moving out from the well. In reality the cell size becomes larger, but MODFLOW6 does not allow this, instead we scale the porosity and hydraulic conductivity to model the groundwater flow correctly. To deal with the buoyancy effect which occurs when injecting less dense fresh water in a brackish aquifer, multiple layers are added to the model. The discharge of the well is distributed equally over all the layers, with a constant head at a distance far from the well. The modelled domain is 300m, this assumption is later checked in the sensitivity analysis. The buoyancy is approximated with the help of linear relation for the density of the water specified in equation 3.1 to interpolate for values between fresh and brackish.

$$\rho = \frac{d\rho}{dc}(c - c_{ref}) + \rho_{ref} \tag{3.1}$$

where:

c_{ref}: reference concentration (kg/m^3)
$\frac{d\rho}{dc}$: Specified gradient (-)
ρ_{ref} Reference density (kg/m^3)

Throughout this section an average value of 25m/d for hydraulic conductivity and 0.35 for porosity are used unless stated otherwise. An initial guess of 0.5 is used for the longitudinal dispersivity. A more thorough analysis into the other parameters can be found in the parameter sensitivity analysis which also covers the number of layers (20) used. The salt transport model in MODFLOW6 models how the injected fresh water interacts with the brackish aquifer with an initial concentration of 30g/l. This can be modeled for the entire period. More interesting to see is the first few days during injection and last few days of injection. The water is assumed to be injected throughout the year (303 days) and extracted in the 62 days during July and August. The total wanted production is 40 000 m^3/year, this is also the amount that is put in at the beginning of injection initially. This results in an extraction of 645m^3/d and an injection of 132m^3/d. The extraction is stopped when the concentration reaches 1g/L as this is a design limit for freshwater. In reality the dutch drinking water regulations are stricter and a tighter threshold could be used. This would give a similar result, but lower efficiencies. In the first year this limit is reached after 3 days of extraction (day 306) as seen in figure 3.1. This results in a low efficiency of 5% in the first year. The situation that could occur if pumping continues is shown on the right of figure 3.1. The model was checked with the mass balance to validate it and the balance was sufficient.

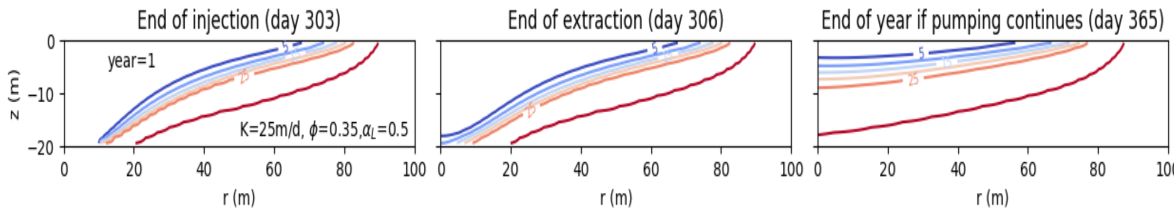
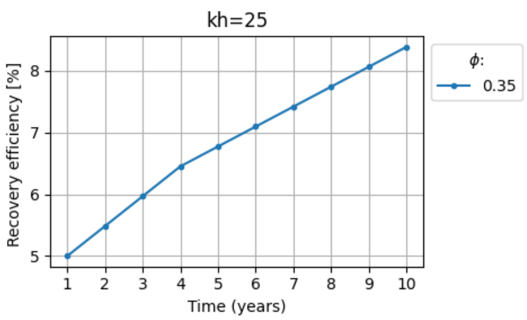


