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

The proposed Large-scale Aquifer Storage and Recovery (ASR) system offers a robust solution for sustainable water supply challenges, addressing critical issues through well- thought design and adaptive strategies. Examining injection-extraction schedules, waste minimization, and compliance to pressure and velocity guidelines, the system emerges as a reliable reservoir.

The system parameters, including hydraulic conductivity (k), porosity (ϕ), and longitudinal dispersivity (α_L), were carefully considered. The modeling results for a 10-year period revealed a recovery efficiency reaching an asymptotic profile and achieving around 40,000 m^3/year total recovered volume from the second year onward. An annual adjustment of injection volumes facilitated the desired design target.

Methodological insights, encompassing modeling steps and results, offer a nuanced understanding of multi-year performance. Optimization through varying injection volumes is explored, while sensitivity analyses underscore the impact of key parameters. The findings underscore the importance of enhancing certainty in porosity and hydraulic conductivity for subsequent optimization cycles.

Despite the need for additional injection in the initial years, the system gradually adapts, demonstrating robustness. The ASR system successfully meets extraction targets, exhibits robustness under challenging conditions, and stabilizes injection volume over the course of 10 years.

A sensitivity analysis highlighted the impact of key parameters, showing that higher porosity reduced efficiency, hydraulic conductivity affected groundwater head response, and increased dispersivity lowered efficiency. The worst-case scenario, with parameters set at their extreme values, demonstrated the system's adaptability, requiring additional injection in the first year but meeting maximum allowed injection rates.

In conclusion, the ASR system outlined in this report provides a comprehensive and adaptive approach to sustainable water supply, addressing both technical intricacies and potential uncertainties. Sensitivity analyses provide insights into parameter impacts, guiding future optimization. Future steps include improving certainty in porosity and hydraulic conductivity and optimizing based on actual performance data after the first cycle. This ASR system stands as a promising solution for a sustainable water supply management.

Contents

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 within them, and later utilize it for various beneficial purposes, such as agricultural irrigation. These systems are instrumental in enhancing the overall quantity of available water for diverse applications, including irrigation and drinking water supply. Furthermore, the cost-effectiveness of these systems stems from their efficient utilization of natural conditions.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 roadmap 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.

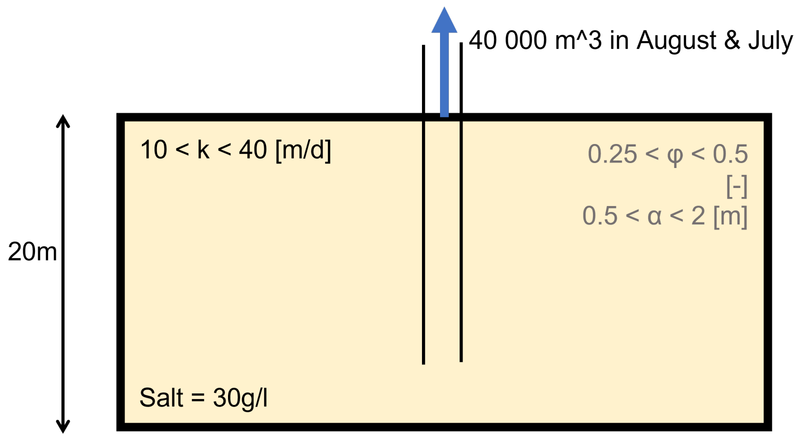


Figure 2.1: Overview situation aquifer

2.1. Comparable systems

In the world many aquifer storage and recovery systems are known, all with very different aspects and characteristics. The system operating in Florida extracts for example 100 times more water from the subsurface as the system in this research. Pirnie, 2011 There was a paper available on the research of several systems that are located all over the globe. This paper produced the parameters per system as showed in figure 2.2

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 (m³)	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

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)

$$f(t) = \frac{C_{ambient} - C_{well}(t)}{C_{ambient} - C_{injected}} \qquad \text{(Ward, Simmons, Dillon, and Pavelic, 2009)} \tag{2.1}$$

