Freshwater Availability in the MEkong delta (FAME)

Freshwater Availability in the MEkong delta (FAME)

Client	Rijksdienst voor Ondernemend Nederland (RVO)
Contact	Robert Proos
Reference	Oude Essink, G.H.P., Faneca Sànchez, M., Phạm, V.H., Quân, N.H., Minderhoud, P.S.J., Mahya, M., Jansen, S., Zimmel, G., Galvis Rodriguez, S., Van Halsema, G.E., Kruijt, A., Shakel, J., Bregman, S., Verduijn, H., Dinh, T. 2022. Freshwater Availability in the MEkong delta (FAME), Deltares report 11203362-001-BGS-0001, 147 p.
Keywords	Freshwater availability, groundwater, Aquifer Storage and Recovery, Mekong Delta, Vietnam, Province Ben Tre, Province Tra Vinh

Document control	
Version	1.0
Date	28-02-2022
Project nr.	11203362-001
Document ID	11203362-001-BGS-0001
Pages	147
Classification	
Status	definitief

Author(s)		
	Gualbert Oude Essink	Sandra Galvis Rodriguez
	Marta Faneca Sanchez	Gerardo van Halsema
	Phạm Văn Hùng	Anne Kruijt
	Nguyễn Hồng Quân	Josh Shankel
	Philip Minderhoud	Sep Bregman
	Mila Mahya	Hanna Verduijn
	Stefan Jansen	Trang Dinh
	Geoff Zimmel	

Doc. version	Author	Reviewer	Approver	Publish
1.0	Gualbert Oude Essink	Marta Faneca Sanchez	Otto de Keizer	

Summary

The Mekong Delta, Vietnam, is increasingly subjected to salinization of surface and groundwater, while sea-level is rising and dry seasons are getting drier. Consequently, freshwater availability for agricultural, domestic and industrial purposes is likely to become less. **Freshwater Availability in the Mekong Delta (FAME)** is a collaborative, multiphase project focusing on scoping, piloting and providing upscaling advice to national partners in Vietnam on how and where to improve the freshwater availability during (very) dry seasons for agricultural purposes on a farmer-scale by using the subsurface via shallow Aquifer Storage and Recovery (ASR) systems.

These ASR systems have been tested and successfully implemented in many countries around the world (Netherlands, Australia, Israel, USA, etc.). These systems provide the opportunity to recharge permeable groundwater systems (so-called aquifers) by infiltrating or injecting rain and/or fresh surface water into the subsurface. Rainwater run-off towards the sea is therefore limited, while the precious freshwater is safely stored in the subsurface for times of droughts.

Based on hydro(geo)logical and water management characteristics in the Mekong Delta, the so-called creek ridge infiltration technique or the shallow ASR system is considered to be promising. This system pumps or infiltrates freshwater into the sandy subsurface during the end of the wet season (between October and November) before the salinity in the surface water starts to increase. As such, the fresh groundwater volume increases, and thus, more freshwater is available during the dry season.

Three potential ASR field sites in the Ben Tre and Tra Vinh provinces of the Mekong Delta, Vietnam have been studied by students during intensive field work. The site Bin Tangh in the province Ben Tre was initially found to have insufficient surface water quality for water infiltration into the subsurface (the nitrite concentration was too high; this normally converts to other forms like NH4 and would need no additional measures). At the site An Duc in the province Ben Tre, farmers don't use groundwater for irrigation while the sand-dune appears to be too narrow and too densely populated.

The pilot is installed at the Long Son Commune in the province Tra Vinh, at an extensive sand-dune complex. This site is also part of an AMD / IFAD funded project. The monitoring campaign carried out during the project at this Tra Vinh site show a decrease in groundwater table during the dry season and water quality parameters all below thresholds (meaning the water quality is good enough for infiltration). On October 11th-13th, 2021, five infiltration pipes of 30 meters were placed horizontally 1 m below the surface, while 4 monitoring wells with divers and 1 monitoring well with CTD were installed. Freshwater was taken from the nearby reservoir and infiltrated through the five infiltration pipes, using a solar pump.

The potentiality map shows that at least 16,000 ha of sand dunes are suitable for the implementation of shallow ASR systems. From these, some 10,230 ha are prioritized, because these are agricultural areas that require freshwater during the dry season. In total, a 17% of the total extension of sand-dunes in the provinces of Ben Tre and Tra Vinh appears to be suitable for shallow ASR systems. It is estimated that between 40 and 245 Mm^3 water can be stored in the provinces of Ben Tre and Tra Vinh, being about 5 to 25% of the total agricultural water demand in the sand-dune areas during the dry season.

Upscaling the Aquifer Storage and Recovery technique in Tra Vinh to other areas in the Mekong Delta depends on several aspects, such as monitoring the effectiveness of the ASR

technique; raising awareness among stakeholders, training local partners on setting up and implementing ASR techniques, taking care of water quality issues; executing a cost-benefit analysis (implementation and maintenance costs versus benefit from a crop production point of view), and arranging a governance framework that make ASR techniques possible (e.g., coordinate governing systems, guide groundwater extractions implementation, create adequate incentives for groundwater use, enforce regulation) .

The experience, gained from investigating the pilot sites, will also help to combat the salinization of fresh groundwater resources caused by salt water intrusion. Shallow ASR systems can be part of a water-management framework to ensure that water resources are managed in a sustainable manner. Successful shallow ASR systems will support farmers who always strive for the access of enough clean water during dry periods in vast volumes to irrigate their crops without having to worry about depleting deep aquifers or increasing local land subsidence.

However, it is envisaged that shallow ASR systems alone will not solve the freshwater resource issue in the Mekong Delta. A combination of other water-related measures is likely needed to ensure the sustainability of water resource availability within the regions. Shallow ASR systems should especially be prioritized to areas where (deep) fresh groundwater resource is scarce, or where land subsidence due to large deep groundwater extractions is serious.

This project is based on the continuing partnership and knowledge exchange between European project partners and Vietnamese knowledge institutes, professionals, authorities, and local communities.

The project is funded by Netherlands Enterprise Agency (RVO) and is a part of the Partners for Water program. Partners of the project are: Deltares, Division for Water Resources Planning and Investigation for the South of Viet Nam (DWRPIS), the Center of Water Management and Climate Change, of the Vietnam National University – Ho Chi Min (WACC), Wageningen University & Research (WUR), Nelen & Schuurmans, and Royal HaskoningDHV.

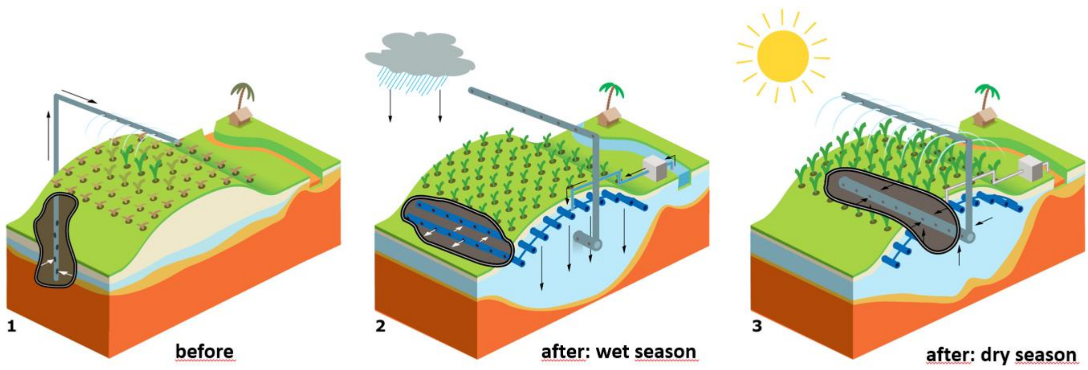


Figure: Shallow Aquifer Storage Recovery Concept: 1. Situation before an shallow ASR system is implemented; 2. Infiltrating water during the fresh surface water excess period (wet season); 3. Extracting the stored groundwater during the surface water shortage period (dry season).

Contents

	Summary	**3**
1	**Introduction**	**9**
2	**Project scope and activities**	**11**
2.1	Project scope	11
2.2	Project activities	11
2.2.1	Scoping phase	12
2.2.1.1	Data gathering	13
2.2.1.2	Potential measures	13
2.2.1.3	Formulation of the ASR pilot characteristics	13
2.2.1.4	First Workshop: evaluation of the feasibility of the proposed pilot sites	13
2.2.1.5	Selection of the pilots and development of the work plan	14
2.2.2	Pilot research phase	14
2.2.2.1	Design and pilot implementation	14
2.2.2.2	Assessment of results and feasibility of the pilot system	14
2.2.3	Upscaling potentiality research phase	14
2.2.3.1	Workshop on feasibility and upscaling	14
2.2.3.2	Mapping the potential of ASR systems	14
2.2.3.3	Workshop (online) on the ASR pilot installation and upscaling possibility	14
3	**Freshwater and agriculture in the Mekong Delta**	**15**
3.1	Introduction	15
3.2	Freshwater availability	16
3.2.1	Surface water	16
3.2.2	Groundwater	19
3.3	Agriculture activities	22
3.4	Water demand and supply	23
3.5	Policy and governance	24
3.5.1	General water governance system in Vietnam	24
3.5.2	Relevant stakeholders	25
3.5.3	Barriers of scaling up the ASR in the context of Vietnam	26
3.5.3.1	General Barrier	26
3.5.3.2	Barriers in specific for groundwater governance	26
3.5.4	Relevant regulations, barriers, and enablers on the scaling up of the ASR	27
4	**On Aquifer Storage and Recovery techniques**	**28**
4.1	Introduction	28
4.2	Types of Aquifer Storage and Recovery systems	29
4.3	Aquifer Storage and Recovery systems in the Mekong Delta	32
5	**Study areas**	**35**
5.1	Selection of the studied areas	35

5.2	Hydrogeology of the selected provinces	37
6	**Study area Ben Tre 2**	**39**
6.1	Introduction	39
6.2	Description of the local situation	39
6.3	Field work	40
6.3.1	Geology	40
6.3.2	Hydrology	41
6.3.3	Storage capacity	42
6.3.4	Water quality	42
6.3.5	Conclusions from the field work	43
7	**Study area Ben Tre 3**	**44**
7.1	Introduction	44
7.2	Description of the local situation	44
7.3	Field work	45
7.3.1	Geology	45
7.3.2	Hydrology	45
7.3.3	Storage capacity	47
7.3.4	Water quality	48
7.3.5	Agriculture	49
7.3.6	Conclusions from the field work	51
7.4	Groundwater monitoring	51
7.5	Monitoring campaign water quality	52
8	**Study area Tra Vinh 2**	**57**
8.1	Introduction	57
8.2	Description of the local situation	58
8.3	Initial field work	58
8.3.1	Geology	58
8.3.2	Hydrology	59
8.3.3	Storage capacity	62
8.3.4	Water quality	63
8.3.5	Agriculture	63
8.4	Groundwater monitoring	65
8.5	Monitoring campaign water quality	67
8.6	Modelling	69
8.6.1	Method	70
8.6.2	Results	70
8.7	Aquifer Storage and Recovery design	73
8.8	Pilot implementation	75
8.9	Pilot monitoring result	77
8.9.1	Water quality in pilot	77
8.9.2	Groundwater level monitoring in pilot	79

9	**Mapping the potential for shallow Aquifer Storage and Recovery in the Mekong Delta**	**80**
9.1	Introduction	80
9.2	Methodology	80
9.3	Results	82
10	**Upscaling and water resources management**	**84**
10.1	Introduction	84
10.2	Link/embedding in existing / ongoing projects	84
10.3	Shallow ASR upscaling potentiality	87
10.4	ASR and Agricultural Practice	88
10.4.1	Field site BT2	88
10.4.2	Field site BT3	88
10.4.3	Field site TV2	88
10.4.4	Conclusions	89
10.5	Webportal application to show FAME data	90
11	**Conclusions, recommendations and key messages**	**92**
11.1	Conclusions	92
11.2	Recommendations	95
11.3	Key messages	96
	Acknowledgements	**98**
	References	**99**
A	**Appendix additional information field work studies**	**103**
A.1	Field site BT2	103
A.1.1	Field impression	103
A.1.2	Coring location	104
A.1.3	Wellbore schematic	104
A.1.4	Lithological column	105
A.1.5	Lithological cross section	107
A.1.6	Storage capacity	109
A.1.7	Installed well	110
A.1.8	Water quality monitoring location	111
A.2	Field site BT3	113
A.2.1	Field impression	113
A.2.2	Coring location	114
A.2.3	Wellbore schematic	115
A.2.4	Lithological column	117
A.2.5	Lithological cross section	118
A.2.6	Storage capacity	119
A.2.7	Installed well	119
A.2.8	Water quality monitoring location	121
A.3	Field site TV2	122
A.3.1	Field impression	122

A.3.2 Coring location 124
A.3.3 Wellbore schematic 124
A.3.4 Lithological column 125
A.3.5 Lithological cross section 126
A.3.6 Storage capacity 127
A.3.7 Installed well 127
A.3.8 Water quality monitoring location 128

B Appendix Workshop: Scoping phase, 7-8 May, 2019 129

C Appendix Online Workshop: Feasibility and upscaling, 2-3 September, 2021 132

D Appendix Online Workshop: ASR pilot installation and upscaling possibility, 21 December 2021 144

E Appendix Summary interviews farmers 145

F Appendix links promotion material 146

1 Introduction

The Mekong Delta (MKD) (Figure 1-1) is one of the largest deltas in the world, lying at the mouth of the complex Mekong River network (Tanabe et al., 2003). The Mekong Delta (MKD) is drained by two main tributaries of the Mekong River, the Mekong and the Bassac, or in Vietnam known as the Tien River and the Hau River, respectively (Cosslet and Cosslet, 2014). The Mekong River system is the world's second richest biodiversity river basin (World Wide Fund for Nature, 2004). The delta is fertile, intensively cultivated, and responsible for 50% of Vietnam's total food production. As Vietnam is the world's second largest rice exporter, and 90% of all rice is produced in the MKD, over 200 million people rely on the delta for food (Minderhoud et al., 2017).

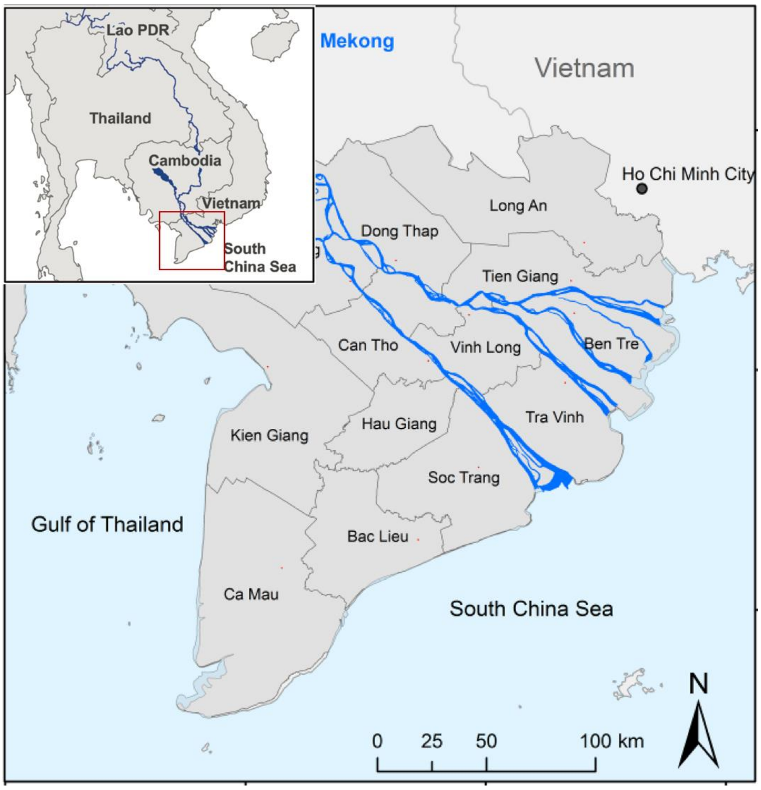


Figure 1-1: Map showing the Vietnamese Mekong River branches and the extent of the Delta and its provinces (Kuenzer et al., 2013).

The Mekong Delta is characterized by a tropical monsoon climate with a wet season from June to November and a dry season from December to May (Cosslet and Cosslet, 2014). The yearly average rainfall is the MKD is 1733 mm (Vietnam-Netherlands, 2013). The Mekong Delta has low elevation that makes the region vulnerable to flooding and salinization. The average elevation of the delta is only 0.8 m above Mean Sea Level which makes the delta vulnerable to climate change and sea level rise. Saltwater intrusion will progress further inland as a direct result of the projected sea level rise, subjecting larger areas of the coastal delta to become brackish (Vietnam-Netherlands, 2013). In addition, upstream dam constructions, threaten the lower delta with lower baseflow during dry periods, enabling saline water to move further inland as well as sediment starvation (Eslami et al., 2019).

The relative sea level rise is exacerbated by the subsidence of the Mekong plains, mainly because of groundwater extraction associated with an increase in freshwater demand. The extracted groundwater originates from ancient phreatic aquifers and will not be replenished in the future (Minderhoud, 2019). Another factor causing subsidence, is the natural compaction and compaction by buildings and infrastructure (Minderhoud, 2019).

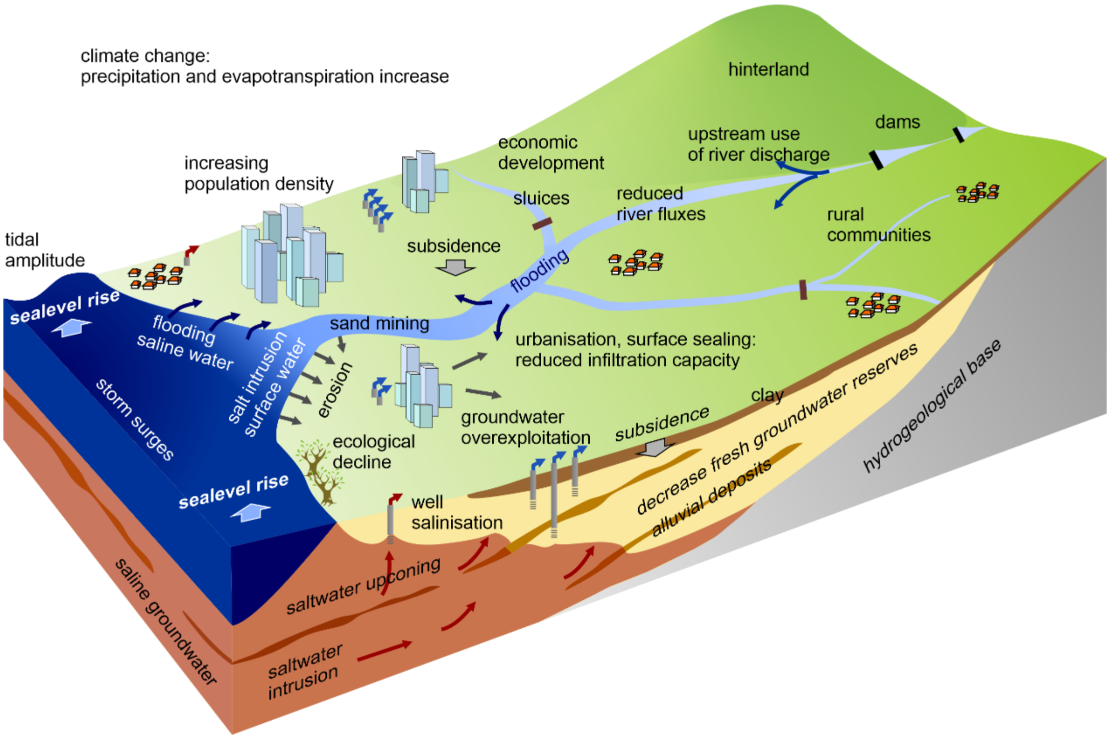


Figure 1-2: Overview of threats to coastal aquifers in the Mekong Delta: urbanization and increasing population density, increasing water demand, land use change, sand mining, salinization, upstream dam constructions, climate changes including sea-level rise all contribute to increasing water resources stresses. Adapted figure after Delsman (2015).

The Mekong Delta ranks amongst the top five deltas in the world that are most likely to be severely affected by climate change. The mean annual water discharge of the Mekong River is 470 km^3 (Lu and Siew, 2006). With climate change, peak flows and river floods are expected to increase in the wet season and decrease in dry season. Higher peak flows that are related to more severe floods, as those that occurred in the year 2000, can cause deep inundation and damage to infrastructure and agricultural production in the delta (Tuan et al., 2007). The lower flows in the dry season lead to serious freshwater shortages during the dry periods.

The water demand of the agricultural sector in the dry season in the Mekong Delta is mostly extracted from groundwater. The main reason is that during the dry season, the surface water becomes more saline. The increasing extraction of groundwater will exacerbate the ongoing subsidence in the delta and cause further inland salinization. A conceptual illustration with the overview of threats occurring in the MKD can be observed in Figure 1-2.

2 Project scope and activities

2.1 Project scope

The scope of this project FAME (Freshwater Availability in the MEkong delta) is to evaluate the potential of Aquifer Storage and Recovery techniques for the Mekong Delta, Vietnam, as a solution for a sustainable freshwater supply for agricultural applications during periods of surface water shortage.

In the project, the feasibility of techniques of Aquifer Storage and Recovery (ASR) in the coastal provinces Ben Tre and Tra Vinh in the Mekong Delta, Vietnam are assessed, potentially leading to practical sustainable water resource management applications.

2.2 Project activities

The project activities are:

- to create a provincial overview of the potential benefits for ASR techniques.
- to collect hydro(geo)logical data on quantity and quality of surface water and groundwater, as well as existing geological data, for the selecting possible ASR locations in the two coastal provinces Ben Tre and Tra Vinh in the Mekong Delta, to obtain more insight in more sustainable fresh (ground)water resource management at farmer scale level.
- to monitor the status of surface and groundwater quality in the selected sites. Areas with a history of pesticides and heavy metals should be avoided.
- to study, design, test and monitor at a field scale level of an ASR technique, with the purpose to determine sustainable fresh (ground)water resources management and efficient water use. Note the scope of FAME does not include major surveys, setting up of permanent monitoring systems, or constructing major water recharge and extraction systems.
- to assess the potential for upscaling through constructing a potential map of ASR for the two provinces Ben Tre and Tra Vinh, including a generic analysis of the success and the limiting factors for upscaling of ASR systems.
- to make recommendations for upscaling potential ASR measures, plans and guidelines for sustainable water use and related potential for food security and livelihood systems in which surface and groundwater are integrated.
- to make the results available to planners, local officials and water users.

The Freshwater Availability in the MEkong Delta (FAME) project covers the identification of problems related to the availability of freshwater in the Mekong Delta area and the conceptualization of possible solutions. The solution related to the implementation of ASR, was then explored and followed by the identification of potential ASR pilot locations in the Mekong Delta. The location selection was discussed during the first FAME workshop together with water related stakeholders from the provinces Ben Tre and Tra Vinh.

To refine the pilot location selection, and to give better understanding on the future upscaling implementation of ASR system in the MKD, a geologic, hydrogeologic, and agricultural and social study was conducted. After the field study analysis, the pilot implementation in the selected area was carried out. The pilot design was defined based on the data collection within the field work investigation (Figure 2-1). A groundwater and water quality monitoring system was set up and measurements were conducted on two selected sites from May 2020 to October 2021 to understand the groundwater and surface water dynamic in the potential ASR area.

The pilot design was presented during the 2nd FAME workshop in August 2021. In October 2021, the pilot was installed in Long Son Commune in the Tra Vinh province. The installation of the pilot was shared with stakeholders during the 3rd FAME workshop in December 2021. Since the pilot was installed close to the finalization of the project, no monitoring results of the pilot could be shared in the last workshop. The project activities and project timeline are illustrated in Figure 2-2.

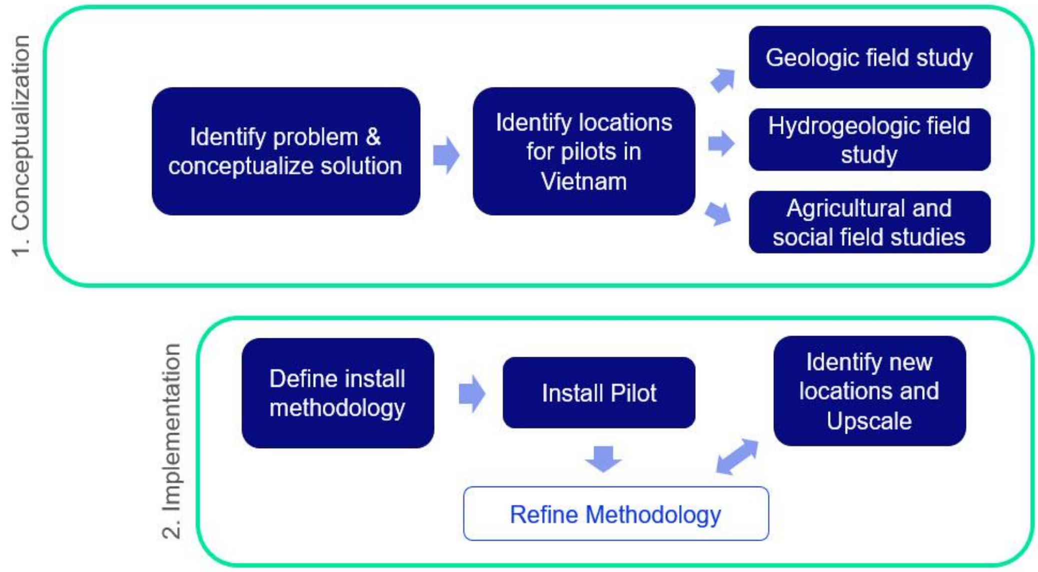


Figure 2-1: Project activities.

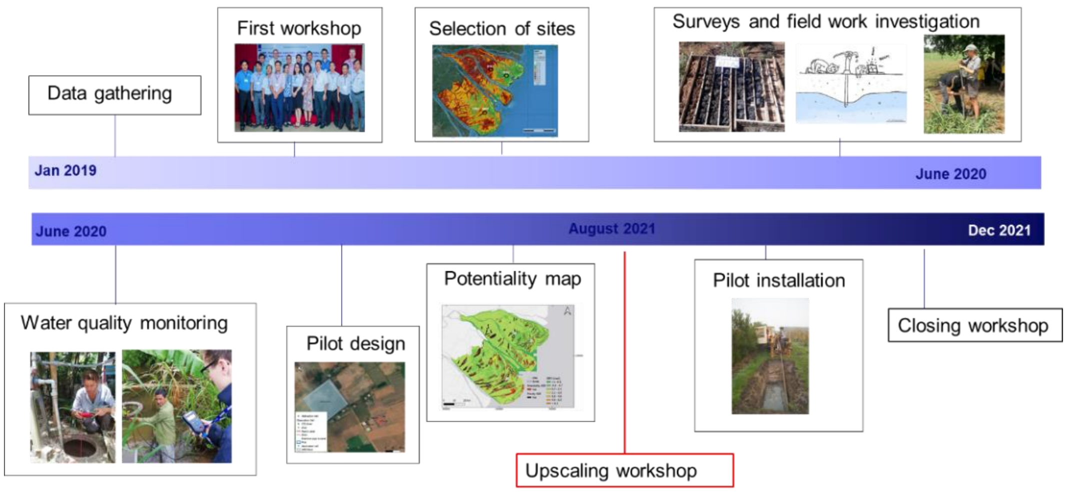


Figure 2-2: Project timeline.

2.2.1 Scoping phase

The Scoping phase covered the identification of the problem, the available data, and the potential measures to be applied in the MKD. This phase also included the formulation of a work plan to install the ASR pilot, together with a workshop to evaluate the ASR pilot design and site selection.

2.2.1.1 Data gathering

Gathering of existing data for the characterization of surface and groundwater resources, which includes:

- inventory of existing concepts, models, reports, and ideas
- hydrometeorological data
- groundwater and surface water quality
- agricultural activities
- water demand and supply
- geology
- hydrogeological data
- other relevant data: e.g., surface elevation level (DEM), groundwater extractions, river fluxes, and drainage system

2.2.1.2 Potential measures

There are several ASR techniques that are currently implemented in various parts of the world. To assess the best technique for the sites in the Mekong Delta, we defined several factors that were evaluated. The factors include for instance local geological conditions (e.g. aquifer permeability and thickness), the capacity of water infiltration, rainfall and evapotranspiration. An integrated assessment of these factors is carried out to identify the appropriate ASR method to be applied in the Mekong Delta. In chapter 4, 'On Aquifer Storage and Recovery techniques', p. 28, extensive information on this topic is given.

2.2.1.3 Formulation of the ASR pilot characteristics

Due to the hydrometeorological and hydrogeological characteristics of the provinces of Ben Tre (2287 km², population ~1.4 million) and Tra Vinh (2369 km², population ~1 million) were selected as the focus provinces for FAME. Specific areas in these provinces were assessed to identify the best locations for an ASR pilot. For the selection of the locations, the following aspects were considered:

- Geometry and morphology of the aquifers (shallow aquifer)
- Water quality within the potential aquifer (fresh / brackish)
- The recharge capacity of phreatic groundwater
- The infiltration capacity of the soil
- Freshwater ponds availability
- Water demand of key crops and water use efficiency.

Once these sites were evaluated, they were discussed in the first workshop with the local stakeholders.

2.2.1.4 First Workshop: evaluation of the feasibility of the proposed pilot sites

The workshop took place from the 6th to the 9th of May in 2019.

The objective of the first workshop was to exchange information with the stakeholders and together select the three high potential locations for the installation of an ASR pilot. The participants of this workshop all came from the provinces of Tra Vinh and Ben Tre. During this workshop, hydrogeological as well as agricultural oriented surveys were executed at the three potential sites to better understand the local conditions. The detailed information about the discussion points of the workshop is discussed in Chapter 5 and the supporting information can be found in Appendix 11.3A.3.

2.2.1.5 Selection of the pilots and development of the work plan

After identifying the feasibility of each potential site for ASR, one field site was selected to implement an ASR pilot. The detailed information about the site selection is discussed in Chapter 5.

2.2.2 Pilot research phase

The pilot research phase covers the pilot design, implementation of the pilot, assessment of the pilot monitoring results, and analysis of the upscaling of shallow ASR system.

2.2.2.1 Design and pilot implementation

The steps taken in the design and implementation of the pilot:

- Designing a pilot based on the selected ASR technique
- Conducting pilot tests with different water sources and water recharge rates
- Evaluating the ASR pilot by monitoring water quality and quantity
- Seeking connections with farmer organizations for collaboration and joint activities in executing the pilot and/or disseminating the results.

2.2.2.2 Assessment of results and feasibility of the pilot system

The feasibility of the pilot and its potential for upscaling were estimated based on the knowledge built during the project. Since the pilot was installed near the finalization of the project, it was not possible to monitor the results and use them for a feasibility study including a cost-benefit analysis.

2.2.3 Upscaling potentiality research phase

2.2.3.1 Workshop on feasibility and upscaling

The workshop took place on 27th August 2021. In this workshop 109 participants attended. The objective of the workshop was to introduce the selected pilot site, pilot design, and to discuss the findings on the potential ASR upscaling based on hydrogeology in the Mekong Delta. The workshop report can be found in Appendix C.

2.2.3.2 Mapping the potential of ASR systems

A potential map covering Ben Tre and Tra Vinh province was developed to identify the potential of the Mekong Delta for an implementation of the selected ASR technique based on its hydrogeology. This map indicates the most suitable places for recharge of groundwater (for the selected ASR technique).

2.2.3.3 Workshop (online) on the ASR pilot installation and upscaling possibility

A final workshop was taken place on the 21st of December 2021. In this online workshop, the pilot implementation was shared and upscaling possibilities of ASR systems in the Mekong Delta were discussed. The workshop was attended by Vietnamese authorities, knowledge institutes / universities, local communities and (international) professionals with interest in subsurface solutions to improve the freshwater availability in the Mekong Delta. The workshop reporting can be found on the website: https://www.deltares.nl/en/projects/freshwater-availability-mekong-delta-fame/.

3 Freshwater and agriculture in the Mekong Delta

3.1 Introduction

The coastal estuaries of the Mekong Delta are increasingly subjected to salinity intrusion during the dry season. The recent dry seasons of 2016 and 2018 to 2020 are now on record as the most saline seasons of the delta, with severe agricultural production and economic loss as a result.

As salinity intrudes into the river mouths (up to 60-70 km upstream), it affects the freshwater intake for agricultural use in the estuary coastal areas of Tra Vinh, Ben Tre, Tien Giang and Soc Trang. Freshwater can no longer be taken in from the river to supply agricultural lands and canals need to be closed off by sluice gates to prevent intrusion into agricultural lands. This cuts-off freshwater supplies to agricultural areas leading to prolonged droughts and crop stresses, oxidation of sulphate acid soils (SAS) and ultimate crop failures. In recent extreme years this has even led to complete evacuation of people and animals of affected districts in Ben Tre, as water supplies were no longer adequate to sustain them during the peak of the dry season.

With the progression of the saline area further, the salinity protrudes more frequently beyond the most upstream sluice gates; resulting in active salinization of the water supply channels and agricultural area. For fruits and rice, this results in an immediate crop damage and economic loss when concentrations exceed the 4 g/l threshold (Dung et al., 2019). For fruit crops, this may be particularly devastating as salt affected trees will have to be cut and replaced, as in the case of Tien Luong commune (Ben Tre) where 60% of the rambutan trees had to be uprooted after the 2016 saline drought.

Even when salinity may be prevented to intrude into the waterways by means of sluice gates, agricultural production in the estuary areas is still affected by freshwater shortages and/or salinization brought by capillary rise of the saline groundwater tables, leading to severe reduction in production and income. This progressive exposure to the combined effects of drought and salinity – that are increasing in frequency and duration – in the estuary coastal zone is imposing a strong driving factor to change crop type and land use patterns towards saline tolerant based agriculture, and towards improving agricultural water usage efficiency.

Having to increasingly endure crop failures due to salinity, and progressively give up a growing season due to shortages in freshwater supply, induce more and more farmers to shift to salt tolerant crops (as coconut in Ben Tre) or saline aquaculture. A trend that was already discernible in Ben Tre before 2016 (Figure 3-1) and has only become more pronounced with the more recent and severe drought/saline years.

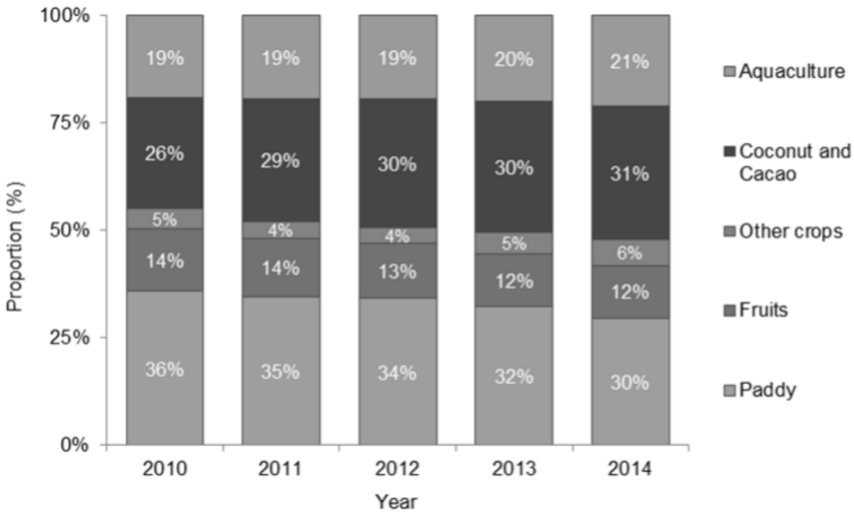


Figure 3-1: Trend of the proportion in the area of agriculture and aquaculture in Ben Tre (Japan International Cooperation Agency, 2016).

3.2 Freshwater availability

3.2.1 Surface water

The source of freshwater to the MKD changes between the wet and the dry season. During the wet season the Tonle Sap River, that connects the Tonle Sap Lake in Cambodia and the Mekong River, drains the Mekong River, fills the Tonle Sap Lake, and floods the surrounding delta plains. During the dry season, when the Mekong River level is significantly lower, the directional flow of the Tonle Sap River reverses and drains the lake (Eslami et al., 2019). The MKD, its main river, and its irrigation network are illustrated in Figure 3-2.

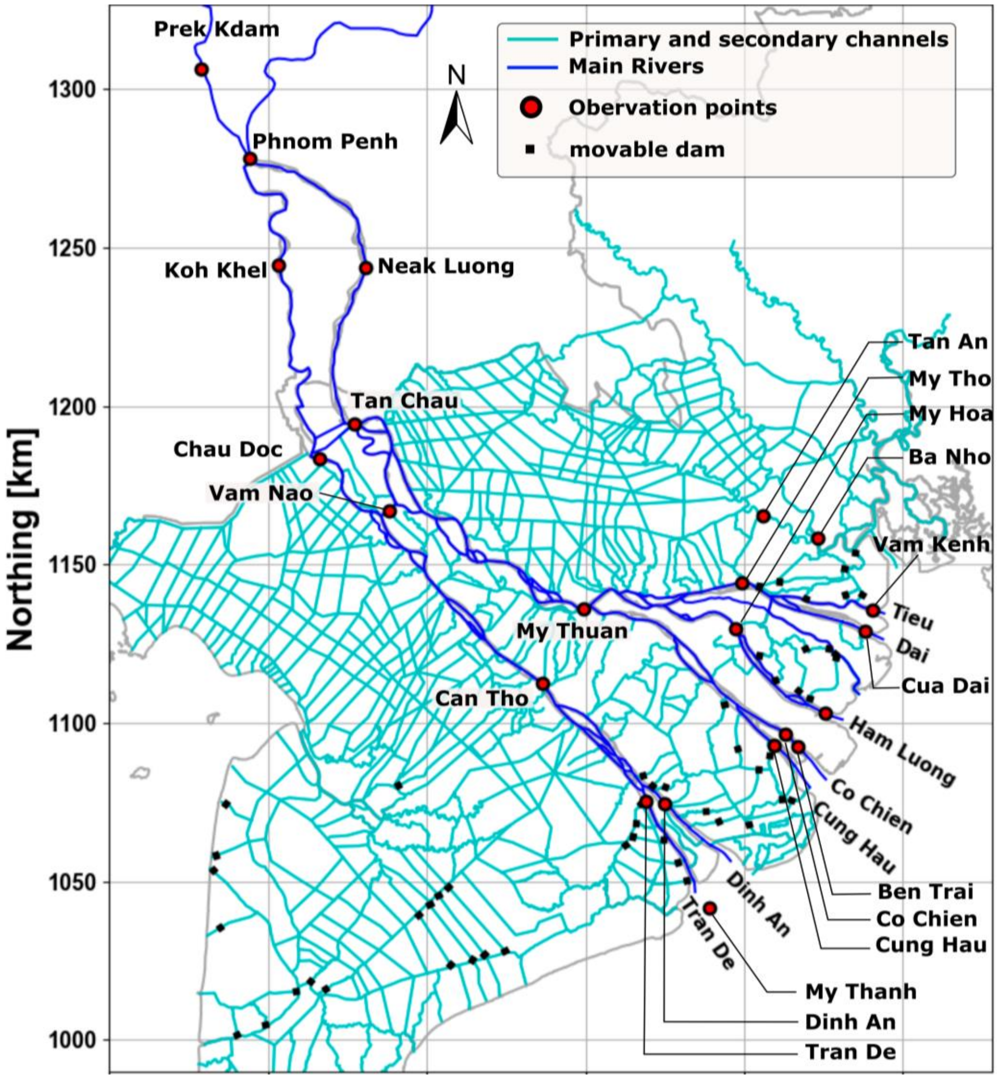


Figure 3-2: An overview of the Mekong Delta with the rivers and the primary and secondary irrigation (Eslami et al., 2019).

Cumulative freshwater distribution in the Mekong River in Vietnam combined with the observation data shows that about 84% of total Mekong freshwater enters through the Tien River, while only about 16% enters through Chau Doc, then about 35% of the total freshwater inflow diverts from the Tien River to the Hau River through Vam Nao channel (Eslami et al., 2019). The total mean discharge in Tan Chau and Chan Doc is illustrated in Table 1. Total annual average inflow at these two locations is about 387 billion m^3. Between Chau Doc and Tan Chau to Can Tho and My Thuan, (Figure 3-2), 15% of the freshwater inflow is consumed and evaporates, while 40% of the total freshwater entering the Mekong Delta drains through Can Tho (Hau River) and 44% through My Thuan (Tien River). In total, 27.4% of the freshwater inflow of the Mekong Delta does not reach the estuary Figure 3-3.

Table 1: Mean Monthly Flows at Tan Chau and Chau Doc in m3/s (Korea Water Resources Corporation, 2000).

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Tan Chau	6220	3720	2600	2010	2640	7180	11270	16390	21140	20340	15260	10180	9830
Chau Doc	1360	700	420	330	460	1450	2390	3970	5200	5480	4700	2710	2440

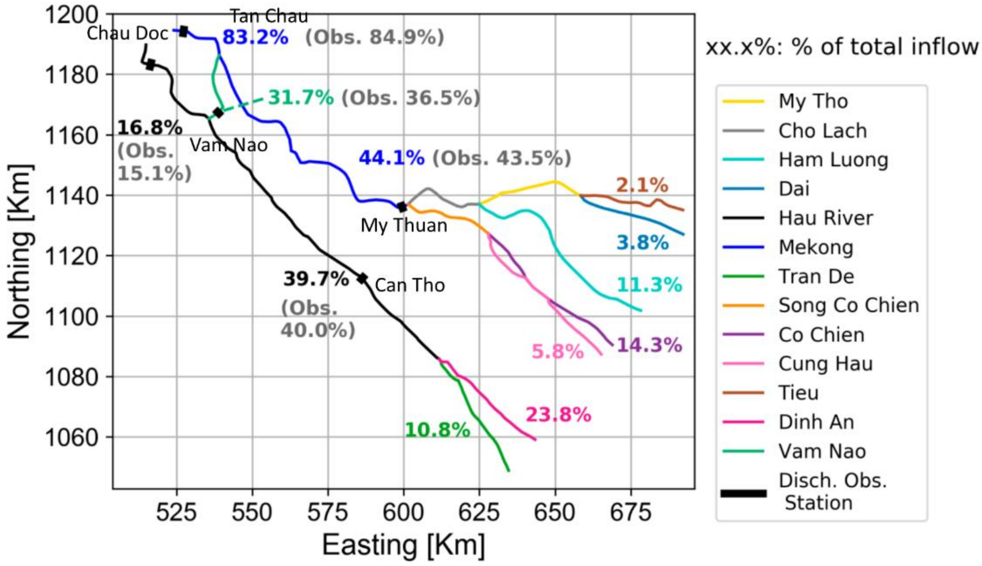


Figure 3-3: Overview of the main rivers in the Mekong Delta, and their share of modelled cumulative freshwater inflow from the sum of Mekong River and Tonle Sap Lake versus (available) observations in grey front (modified from Eslami et al. (2019)).