Figure 3.1: Concentration during injection & extraction

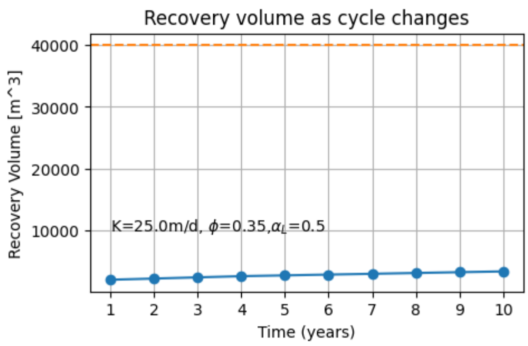
3.2. Repeat for 10 years

Following the first year, the next year can be modelled by setting the initial conditions of the second year as the final conditions of the first. This means that the losses of the previous year create a transition zone from fresh to brackish water. The efficiency in the following year is therefore higher as the previous year has already created a fresh water bubble in the aquifer. Efficiency is defined as the amount of fresh water recovered divided the amount injected multiplied by 100. This efficiency can be seen in figure 3.2a.

We can also consider the total volume produced as seen in figure 3.2b, it is shown that the recovery volume is too low to meet the demand design value of 40 000 m^3/y. This means that the injected volume of water needs to be bigger to comply to this demand. The first year gave a recover efficiency of 5%, assuming a linear trend, the maximum volume of injected water is 800 000 m^3/y. It could be lower because the fresh water bubble will develop differently with these amounts of injection and injection rate. This will have to be experimented with. The maximum injection rate is a big constraint in this case.



(a) Recovery efficiency for 10 cycles



(b) Recovered volume for 10 cycles

Figure 3.2: Recovery efficiency and volume for 10 cycles

3.3. Adjust injection volume yearly

From the second year on, recovery efficiency keeps increasing. Rather than keeping the injection volume constant, this can reduce over time to cut down on the amount of wasted water. Using the design volume divided by the recovery efficiency as a reference start value. The result can be seen in figure 3.3 where the recovery volume is all just far below 40 000 m^3 per year. After 10 years the efficiency seems to level off a bit going more and more towards an asymptotic value. The advantaging of operating more years will eventually become insignificantly small. There will still always be some loss associated with the storage in brackish aquifers.

3.4. Parameter sensitivity

The parameters used to model the flow in groundwater have some uncertainty in them. Until now an average value has been used. The hydraulic conductivity of the aquifer is given in the range of 10 to 40 m/d. The porosity can vary between 0.25 and 0.45 for aquifers as mentioned in figure 2.2 (Ward et al.,

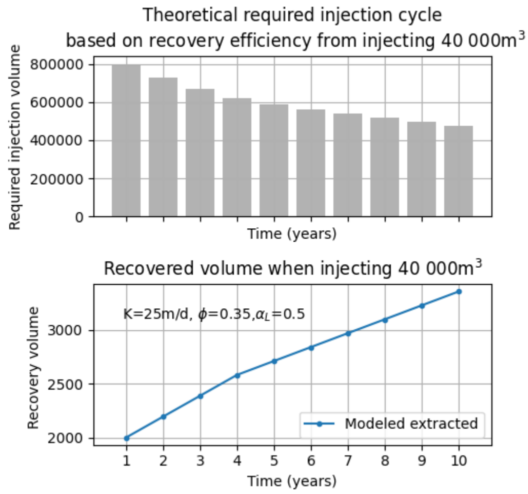


Figure 3.3: Recovery volume after varying injection volume every year

2009). To be absolutely sure, the range between 0.2 and 0.5 is considered. The initial concentration of the aquifer of 30g/l can be seen as fairly constant. This sensitivity analysis is illustrated in figure 3.4 and figure 3.5. Note the end of year plot in figure 3.5 is hypothetical as in reality pumping stops when the concentration limit of 1g/l is reached on average across all layers in the well. The plot does show the behavior of different parameters well over a longer time. Initially a simplification of using a constant injection volume every year is used. This is adjusted later. In the next sub-chapters all important parameters will be discussed.