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 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

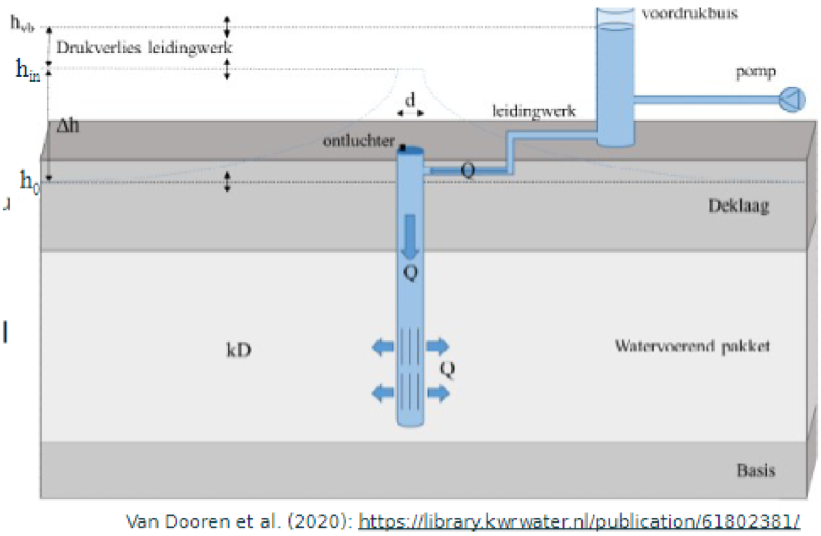


Figure 2.3: Figuration for correlation on maximum infiltration rate

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:

- 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.

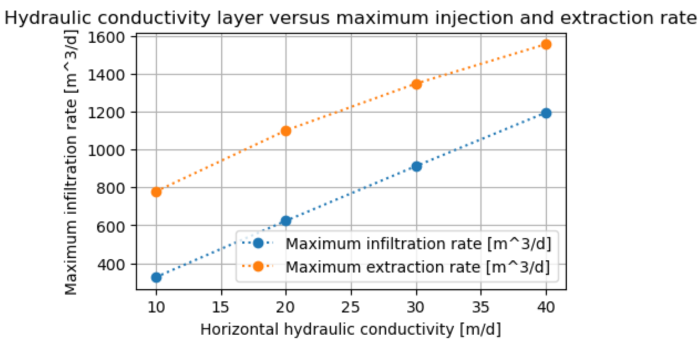


Figure 2.4: Horizontal hydraulic conductivity versus maximum injection and extraction rate

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 $\frac{m^3}{d}$, but because we inject over 303 days, we suspect that the maximum injection rate doesn't will be a constraint for this 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. The maximum extraction rate in the worst case scenario will be 800 $\frac{m^3}{d}$ if this extraction rate is too low, a change can be made in the radius of the extraction well. The extraction rate won't vary as the total of 40 000m^3 in two months is a design requirement.

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.

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

With:

Z:	Soil compaction (m)	d =	10 (m)
d:	Thickness of confining layer (m)	C_p =	[7,10,30,140] (-)
C_p:	Primary compaction constant (-)	C_s =	[80,110,500,1680] (-)
C_s:	Secular compaction constant (-)	ϕ =	100 ($\frac{kN}{m^2}$)
ϕ:	Pore pressure ($\frac{kN}{m^2}$)	$d\phi$ =	40 ($\frac{kN}{m^2}$)
$d\phi$:	Change of pore pressure ($\frac{kN}{m^2}$)	t =	62 (days)
t:	time (days)		

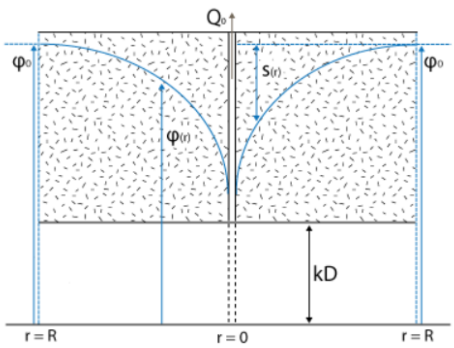


Figure 2.5: Figuration for maximum soil compaction

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.