Surface water quality is related to surface water salinity which changes seasonally with the change in salt water intrusion in response to discharge variations and tidal propagation (Eslami et al., 2019). Saltwater intrusion only reaches a few kilometers in the wet season but can reach up to tens of kilometers in the dry season (Nguyen and Savenije, 2006). Currently, Ben Tre and Tra Vinh province are already affected by salinization during dry season as illustrated in Figure 3-4. With the climate change and ongoing subsidence, the salinity intrusion is expected to move further inland reaching Vien Long and Thien Gang province (Eslami et al., 2019).

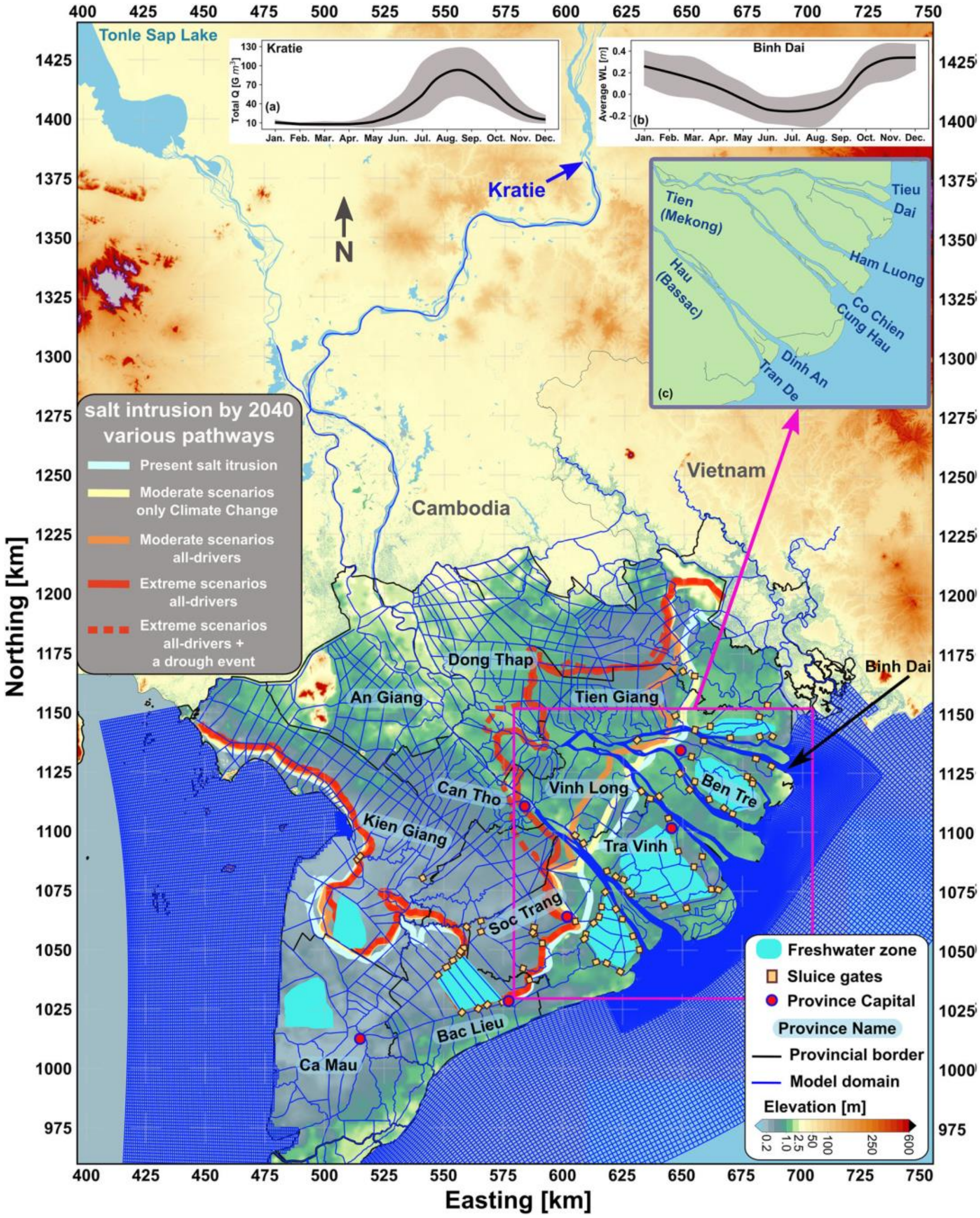


Figure 3-4: Range of expected salinity intrusion changes in the Vietnamese Mekong Delta. Present (light blue line) and projected peak saline water intrusion for year 2040. Yellow line is salinity intrusion line under climate change scenario, orange line is salinity intrusion line under climate change and subsidence (scenario M2 + B1 in Minderhoud et al. (2020), red line is salinity intrusion line under climate change and higher subsidence (scenario M1 + B1 in (Minderhoud, 2019), and dashed line is salinity intrusion line under climate change, and higher subsidence during drought event (Eslami et al., 2021).

3.2.2 Groundwater

Groundwater resources in the Mekong Delta are already systematically depleted (Vietnam-Netherlands, 2013). Modelled and calculated groundwater decline rates for each location within the MKD are illustrated in Figure 3-5 (Minderhoud et al., 2017). The groundwater volume decrease will continue unless sufficient strategies to decrease groundwater extractions are implemented (Shrestha et al., 2016). This raises the concern that present groundwater use is already depleting various aquifers, and that further increase of this groundwater use in the future is unsustainable (Vietnam-Netherlands, 2013).

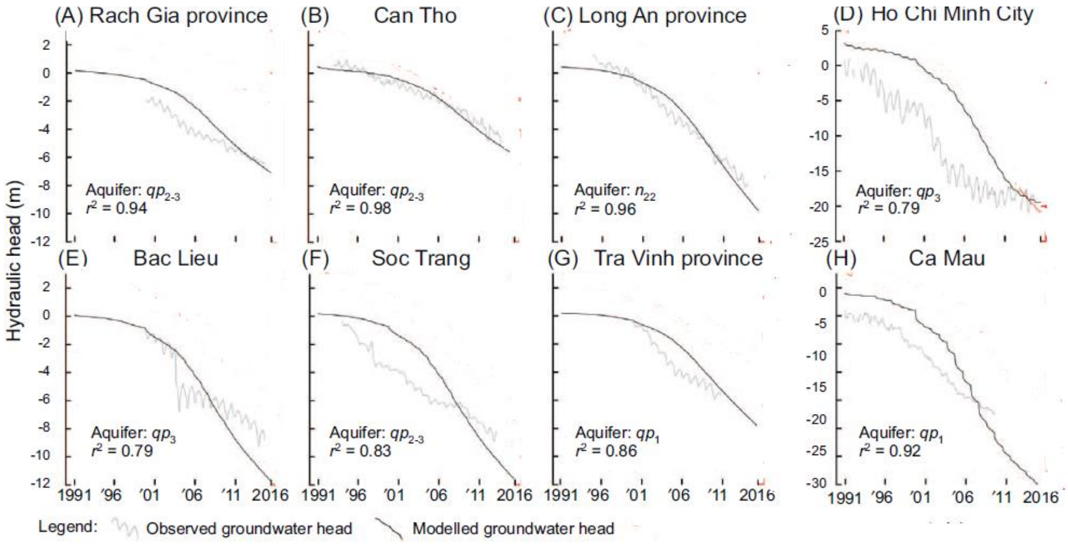


Figure 3-5: Modelled (black line) and measured (grey line) hydraulic head time series at monitoring well locations (modified from (Minderhoud et al., 2017).

During the dry season, the coastal zone in the Mekong Delta receives limited fresh surface water fluxes. This leads to groundwater extraction from deep aquifers as an additional source of freshwater (Vietnam-Netherlands, 2013). Note that these aquifers cannot be replenished due to the thick low-permeable clayey Holocene top layer that permits infiltration of precipitation.

In the study of Gunnink et al. (2021), all existing salinity data from DWRPIS have geostatistically been processed into a 3D groundwater salinity distribution in the entire Mekong Delta, see Figure 3-6. Also fresh groundwater volumes are given per province per aquifer, including uncertainties because the salinity and geological data are not always equal accurate, see Figure 3-7 (Gunnink et al., 2021). Results yield an estimated fresh groundwater volume for the Mekong Delta of 867 km^3 with an uncertainty range of 830–900 km^3. Though this sounds huge compared to the yearly groundwater extractions, at a local scale, severe upconing of saline groundwater under extraction wells can still easily happen.

The quantities of freshwater provided by the shallow sand dune freshwater lenses are much smaller and site-specific, determined by the geological and hydro(geo)logical dimensions at each site.

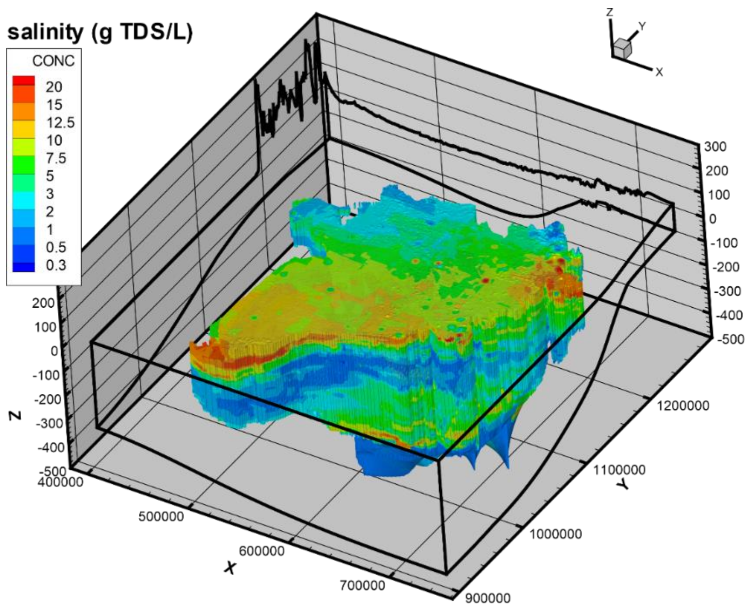


Figure 3-6: Fresh, brackish and saline groundwater in the Mekong Delta, based on data of Gunnink et al. (2021).

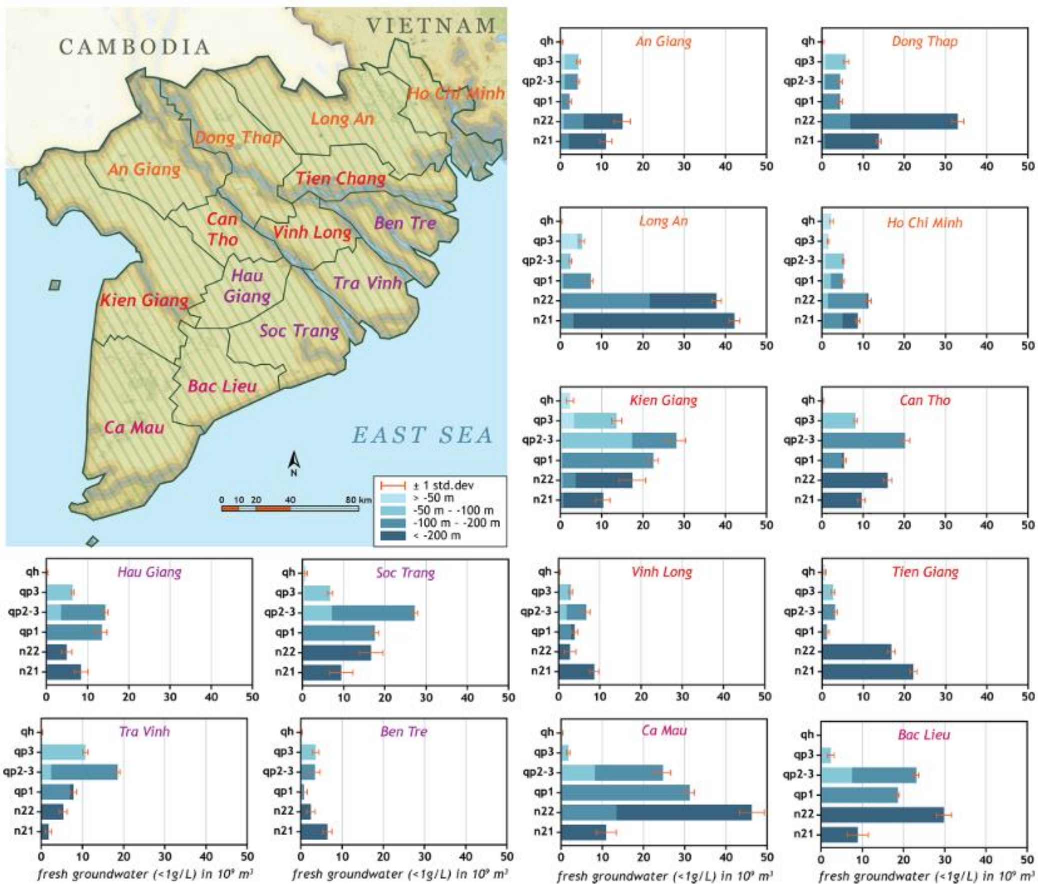


Figure 3-7: Volume of fresh groundwater in the aquifers for each province and depth interval (relative to M.S.L.), including uncertainty. From: (Gunnink et al., 2021).

In the Mekong Delta, groundwater quality issues are mainly related to the salinity. The hydrochemistry of the Mekong Delta is complex due to several transgression and regression periods in the very far past (as well as the human influence more recently). A groundwater salinity model of the MKD shows that the saline water is situated on top of the freshwater to a depth about 100 meters (Pham et al., 2019). In some areas, there is also a thin layer of freshwater at the uppermost layer.

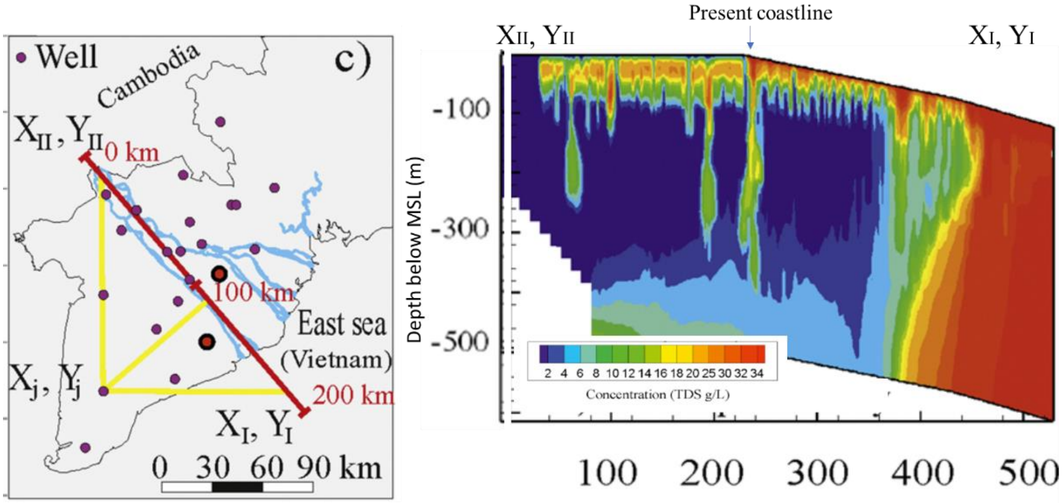


Figure 3-8: Modelled groundwater salinity distribution (in TDS g/L) (Pham et al., 2019).

3.3 Agriculture activities

The agricultural land use practices in the coastal estuary are closely related to the soils and agro-hydrological conditions prevailing at each locality. The specific interactions between soil and water (fresh and saline) determine the options for agricultural land use and production. As these differ starkly between alluvial plains and sand dune ridges, an understanding of both is required as the sand dunes are located within the alluvial plains and hydrologically interact.

The predominant agricultural activity in the coastal plains is rice cultivation. Supported by a decades long rice intensification program of the national government, the alluvial plains of coastal estuary have been developed, by and large, to enable the cultivation of three rice crops per year. The development and completion of the South Mang Thit irrigation scheme (comprising of dikes, canals and sluices) in Tra Vinh Province, is an example of government efforts to shape the agro-hydrological conditions to favor rice cultivation (Le et al., 2018). However, salinity and drought lead to gradual transformation of the intensive rice cultivation practices. Salinity and drought affect the third summer rice crop, forcing farmers to keep their land fallow, and in recent years increasingly affect the second rice crop following the wet season, as salinity intrudes earlier in the season and over prolonged period. As farmers progressively shift towards traditional rice-shrimp systems (rice in the fresh wet season, followed by saline shrimp after the wet season) or intensive shrimp (year-round three crop shrimp cultivation in dedicated ponds), the saline period of the alluvial plains is effectively lengthened by shrimp farmers actively taking in saline water to supply their ponds/fields with. These conditions particularly prevail in Tra Vinh and the south-west of Ben Tre where the salinity is progressively moving inland and upstream.

In the north-east of Ben Tre province, the alluvial soils are of good quality and suitable for fruit cultivation under freshwater conditions. Orchards that are characterised by broad ridges/beds, interspersed with canals, to avoid over wetting of the root zone. With the onset of salinity intrusion, however, fruit trees have been increasingly uprooted and replaced by coconut, shrimp or more saline tolerant varieties as pomelo. Especially coconut has been a boom in Ben Tre province in recent years as it has proven to be a low cost – steady income alternative to cope with salinity intrusion.

On the sand dune ridges, during the monsoon rains, the groundwater table of these freshwater lenses is filled to the brim. In the depression zones, typically situated in the middle of the ridge (i.e. the hollows of the dune) this is manifested by the water table rising to above the ground level. Typically, these depressions are cultivated with rice (which can stand waterlogged conditions) during the wet season. In the event when the rains fall short, farmers may revert to irrigate their rice fields by pumping up water from the freshwater lenses.

The homestead gardens and fields situated outside the depressions, and situated above the maximum groundwater level, are suited for a variety of perennial and seasonal freshwater crops. A variety can be found, ranging from perennial fruit trees and jasmine tea to a mix of short season vegetables (i.e. carrot, peanut, cucumber, watermelon, tomato, chili etc.). These crops are fed by rain during the wet season and irrigated during the dry season, using pumps and wells to access the freshwater lenses, and a mix of sprinkler, micro-sprinkler and drip irrigation to water the plants. The economic returns of fruits and vegetables are generally a factor 2-5 higher than for rice but are limited in scope by relatively small holding/plots related to the limited capacity of the freshwater lens to sustain irrigated vegetables throughout the entire dry and saline period.

Climate change will make the amount of water from precipitation and the length of the wet season unpredictable (Vien, 2011). Fresh groundwater resources as the sole source for agricultural water in dune areas does not fully account for the shortage in precipitation during the dry season. This shortage will negatively affect crop production (Bregman, 2020). Over extraction of the limited amount of fresh groundwater is also a problem. As farmers usually have small plots of land, and as such, they need to create the highest yield so over irrigation their fields is happening easily. The irrigation water is likely to evaporate and/or runoff towards surface water systems. This situation could be countered by technical solutions or by trying to change the habit of the farmers who irrigate with too much water. The interaction between these components which influences the way of farming at the field sites in Ben Tre and Tra Vinh province is illustrated in Figure 3-9.

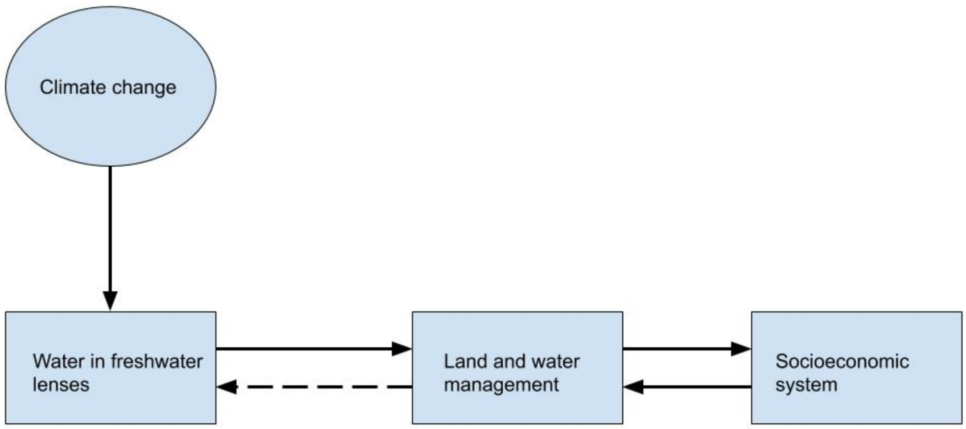


Figure 3-9: Conceptual framework of interaction between components that influences the way of farming at the field sites in the provinces Ben Tre and Tra Vinh. Also climate change will affect freshwater availability in the Mekong Delta.

3.4 Water demand and supply

Rice cultivation account for more than 68% of total freshwater demands in the MKD, while other crops account for 15% of water demand. Domestic and industrial demand only account for 4% of the total water demand in the MKD (Table 2) (Vietnam-Netherlands, 2013).

Table 2: Monthly water demand in the Mekong Delta in million m³ (Vietnam-Netherlands, 2013).

Months	Rice	Other crops	Livestock	Fishery	Forestry	Population and Industry	Total
Jan	2048	347	7	85	142	51	2680
Feb	2020	390	6	77	86	46	2625
Mar	1399	468	7	85	52	51	2062
Apr	1167	421	7	83	50	49	1777
May	1180	171	7	57	70	51	1535
Jun	1027	64	7	-	187	49	1334
Jul	603	83	7	-	231	51	974
Aug	231	54	7	-	220	51	563
Sep	88	11	7	-	137	49	292
Oct	43	37	7	-	170	51	307
Nov	286	145	7	26	164	49	678
Dec	998	291	7	72	152	51	1572
Sum	11090	2482	83	485	1661	599	16400
%	**68%**	**15%**	**0%**	**3%**	**10%**	**4%**	**100%**

When compared to the average annual inflow to the MKD, which is about 387 billion m³, the water demand of 16 billion m³ only accounts for 5% of the inflow. Even in the month with the smallest river discharge (February), in dry years, the supply is around 9.5 billion m³, which is still much higher than demand which is 2.6 billion m³ (Vietnam-Netherlands, 2013). However, during dry season, salinization of surface water makes the available surface water inadequate as a freshwater source for agriculture

Safe water supply is also an issue in the MKD where less than 65% of the urban population have access to clean water and for the rural population this percentage is even lower (Vietnam-Netherlands, 2013). Water supply in the rural areas relies on fresh surface water, which is vulnerable to salinization during dry season, and groundwater that leads to subsidence due to the high extraction rates.

3.5 Policy and governance

3.5.1 General water governance system in Vietnam

At the national level, Vietnam has a triangle structure regime with three power bodies including the Communist Party (with the Politburo as its highest body), the State (with the National Assembly as the highest organ of its power), and the Government (represented by the Prime Minister) (Figure 3-10). Among them, the Communist Party is considered the supreme power and give directions for the decision-making process at the national level via Resolutions (from the National Executive Party) or Directives (from the Politburo) (The National Assembly - The

Socialist Republic of Vietnam, 2013). The directions are institutionalized into Laws and Resolutions by the National Assembly. Implementation of laws is instructed by the Central Government with support from Ministries via Resolutions, Decisions and Decree. The national policies are implemented by local provinces which are instructed by the Central Government. The performance of the Central Government is evaluated and supervised by both the Central Party and National Assembly (Nguyen et al., 2020).

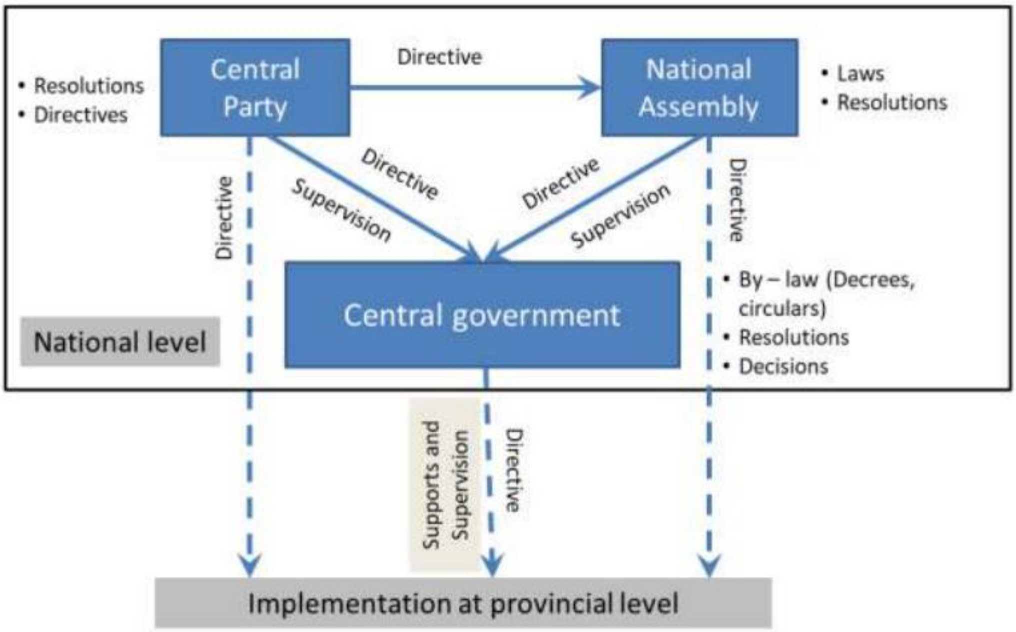


Figure 3-10: Linkages between legislation development at the national level and implementation at the provincial level (source: Nguyen et al., (2020)).

At the provincial level, Provincial People's Council (PPCl) which is the highest local government is responsible for the implementation of the central policies and makes decisions on the local issues. PPCl elects the Provincial People's Committee (PPCe) which is the executive body of the PPCl to implement its Resolutions and other legal documents from the central level. PPCl and PPCe also report to and collaborate with the Fatherland Front and other local associations to implement the higher policies. The Chairman of the Fatherland Front Committee is invited to meetings of the PPCl and PPCe (The National Assembly, The Socialist Republic of Vietnam, 2013)

3.5.2 Relevant stakeholders

Groundwater aquifers are complex systems that involve a wide range of actors from different sectors. Several relevant stakeholders in groundwater governance have been identified. The two most important sectors are agriculture and water management. These sectors are managed by different Ministries at a central level including the Ministry of Natural Resources and Environment (MONRE) and the Ministry of Agricultural and Rural Development (MARD). These Ministries instruct the vertical agencies at lower governing levels including the Department of Natural Resources and Environment (DONRE) and the Department of Agricultural and Rural Development (DARD) at the provincial level to implement the policies. The offices in the vertical line at the district and commune level support the policy implementation.

Besides the governing system, other important stakeholders are water suppliers and end users such as: water supply companies (government and private), industry, households, and other private sectors. Local and international NGOs, experts, social media, and academia also play a critical role in mobilizing public opinions, spreading information, and providing resources and technical support

3.5.3 Barriers of scaling up the ASR in the context of Vietnam

3.5.3.1 General Barrier

In general, the conventional approach of top-down and non-participatory is still prevalent with high expectations and requirements of absolute compliance toward the mainstream mechanisms. Different responsibilities are assigned to different government levels, nevertheless, the responsibilities are not clearly stated. Lower governmental levels are mostly excluded from the decision-making process (Tran and Rodela, 2016). Besides, the managing approach is mainly driven by different interests of the local governments who are constrained by their limited capacity leading to a lack of collaboration between different jurisdiction boundaries (Tran et al., 2019). The traditional managing approach results in a heterogeneity in different provinces and a fragmentation in the region in general.

Due to the causal link between subsidence and groundwater extraction, gaps in groundwater governance also impose challenges on the subsidence governance. A number of deficiencies regarding groundwater governance are identified including (1) the insufficiency of the policies as well as guidance from the central government on implementing and enforcing regulations locally, (2) the unclear and overlapped function of responsible units, and (3) the unlimited accessibility of local people to the groundwater (Phan et al., 2016; Witjes, 2018). These barriers have led to a lack of both quantity and quality of stakeholders' participation in the groundwater governance, especially local people (Phan et al., 2016). Other barriers are identified such as a lack of knowledge on the impacts of over-extraction and the low quality and unavailability of water resources alternatives which are affected by climate change (Witjes, 2018).

3.5.3.2 Barriers in specific for groundwater governance

Several barriers have been identified in groundwater governance in general. Firstly, the governing system is insufficient regarding financial and human resources. Local officials stated that the central government issues regulations on groundwater management but does not allocate financial budget to implement the regulations such as the Decree 167. Local governments must mobilize the resources themselves. Given the fact that groundwater is not the most urgent problem, many local governments have to prioritize the finance for other perceived more important issues such as irrigation infrastructure or transportation. This partly results in an insufficient monitoring system to collect groundwater-related data leading to an insufficient and fragmented database which in return is challenging to manage groundwater. Regarding the human resources, the number of specialists who are trained in water management in general and groundwater in specific is insufficient according to local officials. Therefore, they have to oversee various responsibilities that sometimes do not meet their specialization. Secondly, the price of groundwater use is considered inappropriate. The cost for groundwater treatment is low compared to surface water treatment or wastewater recycling. Private sector, households, and industry therefore prefer to exploit the groundwater to maximize the benefit. It is also noteworthy is that there is a lack of coordination between different governing systems between the different provinces. Each province has its own strategy and priorities in groundwater management while the aquifers overlap province borders, which leads to problems in common use of the groundwater resource. For example, several officials complained that they had been following guidance from the government to implement the Decree 167 by, e.g., limiting groundwater water use of industry that cause the industry to move to another province where they can use groundwater. It is therefore recommended that the collaboration between the provinces as well as between the provinces and the central government should be strengthened. A master planning in groundwater management is suggested at the delta scale. Finally, sanctions for misconducted activities in groundwater use are insufficient and not strong enough to ensure the implementation.

3.5.4 Relevant regulations, barriers, and enablers on the scaling up of the ASR

In the Law for water Resources (2012), article 4, it is recommended to support groundwater recharge as a part of the solution for water resources preservation and development. However, there is no document for further instructing how to do implement this solution (the same with rainwater harvesting). Furthermore, the regulation on groundwater protection is very strict (e.g. Decision 15/2008/QĐ-BTNMT by Minister of Natural Resources and Environment dated 31 Dec. 2008 or Decree 167/2018/NĐ-CP by Prime Minister dated 26 Dec. 2018). This makes the implementation of ASR very difficult i.e. injecting “clean” water into the system. Thus, there is urgent need from the government to develop Decision on Technical guidance for groundwater recharge.

Apart from institutional constrains, technical efficiency is another important factor that needs further attention. (Hydro-geological) complexity in the Mekong Delta and financial limitations are clear barriers that have been observed during the project. Lack of local expertise (both academic and professional) on this topic is also another major limiting factor that prevents up–scaling. It must be shown how the system can be applied with sizable scales as well as providing cost-effective analysis. Investment for public work e.g. water infrastructure is always challenging, especially with those solutions having no clear technical guidance.

However, the MKD, especially in the coastal areas has been in a very alarming stage regarding the increasing salinization and subsidence. Aquifer Storage and Recovery seems to be one of the few solutions that may help to overcome the problem of over exploitation of groundwater resources (and consequently land subsidence and). ASR receives attention from local governments and other stakeholders e.g. water supply companies. In addition, the central government is putting a lot of effort to support sustainable development of the delta. For example, after Resolution 120 on Climate – resilient and sustainable development of the MKD in 2017, there have been quite some new nature-based solutions introduced and applied in the delta (e.g. flood – based or saline – based agriculture). ASR is a very typical nature based and multiple benefit solution that fits well to this direction. Apart from water supply ASR can also bring other benefits. Recently, public-private-partnerships (PPPs) have become increasingly attractive in many countries as a way to accomplish specific projects like ASR (Daus, 2019). Vietnamese Government is also requesting ministries to develop PPP protocols, guidance for attracting PPP investment.

4 On Aquifer Storage and Recovery techniques

4.1 Introduction

Globally, freshwater resources are under pressure due to increasing freshwater demands, salt water intrusion and climate change. Managed Aquifer Recharge (MAR) is the collective term for (e.g. Aquifer Storage and Recovery) techniques to store freshwater in the subsurface for later recovery and use. In freshwater environments, groundwater reservoirs can be replenished by retaining and infiltrating fresh (seasonal) surplus freshwater water. Floods in the rainy season and salt water intrusion in the dry season are the two main physical problems for sustainable development of the Vietnam Mekong Delta.

Aquifer Storage and Recovery (ASR) is the process by which water is injected under pressure or allowed to infiltrate naturally into a permeable underground layer where it is stored until extracted, when needed later (Figure 4-1). These systems can reduce water supply shortages during periods of very high demand, like droughts. ASR systems may have the objective to supply water at seasonal scale, for emergency situations, or as permanent long-term strategy. Another objective of ASR system can also be to improve water quality and/or prevent salt groundwater from intruding into the groundwater system (Rambags et al., 2013).

For certain objectives and situations, ASR may be an alternative to the construction of surface water storage projects. As the reservoir is already in the subsurface (the aquifer), the set-up only requires a small amount of land surface, has a lower environmental impact, and has less evaporation, compared to an above ground reservoir. When the technique is focused on artificially recharging the aquifer and there is no part of the technique with the goal to recover the water, the systems are called Managed Aquifer Recharge (MAR).

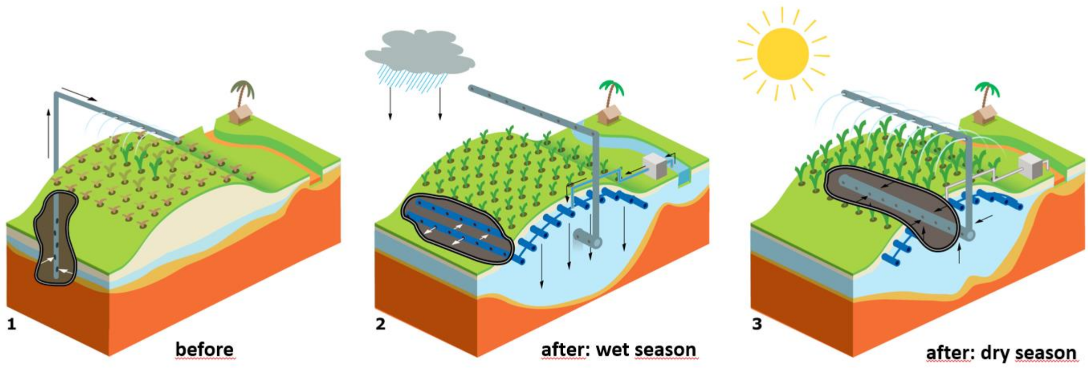


Figure 4-1: Shallow Aquifer Storage Recovery Concept: 1. Situation before an ASR system is implemented; 2. Infiltrating water during the fresh surface water excess period (wet season); 3. Extracting the stored groundwater during surface water shortage period (dry season) (after Oude Essink et al., 2018; Pauw et al., 2015).

There are numerous experiences of implementing ASR and MAR systems in the world. For example, in the Netherlands, since 1957, large-scale ASR systems are used to provide drinking water. Water from the river Rhine is infiltrated artificially in the dunes and then extracted through wells. These groundwater extractions must be managed and monitored systematically. This system consists of 40 km of extraction canals, 9 km of drains, and 40 recharge ponds (86 ha) that can provide 65 Mm^3/year which is equal to 60% of Amsterdam water supply.

The recovery efficiency (viz what fraction of the injected water that is recovered) and storage capacity of ASR systems are dependent on the lithology, structure, thickness, depth and extent and permeability of the aquifers and aquitards (Rambags et al., 2013). Important features that determine the hydrogeological feasibility of an ASR system are aquifer thickness and permeability, and whether low-permeable aquitards restrict the surface water to be infiltrated (Pauw et al., 2015). For example, a (relative) high aquifer at a sandy ridge in the MKD which consist of a thick homogenous sandy layer can store enough water that can bridge the gap between water demand and supply.

4.2 Types of Aquifer Storage and Recovery systems

Aquifer Storage and Recovery (ASR) systems can be generally classified in 3 groups: 1) surficial systems, 2) vadose zone systems, and 3) direct recharge systems.

Surficial systems are typically formed by spreading basins, infiltration ponds, riverbank filtration or percolation tanks, in which the recharge takes place in the contact between the bottom of the surface water body and the ground.

Vadose zone systems are those in which the water is infiltrated in the unsaturated zone through trenches, wells, sand dams or drains. In this report, these are also referred as shallow ASR systems.

The direct recharge systems normally consist of wells drilled in the saturated zone, where water is infiltrated directly. In this report, these are also referred as deep ASR systems.

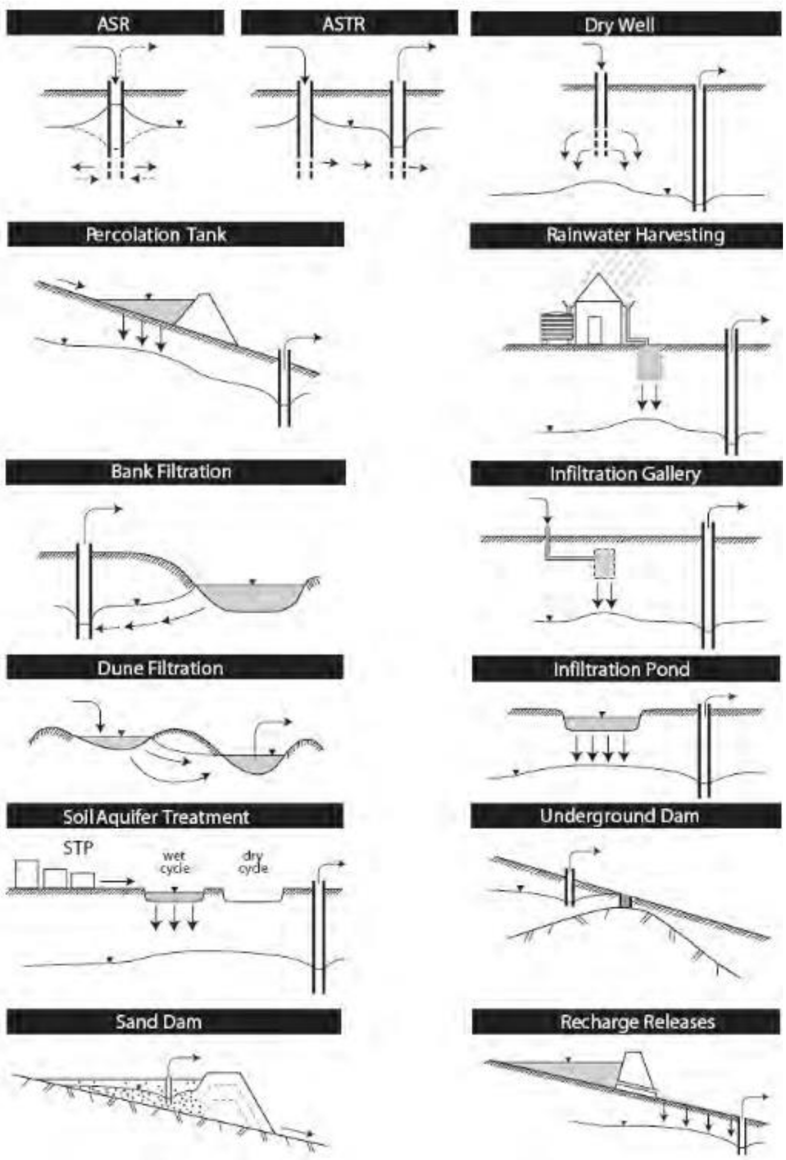


Figure 4-2: Different Managed Aquifer Recharge systems.(Dillon et al., 2009b, 2009a).

In areas with brackish or saline groundwater, a scheme of extracting brackish groundwater and infiltrating freshwater can be a solution to increase the freshwater volume and reduce salt water intrusion. Figure 4-3 shows such a system in which there is a switch from just extracting freshwater, to a combined scheme of extracting brackish water and infiltrating the excess of freshwater when it is available.

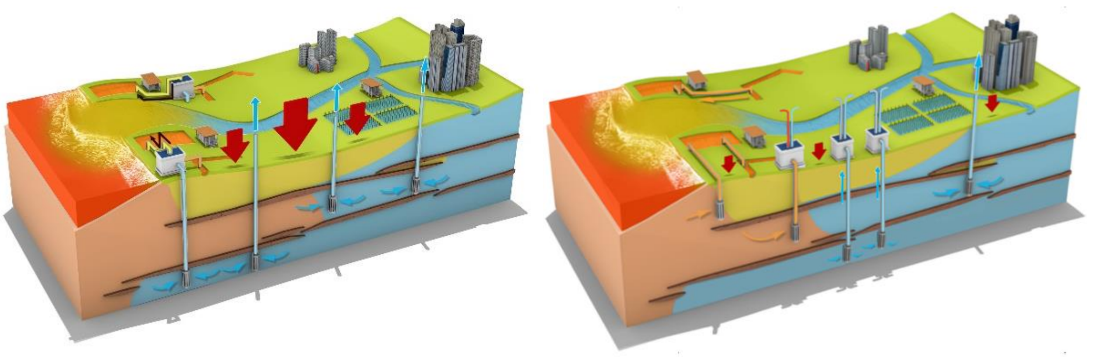


Figure 4-3: Deep-well Aquifer Storage and Recovery combining the extraction of brackish groundwater and the infiltration of fresh surface water.

The type of ASR to be applied in each location is determined by the objective of the ASR system, by the socio-cultural characteristics of the area (an appropriated technique should be chosen), and by several aspects of the hydrogeology such as the lithology and the structural elements, the thickness, depth and extent of the aquifer and surrounding aquitards, the salinity and water quality in the target aquifer, the geochemical composition of the aquifer matrix, and the degree of regional groundwater flow (Rambags et al., 2013).

Table 3 shows a comparison between different techniques.

Table 3: Comparison of advantages and disadvantages of different ASR techniques.