Hydraulic conductivity
The hydraulic conductivity has a large influence on the results. This is visualised in figure 3.5 and figure 3.4 from these figures it can be concluded that a lower hydraulic conductivity causes a larger fresh water bubble to remain near the well. High hydraulic conductivity allows the fresh water to move away and the density difference with the salt water cause the fresh water to spread out more. This can clearly been seen in the right column of the plots in the figures below. A low hydraulic conductivity is beneficial due to the fact that this increases the recover efficiency per cycle due to the buildup of more fresh water. The hydraulic conductivity has an effect on the response of the groundwater heads too. A lower value of hydraulic conductivity means larger head changes, which will affect the underground and the maximum allowed injection and extraction as explained in section 2.2.2. The best value to have for the highest efficiency is an hydraulic conductivity of 10 m/d.

Porosity
The influence of porosity also needs to be investigated. When the porosity is higher, there is more space for the water in the same volume of ground. With a lower porosity, less can be stored and thus is forced away from the well. With a higher porosity, more fresh water can be stored close to the well. This can be concluded from the picture as well, as can be easily seen for example for year 5 in figure 3.4. This will in its place cause the efficiency to go up with a larger porosity, because more volume can be extracted before the limit salt concentration is reached. The aquifer that works the best will have a porosity of 0.5, concluding from these figures.

