Exploration of the Effects of Aquifer Storage and Recovery Solutions on the Water Quality and Quantity in a sandy ridge system in Ben Tre, Vietnamese Mekong Delta

FAME – Freshwater Availability in the Mekong Delta

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MSc Thesis
31/12/2020

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Abstract

In the Vietnamese Mekong Delta, climate change, social economic development and a high population density come together and put severe pressure on the delta's available natural resources and its freshwater availability in particular. Freshwater sources are intensively exploited in order to meet the increasing water demand. This has caused subsidence and saltwater intrusion of both surface and groundwater. Especially in recent years saltwater intrusion is reaching further inland, causing significant damage to crops and is only expected to become more severe in the future. This stresses the need for new sustainable water management strategies. This study will assess the feasibility of such a strategy, an aquifer storage and recovery (ASR) solution, on a shallow phreatic sandy ridge aquifer in the province of Ben Tre in the Vietnamese Mekong Delta and evaluate whether this could provide freshwater security to farmers and secure their agricultural proceeds. As these solutions have shown to be effective in increasing the freshwater lens in the Netherlands on similar geomorphological structures, a pilot study will be done in the Mekong Delta if the solution proves to be effective. The objective of this study was to quantify the impacts of an ASR solution on the freshwater availability and quality at the selected study area in Ben Tre, Mekong Delta, in order to enable a future pilot study. This was done by creating a 3D-variable-density groundwater and coupled solute transport module, using iMOD Water Quality, a feature of iMOD 5.1. Various ASR designs were evaluated, with either vertical or horizontal extraction or infiltration wells. Additionally, the effect of spacing between infiltration wells and the infiltration rate was evaluated. It was shown that the shallow aquifer is sensitive to groundwater extractions and water management practices are required to avoid overexploitation. The study showed that multiple ASR designs can effectively create a water buffer in the dry period. In case of saltwater intrusion of groundwater, horizontal extraction wells are preferable as they prevent extreme chloride concentrations. Note that the concentration of the infiltrated water is crucial to ensure a good water quality, that qualifies for irrigation and drinking purposes. In shallow aquifers with different physical and hydrogeological characteristics ASR solutions were also shown to be effective, which shows the promise of ASR solutions in increasing the water security on a local scale in the Mekong Delta.

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1. Introduction

Deltas have various important functions. They have rich ecosystems with high biodiversity that play a crucial role in coastal protection. A large part of the world's agricultural and aquacultural production and forestry produce takes place in deltas, giving them an important economic function. They are also densely populated and home to a large part of the world's population (Foufoula-Georgiou et al., 2013). Nevertheless, mega delta's are considered to be one of the most vulnerable environments, under major threat of climatic impacts, such as sea level rise and salinization of fresh water resources, as well as human-induced changes, such as land use change, upstream dam construction and groundwater extractions (Foufoula-Georgiou et al., 2013; Nicholls et al., 2007). Delta's are degenerating at alarming rates (Nicholls et al., 2007), which has a major impact on the livelihoods, food security and health of millions of people (Rahman et al., 2019). One of the most threatened deltas is the Vietnamese Mekong Delta, where climate change, social economic development and a high population density come together and put severe pressure on the delta's available natural resources.

1.1. Vietnamese Mekong Delta

The Mekong Delta is the third's largest delta in the world with an area of 39,734 km^2, and is densely populated as it is home to about 20 million people (Nguyen et al., 2019; Shrestha et al., 2016). The Mekong Delta is also a key region for food security (Coleman & Roberts, 1989; Shrestha et al., 2016), being responsible for a large part of Vietnam's aquaculture products and rice production. 65% of the delta is being used for agricultural purposes and 90% of Vietnam's rice production takes place in the Mekong Delta (Boretti, 2020). With Vietnam being a large exporter of rice, the Mekong Delta is also important for food security for larger parts of South East Asia (Minderhoud et al., 2017; IUCN, 2011).

However, the Mekong Delta is predicted to be one of the most vulnerable areas in the context of climate change induced sea level rise, with up to 40% inundation by the end of the century under certain climate change projections (IPCC, 2007; Nguyen et al., 2019, Ward et al., 2009). Freshwater availability is already limited, as 80% of the population in the coastal area depends upon groundwater for domestic consumption and about 4.5 million people depend upon it as a drink water source (Shrestha et al., 2016; Nguyen & Tuyen, 2005). This freshwater availability in the delta is becoming increasingly vulnerable, as the quality decreases as a result of (agricultural) pollution and saltwater intrusion whereas the demand is continually increasing. Groundwater abstractions have increased substantially as a result of intensified rice cultivation (Shrestha et al., 2016), which is only expected to increase in the future as a three-fold increase in agricultural demand compared to 2000 is expected for 2100 (Hamer et al., 2020). With overexploitation of fresh groundwater sources the delta faces continued subsidence, which is reinforced by a lack of sediment supply caused by upstream dam construction. The coastal provinces in the Mekong Delta experience the largest threat from saltwater intrusion into both canal and river water as groundwater, as a result of the combination of sea level rise and continued subsidence – also called relative sea level rise (Minderhoud et al., 2017).

This extreme saltwater intrusion, especially in recent years, stresses the need for new water management strategies. One initiative to combat these problems is the freshwater availability in the Mekong Delta (FAME) project, a collaboration between the Royal Netherlands Enterprise Agency with RoyalHaskoningDHV, Deltares, Utrecht University, Wageningen University (WUR) and local Vietnamese partners: Center of Water Management and Climate Change (WACC) and Division for Water Resources Planning and Investigation for the South of Vietnam (DWRPIS). The project assesses the feasibility of the implementation of Aquifer Storage and Recovery (ASR) systems in relation to sustainable food production on a 'farmer scale level'. ASR is a technique in which excess surface water is injected in times of water abundance and extracted during times of water shortage or times of peak demand (Brown et al., 2016; Culkin et al., 2008). Most of the Mekong Delta comprises rural areas, and even though highest groundwater abstraction rates are found in urban areas, people living in rural areas are responsible for approximately 80% of the total volume of groundwater extractions and are the largest contributors to groundwater extraction-induced subsidence, (Minderhoud et al., 2017). This validates the 'farmer scale level' of the FAME project.

Ben Tre province is the most vulnerable to climate change and sea level rise out of all thirteen provinces in the Mekong Delta (Minh, 2017). Here, old sand dune ridges can be found which serve as shallow aquifers supplying groundwater to the farmers living on or close to the dunes, which have been and still are an important source of freshwater for people living in those areas. (Van Be & Tuyen, 2005). With increasing demands, the pressure on both the quality and quantity of the fresh water is increasing. In order to successfully implement ASR solutions in the Mekong Delta, first a pilot needs to be designed, conducted and monitored (*Freshwater Availability in Mekong Delta (FAME) - Deltares*, n.d.; Kruijt, 2020), before upscaling becomes a possibility. Successful implementation should lead to increased freshwater availability for farmers and counteract groundwater induced subsidence and saltwater intrusion. During the first phase of FAME three potential pilot sites were analyzed, after which the site with the highest potential was selected for further analysis.

The objective of this study is to quantify the impacts of an ASR solution on the freshwater availability and quality at a study area in Ben Tre, Mekong Delta. This will be done by creating a 3D-variable-density groundwater and a coupled solute transport module in order to simulate the movement of saltwater particles. The model will be created using iMOD-WQ (iMOD Water Quality), a feature of iMOD 5.1 (Vermeulen et al., 2020), based on data collected in the previous research phase of FAME as well as data from literature. Various design options will be evaluated on a small and large scale. Additionally, the ASR solutions will be evaluated in the light of the potential for upscaling to different locations.

This has led to the following research question:

How does an operating ASR system in combination with groundwater extractions affect the water quality and quantity of the sand dune aquifer at a field location in Ben Tre?

This research question will be answered by dividing it into several sub research questions:

1. What are the effects of groundwater extraction on the hydrogeological system in the current situation, without an operating ASR system?
2. What is the optimal design for an ASR system, considering the local hydrogeological conditions and what is the potential volume for infiltration?
3. How does an operating ASR system affect the fresh-salt water boundary?

1.2. Report structure

This report will elaborate on the aforementioned research objectives and questions. Chapter 2 will provide a detailed description of the problems experienced in the Mekong Delta and Ben Tre in particular and elaborate on the potential of ASR solutions as a sustainable water management strategy in this region. Additionally, the study site will be discussed in detail. Chapter 3 will expand on the research methodology. The acquirement of data needed as model input, the model set-up and the different research scenarios will be discussed. These results will be presented in chapter 4 and discussed in chapter 5. Chapter 5 will also expand on the research limitation and present some recommendations for further research. Finally, chapter 6 will be utilized to present an answer to the research questions.

2. Theory

2.1. Situational assessment

2.1.1. Threat to freshwater security

The groundwater levels and storage in the Mekong Delta are increasingly vulnerable. According to RCP 4.5 and RCP8.5 climate change will cause a temperature increase between 1.5 and 4.9 C by the end of the 21st century. Rainfall is projected to further increase during the wet period and decrease during the dry period, whereas 90% of the rainfall already occurs during the wet period. Future recharge is projected to remain almost constant at 28mm during the wet period and decrease during the dry period by 2 to 4 mm. As a result the annual groundwater recharge is expected to decline by over 120 to 160 million cubic meter according to the respective climate scenarios (Shrestha et al., 2016).

During the dry period (December to May) low rainfall levels both in upstream and downstream areas of the Mekong Delta reduce the freshwater streamflow, allowing saline water to intrude further upstream. Intrusion can reach an area of 1.3 million hectares (Eslami et al., 2019) and puts additional pressure on the already limited freshwater resources (Ward et al., 2009; Kubo, N. et al., 2005). Networks of canals have been built in order to supply farmers with freshwater for irrigation purposes during the dry period, but these channels allow saltwater intrusion to move even further inland (Rahman et al., 2019). With the frequency and severity of droughts increasing over the last 20 years, saltwater intrusion is becoming increasingly problematic. It has affected 10 out of 13 provinces and caused freshwater shortage as well as significant damage to crops (Boretti, 2020; IFRC, 2020). Although dykes and sluice gates were constructed for protection against salinity, pollution accumulates behind the gates when they are closed. This further enhances the freshwater availability (Renaud et al., 2015; Wagner et al., 2012).

Subsidence in the Mekong Delta has increased significantly over the past 25 years, with groundwater extractions being a dominant driver for this process (Minderhoud et al., 2017). Current groundwater extraction induced subsidence rates are estimated at 1.1 cm/yr for the entire delta, with certain areas surpassing 2.5 cm subsidence per year (see Figure 1). These rates exceed the rate of global sea level rise (~3 mm/yr) by an order of magnitude which is alarming (Minderhoud et al., 2017). Subsidence increases flood and storm surge vulnerability. An additional effect is saltwater intrusion, as the fresh-salt water interface moves towards the points of extraction when freshwater pressure drops. This is further enhanced by the trapping of sediment by upstream dam developments as well as sea level rise (Minderhoud et al., 2017; Shrestha et al., 2016). Saltwater intrusion is enhanced by a combination of factors and this poses a major threat to the delta (Minderhoud et al., 2017).

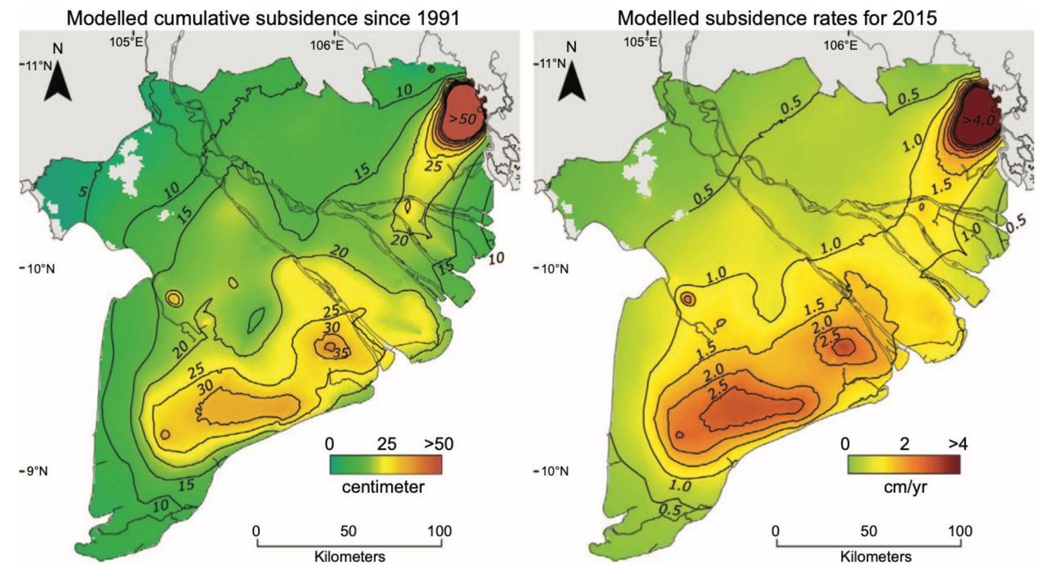


Figure 1. Model outputs of the Mekong Delta showing 25 years of extraction induced subsidence (left), and extraction induced rates of subsidence for 2015 (right) (Minderhoud et al., 2017).

In order to meet the increasing water demands in a sustainable way, new water management strategies are needed. One such a strategy is aquifer storage and recovery, which is the process of infiltrating and storing fresh surface water in permeable zones of confined and unconfined aquifers in times of water abundance for later recovery in times of water shortage (Brown et al., 2016; Culkin et al., 2008). Rainwater run-off to the sea is avoided and fresh water is saved and stored for later use (*Freshwater Availability in Mekong Delta (FAME) - Deltares*, n.d.). As the storage takes place in the already present subsurface, it is cost efficient, minimizes the aboveground water storage infrastructure, prevents water loss from evaporation and the water quality is higher than in aboveground water storage systems. Other benefits include environmental restoration, increased irrigation security, counteracting saltwater intrusion and the replenishment of baseflow (Brown et al., 2016; Culkin et al., 2008). A schematic representation of an ASR system is shown in Figure 2. ASR systems have already been developed in the Netherlands as well as in other countries, such as Australia, Israel and the USA (*Freshwater Availability in Mekong Delta (FAME) - Deltares*, n.d.).

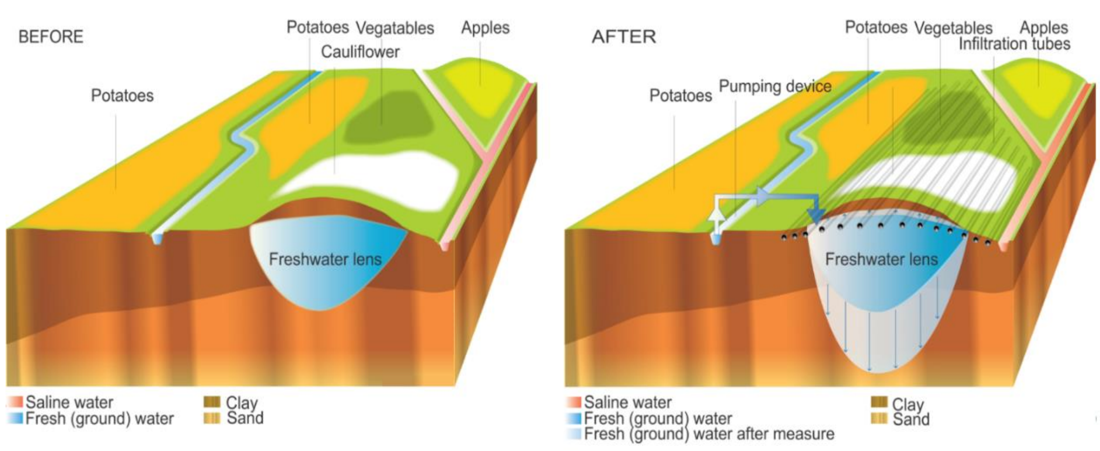


Figure 2. Conceptual visualization of an ASR system (Pauw et al., 2015).

These solutions have been successful in the Netherlands where the freshwater lens below a creek ridge – a geomorphological structure with a slightly higher elevation than the surroundings – in an area experiencing high salinity levels was increased (Pauw et al., 2015). With an artificial recharge and drainage system the freshwater lens was projected to increase with 40% of the total recharge, resulting in an increase of extraction rates with a factor of three. The implementation of horizontal wells in combination with such an ASR solution is worth investigating, since horizontal extraction causes less drawdown and reduces upconing of saltwater in comparison to vertical extraction (Pauw et al., 2015).

In the Mekong Delta 953km^2 of relict beach ridges can be found that were formed during the progradation of the delta (Tamura et al., 2012). These ridges differ significantly from the upper Holocene Delta plain sediments, which mostly consist of silt, clay and a combination of the two, and are therefore generally considered as aquitards (Minderhoud et al., 2017). The sandy ridges consist of well sorted fine sand, with greater infiltration capacities, making the shallow aquifers beneath them suitable for groundwater use and irrigation purposes (Ta et al., 2005). These sandy ridges are morphologically similar to the creek ridge in the example described above, which shows their potential for successful implementing an ASR solution. The muddy inter-ridge deposits that are located in between the sandy ridges may be significant for ASR purposes by acting as aquitards and isolating the shallow sandy ridge aquifers (Tamura et al., 2012).

Successful implementation of an ASR solution requires knowledge of the local hydrogeological conditions, as a low permeability and high storage capacity are crucial (Witjes, 2018). Moreover, the recovery efficiency – the fraction of infiltrated water that is recovered – depends on the local hydrogeological conditions (Rambags et al., 2013). As knowledge on the local hydrogeological conditions was lacking, the first phase of the FAME project focused on collecting hydrogeological data.

2.1.2. Ben Tre Province

Ben Tre is a coastal province in the Mekong data, with an area of 2287 km2, a population of approximately 1.2 million and a population density of 532 people per km^2 (Tuan et al., 2014). The population depends heavily on the natural resources of the area, but Ben Tre is one of the provinces with the largest problem of freshwater availability (see Figure 3). Droughts have occurred throughout history, but their frequency and duration have increased significantly as a result of climate change. This increases the duration of salinity events and the distance of saltwater intrusion. In the past saline events lasted 1 to 1.5 months on average. However, in 2005 the saline event lasted 3 months and during the extreme drought in 2016 this was 5 months. This is likely to worsen in the future as a result of climate change (GFDRR, 2018).

Because of its favorable climate three rotational harvests a year could be achieved in the past (Berg, 2002). As a result of increasing salinity levels during the dry period this three-times-per year cropping system is utilized less and less (Vormoor, 2010). In some parts of Ben Tre the three-times-per-year cropping system has been replaced by rotation scheme with brackish aquaculture in the dry period and rice production during the wet period (JICA, 2016). Complete conversions of agricultural land into brackish shrimp farms are increasing as well, although often done illegally. Even though farmers receive a high profit for aquacultural production, the conversion towards aquaculture ponds allows for brackish water to leach towards surrounding fields and canals. This only aggravates the salinity problems.

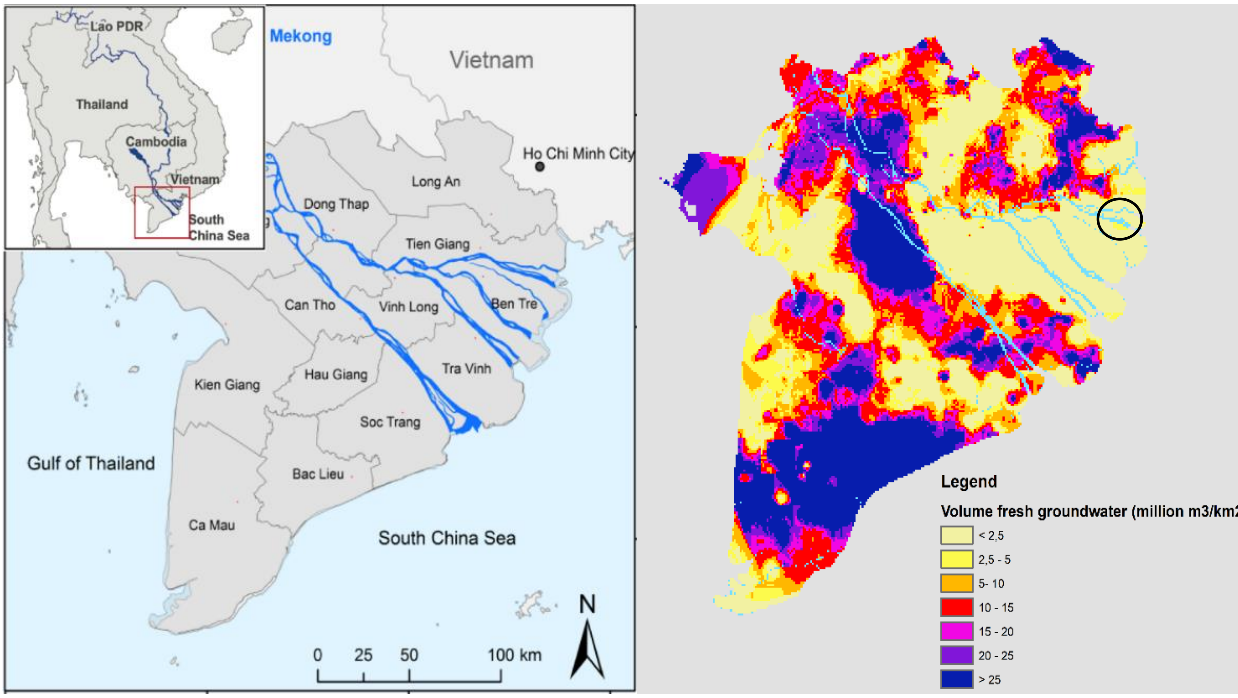


Figure 3. Map showing the Vietnamese Mekong River branches as well as the provinces (left) (Kuenzer et al., 2013) and the volume of fresh groundwater in the Mekong Delta with Ben Tre province encircled (right) (Shankel, 2020 & Oude Essink (2020)).

2.1.3. Pilot site

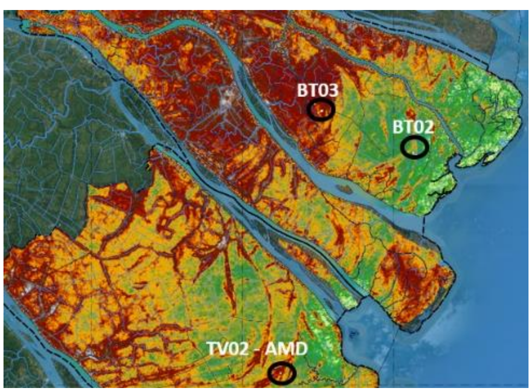


Figure 4. Location of the three study sites of phase one of FAME, shown on a digital elevation model, of which BT03 has been chosen as a pilot site for an ASR solution (Shankel, 2020).

The selected field site (BT03) for the FAME project is located at the heart of the Ben Tre province (see Figure 4) and contains quite a dense forest and a large number of small rivers and canals that originate off the main river near Ben Tre city. None of these canals are crossing through the entire study area. The sand dune system is over 500m wide, and is present as a long-elevated branching structure of approximately 1km long. This is visible in digital elevation models (DEMs), but not in the field because the elevation differences are relatively small and the area is rather densely populated, leading to obstruction of sight (Kruijt, 2020).

2.1.3.1. *Land use*

Crop use is linked to the distance of the field to the canals. Coconut plantation and rice fields are located closest to the canals and slightly higher up the sand dune the production of (e.g.) rice, peanuts, cucumber, citrus fruits and cassava is alternated (Kruijt, 2020). Fruit is being produced by approximately half of the farms and the production of coconut is increasing, because of its tolerance to salt water (JICA, 2016). Usually, the farmers can achieve two harvests of short season vegetables during the dry period, by using water from the shallow aquifer for irrigation purposes.

During the driest month of the year crop production is not possible next to the dune, but it is possible on top of the dune as farmers still have access to fresh groundwater from the shallow aquifer, although at a lower discharge (Bregman, 2020). This suggests full aquifer recharge. With the timing and amount of precipitation changing as a result of climate change (Duc Tran & Duc Vien, 2011), full aquifer recharge during the wet period might no longer be a given. This would decrease the crop quality and would perhaps only allow for one harvest of short season vegetables. This would significantly impact the farmers' income security.

Apart from climate change, poor water management could also be a problem. Since farmers are highly dependent on their agricultural proceeds, unsustainable irrigation with the goal of reaching maximum profit is a possibility (Bregman, 2020). This combination of factors significantly increases the risk of over extraction, which stresses the importance of gaining knowledge on the system's capacity for freshwater infiltration and storage as well as the maximum level of sustainable groundwater extraction by farmers.

2.1.3.2. *Lithology*

Based on corings performed during the first phase of the FAME project, a lithological cross section was made based(Shankel, 2020). The cross section is perpendicular to and cuts through both sandy ridges over a span of 600m, as can be seen in Figure 5. Figure 7 shows that the dune is characterized by well sorted fine sand with a thickness of approximately 7.5m, with intermittent clayey or loamy sand layers and a few clay layers. It is unlikely that these intermittent layers are continuous throughout the system. However, they are likely to have an effect on the hydraulic conductivity. A thick aquitard is present at approximately 7.5m below the surface (Shankel, 2020).