Surface infiltration		**Vadose zone infiltration**		**Direct recharge using wells**
infiltration basin	**in-channel/ streambed**	**wells**	**trenches**	**-**
+ often most cost-effective: most m^3 recharge per $ invested + less stringent requirement of source water quality + SAT (soil-aquifer-treatment) - requires (shallow) unconfined aquifers, with no low permeable features in the vadose zone - natural level of the water tables cannot be too close to the surface, to avoid flooding - shallow infiltration basins give maximum hydraulic loading, thus requiring large surface areas for maximum infiltration	+ simple modifications, small investment - little to no control on the amount of artificial recharge - shallow infiltration areas give maximum hydraulic loading, thus requiring large surface areas for maximum infiltration	+ can be used to bypass low permeable layers in top few 10s of meters + SAT (soil-aquifer-treatment) - only in unconfined aquifers - cannot be backflushed, so clogged wells are not readily cleaned	+ can be used to bypass low permeable top soils in top few meters + SAT (soil-aquifer-treatment) - only in unconfined aquifers - clogging is hard to remediate - deep trenches can be expensive, practically limited to about ~3 m	+ only method to recharge deep, confined aquifers + can extract and inject from same well + control injection / extraction rate + can clean the well e.g. backwashing or jetting + small surface footprint + maximize recovery efficiency using MPPWs or horizontal wells - costly - comparatively sensitive to clogging - may still require large surface storage basins when river discharge excesses are used

4.3 Aquifer Storage and Recovery systems in the Mekong Delta

As mentioned above, the Mekong Delta is a low-lying coastal delta suffering from subsidence, salinization and water availability during the dry season. These challenges frame the objectives of eventual ASR techniques that could be implemented in the delta. To date, there are no studies known that have either evaluated the potential of ASR or run a pilot; FAME is the first project aiming at this.

For a quick assessment of the potential of ASR systems in the MKD, the precipitation regime, the water demand for agriculture, and the hydrogeology has been analysed.

The precipitation regime shows a wet period from June to September and a dry period from December to March, being October, November, April and May, transition months. Water demand for agriculture is rain fed or supplied by surface water during the wet season and by groundwater in the dry season. Therefore, the groundwater levels in shallow phreatic aquifers are low from October to May due to the extractions for irrigation. It is between October and November that there is still an excess of surface water of enough good quality that can be used for infiltration. In this period there is also enough space in the aquifers for this water. Therefore, between October and December, there is a so-called window of opportunity to supplement groundwater levels (Figure 4-4) and sustain a higher groundwater table during the dry season.

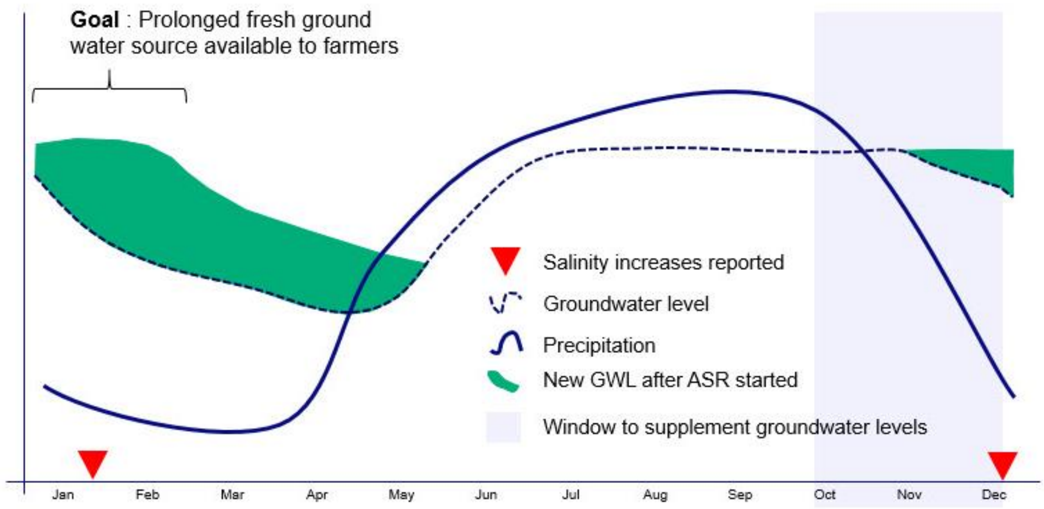


Figure 4-4: Aquifer Storage and Recovery concept in the Mekong Delta.

The storage capacity of the shallow aquifer is limited and is determined by the amount of drawdown that has occurred since the end of the wet season and by freshwater availability in the canals. Delaying replenishment beyond the month of November to target a larger storage capacity following a larger drawdown is not an option, as fresh surface water becomes scarcer, and salinity intrudes into the water channels. This delimits the infiltration of water to be conducted at the on-set of the dry season.

Previous studies indicated that the MKD has shallow and deep aquifers with important volumes of freshwater, which are currently being depleted causing subsidence and salt water intrusion. This implies, although site specific analysis is needed to verify this, that both shallow and deep ASR systems could be interesting for the delta. While the deeper groundwater is mainly brackish, the shallow lens below the dunes, are mainly fresh. In general, the monsoon rains provide (and will continue to provide) enough rainwater within one wet season to refill the freshwater lenses. Climate change is, however, affecting the drawdown of the water lenses as drought spells are increasing in both frequency and duration, forcing farmers to irrigate earlier in the dry season and at higher rates and frequencies.

FAME focusses in finding a solution to increase water availability for farmers, at a small scale and that is cost-effective. For this reason, the attention has been set in the shallow aquifers formed by the old sand dunes (for a detailed description of the hydrogeology, the reader is referred to Section 5.2).

The shallow sandy ridges in the MKD consist of well sorted fine sand, with high hydraulic conductivity, making them shallow aquifers suitable for groundwater use and irrigation purposes (Ta et al., 2002a). The sand dunes in the MKD are morphologically similar to the creek ridges in The Netherlands, which have been utilized in the past to implement ASR with the so-called creek ridge infiltration technique (Figure 4-5). The creek ridges are sandy geomorphological features that are elevated up to 2m above the average surrounding ground surface (Pauw et al., 2015). In the Netherlands, during the wet season, excess precipitation water is infiltrated into the aquifer by means of a dedicated infiltration system and a nearby surface water source. This increases the fresh groundwater volume which can be extracted for irrigation when it is most needed.

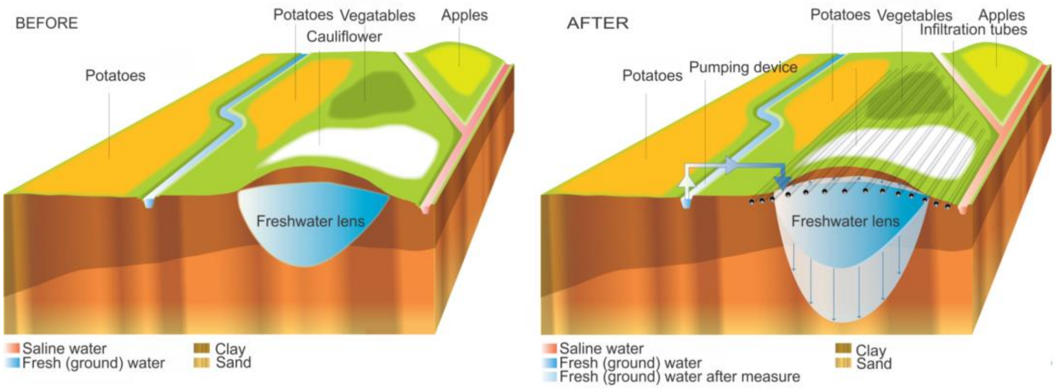


Figure 4-5: Extension of a freshwater lens using the creek ridge infiltration technique to increase freshwater storage in sand dune area. Before the implementation of ASR (left), the freshwater lens is smaller compared to after implementation of ASR (right). The ASR system injects excess water using horizontal wells during wet period to increase shallow groundwater resource to be used in dry period.

The described creek ridge infiltration technique is likely to work in the sand dunes of the MKD.

There are various other techniques that could also be effective in the MKD, however, the initial quick assessment indicated that the creek ridge infiltration technique has the highest potential. Table 4shows the other techniques and the reasoning why the expected potential is lower.

Table 4: Shallow ASR techniques not selected to be implemented in the dunes of the MKD.

Technique	**Description**	**Reasoning the method is not selected to be applied in the dunes area of the MKD**
The Freshmaker (Figure 4-6)	Through 2 horizontal pipes a different depth, deep saline groundwater is extracted, and freshwater is infiltrated	The extraction of saline groundwater is not necessary as the sand dune lens still has the storage that is needed to inject extra freshwater during at the end of wet season
Drains to Buffer (Figure 4-6)	Horizontal drains drain saline groundwater to the ditches or canals so that space is created for the freshwater	Canals or ditches are often not available, so saline groundwater cannot be discharged there

Bank infiltration	extraction of groundwater from a well or caisson near or under a river or lake to induce infiltration from the surface water body thereby improving and making more consistent the quality of water recovered (Dillon, 2005)	Canal / river is often far away from the aquifer to recharge the sand dunes
Dune Infiltration through ponds	Infiltration of water through ponds constructed on top of the dunes and extraction through wells at a lower elevation	Ponds require space, and the dunes of the MKD are used for cultivation. If ponds are built, too much space would be lost. Additionally, dunes are not wide enough for these systems
Infiltration ponds	Infiltration through ponds constructed usually off-stream where surface water is diverted and allowed to infiltrate	Ponds require space which is needed for agriculture. Besides, elevation difference not enough
Sand dams	built in waddies in arid areas of low permeability lithology, these trap sediment when flow occurs, and following successive floods the sand dam is raised to create an “aquifer” which can be tapped by wells in dry seasons (Dillon, 2005)	Not suitable as it requires waddies and an arid climate

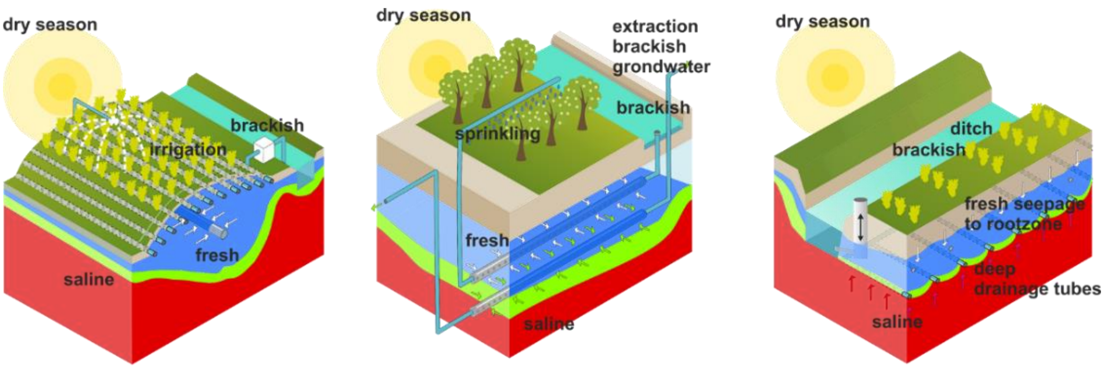


Figure 4-6: Different types of shallow ASR from left to right: Creek Ridge Infiltration, The Freshmaker, Drains2Buffer (Oude Essink et al., 2018).

In the following chapters, a description of the hydrology and hydrogeology of the specific sites leads to the assessment of the potential of the shallow ASR technique in creek ridges.

5 Study areas

5.1 Selection of the studied areas

During the scoping workshop with the related stakeholders, the selection was discussed of high potential shallow ASR system areas, together with the feasibility and practicality of installation. The selection was narrowed down to two provinces in the MKD, Ben Tre and Tra Vinh province (Figure 5-1). These two areas are both situated in the coastal province zone of the MKD that suffers most from salinization during dry season.

The stakeholders of the Tra Vinh and Ben Tre provinces selected six areas where water stress occurs, and the freshwater availability could be improved. Each site was then analysed based on 14 criteria illustrated in Table 5.

Based on the information received during the field visits and after the selection criteria were set and filled in per site, three potential sites were remained: TV2 (Long Son Commune), BT2 (An Duc), and BT3 (Bin Tangh). The three sites are characterized by old sandy ridges which serve as shallow aquifers supplying groundwater to the farmers living on or close to the sandy ridges.

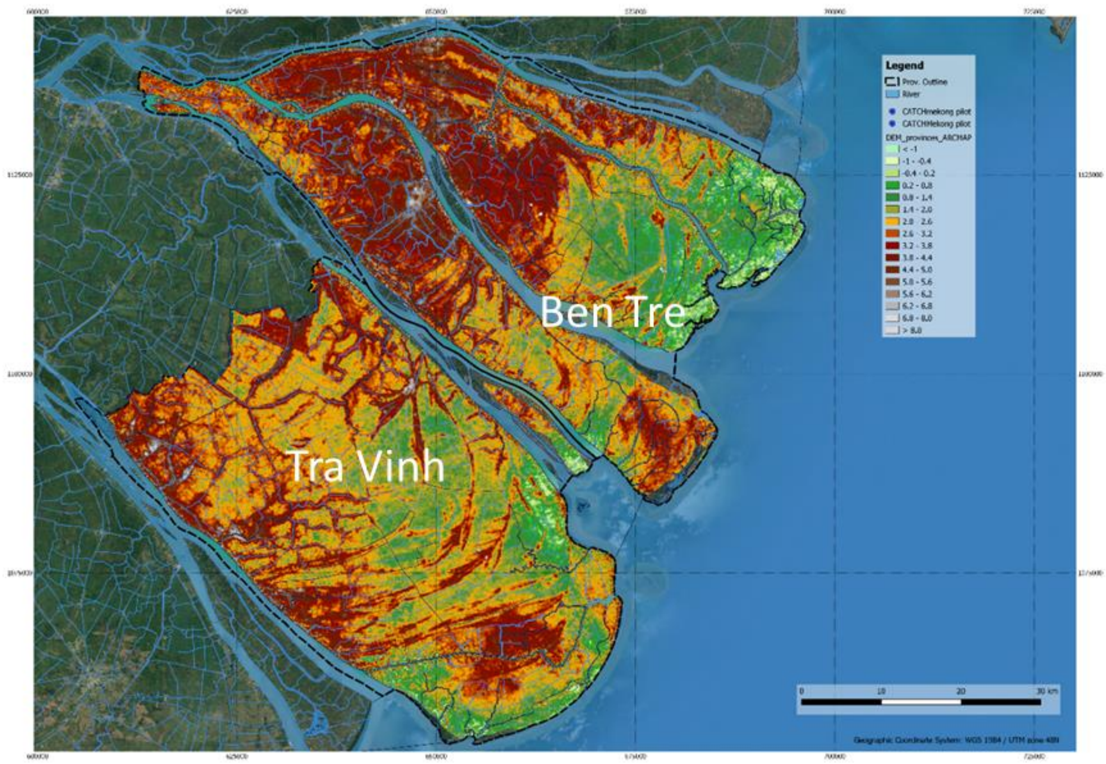


Figure 5-1: Locations of Ben Tre and Tra Vinh province

Table 5:Criteria to select study areas. + indicates that the site meets the criteria, and 0 indicates that the site does not meet the criteria.

Criteria	TV1	TV2	TV3	BT1	BT2	BT3
Front runner	0, not clear	++	+	++	+	++
Construction suitability	++	++	+		+	+ (open field), or 0 (difficult due to present of trees)
Existing data	0	0	+++		0	0
Geological circumstances	+ (sand)	+ (sand)	+ (sand but limited)		+	++ (sandy, more than BT2)
AMD/IFAD present	0	++	0		0	+ (Lan Ahn workshop)
Surface water (available, pollution)	0 (far)	+ (Reservoir but far away)	0 (polluted source)		+	0 (3 to 4 km away)
Energy source close by	+	++ (solar energy)	++		+	+
Size of farm	+ (2000-3000 m^2)	+ (maybe up to 5000 m^2)	+ (maybe up to 5000 m^2)		+ (2000-3000 m^2)	+ (2000-3000 m^2)
In-situ geology (infiltration capacity)	++ (very sandy)	+ (sandy)	+ (sandy on dune but clayey next to dune)		+ (sandy, but less sandy than BT3)	+ (sandy)
Urgency (duration of groundwater shortage)	+ (now) and ++ (in the future)	0 (for farm close to reservoir) and ++ (for farm away from reservoir)	0 (domestic use) and + (for dragon fruit orchard)		+	+ (now) and ++ (in the future due to declining groundwater head)
Land use / land cover	Melon, peanut	++ fruit and vegetables)	+ (Rice, dragon fruit)		+ (for vegetables)	++ (fruit, vegetable, peanut)
Groundwater use	++	++	++		0 (using surface water that gets saline in dry season)	++
Domestic water use			++		0, water supply from local authority company	0, use of groundwater
Permission (authority)	+	++	++		+	++
Extra Info	Flooding / saturated completely during rainy season; No / little fresh groundwater for three months	Distance to reservoir is too far and not enough water stored in the reservoir.	There is groundwater overexploitation that makes it difficult to do aquifer recharge	Saline surface water		Over extraction of groundwater
Preferable site	**No**	**Yes**	**No**	**No**	**Yes**	**Yes**

5.2 Hydrogeology of the selected provinces

The area of the MKD considered in this study is the lower sub-areal delta plain. Presently, the Mekong Delta is classified as a wave-influenced and tide-dominated delta (Ta et al., 2002a). The sediments in the Mekong Delta began deposition around 3 ka ago, when the coastal environment shifted from one of tide-influence, to more wave influenced (Ta et al., 2002a). Sediments were deposited during repetitive transgression and regression events from the late Neogene up to the present Holocene period (Pham et al., 2019).

The Mekong Delta is characterized by well-developed rows of beach or sandy ridges with sometimes dunes on top that trend northeast to southwest. The dunes can be 3m to 10m above Mean Sea Level and are typically separated by interridge swamps or swales. The sandy ridges themselves are known to consist of well sorted, fine sand, making them suitable aquifers for ground water use (Ta et al., 2002b). Many of the sandy ridges are currently being utilized for irrigation purposes and show potential as sites for ASR implementation.

There are 953 km^2 of relict sandy ridges in the MKD (Minderhoud, 2019) that appear as higher elongated structure in DEM (Figure 5-2). The sandy ridges are curved and generally run parallel to the coastline. In the Tra Vinh province, the width of these sandy ridges was found to be typically 1 to 2 km with muddy inter-ridge swale deposits running in between the sandy ridges (Tamura et al., 2012).

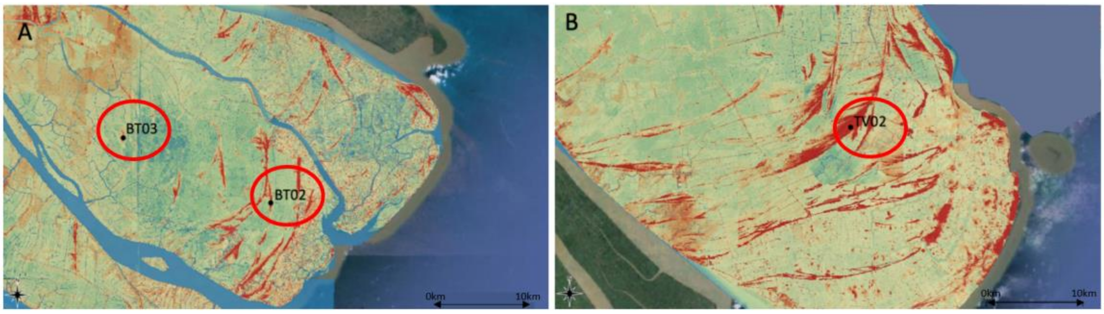


Figure 5-2: High resolution DEM showing sandy ridge structures in Ben Tre (A) and Tra Vinh (B). Red represents higher area.

The sandy ridges in coastal area in the MKD were formed during a progradation of the delta as sediment drifts along the shoreline from river discharge (Tamura et al., 2012) (Figure 5-3). The sandy ridges begin as subaerially exposed islands and expand to longer spits of land as they accumulate sediment. The sub ridge sets are branches of the larger sandy ridge as sediment continues to accumulate and is influenced by wave, tide and fluvial processes (Tamura et al., 2012). The sandy ridges are presented as sandy elevated features with greater infiltration capabilities than other surface deposits.

During formation of the coastal landscape, the sandy ridges are encompassed by low-energy depositional environments. The muddy inter-ridge deposits ‘consisting of silt, silty clay and clay are significant as they may act as aquitards that isolate the shallow sandy ridge aquifers (Minderhoud et al., 2017). The aquitard limits the extent of the shallow aquifer. The thickness of the aquifer is also affected by the presence of aquitards that extend across the system. Coring reveals deeper older sediments that were deposited during earlier progradation stages of the delta (Figure 5-4).

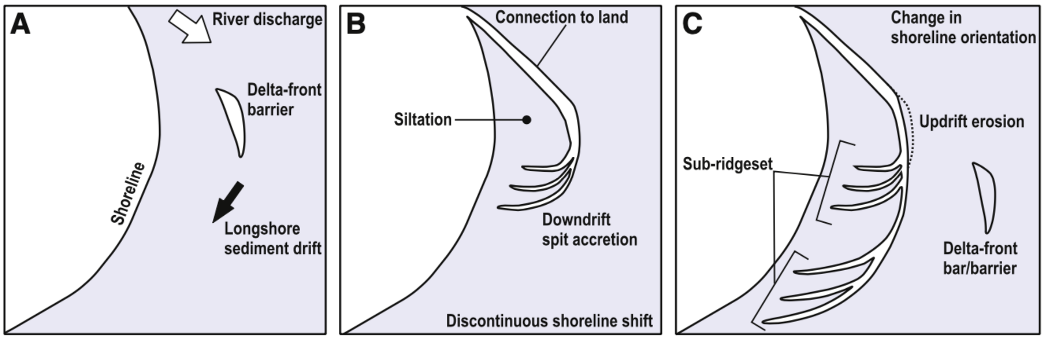


Figure 5-3: Depiction of Tra Vinh sandy ridge development during progradation of the delta, including base ridge formation and sub-ridge sets (Tamura et al., 2012).

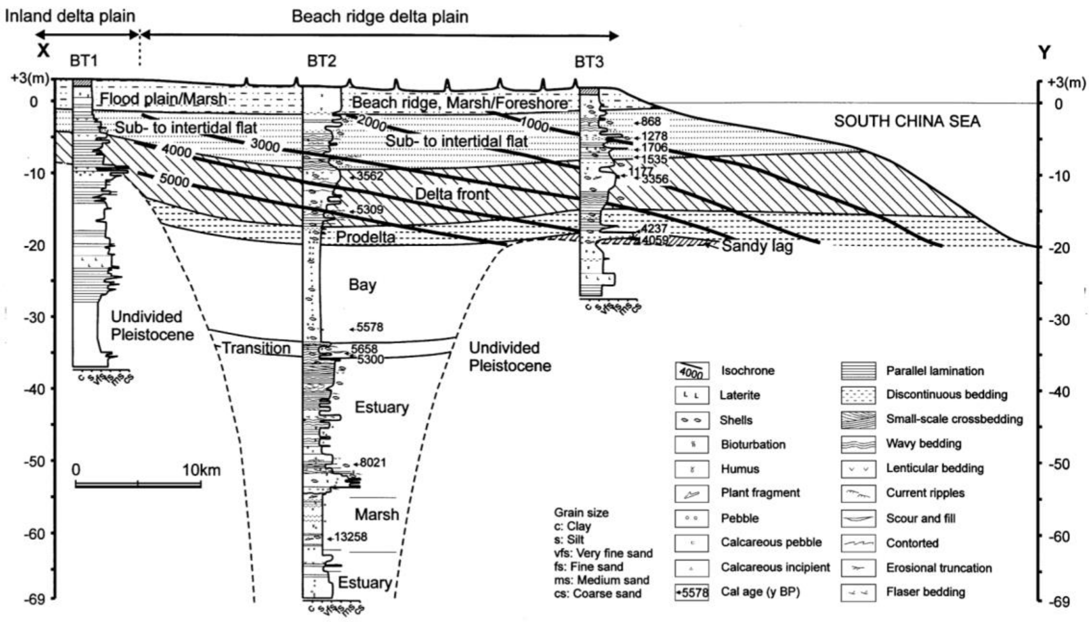


Figure 5-4: Cross section and core logs of sedimentary facies in the lower Mekong Delta plain the in the province of Ben Tre. From: Ta et al. (2002).

The aquifers at sandy ridges may potentially benefit from ASR techniques that are similar to the ASR systems implemented in the Netherlands in a similar delta environment. In order to implement water conservations projects, such as ASR, suitability recommendations need to be made on a local scale. Establishing new knowledge about these sandy ridges is an early step towards the first pilot ASR system in the Mekong Delta.

6 Study area Ben Tre 2

6.1 Introduction

In Ben Tre province, two sites have been selected (BT2 and BT3) from the scoping workshop (section 5.1). A big part of the livelihoods in Ben Tre depends on agriculture. Main agricultural commodities cultivated in this area are rice and fruit. Coconut trees are increasingly cultivated because of their salt tolerant nature (Vormoor, 2010). The urgent problem in this area is the saltwater intrusion. In the dry season the saltwater flows upstream into the river and canals and intrudes inland through surface water and groundwater. The intrusion area in the dry season has been steadily moving further inland over the years (Bregman, 2020).

To produce crops during the dry season, people try to store freshwater during the rainy season in ditches and canals (Japan International Cooperation Agency, 2016). In combination with the high risk of yield reduction by saltwater intrusion, farmers also get higher profits from shrimp or fish production. In some parts of Ben Tre, a rotation scheme is applied with shrimp production in the dry season utilizing brackish water and rice cultivation during the rainy season to reduce the risk of diseases in the shrimp ponds and the risk of yield reduction of rice (Japan International Cooperation Agency, 2016). However, this type of rotation scheme may leak brackish water to the surrounding.

The dune areas are generally not suitable for shrimp production, because the soil is too sandy and the ponds need clay to hold the water in the shrimp ponds (Kungvankij et al., 1989); so, rice-shrimp production rotation is not a suitable solution to the lack of freshwater for the farmer in the dune area. The impression of the BT2 site is illustrated in Figure 6-1.

Figure 6-1: Ben Tre 2 (BT2) site.

6.2 Description of the local situation

The field site is located south of the village Phú Ngãi. The sand dune in BT2 location is quite narrow, only approximately 210 m across, and mostly occupied by the main road, houses and gardens. Most farmers have (rice)fields situated left or right of the elevated sandy ridge. There are several small communities of houses, accessible by little paths off the main road. Many houses have pump wells, but communities often also have an older, sometimes shared, open well that is mostly used for domestic activities. Small canals are found in the west and east of the dune, and its water is used for irrigation of the fields.

On average, farmers used 734 to 837 liters per family per day (Bregman, 2020). The wells were only used for domestic use and livestock. The pumping-wells were 5.5 meters deep on average and the open wells around 4.4 meters. The wells never dry up but decrease in discharge or water quality issue occurs during the onset of the dry season. In the open wells, the water level decreases 1.7 meters on average from rainy to dry season. Farmers reported salt and pH problems in the wells, which occurred mainly in March, April and May.

The surface water system is, almost exclusively, used for agriculture. The farmers mainly have rice and grass fields, which are low elevation fields with natural inflow for irrigation. Fields need to be set higher than the canal water level to make it suitable for vegetable or coconut farming. The surface water is reported to be insufficient in quantity or quality (too saline) from the end of February according to most farmers. Groundwater is sometimes also used for watering the gardens.

6.3 Field work

Field work covering geology, hydrogeology, and water quality studies have been conducted by three students from Utrecht University: Anne Kruijt, Josh Shankel, and Sep Bregman. An impression of the field work is illustrated in Figure 6-2.

Figure 6-2: Clockwise, from upper right: coring on the western side of the dune, a small communal field on dune, coring on dune, farmhouse, coring between the banana trees, interviewing farmer Mr. Phuoc.

6.3.1 Geology

The sedimentology of the shallow subsurface was determined with coring using a hand operated coring device. Deeper coring and deep well installation, where the groundwater monitoring device will be installed, were also conducted. The coring at this site (Appendix A.1.2) helped determining the lateral limits of the sand dune, with a thick layer of sand often found at sites close to the road and clay encountered almost immediately off the sides of the dune.

A single small dune with the width of 200m was studied on this site. It is characterized by a layer of well sorted, fine sand bound by clay layers in the dune slacks and marine sand at approximately 2.0m-3.5m depth (appendix A.1.4). The sides of the dune yielded significant amounts of clay. However, based on anthropogenic influence, based on coring result (Appendix A.1.3), this core does not reflect the natural environment. A deep coring yielded evidence of a shallow clay layer at 4m below the surface, followed by another large sand layer of 11m thick, both are considered continuous. The aquifer boundary is represented by a large clay layer at approximately 14m below Mean Sea Level.

6.3.2 Hydrology

At this site, four observation wells with divers that monitor groundwater changes from the wet to the dry season have been installed (Figure 6-3). The first three wells are quite shallow and were installed by hand, and the fourth well is a deep well.

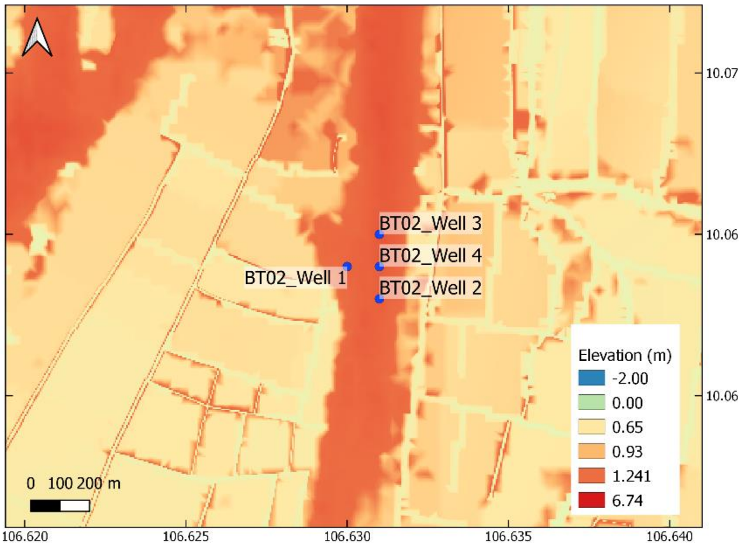


Figure 6-3 Digital elevation model of the area, with legend (showing height in meters). Installed measuring devices are indicated with blue dots.

A diver was installed on Well 1 on 23rd of October 2019 and was placed 190 m below surface level. At this location, a barometer diver was also installed on 11th of November 2019. Another diver was installed on the 7th of December 2019 in Well 2 located near the highest point of the sand dune. On 7th of December 2019, a diver was installed on Well 3 on the eastern side of the sand dune. A diver was also installed in the deep well, Well 4, on the 15th of December 2019.

Measurements from the longest running diver at this site, located in Well 1, are shown in Figure 6-4. A steady decline in groundwater level was observed, with some interesting spikes at 27th of October, 13th of November, 16th of November, 1st of December and 7th of December 2019. These might be due to heavy rainfall, however there is no rain gauge on site. Because rain fall in this region can be very local, data from the rain gauges at the other two sites might not be representative. Another possibility is that human activity in the garden in which this piezometer is located has caused these momentary higher water levels. In total, the water level has dropped approximately 40 cm over the months of October to December (Figure 6-4).

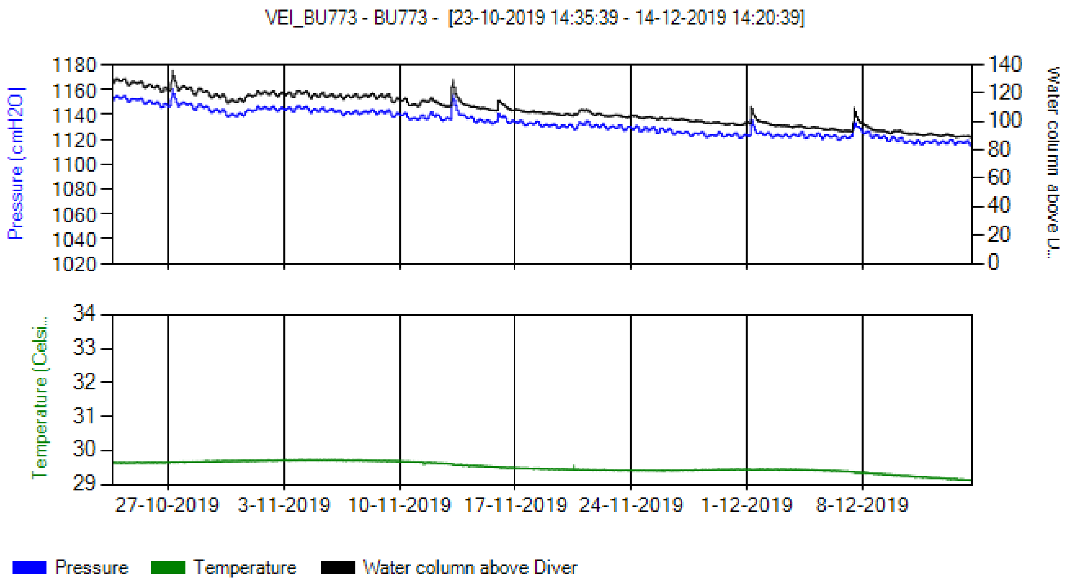


Figure 6-4: Water pressure recorded by diver in Well 1

6.3.3 Storage capacity

The volume of water that can be stored in the subsurface in BT2 was calculated by a student from Utrecht University, Josh Shankel, as part of his master thesis (Shankel, 2020). The volume per stretched meter is extrapolated perpendicular across the length of the sandy ridge structure which is approximately 1.5km. The reliable lowest groundwater level was inferred from three cores that were taken. The aquitard / system boundary line extrapolated across the center core (Appendix A.1.4). But it is considered as a fairly reliable estimation as this boundary is found in nearby cores. Looking at the deep core (Appendix A.1.4), this aquitard may be quite thin, and may have connectivity to the lower confined aquifer. The calculated storage considering minimum and maximum porosity (0.25 and 0.30 respectively), are listed in Table 6. In this site, groundwater levels fluctuate between 2 and 3 meters below surface.

Table 6: BT2 Cross sectional area and storage calculations for maximum and minimum effective porosity values, and stretched

BT2	Cross sectional area (m2)	Volume per stretched meter considering minimum porosity (m3)	Volume per stretched meter considering maximum porosity (m3)
Surface to groundwater level	238	60	71
Groundwater level to bottom of aquifer	264	66	79
Total aquifer	660	165	198

6.3.4 Water quality

The water quality of both groundwater and surface water was tested with the use of a CTD diver, measuring electrical conductivity in open wells and pump wells. Measuring sites are spread out across the study area, on both sides of the main road (Appendix A.1.7). The measurements are conducted in the months of November and December. Measured values range from approximately 600 to 5800 µS/cm, with one extreme value of 15,000 at location 11 (Appendix A.1.7). Salinity values measured in wells on both sides of the dune are higher than those measured on top of the dune. Wells on the western side of the dune, show slightly higher salinities than the houses on the eastern side of the dune.

Water quality measurements were also conducted for surface water. Measurements were performed in a few canals, ditches and ponds surrounding the field site (Appendix A.1.7). A larger canal is located east and south of the field site. Smaller canals both west and east of the field site are fed by water from the larger canal. These smaller systems of canals are close enough to potentially serve as freshwater source for infiltration to the dune. The measurements performed in the months November and December. Measured values range from approximately 1100 to 5200 µS/cm, with no clear trend observable. The high (5000 µS/cm) values that were observed in ponds (most likely resembling groundwater rather than surface (canal) water as the values are higher during the wet as well as the dry season).

6.3.5 Conclusions from the field work

There has been a steady decline in groundwater level in the months October to December 2019, while at the same time water levels in the nearby canal are still high and salinity levels were low. This means there is a window of opportunity at this site to infiltrate fresh surface water into the dune during these months, thereby enlarging the freshwater availability in the dry season. However, the dune is quite narrow and is densely populated, most of its surface covered by houses, gardens and the main road. This might make finding a suitable spot for the installation of ASR complicated. Moreover, farmers currently do not use groundwater for agricultural purposes. For their domestic activities there is enough groundwater available all year-round.

7 Study area Ben Tre 3

7.1 Introduction

This site is located in the middle of the Ben Tre province, which is quite densely forested and contains a lot of small rivers branching off the main canal near Ben Tre city. 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 for 3 months and during the extreme drought in 2016 it lasted for 5 months (Global Facility for Disaster Reduction and Recovery, 2018) and is likely to worsen in the future as a result of climate change.

In Ben Tre, 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 becoming less possible (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 (Japan International Cooperation Agency, 2016). Complete conversions of agricultural land into brackish shrimp farms are increasing as well, although often done illegally. The conversion towards brackish aquaculture ponds allows for brackish water to leach towards surrounding fields and canals. This only aggravates the salinity problems. The impression of BT3 site is illustrated in Figure 7-1 and Figure 7-2.

Figure 7-1: Ben Tre 3 (BT3) site.

7.2 Description of the local situation

BT3 is an extensive dune area where groundwater is used for irrigation. The sand dune system at this site is more than 600m across. The area is densely populated and small fields are alternated with groups of trees, houses and little roads. There is canal in the west and east of the field site, but there are no continuous ditches crossing the field site. Most farmers use a combination of groundwater and water from dug out water holes to irrigate their crops. Most irrigation is done by hose and hand with a high frequency, only one farmer had overhead sprinklers. Coconut plantations and rice fields can be found close to the canals, and slightly higher up on the dune the farmers alternate between e.g. rice, peanuts, cucumber, citrus fruits and cassava.

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 they experienced with salinity during the dry period. On average, a water usage of 1883 – 2110 litres per person per day was reported. The water users in this area have different types of wells. 12 users only have a hand well, 11 users have pumping-wells and 7 users have both hand- and pumping wells. The average depth of the pumping well is 8.1 meters and for the open well depth is 6.2 meters. Many pumping-well users have multiple wells. Some people report that their wells fall dry in the dry season, but this occurs in the shallower open wells only. In the pumping wells there is a decrease of discharge from the wells. In the open wells, the water level drops 2.8 meters from rainy season to dry season. Eight people report low pH in their wells. All these problems occur at the end of February, March and April.

Figure 7-2: Clockwise, from upper left: Farmer on his front porch, cassava on the dune, fields to the side of the dune, small ditches between coconut trees, a dug-out water hole on the dune, farm field, farmers harvesting peanuts

7.3 Field work

7.3.1 Geology

To identify the lithology of the subsurface, several corings (Appendix A.2.2) using a hand auger and self-made suction corer were performed to a depth of 4m. The site covers two dunes over a span of 500m. The dune layer is characterized by well sorted fine sand with intermittent layers of clayey/loamy sands and few clay layers with a maximum thickness of 30cm (Appendix A.2.4). These layers are significant enough to have an effect on hydraulic conductivity but are unlikely to be fully continuous across the system.

Three deep cores were completed on this site yielding a reliable aquifer boundary at approximately 6.5m below MSL (Appendix A.2.3). The sand layer from the surface is approximately 7.5m thick. Cores taken from this site show reliable reduction zone boundary which denotes the lowest average ground water level in the dry season.

7.3.2 Hydrology

A rain gauge was installed on the 24th of October 2019. The graph in Figure 7-3 shows the cumulative rainfall for the months October to the end of November and end of November to the middle of December. Between the 24th of October 2019 and the 8th of November 2019, approximately six rainfall events were observed. The largest rainfall an event occurred on the 31st of October 2019 (15mm in one day) and the 6th of November 2019 (20mm in one day). The cumulative rainfall between 24th of October 2019 and the 8th of November 2019 was 60 mm. The rest of November and the start of December 2019 was much dryer. The rain gauge recorded a cumulative rainfall of 12 mm for this latter period, but since the rainfall events coincide with coupling and decoupling of the logger, these measurements might be incorrect.

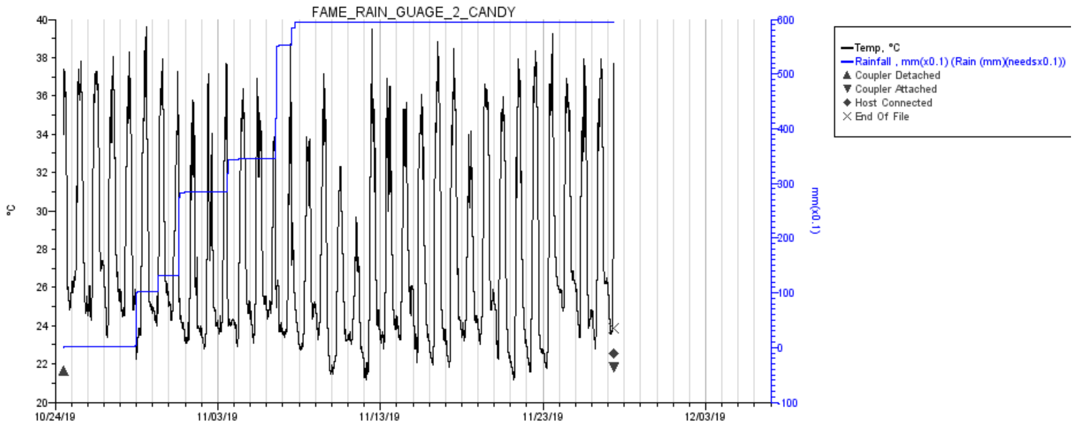


Figure 7-3: Cumulative rainfall for the 24th of October to the 27th of November. Red arrows indicate the above-mentioned large rainfall events.

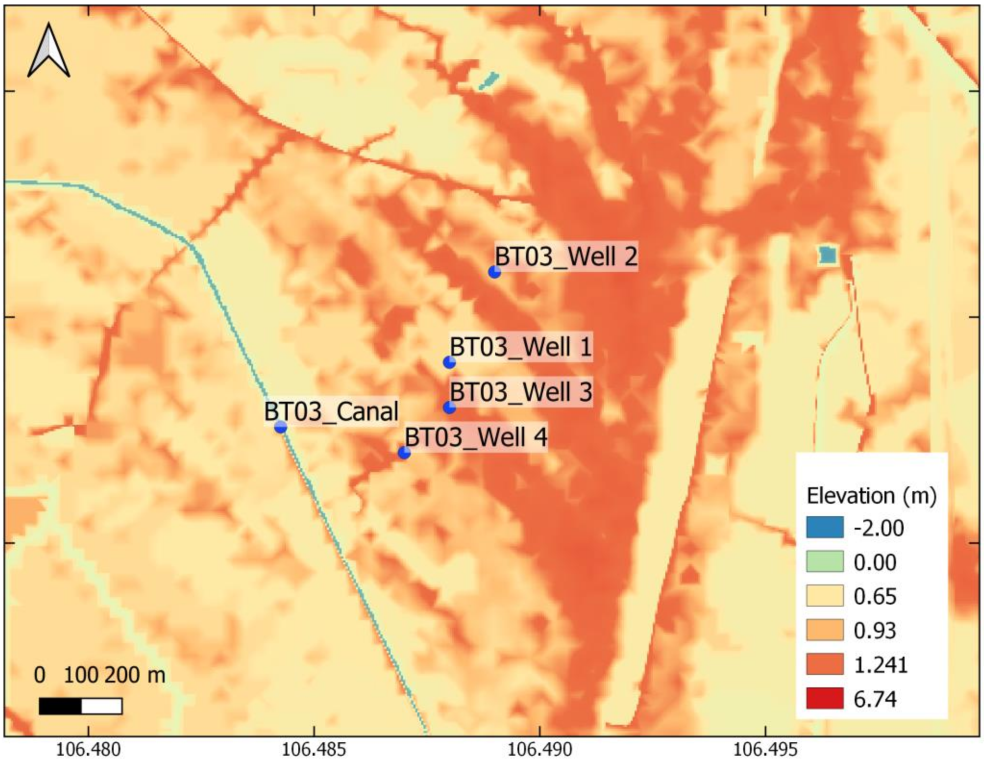


Figure 7-4: Digital elevation model of the area, with legend (showing height in meters). Installed measuring devices are indicated with blue dots, the rain gauge is installed at the location of well1

At this site, four observation wells have been made containing divers that will monitor groundwater changes from the wet to the dry season (Figure 7-4). The first well is quite shallow and was installed by hand, and the other three are deep wells. A CTD-diver was installed on the 24th of October 2019, in the shallow well, well 1, that is located close to the top of the sand dune. On the 14th of December 2019, the diver was moved into well 3 that is located on top of the sand dune and replaced by a normal diver measuring only temperature and water level.