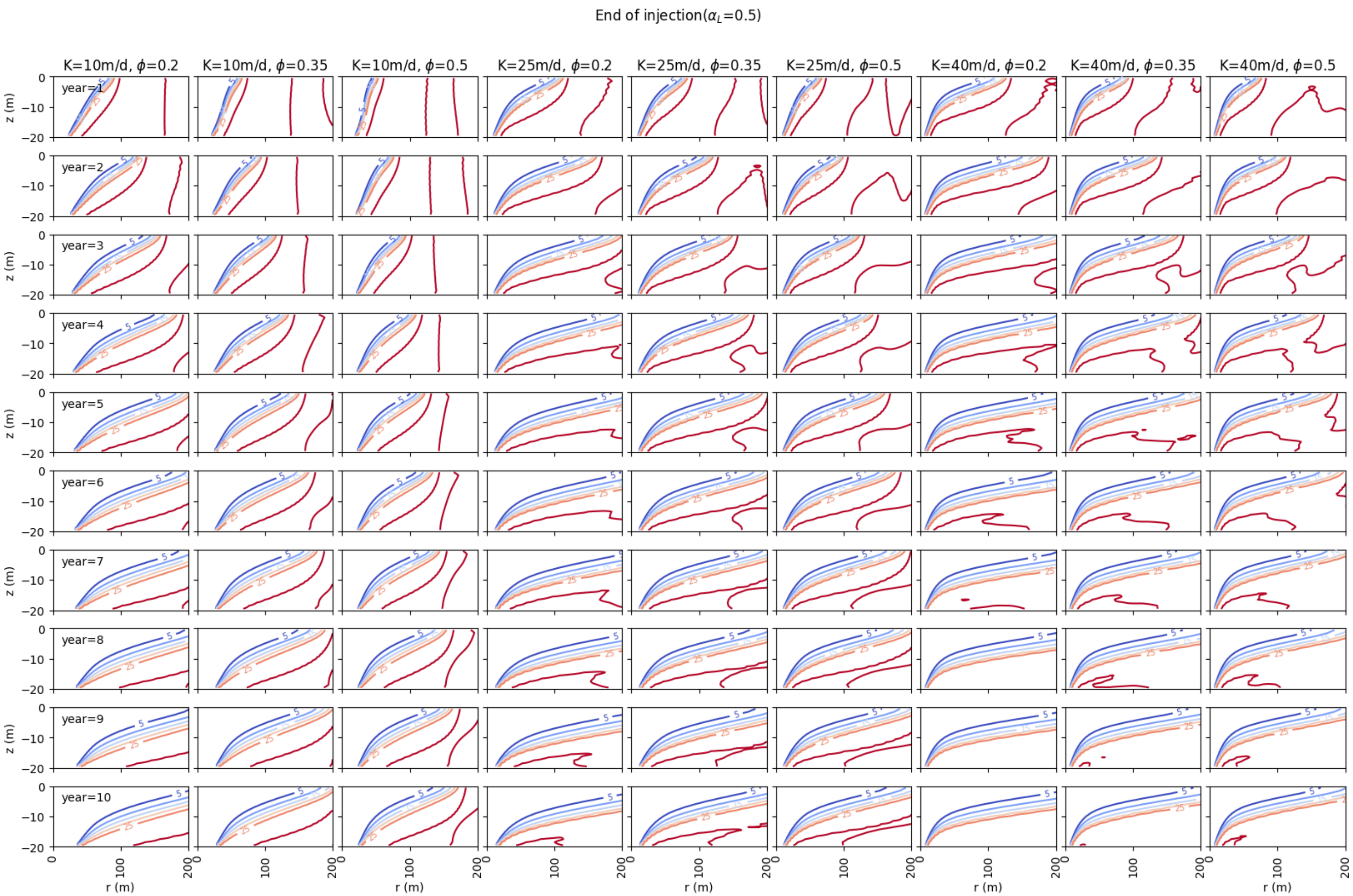


Figure 3.4: Overview flows at End of injection (day 303)