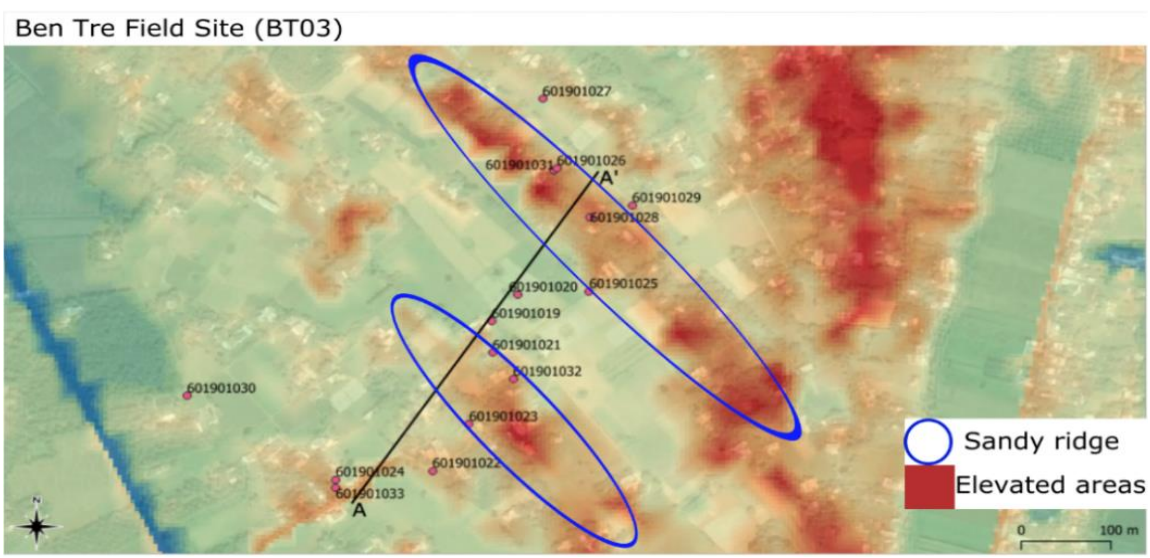


Figure 5. Digital elevation model of the area showing the elevated areas, with the sandy ridges highlighted in blue and the cross section defined (Shankel, 2020).

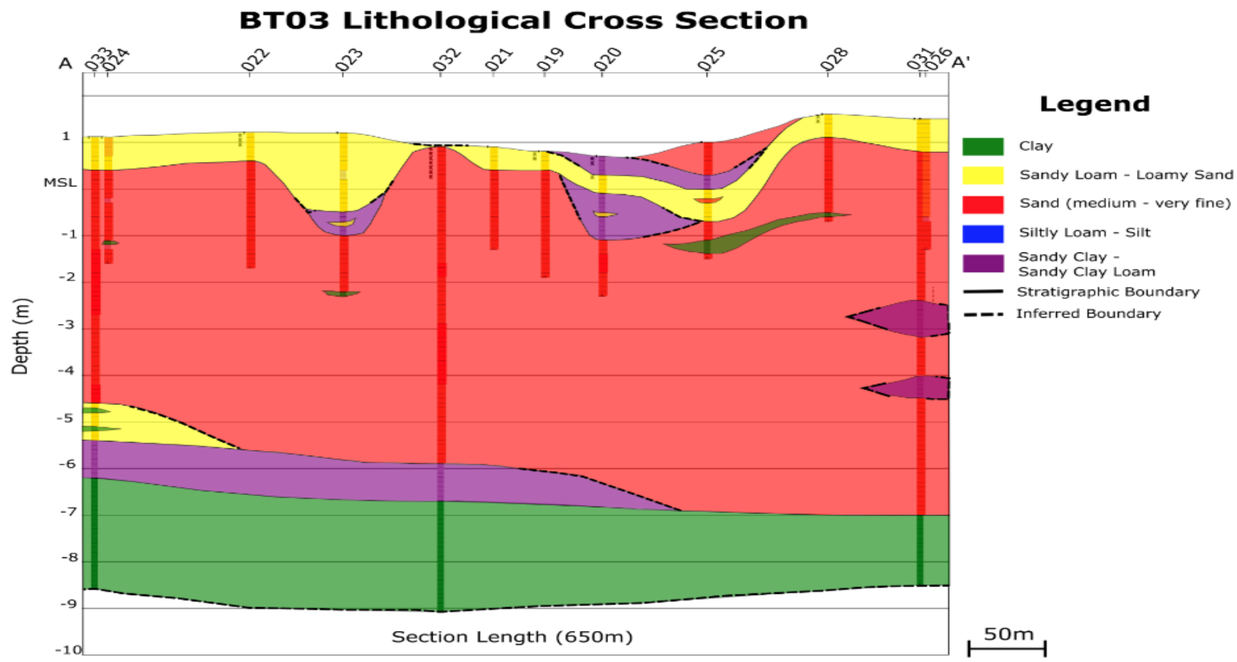


Figure 6. Lithological cross section of the BT03 field site (Shankel, 2020).

2.1.3.3. *Groundwater extractions*

During the first phase of the FAME project, 30 farmers were interviewed about their groundwater use, the volumes they extracted, the purpose of the extracted groundwater and the problems experienced with salinity during the dry period. An average water use of 1883 to 2110 liters per person per day was reported. The farmers utilize hand-wells, pumping-wells and a combination of the two. The average depth of a pumping-well is 8.1m, as opposed to 6.2m for a hand-well. A drop in groundwater level is reported in the hand-wells, with some shallow hand-wells even drying up, whereas pumping-wells are reported to have a decreased discharge. Salinity has not yet been reported as a problem during the dry period. Water from these wells is mainly used for domestic purposes. For irrigation farmers are dependent upon deep waterholes in the field of approximately two to three meters deep. These holes need to be dug out further below the groundwater level in the dry period (Bregman, 2020). Almost all farmers irrigate frequently, and do so by hose and hand.

Bregman (2020) estimated the irrigation requirement for the crops in the study area (Table 1). The average irrigation requirement is 3.9mm/day, but not all irrigation has a groundwater source. Part of the irrigation requirement will be met with precipitation. The groundwater extraction rate for irrigation purposes will therefore be smaller than the average irrigation requirement. The exact rate cannot be determined, but is assumed to be between 3 and 3.5 mm/d.

Table 1. Water used (evapotranspiration) by the crops grown in the study area in an averaged cropping schedule

Crop	**Start**	**Days till harvest/ removal**	**Irrigation requirement (mm/growth season)**	**Average water use (mm/day)**	**Efficiency of irrigation (%)**
Cucumber	December	66	244.2	3.7	22.1
Bitter cucumber	February	66	311.3	4.7	28.2
Peanut	December	96	396.6	4.1	38.0
Peanut	March	96	469.6	4.9	44.9
Jasmine and fruit trees.	December	121	376.0	3.1	36.1
Rice	September	120	360.6	3.0	100

2.1.3.4. Water quantity and quality

Reports show that groundwater reaches field level during the wet period, indicating a fully saturated shallow dune aquifer. But in the transition from the wet to the dry period, a negative trend in groundwater levels can be observed. A total groundwater level drop of 30cm together with a small increase in salinity were observed over the observation period from October to December during phase one of the FAME project. The water level in ponds dropped significantly, from reaching surface level in October to being 1 to 1.5m below surface in December. Some ponds had even dried up or had to be deepened (Kruijt, 2020). During this period no significant changes were observed in the surface water levels in ditches next to the dune. Data collected from the divers from December to May show an average grounwater level decline of one meter. Salinity levels reach a stable level in January which lasts for the duration of these measurements, with the exception of a small salinity drop in January (see Figure 7). As this occurs during the dry period which is against expectation, no explanation can be provided.

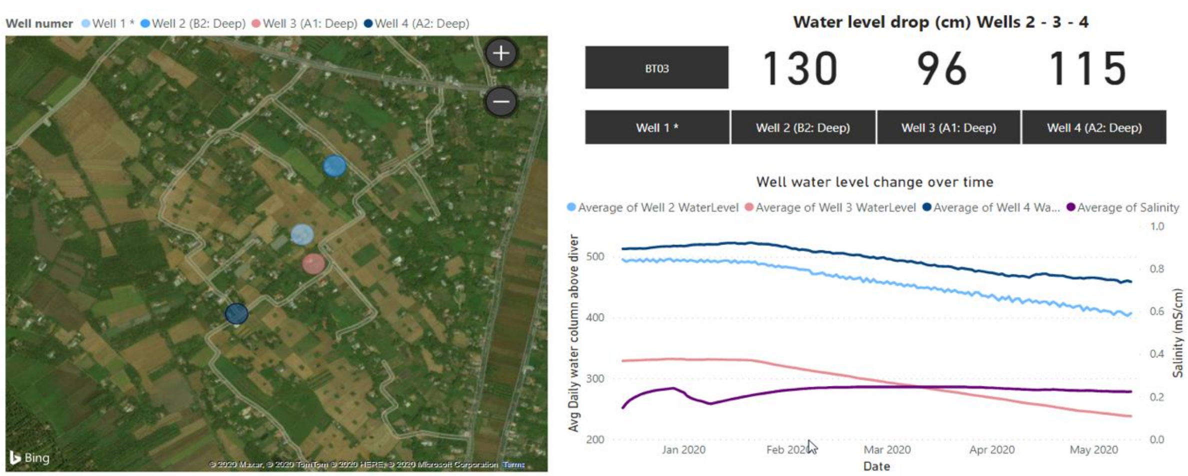


Figure 7. Map showing the location of the wells with installed divers (left). Graph showing the water level drop in cm in different wells from January to May (right) (Deltares, 2020).

The salinity levels measured in the period from October to December ranges from 600 to 2000 µS/cm in wells (see Figure 8). Wells on top of the dune were found to have lower salinity values than those located at the sides of the dune. This reaffirms the presence of a shallow freshwater lens that is mainly fed by infiltrated rainwater. Salinity levels measured in surface waters range from 1000 to 2000 µS/cm (see

Figure 8), which is quite similar to the values measured in the groundwater wells. The highest salinity values were measured in ponds, located on the sides of the sand dunes. This corresponds with the values in groundwater wells measured at those locations. Lowest salinity values were measured in small canals and ditches that are connected to the larger river system in this part of the province of Ben Tre. This suggests that salinization of the surface waters is not (yet) occurring at the time of measurement, during the transition from the wet to the dry period, indicating the presence of a window of opportunity in which surface water of relatively high quality can be infiltrated into the shallow dune aquifer (Kruijt, 2020).

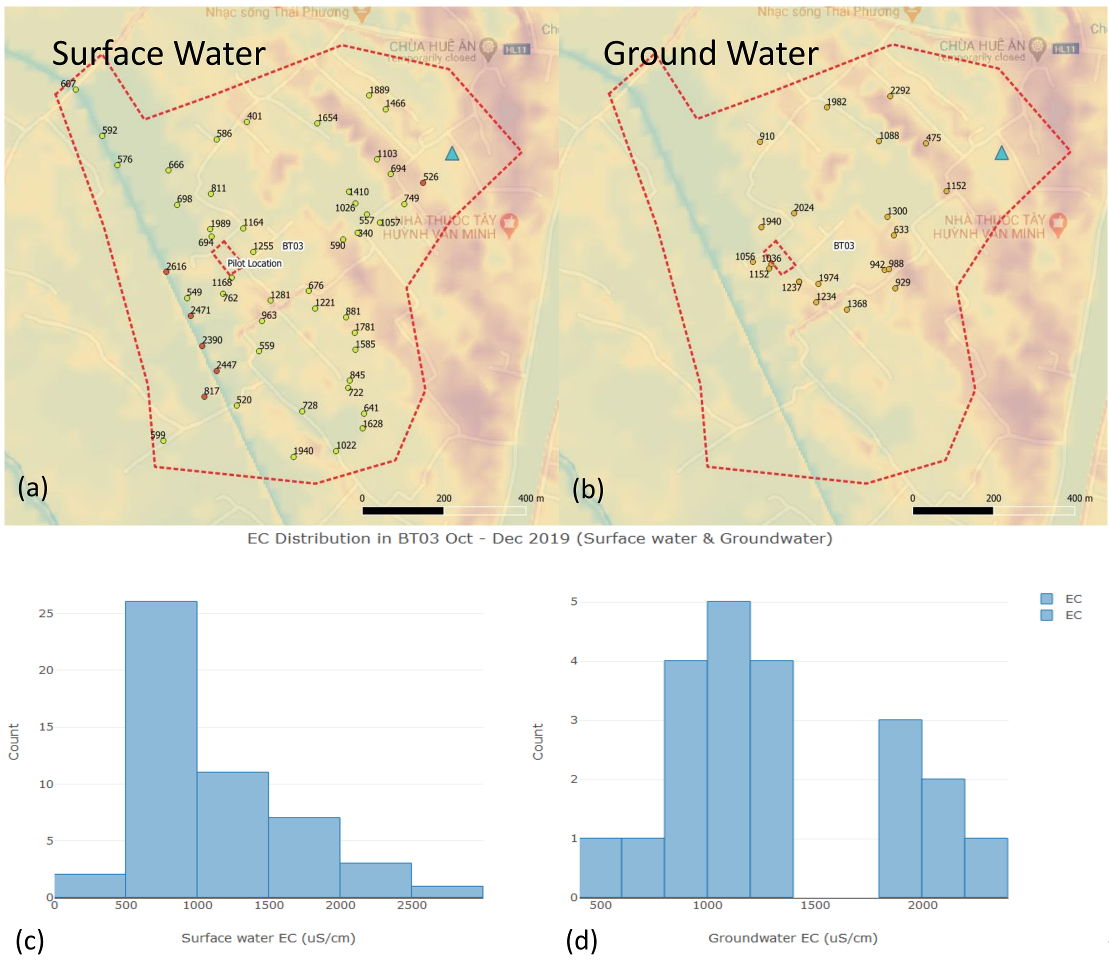


Figure 8. Map of study area showing the electroconductivity of groundwater (a) and the surface water (b) in December. The distribution of the electroconductivities of surface water (c) and groundwater (d) in the area (Deltares, 2020).

2.1.3.5. Storage capacity

A reliable reduction zone boundary was found with corings, denoting the lowest average groundwater level in the dry period. Groundwater extractions seem to have affected this boundary at certain locations. Nevertheless, this boundary allows for reliable comparison of the lowest average groundwater level with the low groundwater readings taken at the start of the dry period, in early December. An indication of the storage capacity horizons different storage capacities was given by calculating the cross sectional areas between the surface level, the groundwater level, the lowest groundwater level and the aquitard, also called (Shankel, 2020). These storage capacity horizons are depicted in Figure 9.

In order to determine the storage capacity for the entire aquifer, the volume per stretched meter (of the cross section) was extrapolated across the length of the dunes (~1000m), perpendicular to the cross section (Shankel, 2020). The potential capacity for infiltration is the area between the surface and the lowest groundwater level. This is a volume in the range of 4.0E+05 m^3 and 4.97E+05 m^3, which can be stored over a depth of 0.67m and 0.83m when considering an area of 60 ha. The volume that can be stored between the surface and the measured groundwater level is considered the infiltration capacity in 2019, as this area will become unsaturated in the transition from the wet to the dry period. An overview of the determined storage capacities can be found in Table 2. Note that these values are merely an indication. As the crops cultivated in the dry period require a non-saturated rootzone (Bregman, 2020) the infiltration capacity will be lower than estimated. The actual infiltration capacity will vary on a yearly basis, as rainfall and salinity events are variable.

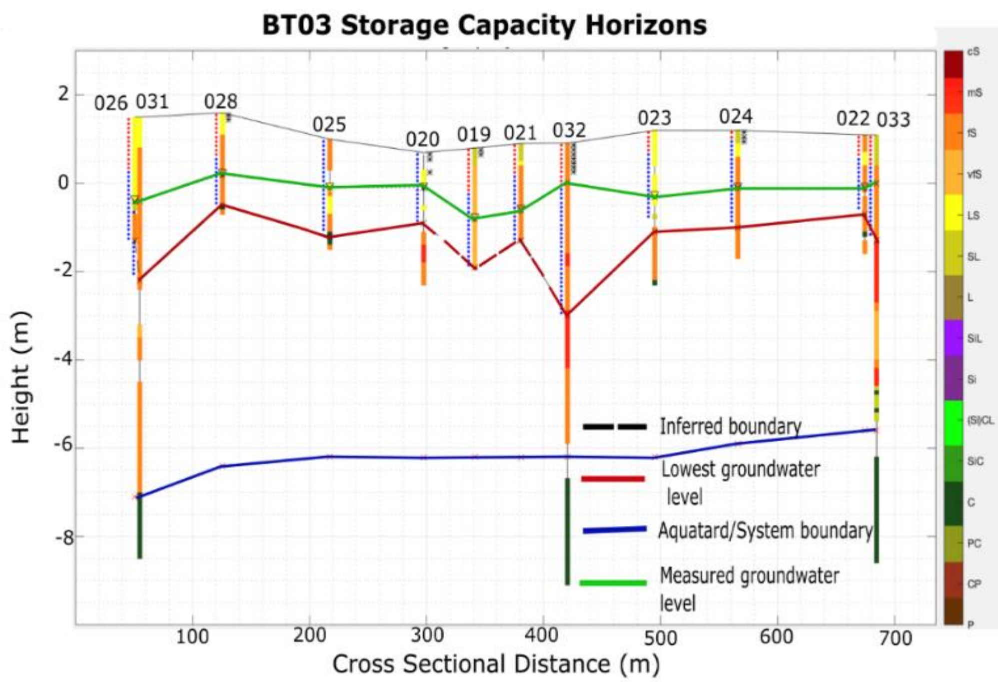


Figure 9. Groundwater level, lowest groundwater level and the aquitard depicted long the cross section of the field site (Shankel, 2020).

Table 2. Overview of the porosity volumes between the surface level and observed hydraulic head (potential capacity of infiltration) and the storage capacity from the observed groundwater level to the lowest measured groundwater level (rest of the aquifer) (Shankel, 2020).

BT03 Horizons	Area (m^2)	Min porosity volume per stretched m (m^3)	Max porosity Volume per stretched m (m^3)	Min Volume over 1000 meters (m^3)	Max Stretched Volume over 1000 meters (m^3)
Surface – GW level	886	221	266	2.24E+05	2.68E+05
GW level – Low GW level	697	174	209	1.76E+05	2.11E+05

2.1.3.6. Conceptualization

Based on the observations discussed above, a conceptualization of the hydrological system with and without ASR solution has been created (Figure 10). The significant drop in groundwater levels at the end of the measurement period (October-December), in combination with the lack of change in water level and quality in the ditches next to the dune (during this period), suggests the presence of a window of opportunity that would allow for surface water infiltration (Kruijt, 2020). The infiltration window will be at the start of the dry period, when hydraulic heads decline, pore volume space becomes available and the quality of the surface water remains high. This period would be in November or December, with the exact period varying on a yearly basis, as the length and timing of the infiltration window depend on the length of the rainy season, as well as the timing and severity of saltwater intrusion to surface waters (Shankel, 2020). An ASR solution would result in an elevated hydraulic head throughout the dry period. This would allow to maintain the hydraulic head of a ‘normal year’ even during periods of drought.

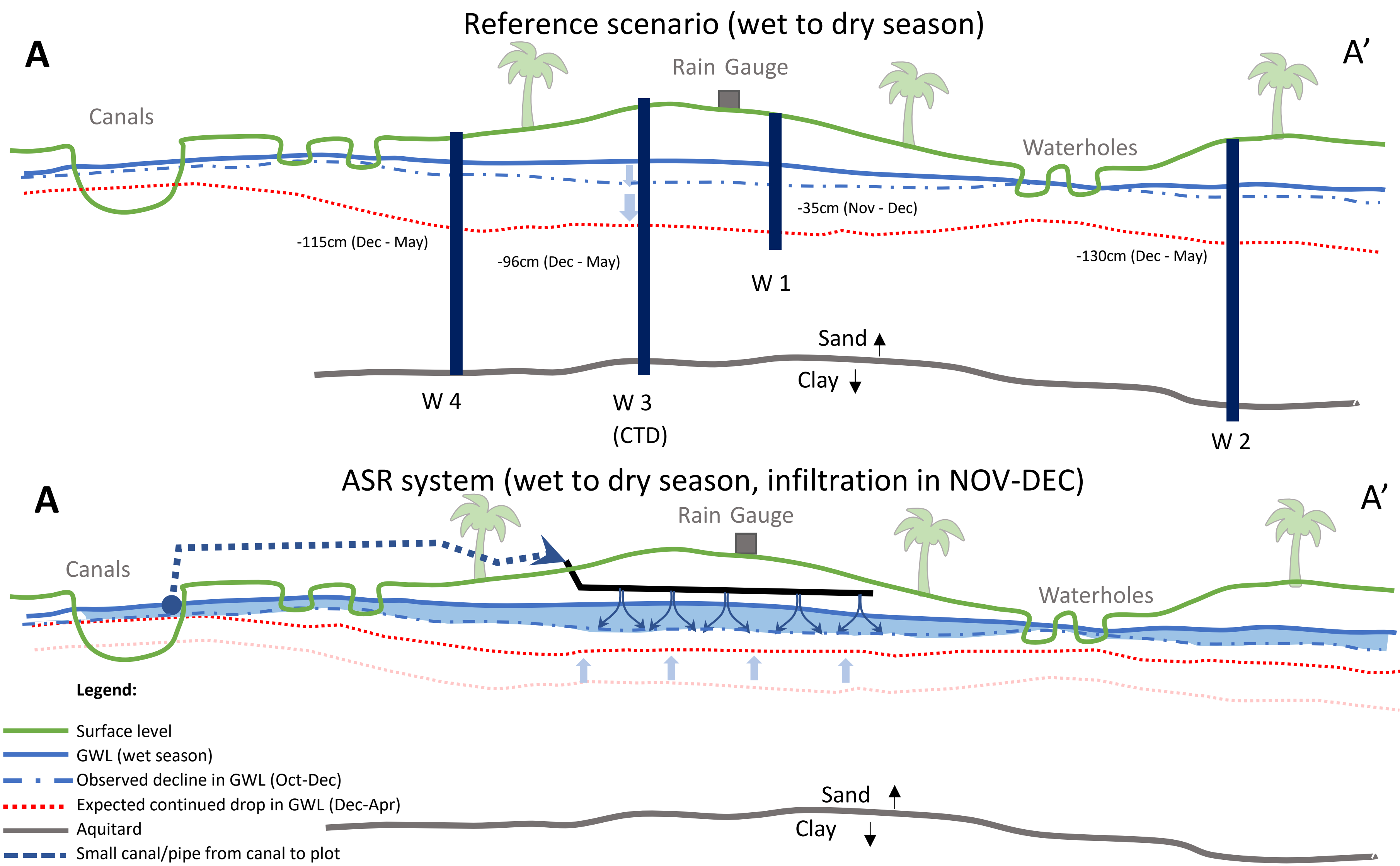


Figure 10. Conceptualization of the decline in groundwater levels (GWL) from the wet to the dry season (upper), as well as the potential for infiltrating water in the window of opportunity (lower) (Deltares, 2020)

A site of 30 by 30m has been selected as the for an ASR pilot study. Across the pilot site horizontal drain pipes will be placed, connected to the main canal by a small pipe. The drain pipes will be placed at a depth of 1 meter. One extraction wells be placed at the site, as well as several observation wells in order to observe the change in head and concentration in the aquifer over time. Figure 11 shows the location of the pilot site, as well as the conceptual design of an ASR solution.

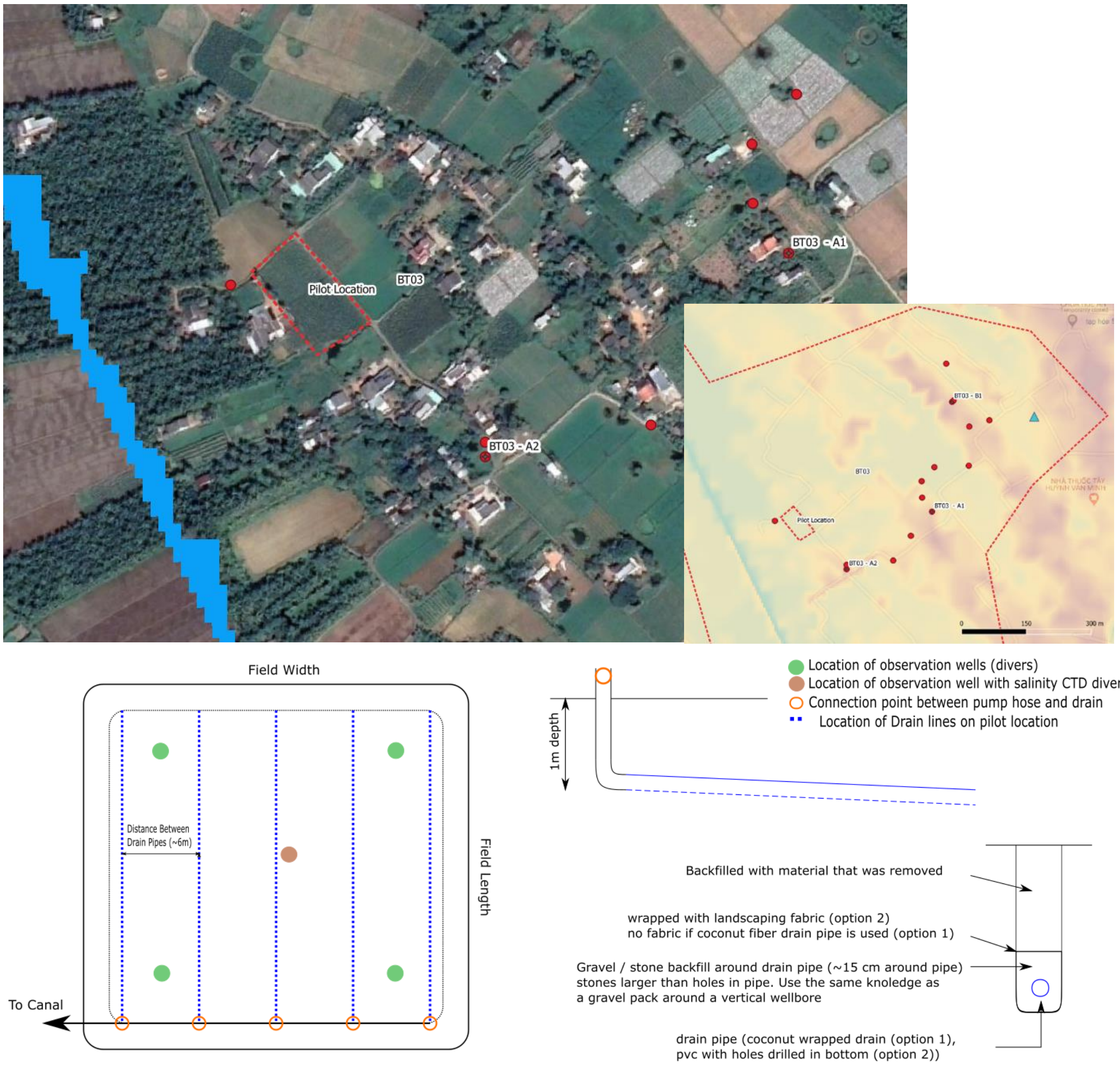


Figure 11. Map indicating the location of the pilot site in light of the measurement locations (upper) and conceptual design of an ASR solution for this pilot study (lower) (Deltares, 2020).