Another diver installed on well 2 on the 13th of December 2019. This well is located on top of the sand dune, next to a field of fruit trees.

A deep well, well 4, was installed on 14th of December at the side of the sand dune. A layer of sandy clay was encountered from 5.7 to 6.8 m and sandy layer was encountered below it. A detailed well schematization of these deeper wells, with descriptions of encountered lithologies is shown in Appendix A.2.3.

Measurements from the longest running diver at this site, located in Well 1, are shown in Figure 7-5. A decline in groundwater level from the 24th of October to the 6th of November 2019 was observed, interrupted by a sudden rise on the 31st of October 2019, probably related to the rainfall event observed in the rain gauge data. A second large rise occurs on the 6th of November 2019, related to another large rainfall event. After this second rise, the groundwater starts to steadily drop again from the 10th of November 2019 onwards. There has been a total drop in groundwater level of 30 cm over this entire period. The bottom graph shows the salinity of the groundwater in the well. There is a slight increase in salinity over the months, from 880 to 1200 µS/cm. When this site was first visited in the beginning of October, water levels were high, water holes almost full and water present in the rice fields. At the time of the installation of the diver, at the end of October, the groundwater level had already dropped significantly. Rice fields had dried up and the water level in the water holes was about a meter lower than at the beginning of October.

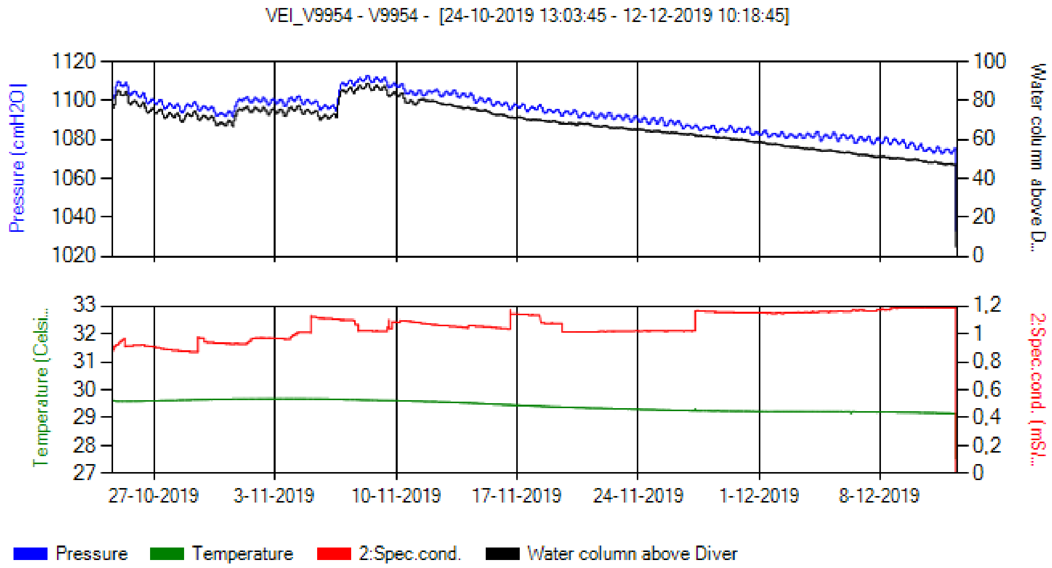


Figure 7-5: Groundwater level (top) and salinity (bottom) in Well 1

7.3.3 Storage capacity

The volume of water that can be stored in the subsurface in BT3 was calculated by a student from Utrecht University, Josh Shankel, as part of his master thesis (Shankel, 2020). The volume per stretched meter is extrapolated perpendicular to the cross section across the length of the sandy ridge structure which is taken as approximately 1km (Appendix A.2.5, p. 118).

The BT3 site has the most cores and the most reliable hydrogeological data. This cross section is also having the highest density of cores and low groundwater table reading. This cross section also includes three deep cores which all have a sharp contact with a clay aquitard at the base of the shallow aquifer. This contact is extrapolated across the system and used to calculate the total capacity of the aquifer from surface to base.

The groundwater table readings in this area were taken early December, which is considered the dry season. The surface to groundwater level volume is representative of the potential capacity for infiltration in this site, depending on the availability and quality of fresh surface waters available for infiltration during this time. The calculated storage capacity per stretched meter for BT3 considering minimum and maximum porosity (0.25 and 0.30 respectively) is listed in Table 7. In this site, groundwater levels fluctuate between 2 and 4 meters below surface.

Table 7: BT3 Cross sectional area and storage calculations for maximum and minimum effective porosity values, and stretched

BT3	Cross sectional area (m2)	Volume per stretched meter considering minimum porosity (m3)	Volume per stretched meter considering maximum porosity (m3)
Surface to groundwater level	886	221	266
Groundwater level to bottom of aquifer	697	174	209
Total aquifer	4635	1159	1391

7.3.4 Water quality

Water quality measurements were performed with CTD-diver in open wells and pump wells. Measuring sites are spread out across the study area (Appendix A.2.8) on and next to both dunes. The measurements were performed in the months of November and December 2019. Measured values range from approximately 600 to 2000 µS/cm. Salinity values seem to be lowest on top of the most western dune, and highest on the sides of both dunes, but other than that there is no clear pattern observed. The measured pH is around 6.8 and 7.8 for all wells. Nitrate was not always measured but when measured, there was no nitrate detected.

Water quality measurements were also conducted in small dug out irrigation ponds. A small canal is located to the west of the field site, which is connected to the larger river system in this part of the province (Appendix A.2.8) (Figure 1-1Figure 7-6). The water level in the irrigation ponds dropped significantly over the months November to December, whereas the water level in the canal did not drop much. The measured salinity values in the ponds are highest and range between 1000 and 2000 (µS/cm). These ponds are mostly located on the sides of the sand dunes. Lowest salinity values of between 300 and 600 µS/cm, were measured in the small canal and ditches attached to the canal. This suggests that salinization is not (yet) occurring in the canals at this time of the year.

Figure 7-6: Canal to the east of the field site (locations 42 (left) and 13 (right) in Appendix A.2.8)

7.3.5 Agriculture

Agriculture in BT3 site differ between rainy season and dry season. During rainy season, in lower elevation, coconut and rice dominate, while in sloped areas, orchard and jasmine dominate. Schematic representation of the dune and the associated crop in the rainy season is illustrated in Figure 7-7, while the cropping schedule is listed in Table 8.

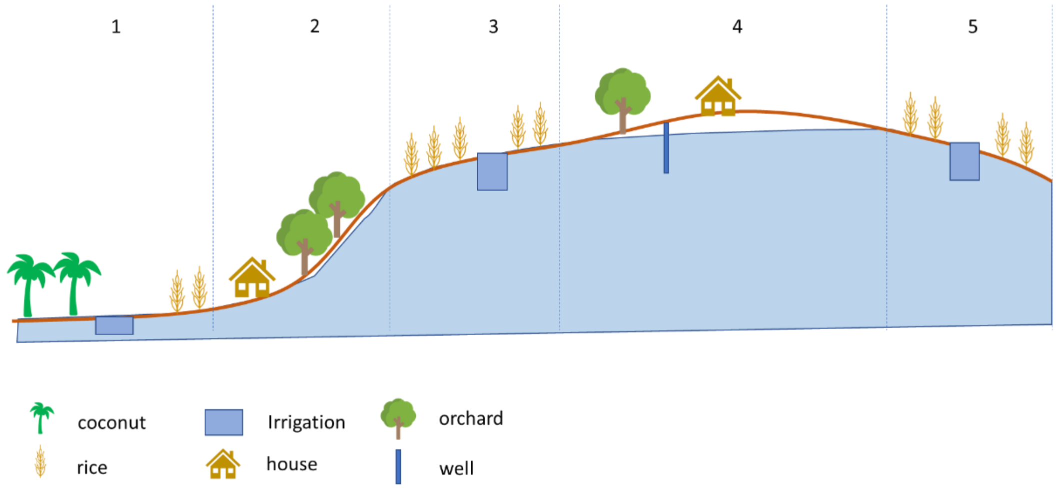


Figure 7-7: Schematic cross-section of the dunes during the rainy season and early dry season

Table 8: Average cropping scheme in normal rainy season

BT3	April	May	June	July	August	September	October	November
1	Coconut / Rice	Coconut / Rice	Coconut / Rice	Coconut / Rice	Coconut / Rice	Coconut / Rice	Coconut / Rice	Coconut / Rice
2, 4	Jasmine, Orchard	Jasmine, Orchard	Jasmine, Orchard	Jasmine, Orchard	Jasmine, Orchard	Jasmine, Orchard	Jasmine, Orchard	Jasmine, Orchard
3	Peanut	Cucumber, Peanut	Cucumber	Cucumber	Rice	Rice	Rice	Rice

In the wet season, area 1 (low lying) (Figure 7-7) consists of paddy rice and coconut farms. The canals carry freshwater at this moment for cropping rice. Lower parts of area 2 sometimes use surface water, but the higher parts already use groundwater in the wet season, on the side of the dune in area 2, the crops consisted of coconut farms and rice, but also some seasonal fruit and vegetables are cultivated. houses are situated on these slopes. Area 3 is a part of the dune that is a bit lower, possibly a dune pan. At the BT3 field site there is only enough water in the fields at the end of the wet season to grow paddy rice. Farmers say that the groundwater reaches above surface level during this time. This could be an indication that the shallow aquifer is filled to its maximum storage. Area 4 is the dune top. In the wet season, the dune top is filled with fruit trees, and jasmine tea plants. The dune continues with alternately areas 3 and 4, and eventually 2 and 1.

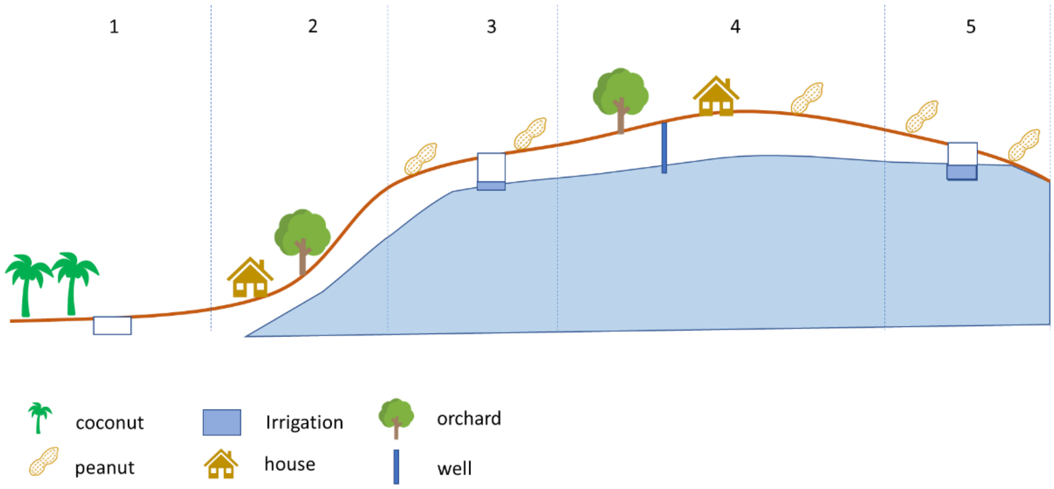


Figure 7-8: Schematic cross-section of the dunes during the early dry season till the end of February.

Table 9: Average cropping scheme in a normal start of the dry season, with no water shortage in the wells.

BT3	**December**	**January**	**February**
1	Coconut	Coconut	Coconut
2, 4	Jasmine, Orchards	Jasmine, Orchards	Jasmine, Orchards
3	Cucumber, Peanut	Cucumber, Peanut	Cucumber, Peanut

During dry season, area 1 is filled with coconut trees. The salinity of the surface and groundwater is slowly increasing. The water is most of the time still usable for crops and the quality could be sufficient to be stored in the dune. Saline water will increasingly infiltrate in the canals and groundwater. In normal years, the surface water is not sufficient in quality or quantity in December and January, with February getting increasingly worse. In area 2, the groundwater level is decreasing and slowly moves towards the middle of the dry season. On the slopes, towards the canals in the low area, the groundwater in the wells becomes saltier. The area starts to rely on the groundwater for irrigation through waterholes and pumping wells. In area 3, during the dry season, short season high value vegetables and peanuts are produced in the low areas. The main form of irrigation is from waterholes, which are connected to the groundwater. In area 4, people still irrigate the fruit trees to make sure they survive the dry season. Schematic representation of the dune and the associated crop in dry season is illustrated in Figure 7-8, while the cropping scheduled is listed in Table 9.

The irrigation rate of different crop during dry season in BT3 is listed in Table 10. The period of harvesting, total irrigation per harvest season, evapotranspiration, and efficiency of irrigation in BT3 is listed in Table 11.

Table 10: Crops grown in the dry season per field site, with the months they are grown in normal years

	Months	Irrigation (mm/day)
Jasmine and orchards	December – March	8.3
Cucumber	December – March	17.1
Peanut	December – March	11.4

Table 11: Water used and irrigation efficiency of several crops in an averaged cropping schedule in TV2

Crop	Start of plantation	Days till harvest	Irrigation requirements (mm/growth season)	Average water use or evapotranspiration (mm/day)	Efficiency of irrigation (%)
Peanut	December	96	396.3	4.1	41.7

Carrot	December	45	160.9	3.6	36.6
Carrot	January	45	196.2	4.4	44.6
Rice	September	120	361.6	3.0	100

7.3.6 Conclusions from the field work

Similar to the site BT2, in the months October to December 2019 there has been a steady decline in groundwater level while at the same time water levels in the nearby canal are still high and salinity levels are low. This means there is a window of opportunity at this site to infiltrate fresh surface water into the dune during these months, thereby enlarging the freshwater availability in the dry season.

In BT3 farmers depend in part on the groundwater from their wells for the irrigation of their crops. They do not report any problems with saline groundwater in the dry season but do report that the availability of groundwater decreases, with some of the shallower wells falling dry. This means that the installation of the ASR-technique at this site will potentially benefit the farmers by increasing the water availability for irrigation during the drier months.

7.4 Groundwater monitoring

A groundwater monitoring has been conducted in BT3 site from December 2019 to May 2020 by installing divers in well 2, well 3, and well 4 (Figure 7-4). The monitoring period covers the dry season groundwater table. The result shows that there is still more than 200 cm thickness of groundwater storage in well 2 and well 3 that are located at the top of sand dunes (Figure 7-9). At well 4, that is located at the side of the dune, the water table is closer to the surface (less than 200 cm thick of shallow lens aquifer).

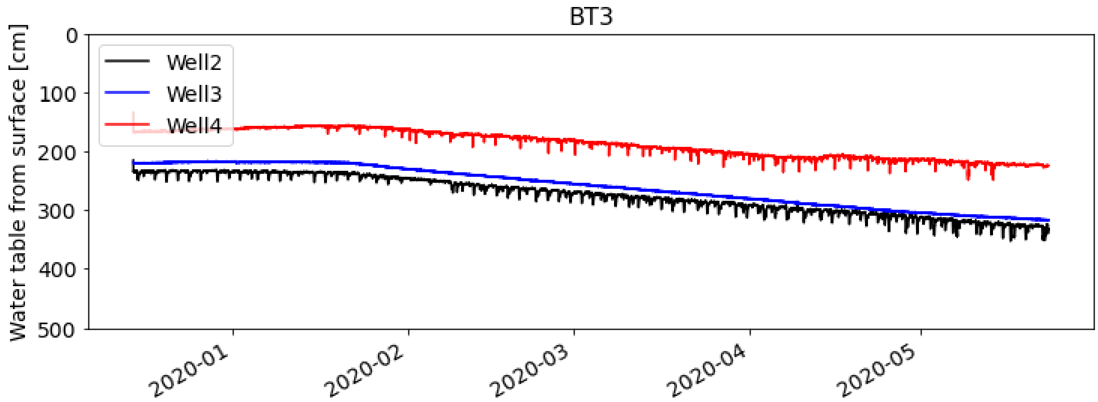


Figure 7-9: Depth of groundwater table from surface in BT3 site

Canal water monitoring covering the period from November 2020 to November 2021 shows a decline in the canal water stage from January 2021 to July 2021 (Figure 7-10). On July, the diver placed in the canal was not working and starts to operate again on November 2021. The water level in November is significantly higher than in July. this indicates that there is still surface water available in November, at the end of the wet season.

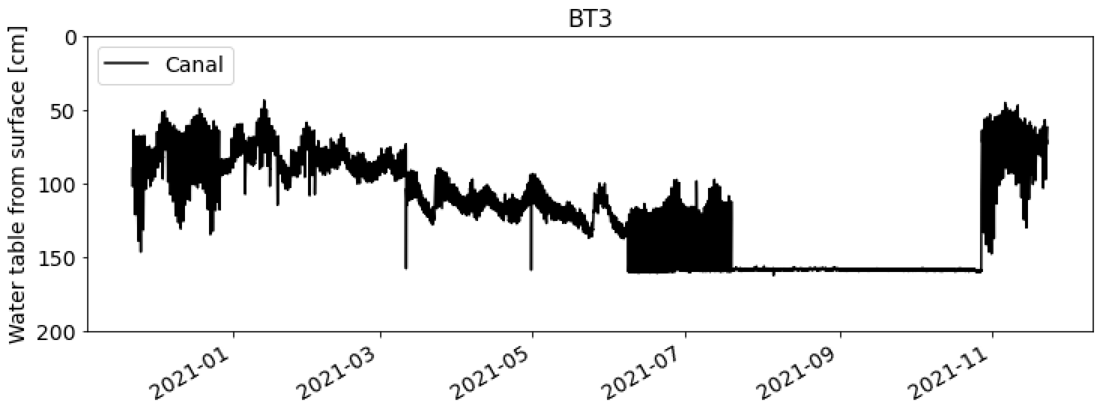


Figure 7-10: Canal water from the surface.

Based on the monitoring in BT3, it can be interpreted that at the end of the wet season in December, there is over 200cm of storage is available at the top of the dune. While, at the end of wet season in November, the surface water is still available, indicated by high canal stage, therefore this period can be interpreted as window of opportunity for ASR injection. The interpretation of BT3 site shallow groundwater state during wet and dry condition is illustrated in Figure 7-11.

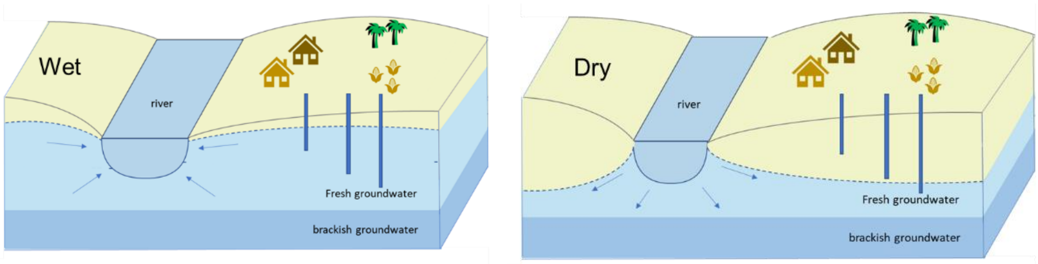


Figure 7-11: Interpretation of system condition in BT3 during wet and dry period.

7.5 Monitoring campaign water quality

An assessment of the water quality has been carried out in BT3 well4 (at the side of the dune) and BT3 canal. This investigation is necessary to understand the dynamics of water quality within the potential sites for installing an ASR pilot.

The surface water quality state is critical during the window of opportunity to inject the surface water into the aquifer at the end of the wet period (from November to December). The methods used in the monitoring are given shown in Table 12. To be able to inject surface water into the aquifer, the surface water quality must meet the Vietnam standards, or if not available the WHO standard to make sure that the surface water injected into the aquifer would not deteriorate the groundwater quality.

Table 12: The methods used for water monitoring and sampling.

Method	Parameter
Comprehensive sample with 8 cations and 6 anions	Electrical Conductivity (EC) pH Hardness Cations: Na^+, K^+, Ca^{2+}, Mg^{2+}, NH_4^+, Fe^{2+}, Fe^{3+}, Al^{3+} Anions: HCO_3^- , Cl^-, SO_4^{2-}, NO_3^-, NO_2^-, CO_3^{2-}

	Dry residue to determine the suspended-solids concentration
Contaminant Sample	COD_{KMnO4} , NH_4^- ' NO_2^- , NO_3^- , PO_4^{3-}
Fe sample	Fe^{2+} and Fe^{3+}
Heavy metal sample	As, Mn, Zn

The water quality monitoring effort focused on the BT3 site as the first results of the surface water quality analysis showed that ammonium and phosphate exceeded the thresholds for infiltration in the subsurface, while the dune area is quite big to store the injected water. More detailed monitoring was necessary to further plan a strategy to improve the water quality within the site that does not yet meet the water quality standards.

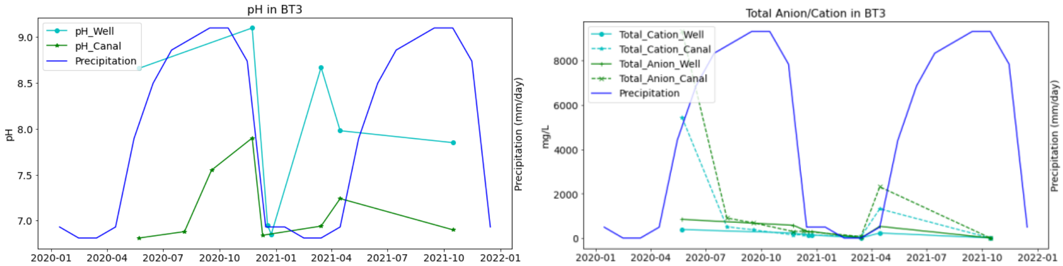


Figure 7-12: pH (left) and total anion and cation (right).

In the BT3 site, water samples were taken from the well and the canal. pH in the well is generally higher than in the canal, which indicates that the water in the well is not only affected by recharged water (Figure 7-13). The high pH in the wells can be caused by two different effects; either the pH in the groundwater is already higher or the pH gets higher due to interaction with the soil in the vadose zone during the wet period. During the dry season, the high pH might be influenced by the interaction with brackish groundwater in the bottom of the freshwater lens. The pH in the canal is higher only in the second half of the wet season and remains low throughout the dry period. An increase in pH at the beginning of the wet period is also observed.

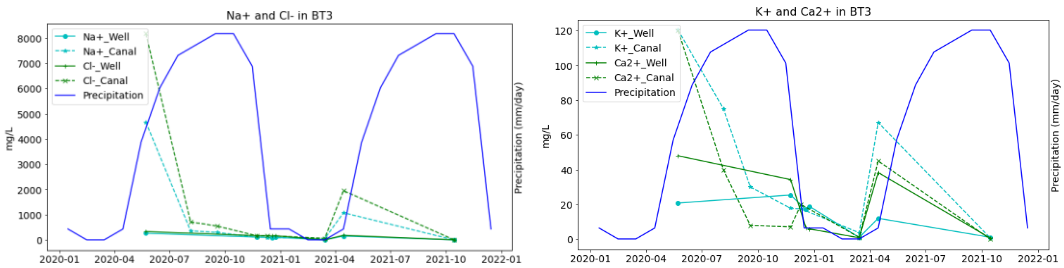


Figure 7-13: Na+ and Cl- (left) and K+ and Ca2+ (right).

In the canal water, the total concentrations of anions and cations is significantly higher in the beginning of the wet season and drop in the middle of the wet season. This might indicate that the high concentrations of anions and cations in the canal are mainly caused by the flush of the anions and cations in the system. Na^+, Cl^-, Mg^{2+}, SO_4^{2-} have the same trend as total anions and cations, with Na^+ and Cl^- as the main contributors to the ion concentration (Figure 7-14). K^+ and Ca^{2+} are also higher at the beginning of the wet period. In the middle of the wet season, the K^+ and Ca^{2+} concentrations in the well are higher than in the canal which indicates that K^+ and Ca^{2+} in the well do not originate from the surface water.

The high ion concentrations in the canal cannot be attributed to the high salinity of input water because the surface water is generally becoming more saline during dry season as there is a low volume of stream discharge into the ocean enabling the salinization to go further inland. However, the high ion concentration is observed at the beginning of the wet season only, and not during the dry season.

The Na^{+} and Cl^{-} concentrations in the well are also higher at the beginning of the wet period which indicates that the groundwater is also influenced by the canal water during the wet period. Not all the ions that are found in the groundwater originate from recharge.

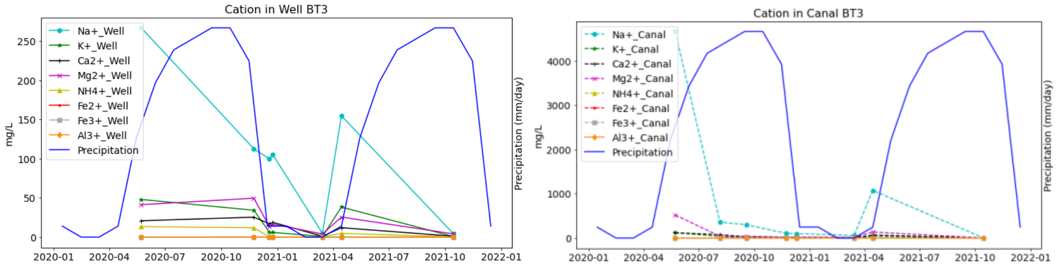


Figure 7-14: Cations in well (left) and cations in canal (right).

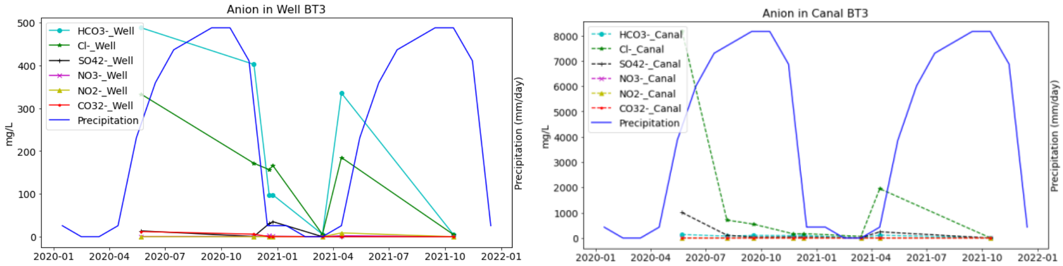


Figure 7-15: Anions in well (left) and anions in canal (right).

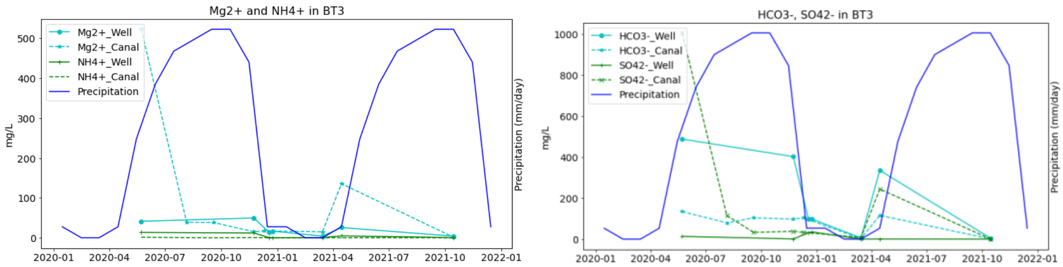


Figure 7-16: Mg^{2+} and NH_4^{+} (left) and HCO_3^{-} and SO_4^{2-} (right).

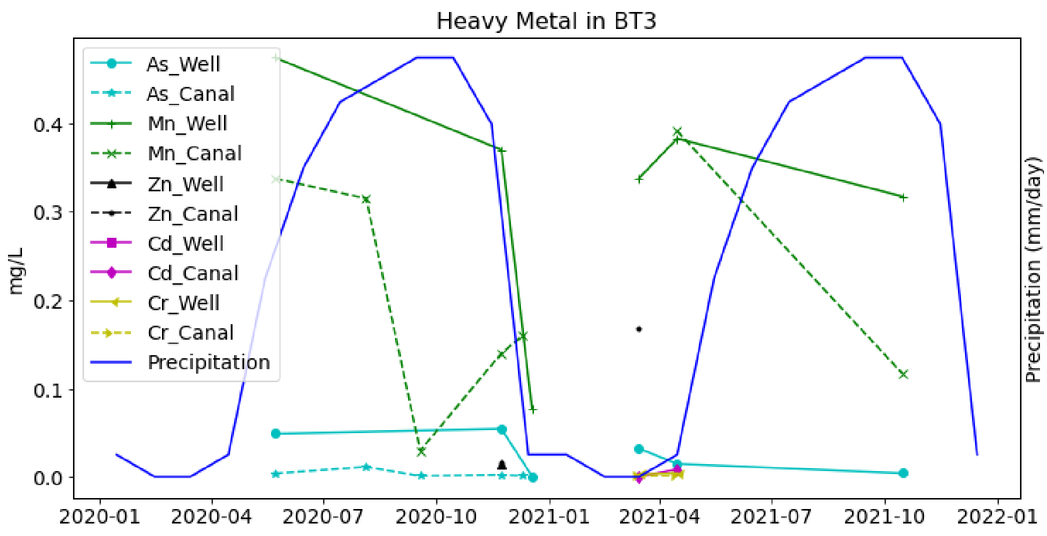


Figure 7-17: Heavy metal concentration.

The concentrations of total anions and cations in groundwater are lower at the end of the wet period and stay low during the dry period when there is no recharge (Figure 7-15 and Figure 7-16). The higher concentrations of anions and cations in the well during wet season (Mg^{2+}, NH^{4+}, HCO_3^{-}) (Figure 7-16) and the higher heavy metal concentrations (Figure 7-17), indicate that the groundwater anions and cations were influenced by the interaction with parent rock (more ions dissolved as the groundwater table is getting higher) rather than by the recharged water. This is also indicated by higher bicarbonate (HCO_3^-) concentrations in the wet period compared to the concentration in the canal (Figure 7-18), as the occurrence of bicarbonate in the aquifer is common, especially in the aquifer that was influenced by marine deposit, like in Ben Tre. It is also observed that HCO_3^- remains high during the wet season in the well and low in the canal for the entire period.

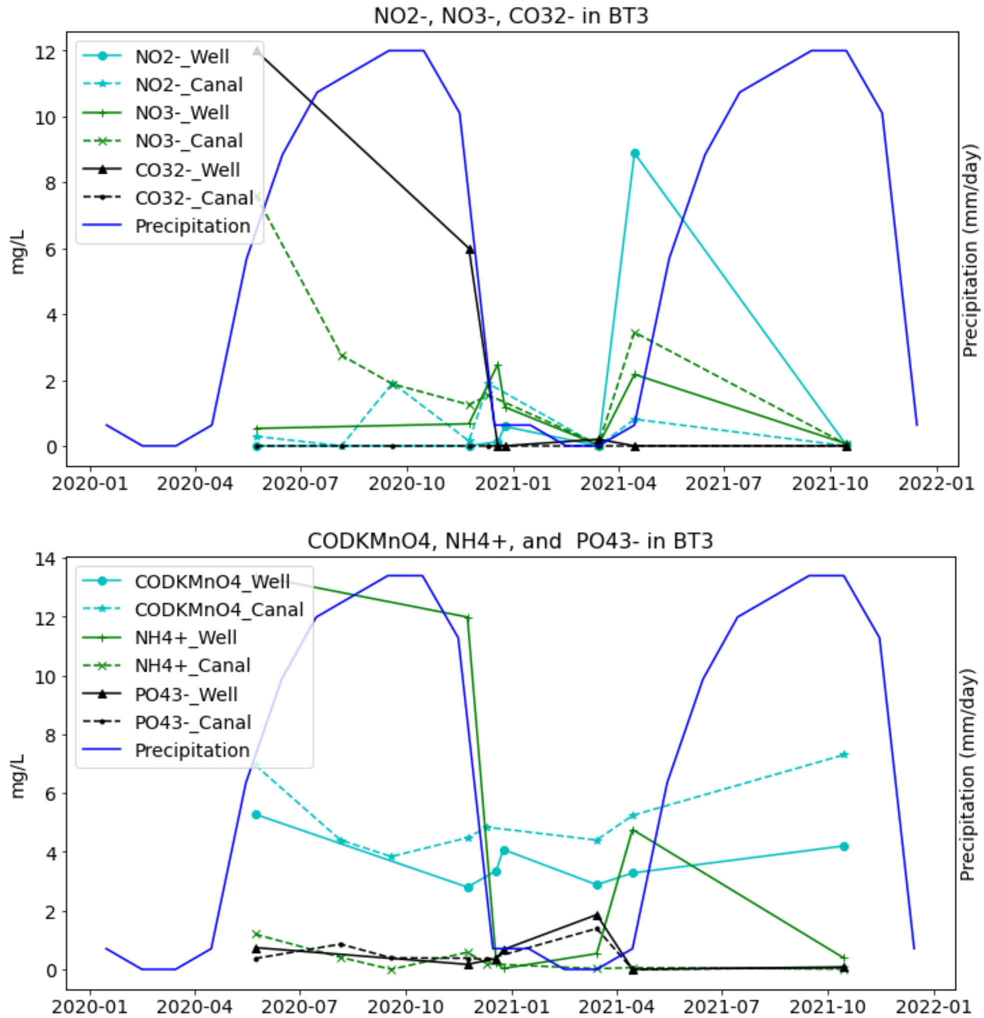


Figure 7-18: NO2-, NO3-, and CO32- (left) and CODKMnO4, NH4+, and PO43- (right).

NO^{3-} (nitrate) concentration in surface water is higher than in the well while ammonia concentrations (NH^{4+}) in groundwater are higher (Figure 7-18). This might be caused by the conversion of ammonia in surface water to nitrite and nitrate through the nitrification process, while ammonia levels in groundwater stay constant due to the anaerobic condition. CO_3^{2-} in the well is higher than in the canal indicating that it does not come from the surface water.

COD_{KMnO4} and PO_4^{3-} concentration remains constant throughout the wet and dry season, both in the well and in the canal and has similar concentrations. This indicates that this contaminant comes from recharged water and depends on the input water concentration.

In BT3, surface water influences the groundwater (Na^+, Cl^-), but not all ions in groundwater originated from the surface water. Mg^{2+}, HCO_3^-, Ca^{2+}, K^+, CO_3^{2-}, NH_4^+ and heavy metals concentrations are higher during the wet period due to interaction with parent rock.

Table 13 compares measured concentrations of ions in well and canal water versus various water quality limits. During the window of opportunity in BT3 (October to November), most ions in the canal do not simultaneously exceed concentrations in the well and water quality limits. For amonium (NH_4^+), nitrite (NO_2^-) and phosphate (PO_4^{3-}) the concentrations in the canal incidentally exceed concentrations in the well water and water quality standards, and this indicates the need for further monitoring. However, the risk of contamination of the groundwater is small and this is not considered that critical to pose an insurmountable barrier for ASR.

Table 13: Parameters exceeding water quality standard during opportunity window (October-December).

Parameter (mg/l)	Limit WHO (mg/l)	Limit Ground water (mg/l)	Limit Irrigation (mg/l)	Nov 2020 well	Dec 2020 well (18-12)	Dec 2020 well (24-12)	Oct 2021 well	Dec 2021 well	Nov 2020 canal	Dec 2020 canal (10-12)	Oct 2020 canal	Dec 2021 well
Na^+	50			113	100	105	4	69	105	100	4	86
K^+	20			34	7	6	1	5	7	20	0	7
Mg^{2+}	30			50	14	17	4	60	15	17	1	18
NH_4^+		1.000	0.900	11.41	0.185	0.015	4.78	0.715	0.555	0.22	0.15	1.68
Cl^-	250	250	350	172	157	166	5	233	163	173	5	144
SO_4^{2-}	250	400		0.67	30.51	35.10	0.03	27.31	38.13	33.2	0.63	30.2
NO_2^-	1	1	0.05	0.00	0.10	0.50	0.02	0.01	0.11	1.84	0.01	0.00
NO_3^-	50	15	10	0.58	2.60	1.27	15.00	0.69	1.19	1.28	1.28	2.00
PO_4^{3-}			0.300	0.170	0.370	0.670	0.08	0.020	0.380	0.34	0.06	0.110
Dry residue - 105ºC	500			696	448	466	671	671	445	465	446	446
Fe^{2+}	0.3			0.275	0.225	0.185	0.71	5.56	0.275	0.20	0.59	0.72
Fe^{3+}	0.3			0.245	0.070	0.175	0.45	0.385	0.150	0.18	0.20	0.07
As	0.01	0.05	0.05	0.055	0.001		0.00		0.003	0.00		
Mn	0.05	0.50	0.50	0.370	0.077		0.32	2.183	0.140	0.16	0.12	0.17

8 Study area Tra Vinh 2

8.1 Introduction

The Tra Vinh site (TV2 Long Son Commune) is located in the eastern part of the Tra Vinh province (Figure 8-1) which is one of the poorest areas in the Mekong Delta (International Fund for Agricultural Development (IFAD), 2014). Tra Vinh population often lack access to education, have lower incomes, limited access to financial services, lower market access, and own small parts of the agricultural land.

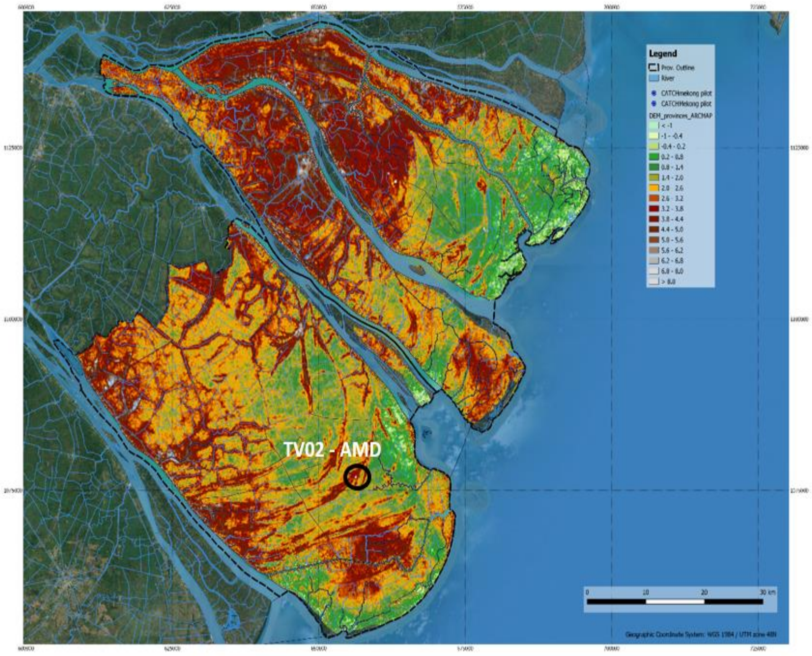


Figure 8-1 Location of the Tra Vinh site Long Son Commune.

The sand dune complex at this site is quite extensive, and farmers have land on top of the dunes and also rice fields in the lower areas. The area in the immediate vicinity of the field site is relatively high and sandy, with little to no surface water available. The International Fund for Agricultural Development has installed a surface water reservoir as part of the Adaptation in the Mekong Delta project. The pond has been built by the government and is linked to groundwater underneath the dune. The government is still working on the distribution system to utilize the pond water for agriculture. Since the pond was built, only the farmers living next to the pond were able to utilize the pond water, but since November 2019, a pilot test started to connect 10 to 12 farmers to the pond, with a solar pumping system.

A relative larger area of Tra Vinh is used to produce paddy rice, with a smaller portion for perennial crops like fruit trees and coconut trees and a smaller portion for aquaculture (Japan International Cooperation Agency, 2016). To deal with the increasing salinization in Tra Vinh, farmers near the coast are increasingly switching to shrimp production that uses brackish water (Thu and Populus, 2007). However, the problem of converting from paddy rice to shrimp farming is that the brackish water leaches to the nearby fields and is flushed into the canals, thereby polluting the area with brackish (Tho et al., 2008).

One of the solutions to cope with the salt water intrusion is to use brackish water in the dry season for shrimp production, and to cultivate rice during the rainy season. The salt accumulated in the dry season needs to be flushed away by rain, after which a rice crop can be produced. This is a so-called rice-shrimp rotation scheme. This is more sustainable for the quality of the water and soil and also reduces the risk of disease outbreaks during shrimp production. However, this method requires a large amount of freshwater to flush the accumulated salt in the soil and the water (Birkmann et al., 2012). In addition, rice-shrimp rotation scheme is not suitable to be applied in the dune area, as the shrimp farming requires silty soil that is not available in the sandy dune area. The impression of field site in TV2 is illustrated in Figure 8-2.

Figure 8-2: Impressions from the TV2 site.

8.2 Description of the local situation

Farmers in this area live quite far apart from each other and often own a piece of land on the top of the dune as well as a rice or grass field off the dune. The main source of water are shallow pumping wells. Out of 28 farmers, 27 only used pumping wells and one farmer used both a pumping well and a dug well. The shallow pumping-wells are on average 7.4 meters deep. Most farmers used a single point well, with only two of them having the option to combine a second point well to increase the discharge of the wells in the dry season. Several farmers reported a decrease in discharge from their wells and sometimes even had to wait for the well to fill up again during the dry season. Three farmers reported high salinity in their wells, but the water was still usable for their crops. The decrease of groundwater levels and increase in salinity happens in the months of February, March and April. Most farmers use their wells to irrigate their crops by hose, with some exceptions: two farmers use drip irrigation, one farmer uses buckets, two use micro-sprinklers and one farmer uses overhead-sprinklers.