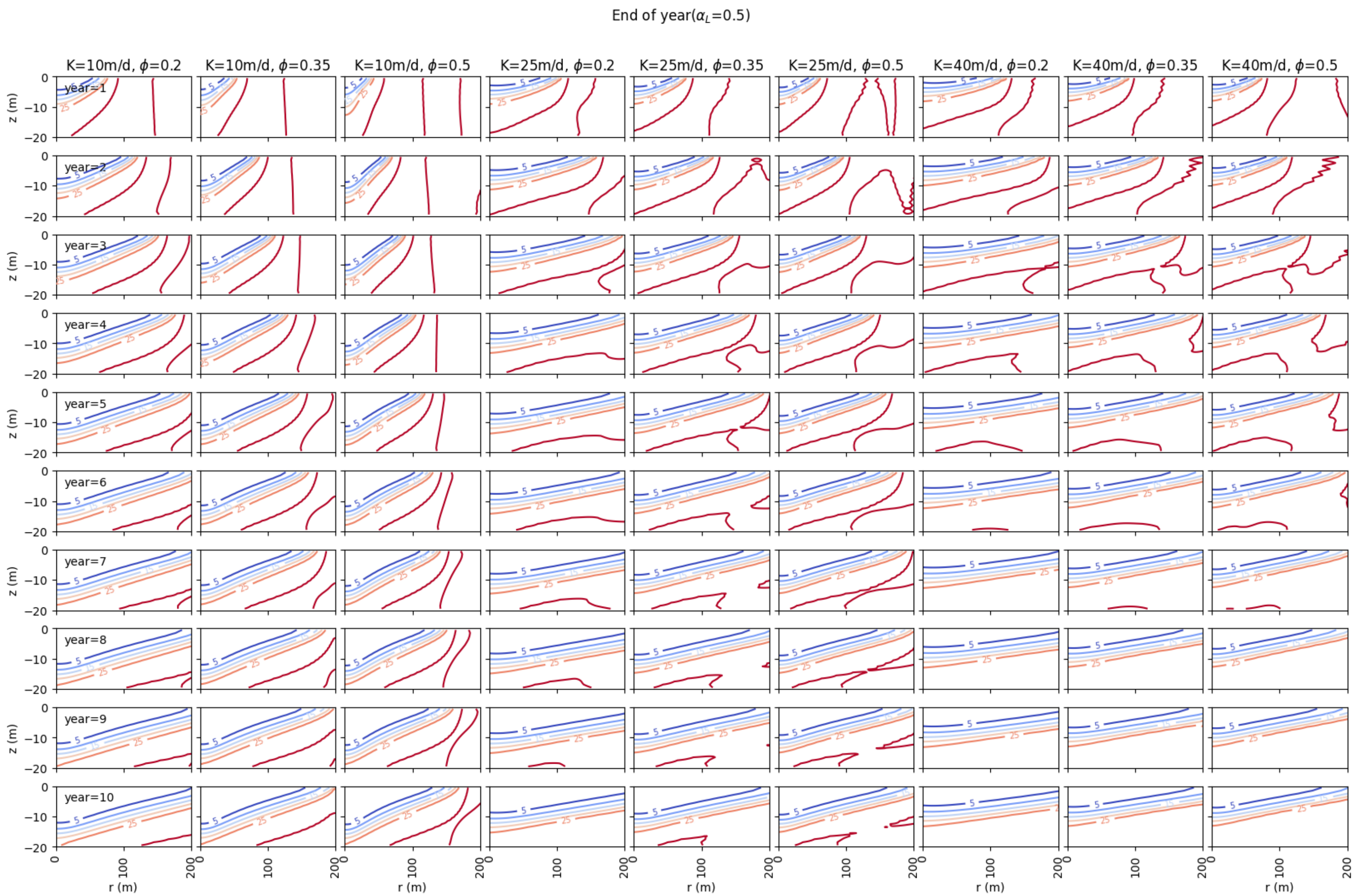


Figure 3.5: Overview flows at End of year (day 365)

The influence of the porosity and hydraulic conductivity on the recover efficiency is summarised in figure 3.6 it is clearly shown here that an higher hydraulic conductivity means a lower recover efficiency and an higher porosity means an higher recover efficiency.

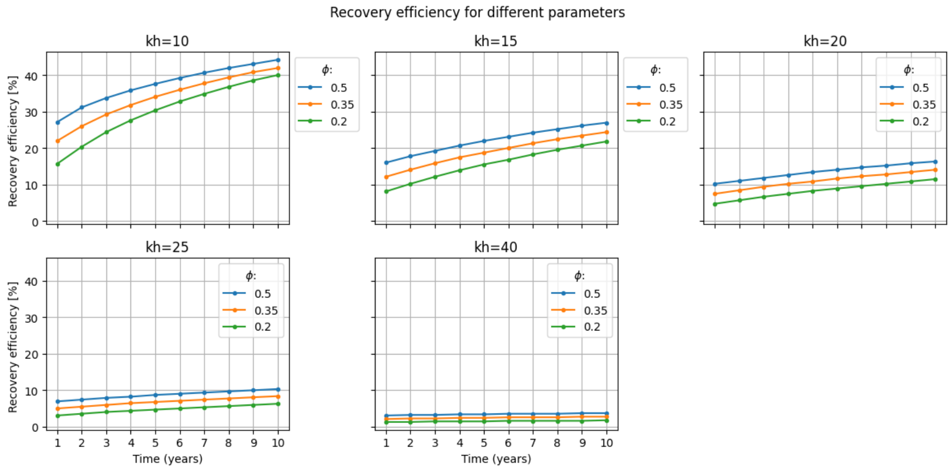


Figure 3.6: Sensitivity analysis of porosity and hydraulic conductivity in terms of recover efficiency

Longitudinal dispersivity
The same process can be repeated for the longitudinal dispersivity (α_L). Here the hydraulic conductivity and porosity are kept at 10m/d and 0.35 respectively. Figure 3.7 shows that a higher value of dispersivity lowers the efficiency in the first year, but increases the efficiency in the years after a certain turning point, which is around 4,5 years in this figure.