3. Methods

3.1. Model setup

A 3D-variable-density model with coupled solute module was created using the iMOD-WQ (iMOD-Water Quality) modelling software, which is included in the iMOD 5.1 release but also functions as a stand-alone feature. The density-dependent flow and reactive transport calculations are performed with a separate executable (Vermeulen et al., 2020). iMOD-WQ is a combination of three codes: SEAWAT Version 4.0 (Langevin et al., 2008), MT3DMS Version 5.3 and RT3D Version 2.5. SEAWAT is a code for density-dependent flow and transport, whereas MT3DMS and RT3D are codes for 3D multispecies reactive transport, of which only RT3D can be utilized for more complex reactions.

3.1.1. Model dimensions and design

A local and community model will be made with slightly different model dimenstions. The modelling grid for the local model comprises an area of 1030x1030m and consists of 83 rows and columns. For the community model an area of 1100 x1100m is used consisting of 160 rows and columns. A telescopic setup was used with cell sizes starting at 50x50m and becoming increangly fine towards the center of the grid. For the local model the pilot site of 30x30m is located at the center and has a cell size of 2x2m. The cells in between have a size of 50x2m (Figure 12). Since hydrogeological effects tend to be distinguishable on a larger scale, the area comprised of fine cells is extended beyond the area of interest, resulting in a fine area of 130x130m. In the community model this area of interest will be increased to 600x600m, with a fine cell size of 4m. The model consists of 10 layers of each 1 meter thick, reaching a depth of 10m.

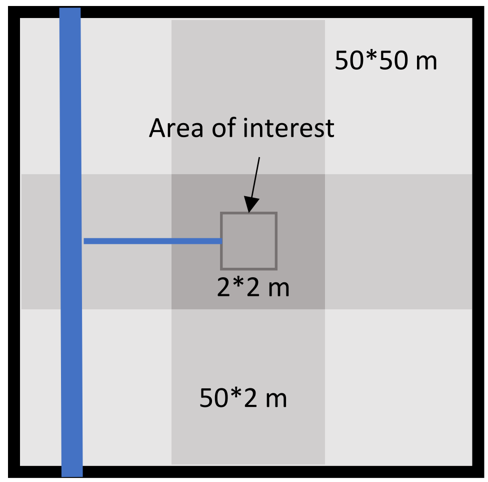


*Figure 12. S*chematic representation of the local model with different cell sizes (shades of gray), area of interest, general head boundary applied to the boundaries (black) and a river system

As the knowledge on the local hydrogeological conditions is limited, a conceptual model will be built, providing us with a general idea of the effects of an ASR solution on the hydrogeological system. A general head boundary will be applied to the boundary cells of the grid, as can be seen in Figure 12. A river system is introduced as a freshwater source for infiltration. The river system in the model is located on the left side and covers an area of 1x83 cells. In the middle it branches off towards the area of interest (Figure 12). Here the channel has a depth of 1m as opposed to 2m for the main channel and is also smaller in width. A drainage and recharge system are applied uniformly to the entire model grid (and are therefore not distinguishable in Figure 12). The model will be transient and run over a period of 50 years, consisting of monthly stress periods.

3.1.2. Model input

A general head boundary is applied to the boundaries to avoid unnecessary extension of the model toward the location of the element affecting the head in the model. An initial head distribution has been calculated for the model, and is assigned to the general head boundary condition during the wet period. During the dry period the assigned values lie 1m lower, to represent the observed decline in hydraulic head. The conductance determines to what extent the head in the boundary cell is influenced by the assigned boundary condition. A large conductance will result in an almost constant head, whereas a small conductance will result in a larger difference between the assigned and calculated head because other model variables are more important. River systems and drains are implemented with a similar general head boundary. As the conductance depends on the cell dimensions, the three required conductance values are presented in Table 3.

Table 3. Overview of the conductance values for each package.

Conductance (m^2/d)			
Cell size	**GHB**	**RIV**	**DRN**
50x50m	5	50	12.5
50x2m	0.2	2	0.5
2x2m	-	0.08	0.02

Since hydraulic conductivity was not measured in the field, values obtained from literature were utilized. The research of Minderhoud et al. (2017) focuses on the Mekong Delta and values for horizontal conductivity in this study ranged between 8.0 and 22.8 m/d. As the shallow dune aquifer mostly consists of fine well sorted sand, with a few non-continuous loamy or clayey sand layers in between, which has a high permeability, a horizontal hydraulic conductivity of 8.0 m/d has been chosen for this study. The process of evapotranspiration has been simplified by including it in the recharge rate: during the wet period a positive recharge rate is applied and during the dry period this changes to a small negative recharge rate. The drainage system is applied to an elevation where drainage only occurs during the wet period. Wells are defined by specifying their location, the layer they act on and their extraction or infiltration rate. An overview of the parameter values is given in Table 4.

Table 4. Model properties and parameters used in the reference scenario.

Parameter	**Value**
Model area	Local model: 1.06 km^2
	Community model: 1.21 km^2
Horizontal cell size	Rough area: 50 m
	Fine area: 2 m
Verticle cell size	1 m
Bottom of model domain	-10 m
Number of cells	Local model: 83
	Community model: 160
Stress period length	1 month
Timestep groundwater flow	≈ 1 week (1 month/4)
Hydraulic conductivity (kh)	8 m/day
Hydraulic conductivity (kv)	0.8 m/day
Porosity	0.35 (-)
Specific storage	Upper layer: 0.15
	Other layers: 0.0001
Density concentration slope	1.3889 (-)
Longitudinal dispersivity	0.1 m
Diffusion_coefficient	8.64E-05 m^2/s
Concentration gradient ghb	Top layer: 0.2 g/L
	Bottom layer: 0.6 g/L
River elevation	Wet period: -0.3 m
	Dry period: -0.8 m
River concentration	Wet period: 0.3 g/L
	Dry period: 1.3 g/L
Recharge rate	Wet period: +0.003 m/day
	Dry period: -0.0005 m/day
Drainage elevation	-0.2 m

three models for varying scenarios have been created: 0) model representing the situation in the past without groundwater extractions, 1) representing the current situation (reference scenario) with groundwater extractions and 2) representing the future situation with an ASR solution in place. These models have the same model properties mostly the same parameter values (see Table 4). The differences in input values is represented in Table 6. One year consists of 6 stress periods combining into the wet period, 1 stress period for the infiltration period – at the start of the dry period – and 5 stress periods for the rest of the dry period. In model 1 (reference scenario) no extraction will take place during the period intended for infiltration, in order to allow for comparison between the two models. Merely having water extraction during 5 months in the reference case allows for a volumetric comparison as the total extracted volume of groundwater remains the same.

As the parameter values are not entirely based on field observations, a sensitivity analysis will be performed on a variation of parameter values for model 0 (see Table 6). Depending on whether the model results are a realistic representation, the input parameters will or will not be adjusted. Additionally, groundwater extraction rates were varied for model 1 but for time management reasons no extensive sensitivity analysis was performed on model 1 and 2.

Table 5. Model parameters that have different values for the different model systems.

Model	0	1 (reference)	2
Characteristics	Past system: No groundwater extractions	Current system: groundwater extractions	Future system: Additional water infiltration (ASR)
Initial concentration	Cl_min = 0.2 (g/L)	Final concentration distribution of model 0	Final concentration distribution of model 1
	Cl_max = 0.6 (g/L)		
*Discharge rate wells **	-	10 m^3/d	Extraction: 10 m^3/d Infiltration: variable

** One extraction well is located at the center of a farmer's plot (41,41) with the filter depth at -5m (layer 5). Infiltration wells have different spacing and thus varied locations on the xy-plane, but they are located at a depth of -1m (layer 1).*

Table 6. overview of parameter values for the sensitivity analysis.

Parameter	Original	Adaptation 1	Adaptation 2
Horizontal conductivity	8 m/d	2x larger	2x smaller
Specific storage	0.0001	0.001	-
Recharge	0.003 / -0.0005 m/d	1.5x larger	1.5x smaller
Drainage conductance	12.5 / 0.5 / 0.02 m^2/d	2x larger	2x smaller
Well discharge	(-)10 m^3/d	2x larger	2x smaller

3.2. Research scenarios

Various scenarios will be studied for both the local and community model. In the local model three potential ASR systems will be compared with each other (Figure 13). Design 1 will have a vertical extraction well as opposed to design 2 with a horizontal extraction well. Both designs contain horizontal infiltration wells. Both designs will be compared by varying the spacing of the infiltration wells, affecting the number of wells, and the infiltration rate. This will be done with four scenarios, presented in Figure 14. Design 3 contains vertical extraction and infiltration wells, in which scenarios with a varying number of wells will be studied. Finally, the three designs will be evaluated with the incorporation of saltwater intrusion of groundwater, as this could affect the performance of an ASR solution.

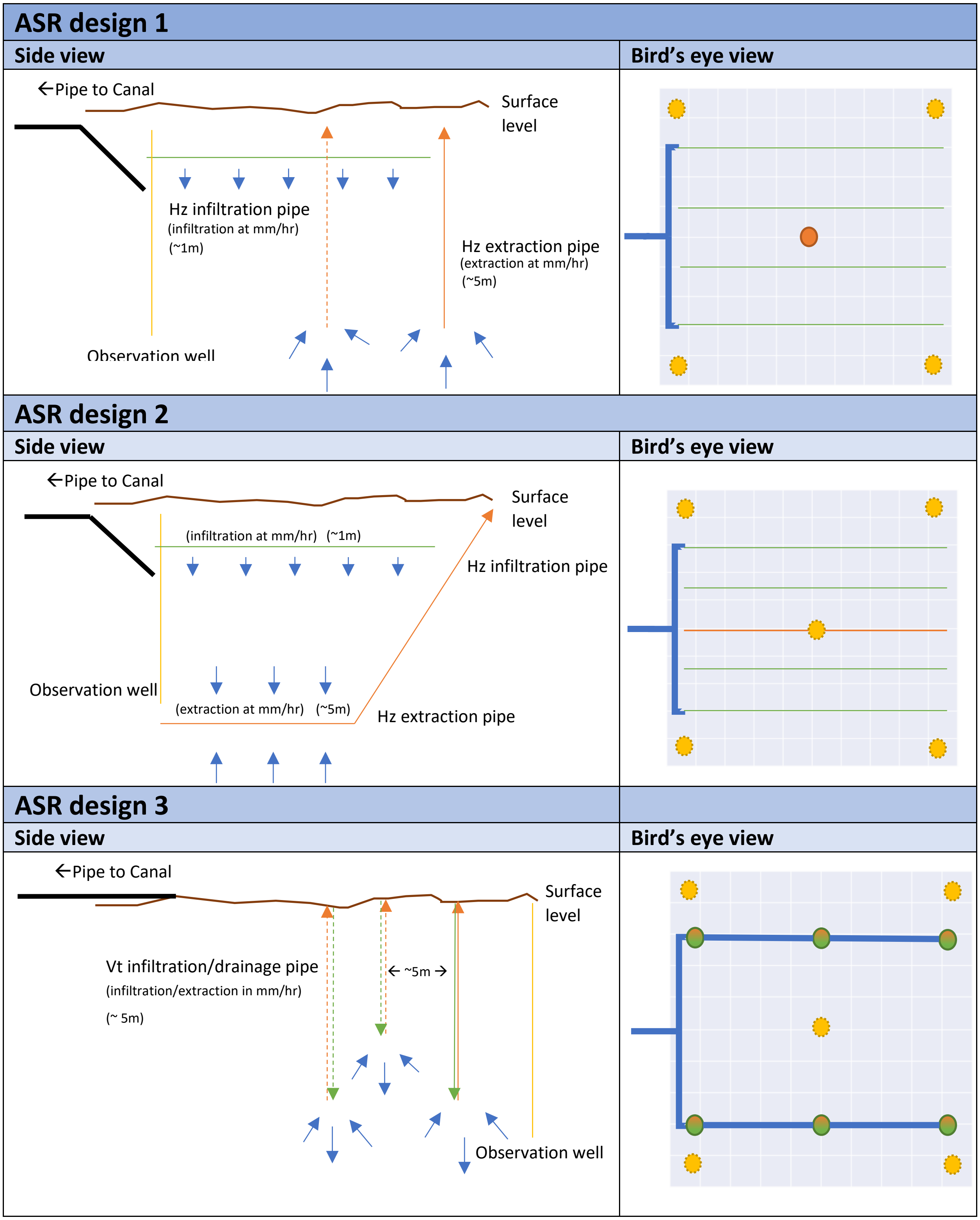


Figure 13. Conceptual design of the two ASR systems from both a side and bird's eye view.

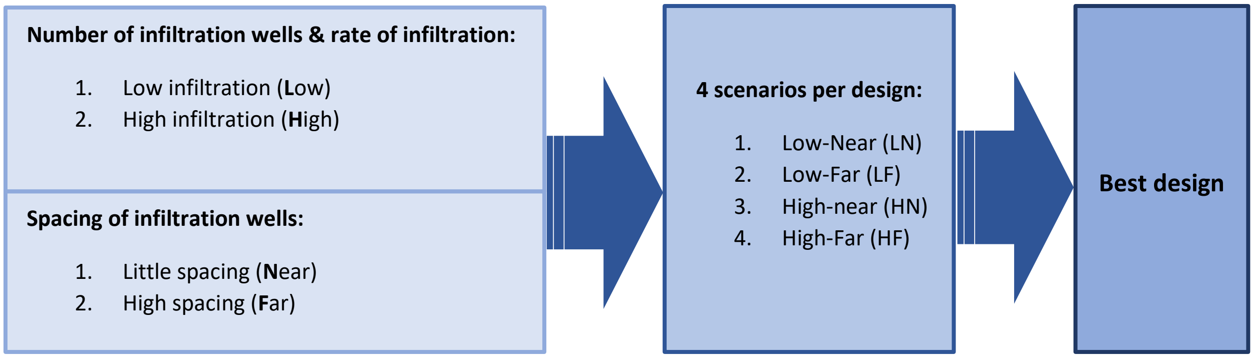


Figure 14. Overview of scenarios for design 1 and 2 in order to determine the best ASR design.

It is more interesting to evaluate the performance of an ASR solution on a community level, when more farmers will utilize it. The area of interest in the community model will be enlarged to include 9 agricultural plots of 200x200m, summing up to an area of 600x600m. The number of extraction and infiltration wells will be adjusted. One plot will have two extraction wells, either vertical or horizontal throughout the plot. Evaluation of ASR solutions on a community level allows for an analysis of the threat of over extraction by varying the extraction rate. Design 1 and 2 will be compared with each other in the same manner as in the local model.

Lastly, the potential of upscaling to other areas in the Tra Vinh and Ben Tre provinces will be analyzed, by varying some of the hydrogeological variables and system characteristics and reevaluating the performance of an ASR solution. Because of time management reasons, only design 2 will be evaluated. Uniform changes for these extra scenarios are the addition of a river system on the east side of the model and an increase of the model depth to 20m. The variable changes for these scenarios can be found in Table 7.

Table 7. Overview of the variation in the scenarios that will be run to represent other shallow dune aquifers in the Ben Tre and Tra Vinh region.

Code	Horizontal conductivity (m/d)	Vertical conductivity (m/d)	Chloride concentration bottom layer (g/L)
Alt1A	4.0	0.4	0.6
Alt1B	4.0	0.4	10
Alt2A	16.0	1.6	0.6
Alt2B	16.0	1.6	10

An overview of this study – being part of the FAME project – and its relevance is shown in Figure 15.

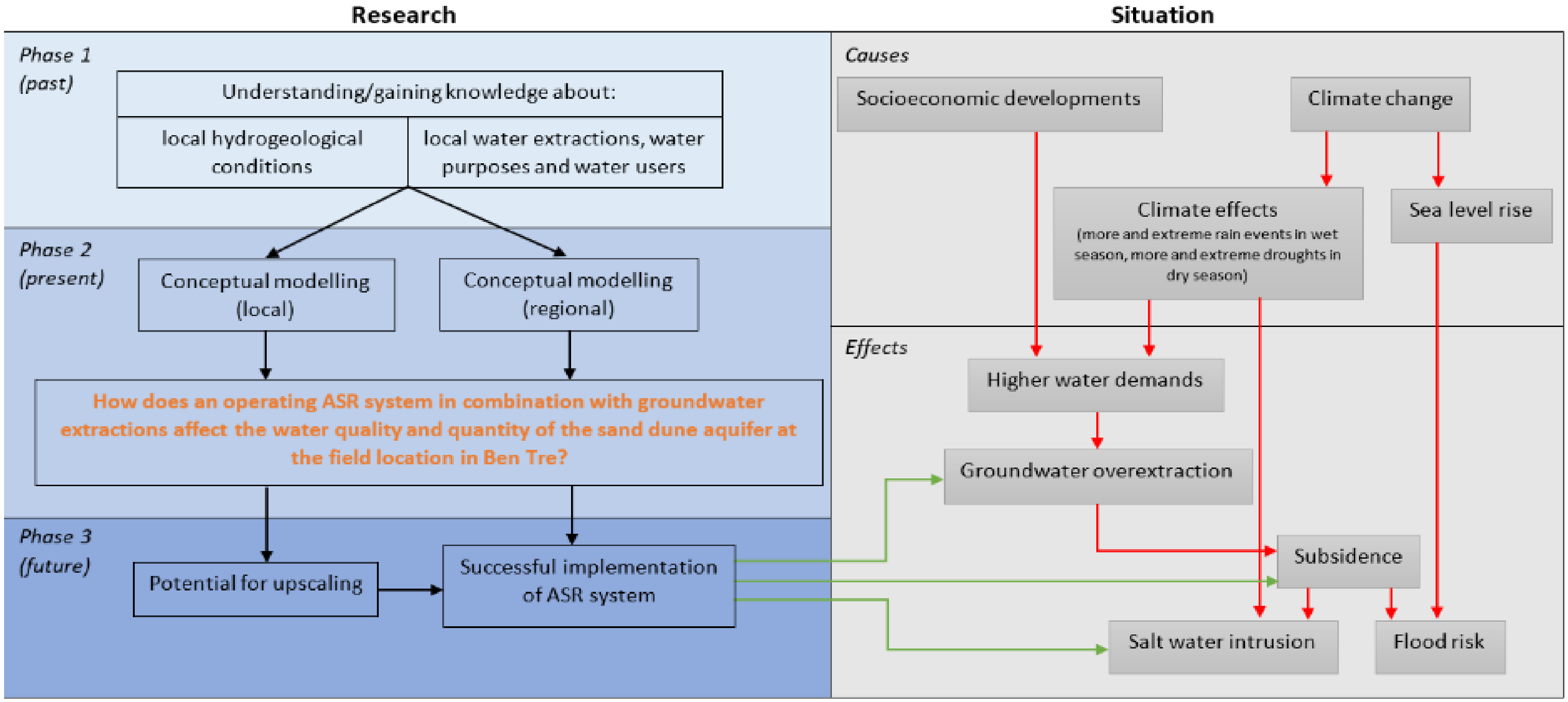


Figure 15. Conceptual framework showing the situation in the Mekong Delta related to subsidence, saltwater intrusion, and flood risk. It also shows that research on designing, conducting and monitoring an ASR pilot could already help counteract these processes on a local scale, but also increases the potential for upscaling which would have even larger beneficial effects. Positive and negative effects are shown as green and red arrows respectively, whereas the research process is shown with black arrows with the research questions being presented in orange.

4. Results

4.1. Local model

4.1.1. Model 0: no groundwater extraction

Results showed that during the wet period the river is draining the system and the drainage system is active. Recharge during the wet period is the largest positive flux. The inflow from the general head boundary is unsurpassable, regardless of the parameter values. This flux is 10% of the largest flux, and therefore considered acceptable. During the dry period the drainage system is inactive, as groundwater levels are already below the drain levels. The river system is supplying water to the groundwater system. Recharge remains the largest flux, but is negative instead. An outflow towards the general head boundary occurs, which is of 50% of the recharge flux. This is significant, but essentially this value is smaller than the ghb flux in the wet period. Hence it is considered acceptable.

A clear difference between the concentration at the start and end of the simulation can be observed in Figure 16. At the start the difference between the wet and dry period is more pronounced, whereas it is more evenly distributed at the end. Moreover, the system seems recharge dominated, as the number of layers with a concentration of almost 0 increases over time. The concentration ranges from 0 to 0.8g/L, which is rather low when comparing it to the concentration of seawater at 19g/L. The water quality in model 0 is thus under no circumstance under threat.

The main observable difference in hydraulic head over time (Figure 17) is the difference between the wet and the dry period. During the wet period, a uniform head of 0m is found in a large part of the system, except near the main river channel where the head slightly decreases, as the river stage is -0.3m. During the dry period the hydraulic head in a large part of the system is lower than the river stage (-0.8m), therefore the hydraulic head increases towards the river. No difference can be observed between the start and end of the simulation. This can be explained by the fact that hydraulic head stabilizes quickly, whereas the concentration requires time to stabilize.

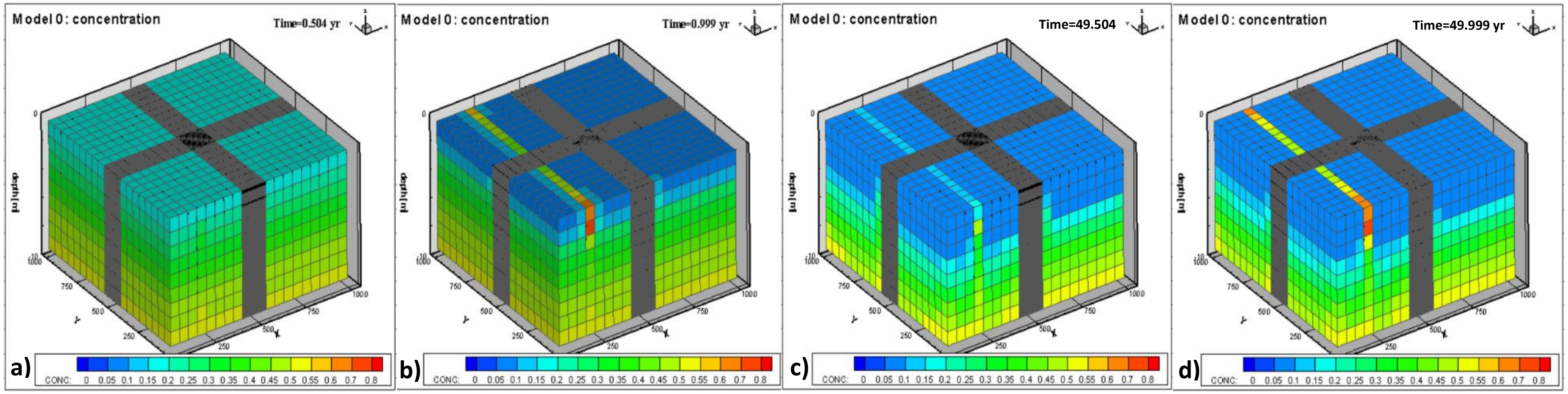


Figure 16. 3D figure of model 0 with the concentration in the wet period at the start (a) and end (c) of a simulation, as well as the concentration in the dry period at the start (b) and end (d) of a simulation.

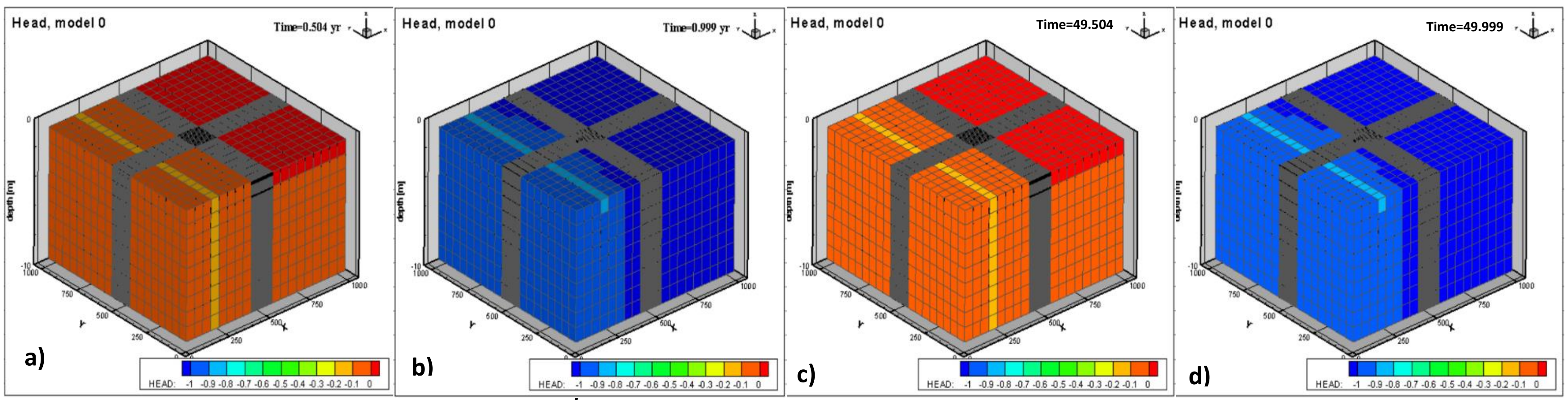


Figure 17. 3D figure of model 0 with the hydraulic head in the wet period at the start (a) and end (c) of a simulation, as well as the hydraulic head in the dry period at the start (b) and end (d) of a simulation

A sensitivity analysis was performed on model 0. Without groundwater extractions the system becomes recharge dominated, with the concentration approaching and stabilizing at the recharge concentration (0.05 g/L), regardless of the parameter value. Small variations in concentration can be observed for different parameter, however they are too small to be significant (Figure 18). The hydraulic head during the wet period is sensitive to an increase of the drainage conductance. During the dry period it is sensitive to the horizontal conductivity and year-round it is sensitive to the recharge rate. The specific storage seems to have rather little effect (Figure 19).