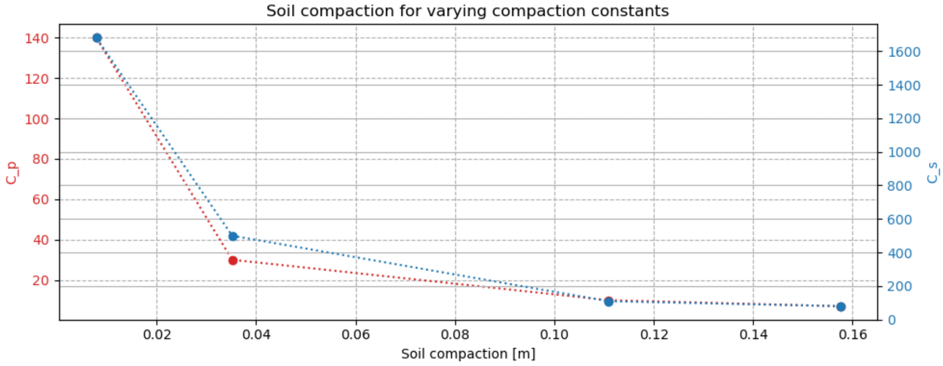


Figure 2.6: Soil compaction for varying compaction constants

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.

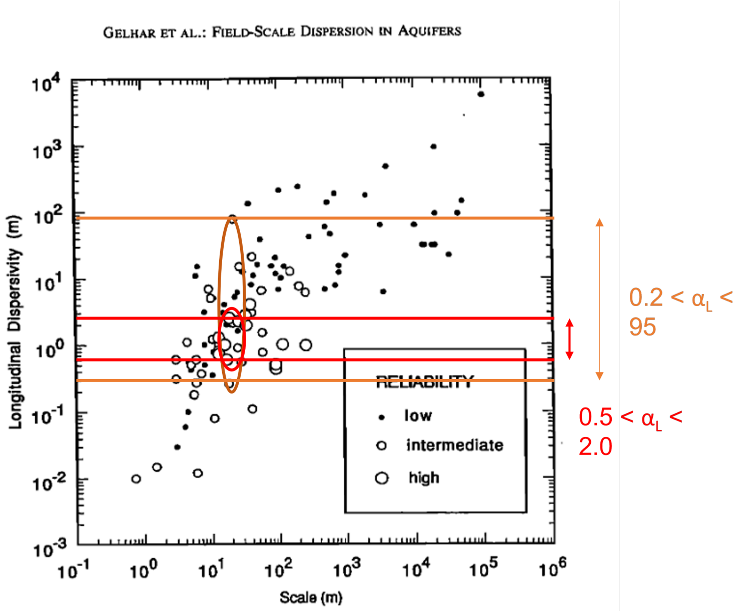


Figure 2.7: Dispersivity versus scale for different sites

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 1D 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. The model can then be compared to the exact formula for radial flow which is given by equation 3.1. This yields the plot shown in figure 3.1.

$$h = -\frac{Q}{2\pi kH}\ln(r/R) \tag{3.1}$$

With:

h: Hydraulic head (m)
Q: Discharge in well ($\frac{m^3}{d}$)
k: Hydraulic conductivity ($\frac{m}{d}$)
H: Thickness aquifer (m)
r: Radius of well (m)
R: Distance to point (m)