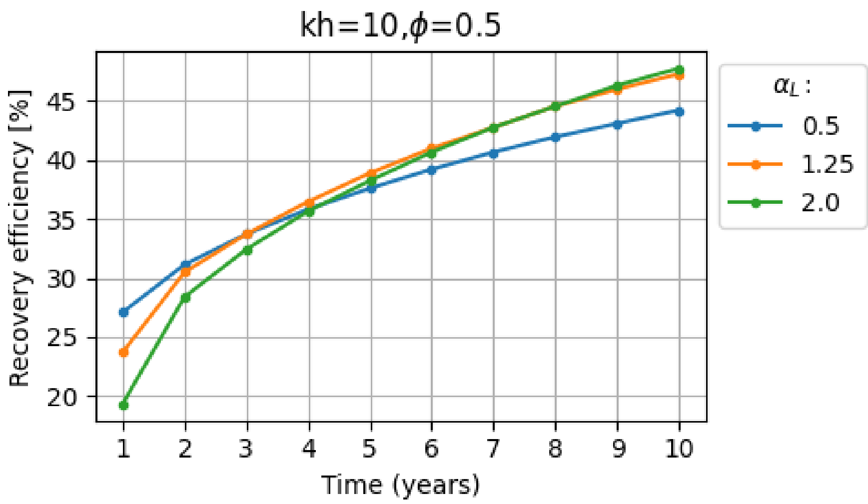


Figure 3.7: Recovery efficiency for different values of α_L

Number of layers
The amount of layers for the system was also analysed. The results from this analysis are showed in figure 3.8. This figure indicates that the increase in layering causes the model to run more smooth and gives the contours more smoother lines, which is better for the model and indication for the contour lines. The limit in this case is the computational time, because it would be good to have 30/40 layers of $\sim$0.5m thickness instead of 10 or 20 layers of 2 and 1 m thickness respectively. The middle way was chosen for this model to run it with 20 layers.

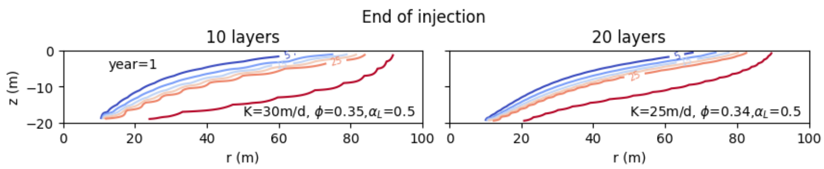


Figure 3.8: Overview difference in layers for the end of injection

Domain size
The chosen modelled domain is 300m. This is a fair assumption as the furthers the bubble reaches is just beyond 200m as shown fig 3.8 for a hydraulic conductivity of 40 and prorosity of 0.35.

The most important finding is that all parameters still keep a asymptotic profile towards a certain efficiency. In the range of parameters mentioned, over time the efficiency in all cases will keep increasing. If more detailed information about the parameters from the aquifer is known, a more concrete design could be made to develop an injection and extraction scheme. Some combination of parameters are shifted down, but these can likely be compensated through the injection scheme proposed. The main question then is whether a aquifer economically viable if the efficiency is lower. This however is outside of the scope of this report.

3.5. Adjusting injection scheme

Using the parameters from the sensitivity analysis a best case scenario can be explored to construct a guideline for a selection in aquifer for this demand. The best case includes an hydraulic conductivity of 10 m/d, a porosity of 0.5 and a longitudinal dispersivity coefficient of 0.5. The limiting factor in the search of a good aquifer is the guideline on the injection pressure. This makes it impossible to use an aquifer that has other parameters than this case, because more water is needed to meet this demand and running the aquifer for more years will not contribute significantly enough to an increase in efficiency to make 'lesser' aquifers worth it. 3.9.