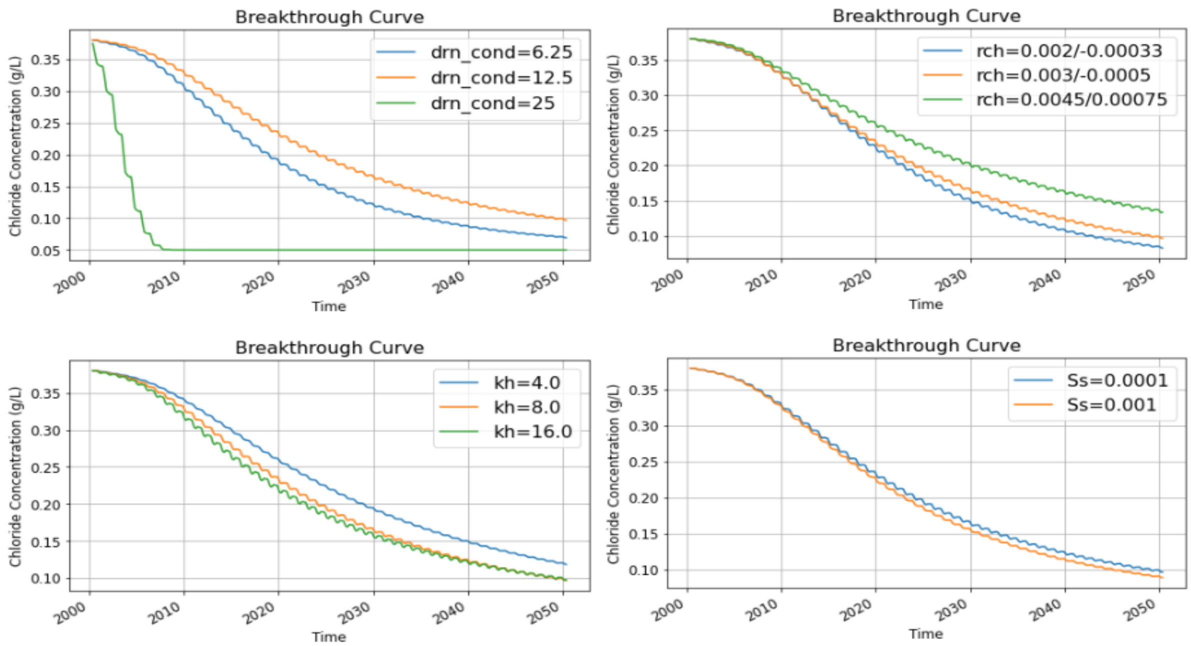


Figure 18. Breakthrough curves at (0,0) layer 5, showing variation in drainage conductance (upper left), recharge rate (upper rate), horizontal conductivity (bottom left) and specific storage (bottom right).

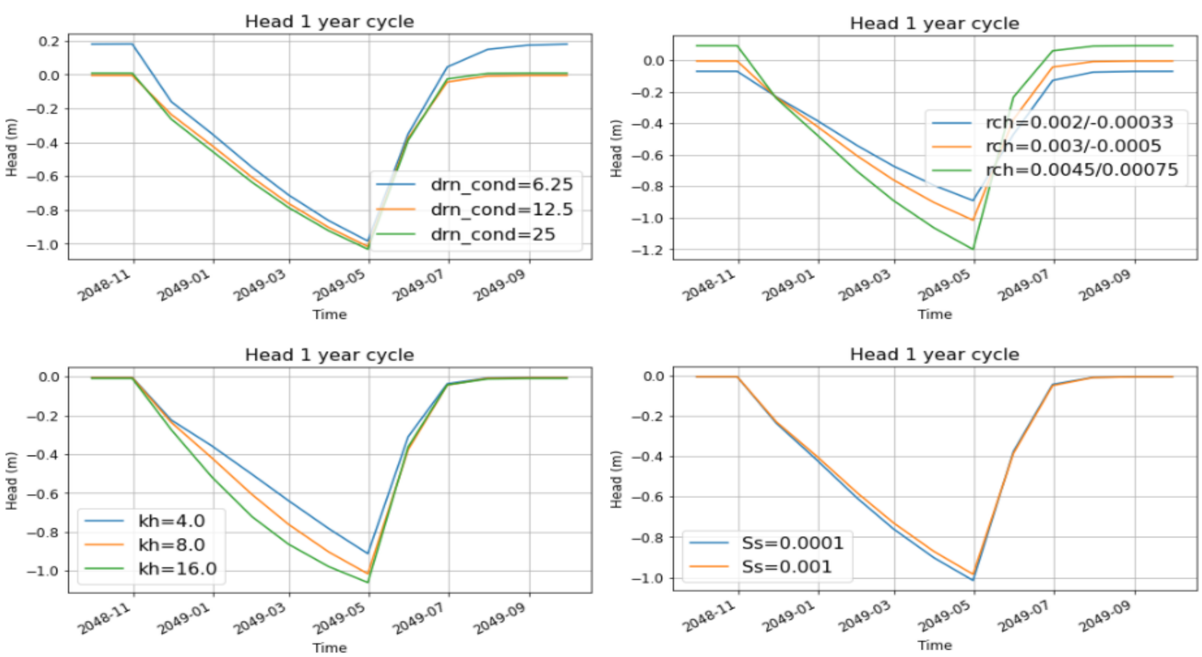


Figure 19. One-year cycle of the hydraulic head at (0,0) layer 1, showing variation in drainage conductance (upper left), recharge rate (upper rate), horizontal conductivity (bottom left) and specific storage (bottom right).

4.1.2. Model 1: groundwater extraction

The sensitivity of the model to groundwater extractions was analyzed by varying the groundwater extraction rate from 5 m^3/d to 10 m^3/d and 20 m^3/d. None of these extraction rates significantly affect the concentration of the groundwater (Figure 20), but a decline in hydraulic head between 5 and 20cm can be observed. An extraction rate of 20 m^3/d is unrealistic, and will not be considered. An extraction rate of 10m^3/d causes a small decline in hydraulic head of 11cm. This makes sense considering the fact that extraction in a 30 by 30m area is evaluated in isolation, whereas the shallow aquifer covers a larger area. But considering the average crop requirement of 3.9mm/d, an extraction rate of 10m^3/d is quite high. Since the farmer is planning on irrigating a larger area with the water extracted from the pilot study site, this rate will be continued with. On a community level however, this extraction rate will be too large.

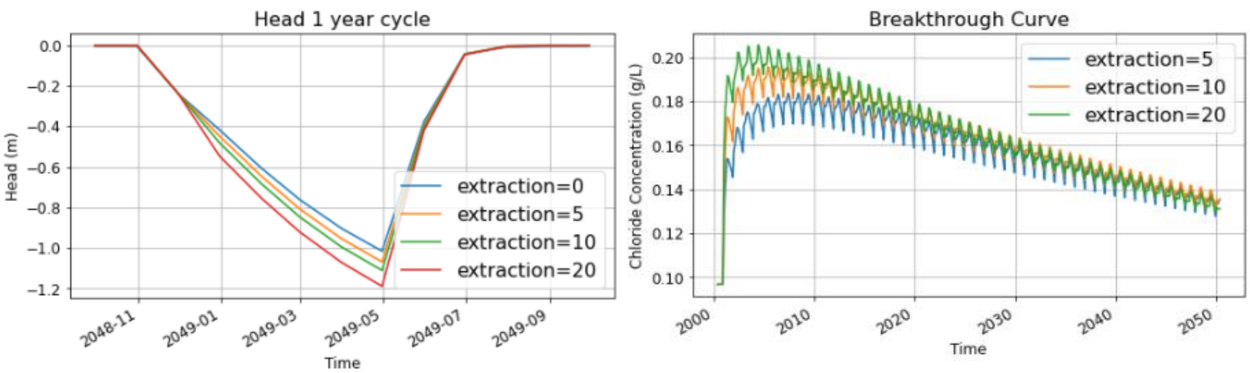


Figure 20. Hydraulic head at (0,0) layer 1 showing variation in the groundwater extraction rate (left) and breakthrough curve showing variation in the groundwater extraction rate (right) in a one-year cycle.

4.1.3. Model 2: ASR solution

4.1.3.1. Horizontal or vertical extraction

ASR design 1 and 2 were evaluated according to four scenarios, where the scenarios labeled as 'near' had a spacing of 4m between the infiltration wells and scenarios labeled as 'far' had a spacing of 8m. These scenarios respectively have 8 and 4 infiltration wells. Scenarios labeled as 'high' had an infiltration rate of 10 m^3/d, resulting in an infiltration rate per well of 2.5 m^3/d for the 'high-far' scenario and 1.25 m^3/d for the 'high-near' scenario. Scenarios labeled as 'low' had an infiltration rate of 2 m^3/d, resulting in an infiltration rate per well of 0.5 m^3/d for the 'low-far' scenario and 0.25 m^3/d for the 'low-near' scenario. The placement of the infiltration wells can be observed in Figure 21.

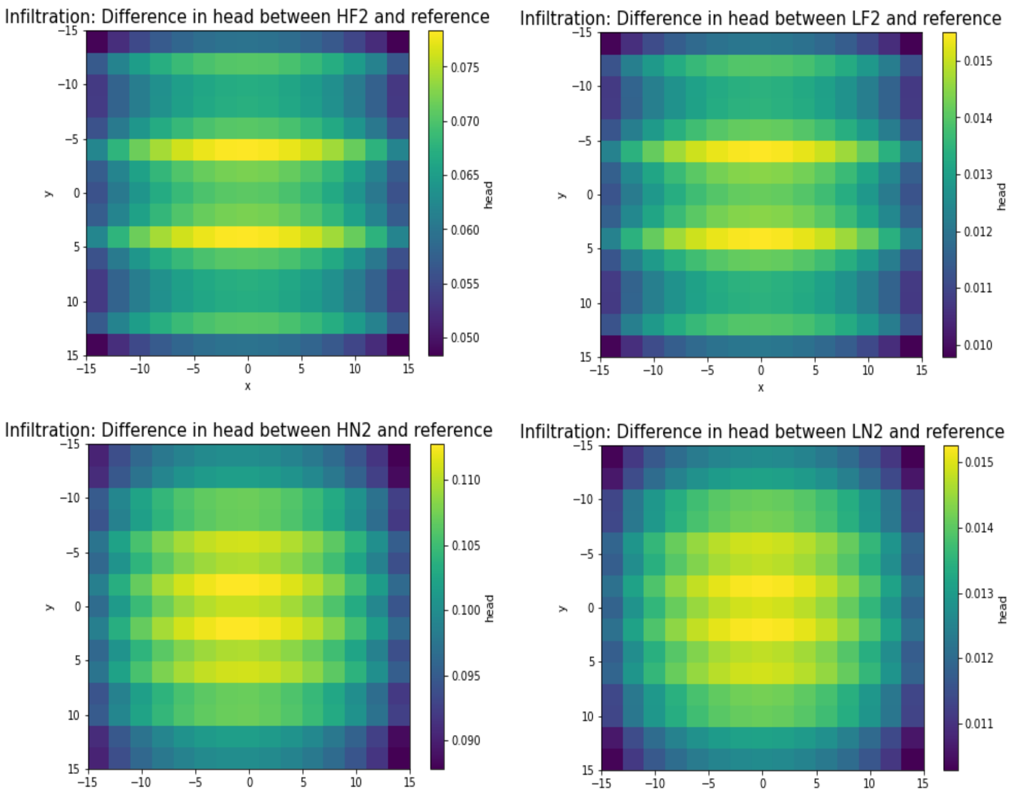
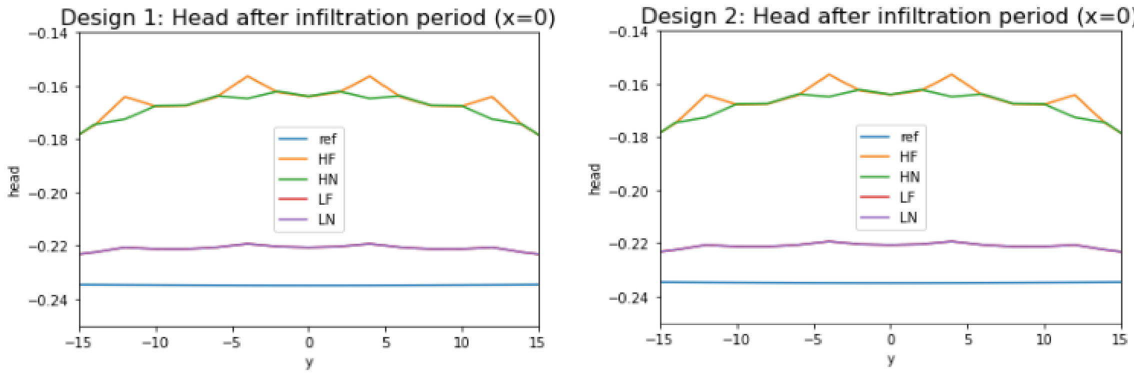


Figure 21. Head difference between ASR design 2 and the reference case after infiltration, highlighting the location of the infiltration wells for the different scenarios: HF (upper left), LF (upper right), HN (bottom left), LN (bottom right).

The difference between the various scenarios and designs is not noticeable when considering the entire model since the area of interest only covers 0.085% of the model. On a smaller scale some differences can be observed. The hydraulic head in the 'high' scenarios of design 1 shows a slight elevation in the first month of the dry period (Figure 22). Halfway through the dry period this difference has almost entirely vanished. For design 2 not only the 'high' scenarios, but also the 'low' scenarios show a slight elevation the hydraulic head with approximately 1cm at the start of the dry period. But contrary to design 1, the hydraulic head remains elevated throughout the dry period. This elevation is rather small and does not allow for a significant water buffer, but as this elevation can be observed in all design 2 scenarios, it is considered significant. For neither of the designs does the spacing of the infiltration wells have an effect.

Hydraulic head after infiltration



Hydraulic head throughout the dry period

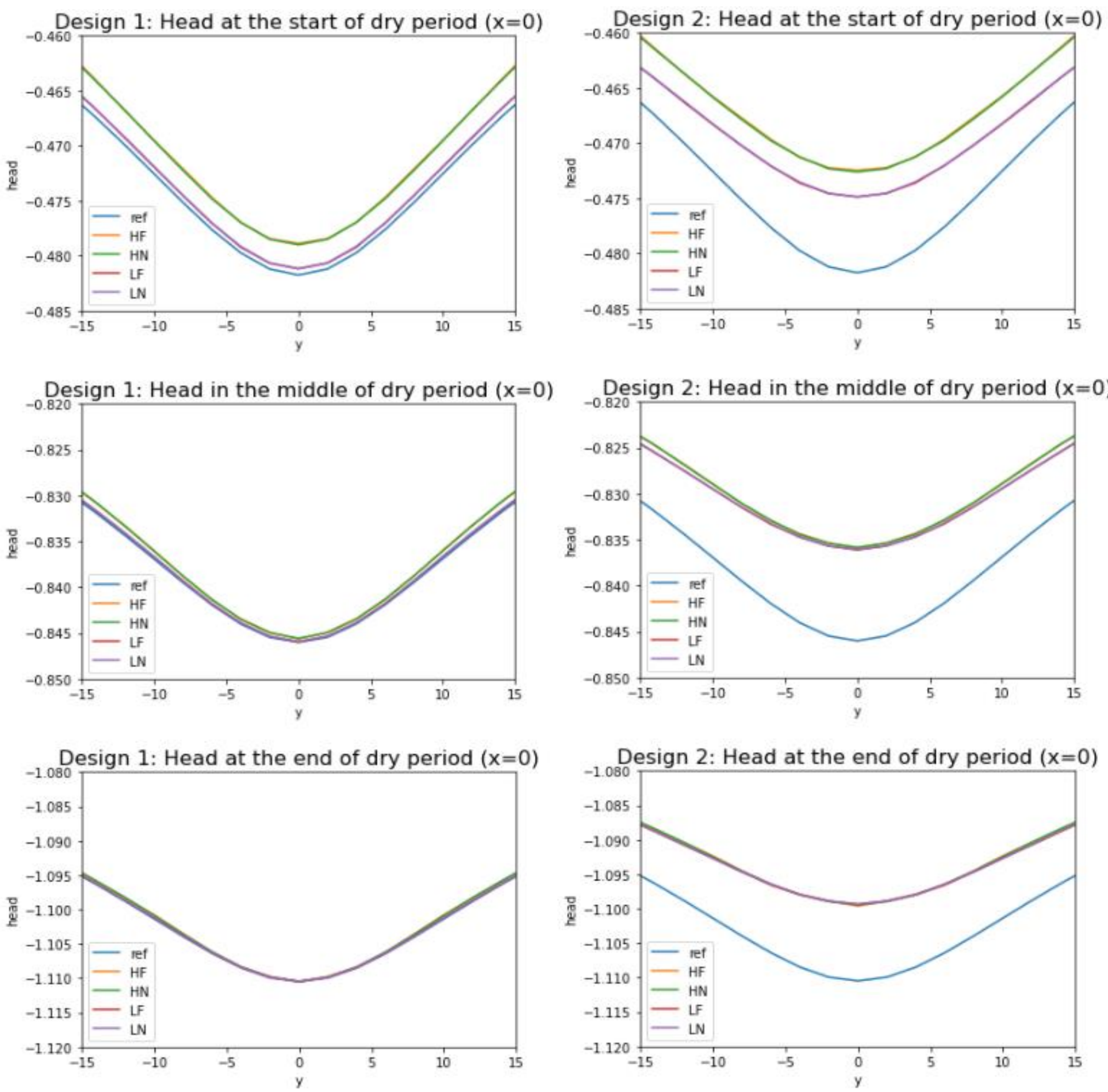


Figure 22. Hydraulic head in a cross section at x=0 for ASR design 1 (left) and 2 (right) at various months of the year: after infiltration, start of the dry period, middle of the dry period and end of the dry period.

Some small differences in the breakthrough curves for the different scenarios can be observed in Figure 23, however significant differences between design 1 and design 2 have not been observed. In the 'low' scenarios the concentration of both designs remains similar to the reference case. In the 'high' scenarios the maximum concentration is higher than in the 'low' scenarios, but the high concentration of infiltrated water has caused an overall increase of the groundwater concentration from fresh-brackish to brackish (Stuyfzand, 1986). Moreover, design 2 has a slightly smaller concentration range than design 1. When evaluating the concentration of the 'high' scenarios after infiltration and at the end of the dry period in Figure 24, it can be observed that the infiltrated water has the highest concentration and that a mixing zone of approximately five layers exists in which the concentration is affected by this infiltrated water. At the end of the dry period, the concentration is more homogenously distributed. The highest concentration of extracted water can thus also be found right after infiltration.

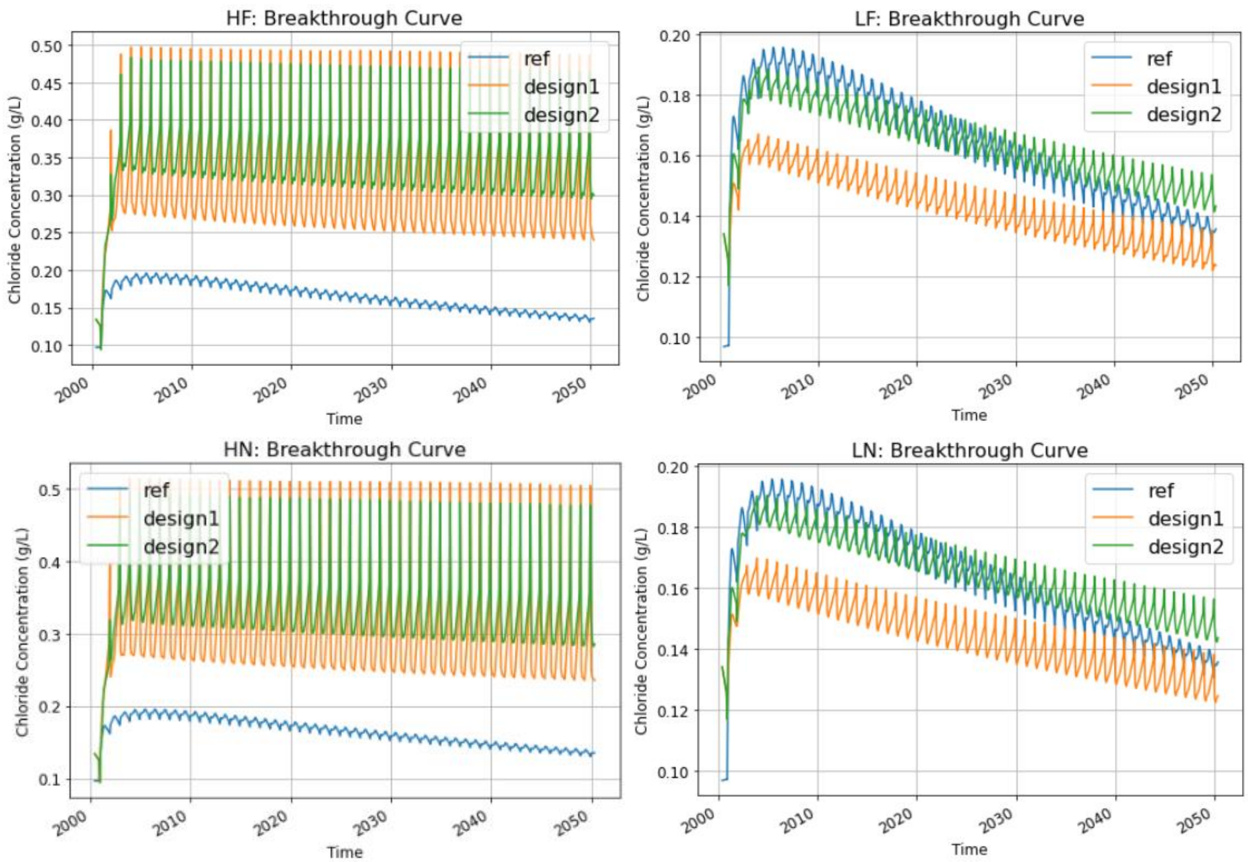


Figure 23. Breakthrough curves at (0,0) layer 5, showing the effect of the different scenarios of design 1 and 2 on the groundwater concentration as opposed to the reference case without infiltration: HF (upper left), LF (upper right), HN (lower left), LN (lower right).

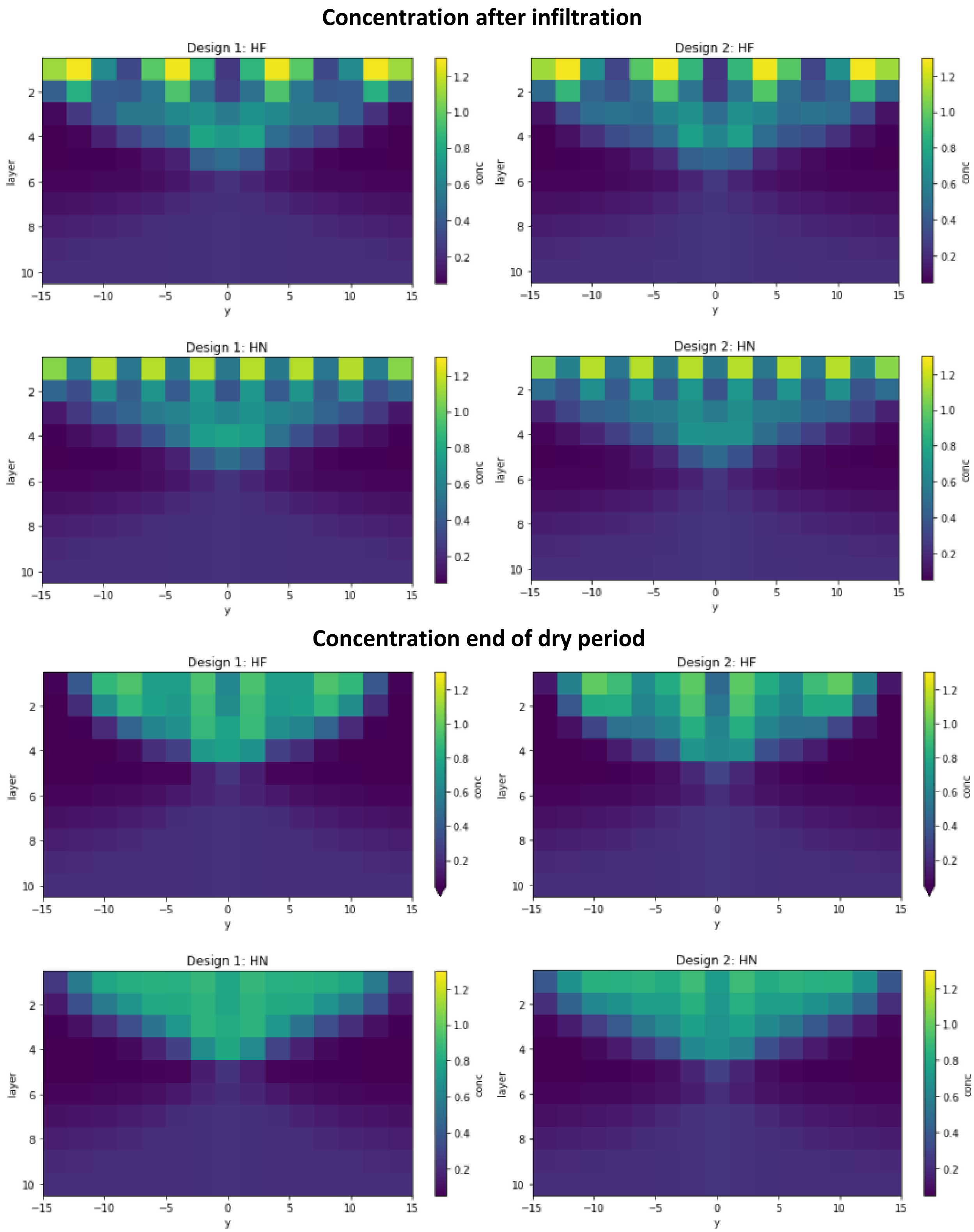


Figure 24. Groundwater concentration at transect x=0 for the scenarios HF and HN of ASR design 1 (left) and 2 (right) after infiltration (upper) and at the end of the dry period (lower).