8.3 Initial field work

8.3.1 Geology

The lithology of the uppermost 3 to 4 meters of the sand dune was determined by analysing core samples of 6 shallow boreholes (maximum depth of 4 meters) and two deep ones (maximum depth of 14m). The two deep boreholes were not enough to get an accurate estimate of the size of the dune system. The coring results indicate that this site is characterized by a largely, deep and uniform sand layer of well sorted very fine sand. This was observed across two dune structures spanning approximately 670m. Very few clay or sandy clay (maximum of 20cm thick) deposits were found on the shallow coring. These small layers do not appear to be significant or continuous across the dunes. The deep coring shows a thick clay layer, which is considered as a continuous base of the dune and an aquitard. Based on this boundary and varied surface elevation, the sand layer is approximately 7.4m – 6.2m thick. A detailed description of the geological field work can be found in Appendix A.3, p. 122.

8.3.2 Hydrology

A rain gauge placed next to the reservoir monitors the rainfall at this site since the 3rd of October 2019 and until the end of 2019 (Figure 8-3). The graphs in Figure 8-4 show the cumulative rainfall for the months October to end of November and end of November to middle of December 2019. Between the 3rd of October and the 5th of November, several small rainfall events were observed, and one larger event was observed on the 19th of October. The rain gauge recorded a cumulative rainfall of 100 mm for the month of October, 50mm of which fell on the 19th of October. The rest of October, November and the start of December are much dryer; the rain gauge recorded a cumulative rainfall of 30 mm for this latter period.

Figure 8-3: Rain gauge installed in TV2 site.

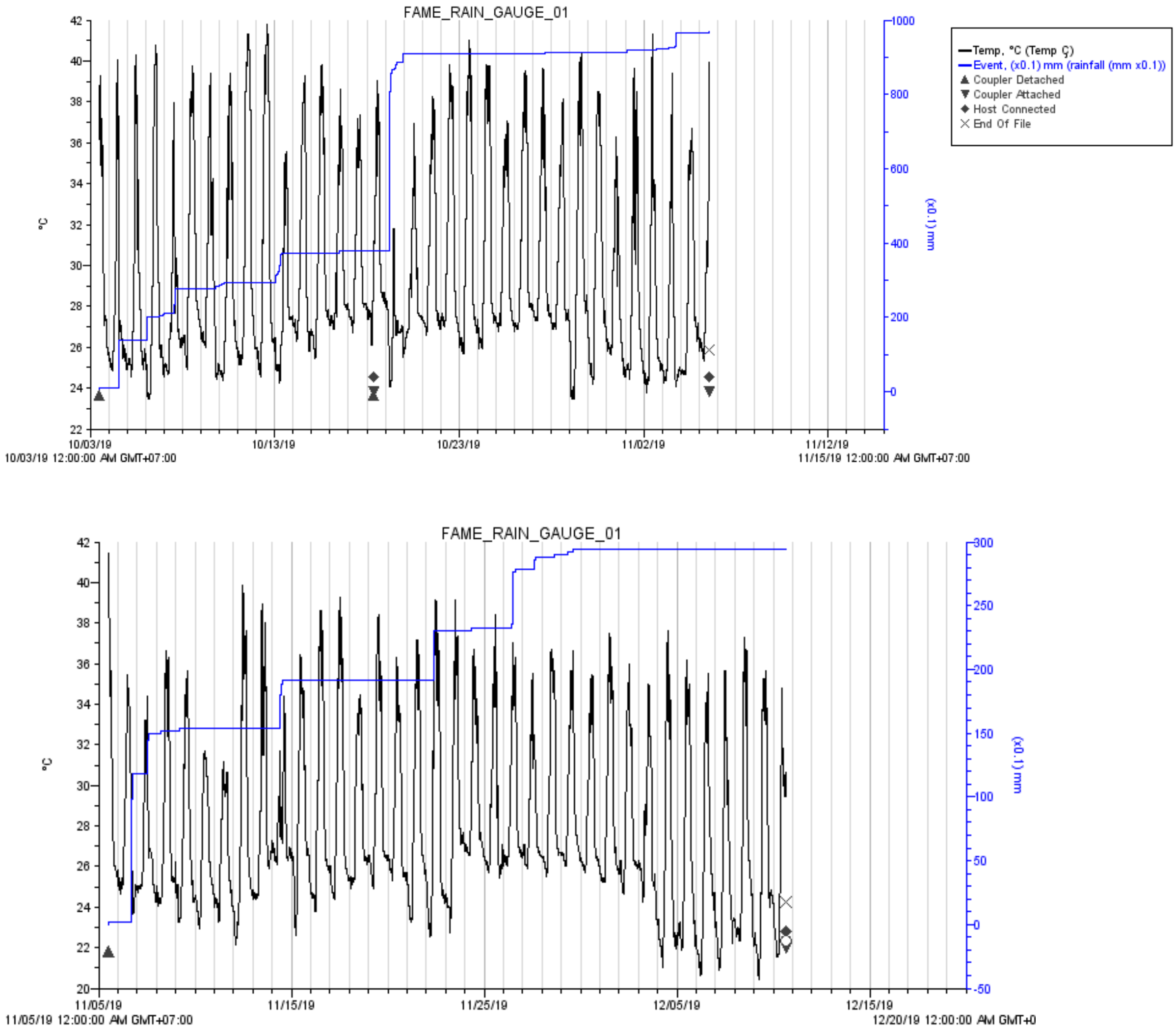


Figure 8-4: cumulative rainfall from the 3rd of October to the 5th of November (top) and from the 5th of November to the 11th of December (bottom).

Figure 8-5: Digital elevation model of the area, with legend (showing height in meters). Installed measuring devices are indicated with blue dots.

A groundwater level logging sensor was installed in Well 1 on the 3rd of October 2019. This well is located close to the AMD reservoir (Figure 8-5). Another sensor was placed in Well 2 on 16th of December 2019. A diver was also installed in the AMD reservoir between the 30th of October and the 10th of December 2019. Measurements from the longest running diver in Well 1, are shown in Figure 8-6. A slight rise in groundwater level from the 3rd to 19th of October was observed, with a short interruption between the 15th and 16th of October when the sensor was accidentally de-installed. There is a sudden rise on the 19th of October, and a steady decline from the 20th of November onward. In total there has been a drop of 27 cm in groundwater level over the months of October to December. Since the rain gauge registered quite some rain fall in October and an especially large amount on the 19th of October, this might explain the sudden rise in ground water level on the 19th of October.

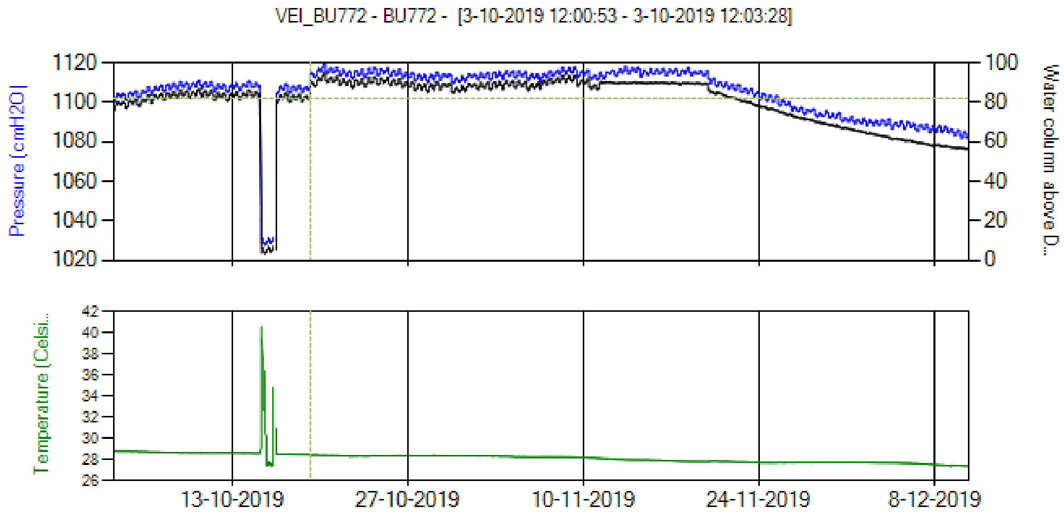


Figure 8-6: Water pressure recorded by diver in well 1.

The graph shown in Figure 8-7 shows the surface water level in the AMD reservoir between the 30th of October and 10th of December. A steady drop in water level is observable between the 22nd of November and the 3rd of December, after which the water level seems to stabilize again. This drop, of approximately 26 cm, is similar in timing and magnitude to the drop observable in the groundwater, indicating that these two systems are connected.

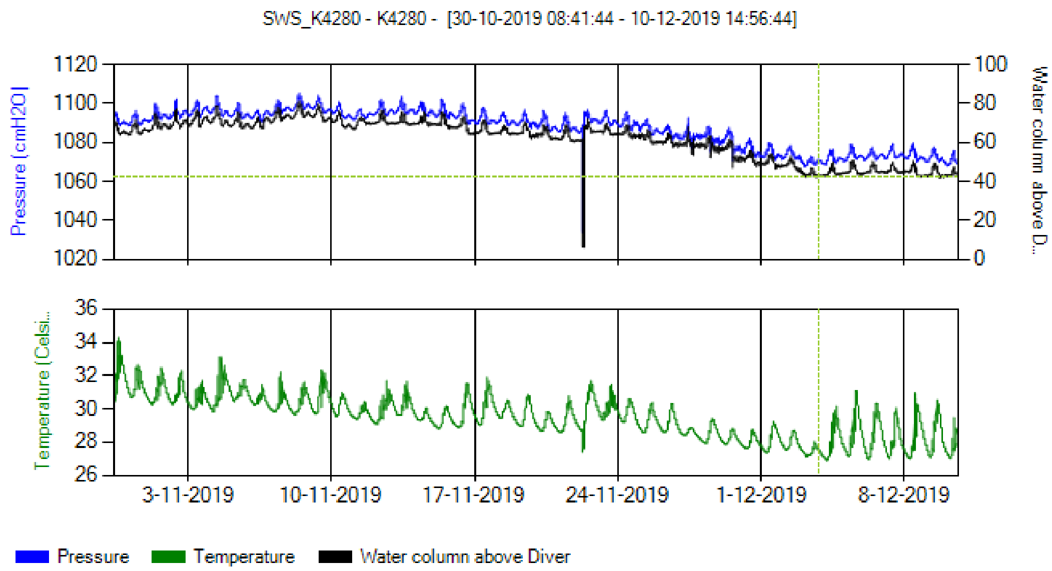


Figure 8-7: Water pressure recorded by diver in reservoir.

There is room in the sand lenses at this site to infiltrate freshwater in the months of November to December. Groundwater levels on the sand dune was declining from the end of November onwards.

8.3.3 Storage capacity

The volume per stretched meter is extrapolated perpendicular across the length of the sandy ridge structure which is taken as approximately 3km. The lowest average groundwater reading, was only found in 3 cores. This is not enough to extrapolate across the system with reasonable accuracy. The most reliable reading was the groundwater level, found in all coring locations. The most reliable results for the cross-sectional area is the surface to groundwater level. The ground water levels were taken in October, near the start of the dry season. This is also the zone that could be useable for infiltration of freshwater.

The base of the system is assumed to be the aquitard in the deepest core (Appendix A.2.4), and in order to estimate the cross-sectional area of sand in the system this is assumed to be continuous. This site is largest sandy ridge studied and has largest storage capacity of the three sites. The volume per stretched meter considering maximum (0.30) and minimum (0.25) porosity is listed in Table 14. In this site, groundwater levels fluctuate between 1 and 5 meters below surface.

Table 14: TV2 Cross sectional area and storage calculations for maximum and minimum effective porosity values.

TV2	Cross sectional area (m2)	Volume per stretched meter considering minimum porosity (m3)	Volume per stretched meter considering maximum porosity (m3)
Surface to groundwater level	864	216	259
Groundwater level to bottom of aquifer	697	413	495
Total aquifer	5000	1250	1500

8.3.4 Water quality

Water quality was measured in four locations across the dune; a small ditch and a dug-out pond to the west, the AMD reservoir and a dug-out pond on the east of the sandy ridge (Appendix A.3.8). Besides, the water quality of Well 1 and Well 2 was also measured. At each location, the electric conductivity was between 300 and 500 µS/cm in both the surface water and in the wells. This suggests there is no issue with salinity in this region.

8.3.5 Agriculture

The crops cultivated in TV2 differ between the rainy and the dry season. The schematic representation of the cropping system in the rainy season is illustrated in Figure 8-8 and the cropping schedule is listed in

Table 15. The figure shows 5 areas: area 1 is low and consists of rice fields and shrimp farms. The canals carry freshwater in the rainy season that is used for rice irrigation. The lower part of area 2 sometimes uses surface water, but the higher parts already use wells. In this area there are also coconut farms and rice fields, but also some seasonal fruit and vegetables. Also, farmers live on these slopes of area 2. In area 3 the dunes are a bit lower, possibly this is a dune pan. In the rainy season, farmers in this area grow rice twice without active irrigation. Rain is enough for the fields to fill up. Farmers say that the groundwater reaches above field level, this could be an indication that the shallow aquifer is filled up to its maximum storage. Area 4 represents the dune tops. The main crop during the rainy season is watermelon, which is cropped up to three times a year. The dune continues with area 5 which is similar to area 3 and eventually areas 2 and 1 towards the other end of the dune.

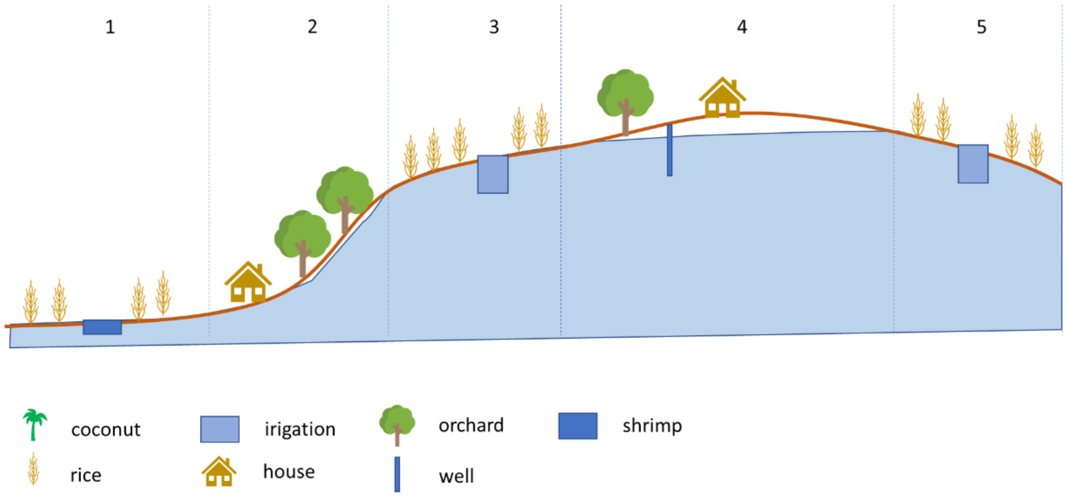


Figure 8-8: Schematic cross-section of the dunes during the rainy season and early dry season.

Table 15: Schematic overview of an average cropping scheme in normal rainy season, with average amount of precipitation

TV2	April	May	June	July	August	September	October	November
1	Shrimp	Rice / Shrimp	Rice / Shrimp	Rice / Shrimp	Rice / Shrimp	Rice / Shrimp	Rice / Shrimp	Rice / Shrimp
2, 4, 5	Water-melon	Water-melon	Water-melon	Water-melon	Water-melon	Water-melon	Water-melon	Carrot
3	-	-	Rice	Rice	Rice	Rice	Rice	Rice

The schematic representation of the cropping system in dry season is illustrated in Figure 8-9 and the cropping schedule is listed in
Table 15. During dry season, in area 1, the salinity of the surface and groundwater is slowly increasing. The water is for the biggest part of the time still usable for crops and the quality is sufficient for irrigation. Saline water infiltrates the canals and groundwater and replace more and more freshwater through the dry season. In normal years the surface water is not sufficient in quality and quantity in December and January, with February getting increasingly worse. In area 2, the groundwater level is decreasing. On the slopes, towards the canals in the low area, the groundwater in the wells gets saltier. The area starts to rely on the groundwater for irrigation through waterholes and pumping wells. Area 3 is bare for the whole dry season, and there are no active wells in this area. In area 4, people start to grow almost exclusively peanuts and carrots. When there are predictions of very dry years, the area where it is grown, is made smaller to make sure that the farmer can irrigate their crops enough. The pumping wells in Tra Vinh are located on this area and reach deeper than the waterholes in Ben Tre. The dune continues with alternately areas 3 and 4, and eventually 2 and 1.

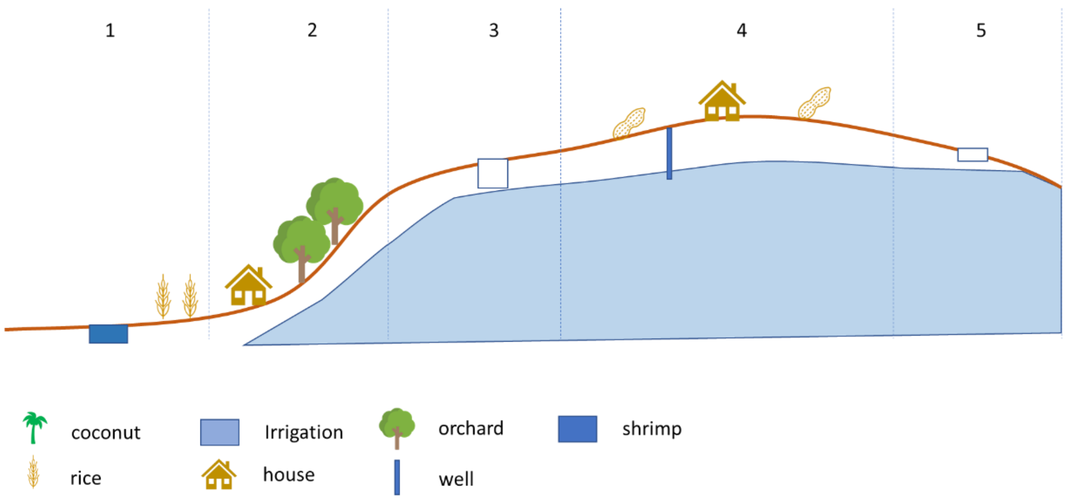


Figure 8-9: Schematic cross-section of the dunes during the early dry season till the end of February.

Table 16: Schematic overview of an average cropping scheme in a normal start of the dry season, with no water shortage in the wells.

TV2	December	January	February
1	Rice / Shrimp	Rice / Shrimp	Rice / Shrimp
2, 4	Carrot, Peanut	Carrot, Peanut	Carrot, Peanut
3	-	-	-

The irrigation rate of different crops in TV2 is listed in Table 17. The period of harvesting, total irrigation per harvest season, evapotranspiration, and efficiency of irrigation in TV2 is listed in

Table 18.

Table 17: Crops grown in the dry season per field site, with the months they are grown in normal years.

	Months	Irrigation (mm/day)
Peanut	December – February	11.4
Carrot	December – February	11.4

Table 18: Water used and irrigation efficiency of several crops in an averaged cropping schedule in TV2.

Crop	Start of plantation	Days till harvest	Irrigation requirements (mm/growth season)	Average water use or evapotranspiration (mm/day)	Efficiency of irrigation (%)
Peanut	December	96	396.3	4.1	41.7
Carrot	December	45	160.9	3.6	36.6
Carrot	January	45	196.2	4.4	44.6
Rice	September	120	361.6	3.0	100

8.4 Groundwater monitoring

After the first assessment of the site hydrogeology carried out in 2019, another groundwater level sensor was installed in January 2020 in Well 2 to monitor the dynamics of groundwater and evaluate the potential for the installation of an ASR pilot. Since no barometer was installed in this area, the pressure data was compensated with the measurements taken by a barometer from the national observation network located 11km away from TV2.

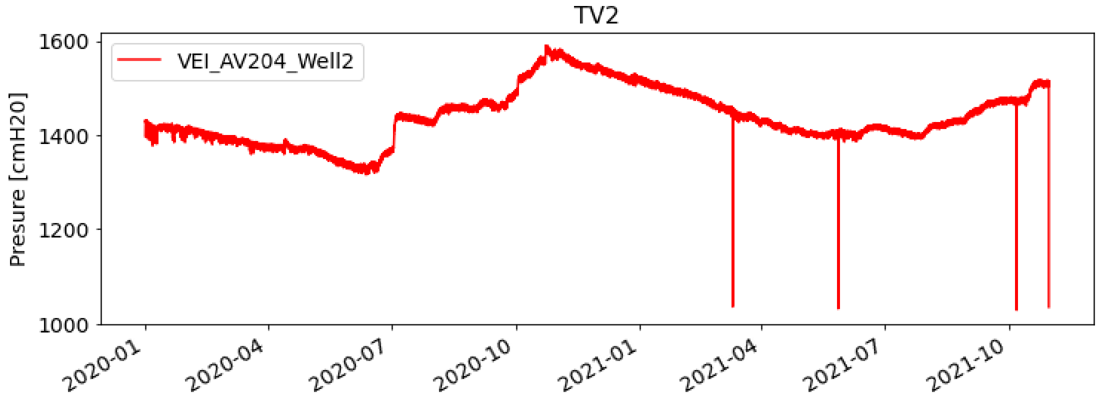


Figure 8-10: Uncompensated water pressure in Well 2 TV2, recorded in well 2.

From the uncompensated data in TV2, the decrease in groundwater pressure is observed from January 2020 until mid-June 2020 (Figure 8-10), as expected to happen in the dry season. At the end of July, the groundwater pressure increases until it reaches the peak in October and then the groundwater pressure decreases again at the end of October until the end of August 2021, when it starts increasing again until the end of the observation period (October 2021).

A sudden change of 67.5 cm pressure is observed in early 1st to 3rd of July 2020. As the increase in groundwater pressure is too high for one day fluctuation, this may indicate that in July 2020, the diver was moved 67.5 cm below its original location. After compensating the groundwater pressure to the atmospheric pressure and recalibrating the diver to its original location, the groundwater level depth from the surface can be observed in Figure 8-11. The groundwater level fluctuates between 1.3 meters below surface at the end of October, and more than 3 meters below surface in July.

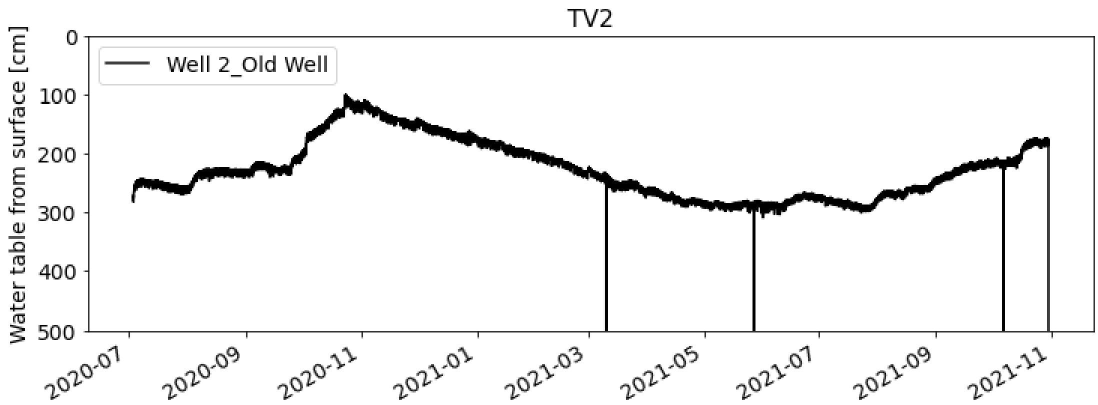


Figure 8-11: The water table depth relative to the surface in TV2 site, recorded in well 2.

The total groundwater drop from October 2020 to July 2021 is about 200 cm. Since the end of the wet season by the end of October, there is a steady decline of the groundwater level.

The interpretation of the dynamics of the shallow groundwater in TV2 for both wet and dry conditions is illustrated in Figure 8-12.

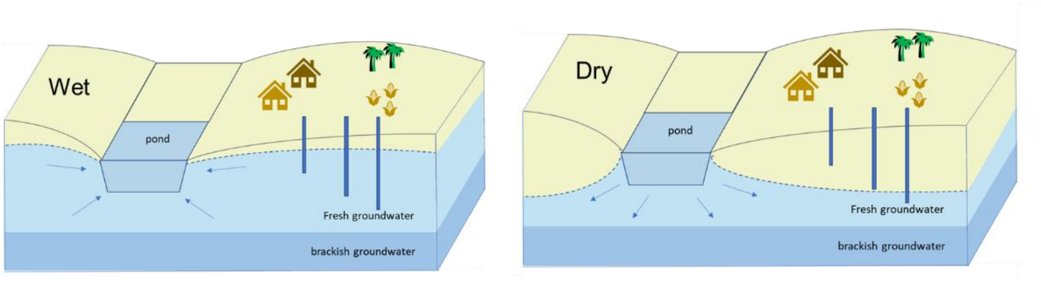


Figure 8-12: Interpretation of system condition in TV2 during wet and dry period.

8.5 Monitoring campaign water quality

Similar to the BT3 site, a water quality monitoring campaign was conducted at the TV 2 site. The camping consisted of sampling the reservoir and the Well 2 in October 2020 and in January, April, July, and October 2021. The parameters measured were: pH, anions and cations, dry residue, contaminants, Fe, and heavy metals.

The pH in the pond during the wet period in 2020 was high, while in 2021, the pH in the pond was much lower and also lower than the pH in the well (Figure 8-13).

Total anion and cation concentrations during the wet season were higher than in the dry season both in the pond and in the well (Figure 8-13). This indicates that there is little of surface water and groundwater during the dry period. The total cation and anion concentrations in the well during the wet season were higher than in the pond (Figure 8-14). This indicates that the majority of ions in the groundwater did not come from the pond, but from the interaction between the groundwater and the aquifer sediment. This is also reflected in Na^+, Cl^-, and K^+ concentrations in the groundwater, which were higher in the well during the wet period (Figure 8-14).

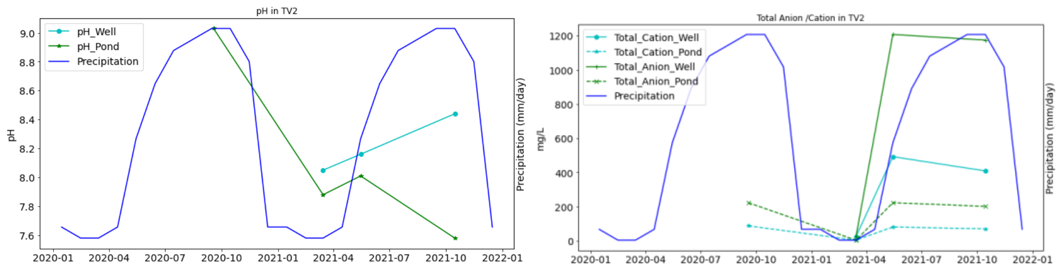


Figure 8-13: pH (left) and total anion and cation (right).

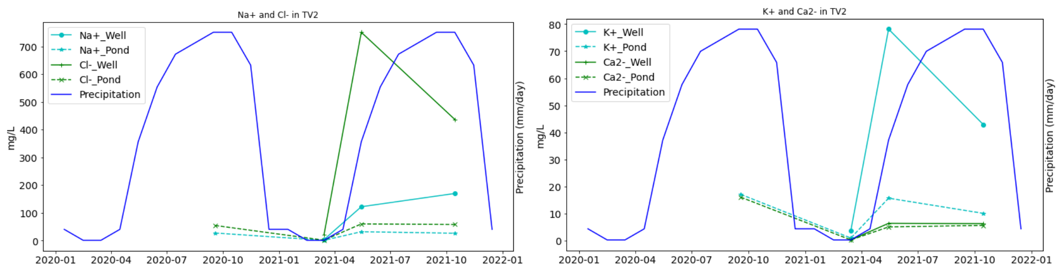


Figure 8-14: Na+ and Cl- (left) and K+ and Ca2+ (right).

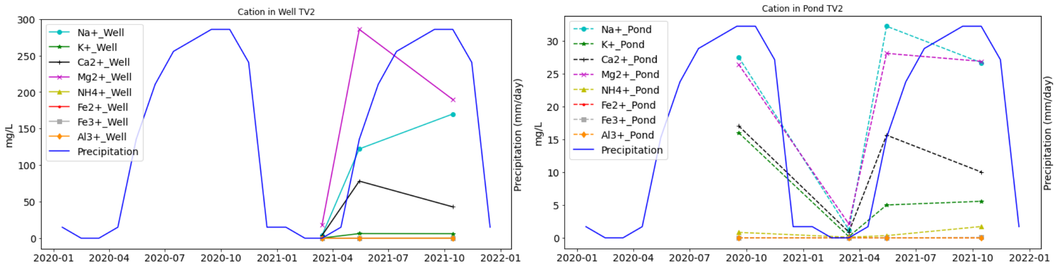


Figure 8-15: Cation in well (left) and cation in canal (right).

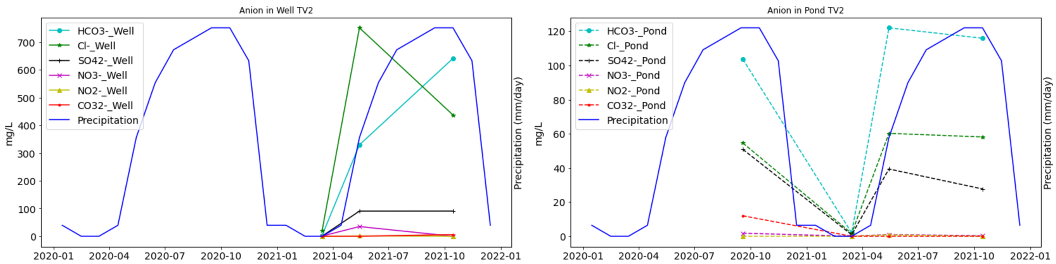


Figure 8-16: Anion in well (left) and anion in canal (right).

The main cations in groundwater and pond water during the wet period are similar, namely Mg^{2+}, Na^{+}, and Ca^{2+} with the absolute concentration in the well significantly higher than in the pond (Figure 8-15). The main anions in groundwater and pond water during the wet period are also the same, namely HCO_3^-, Cl^-, and CO_3^{2-} (Figure 8-16). This might indicate that the groundwater may flow towards the pond during the wet period, since the concentrations in groundwater are significantly higher than in the pond.

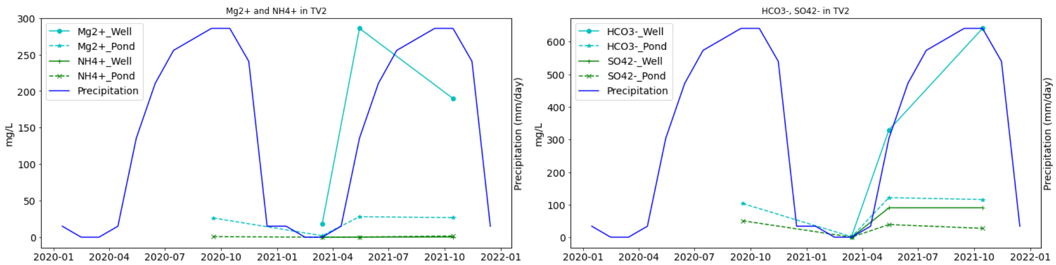


Figure 8-17: Mg^{2+} and NH_4^+ (left) and HCO_3^- and SO_4^{2-} (right).

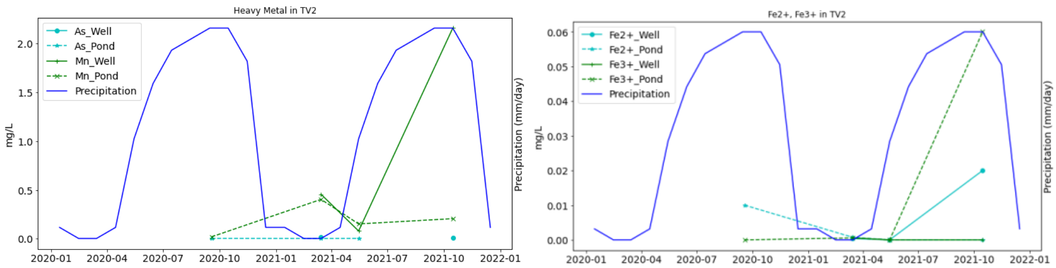


Figure 8-18: Heavy metal (left) and Fe^{2+} and Fe^{3+} (right).

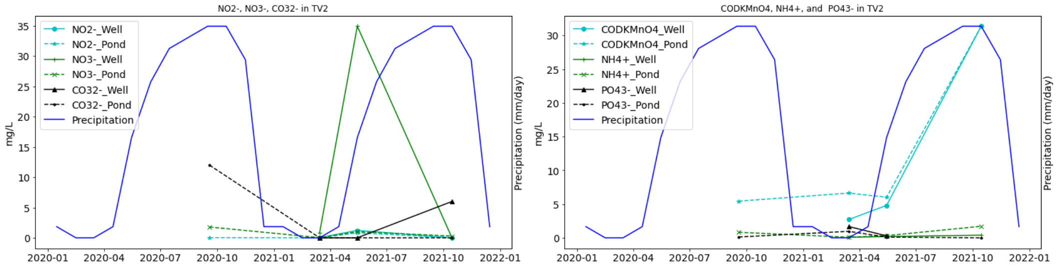


Figure 8-19: NO_2^-, NO_3^-, and CO_3^{2-} (left) and COD_{KMnO4}, NH_4^+, and PO_4^{3-} (right).

In general, ion and heavy metal concentrations in the groundwater were higher than in the pond. For Fe^{2+} and Fe^{3+}, the behavior looks rather complex (Figure 8-18), which can be explained by the sensitivity of these ions towards changing redox potential. However, overall, the concentrations of Fe^{2+} and Fe^{3+} are low. The concentration of COD_{KMN04} is comparable between pond and groundwater (Figure 8-19), that indicates this contaminant travels to both systems.

As groundwater generally has higher concentrations of ions and contaminants, in TV2, the risk of polluting groundwater by infiltrating water from the pond, is small compared to BT2 and BT3. From the cations, anions, and pesticide analysis, the quality of the pond and groundwater is such that no problems are expected during infiltration.

Table 19: Parameters exceeding water quality standard during opportunity window (month October). Grey table represents the value exceeding the water quality standard.

Parameters (mg/l)	limit WHO (mg/l)	Limit Groundwater (mg/l)	Limit Irrigation (mg/l)	Oct 2021 (well)	Oct 2021 (pond)
Na^+	50	-	-	170.00	26.67
Mg^{2+}	30		-	189.82	26.87
NH_4^+		1.00	0.90	0.40	1.72
HCO_3^-	500	-	-	640.71	115.94
Cl^-	250	250.00	350.00	436.74	58.14
Dry residue	500	-	-	1417.00	271.00
COD_{KMnO4}	10	-	-	31.36	31.36
Mn	0.05	0.50	0.50	2.16	0.21

8.6 Modelling

A modelling study was conducted to evaluate the optimum ASR design in sand dune area in the MKD by a student from Utrecht University, Hanna Verduijn (Verduijn, 2020). This was done by creating a 3D-variable-density groundwater and coupled solute transport model, using iMOD Water Quality (https://oss.deltares.nl/web/imod). Various ASR designs with the same size of plot (600 by 600 m) were evaluated, with either vertical or horizontal extraction wells. Additionally, the effect of spacing between infiltration wells and the infiltration rate were evaluated. Design 1 incorporates horizontal infiltration well and vertical extraction well. Design 2 incorporates horizontal infiltration and extraction well.

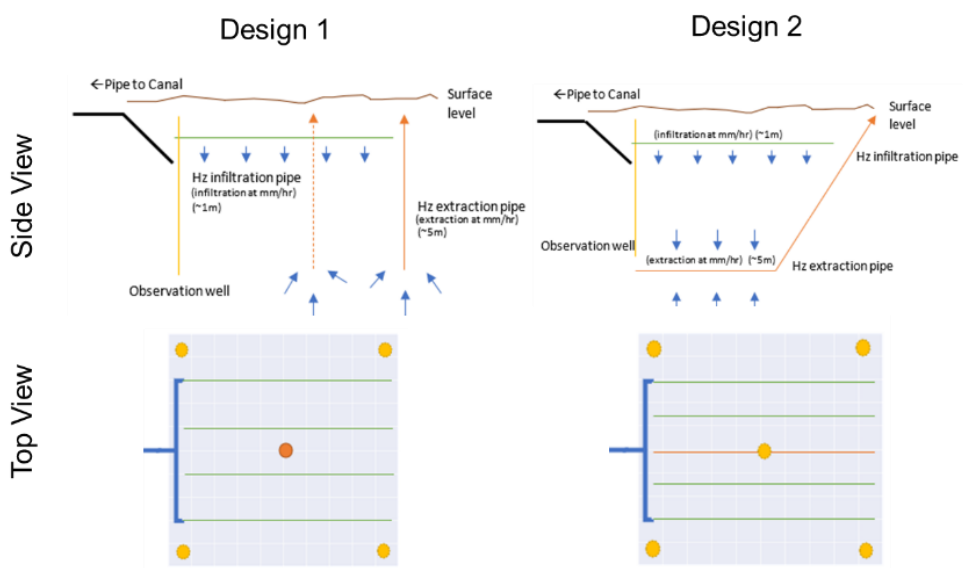


Figure 8-20: Designs compared in modelling to determine optimum pilot configuration. Design 1 incorporates horizontal infiltration well and vertical extraction well, design 2 incorporates horizontal infiltration and extraction well.

8.6.1 Method

Scenarios were developed for design 1 and design 2 based on different combination between rate of infiltration and spacing of infiltration well. Scenario 1 is the scenario where rate of infiltration is low (0.0056 m/d) with near spacing (4m). Scenario 2 is the scenario where rate of infiltration is low (0.0056 m/d) with far spacing (8m). Scenario 3 is the scenario where rate of infiltration is high (0.0022 m/d) with near spacing (4m). Scenario 4 is the scenario where rate of infiltration is low (0.0022 m/d) with far spacing (8m). The modelling result for these 4 scenarios were then compared to decide on the best design for the shallow ASR pilot. As for design 3, different number of wells were compared to analyse the best well distribution under design 3 set up.

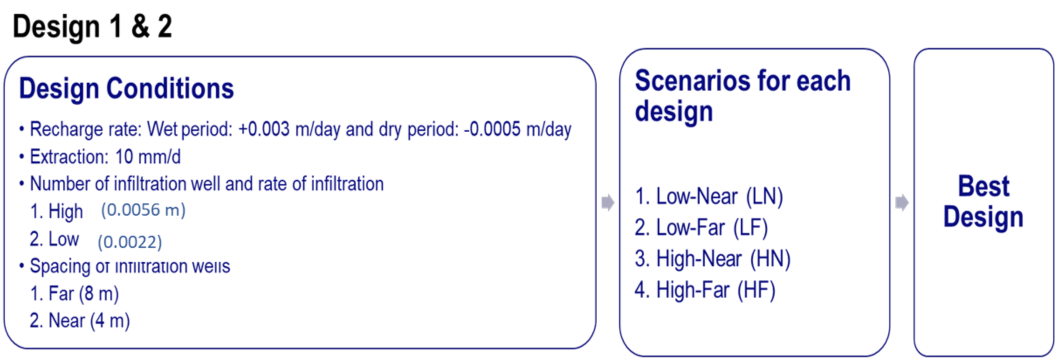


Figure 8-21: Overview of scenarios for design 1, and 2 in order to determine the best ASR design.

After deciding on the best design, a model developed for the TV2, based on its hydrogeology and agricultural practice.

8.6.2 Results

The result shows an increase in head at the end of the dry period compared to the scenario where there is no groundwater extraction and ASR infiltration (reference scenario as blue line in Figure 8-22). The salinity concentration between design 1 and 2 only differs slightly. Maximum chloride concentration for both designs is around 0.27 g/L for high rate infiltration and 0.18 g/L for low rate infiltration. These values are still within bounds of salinity tolerance of the crop. Horizontal drainage spacing has very small influence on the increase of head.

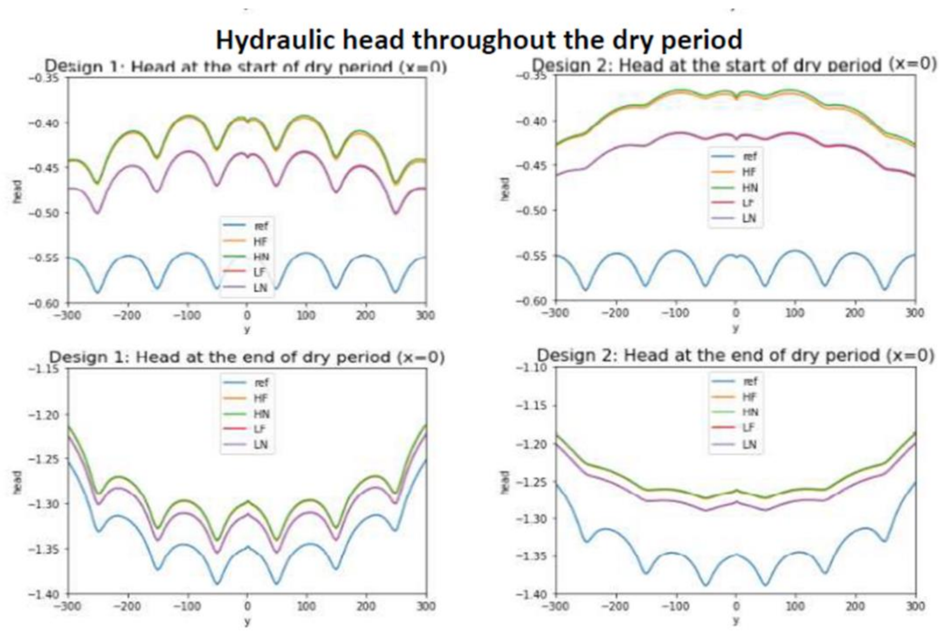


Figure 8-22: Hydraulic head (m) model result for design 1 (left) and design 2 (right).