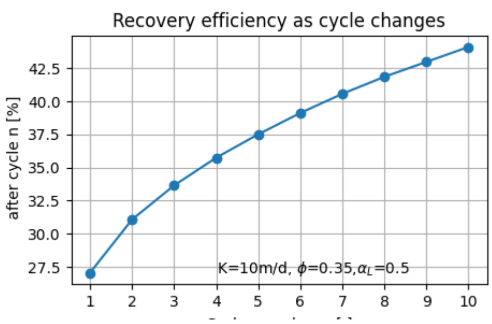
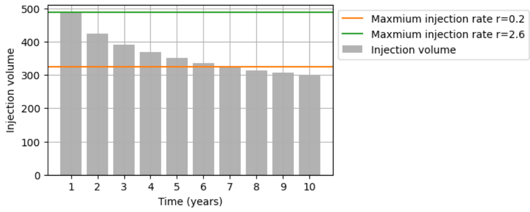


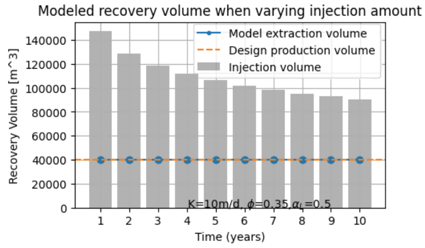
Figure 3.9: Recovery efficiency for best case scenario

In the best case in the first year, around 145000 m^3/year needs to be injected to meet the required 40 000m^3/year as the efficiency is still quite low. As explored in section 2.2.2, the maximum allowed injection rate in the case of a hydraulic radius of 10 m/d is 300m^3/d. This is lower than the 487m^3/d injected during the 303 days of the first year. This means that the guideline will be violated slightly when a well radius of 0.2m is used. Using equation 2.2, increasing the radius to 2.6m solves this issue. This is quite a large well radius. In reality two wells slightly apart would make more sense. The injection volume per day will flatten out over the years as is depicted in figure 3.10a. Here it is shown that after 6 years the guideline is met. Small disclaimer on this guideline is that it was established by an empirical approach, so there will be some wiggle room in the first years, however monitoring stations are advised.

The best case system with an injection, extraction and storage schedule can be modelled and the resulting recovered volume is depicted in figure 3.10b.



(a) Maximum injection rate versus required injection rate



(b) Recovery efficiency with schedule for injection and storage

We see that increasing the injected volume has no effect on the efficiency in this case. Thus to obtain the required extraction volume, the amount injected can be adjusted accordingly. This procedure can be done for some the results from the sensitivity analysis. Using the model this can be done for any combination of parameters found in reality in the field by the drinking water company. Figure 3.11 shows this for 9 different scenarios. Note that the y-axes are of a very different order of magnitude.

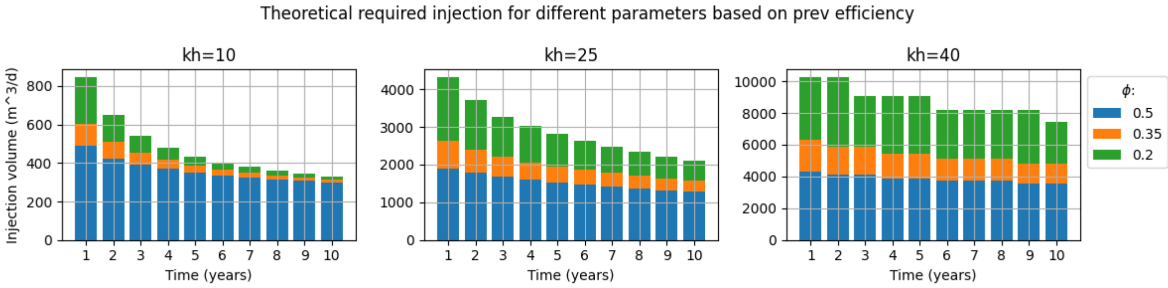


Figure 3.11: Required injection to meet design volume

To meet the required injection volumes shown above, the radius of the well needs to be increased. Different values are illustrated below in figure 3.12. However, increasing the radius, causes very little for the low values of porosity as the relationship is not linear. In this case multiple wells would be the better option to be investigated should this be the case.