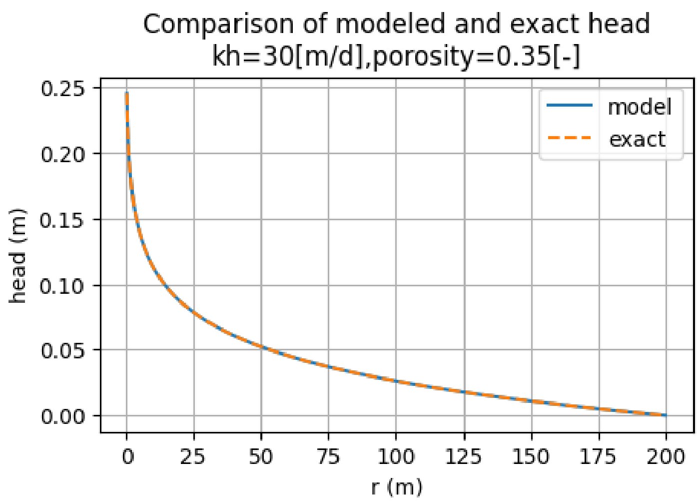


Figure 3.1: Comparison of modeled and exact head

Throughout this section an average value of 30m/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 sensitivity analysis for these parameters is done once the model is fully functional. With realistic head values, we know the groundwater flow in the model is also realistic as these are related directly in the finite difference model used by MODFLOW6. The salt transport model can be added to model how the injected fresh water reacts 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, initially a design factor of 1.25 is applied to account for losses resulting in a total injection of 50 000 m^3/year. For the later years where efficiency reaches around 90% this factor is too high, but this is adjusted later. This results in an extraction of 806m^3/d and an injection of 165m^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 27 days of extraction (day 340) as seen depicted as the purple line in figure 3.2. This results in a low efficiency of 61%.

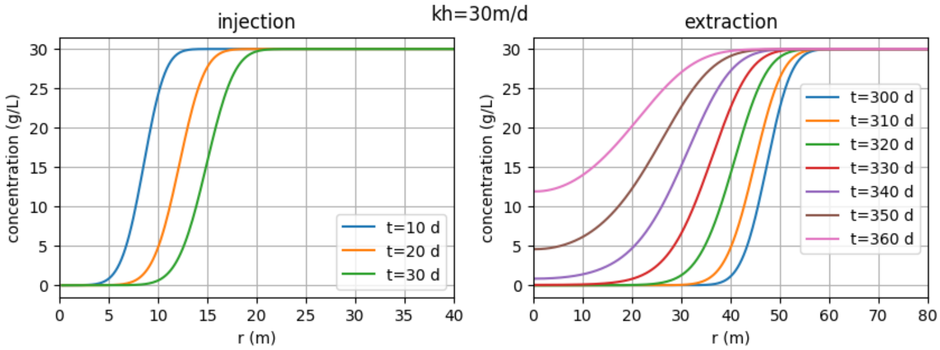
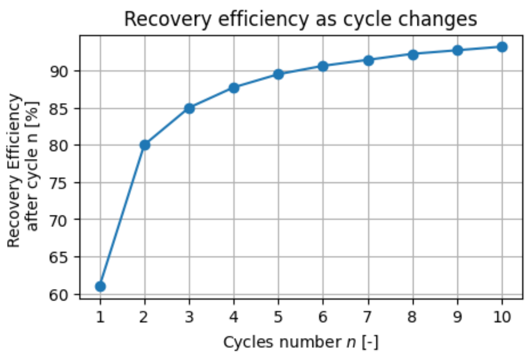


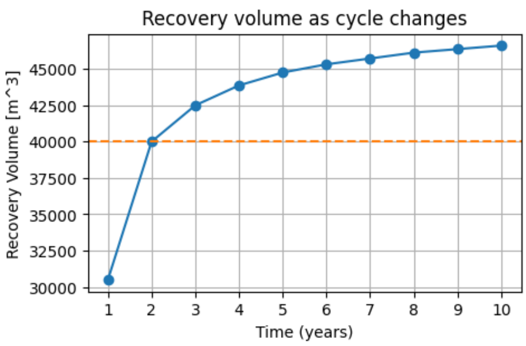
Figure 3.2: Concentration during injection & extraction

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 3.3a. We can also consider the total volume produced as seen in figure 3.3b, the factor of 1.25 mentioned before was set such that from the second year on wards, the design value of 40 000 m^3/y is met.