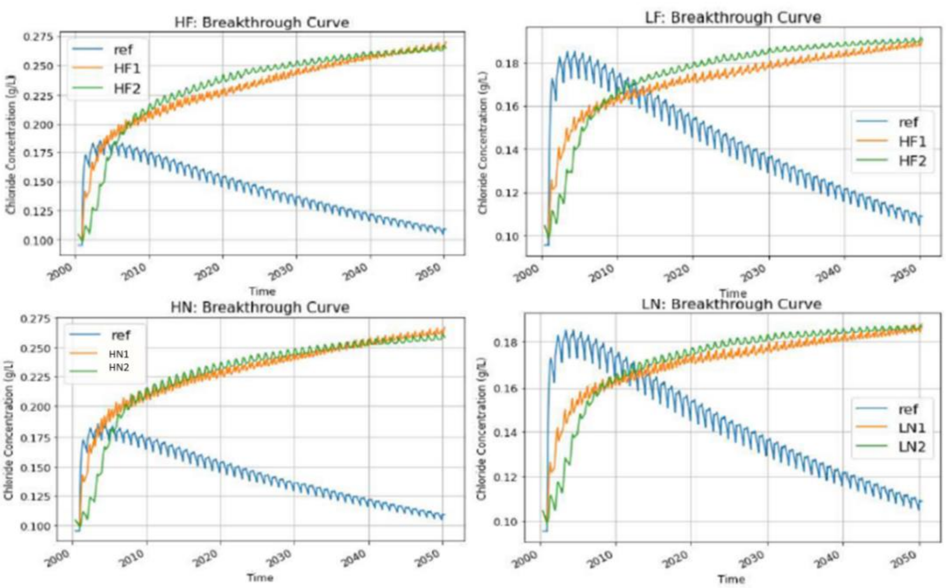


Figure 8-23: Concentration model result for reference case (no ASR), design 1 and 2 for the scenarios: high-far (upper left), high-near (lower-left), low-far (upper-right), and low-far (lower-right).

Design 1 and 2 shows little different in hydraulic head and concentration result. 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 has already removed. The modelling shows that approximately 20% of the volume that was infiltrated can be found back in the groundwater system. A large part of the fresh groundwater volume is drained by the drainage system or by the surface water system during the dry period. Given the total plot size of 600*600m^2, an infiltration rate of 0.0056m/d for the duration of one month (30days), this ends up to a bit more than 12,000 m^3.

Design 2 was then applied to TV2 condition. The result shows that the model is sensitive to the hydraulic conductivity value (Figure 8-24). As the monitoring groundwater data is available (section 8.4), the hydraulic conductivity of scenario Alt1 (4m/day) is selected as it results in the groundwater head at the end of dry closer to the observed head. The model shows a head elevation of about 0.55m at the center of the dune in TV2.

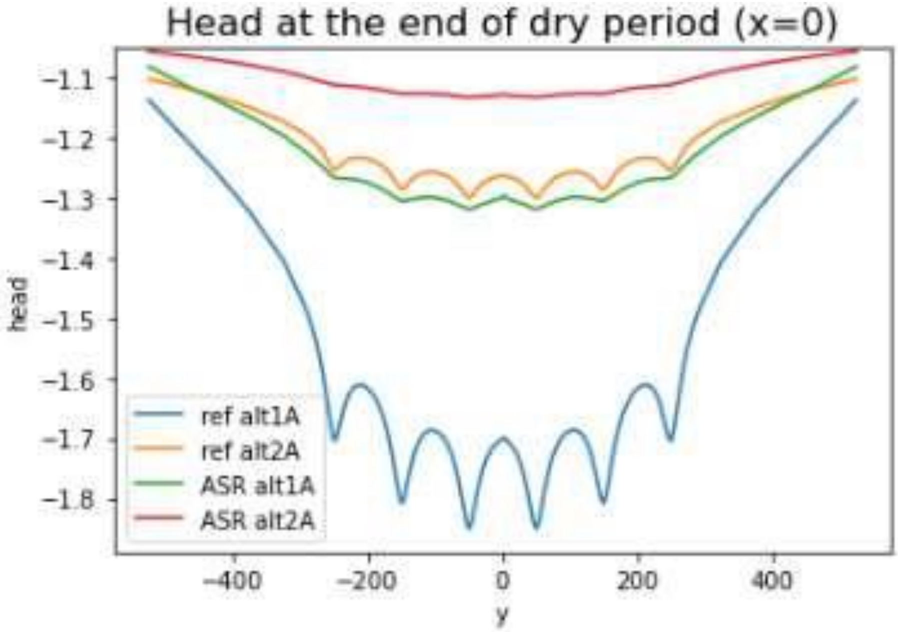


Figure 8-24: Hydraulic head in an y-transect at the end of the dry period with only groundwater extraction in TV2 site. The cases with symbol alt1 are for the model with a horizontal conductivity of 4m/d, for alt2 this is for the model with a horizontal conductivity of 16m/d.

The study showed that both design 1 and design 2 can effectively create a water buffer in the dry period. 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.

The spacing of the infiltration wells was found to have no effect on the hydraulic head throughout the dry period nor on the concentration. Therefore, far spacing is preferred to reduce the cost of well installation.

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 only a few centimeters, the low infiltration rate scenario is preferred.

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 potential of ASR solutions in increasing the water security on a local scale in the Mekong Delta.

8.7 Aquifer Storage and Recovery design

Based on dune hydrogeology and modelling work, the ASR system proposed is a shallow system which includes horizontal drainage pipes for the injection, and vertical wells for extraction. The ASR was designed to achieve higher groundwater level in dune area during dry season as depicted in Figure 8-25.

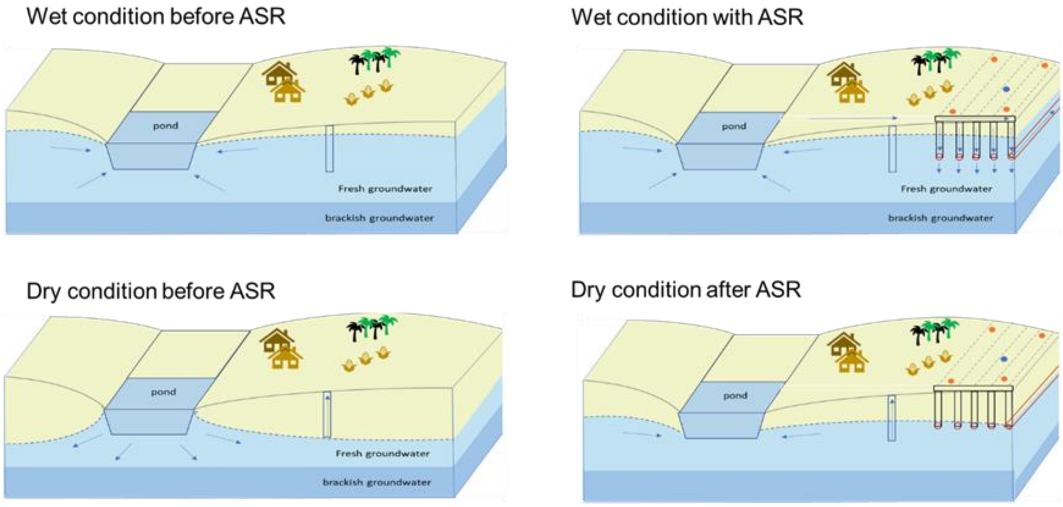


Figure 8-25: Conceptual model of ASR implementation effect on groundwater system in wet and dry condition.

The proposed injection well and monitoring well schematization is illustrated in Figure 8-26. The system for one plot consists of 5 infiltration horizontal pipes with pump hose, 4 monitoring wells with divers (in orange in the schematization), and 1 monitoring well with CTD (in blue) diver to monitor salinity besides groundwater level. Injection wells are linearly placed with 6 m distance between them. The monitoring wells with divers and CTD diver are placed in between the horizontal injection.

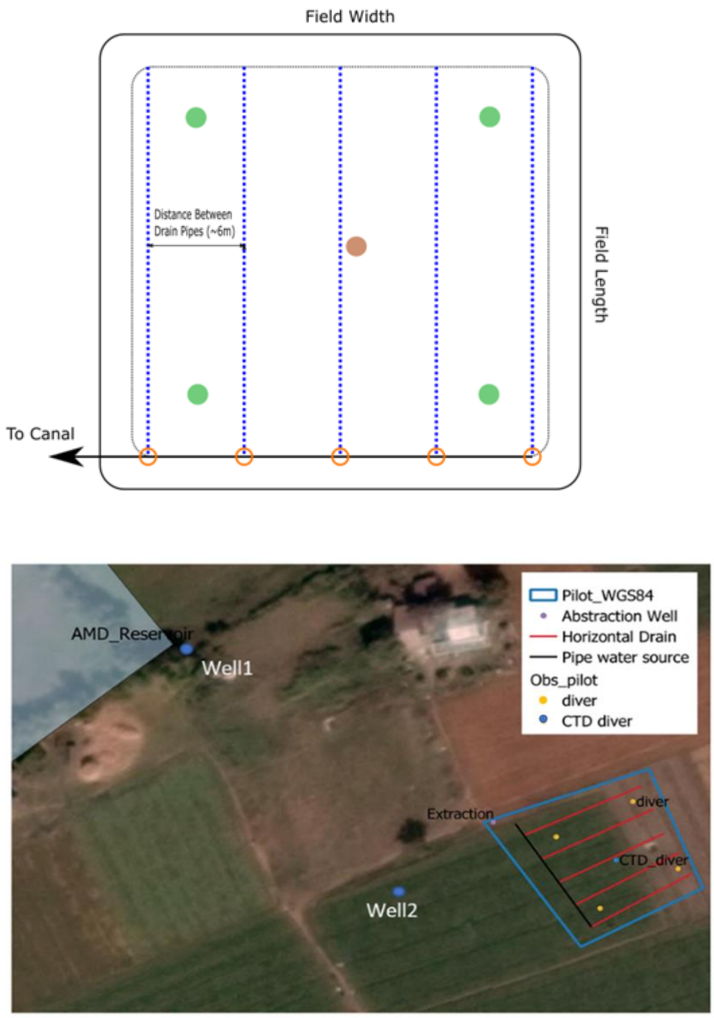


Figure 8-26: Design of horizontal injection wells and monitoring wells plot.

The horizontal drainage pipes acting as injection wells are placed at 1 m depth below the surface by removing the soil materials first. The horizontal drainage pipes must be wrapped either by coconut wrap, or pvc with holes drilled in the bottom. The gravel or stone larger than the pipe holes is then used to fill the surrounding drainage pipes (15 cm around the drainage pipes). If PVC is used instead of coconut wrap, the landscaping fabric is required in between the gravel / stone backfill and the top backfill from the materials that was removed (Figure 8-27). For the pilot, infiltrated water can be taken from the well close to the pilot. For the future community implementation, the water for the infiltration can be pumped from the AMD reservoir. This reservoir is filled partly with groundwater and partly with rainwater.

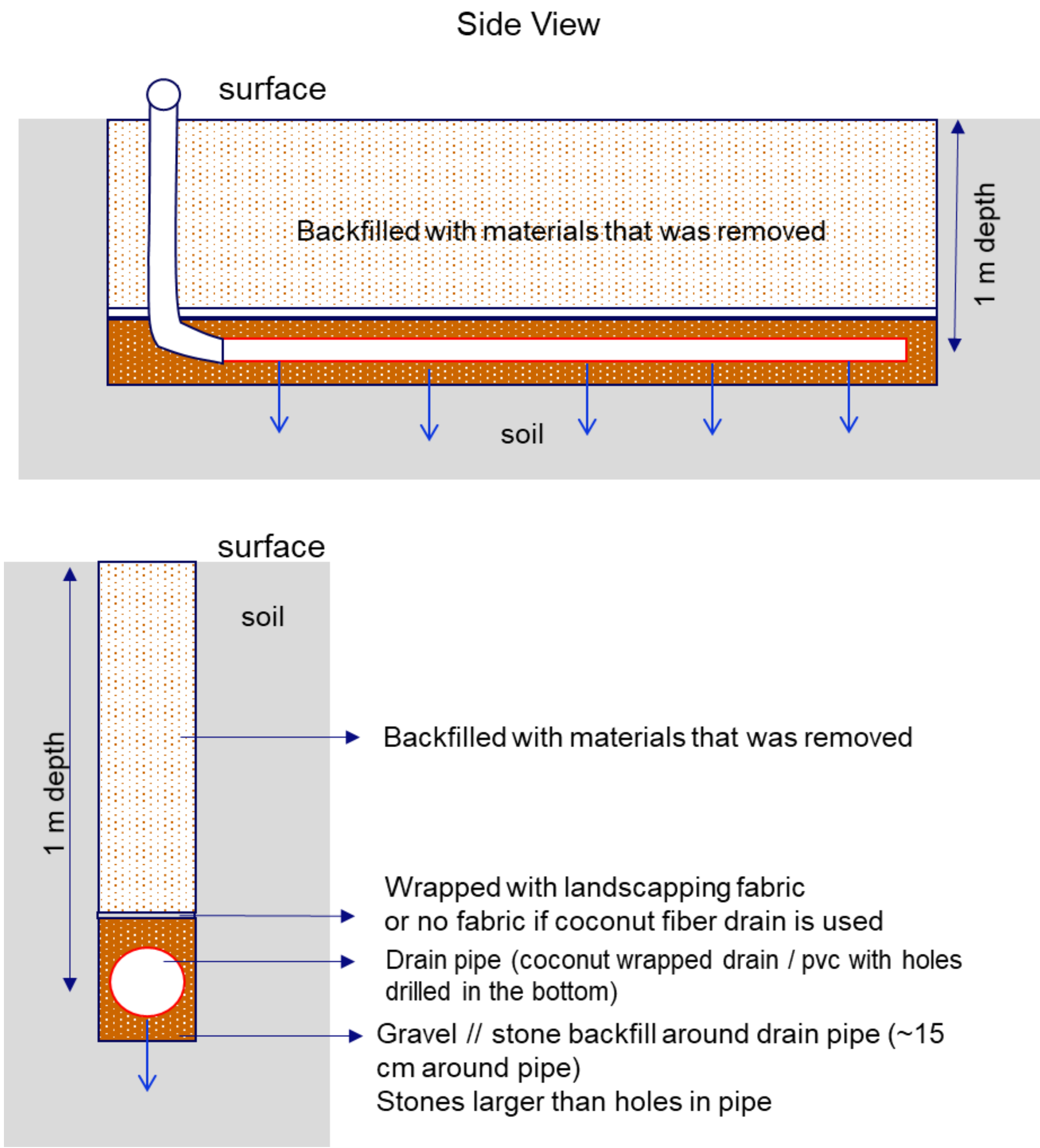


Figure 8-27: Horizontal Injection well design to be implemented in Tra Vinh site – ASR.

8.8 Pilot implementation

The implementation of the installation of an ASR pilot system is carried out from October 11th to October 13th, 2021. Due to the complicated situation of the Corona virus 2019 epidemic in the Mekong Delta, to speed up the installation of the system, more than twenty local workers have been mobilized by the project and under the direction of a team of experts experienced in PVC system installation, gravel wrapping, and geotextile wrapping before backfilled with hundreds of cubic meters natural sand material that was removed to return the ground as it was originally for farming and cultivation of farmers.

Figure 8-28: Pilot implementation at TV2 (Long Son Commune, Cau Ngang district, Tra Vinh).

One-meter-thick soil layer dug up is homogeneous fine sand composition. At the time of construction, there is no groundwater level at this depth. After the soil was dug up to a design depth (minus one meter), the geotextile is spread, the first fifteen centimes thick rock layer is wrapped, then five-horizontal well system is installed, then the next 15 rock layer is covered. The geotextile is folded before returning the full volume of natural sand.

The Solar pump system and the PVC transportation PVC pipe (diameter of 21mm) bring water to the pilot are fully installed. System of 3 solar panels is fixed on the roof of the house. After stable operation, the solar pump is set with a protection system and a shut-off device to use it to interrupt operation at night so that the pump can operate sustainably. After the equipment is fully installed, the water from reservoir is pumped and flows through the PVC pipe to the pilot area, the water flows at a rate of 2 m3 for 1 hour, through observation at the vertical PVC well, the first point of the Pilot system, showing strong water flow and very fast water consumption indicating that water has been absorbed very quickly into the horizontal drainage pipes acting as injection wells. Then water go to aquifer system through the gravel and textile system, this can be confirmed as an initial success for the ASR Pilot.

Figure 8-29: Set up the monitoring wells plot with both groundwater and quality (EC).

In parallel with the installation of an ASR pilot system, 6 monitoring points were installed, in which divers were installed in 3 observation wells to monitor groundwater level, CTD diver is installed in 2 observation wells to monitor groundwater level and EC, and another CTD diver was installed in AMD reservoir to monitor both EC and water level. All six devices were officially recording from October 13, 2021.

The results of the drilling and full lithological sample taken at the pilot site show that the stratigraphy of the boreholes is basically uniform. The composition of fine grey-yellow sand is distributed from the surface to a depth of 5.0 m; from 5.0 to 7.9 m the composition is grey-green fine-grained sand; from 7.9 to 10 m is a grey-blue clay layer. Based on the stratigraphy, the observed borehole structure is as follows: from +0.3m to 6.5m is set a 60 mm diameter PVC pipe, from 6.5-7.5m is a 60mm diameter filter PVC structure; from 7.5-7.8 is a settling PVC structure, from 7.8-10 filled with bentonite clay. All observation wells are pumped and washed the screen by the compressor until the groundwater is completely clean. Then devices (CTD-diver and Diver) were officially installed to monitor of groundwater pressure and EC.

8.9 Pilot monitoring result

8.9.1 Water quality in pilot

The cation and anion level in reservoir, well1, well2, well3, well4, and well5 are low and under Vietnam maximum standard. Therefore, the reservoir water is safe enough to be injected to the shallow sand dune lens.

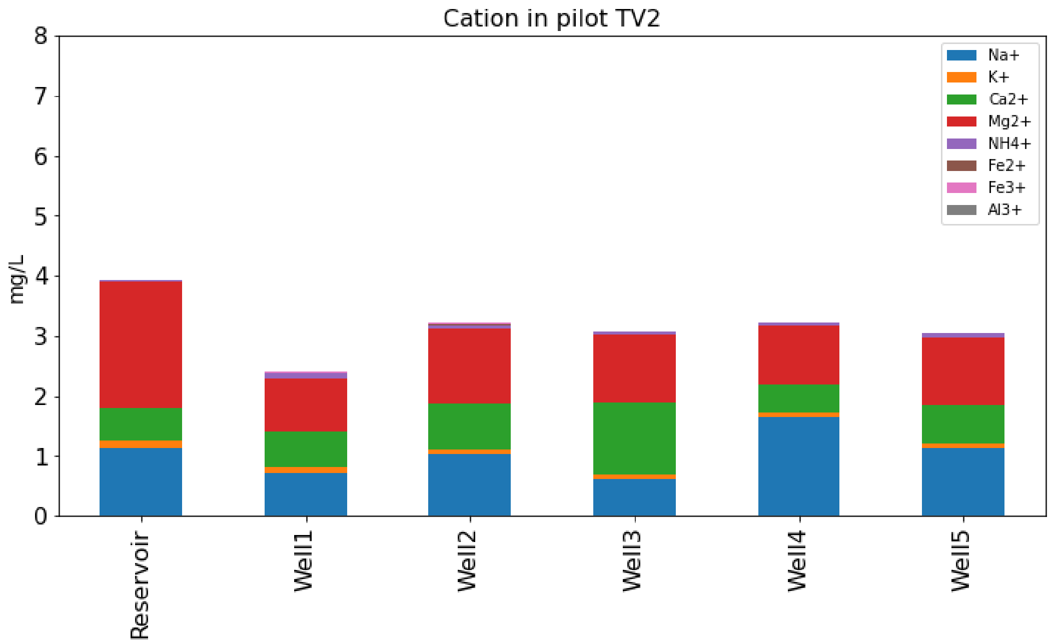


Figure 8-30: Cation concentration at TV2 site, taken in November 2021.

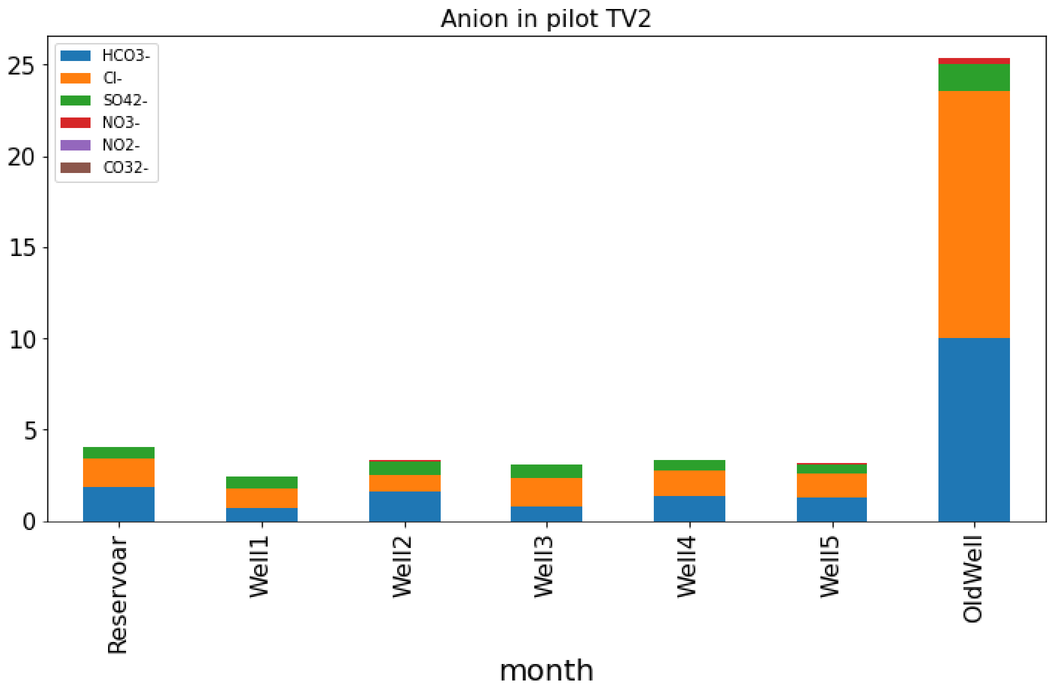


Figure 8-31: Cation concentration at the TV2 site, taken in November 2021.

In addition to anions and cations observation, eight selected pesticides were also measured from the reservoir water to make sure that pesticides will not contaminate the shallow groundwater lens. The results show that there are no pesticides detected in the reservoir above detection or water quality limits.

Table 20: Pesticide in the reservoir water at the TV2 site.

Compound	Unit	test result	limit of detection	qual limit
Aldrin	ug/L	not detected	0.02	0.1
Dieldrin	ug/L	not detected	0.02	0.02
Hexachlorobenzene	ug/L	not detected	0.005	0.1
4,4'-DDD	ug/L	not detected	0.2	1
4,4'-DDE	ug/L	not detected	0.2	
4,4'-DDT	ug/L	not detected	0.2	
Heptachlor	ug/L	not detected	0.02	0.2
Heptachlor epoxide	ug/L	not detected	0.02	

8.9.2 Groundwater level monitoring in pilot

In TV2, there is 200cm of storage available during October to November period that represents the window of opportunity period.

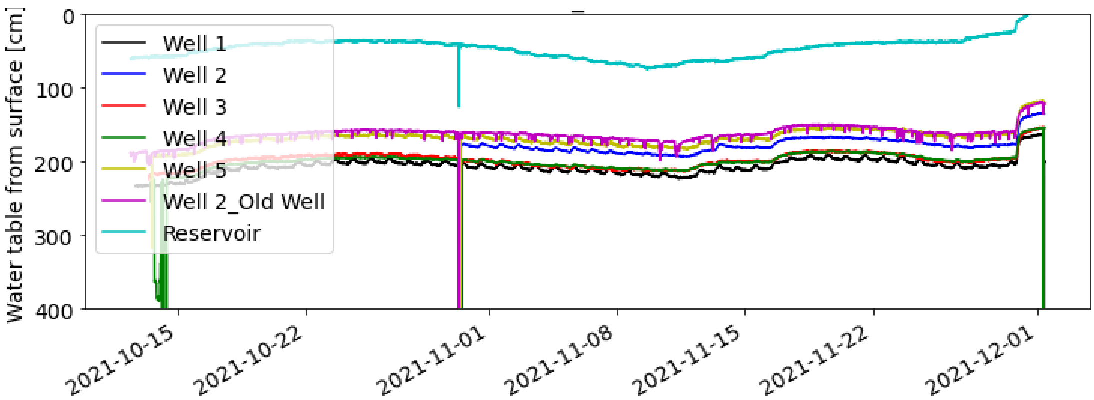


Figure 8-32: Water level monitoring at TV2.

9 Mapping the potential for shallow Aquifer Storage and Recovery in the Mekong Delta

9.1 Introduction

The potential to upscale Aquifer Storage and Recovery (ASR) to other areas other than the three investigated sites in the provinces of Ben Tre and Tra Vinh (Chapters 6 to 8), can be shown in a potentiality map. Such a map indicates whether the right hydrogeological conditions are met, so that an ASR system can be successfully implemented from a technical perspective.

The map developed is focused in the two provinces of Ben Tre and Tra Vinh as these provinces are the most vulnerable as shown in the first chapters of this report; 1) saltwater intrusion in the surface water is currently a serious problem, especially during dry seasons (Eslami et al., 2021), see Figure 3-4 (page 19), 2) the salinization is expected to be more severe in 2040 due to for instance sand mining, and 3), the existing fresh groundwater resources are scarce (Gunnink et al., 2021).

9.2 Methodology

Potentiality maps for ASR systems have been prepared for several regions. Examples are for projects in The Netherlands (Bos - Burgering et al., 2021; Delsman et al., 2018; Oude Essink et al., 2018; Van Bakel et al., 2014), Belgium (De Louw et al., 2019) and Spain (Delsman et al., 2015). In these studies, some important hydrogeological features are: a good permeable and thick aquifer, soil suitable for active infiltration, and enough space between groundwater level and ground surface. On top, fresh surface water must be available for infiltration, and the water quality must be good enough.

The three study areas (TV2, BT3 and BT2) have been selected during the scoping workshop with stakeholders (section 5.1). An analysis of the geological architecture of the sandy ridge structures was explored during a three months field campaign in 2019 at the three potential sites as part of student field work conducted by Josh Shankel (Shankel, 2020). The sandy ridges were evaluated in terms of lithology, storage capacity, and ultimately, hydrogeological feasibility for an ASR system, using shallow suction coring, deep coring and cross section analysis.

The first phase of the selection of feasible locations starts with analysing the digital elevation model (DEM). The DEM is an important feature, as it highlights and identifies possible high-lying areas where infiltration of precipitation is taking place and it hints on areas where possible enough clearance between the ground surface and groundwater level is occurring. In these areas, water storage is frequently possible. The DEMs are based on LiDAR data with a 5m resolution. For the analyses, GIS software has been used.

During the field campaign, the subsurface has been explored with shallow suction coring devices. Preliminary coring site selection has been used to observe where potential cross sections that can be made perpendicular to the sandy ridges (Shankel, 2020).

The coring sites are selected away from buildings and infrastructure, and closer to undisturbed land (and large trees), when possible, to get a more accurate representation of the natural state of the sandy ridges. This procedure also diminishes the influence of wells on groundwater level data. Note that ideal coring sites for generating cross-sectional schematisation have been often obstructed by buildings and fences.

The combined hydrogeological and geological factors determine the potential of shallow ASR systems in sandy ridge areas of the Ben Tre and Tra Vinh provinces. Table 21 shows the hydrogeological characteristics that are used to prepare the potentially map: a. a (shallow) unconfined aquifer in sandy ridges, b. good permeability, c. does not contain thick layers of clay, d. has storage available at the end of wet season, and e. contains freshwater. On top, the area of consideration must be utilized as agricultural area. The area should not be at risk of subsidence due to groundwater extractions. Finally, if in the future salinization of surface water is expected, the potential affected area is also of interest and should be prioritized.

Table 21: Data used in determining potentiality map. DWRPIS is the Division for Water Resources Planning and Investigation for the South of Vietnam.

Criteria based on hydrogeological conditions		Data source
1	Shallow unconfined aquifer to store water	Based on geology map
2	Presence of dunes where water can infiltrate	Based on morphology map
3	Good permeable aquifer (homogenous sand)	Hydraulic conductivity values (data DWRPIS)
4	Absence of very low permeable layers (clay)	Vertical resistance values (data DWRPIS)
5	Storage capacity available starting from the end of wet season	Elevation (DEM) and groundwater level, derived from model output (Pham et al., 2022)
6	Storing water in existing fresh groundwater volume instead of brackish groundwater aquifer	Salinity concentration, derived from model output (Pham et al., 2022)
7	Agricultural area that uses the water from the ASR	From land use map
8	Availability of large volumes deep fresh groundwater	See section 3.2.2 (p. 19) and Gunnink et al. (2021)
9	Risk of subsidence due to extracting deep fresh groundwater	Future elevation of the Mekong Delta in relation with extraction-induced subsidence and absolute sea level rise (Minderhoud et al., 2020),
10	High (future) salinity of surface water during dry season	See surface water salinisation map, section 3.2.1, Figure 3-4 (page 19) and Eslami et al., (2021)

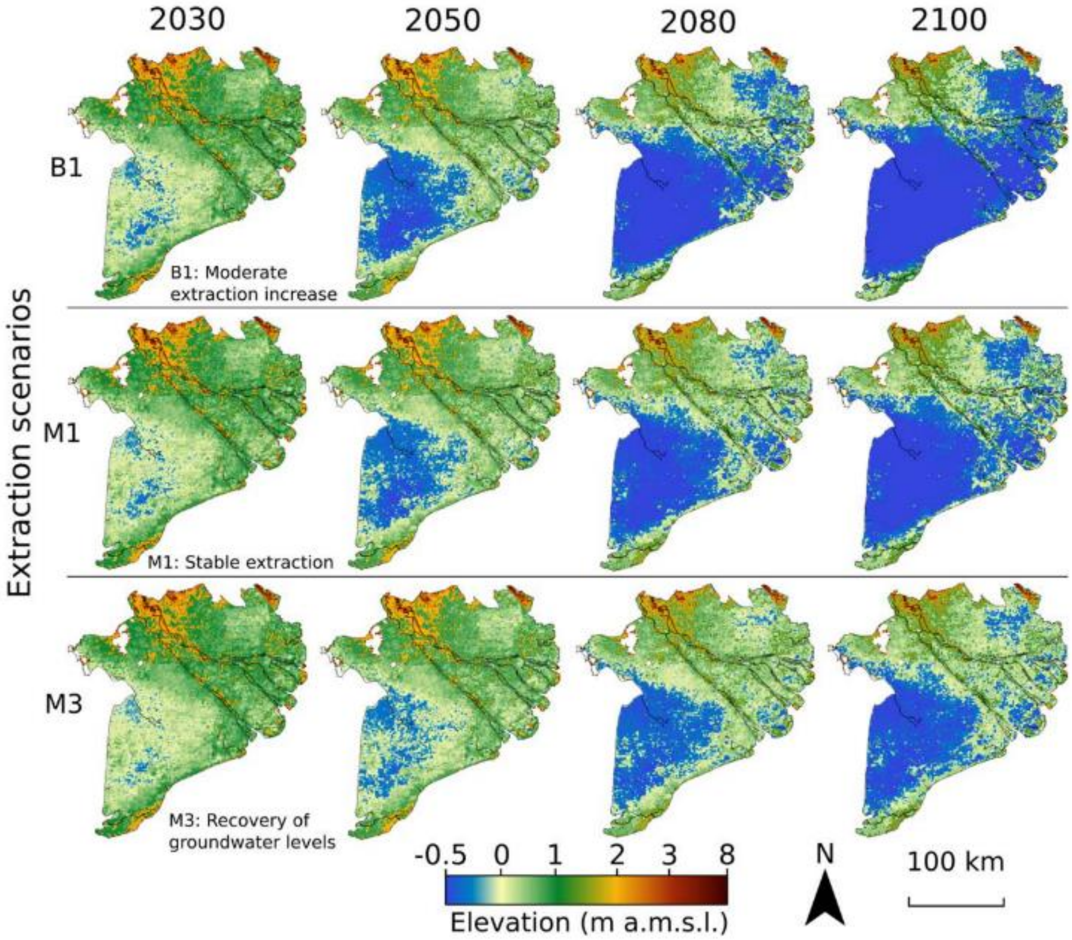


Figure 9-1: Projections of future elevation with extraction-induced subsidence following three different extraction scenarios and absolute sea-level rise according to the mid-range projections of SLR (median) of RCP 4.5 (source: Minderhoud et al. (2020).

9.3 Results

The map in Figure 9-2 is generated using the highest resolution DEM available. The total area of Ben Tre and Tra Vinh together is 4230 km^2, with 974 km^2 sand dunes area. The red areas (163.1 km^2, 16.7% of the sand dunes) are potential areas where ASR systems can be implemented based on the hydrogeological conditions. The black areas (102.3 km^2, 10.5% from sand dunes) are prioritized, as these areas are agricultural areas that require freshwater during the dry season. BT2 and TV2 are within the priority locations, while BT3 falls just outside the potential area.

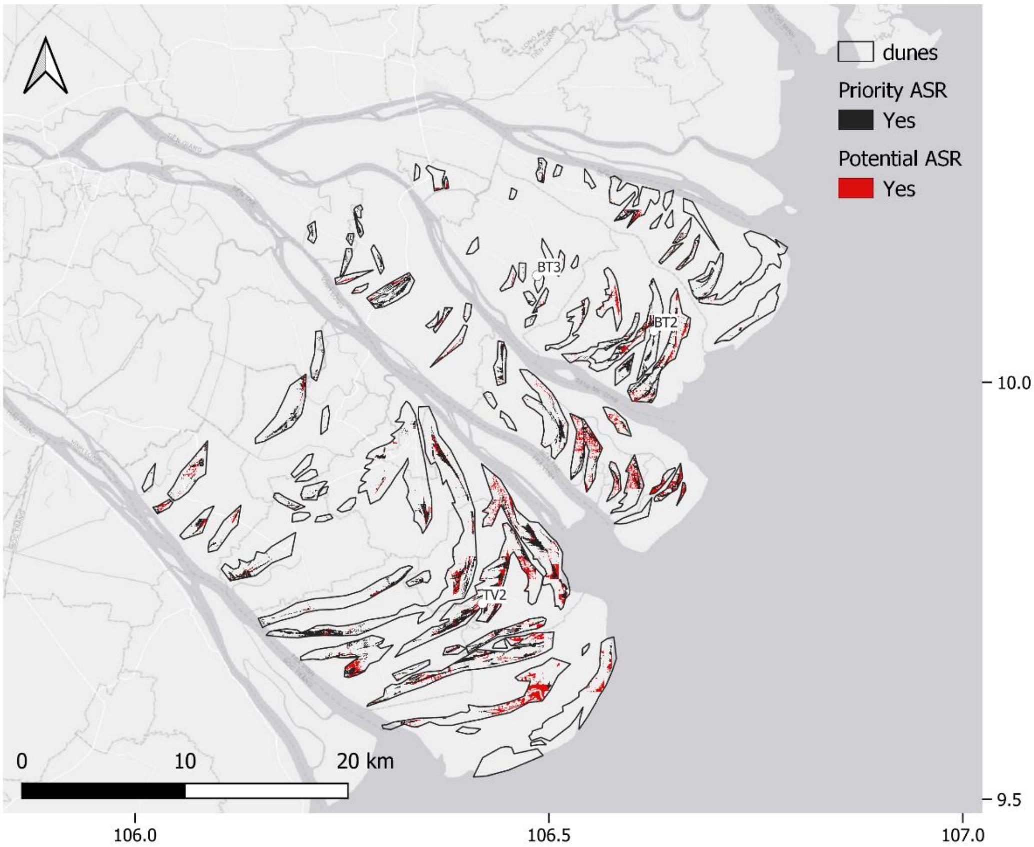


Figure 9-2: Potentiality Map for Ben Tre and Tra Vinh.

Based on the coring analysis in BT2 and 3 (section 7.3.1, Appendix A.2.5) and TV2 (section 8.3.1, Appendix A.3.4), the depth of the groundwater level and the considered porosities, (section 7.3.3 and section 8.3.3), between 40 and 245 Mm^3 water can be stored in the sand dune system in the Ben Tre and Tra Vinh, in which between 25 to 150 Mm^3 water can be stored in sand dunes located in agricultural area.

10 Upscaling and water resources management

10.1 Introduction

Agricultural sector growth, salinization, subsidence and climate change has exposed water supply vulnerabilities in the MKD. The MKD is a critical component of the Vietnam’s economy and food security as it is responsible for 50% of the country’s food production and grows 90% of the rice in Vietnam. The agricultural demand for 2100 is expected to be three times as high as it was in the year 2000 (Smyle and Cooke, 2014). With the Mekong and Bassac river of the MKD providing enough quantity of water all year round, currently the salinity remains as a main issue to utilize surface water in coastal provinces of the MKD. Moreover, with Vietnam has been predicted to be one of the countries that is most vulnerable to climate change, dry season flow will likely to be more unreliable.

Considering the growing complexities and unpredictability of freshwater problems in the MKD, adaptive management may be a promising strategy for sustaining the region’s freshwater resources. Vietnam government has already implemented Mekong Delta Plan and formulated its intentions for "high tech agriculture". However, an adaptive management is designed to always be improved with the evolving system. In the absence of adaptive adaptation measures, agricultural yields will likely be reduced.

10.2 Link/embedding in existing / ongoing projects

The Mekong Delta Plan, as long-term vision and strategy for MKD, is main reference document for Government agencies and organisations to support the review, coordination and integration of master plans to be implemented in the MKD. It includes 'no-regret' and priority measures.

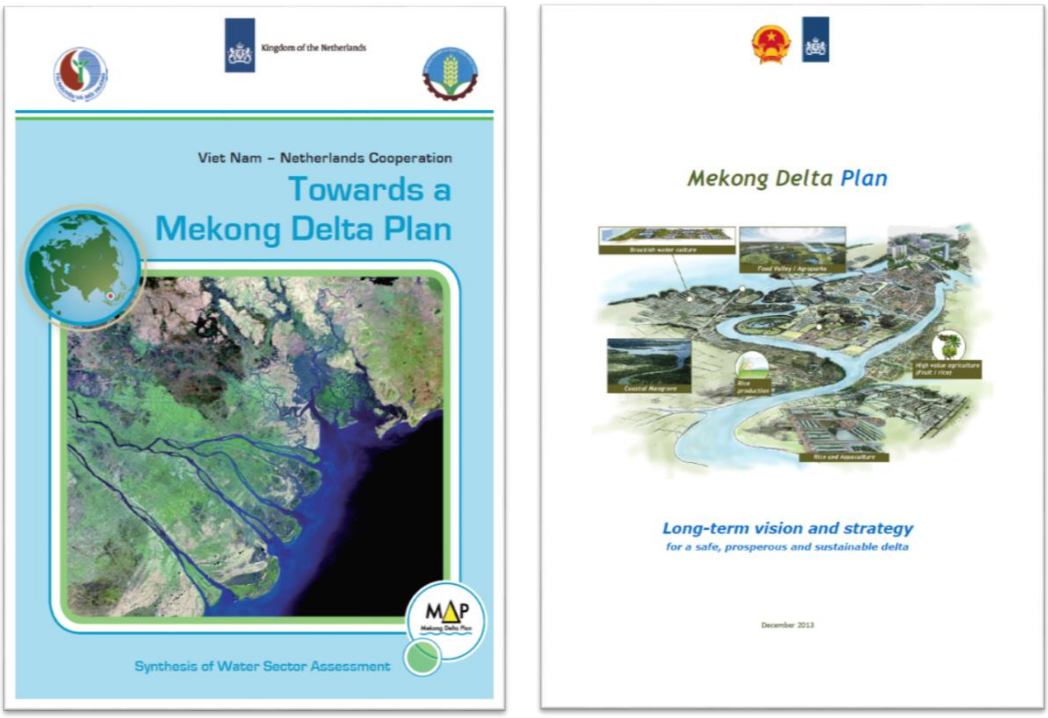


Figure 10-1: Mekong Delta Plan.

In line with the Mekong Delta Plan, the Rise and Fall project[1] that focus on groundwater dynamics and salt water Intrusion in the subsiding Mekong Delta was conducted by researchers from Utrecht University in cooperation with Can Tho University, DWRPIS, SIWRR, Deltares, TNO, Vitens Evidens International, and Netherlands Organization for Scientific Research.

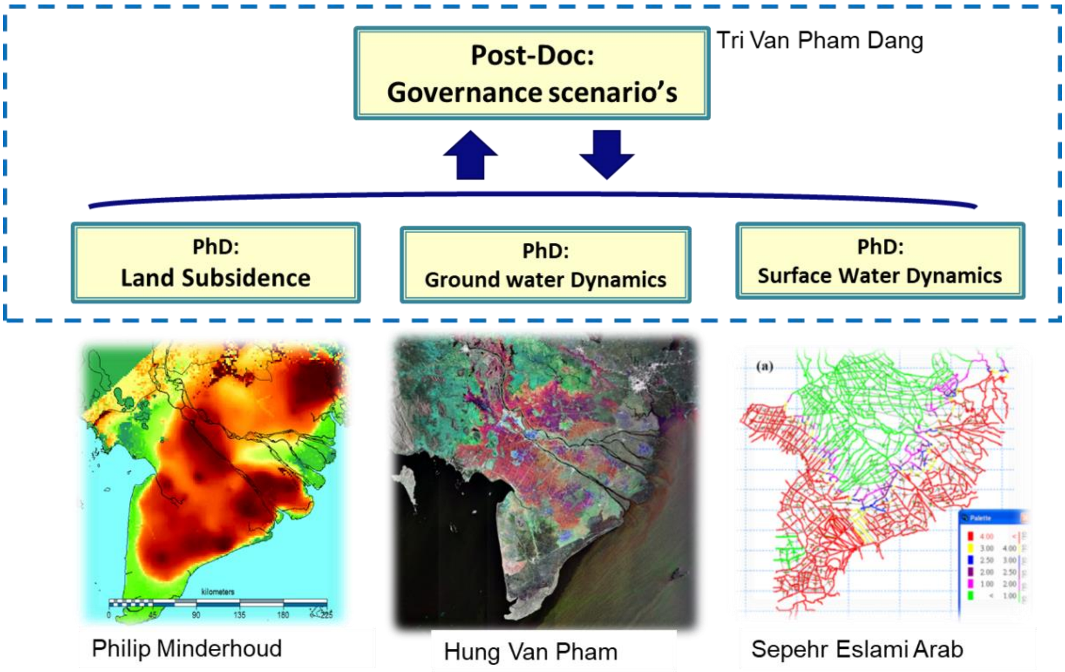


Figure 10-2: The different topics (including the PhD candidates and Postdoc) within the Rise and Fall Project.

The *Rise and Fall* project reveals that the coastal provinces of the MKD are extremely vulnerable to both surface water salinization and subsidence. It makes this region urgently need additional measures to avoid over extraction of groundwater resources that inflict subsidence and as reliable water resource during dry season when the surface water is increasingly becoming more saline.

Figure 10-3: Existing fresh groundwater map (Gunnink et al., 2021) (left), Severe land subsidence map (Minderhoud, 2019) (middle), Salinized surface water in dry period (intermediate scenario) (Eslami et al., 2021) (right).