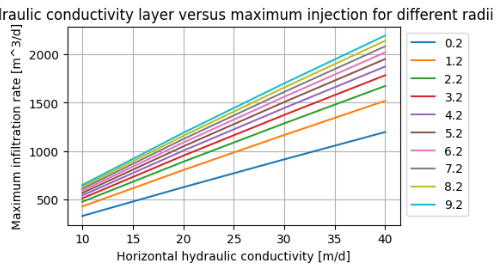


Figure 3.12: Injection volumes allowed for different well radii

4

Conclusion and discussion

In conclusion, the proposed Large-scale Aquifer Storage and Recovery (ASR) system serves as a vital solution for addressing the challenges posed by climate variations and population growth in ensuring a sustainable and reliable water supply.

The system's significance lies in its ability to use brackish aquifers to provide a dependable reservoir for drinking water during critical summer months. As highlighted in the report, the aquifer's characteristics, namely porosity and dispersivity, play a crucial role in determining the system's efficiency. The efficiency goes up if the dispersivity is smaller so that means that a lesser deep aquifer is better for your losses. The hydraulic conductivity plays an important role in the efficiency due to the fact that a larger freshwater bubble can be formed and its influence on the maximum injection and extraction rate. The only viable system in this research is one with a small hydraulic conductivity. Other soil properties influence the amount of settlement that takes place and this settlement needs to be limited in every case or good precautions need to be taken out to limit the damage.

The methodology employed, including modeling steps and results, provides valuable insights into the system's performance over multiple years with a multi-layered system including the buoyancy effect. Varying injection volumes is considered to optimize efficiency, and sensitivity analyses shed light on the impact of parameters such as hydraulic conductivity, porosity, and dispersivity. This lead to the conclusion that more certainty in the porosity and hydraulic conductivity is needed to know if a system is economically viable in a future design stage. These results show that a system in a comparable aquifer is technically possible, but will exceed some guidelines. If a system is used with worse parameters than presented in the best case, it will probably not be operable. Varying the well radius to meet injection rate guidelines will be necessary once the hydraulic conductivity and porosity are known with more accuracy. Possibly two or three wells could be more suitable, but this effect is yet to be investigated.

In summary, the ASR system presented in this report is a theoretical framework to investigate the sensitivity of the important parameters and to investigate a schedule including storage to make it operable. This system however will not operate with a lesser compatible aquifer and will drastically exceeds guidelines then. This system will be safely operable with enough monitoring and more certainty in the characteristics of the aquifer that is used.

References

Dillon, P. J., Pavelic, P., Toze, S., Rinck-Pfeiffer, S., Martin, R. R., Knapton, A., & Pidsley, D. (2006). Role of aquifer storage in water reuse. *Desalination*, *188*(1-3), 123–134. doi:10.1016/j.desal.2005.04.109

Drijver, B. (2002). *Zettingen bij afwisselend onttrekken/infiltreren en variërende onttrekkingen* (tech. rep. No. 1156604485). H twee O. Retrieved from https://wur.on.worldcat.org/oclc/1156604485

Pirnie, M. (2011, February). *An Assessment of Aquifer Storage and Recovery in Texas*. Texas Water Development Board. Retrieved from https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/0904830940_AquiferStorage.pdf

Van Dooren, T., & Zuurbier, K. (2020). COASTAR Cities2Recharge. Monitoringsparameters voor fuctioneren van diepinfiltratiesystemen in stedelijke omgeving. *KWR*, (KWR 2020.185). Retrieved from https://library.kwrwater.nl/publication/61802381/

Ward, J., Simmons, C. T., Dillon, P. J., & Pavelic, P. (2009). Integrated assessment of lateral flow, density effects and dispersion in aquifer storage and recovery. *Journal of Hydrology*, *370*(1-4), 83–99. doi:10.1016/j.jhydrol.2009.02.055

A

Source Code

Modflow 6 can be used with python using the FloPy package which acts as an interface. This allows quick and easy scripting of ground water models. All code can be found on GitHub. Which is a series of Jupyter notebooks producing the plots found in this report. To optimise this,