The lack of a significant elevation in hydraulic head at the end of the dry period raises the question whether a further increase in infiltration rate to 20 m^3/d, even though unrealistic, would further elevate the hydraulic head. However further increasing the infiltration rate does not result in a further elevation of the hydraulic head at the end of the dry period, as can be observed in Appendix A. We found that that concentration increases in the scenario with 'far' spacing, whereas it stays the same in the scenario with 'near' spacing due to the difference in infiltration wells (Appendix A).

One possible explanation for the lack of significant differences in concentration between both designs is the lack of saltwater intrusion from the groundwater. Horizontal extraction wells have been shown to have an advantage over vertical extraction wells in cases with saltwater intrusion of groundwater (Pauw et al., 2015), but this is not currently the case. Therefore, another model simulation was done where the bottom layer was assigned a constant concentration of 15g/L. This represents extreme saltwater intrusion of groundwater, as the concentration of seawater is 19 g/L. The initial chloride distribution is depicted in Figure 25.

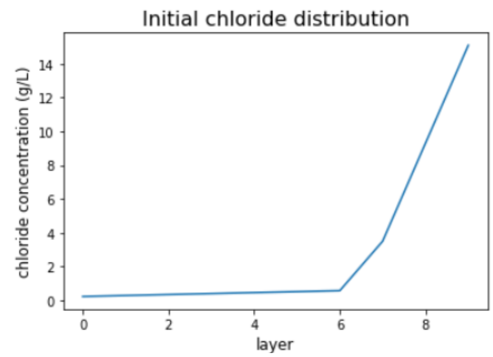


Figure 25. Initial chloride distribution when adding a layer of saltwater (15g/L) to the model.

The addition of saltwater intrusion of groundwater will mostly affect the concentration. Because the infiltrated water has a higher concentration than the groundwater, the largest difference is expected to occur in the 'high' scenarios. Therefore, the concentration of the 'high' scenarios with and without saltwater intrusion are compared in Figure 26. In the scenarios with salt groundwater intrusion the concentration at the center of the area of interest has increased from approximately 0.45 g/L to 1.9 g/L at the end of the dry period. When comparing it to the concentration of seawater (19g/L) this is still relatively small. However, for irrigation purposes this becomes problematic, as it qualifies as brackish-saline water (Stuyfzand, 1986). Still no significant difference in concentration between design 1 and 2 can be observed after saltwater intrusion of groundwater is introduced.

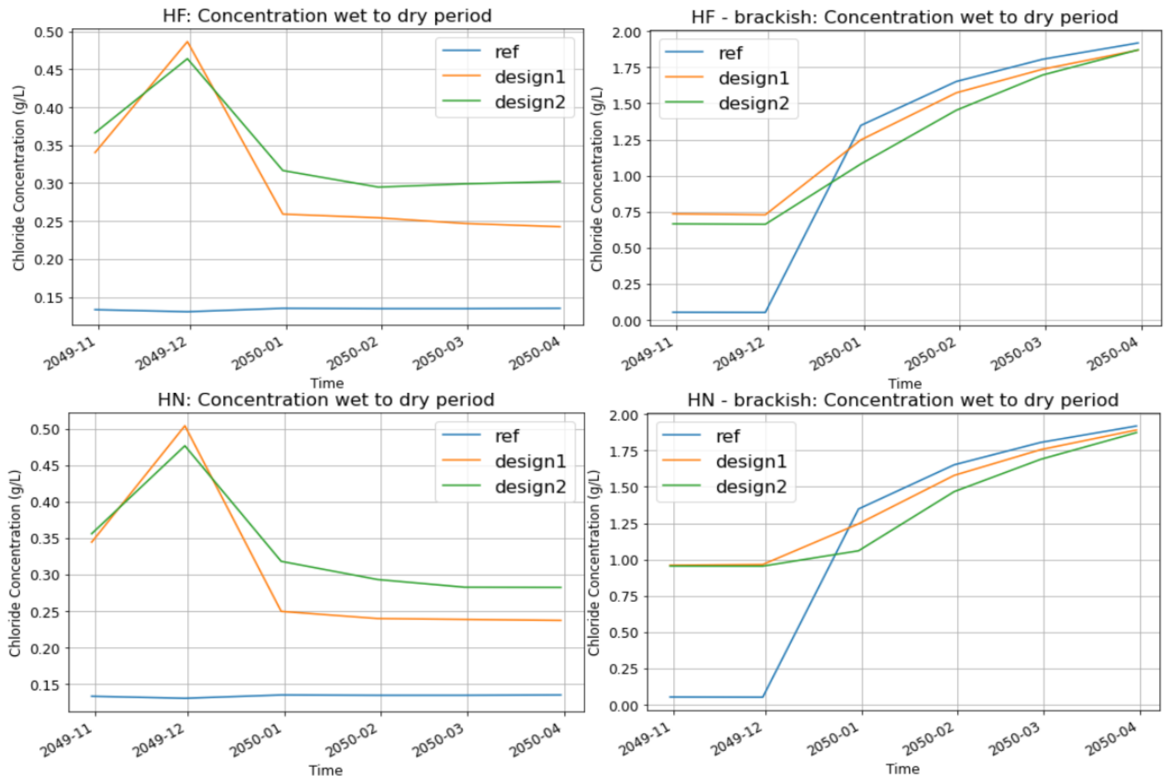


Figure 26. Breakthrough curves of a one-year period showing the difference between the reference case, design 1 and 2 for the scenarios HF (upper) and HN (lower) in the simulation without saltwater intrusion (left) and the simulation with saltwater intrusion (right).

4.1.3.2. Vertical infiltration

For design 3, the extraction rate remains 10 m^3/d and only 'high' infiltration of 10m^3/d is considered. Even though infiltration results in a significant elevation of the hydraulic head after infiltration (Figure 27), the hydraulic head (1H) throughout the dry period is lower than in the reference case (ref). This remains the case when the infiltration rate is raised to 20 m^3/d (1E), even though this is unrealistic. Additionally, the number of wells was increased to 2 and 4 in order to evaluate the effect. Only with four vertical wells could a small elevation of 0.5cm in the hydraulic head be observed, both at the start and end of the dry period. This elevation is however still smaller than the one observed with design 1 or 2. Four wells on a 30x30m plot requires four times as much surface area. For a more significant increase in hydraulic head, it is likely that the number of wells needs to be further increased, which is far from ideal.

The concentration after infiltration is twice as high as for design 1 and 2, because infiltration and extraction take place in the same layer. Interestingly, at the end of the dry period the concentration is lower than for design 1 and 2 (Figure 28). When adding extreme saltwater intrusion of groundwater, as was done for design 1 and 2, the concentration increases to the same level as with design 1 and 2 in case of 1 well, but increases slightly less in case of 2 wells (Figure 28).

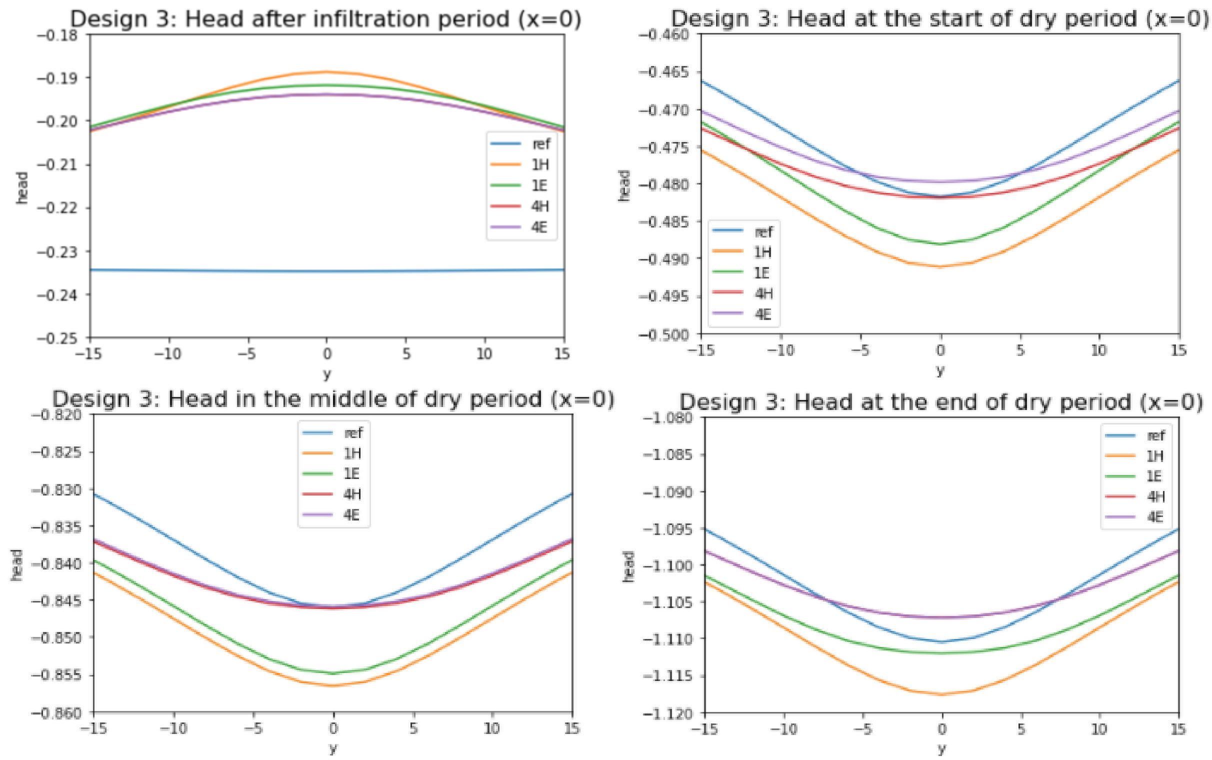


Figure 27. Hydraulic head at transect x=0 for the design 3 scenarios at various months of the year: after infiltration (upper left), start of the dry period (upper right), middle of the dry period (bottom left) and end of the dry period (bottom right).

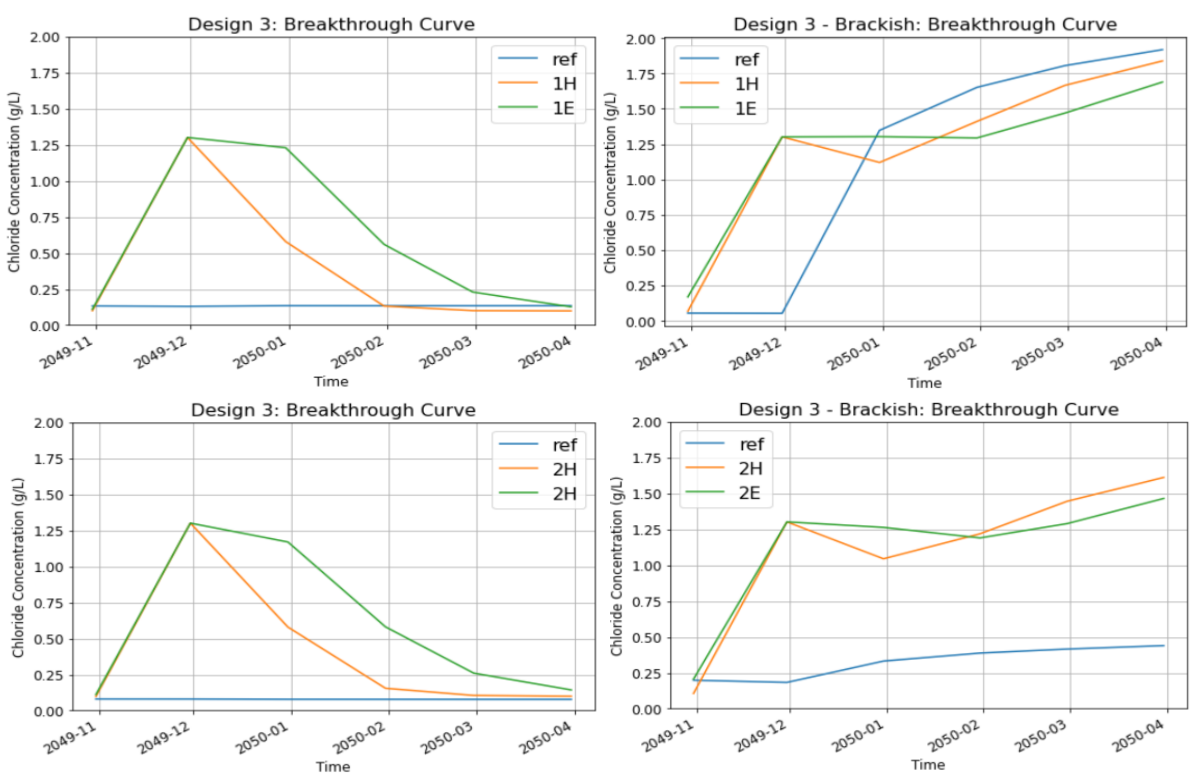


Figure 28. Breakthrough curves of a one-year period showing the difference between the reference case and the design 3 scenarios with one well (upper) and two wells (lower) in the simulation without saltwater intrusion (left) and the simulation with saltwater (right). * the reference concentration in the bottom right figure is lower because the location of the reference extraction well is different from the locations of the design 3 wells in this figure.

4.1.3.3. Synthesis of results

The differences between design 1 and 2 on a local scale are too small to decide on an optimal ASR design. Both designs are able to elevate the head, although only by a centimeter, and no distinction can be made based on the concentration. Design 3 can also be an effective ASR solution, but only when increasing the number of vertical wells. A 30x30m plot would require at least four wells, which costs four times as much surface area than is required for design 1 and 2. Bearing in mind that an ASR solution might be applied on a community level, design 3 would require a much larger number of wells which is inconvenient to farmers, as they will have to be very careful when working the agricultural land with machines. Thus, with the possibility of upscaling to a larger area in mind, this design would be advised against.

The concentration of all three designs is highest after infiltration, which can be explained by the fact that the infiltrated water has a concentration equal to the river water during the dry period. The relatively high concentration in the well right after infiltration could already be a problem, as the average soil-water salinity (in EC) in the root zone of crops will be on average 3.2 times higher than the concentration of the applied irrigation water when assuming a leaching fraction of 15% and a 40-30-20-10 water use pattern (FAO, 2012). Even though the concentration in the rootzone after infiltration is higher for design 1 and 2 as a result of horizontal infiltration in the first layer, the concentration of the supplied irrigation is lower (0.5g/L) as a result of extraction from a deeper model layer. The applied irrigation will have a lower concentration than the water in the rootzone leaching out the salt and decreasing the concentration in the rootzone. The groundwater concentration for design 1 and 2 will likely not cause reduced crop yield, as cucumber is moderately tolerant to saltwater with a chloride tolerance that lies between 0.36 and 0.71g/L (Department of Primary Industries and Regional Development Government of Western Australia, n.d.). The chloride tolerance for the other seasonal crop, peanut, was not found. However, it has been assumed to be similar to cucumber as they are grown at the same time in the same area.

For design 3 however, the applied irrigation after infiltration will have a concentration that is equal to the concentration of the infiltrated water, because extraction and infiltration act upon the same layer. This will likely result in a more concentrated soil-water salinity at first, until the concentration of the supplied irrigation decreases. Since a concentration of 1.3g/L surpasses the chloride tolerance of cucumber (0.36 – 0.71g/L), this might already reduce crop yield. The duration of irrigation with this concentration will determine the extent of crop damage. The concentration of the infiltrated water is important for all three designs but has a larger impact on design 3, resulting in a smaller infiltration window. This is another reason that design 3 will be advised against.

4.2. Community model

4.2.1. Model 1: groundwater extraction

Because a large increase in the area of interest would significantly increase the simulation runtime, the cell size of the area of interest has been adjusted to 4x4m. As previously discussed, an extraction rate of 0.010m, although appropriate for the local model, is unrealistic on a community level. Several factors were considered when reducing the groundwater extraction rate for the community model (Table 8). When considering the average crop water requirement as well as the fact that not all irrigation water has a groundwater source, an extraction rate of 3.5 mm/d is assumed. Another reduction factor of 20% was assumed, because the 600x600m area does not solely consists of agricultural land, part of the area consists of trees, roads, or houses. Moreover, not all irrigation during the dry period is extracted from the groundwater. The model assumes that no rainfall events take place during the dry period, whereas this is not the case. Therefore, another reduction factor of 10% was applied. The last reduction factor represents the already applied water management practice, where farmers reduce the amount of irrigated agricultural land during the dry period to ensure maximum crop yield. This reduction factor was first set to 50%, but the resulting strain on the aquifer was too large, as can be observed in Figure 29. An acceptable reduction factor of 75% was found. Interestingly, the concentration was only slightly affected by these variations in extraction rate. The maximum amount of irrigated agricultural land during the dry period is thus 25% of the active agricultural land during the wet period. This means that an extraction or irrigation rate of 0.63mm/day can be applied to an area of 600 by 600m or one of 2.52mm/d to an area of 300 by 300m.

*Table 8. O*verview of reduction factors applied to the extraction rate when upscaling from the local to the community level.

Factor	**explanation**	**Reduction factor**	**Original extraction rate**	**New extraction rate**
1	No additional irrigation	65%	10 mm/d	3.5 mm/d
2	Non-agricultural land	20%	3.5 mm/d	2.8 mm/d
3	Rainfall dry period	10%	2.8 mm/d	2.52 mm/d
4	Selective land-use dry period	75%	2.52 mm/d	0.63 mm/d

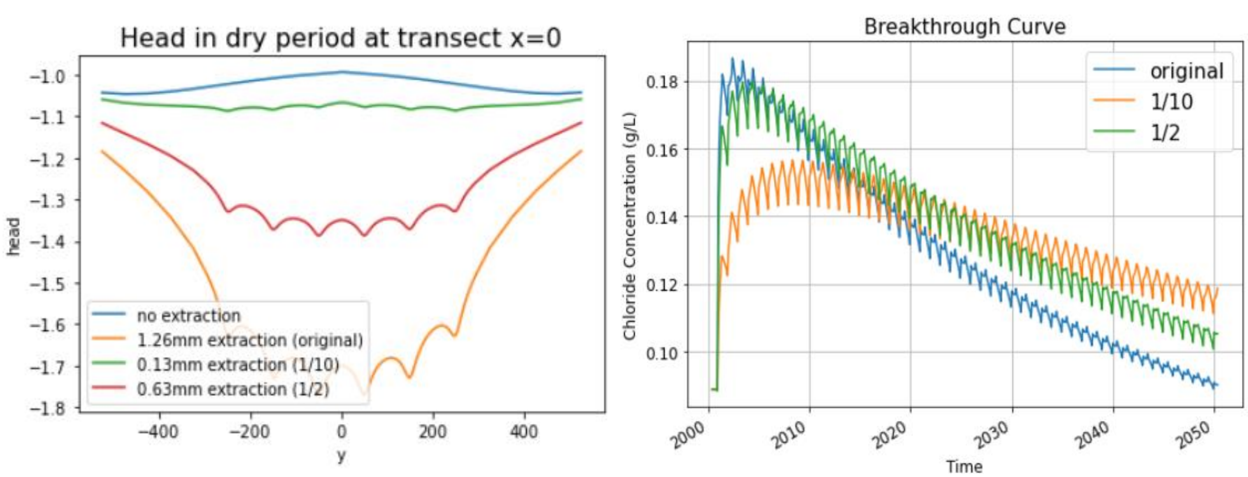


Figure 29. Hydraulic head at transect x=0 at the end of the dry period showing the effect of various groundwater extraction rates (left). Breakthrough curve at location of extraction well showing the effect of various groundwater extraction rates on the concentration in the well (right).

4.2.2. Model 2: ASR solution

4.2.2.1. Horizontal or vertical extraction

The ‘high’ infiltration rate of 0.011m in the local model was too high to wield in the community model, as it resulted in a hydraulic head of +0.3m after infiltration. Such levels of yearly inundation are too high. Instead, a ‘high’ infiltration rate of 0.0056m was used, which results in a hydraulic head at surface level after infiltration. This is the maximum infiltration rate possible without causing inundation. Nevertheless, this infiltration rate could be problematic for the crops grown during this time, as they require an unsaturated root zone (Bregman, 2020). The ‘low’ infiltration rate of 0.0022 in the local model will be used in the community model.

Even though both designs are effective in raising the hydraulic head throughout the dry period, as can be observed in Figure 30, all design 2 scenarios elevate the hydraulic head slightly more. However, this is only a matter of a few centimeters. The difference between the ‘high’ and ‘low’ scenarios for both designs is remarkably small. At the start of the dry period this difference is approximately 5cm, decreasing to 1cm at the end of the dry period. The head elevation of both designs over the entire grid at the end of the dry period is depicted in Figure 31. Even though both designs caused a similar elevation in hydraulic head in one cross section, design 2 affects a larger area which is most prominent for the ‘low’ scenario. The spacing of the infiltration wells has no effect on the elevation of the hydraulic head throughout the dry period on a community level, as was the case in the local model. As there is no difference in impact but there is a significant difference in the number of infiltration wells, the ‘far’ scenarios will be more cost efficient because they have twice as little wells.

The concentration over time at one of the well locations is shown in Figure 32. It is slightly higher with high infiltration, but remains relatively low for all scenarios. Nevertheless it classifies as fresh-brackish and could probably not be used to irrigate sensitive plants (Stuyfzand, 1986; Zaman et al., 2018). No difference can be observed between the two designs. As was the case in the local model, the highest concentration can be found in the upper layers of the model (Figure 33), which can be explained by the relatively high concentration of infiltrated water. The cones have a lower concentration than their surroundings. The mixing zone seems to reach layer 4, which explains why the concentration of the extracted groundwater in layer 5 remains fairly constant and low.

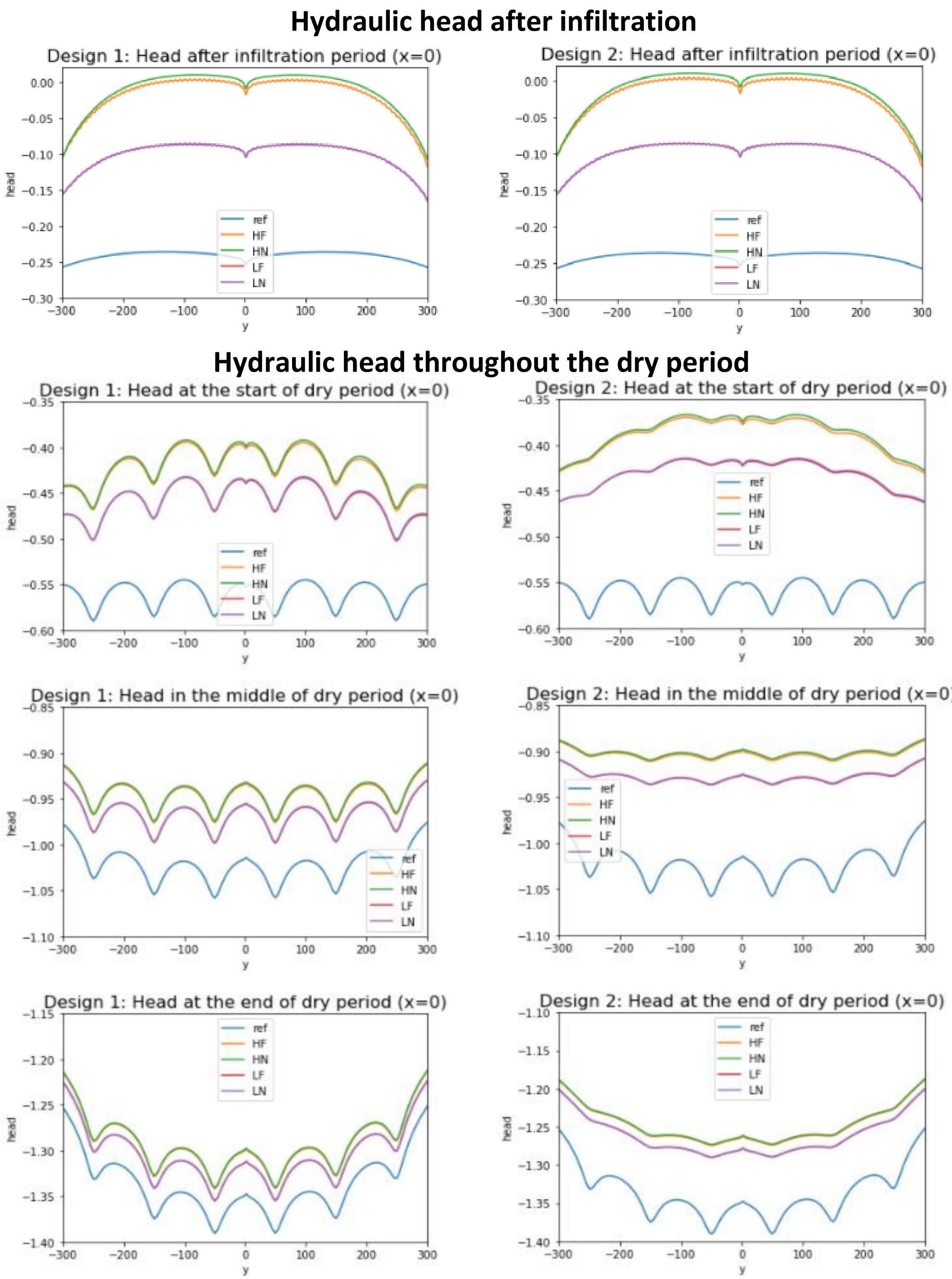


Figure 30. Hydraulic head in a cross section at x=0 for ASR design 1 (left) and 2 (right) at various months of the year: after infiltration, at the start of the dry period, in the middle of the dry period and at the end of the dry period.