[1] *https://www.uu.nl/en/futuredeltas/project-rise-and-fall*

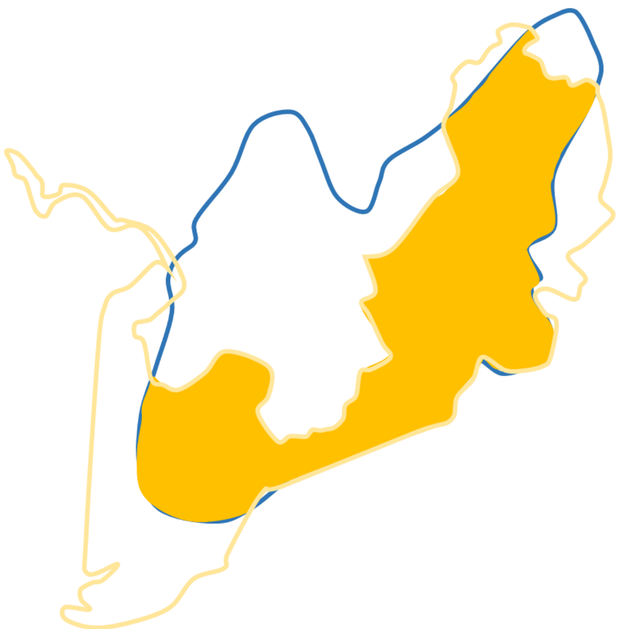


Figure 10-4: Area in the Mekong Delta that experience severe subsidence and salinized surface water.

The orange area in Figure 10-4, that covers Ben Tre and Tra Vinh province, is the area where alternative water resource is urgently needed. The surface water is not reliable in dry season due to salinization, while the utilization of deep groundwater resource, even though the resource in some areas is available, should be reduced due to severe subsidence in the area. Especially for the agriculture sector in Ben Tre and Tra Vinh, ASR may be the most optimal solution compared to the other identified solution (Table 22).

Table 22: Measures applied in the MKD

Measures	Upside	Downside
Groundwater extraction	1. Technically familiar	1. Worsen subsidence that further worsen flooding and salinization 2. Over extraction of shallow groundwater lens may lead to upconing of the brackish groundwater and polluting the shallow freshwater system
Direct surface water utilization	1. Technically familiar	2. Surface water becomes more saline during dry period 3. Fresh surface water availability becomes more uncertain under climate change
Shrimp farming instead of rice farming	1. Can be applied under salinization	2. Cannot be applied in dune area as the dune area is sandy area while shrimp pond requires clayey soil 3. Brackish water leaks to nearby field
Rice-Shrimp farming rotation	1. Can deal with brackish water during dry period	2. Cannot be applied in dune area as the dune area is sandy area while shrimp pond requires clayey / silty soil
ASR	1. Can store excess water in dune area during wet period to be used during dry period when surface water is not available 2. Avoid over extraction of shallow groundwater aquifer that cause brackish water to go upwards polluting shallow freshwater lens	1. Technically unfamiliar 2. Only can be applied in sand dunes area

However, ASR alone will not solve the water resource issue in the MKD. Combination of measures is needed to ensure the sustainability of water resource availability within the region. Combinations of potential measures that can be applied in the MKD are:

1. Regulate and minimize groundwater extractions (as soon as possible).
2. Save precious fresh groundwater as a strategic reserve for the uncertain future.
3. Promote water savings in agriculture, drinking water sector and industry.
4. Create land use shifts to relieve freshwater demand (salt-resistant agriculture, reallocate crops).
5. Store water in the subsurface through Aquifer Storage and Recovery techniques.
6. Increase the capacity of rainwater infiltration.
7. Use waste water in a circular economy.
8. Desalinize brackish groundwater.

10.3 Shallow ASR upscaling potentiality

As shown in the potentially map, there are more than 16,000 ha in the dunes with high potential to install shallow ASR systems. These shallow systems are thought for small scale farming in areas where freshwater is scarce in the dry season. From the potential area, priority should be given to:

- dunes with arable land – given the space needed and the area that will profit for the installation, these systems can be profitable for farmers. The water that can be stored should help them going through the dry season without a decrease on the crop yield and production. This technique of shallow ASR in the dunes is not sufficiently interesting for water supply companies, since the volumes of water that can be stored are not big enough.

- areas where deep fresh groundwater is scarce – in the Mekong Delta, deep aquifers are present but, in some areas, they are being over-exploited causing subsidence and salt water intrusion. Projections of future elevation with extraction-induced subsidence (Minderhoud et al., 2020) following three different extraction scenarios and absolute sea-level rise shows that the majority of Mekong Delta will be under future 2100 Mean Sea Level. As such, these aquifers should be prioritized for ASR, either shallow or deep.

- in provinces where there is already knowledge of these systems and a positive opinion about them – some provinces like Tra Vinh and Ben Tre are part of multiyear and multi-donor programs like the ones managed by IFAD.

Regarding the volume of water that can be stored, it is estimated at approximately between 40 and 245 Mm^3 in the provinces of Ben Tre and Tra Vinh (see 9.3). The agricultural water demand in the dune areas can be estimated based on the water needs for the crops. For example, for carrots and peanuts, farmers use 11mm/d from December to February; if the ground surface of the sand-dunes is some 974km^2, this is approximately 11 Mm^3 of water demand per day. This would be over the entire dry season time 3 months, 960 Mm^3. Therefore, the water that can be stored is ~5-25% of the total agricultural water demand in the sand-dune area during the dry season.

10.4 ASR and Agricultural Practice

10.4.1 Field site BT2

At BT2 the farmers use the groundwater not as extensively as farmers living around the field sites in BT3 and TV2. Farmers at BT2 realize the different qualities of the groundwater and do not use it for agriculture, but mainly for livestock and domestic use. BT2 is a smaller dune, so their use is tuned in for a smaller amount of water that is available in the freshwater lens.

10.4.2 Field site BT3

During dry period, the rootzone in the top of the dune has already dried. The estimated amount of water that is stored below the surface is between 800 to 958 mm. At the end of the rainy season, all the layers contain water. When farmers start growing vegetable crops at the start of the dry season, the rootzone layer are already dry and the saturated soil shrinking fast. In normal years, during the window of opportunity in the months of December and January, the yellow layer could be filled till the rootzone to grow vegetable crops.

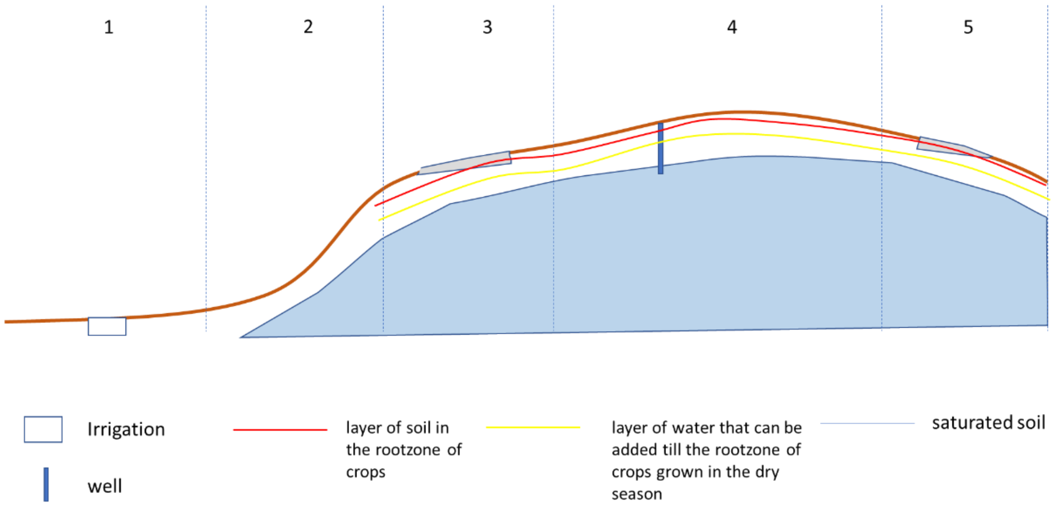


Figure 10-5: Conceptual subsurface condition in BT3 during dry period.

The rainy season in 2019 was short and did not deliver enough rain to fill to create standing water in dune area to grow rice. This meant that in October, farmers had to pump up groundwater to irrigate the rice crops. At the start of December, the saturated soil layer was already 1.3 to 1.6 below field level. This mean at the start of December, extra water is required to reach the rootzone of cucumber, which is halve a meter. The window of opportunity for filling this layer therefore, shifted to earlier months before December. When the rice is still in the paddy phase of the growth, the water can be stored until it reaches the surface, because paddy rice can cope with ponding water. The amount of water that can be stored is enough for 44 to 52 days, when considering the amount of water that is used during the long time average.

10.4.3 Field site TV2

In TV2, the estimated amount of water that is stored below the surface is between 880 to 1075 mm. The dune pans that overflow during the rainy season, are left bare during the dry season. This means the groundwater can be filled up to the surface, without affecting crops.

At the end of the rainy season in 2019 (which ended earlier than most years), only between 302 to 363 mm could be stored in in subsurface. A problem could be the reservoir in this area drains the groundwater and evaporate. Another problem is the higher amount of water the farmers use during the dry period in 2019. The long-time average measured for the site was a use of 4.2 mm/day. However, during dry period of 2019 shows water usage of 17 mm/day. With the long-time average usage, the amount of water stored should be enough for 71 to 86 days. However, for the usage in dry season 2019, the water stored is only enough for 17 to 21 days.

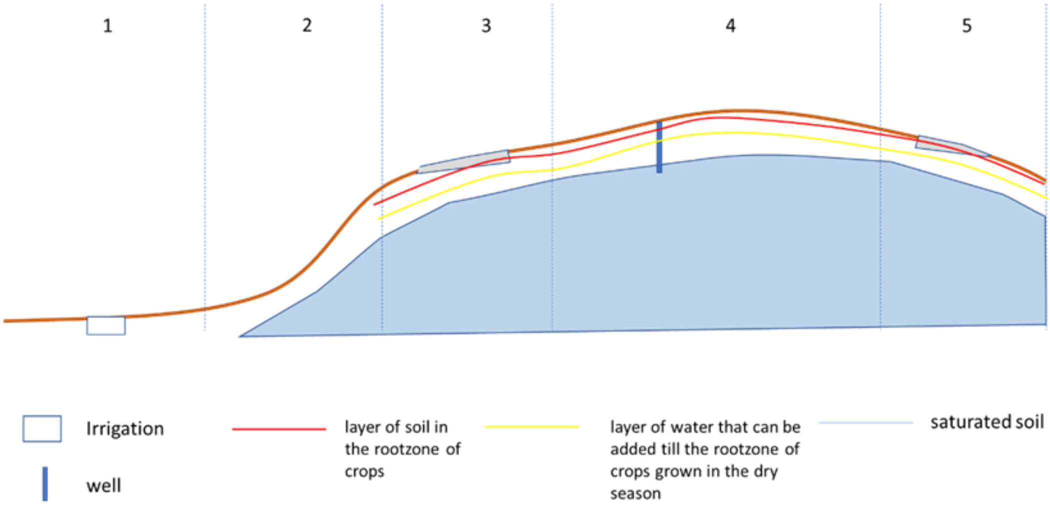


Figure 10-6: Conceptual subsurface condition in TV2 during dry period.

In TV2, on the higher dune tops there is a gap in the cropping schedule around March (section 8.3.5). This gives possibilities to have a short season crop scheduled there. The area already has carrots growing and it is a short season crop to fill in this gap. Another option is to crop peanut after the first carrot scheduled, using a part of the time for the first watermelon crop. The only problem is the decrease of discharge from pumping wells, which can be an indicator of water shortage.

Table 23 shows how much water is needed to support crops that can be grown in March. This shows that at least 155 mm is needed to grow carrots in March alone (water use times days of March). Peanut needs just a little bit less at around 152 for March alone. Both crops also need some time growing in April, this is officially the month where the rainy season starts, but with climate change the start gets less certain. To be sure that there is enough, at least 223 mm is needed for carrot and 260 mm for peanut. For a hectare this is already between 2232 and 2600 cubic meters of infiltrated water needed to be sure farmers have enough water in that area.

Table 23: Water use of crops that can be grown in the break of March in TV2.

Crop	**Start of plantation**	**Days till harvest**	**Irrigation requirements (mm/growth season)**	**Average water use / evapotranspiration (mm/day)**	**Efficiency of irrigation (%)**
Carrot	March	45	223.2	5.0	50.7
Peanut	January	96	473.4	4.9	49.8

10.4.4 Conclusions

TV2 and BT3 show extensive use for agricultural purposes of the freshwater lenses in the dune. Both sites use the lower dune pans (area 3 and 5 in Figure 10-5Figure 7-7 and Figure 8-8) for production of rice during the end of the rainy season, when natural paddies form. The dune is used for seasonal vegetables and seasonal fruits at TV2, and for jasmine and fruit trees at BT3.

During the dry season, farmers at BT3 use the groundwater to grow seasonal vegetables in the dune pans (area 3 and 5 in Figure 10-5Figure 7-7). Leaving the option of growing one short season vegetable less during very dry years without enough groundwater. At TV2 on the other hand, the farmers have a break in growing crops on the dune tops (area 4 Figure 8-8) and leave the dune pans (area 3 and 5 in Figure 10-5 Figure 8-8) bare, because of limited amounts of groundwater. In dry years the cropping area is decreased, if necessary. This shows that in normal years, farmers make most of the resource of the shallow freshwater lenses.

When an ASR system is implemented, several factors should be taken into consideration. One of them is the amount of water that can be infiltrated and when this water can be infiltrated. The amount of water that can be infiltrated differs, depending on the amount of rain that fell during the rainy season, the part of the cropping cycle where the farmers are, and the availability of fresh surface water in the surrounding canals and rivers. In most years, the salinity in the canals and rivers surrounding the field sites is increasing towards the end of February. This means that only December and January can be used to fill the shallow freshwater lens. In dry years, this window will shift to earlier months.

Year 2019 was a dry year and farmers had to irrigate rice with some of the groundwater, to still have enough yield. This groundwater already lower in December compared to the normal year and cannot be used for cash crops anymore, decreasing the income of the farmers. At BT3, in December 2019, there was room to store water for 44 to 52 days. This can provide almost enough water for one harvest of cucumber crop that most farmers grow in the dry season. At TV2, the water that could be stored, can be used for less days, only 17 to 21 days. This can only partially fulfil the amount needed for a crop of carrot.

In TV2, as the groundwater and reservoir are connected, there is a possibility that the groundwater drains to the reservoir and evaporates. If the daily use at TV2 can be reduced, the amount of water could be used for irrigation of a short season crop.

At field site BT3, the installation of ASR would result in that farmers can grow crop the same amount of times even for very dry years where the rainy season ends earlier than expected. Farmers can still crop two or three cash crops during the dry season, securing their main form of income. In normal years, it does not seem to have an additional benefit, as farmers use the freshwater in a very efficient way.

At TV2 the amount of water can only support carrots, which is a crop in their current cropping schedule. Carrots are not cash crops and it will not increase the income of farmers by much. It is difficult to say if this technical intervention could be profitable. Concluding from this, installing the ASR system would be economically viable at BT3, where this intervention secures income from two or three cropping cycles of cash crop. TV2 is less economically viable, because the crops grown during the dry season are not cash crops and the extra income from the amount of water that can be stored is low.

10.5 Webportal application to show FAME data

Lizard, a data and analytics platform, is the webportal to make the FAME data easily accessible: https://fame.lizard.net/viewer. See an example in Figure 10-7. Water level timeseries, salinity concentration (in TDS g/L), horizontal hydraulic conductivity (m/day), vertical resistance (days) and head uppermost level layers (meter above Mean Sea Level) can be provided. The potential map of shallow ASR can also be made visible.

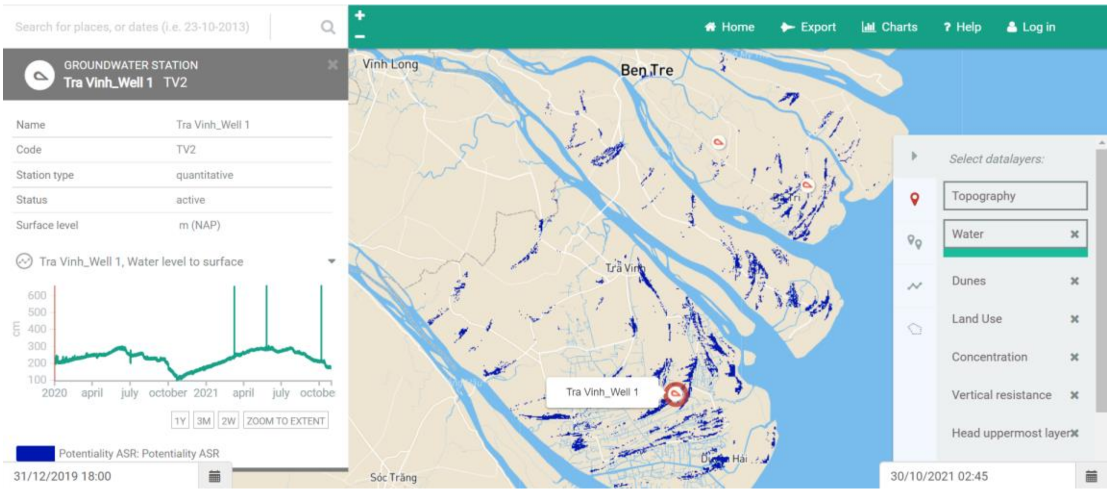


Figure 10-7: Example of output on the webportal https://fame.lizard.net/viewer: it shows the water level to ground surface at the site TV2 in the Province of Tra Vinh.

11 Conclusions, recommendations and key messages

11.1 Conclusions

Water availability in the Mekong Delta

The coastal estuaries of the Mekong Delta are increasingly subjected to salt water intrusion of surface and groundwater during the dry season; in the future, this situation will become more pressing as sea-level is rising, dry seasons getting drier and less fresh surface water is available. As salt-water intrudes into the river mouths, freshwater from the rivers can no longer be taken in to supply agricultural lands and canals need to be closed off by sluice gates. In Tra Vinh and the south-west of Ben Tre, salinity is progressively moving inland and upstream into the surface water systems. When the saline concentration in irrigation water for rice and fruits exceeds 4 TDS g/l, there is an immediate crop damage and economic loss. Together with salinization, freshwater shortages for agriculture are also affecting crop production in the dry season.

When surface water is not available, farmers use groundwater. In the Mekong Delta, besides the deep confined aquifers shallow sand-dune fresh groundwater lenses are exploited in the dry season for agriculture purposes. Mostly in deep aquifers, fresh groundwater resources are systematically depleted and further increase of groundwater use is unsustainable.

Agricultural demand in the Mekong Delta accounts for 83% of all water demand, reaching the 13,500 Mm^3 per year (data from 2013). The economic returns of fruits and vegetables are generally a factor 2-5 higher than for rice but are limited in scope by relatively small holding/plots. This is related to the limited capacity of the fresh groundwater lens to sustain irrigated vegetables throughout the dry period when surface water is also saline.

The fresh groundwater resources as the sole water source for agricultural water in sand-dune areas during the dry season do not fully replace the shortage in precipitation which negatively affects crops production (Bregman, 2020). This dependency on the amount of water in the fresh groundwater lenses in sand-dune areas is large and over extraction is a serious problem. This problem is partly caused by climate change and partly by inefficient water management on the farms.

Governance

The main barriers for a good governance of the groundwater are related to financial and human resources, the price of groundwater use, a lack of coordination between governing systems, between the provinces, sanctions, and inadequate incentives for groundwater use.
Besides, other barriers are related to the insufficiency of water policies, lack of guidance on implementing groundwater extractions and enforcing regulations, and the unclear and overlapped function of responsible units. The complex hydrogeology and the lack of local expertise also interfere in adequate groundwater management.

Regarding the governance of Aquifer Storage and Recovery (ASR) systems, Article 4 in the Law for Water Resources recommends groundwater recharge as solution, but there is no document instructing how to implement it. A positive not is that ASR receives attention from local governments and other stakeholders like water supply companies, which can trigger the development of dedicated regulations or legislations regarding its implementation and management.

Aquifer Storage and Recovery in the Mekong Delta
FAME is the first project focusing on evaluating the potential of Aquifer Storage and Recovery and running a pilot in South Vietnam. According to the assessment carried out in the project, both shallow and deep ASR systems could be interesting for the Mekong Delta. Since FAME focusses in finding a solution to increase freshwater availability for farmers, at a small scale and in a cost-effective way, the project was focused on Aquifer Storage and Recovery in the shallow aquifers.

The shallow aquifers in the dunes need to be replenished during the wet season. The monitoring results showed that between October and November there is still an excess of fresh surface water, while there is enough space in the aquifer to infiltrate water. Before October, groundwater levels are too high and there is no space for new water. After November, even though there is more space in the aquifer to infiltrate water due to the pumping, fresh surface water becomes scarcer and salinity intrudes into the water channels and therefore infiltration is not possible. This delimits the time to infiltrate water.

The assessment of the characteristics of the sand dune aquifers in the Mekong Delta, shows that the so-called creek ridge infiltration technique is the most appropriate ASR technique for these areas.

Study sites
Three sites in the provinces of Ben Tre and Tra Vinh were found most suitable to conduct field research and assess the potential for a pilot study. All sites suffer from water stress. The sand-dunes serve as shallow aquifers supplying fresh groundwater to the farmers living on or close to the sand-dunes.

The site Long Son Commune in the province Tra Vinh was selected for the pilot installation. The other two sites were disregarded. The site Bin Tangh the province in Ben Tre was initially found to have variable surface water quality which posed a risk for water infiltration into the subsurface, while in the site An Duc in the province Ben Tre farmers don’t use groundwater for irrigation and the sand-dune is too narrow and too densely populated.

For the site Bin Tangh in Ben Tre, a specific monitoring plan for water quality was defined, to understand if indeed water quality is a limitation factor for ASR in this site. The results of the monitoring showed that the only parameter that exceeds drinking water quality and groundwater standards is nitrite. Nitrite is very unstable and will be converted to other forms of N quickly. After that, it will be small or in the same order of magnitude as the other forms of N, e.g. NH4. This indicates that no additional measures are needed in this site and that in the future an ASR system could be installed here.

At the Long Son Commune in Tra Vinh, farmers have a break in growing crops on the sand-dune tops and leave the sand-dune pans bare because of limited amounts of fresh groundwater. In some dry years the cropping area is decreased.

This site in Tra Vinh was also chosen because it is part of the *Project for Adaption to Climate Change in the Mekong Delta in Ben Tre and Tra Vinh Provinces* (AMD) funded by The International Fund for Agricultural Development (IFAD), which gives perspective for future investments in adaptive management for climate adaption and water availability.

A downside of the Tra Vinh site for the pilot, is the existence of a surface water reservoir connected to the groundwater developed within the AMD project. This connection means that the dynamics of groundwater and the reservoir are interdependent. To capture this relation and to understand the results of the pilot, both the reservoir and the groundwater were included in the monitoring plan for the site.

Pilot site investigation, pilot design and implementation

The site in Tra Vinh is located on an extensive sand-dune complex. The reservoir built within the AMD project is not connected to a distribution system for the farmers, so the main source of water during the dry season remains water from the fresh groundwater lenses which are exploited with pumping wells.

The monitoring campaign and the field observations carried out during the project at the Tra Vinh site show: 1) a decrease of the groundwater table during the dry season, and 2) water quality parameters all below thresholds and therefore good enough for infiltration. These are suitable conditions for the installation of an Aquifer Storage and Recovery pilot.

Modelling results of the site at Tra Vinh illustrates that an ASR system of horizontal infiltration drains and horizontal pumping wells, or an ASR system of horizontal infiltration drains and various vertical pumping wells would have a positive effect in buffering freshwater in the subsurface at the beginning of the dry period. Groundwater level is estimated to rise at least some decimeters and the water quality is expected to improve with time. With these results, we expect that water of good quality can be buffered in the groundwater system and later be recovered during dry seasons when no alternative water is available. For instance, the total volume of water stored in the subsurface could be enough to crop carrots for one crop cycle. However, as carrots are not a cash crop, it is uncertain yet if an ASR system at this site in Tra Vinh would be financially interesting; other crops might be potentially more interesting.

More water could be stored at the site Bin Tangh in the province of Ben Tre, possibly allowing the farmers to irrigate three cycles of cash crops in dry years. As such, this would have a direct economic benefit for the farmers.

Regarding the costs, constructing a vertical groundwater extraction well will be less costly than installing a horizontal well at a depth of 5m. Therefore, one might consider choosing a vertical well design over a horizontal well design in the current situation. However, if the shallow ASR system would be implemented in an area with saline groundwater, the horizontal well design would significantly improve the recoverability of fresh groundwater, as the salinity concentration in the collected groundwater would be much lower during extractions throughout the dry period.

Results of the field and desk investigation were used to design the ASR pilot. The system consists of 5 infiltration pipes of 30 meters placed horizontally 1 meter below the surface, 4 monitoring wells with divers, and 1 monitoring well with CTD. The water is taken from the reservoir with a solar pump and infiltrated through the 5 infiltration pipes.

The implementation of the ASR pilot system was successfully carried out from October 11th to October 13th, 2021. The project ended in December 2021, so pilot monitoring results are not available yet.

Upscaling and potentiality maps

The potentiality map shows that at least about 16,000 ha of sand dunes are suitable for the implementation of shallow ASR systems. From these, some 10,230 ha are prioritized as these are agricultural areas that require freshwater during the dry season. In total, a 17% of the total extension of sand-dunes in the provinces of Ben Tre and Tra Vinh is suitable to implement ASR systems.

Regarding the volume of water that can be stored, it is estimated at approximately 40-245 Mm3 in the provinces of Ben Tre and Tra Vinh. This is ~5-25% of the total agricultural water demand in the sand-dune area during the dry season.

The financial benefits of installing an ASR system need to be studied per site, as they depend on the amount of water that can be stored, the crops that can be irrigated with that water, and the size of the farmer land. First estimations of the two studied sites show that while the ASR system could be interesting for the site at Ben Tre, it might not be interesting for the site at Tra Vinh. However, no conclusions can be drawn until monitoring results from the pilot are collected, and the volume of fresh groundwater stored in the subsurface is known.

Shallow ASR should be prioritized to areas where (deep) fresh groundwater resource is scarce, or where land subsidence due to deep groundwater extractions is serious. As projections of future ground surface over time given extraction-induced subsidence (Minderhoud et al., 2020) following three different groundwater extraction scenarios and absolute sea-level rise shows that the majority of Mekong Delta will be under Mean Sea Level by the year 2100. To reduce subsidence, especially in the Ben Tre and Tra Vinh provinces, alternative water resource is needed. As such, shallow ASR systems could be part of the solutions.

It is envisaged that shallow ASR systems alone will not solve the freshwater resource issue in the Mekong Delta. A combination of water measures is likely needed to ensure the sustainability of water resource availability within the regions.

11.2 Recommendations

It is envisaged that on the long run, freshwater availability in the coastal zone of the Mekong delta is not obvious anymore if no measures are taken in time. There is a need to trigger actions under water managers, policy makers and investors. There are multiple aspects that need to be tackled to create this momentum, including:

- reinforcing the technical basic knowledge of the groundwater system as an integrated part of the water system, before implementing measures. That means understanding the hydrogeological context but also looking into the connections of water bearing aquifers with the coast, surface water system, nature ánd human activities. With that, the causes of water shortages and possible associated effects like land subsidence can be considered from an integral perspective, and the benefits and co-benefits can come to light.
- prioritize shallow ASR techniques to areas where (deep) fresh groundwater resource is scarce, or where land subsidence due to deep groundwater extractions is serious.
- upscaling the studied Aquifer Storage and Recovery technique in Tra Vinh to other areas in the Mekong Delta and beyond, by considering the following aspects: monitor the effectiveness of ASR techniques; raise awareness among stakeholders; train local partners on setting up and implementing ASR techniques; solve water quality issues; execute a cost-benefit analysis (implementation and maintenance costs versus benefit from a crop production point of view), and arrange a governance framework (coordinate governing systems, guide groundwater extractions implementation, create adequate incentives for groundwater use, enforce regulation) that make ASR techniques possible.

In order to explore further the potential of ASR in the Mekong Delta, FAME could be taken as a case in the Climate Smart Agriculture Transformation Project in the Mekong Delta (CSAT) that IFAD is preparing for the provinces of Ben Tre and Tra Vinh. Both provinces have the physical potential for ASR and have also the urgency for water demand. Clearly, one single pilot, such as the one installed in the Long Son Commune in Tra Vinh, is not enough to obtain clear conclusions on the upscaling potential. Within CSAT, it should be worked on a more complete analysis of the feasibility including the limiting factors, a cost-benefit analysis, a local and regional model to simulate the result of upscaling different ASR systems, and the best schemes to work towards a conjunctive use of surface water and groundwater.

As a final note: recognize that fresh groundwater is not a free resource, as in the end, communities 'pay for it' with subsidence and salinization of water resources. This means the water resources issues in a delta like the Mekong Delta should consider the following aspects:

- regulate and minimize groundwater extractions (as soon as possible); save precious fresh groundwater as a strategic reserve for the uncertain future.
- promote water savings in agriculture, drinking water sector and industry.
- create land use shifts to relieve freshwater demand (apply salt-resistant agriculture where possible, reallocate crops).
- increase the capacity of rainwater infiltration, to reestablish the groundwater resource.
- use waste water in a circular economy.
- desalinize brackish groundwater.
- do not delay mitigation measures; integrated tailor-made water strategies are needed in an adaptive pathway setting.

11.3 Key messages

- The fresh groundwater resources as the sole source for agricultural water in sand-dune areas during the dry season, does not fully replace the shortage in precipitation which negatively affects crops production.
- Regarding groundwater governance, the main barriers are related to financial and human resources, interinstitutional coordination, insufficiency of the water policies and guidance
- There is just one article in the law related to ASR; Article 4 in the Law for Water Resources recommends groundwater recharge as solution, however, there is an increasing interest from local governments and other stakeholders like water supply companies
- FAME is the first project focusing on evaluating the potential of Aquifer Storage and Recovery and running a pilot in South Vietnam
- Both shallow and deep ASR systems could be interesting for the Mekong Delta, but FAME focusses in finding a solution to increase water availability for farmers, at a small scale and that is cost-effective and therefore FAME focusses on ASR in the shallow aquifers.
- Between October and November there is still an excess of freshwater from the surface water system, while there is enough space into the aquifer to infiltrate water.
- The so-called creek ridge infiltration technique (shallow infiltration drains distributed in the plot) is the most suitable for the sand-dunes of the Mekong Delta.
- Three sites in the provinces of Tra Vinh and Ben Tre were found to be most suitable to conduct field research and assess the potential for a pilot study. The Long Son Commune in the province of Tra Vinh was selected.
- Field observations in Tra Vinh site show: 1) a decrease of the groundwater table during the dry season, and 2) water quality parameters all below thresholds and therefore good for enough infiltration. These are suitable conditions for the installation of an Aquifer Storage and Recovery pilot.
- Modelling results of the site at Tra Vinh illustrates that a shallow ASR system could have a positive effect in buffering freshwater in the subsurface at the beginning of the dry period. Groundwater level is estimated to rise at least some decimeters and the water quality is expected to increase over long time periods.
- The total volume of water stored in the subsurface could be enough to crop carrots for one crop cycle. However, as carrots are not a cash crop, it is uncertain yet if an ASR system at this site in Tra Vinh would be financially interesting; other crops might be

potentially be interesting. Yet, the other conditions were positive, and the pilot was installed here.

- The implementation of the installation of an ASR pilot system was successfully carried out from October 11th to October 13th, 2021.
- The project ended in December 2021, so pilot monitoring results are not available due to a lack of measurement time.
- The potentiality map shows that 17% of sand-dunes (viz ~16,000 ha) are suitable for the implementation of shallow ASR systems in the provinces of Tra Vinh and Ben Tre. From these, some 10,000ha are prioritized as these are agricultural areas that require freshwater during the dry season.
- A total of 40 Mm^3 to 245 Mm^3 can be stored in the sand-dun areas in the provinces of Ben Tre and Tra Vinh, which is 5-25% of the total agricultural water demand in the sand-dune area during the dry season.
- ASR alone will not solve the freshwater resource issue in the Mekong Delta. Combination of measures is needed to ensure the sustainability of water resource availability within the region.
- Shallow ASR should be prioritized to areas where (deep) fresh groundwater resource is scarce, or where land subsidence due to deep groundwater extractions is serious.

Acknowledgements

First of all, we thank the Netherlands Enterprise Agency (RVO) for supporting us financially to work on this project which is part of the Partners for Water program. We thank Robert Proos for his willingness and flexibility to let us execute all the tasks in the project plan as flexible as possible, given the tough covid-19 pandemic circumstances. We also thank Laurent Umans, our First Secretary Water Management and Climate Change in Vietnam, for his passionate support in communicating the outcomes of this this project with many others from different (international) organisations.

Maartje Wise-Hoevenaars and Jarda van Spengen from Royal HaskoningDHV are thanked for their advices on how to manage our project as part of their overall agreement with the Dutch Ministry of Foreign Affairs.

The project has gone through some difficult stages due to especially the covid-19 pandemic. For instance, covid-19 made it impossible for us to visit Vietnam and the Mekong Delta during the entire second part of the project. Three new students were ready to travel for Vietnam to continue the hydrogeological surveys that were executed by the students Anne Kruijt, Josh Shankel and Sep Bregman, but covid-19 unfortunately cancelled all activities.

Special thanks are given to all participants who joined us during the last two online workshops. We thank the experts in the penal discussions for giving us useful advice; their input was valuable to better shape the outcomes of the project.

Of course, executing the work presented in this report would not have been possible without the help of many persons. For now, we limit our thanks to the authorities who granted us the license to implement the pilot in Tra Vinh and to the farmer at whose site we constructed the pilot when he did not expect it anymore.

Finally, though the overall duration of the FAME project was not exceptionally long, we wish to thank the two project managers Sandra Galvis Rodriguez and Geoff Zimmel. They left Deltares during the project but their input was essential for the outcomes of this complex project.

References

Berg, H., 2002. Rice monoculture and integrated rice-fish farming in the Mekong Delta, Vietnam - Economic and ecological considerations. Ecol. Econ. 95–107.

Birkmann, J., Garschagen, M., Van Tuan, V., Binh, N.T., 2012. Vulnerability, coping and adaptation to water related hazards in the Vietnamese Mekong Delta. Environ. Sci. Eng. https://doi.org/10.1007/978-94-007-3962-8_10

Bos - Burgering, L., Buijs, S., America, I., Klooster, J., De Louw, P.G.B., Delsman, J.R., Stofberg, S.F., Raat, K., Franssen, R., Posma, J., 2021. COASTAR; Regionale en nationale opschaling COASTAR toepassingen, Deltares rapport 11204487-001-BGS-0005.

Bregman, S., 2020. Viability of an alternative cropping system using shallow freshwater lenses in Tra Vinh and Ben Tre, Vietnam.

Cosslet, T.L., Cosslet, P.D., 2014. Water resources and food security in the Vietnam Mekong Delta. Springer International Publishing. https://doi.org/10.1007/978-3-319-02198-0

Daus, A., 2019. Aquifer Storage and Recovery; Improving Water Supply Security in the Caribbean: Opportunities and Challenges, Water and Sanitation Division; paper IDB-DP-00712.

De Louw, P.G.B., Van Baaren, E.S., Kaandorp, V.P., Rodriguez, S.G., Dupon, E., Huits, D., Van Camp, M., Walraevens, K., Vandenbohede, A., 2019. TOPSOIL - GO-FRESH Vlaanderen: Potenties om de zoetwaterbeschikbaarheid te verbeteren, TOPSOIL.

Delsman, J.R., 2015. Saline groundwater – surface water interaction in coastal lowlands. IOS Press, Inc., Amsterdam. https://doi.org/10.3233/978-1-61499-518-0-i

Delsman, J.R., De Paz, J.M., De Klerk, M., Stuyt, L.C.P.M., De Louw, P.G.B., Visconti, F., Del Longo, M., Pecora, S., 2015. Application of the FWOO method in the Vega Baja Segura catchment, Deltares rapport 1220325.

Delsman, J.R., Van Boekel, E., Reinhard, S., Te Winkel, T., Van Loon, A., Bartholomeus, R.P., Mulder, M., Massop, H., Polman, N., Schasfoort, F., 2018. Regioscan Zoetwatermaatregelen - Verkennen van het perspectief van kleinschalige zoetwatermaatregelen voor de regionale zoetwateropgave. STOWA Rapp. 2018-13 160.

Dillon, P.J., 2005. Future management of aquifer recharge. Hydrogeol. J. 13, 313–316. https://doi.org/10.1007/s10040-004-0413-6

Dillon, P.J., Page, D., Pavelic, P., Toze, S., Vanderzalm, J., Levet, K., 2009a. Australian Guidelines for Water Recycling: Managed Aquifer Recharge, National Water Quality Management Strategy.

Dillon, P.J., Pavelic, P., Page, D., Beringen, H., Ward, J., 2009b. Managed aquifer recharge: An Introduction, Waterlines Report Series No. 13. Canberra, Australia.

Dung, D.T., Van Halsema, G.E., Hoang, L.P., Hellegers, P.J.G.J., 2019. Long-term sustainability of the Vietnamese Mekong Delta in question: An economic assessment of water management alternatives. Agric. Water Manag.

Eslami, S., Hoekstra, P., Kernkamp, H., Trung, N.N., Duc, D. Do, 2019. Flow Division Dynamics in the Mekong Delta: Application of a 1D-2D Coupled Model 1–25. https://doi.org/10.3390/w11040837

Eslami, S., Hoekstra, P., Minderhoud, P.S.J., Trung, N.N., Hoch, J.M., Sutanudjaja, E.H., Dung, D.D., Tho, T.Q., Voepel, H.E., Woillez, M.-N., Van der Vegt, M., 2021. Projections of salt intrusion in a mega-delta under climatic and anthropogenic stressors. Nat. Commun. Earth Environ. 1–11. https://doi.org/10.1038/s43247-021-00208-5

Global Facility for Disaster Reduction and Recovery, 2018. City Resilience in the Mekong Delta; Soc Trang Resilience Assessment.