(a) Recovery efficiency for 10 cycles



(b) Recovered volume for 10 cycles

Figure 3.3: 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 recovery efficiencies multiplied by the design volume as a reference start value, the injection amounts can be manually updated to achieve the required extraction amount every year.The efficiency increases over time and not linearly. A minimisation scheme using more iterations has the same effect, however takes long to run and thus was not used. The result can be seen in figure 3.4 where the recovery volume is all just above 40 000 m^3 per year. After 10 years the efficiency seems to almost level off. There will always be some loss associated with the storage in brackish aquifers.

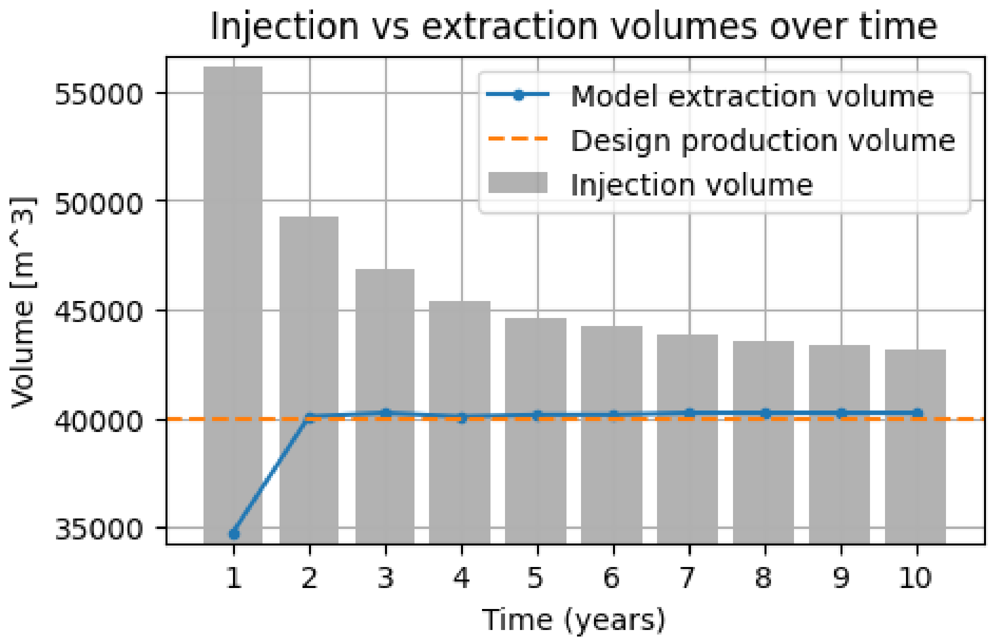


Figure 3.4: Recovery volume after varying injection volume every year

3.4. Parameter sensitivity

The parameters used to model the flow in groundwater have some uncertainty in them. 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., 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. Running the model and varying these parameters can bee seen in figure 3.5. The simplification of using a constant injection volume every year is used in this case. From this we see that a higher porosity means a lower efficiency, due to more mixing with the brackish groundwater. The hydraulic conductivity has an effect on the response of the groundwater heads, but not on the efficiency as this is mostly effected by the mixing processes. A lower value of hydraulic conductivity means larger head changes, which will affect the underground, but doesn't affect the efficiency of the ASR system as such. It does affect the maximum allowed injection and extraction as explained in section 2.2.2