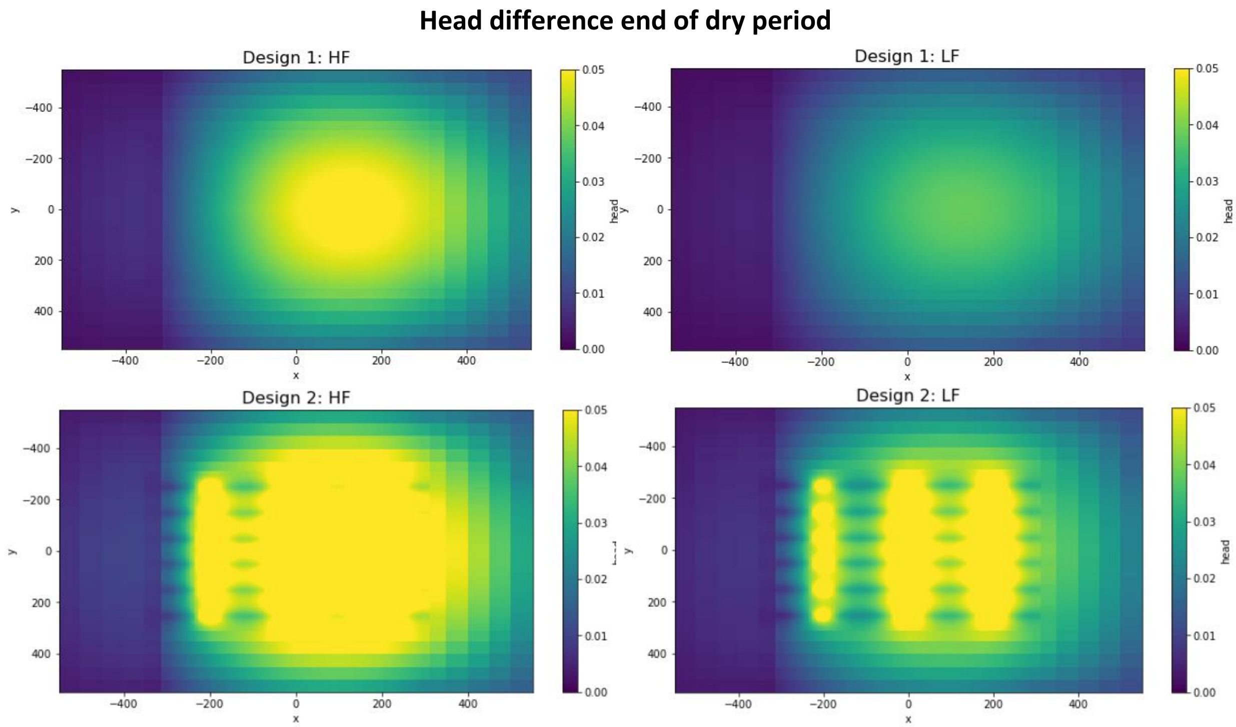


Figure 31. Difference in hydraulic head at the end of the dry season between design 1 (upper) and 2 (bottom).

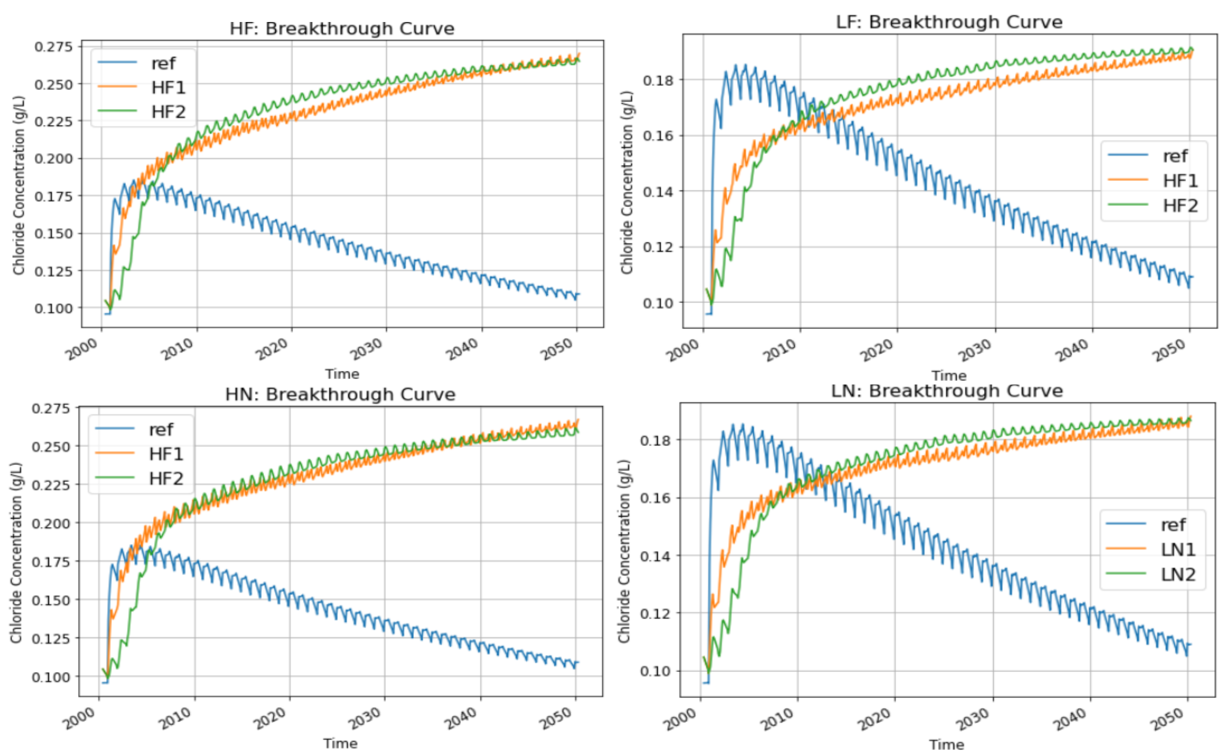


Figure 32. Breakthrough curves showing the difference between the reference case, design 1 and 2 for the scenario's HF (upper left), HN (bottom left), LF (upper right), LN (bottom right).

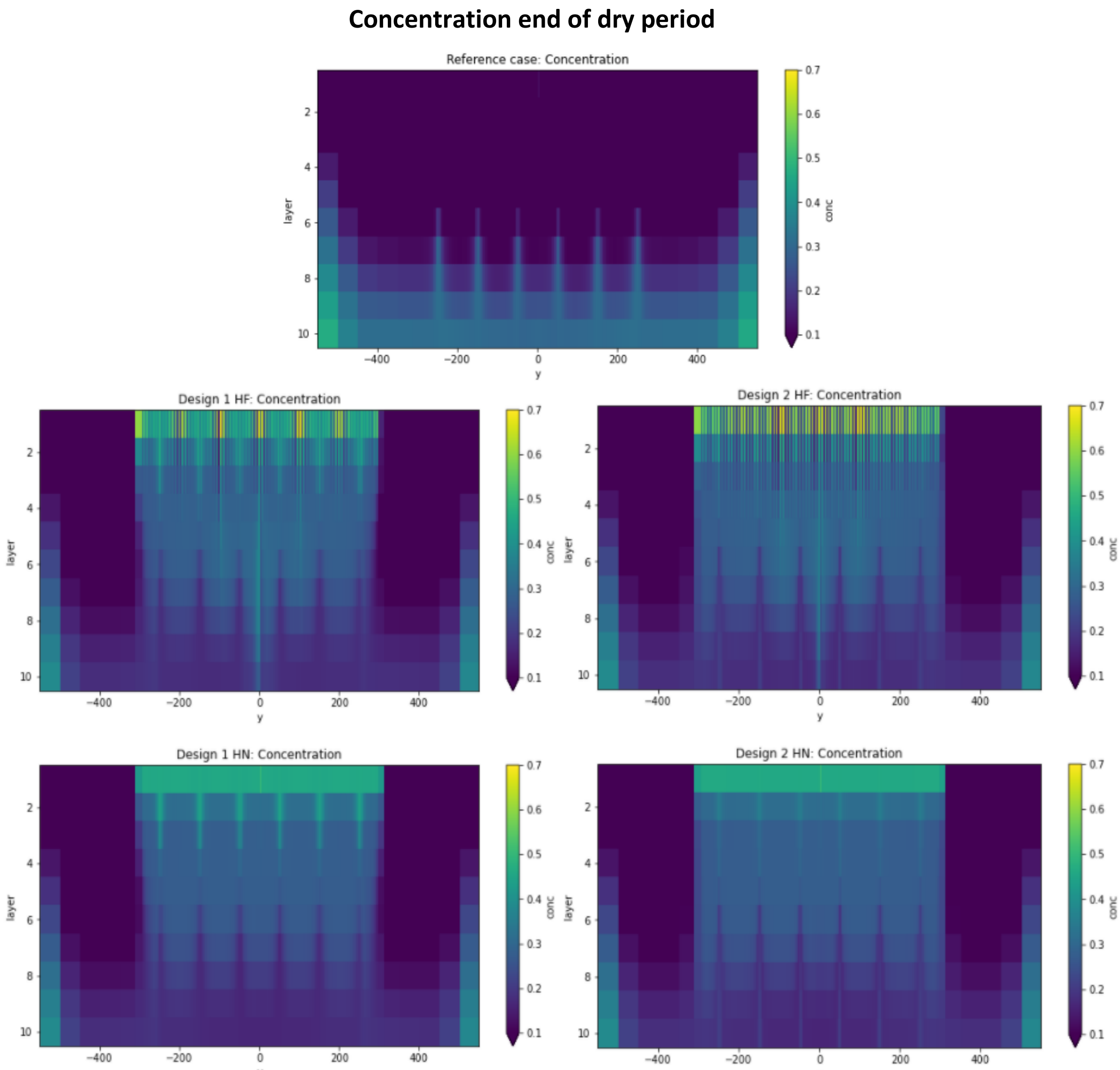


Figure 33. Groundwater concentration at transect x=0 for the scenarios HF and HN of ASR design 1 (left) and 2 (right) at the end of the dry period.

As was done for the local model, extreme saltwater intrusion of groundwater was introduced to the model, after which the concentration of design 1 and 2 was evaluated again. However instead of the 'high' scenarios, the 'low' scenarios will be compared, because these scenarios seem more beneficial for crop yield as the root zone of the crops grown during the dry period is not fully saturated. Upconing was shown to be much stronger in the situation with saltwater intrusion (Appendix C). When comparing the concentration at one of the locations of the extraction wells with an ASR solution present (Figure 39), it can be observed that the concentration in the design 1 scenarios remains similar to the reference case. Throughout the wet period and the infiltration period the concentration is low enough to qualify as freshwater. Afterwards the concentration quickly increases and reaches a value over 2.0g/L at the end of the dry period, classifying it as brackish-saline (Stuyfzand, 1986). The concentration in the design 2 scenarios is much more stable: the maximum concentration (1.0g/L) is much lower than for design 1 and the reference case, but the minimal concentration is higher (0.6g/L). Both concentrations classify as brackish (Stuyfzand, 1986).

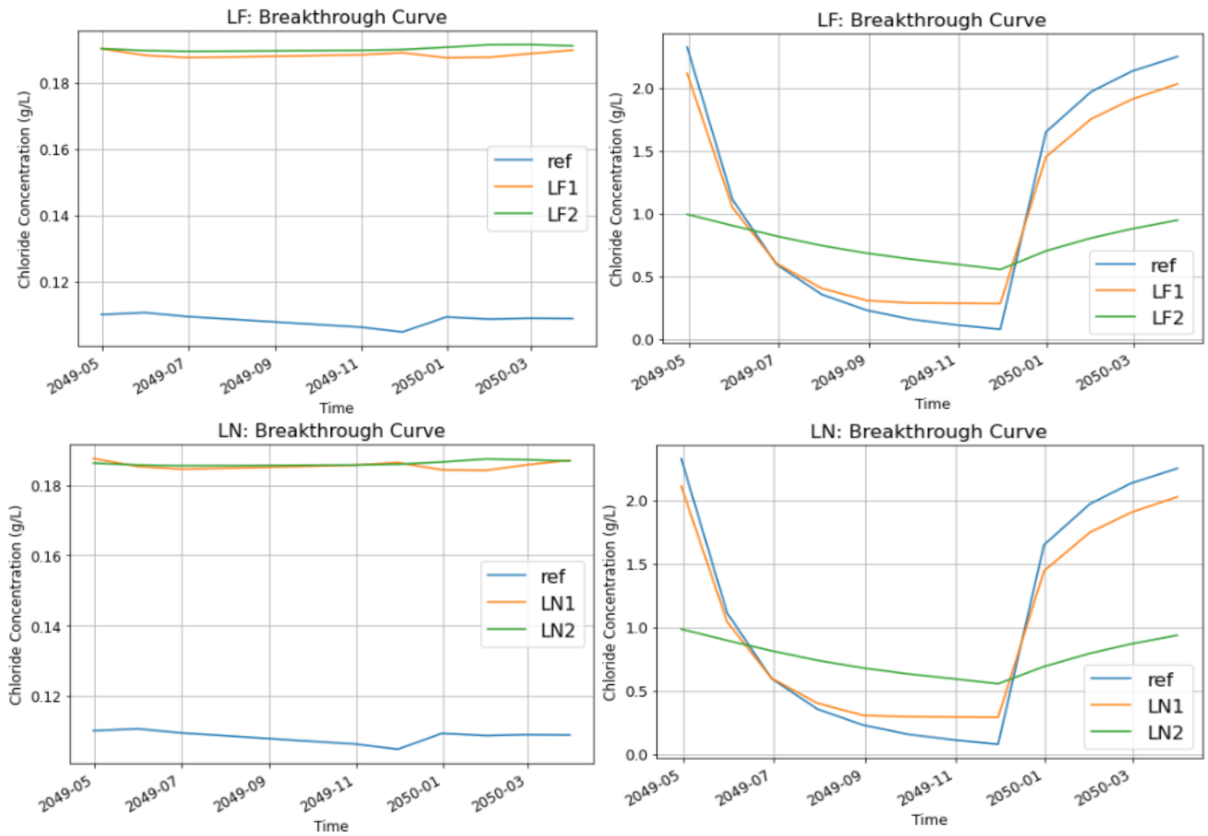


Figure 34. Breakthrough curves of a one-year period showing the difference between the reference case, design 1 and 2 for the scenarios LF (upper) and LN (lower) in the simulation without saltwater intrusion (left) and the simulation with saltwater intrusion (right).

4.2.2.2. Volume of infiltration

Comparing the total amount of infiltrated water with what remains of it at the end of the dry period, shows that a large part of the infiltrated water is removed. The water is infiltrated with a rate of 0.0056m/d for the duration of a month resulting in a volume of 2016 m^3. The remaining volume at the end of the dry period is 357m^3, which is approximately 20% of the volume that was infiltrated. A large part of the volume is drained by the drainage system or by the river and the general head boundaries with their low boundary conditions during the dry period. This volume does not account for the entire elevation in head at the end of the dry period. Part of the elevation is caused by an increase of the storage inflow throughout the dry period compared to the reference scenario.

At the end of the dry period the hydraulic head in the area of interest with design 2 is elevated with approximately 0.12m and 0.10m for the ‘high’ and ‘low’ scenario respectively. Upon evaluation of the average cropping schedule of several crops in Table 9, the elevation in hydraulic head of 120mm at the could support 39% required irrigation of bitter cucumber or 26% of required irrigation of the second peanut crop. The elevation in hydraulic head of 100mm could support 32% of the growing season of bitter cucumber or 21% of the growing season of the second peanut crop. The permanent fruit trees are given enough water to overcome the dry period, but they are not irrigated with the goal of maximum produce as is done with cucumber and peanut (Bregman, 2020), and are therefore left out of consideration. Rice is grown during the wet period, from September to December, and does usually not require irrigation. However, when the wet period is shortened with one month because of a lack of precipitation, farmers currently need to irrigate at least 90mm of groundwater, which can then no longer be used to irrigate the more profitable peanut and cucumber crops. With an extra buffer of 100 or 120mm, irrigation of the profitable crops would still be possible.

Table 9. Overview of the growth season and the irrigation requirements of the crops grown in the study area.

Crop	Start	Days till harvest	Irrigation requirement (mm/growth season)
Cucumber	December	66	244.2
Bitter cucumber	February	66	311.3
Peanut	December	96	396.6
	March	96	469.6
Jasmine and fruit trees	December	121	376.0
Rice	September	120	360.6

4.2.2.3. Upscaling to the region Ben Tre & Tra Vinh

As can be observed in Figure 35, the aquifer is rather sensitive to the hydraulic conductivity. A smaller hydraulic conductivity (system 1) results in a much larger decline of the hydraulic head, which means a larger risk of overexploitation exists. However, with an ASR solution in place the excess volume of water at the end of the dry period is five times larger than in the system with a large hydraulic conductivity (system 2), which has the same elevation in hydraulic head as the BT03 system. As a result, the remaining difference between the two systems is merely 0.1m instead of the original 0.55m. A low horizontal conductivity thus results in a larger sensitivity to groundwater extractions, but at the same time the potential for an ASR solution is larger.

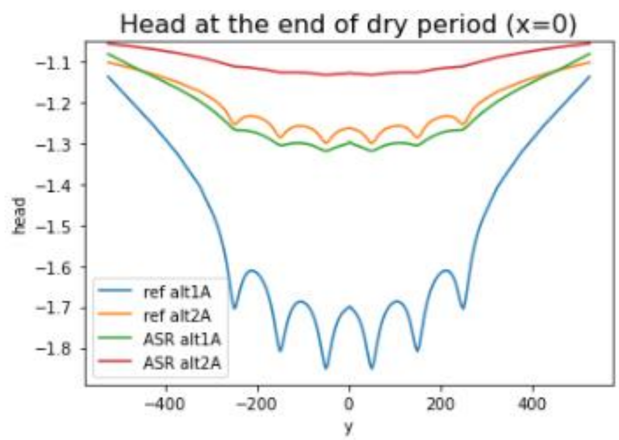


Figure 35. Hydraulic head in an y-transect at the end of the dry period with only groundwater extraction. Alt1 is the model with a horizontal conductivity of 4m/d, for alf2 this is 16m/d.

The difference in storage capacity of the two systems can only be explained by the difference in hydraulic conductivity. System 1 has a much larger storage inflow during the dry period than the BT03 system, system 2 has a smaller storage inflow. As system 2 shows the same elevation in hydraulic head, the smaller inflow into storage needs to be compensated. An increased inflow from the additional river system is observed in both systems. This flux is larger in system 1, but large enough to compensate for the smaller storage inflow in system 2. With a larger river inflow during the dry period an increased chloride concentration would be expected, as the river concentration has a concentration of 1.3g/L during the dry period. However, this is not the case. As can be observed in Figure 36, the concentration in the reference and ASR scenario of the systems without saltwater intrusion of groundwater falls within the same range as in the BT03 system, with the concentration in system 1 being slightly larger. The main difference in concentration between the reference and ASR scenario is the stability of the concentration with an ASR solution. The 'extremes' that can be observed for the reference scenario are not present in the ASR scenario. In situations with saltwater intrusion of groundwater however, the chloride concentration in an ASR scenario is much lower than in the reference scenario. It remains stable at or below the minimum concentration observed in the reference case. This shows the effectiveness of an ASR solution with horizontal extraction wells in different systems with different variables, especially in systems with saltwater intrusion of groundwater.

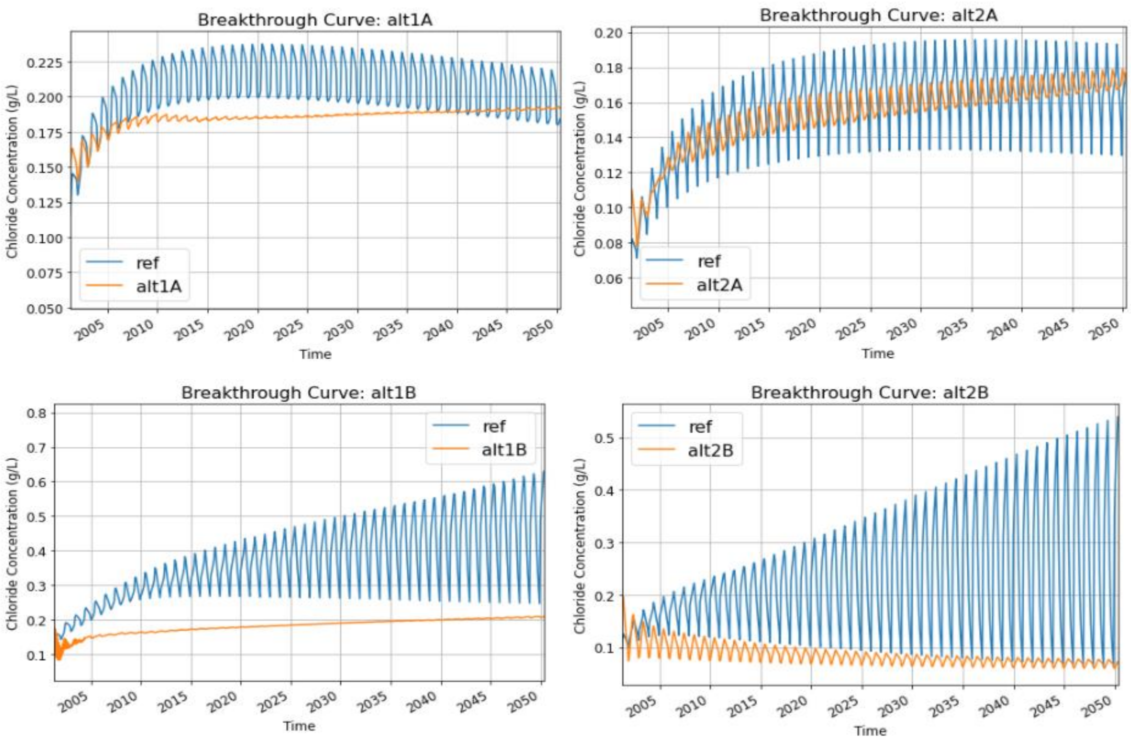


Figure 36. Breakthrough curves for the different systems (1 and 2) and scenarios (A and B). Alt1 is the model with a horizontal conductivity of 4m/d, for alf2 this is 16m/d. 'A' is the scenario without and 'B' with saltwater intrusion of groundwater.

4.2.2.4. Synthesis of results

It was shown that both design 1 and 2 are effective in raising the hydraulic head on a community level. Design 2 affects a larger area and shows a slightly larger elevation than design 1. However, this difference is rather small and the chloride concentration is similar as well. In addition, the costs of constructing a vertical well will be lower than a horizontal well at a depth of 5m, therefore one might consider choosing design 1 over design 2 in the current situation. However, if the situation would evolve to include saltwater intrusion of groundwater, design 2 would significantly improve the recoverability of freshwater, as the concentration is much lower throughout the dry period. It will also be higher during the wet period, but since no groundwater is extracted during this time this makes no difference. The chloride concentrations of the extracted water in this situation are too high for irrigation purposes. Note that only an extreme situation was modelled and that concentrations will be lower in in a less extreme situation.

When comparing the maximum chloride concentration found in this study to the chloride tolerance found for cucumber (0.36 to 0.71g/L) it can be concluded that design 1 and 2 will cause no reduction in crop yield, since the observed range of 0.18 and 0.27g/L is within bounds. The concentrations found with extreme saltwater intrusion of groundwater surpass the chloride tolerance of cucumber. Design 2 would possibly still allow for one month of irrigation, which would be longer in a less extreme situation. For design 1 this is less likely as the concentration followed that of the reference scenario. However, this cannot be said with certainty as this situation was not simulated. The saltwater intrusion in the alternative aquifer systems was less extreme and chloride concentrations remained below 0.2g/L and 0.1g/L for both systems, which is within bounds for irrigation of cucumber. Since the concentration in these systems is significantly lower than in the BT03 system, the lower chloride concentration at the bottom of the model cannot provide a full explanation. The increased depth of the aquifer will also have contributed, since upconing is less strong in the layer with the extraction well filter.

The spacing of the infiltration wells was found to have no effect on the hydraulic head throughout the dry period nor on the concentration. Consequently, it will be more cost efficient to implement infiltration wells with a spacing of 8m between them, as this requires twice as little wells. With a spacing of 4m, 150 wells need to be placed, whereas only 75 wells need to be placed when a spacing of 8m is maintained. It might even be possible to further increase the spacing of the infiltration wells, however this requires further analysis. Note that the numbers mentioned assume the length of an infiltration well to be 600m, whereas in reality infiltration wells have a maximum length of approximately 80 to 100m. Therefore, the total number of wells will be higher, but the ratio remains the same.

Bregman (2020) mentioned that the crops grown during the dry period require an unsaturated root zone. The start of their growing season is in December, which coincides with the modelled infiltration period. As the 'high' infiltration rate caused an elevation of the hydraulic head to surface level and the difference in hydraulic head at the end of the dry period between the high and low infiltration scenarios is merely a few centimeters, a preference would be given to the low infiltration rate.