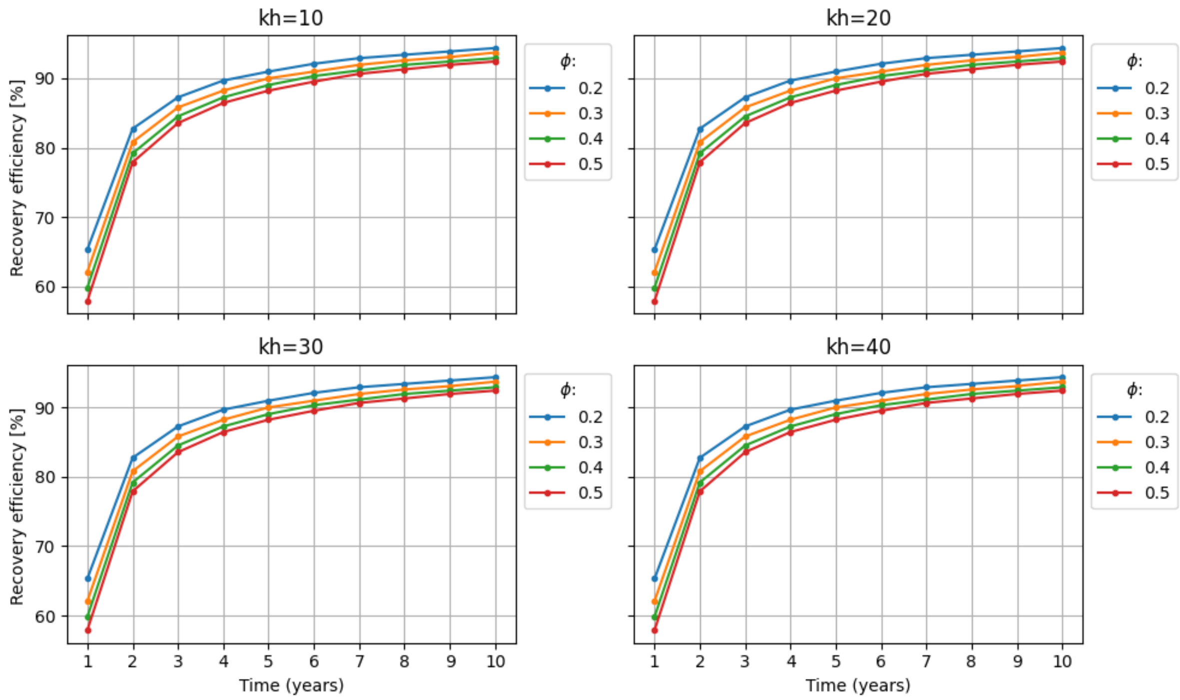


Figure 3.5: Recovery efficiency for different parameter combinations of K & porosity

The same process can be repeated for the longitudinal dispersivity (α_L). Here the hydraulic conductivity and porosity are kept at 30m/d and 0.35 respectively. Figure 3.6 shows that a higher value of dispersivity lower the efficiency.

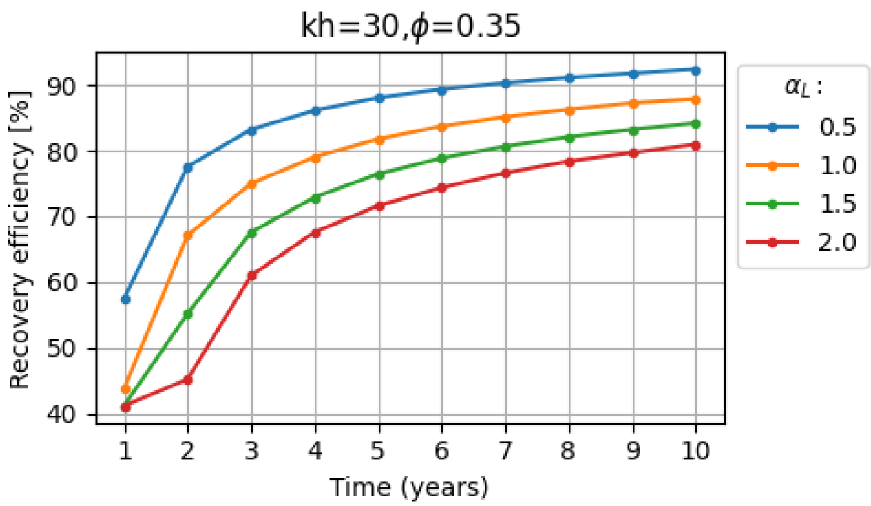


Figure 3.6: Recovery efficiency for different values of α_L

The most important finding is that all parameters still keep a asymptotic profile towards an efficiency of 100%. In the range of parameters mentioned, over time the efficiency in all cases will keep increasing. This means the method is viable for all aquifers with properties in the range of parameters mentioned. 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. worst case

Using the parameters from the sensitivity analysis a worst case scenario can be explored to double check that it works in this case. We have a good idea that it should function from the sensitivity analysis. This worst case is a situation with a hydraulic conductivity of 10 m/d, porosity of 0.5 and longitudinal dispersivity coefficient of 2. This gives an indication of an average case as shown previously in figure 3.4 and worst case shown below in figure 3.7. In the worst case in the first year, around 70 000m^3/year needs to be injected to meet the required 40 000m^3/year as the efficiency in the worst case is very low. As explored in section 2.2.2, the maximum allowed injection rate in the case of a hydraulic radius of 10m/d is 350m^3/d. This is higher than the 232m^3/d pumped in during the 303 days of the first year in the worst case and thus the design meets the requirements. To meet the extraction requirements a larger well radius should be used compared to higher hydraulic conductivity's to meet the extraction design requirements.

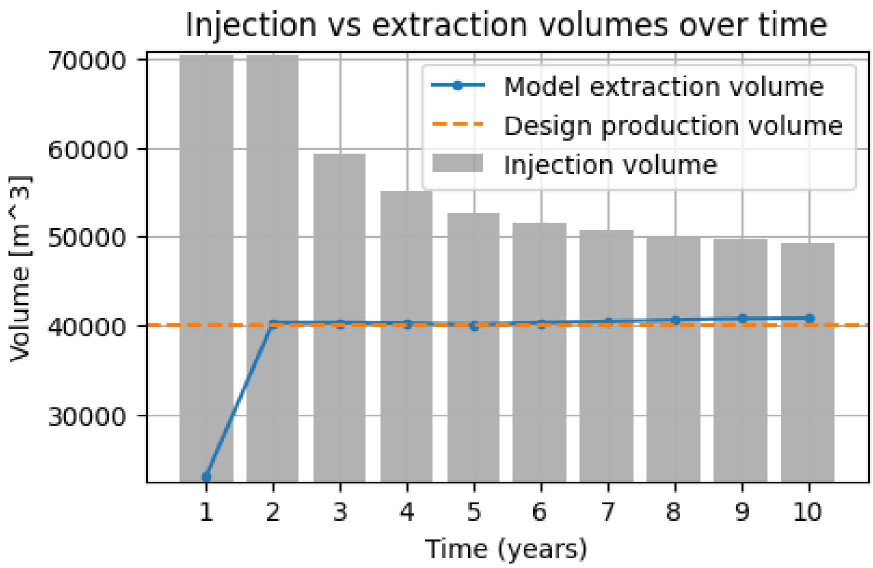


Figure 3.7: Injection scheme for worst case scenario

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 brakish 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 minder deep aquifer is better for your losses. The hydraulic conductivity also play an important role in the maximum injection and extraction rate. Other soil properties influence the amount of settlement that takes place.

The methodology employed, including modeling steps and results, provides valuable insights into the system's performance over multiple years. 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.

In summary, the ASR system presented in this report not only successfully meets extraction targets but also exhibits resilience even under challenging conditions, as demonstrated in the worst-case aquifer scenario.

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,