5. Discussion

5.1. Synthesis of modelling results & model uncertainties

The maximum elevation in hydraulic head for the local model was only 1cm. As this was observed with all scenarios of design 2, the elevation in itself cannot be disregarded and is considered significant in relevant terms. However, an elevation of 0.1m could only support 3% of the growing season of bitter cucumber, and is therefore insignificant in absolute terms. Note that the 30x30m plot was evaluated in isolation: groundwater extraction only took place on this plot. However, in reality groundwater extractions also occur in the surrounding area. As a result, the decline in hydraulic head following groundwater extractions might be larger than estimated by the model. This could in turn affect the elevation in hydraulic head. Consequently, the results from the local model are not sufficient to choose the optimal design.

Various reduction factors in the conversion to the community model were applied to the groundwater extraction rate used in the local model, after which an acceptable extraction rate for the 600x600m area of 0.63mm/d was chosen. Note that these reduction factors are required, but their value was estimated and might be different in reality. The final extraction rate was based on the model results, but as this model is conceptual the acceptable extraction rate for this area in reality might differ from the modelled one. In addition, a large part of the extracted water is used for domestic purposes, which was excluded from this research, but will result in higher extraction rates than modelled. Nevertheless, this study showed that a delicate relation exists between farmers and the groundwater levels in the aquifer. Overexploitation is a large risk, since farmers can only irrigate a small part of their agricultural lands during the dry period and this requires great community cooperation.

Bregman (2020) mentioned that the crops grown during the dry period require an unsaturated root zone. Therefore, a preference was given to the low infiltration rate. The low infiltration rate initially raises the head to 0.1m below surface, whereas the root zone of the crops is 0.5m (Bregman, 2020). Therefore, the low infiltration rate might still be too high, but further decreasing the infiltration rate will also decrease the water buffer at the end of the dry period. The use of smaller stress periods, days or weeks instead of months, would allow us to determine when the hydraulic head reaches the root zone during infiltration, as the duration of saturation will likely affect if and to what extent the crop yield is reduced. Hence, the optimal infiltration rate could be determined. As this would significantly increase the simulation time of the model, this was left out to limit the scope of the study.

The chloride tolerance of cucumber (0.36 to 0.71g/L) was used to determine whether the extracted water was suitable for irrigation. Note that the genotype of the cucumber grown in BT03 is not known and the actual chloride tolerance might be more towards the limits of the range. In addition, the chloride tolerance of peanuts was assumed to be the same, whereas this is not necessarily the case. Even though the effect of the chloride concentration in the extracted, and thus irrigated water, on the crop yield was discussed and estimated, reliable conclusions on the effects of the various ASR designs and the concentration of the infiltrated water on the crop yield would require a more detailed and realistic model, involving crops, the crop water requirement and evapotranspiration. Moreover, recharge should not be modelled conceptually, instead precipitation and evaporation records should be included in the model. This would also allow for the verification and calibration of the groundwater model, as the model results with input values from one period could be compared to the observation in a different period. In addition, it is likely that the concentration of infiltrated water was overestimated in this study. The concentration of infiltrated water equaled that of the river water during the dry period, whereas in reality the concentration of the river water gradually increases to 1.3g/L, resulting in a lower concentration of the surface water during the infiltration period. This overestimation is however no problem, as saltwater intrusion of surface water is only projected to increase. Nevertheless, a lower concentration would reduce the potential crop damage. Therefore, more knowledge is required on this topic.

5.2. Further research

On a larger scale, deeper ASR solutions could be applied in the area, as this would directly counteract land subsidence as well as saltwater intrusion and replenish aquifers that were being depleted. Shallow ASR solutions do not directly have these effects, since the aquifers are replenishable, saltwater intrusion is less of an issue and land subsidence is mostly caused by groundwater extractions from deeper aquifers. However, it could indirectly serve these causes, as it might decrease the amount of deeper groundwater extraction by increasing the volume available for extraction in shallow aquifers. To properly address these delta-wide problems the solution should also be taken wider: upstream damming and inefficient water use or unsustainable water management practices should also be addressed. Nevertheless, shallow ASR solutions could be a small part of the larger solution. It cannot be widely used because of the requirement of slightly elevated sandy structures, but it can provide a solution for farmers on a local scale.

When assessing the local situation, it is important to consider a range of factors. A combination of hydrogeological and geological data is required, as well as more detailed information on land and water use. Knowledge on already applied water management strategies as well as governmental policies of interest is also important. For instance, interviews showed that residents in this area use the extracted groundwater as drinking water (Bregman, 2020). Ensuring a sufficient groundwater quality is extremely important and requires extra attention in the course of the FAME project. There is limited knowledge on the local hydrogeological variables. The storativity, transmissivity and hydraulic conductivity were estimated based on literature values, whereas they could be estimated with pumping tests. The deeper wells that were cored during phase one of the FAME project could be used for a hydrogeological assessment of the aquifer. During phase one of the project, infrastructure was set up to enable the long-term assessment of the hydrological fluctuations. For this study only a limited amount of the collected data could be used, as only one year had passed, but hopefully this infrastructure will enable more research in the future.

More knowledge on the local hydrogeological variables, as well as the geological system, will allow for a more detailed model with a less simplified geology and a more heterogeneous aquifer. As the model used in this study was conceptual, the effects that an ASR solution has on the hydraulic head and chloride distribution in the aquifer might differ from the model results. It will be advised to closely monitor the dynamics of the hydrogeological system in the field in order to compensate for this and find the sustainable extraction and infiltration rates for this study area.

In addition, it would be interesting to do an assessment considering the effects of climate change in this area. Temporal and spatially variation in the recharge rate could be included, in order to evaluate the effects of an ASR solution in one dry year or multiple dry years in a row. The window of opportunity could be pushed forward as a result of limited precipitation creating a shorter wet period. In addition, the length of the window of opportunity could be adjusted, as well as the concentration of infiltrated water. The level of saltwater intrusion could also be varied in order to evaluate the effects of salinity events on the system. This will be helpful in determining sustainable infiltration and extraction rates in various situations, as well as the limit of the concentration of the infiltrated water. Apart form assessing merely technical solutions, it is also important to consider a range of water management strategies and assess their effect. In case saltwater intrusion of groundwater is expected or if saltwater intrusion of surface waters increases, it might be worth researching whether the salinity tolerance of the specific crops grown in this area can be increased or whether it is possible to exchange the less tolerant crops with more tolerant crops of equal revenue.

6. Conclusion

This section will answer the sub-research questions after which the main research question shall be answered.

1. *What are the effects of groundwater extraction on the hydrogeological system in the current situation, without an operating ASR system?*

Groundwater extraction has a limited effect on both the hydraulic head and the concentration upon evaluation of a 30 by 30m plot in isolation. On a community level the local model extraction rate has a much larger impact on the hydraulic head, as the same extraction rate resulted in a much larger decline in hydraulic head. This means that the hydrogeological system is rather sensitive to groundwater overexploitation and water management practices such as reducing the irrigated agricultural land during the dry period are crucial. It was shown that farmers can only irrigate 25% of their total agricultural land during the dry period if overexploitation of the aquifer is to be avoided.

2. *What is the optimal design for an ASR system, considering the local hydrogeological conditions and what is the potential volume for infiltration?*

All three designs that were evaluated on a local scale to some extent showed an elevation in hydraulic head during the dry period. This elevation is however rather insignificant in light of creating a water buffer. Design 3, consisting of vertical wells for both extraction and infiltration, was advised against because infiltration and extraction act upon the same layer, resulting in a high chloride concentration in the extracted and irrigated water, right after infiltration. This will likely negatively impact crop yield. In addition, more vertical wells are required to elevate the hydraulic head. Especially on a community level, the number of wells required for design 3 will be impractical as this takes up surface space and farmers will have to evade these wells when working their land with machines. Both design 1 and 2 show a significant elevation of the hydraulic head throughout the dry period on a community level. Even though this elevation is higher for design 2, the difference is small. As vertical wells are more cost efficient than horizontal wells (at a depth of 5m), in the current situation without saltwater intrusion of groundwater, design 1 might be favorable.

Evaluation of the scenarios showed that the spacing of the infiltration wells has been shown to have no effect. As a larger spacing between the infiltration wells automatically implies that less wells are required, this will be more cost efficient and therefore has our preference. A high infiltration rate was shown to elevate the hydraulic head to surface level, whereas the crops grown during the dry period require an unsaturated root zone. In combination with the observation that the difference in excess volume created at the end of the dry period between scenarios with a high and low infiltration is merely a few centimeters, our preference goes to a low infiltration rate.

At the end of the dry period the elevation in hydraulic head for design 2 was shown to be approximately 0.10m in the area of interest (600x600m), which corresponds to an excess volume of 36000m^3. Especially at the end of the dry period water shortage is dire and will increasingly become so. This excess volume will be sufficient for the irrigation of 32% of the growing season of bitter cucumber or 21% of the growing season of the second peanut season.

3. *How does an operating ASR system affect the fresh-salt water boundary?*

The concentration of the surface water during the infiltration window is crucial. It impacts the chloride concentration measured in the extraction wells, which will be used for irrigation purposes. If the concentration is too high crop yield will be reduced. Moreover, groundwater extractions have also been used for a drinking water purpose, which stresses that a good water quality is requisite.

When introducing extreme saltwater intrusion of groundwater, no distinction can be made between the performance of design 1 and 2 on a local level. On a community level however, a clear distinction could be observed. Design 2 outperforms design 1, as the chloride concentration is far more stable and does not reach extreme values. Thus, when incorporating the potential effects of climate change into the decision for the ASR solution in BT03, design 2 is more desirable. As design 2 was also shown to be effective in alternative aquifers, especially with saltwater intrusion of groundwater, design 2 will be advised whenever saltwater intrusion of groundwater occurs.

How does an operating ASR system in combination with groundwater extractions affect the water quality and quantity of the sand dune aquifer at a field location in Ben Tre?

In this modelling study the dune aquifer has been shown to be rather sensitive to groundwater extraction, with only 25% of the agricultural area that can be irrigated during the dry period. ASR solutions have been shown to effectively increase the hydraulic head in the dune aquifer throughout the dry period. The concentration of the surface water during the infiltration window turned out to be crucial in ensuring a proper water quality that can be used for irrigation without reducing the crop yield, and potentially as drinking water. In the current situation, without saltwater intrusion of groundwater, design 1 with vertical extraction wells might be preferable. However, whenever saltwater intrusion of groundwater occurs or is predicted to occur a strong preference is given to design 2 with horizontal extraction wells. Regardless of whether design 1 or 2 will be chosen for the pilot study in BT03, the optimal ASR design based on the simulated scenarios will have a spacing of (at least) 8m between the infiltration wells and an infiltration rate of (maximal) 0.0056mm/d.

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Appendix

Appendix A: Additional local model results

Model 1

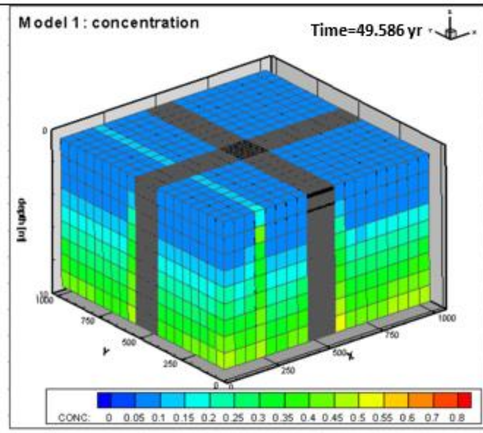
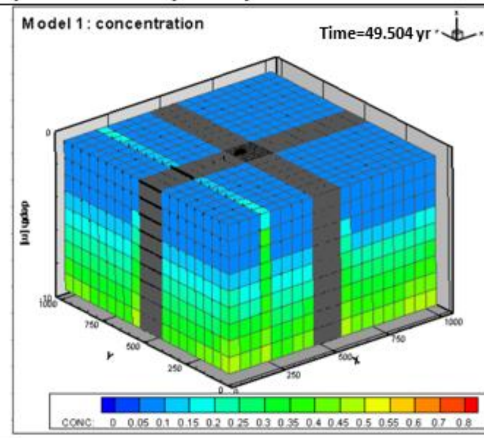
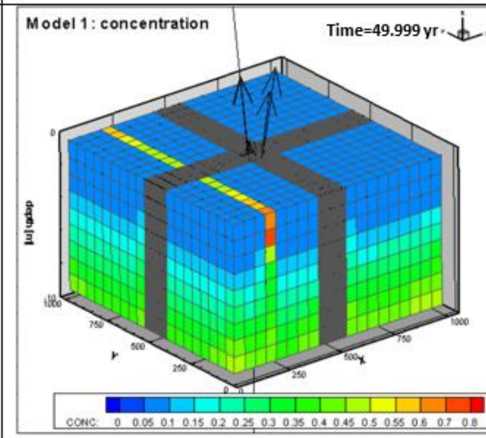
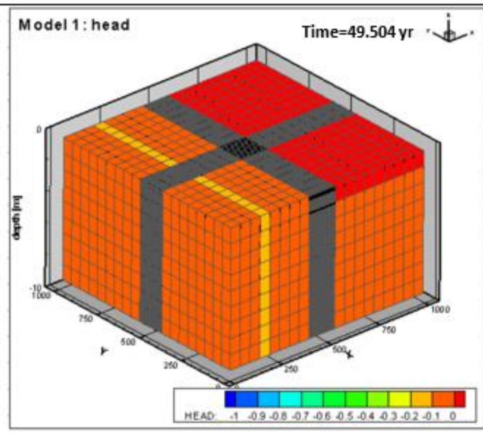
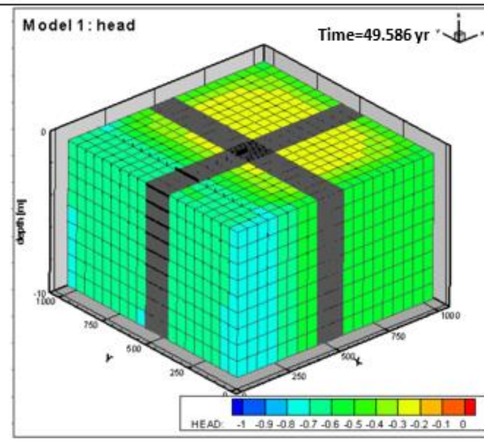
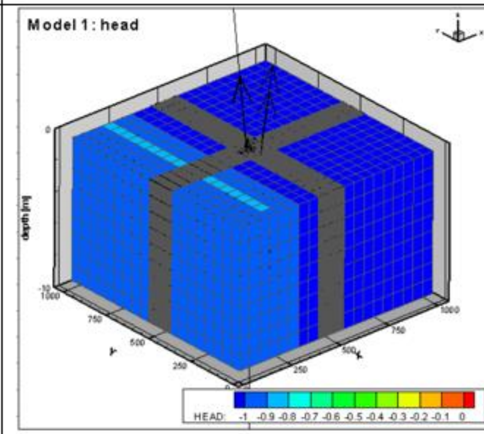
Year		End of wet period	1st month of dry period (intermediate period)	End of dry period
50	Conc			
	Head			

Figure 37. 3D figure of model 1 showing the concentration and hydraulic head at the end of the model simulation at different times: end of wet period (left), intermediate period (middle), end of dry period (right).

Model 2

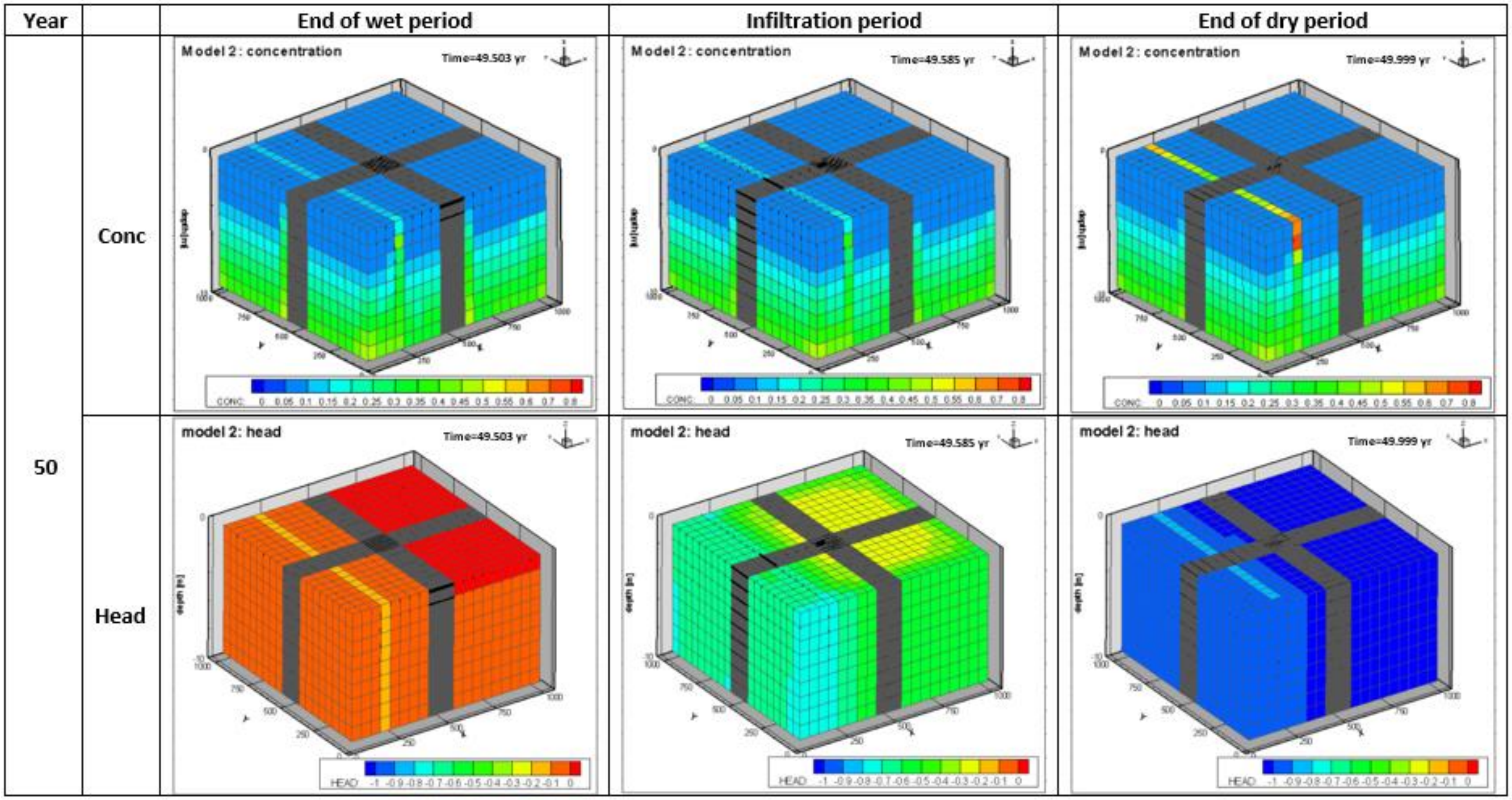


Figure 38. 3D figure of model 2 showing the concentration and hydraulic head at the end of the model simulation at different times: end of wet period (left), intermediate period (middle), end of dry period (right).

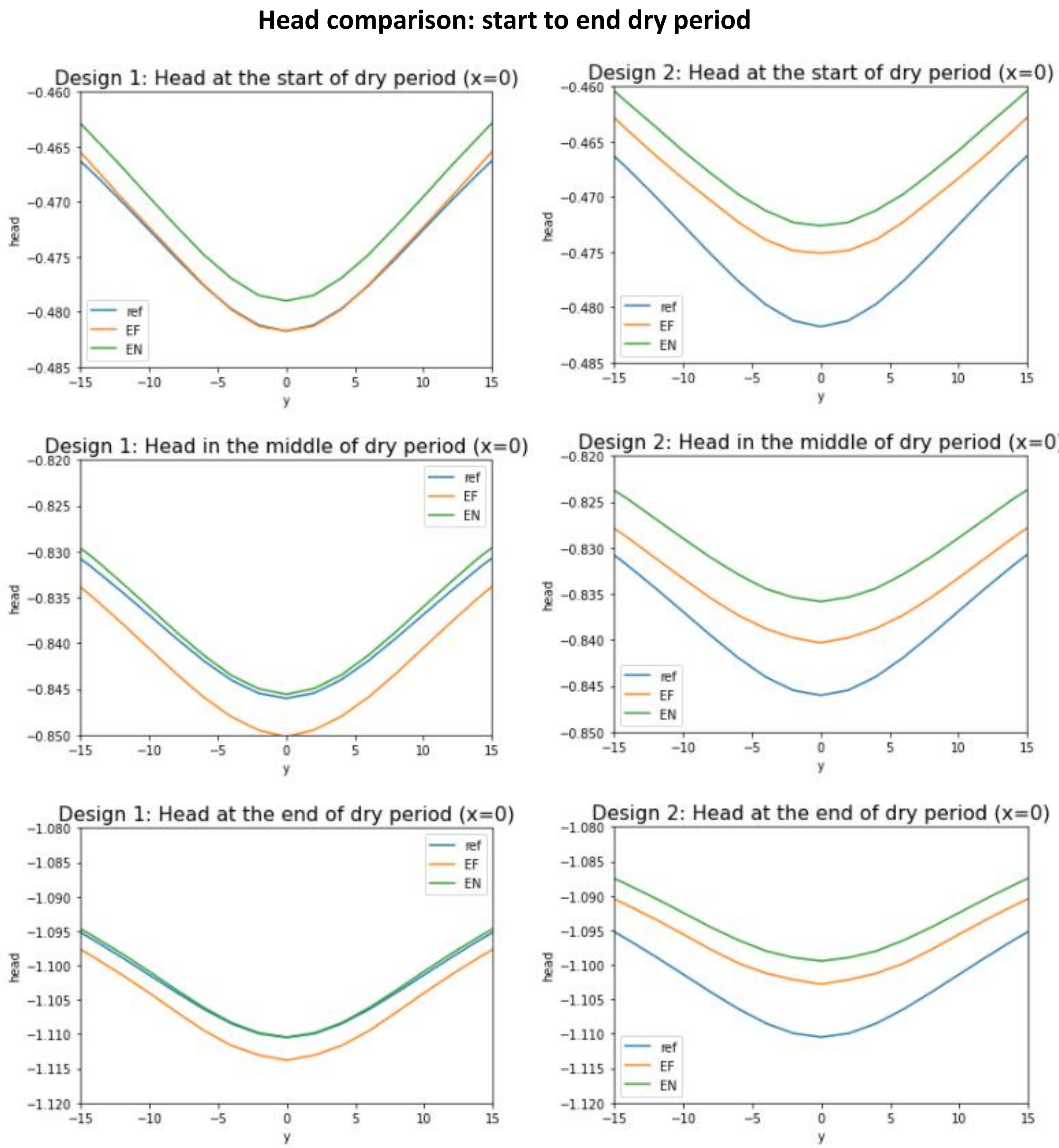


Figure 39. Hydraulic head in a cross section at x=0 for ASR design 1 (left) and 2 (right) comparing extreme infiltration scenarios EN & EF to the reference case at various months of the year: after infiltration, start of the dry period, middle of the dry period and end of the dry period.

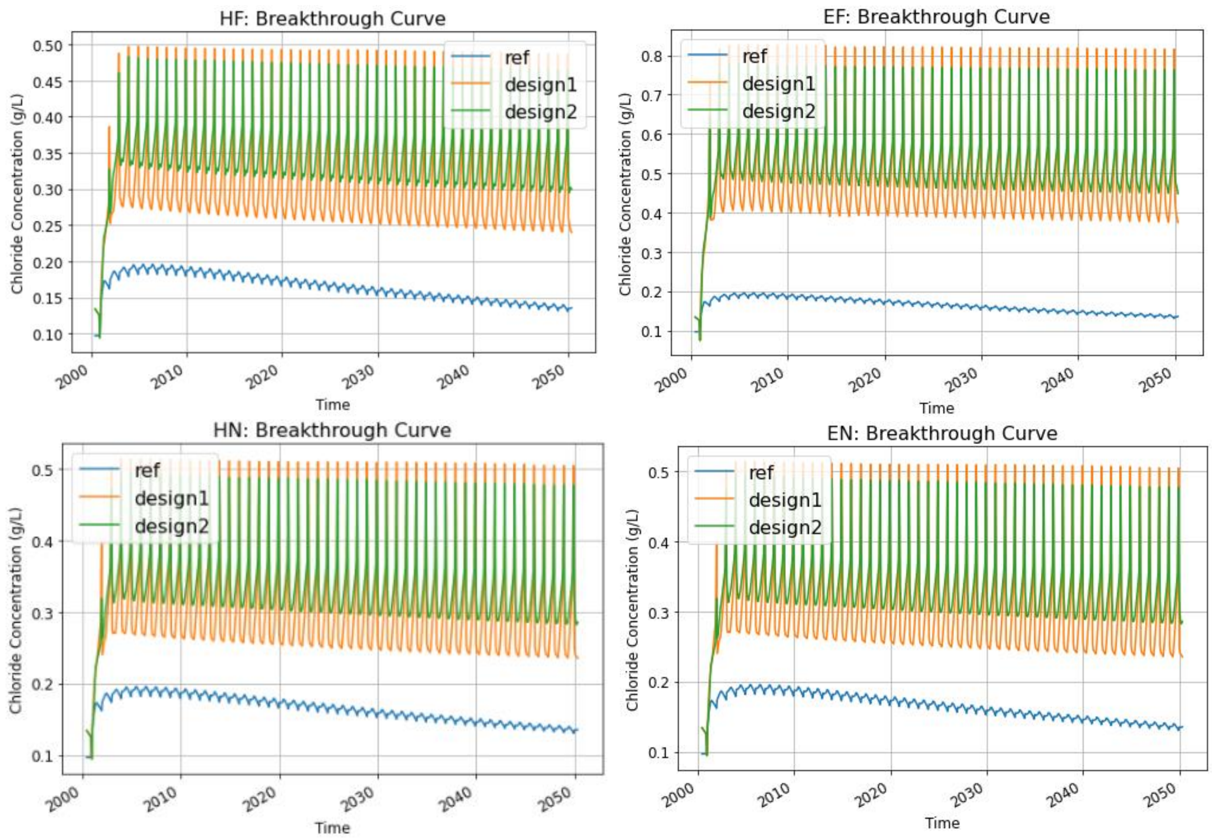


Figure 40. Breakthrough curves comparing design 1 and 2 and the reference case for the 'high' scenarios (left) and the 'extreme' scenarios (right).

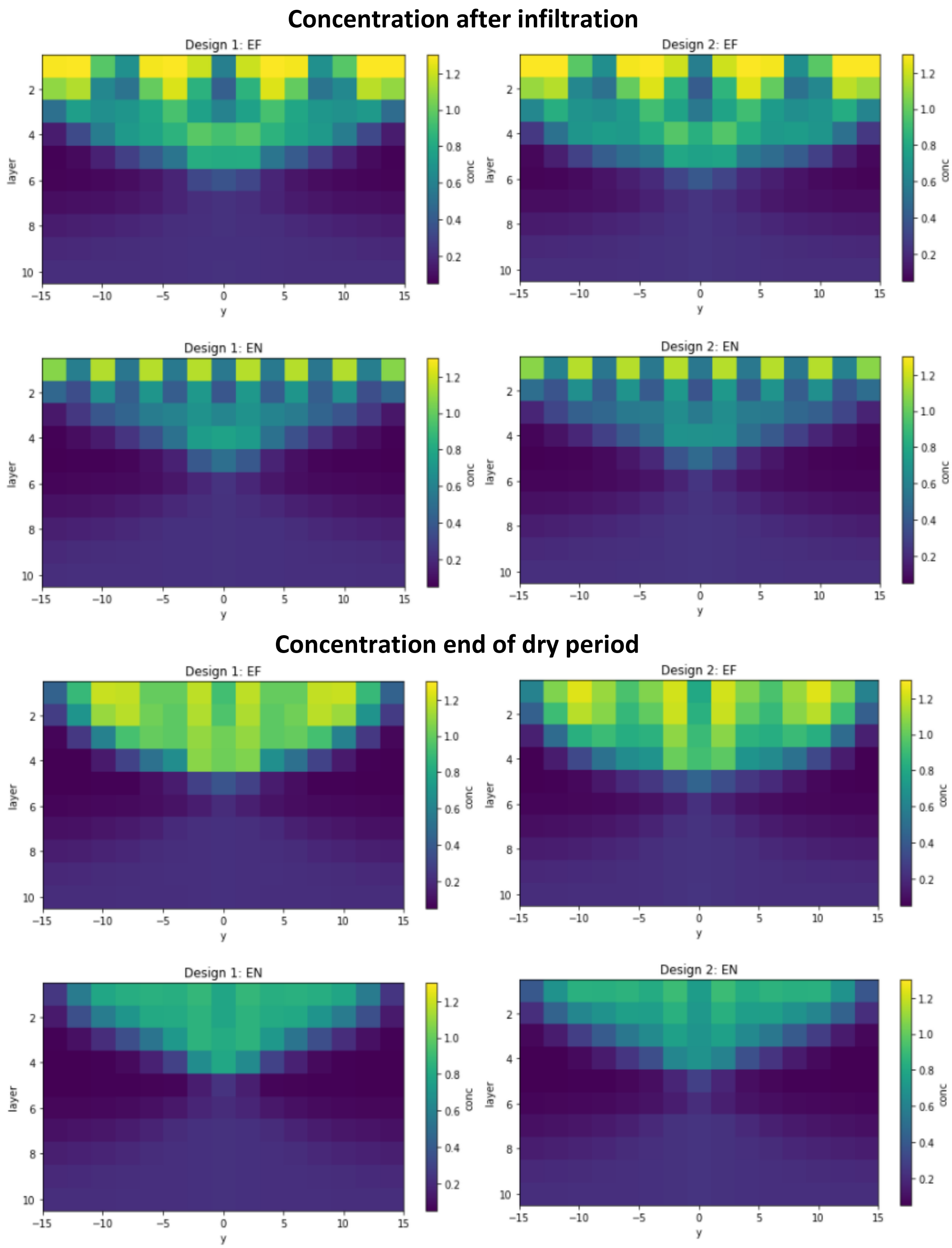


Figure 41. The concentration at the end of the dry period for the transect at x=0 for design 1 (left) and design 2 (right) for 'extreme' scenarios.

Appendix B: Additional community model results

BT03

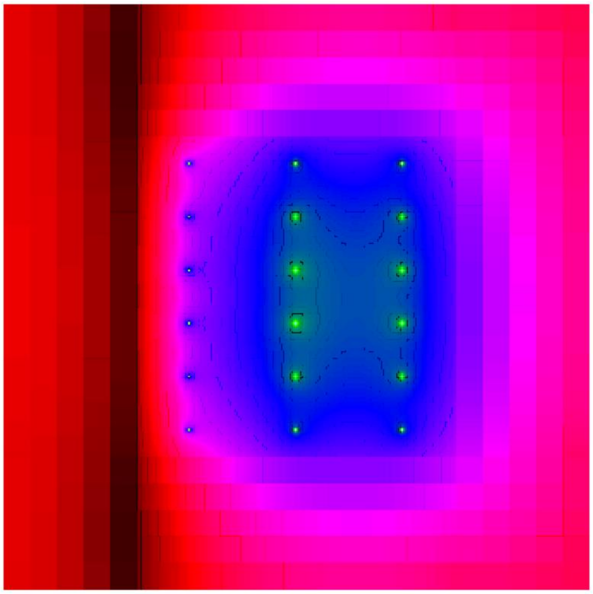


Figure 42. Hydraulic head of the reference scenario at the end of the dry period in layer 5, highlighting the location of the extraction wells in green at the center of the model.

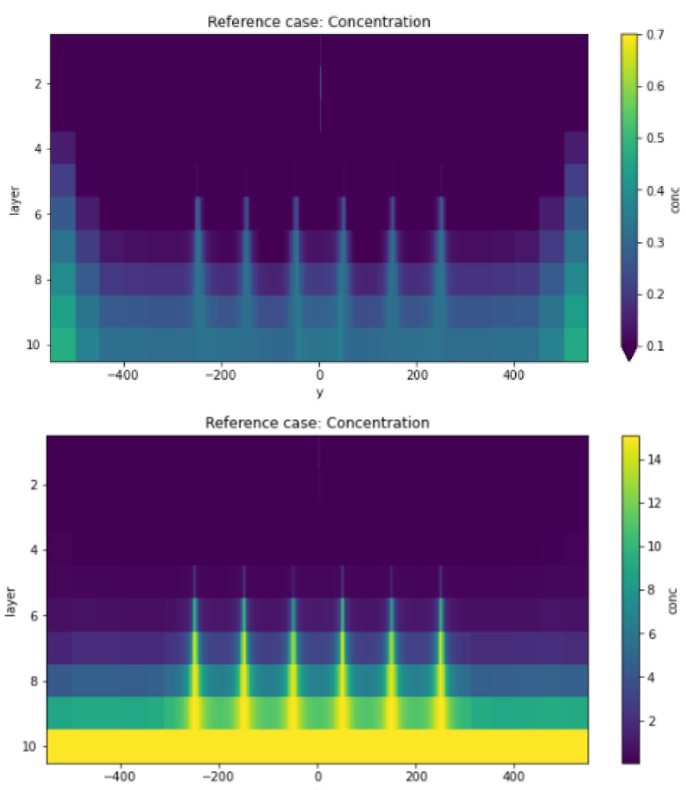


Figure 43. Upconing in model 1 without saltwater intrusion of groundwater (left) and with saltwater intrusion of groundwater (right). Upconing is stronger in with saltwater intrusion of groundwater, as expected.

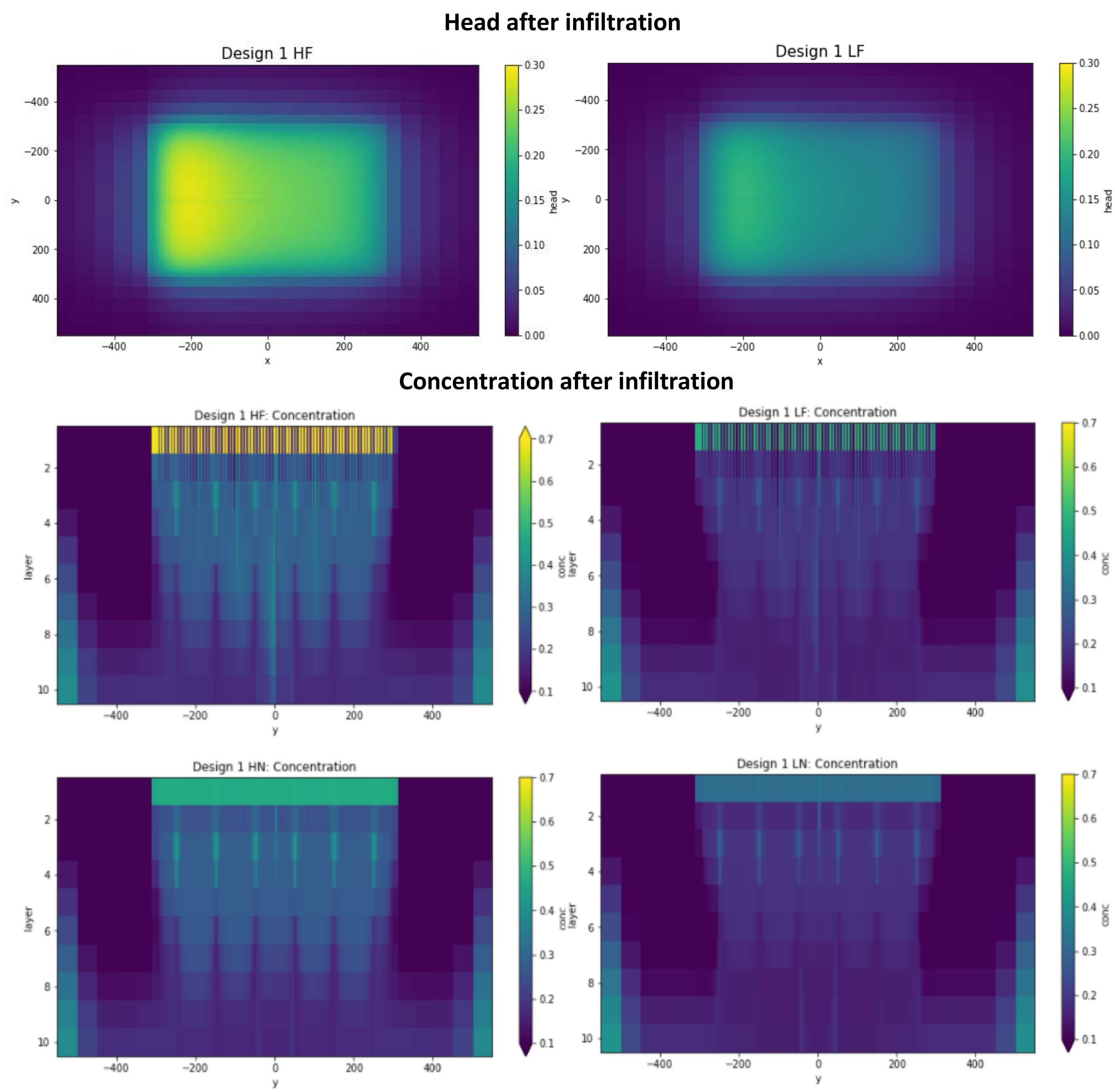


Figure 44. The upper row shows the hydraulic head after infiltration (upper) for the scenarios with high infiltration (left) and low infiltration (right). Since there is no difference in concentration between design 1 and 2, only the figures for design 1 are shown. The figures on row 2 and 3 show the concentration after infiltration for all four scenarios. All figures show a y-transect at x=0.

Upscaling

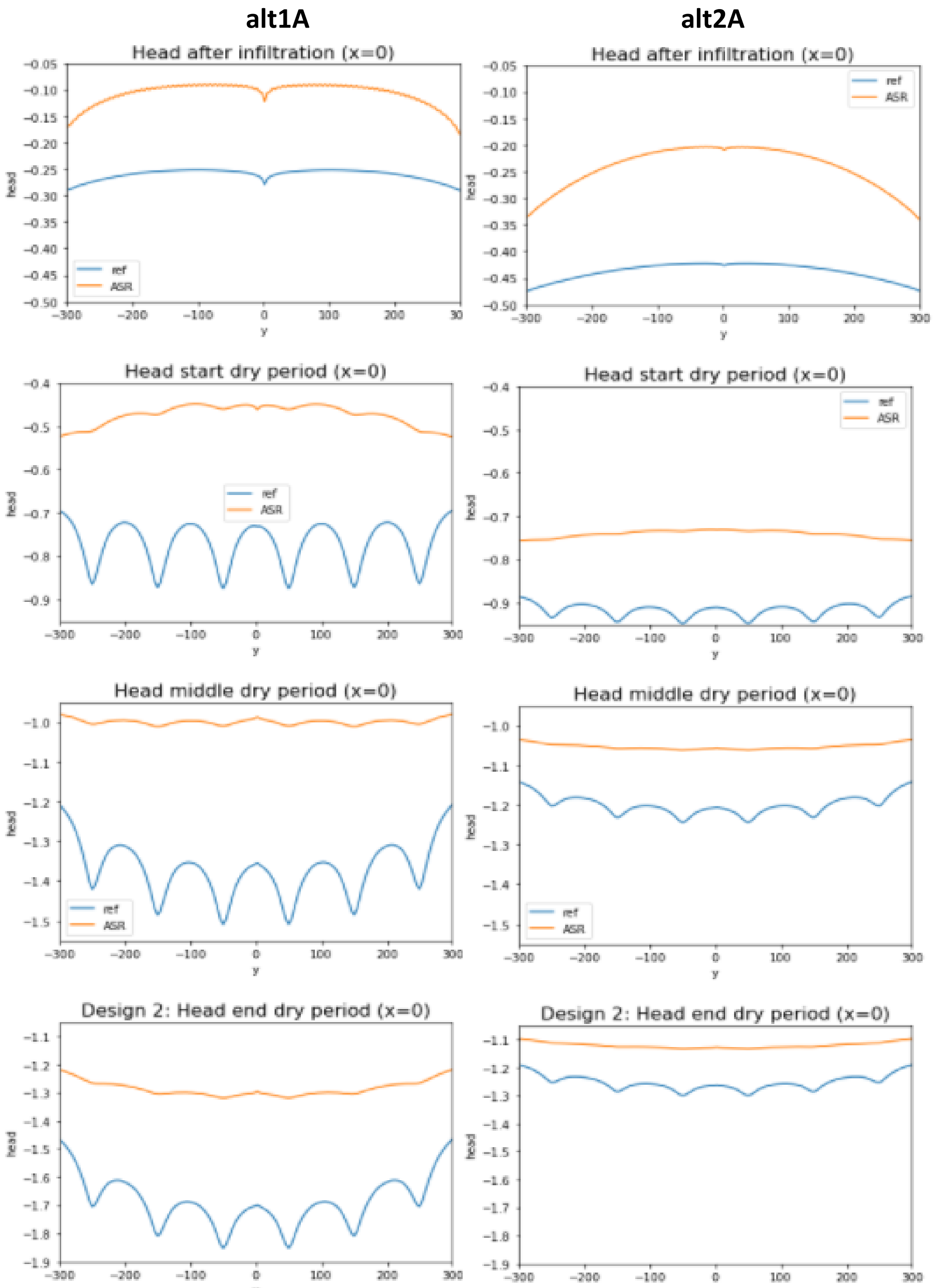
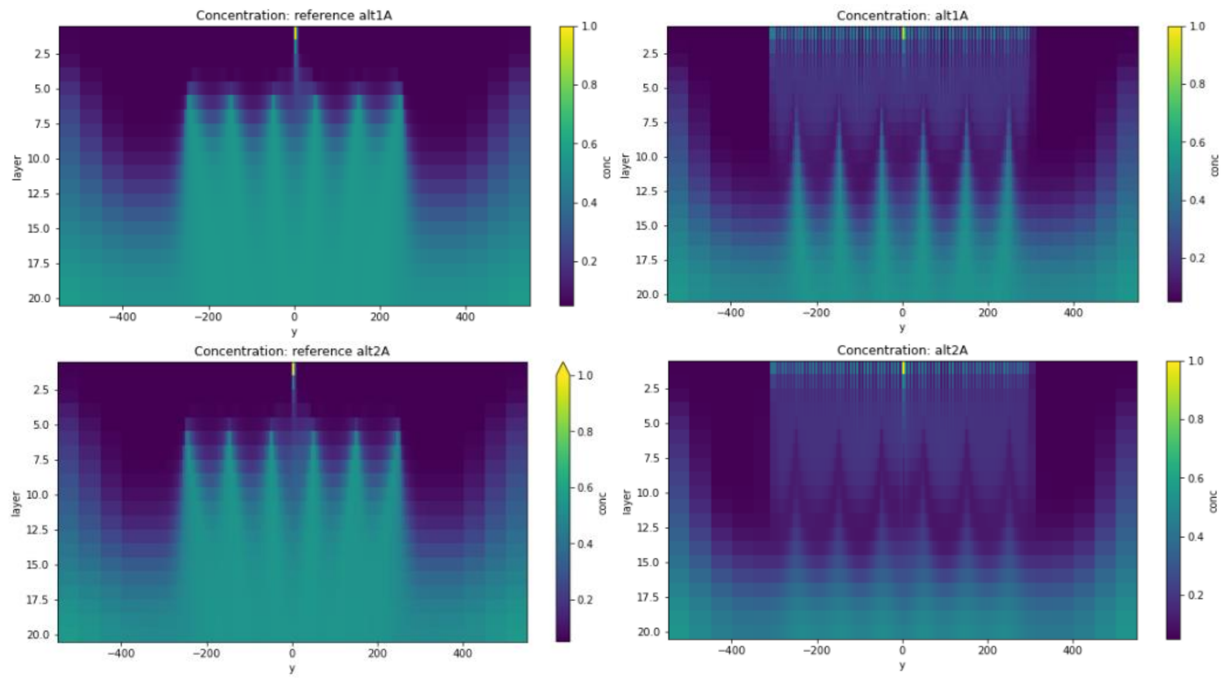


Figure 45. Hydraulic head comparison of the reference and ASR scenario throughout the dry period without saltwater intrusion of groundwater for a system with a horizontal conductivity of 4m/d (1: left) and one of 16m/d (2: right).

Concentration end dry period: without saltwater intrusion of groundwater



Concentration end dry period: with saltwater intrusion of groundwater

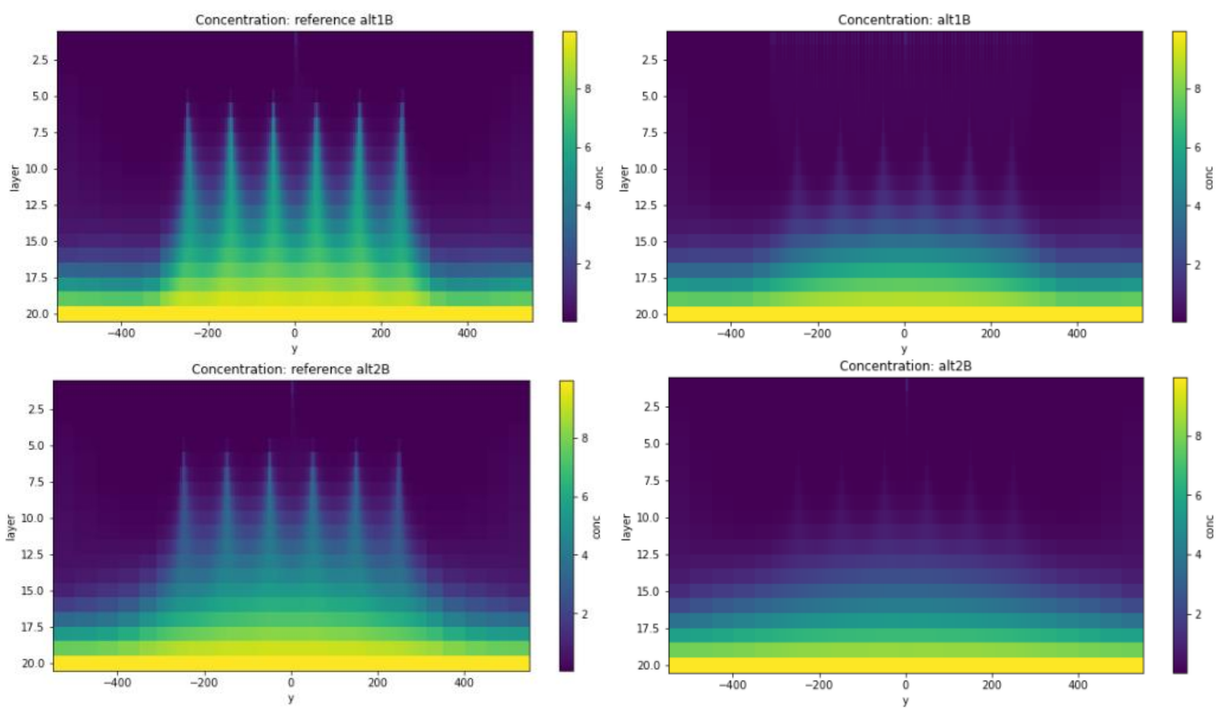


Figure 46. Comparison of the amount of upconing in the reference scenario (left) and ASR (scenario) in a system without saltwater intrusion of groundwater (upper) and with saltwater intrusion of groundwater (bottom). As expected, an ASR solution decreases the amount of upconing, but it increases the concentration in the upper layers throughout the year. Therefore, the concentration of the infiltrated water is crucial for ensuring a proper water quality.

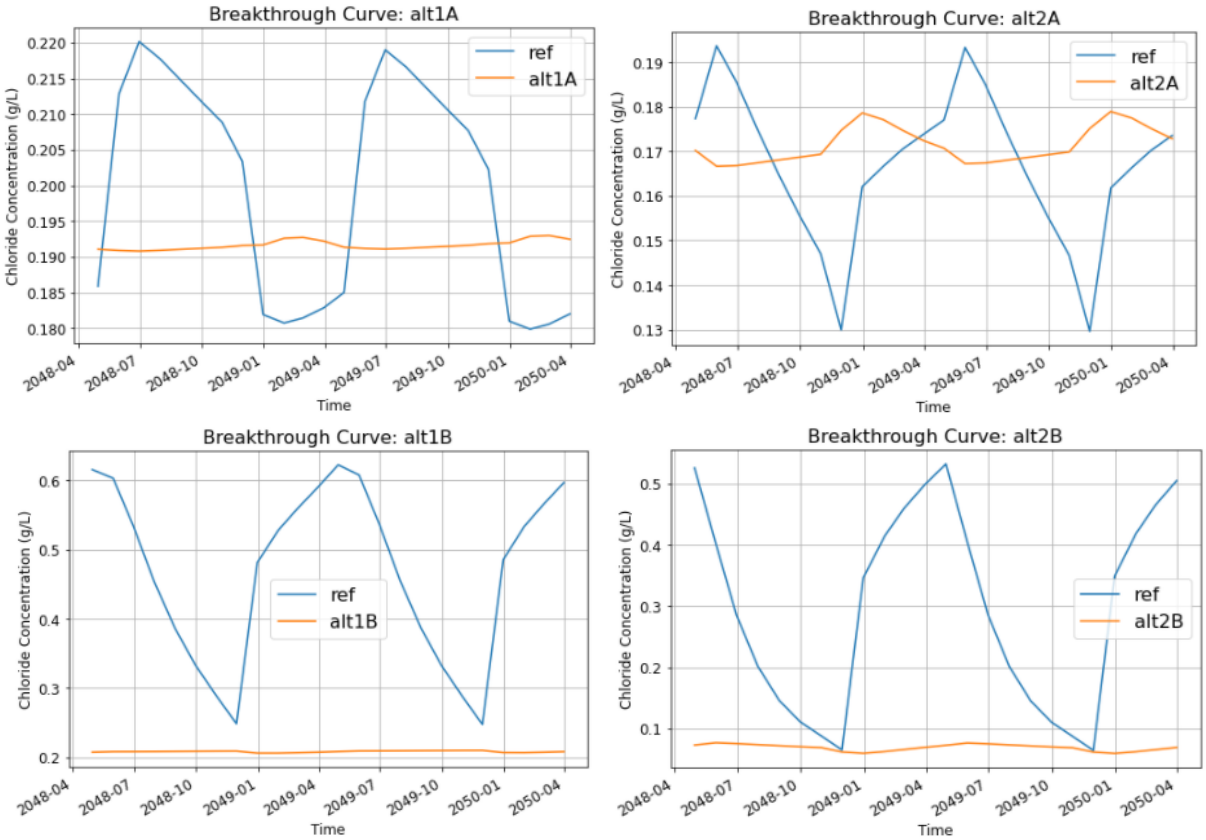


Figure 47. 2-year breakthrough curve for the systems with a horizontal conductivity of 4m/d (system 1: left) and of 16m/d (system 2: right), and the systems without (upper) and with (lower) saltwater intrusion of groundwater. The reference scenario of system 1 without saltwater intrusion shows a bit of a delay since the maximum concentration is reached a few months into the wet period and the concentration remains low throughout most of the dry period. System 2 shows a more immediate response, but as a consequence the concentration immediately increases after infiltration has stopped. In the saltwater intrusion scenario, the concentration immediately increases after infiltration in both systems. The maximum concentration of both systems is approximately equal, but the minimum concentration in system 2 is lower than in system 1, which can only be explained by the difference in hydraulic conductivity.