Gunnink, J.L., Pham, V.H., Oude Essink, G.H.P., Bierkens, M.F.P., 2021. The 3D groundwater salinity distribution and fresh groundwater volumes in the Mekong Delta, Vietnam, inferred from geostatistical analyses. Earth Syst. Sci. Data 13, 3297–3319. https://doi.org/10.5194/essd-13-3297-2021

International Fund for Agricultural Development (IFAD), 2014. Adaptation to climate change in the Mekong Delta in Ben Tre and Tra Vinh Provinces; Final project design report.
Japan International Cooperation Agency, 2016. The preparatory survey for the Ben Tre water management project; Final report.
Korea Water Resources Corporation, 2000. Flood Control Planning for Development of the Mekong Delta; Mekong River Commission.
Kuenzer, C., Guo, H., Huth, J., Leinenkugel, P., Li, X., Dech, S., 2013. Flood mapping and flood dynamics of the mekong delta: ENVISAT-ASAR-WSM based time series analyses. Remote Sens. 5, 687–715. https://doi.org/10.3390/rs5020687
Kungvankij, P., Chua, T.E., Pudadera Jr, B.J., Corre, K.G., Borlongan, E., Tiro Jr, L.B., Potestas, I.O., Taleon, G.A., Paw, J.N., 1989. Shrimp culture: Pond design, operation and management. Food Agric. Organ. United Nations.
Le, T.N., Bregt, A.K., Van Halsema, G.E., Hellegers, P.J.G.J., 2018. Interplay between land-use dynamics and changes in hydrological regime in the Vietnamese Mekong Delta. Land use policy 269–280.
Lu, X.X., Siew, R.Y., 2006. Water discharge and sediment flux changes over the past decades in the lower Mekong River: Possible impacts of the Chinese dams. Hydrol. Earth Syst. Sci. 10, 181–195. https://doi.org/10.5194/hess-10-181-2006
Minderhoud, P.S.J., 2019. The sinking mega-delta; Present and future subsidence of the Vietnamese Mekong delta.
Minderhoud, P.S.J., Erkens, G., Pham, V.H., Bui, V.T., Erban, L.E., Kooi, H., Stouthamer, E., 2017. Impacts of 25 years of groundwater extraction on subsidence in the Mekong delta, Vietnam. Environ. Res. Lett. 12, 13. https://doi.org/10.1088/1748-9326/aa7146
Minderhoud, P.S.J., Middelkoop, H., Erkens, G., Stouthamer, E., 2020. Groundwater extraction may drown mega-delta: projections of extraction-induced subsidence and elevation of the Mekong delta for the 21st century. Environ. Res. Commun. 2, 011005. https://doi.org/10.1088/2515-7620/ab5e21
Nguyen, A.D., Savenije, H.H.G., 2006. Salt Intrusion in multi-channel estuaries: A case study in the Mekong Delta, Vietnam. Hydrol. Earth Syst. Sci. 743–754.
Nguyen, Q.H., Tran, D.D., Dang, K.K., Korbee, D., Pham, L.D., Vu, L.T., Sea, W.B., 2020. Land-use dynamics in the Mekong Delta: From national policy to livelihood sustainability. Sustain. Dev. 448–467.
Oude Essink, G.H.P., Pauw, P.S., Van Baaren, E.S., Zuurbier, K.G., De Louw, P.G.B., Veraart, J.A., MacAteer, E., Van der Schoot, M., Groot, N., Cappon, H., Waterloo, M.J., Hu-A-Ng, K.R.M., Groen, M.M.A., 2018. GO-FRESH: Valorisatie kansrijke oplossingen voor een robuuste zoetwatervoorziening; Rendabel en duurzaam watergebruik in een zilte omgeving.
Pauw, P.S., Van Baaren, E.S., Visser, M., De Louw, P.G.B., Oude Essink, G.H.P., 2015. Increasing a freshwater lens below a creek ridge using a controlled artificial recharge and drainage system: a case study in the Netherlands. Hydrogeol. J. 1–21. https://doi.org/10.1007/s10040-015-1264-z
Pham, V.H., Minderhoud, P.S.J., Meggiorin, M., Oude Essink, G.H.P., 2022. On fresh groundwater resources in the Mekong Delta Vietnam under large extraction rates, using a 3D variable-density groundwater model; to be submitted.
Pham, V.H., Van Geer, F.C., Bui, V.T., Dubelaar, W., Oude Essink, G.H.P., 2019. Paleo-hydrogeological reconstruction of the fresh-saline groundwater distribution in the Vietnamese Mekong Delta since the late Pleistocene. J. Hydrol. Reg. Stud. https://doi.org/10.1016/j.ejrh.2019.100594
Phan, K.T., Tri, P.D., Nguyen, Y.M., 2016. Assessing the groundwater resources management in the Bac Lieu Province, Mekong Delta, Vietnam. J. Vietnamese Environ. 8, 257–261. https://doi.org/10.13141/jve.vol8.no5.pp257-261
Rambags, F., Raat, K.J., Zuurbier, K.G., Van den Berg, G.A., Hartog, N., 2013. Aquifer Storage and Recovery (ASR); Design and operational experiences for water storage through wells. Geochemistry 27, 2435–2452.
Shankel, J., 2020. Exploration of shallow sandy ridge systems for aquifer storage and recovery solutions in the Vietnamese Mekong Delta.
Shrestha, S., Bach, T.V., Pandey, V.P., 2016. Climate change impacts on groundwater

resources in Mekong Delta under representative concentration pathways (RCPs) scenarios. Environ. Sci. Policy 61, 1–13. https://doi.org/10.1016/j.envsci.2016.03.010
Smyle, J., Cooke, R., 2014. Comprehensive environment and Climate Change Assessment in Vietnam; International Fund for Agricultural Development.
Ta, T.K.O., Nguyen, V.L., Tateishi, M., Kobayashi, I., Tanabe, S., Saito, Y., 2002a. Holocene delta evolution and sediment discharge of the Mekong River, southern Vietnam. Quat. Sci. Rev. 21, 1807–1819. https://doi.org/10.1016/S0277-3791(02)00007-0
Ta, T.K.O., Nguyen, V.L., Tatheisi, M., Kobayashi, I., Saito, Y., 2002b. Sediment facies and late Holocene progradation of the Mekong River Delta in Ben Tre Province, Southern Vietnam: An example of evolution from a tide-dominated to a tide- and wave-dominated delta. Sediment. Geol. 313–325.
Tamura, T., Saito, Y., Bateman, M.D., Nguyen, V.L., Ta, T.K.O., 2012. Luminescence dating of beach ridges for characterizing multi-decadal to centennial deltaic shoreline changes during late Holocene, Mekong River delta. Mar. Geol. 326–328.
Tanabe, S., Ta, T.K.O., Nguyen, V.L., Tateishi, M., Kobayashi, I., Saito, Y., 2003. Delta evolution model inferred from the Holocene Mekong Delta, Southern Vietnam, in: Sidi, F.H., Nummedal, D., Imbert, P., Darman, H., Posamentier, H.W. (Eds.), Tropical Deltas of Southeast Asia—Sedimentology, Stratigraphy, and Petroleum Geology. SEPM Society for Sedimentary Geology, pp. 175–188. https://doi.org/10.2110/pec.03.76.0175
The National Assembly - The Socialist Republic of Vietnam, 2013. The constitution of The Socilatist Republic of Vietnam.
Tho, N., Vromant, N., Hung, N.T., Hens, L., 2008. Soil salinity and sodicity in a shrimp farming coastal area of the Mekong Delta, Vietnam. Environ. Geol. 54, 1739–1746. https://doi.org/10.1007/s00254-007-0951-z
Thu, P.M., Populus, J., 2007. Status and changes of mangrove forest in Mekong Delta: Case study in Tra Vinh, Vietnam. Estuar. Coast. Shelf Sci. 71, 98–109. https://doi.org/10.1016/j.ecss.2006.08.007
Tran, T.A., Rodela, R., 2016. Integrating farmers adaptive knowledge into flood management and adaptation policies in the Vietnamese Mekong Delta: A social learning perspective. Glob. Environ. Chang. 55, 84–96. https://doi.org/10.1016/j.gloenvcha.2019.02.004
Tran, T.H., Pittock, J., Tuan, L.A., 2019. Adaptive co-management in the Vietnamese Mekong Delta: Examining the interface between flood management and adaptation. Int. J. Water Resour. Dev. 35, 326–342. https://doi.org/10.1080/07900627.2018.1437713
Tuan, L.A., Hoanh, C.T., Miller, F., Sinh, B.T., 2007. Flood and salinity management in the Mekong Delta, Vietnam, in: Be, T.T., Sinh, B.T., Miller, F. (Eds.), Challenges to Sustainable Development in the Mekong Delta: Regional and National Policy Issues and Research Needs: Literature Analysis. Bangkok, Thailand: The Sustainable Mekong Research Network (Sumernet). pp. 15–68.
Van Bakel, P.J.T., De Louw, P.G.B., Massop, H.T.L., Stuyt, L.C.P.M., Tolk, L., Velstra, J., Hoogvliet, M., Nikkels, M.J., 2014. Methode voor het selecteren van lokale zoetwateroplossingen en het afwegen van hun effecten: “Fresh Water Options Optimizer,” KvK rapportnummer KvK141/2014 STOWA rapportnummer 2014-43.
Verduijn, H., 2020. 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, based on 3D Variable-Density Groundwater Modelling.
Vien, T.D., 2011. Climate change and its impact on agriculture in Vietnam. J. ISSAAS (International Soc. Southeast Asian Agric. Sci. 24(s1), 50–57. https://doi.org/10.2478/ahr-2021-0010
Vietnam-Netherlands, 2013. Mekong Delta Plan; Long-term vision and strategy for a safe, prosperous and sustainable delta.
Vormoor, K., 2010. Water engineering, agricultural development and socio-economic trends in the Mekong Delta, Vietnam. ZEF Work. Pap. Ser.
Witjes, M., 2018. Towards feasible strategies for reducing groundwater over-extraction in the Vietnamese Mekong Delta. Utrecht University.
World Wide Fund for Nature, 2004. Seven from mountain to sea: Asia Pacific river basin big wins.

A Appendix additional information field work studies

A.1 Field site BT2

A.1.1 Field impression







Canal: fresh in wet season, brackish in dry season.


A.1.2 Coring location

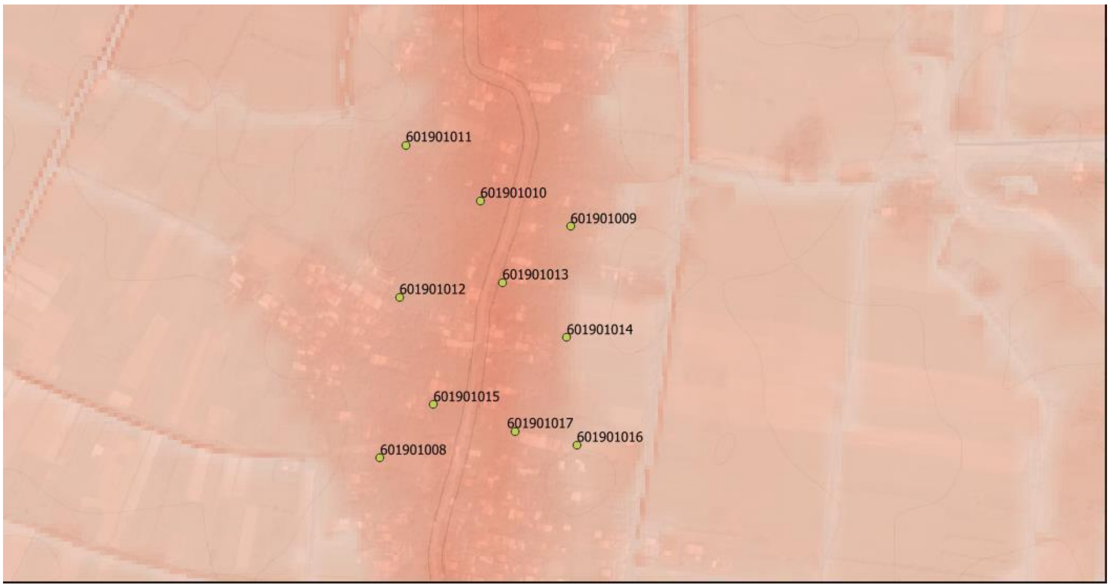


Figure 11-1: Coring location at the BT2.

A.1.3 Wellbore schematic

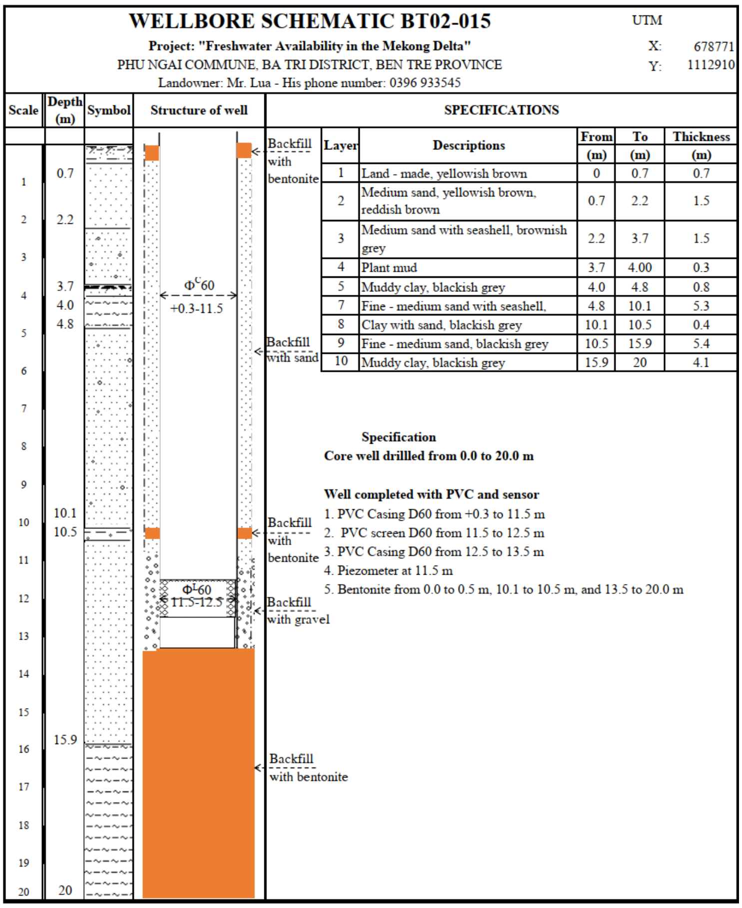


Figure 11-2: Well bore schematic of well 4 at the BT2.

A.1.4 Lithological column

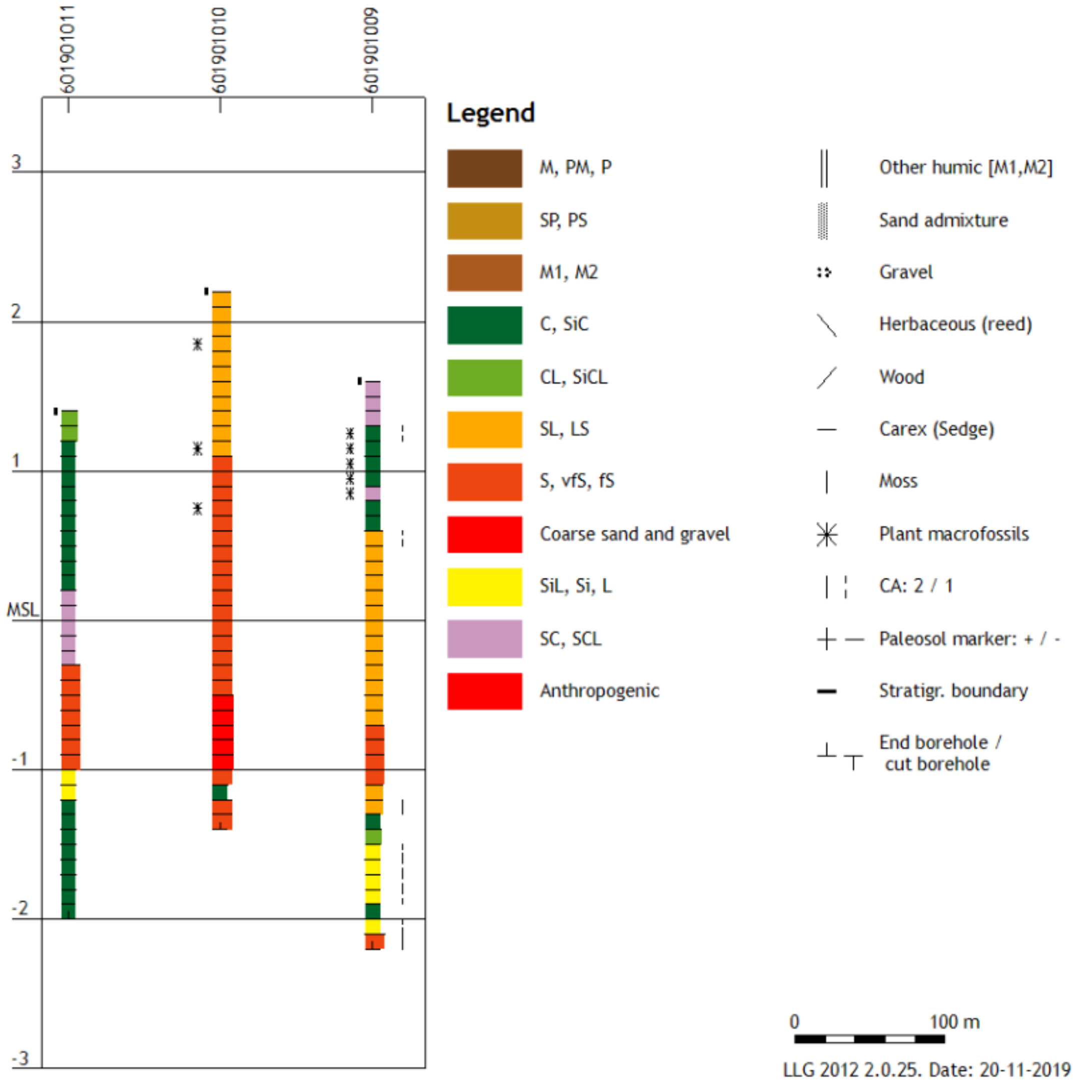
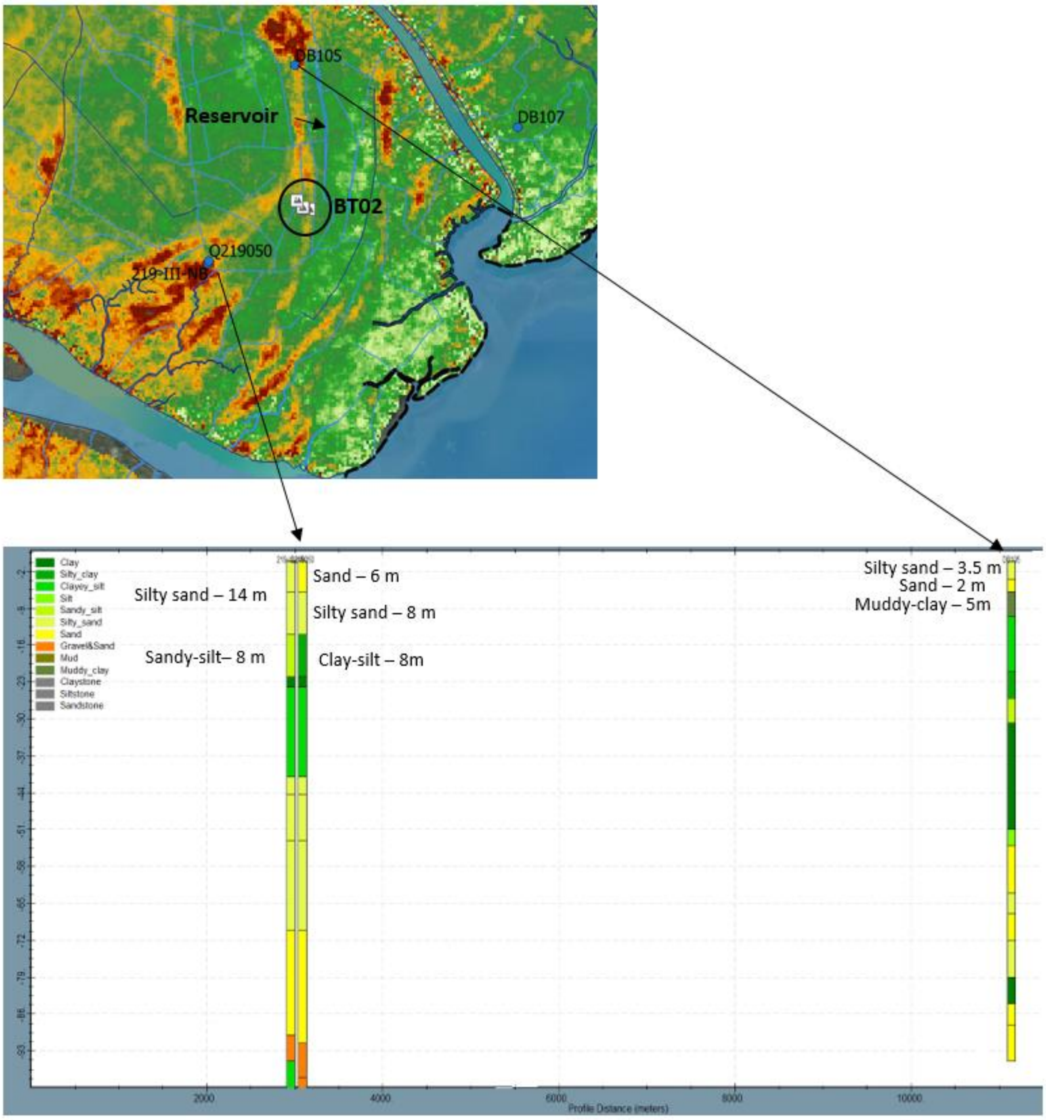


Figure 11-3: Lithological Cross section at the BT2.


DB105
Reservoir
DB107
BT02
Q219050
219-III-NB
Clay
Silty_clay
Clayey_silt
Silt
Sandy_silt
Silty_sand
Sand
Gravel&Sand
Mud
Muddy_clay
Claystone
Siltstone
Sandstone
Silty sand – 14 m
Sandy-silt– 8 m
Sand – 6 m
Silty sand – 8 m
Clay-silt – 8m
Silty sand – 3.5 m
Sand – 2 m
Muddy-clay – 5m
2000
4000
6000
8000
10000
Profile Distance (meters)

A.1.5 Lithological cross section

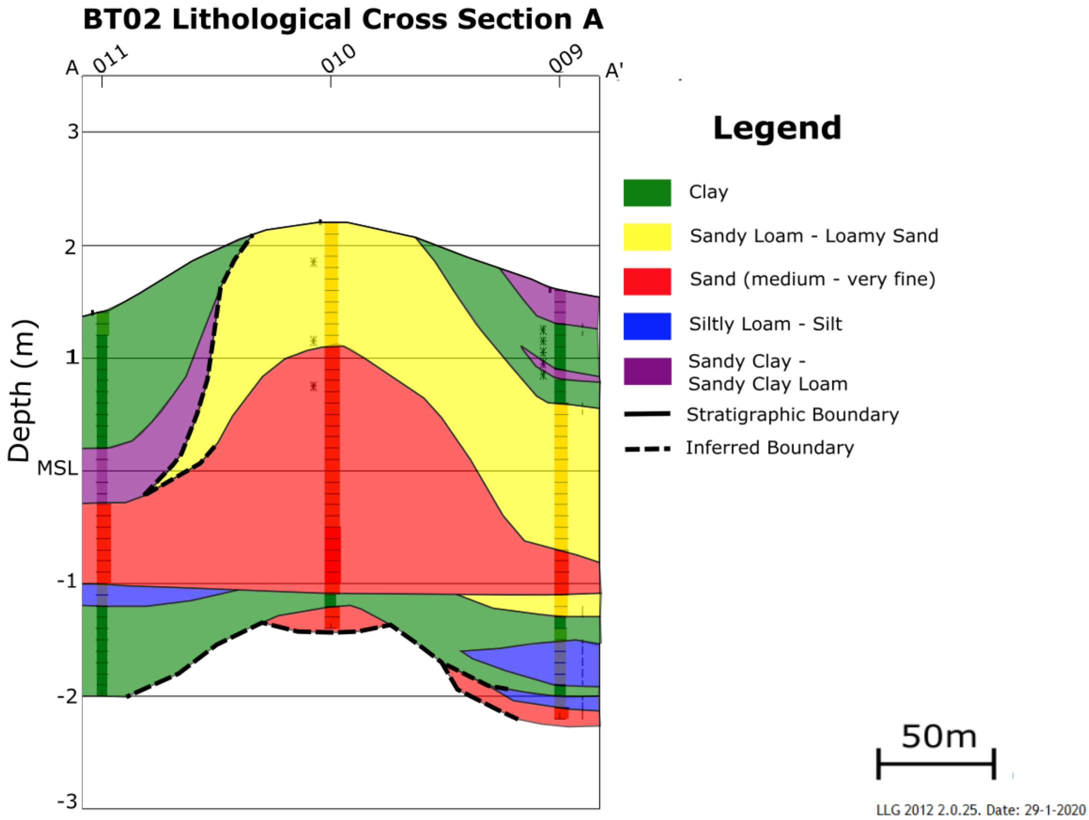


Figure 11-4: Lithological cross section of BT2.

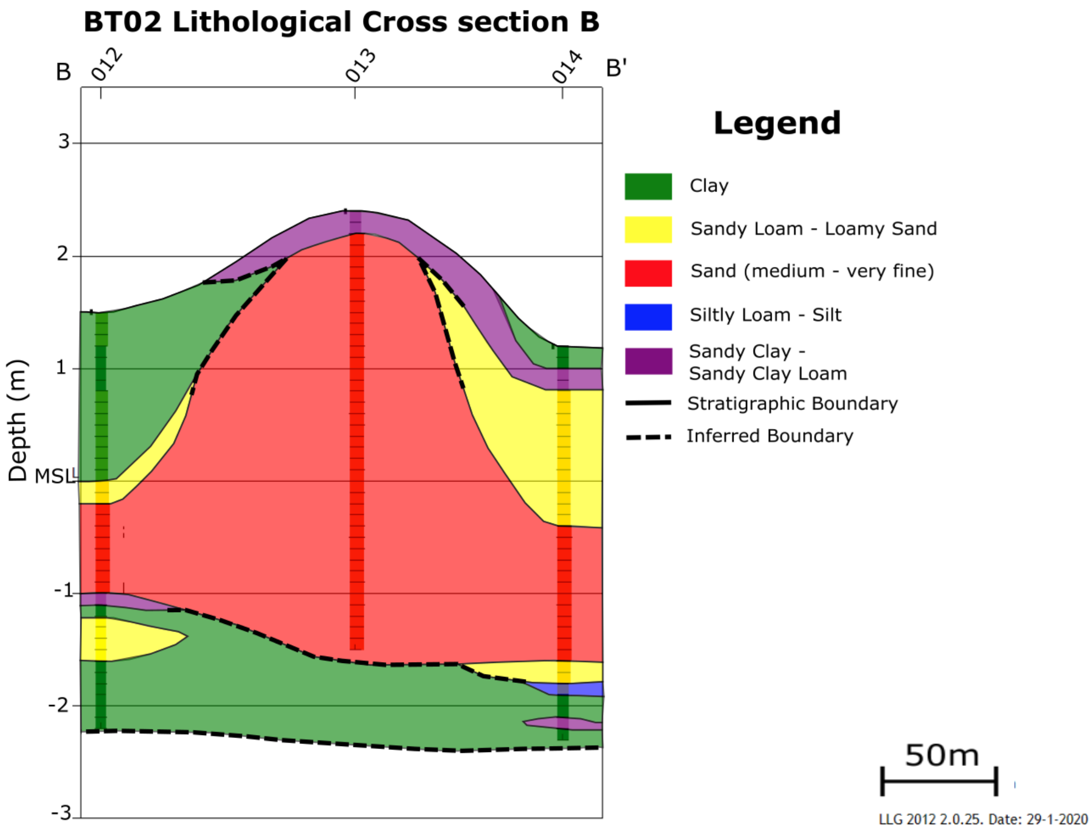


Figure 11-5: Lithological cross section of BT2.

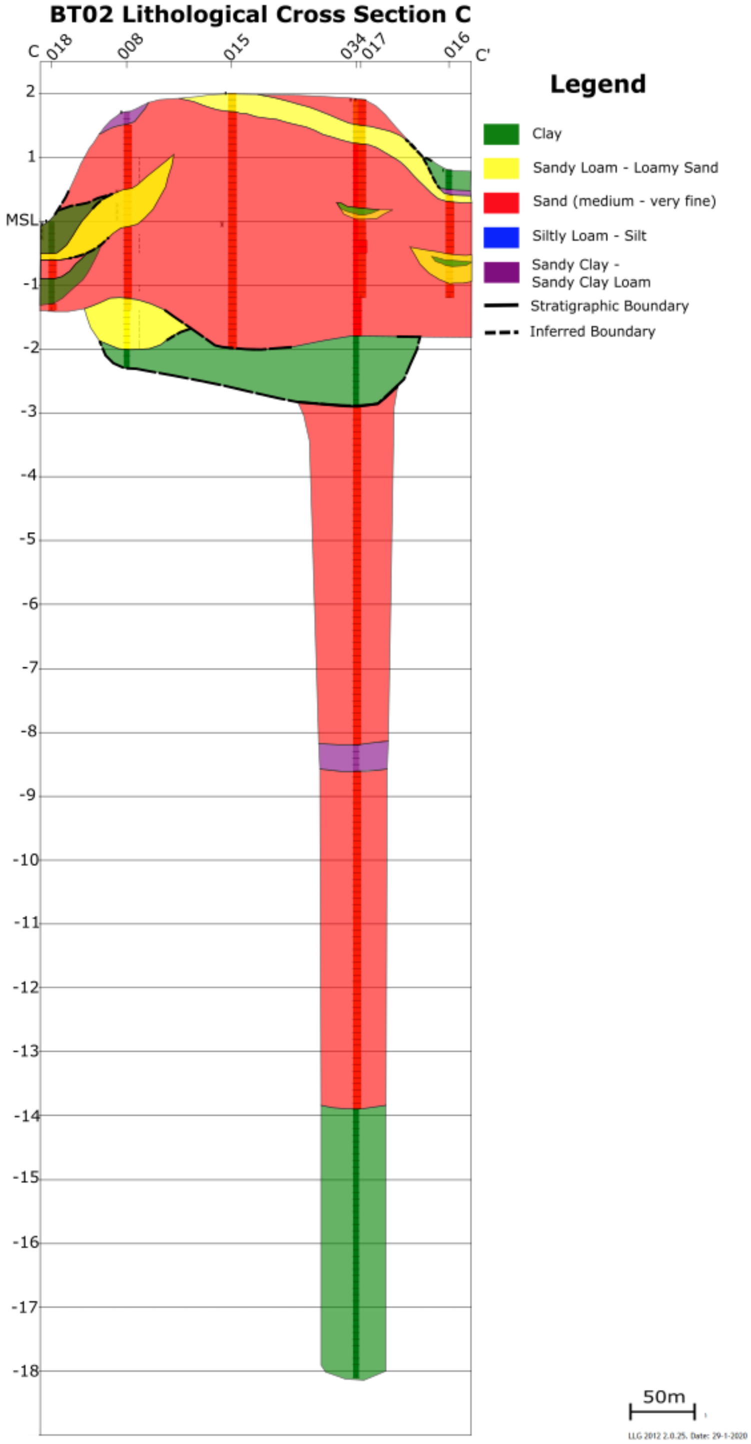


Figure 11-6: Lithological cross section of BT2.

A.1.6 Storage capacity

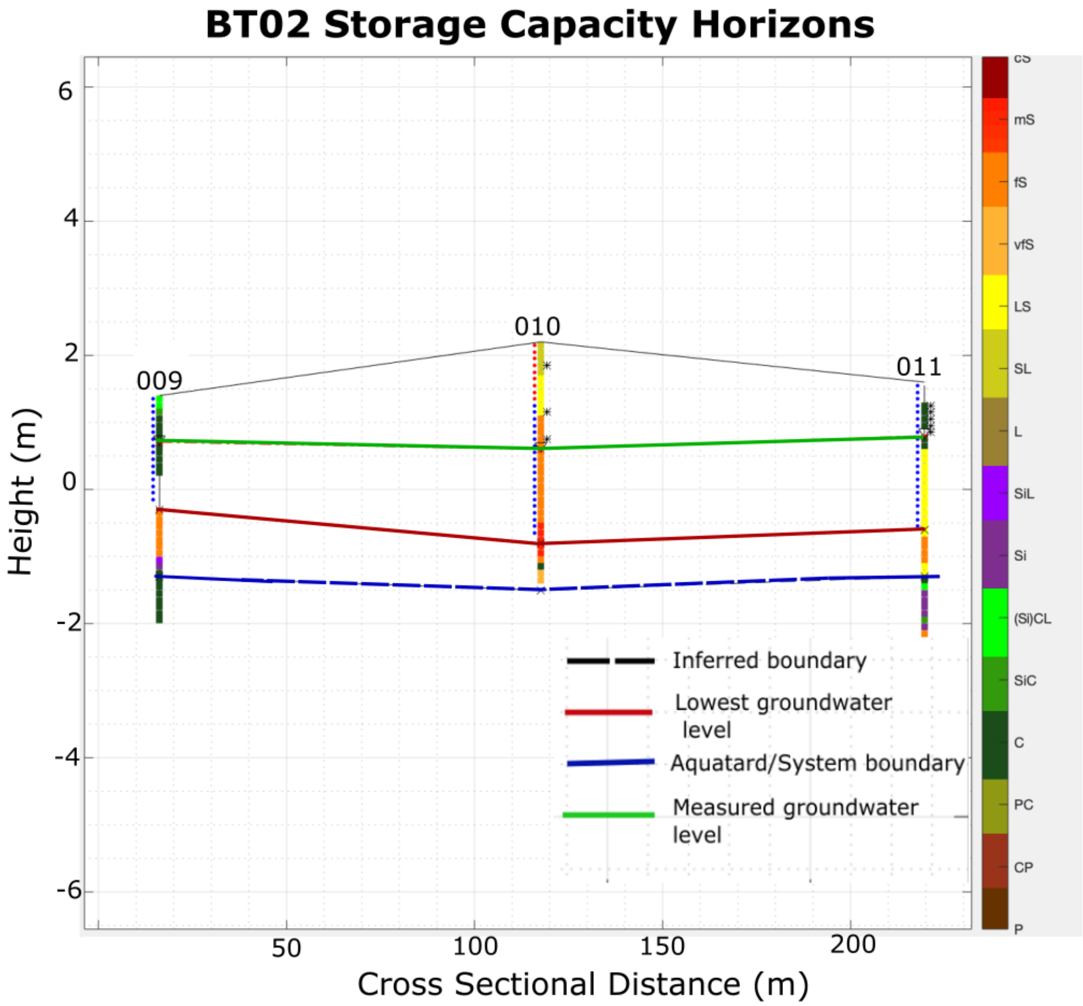


Figure 11-7: BT2 cross section depicting the surface level, groundwater level, lowest groundwater level and the base of the hydrogeological system.

A.1.7 Installed well

Figure 11-8: Well 2 and Well 3 at the BT2 site.

Figure 11-9: Well 4 at the BT2 site.

A.1.8 Water quality monitoring location

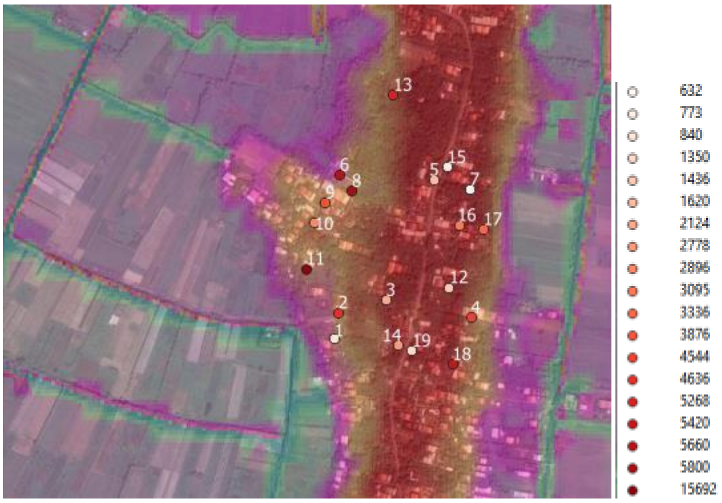


Figure 11-10: Salinity measurements in groundwater wells, legend showing the measured EC values in µS/cm.

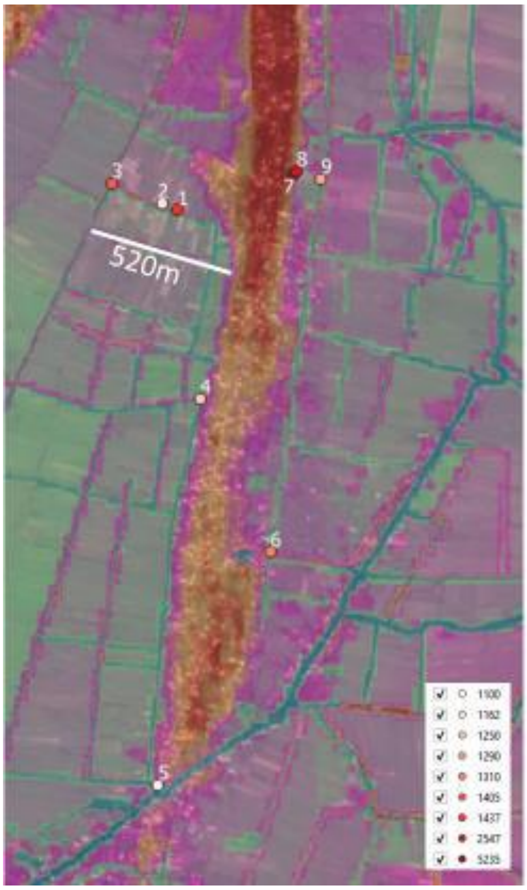


Figure 11-11: Surface water quality measurements, legend showing the measured EC values in µS/cm.

Figure 11-12: Small system of ditches west of dune (location 1) .

Figure 11-13: Small canal east of dune (location 9).

Figure 11-14: Example of a pump well (location 15).

Figure 11-15: Example of an open well (location 19).

A.2 Field site BT3

A.2.1 Field impression








A.2.2 Coring location

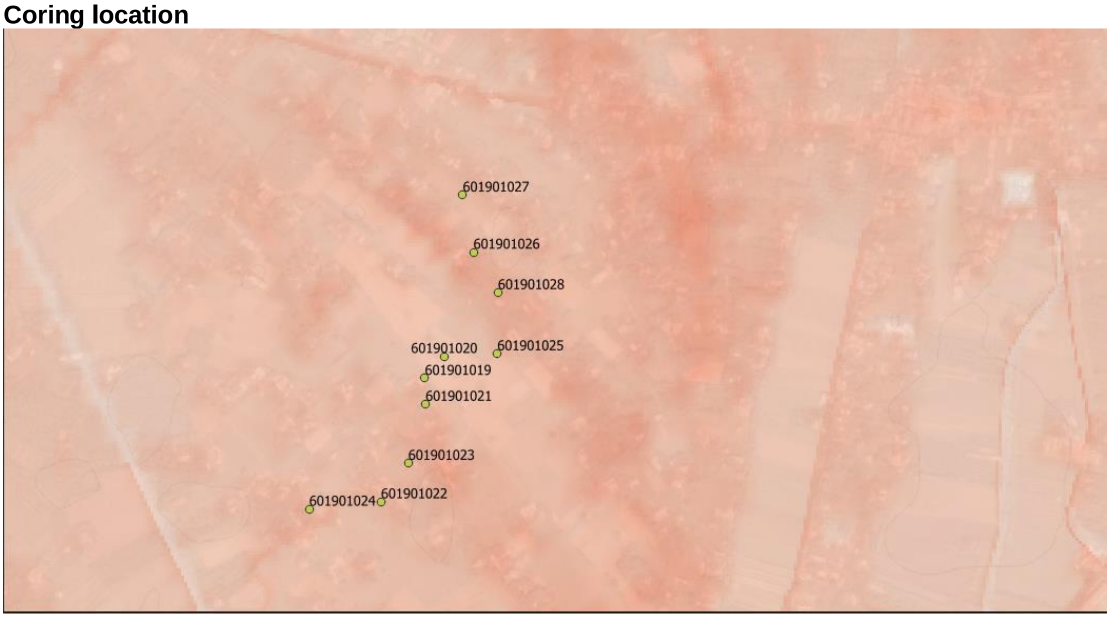


Figure 11-16: Coring location at the BT3.

A.2.3 Wellbore schematic

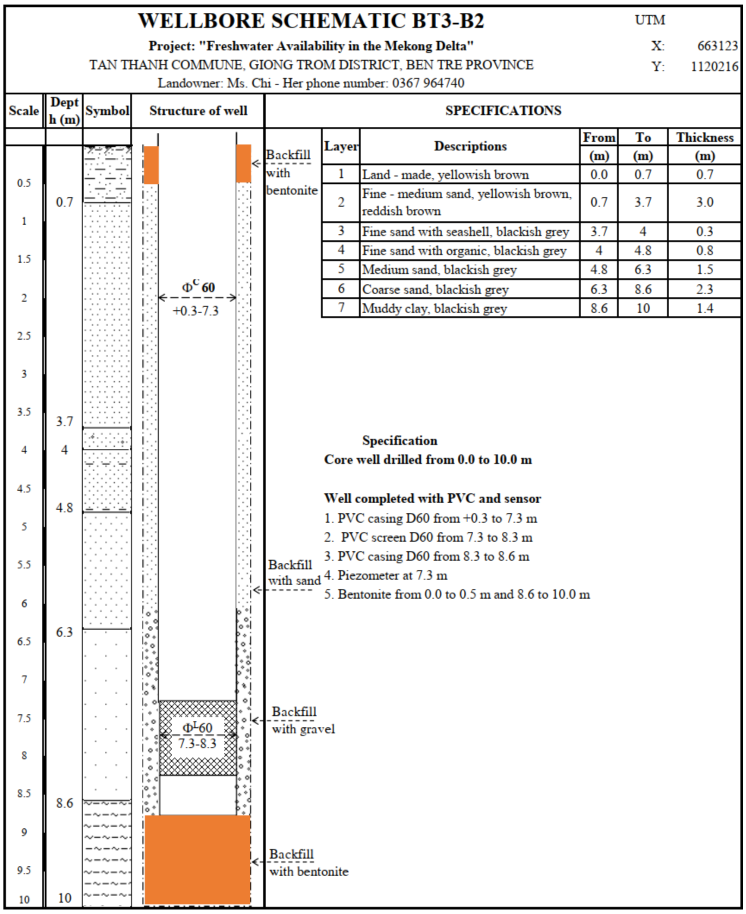


Figure 11-17: Wellbore schematic of well 2 at the BT3.

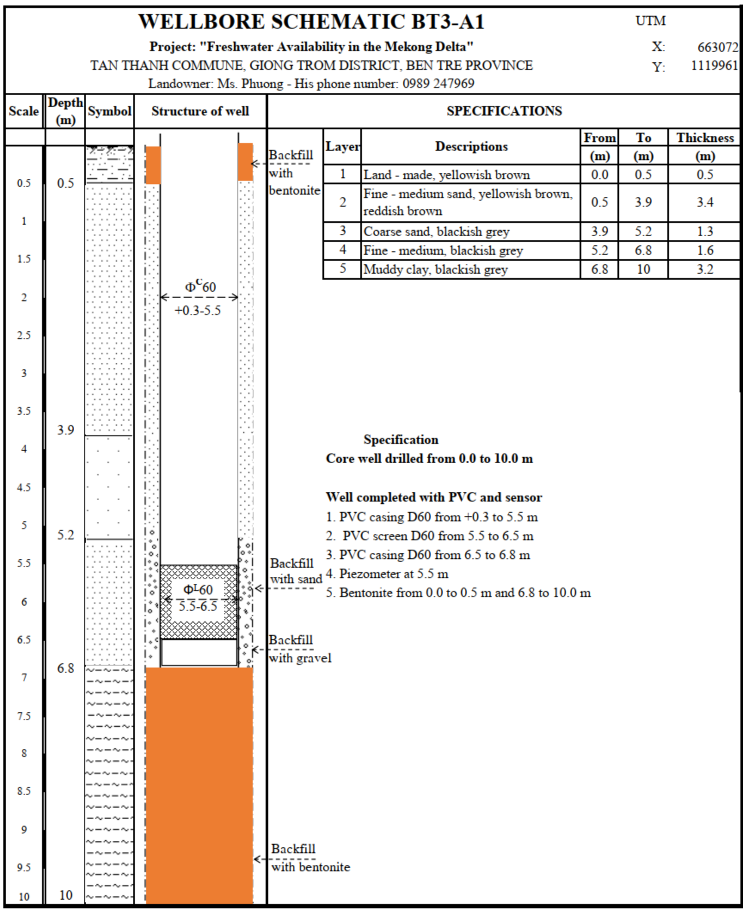
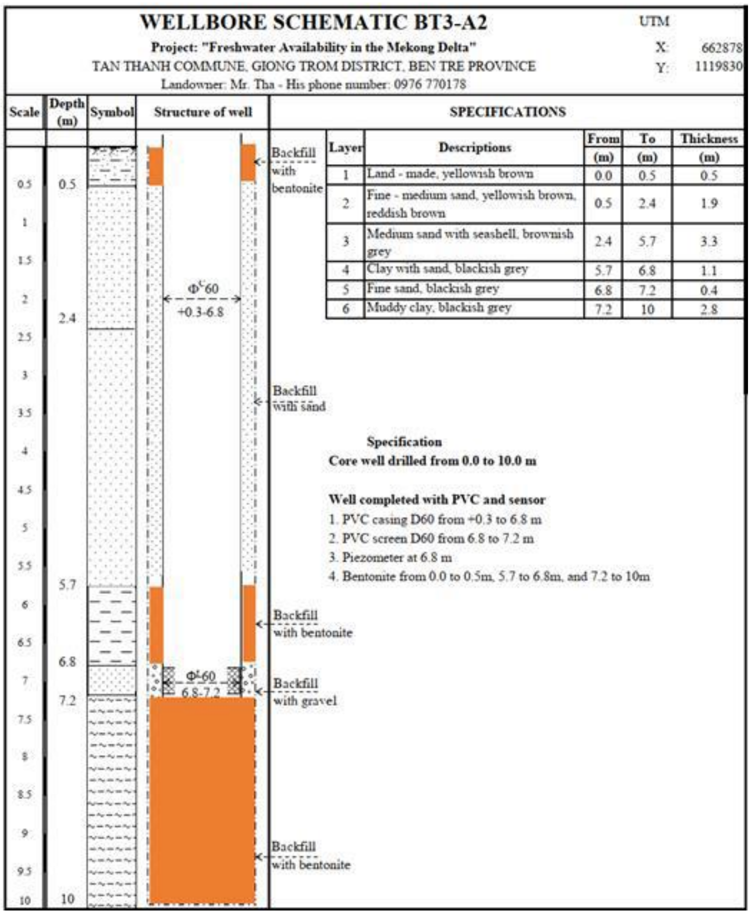


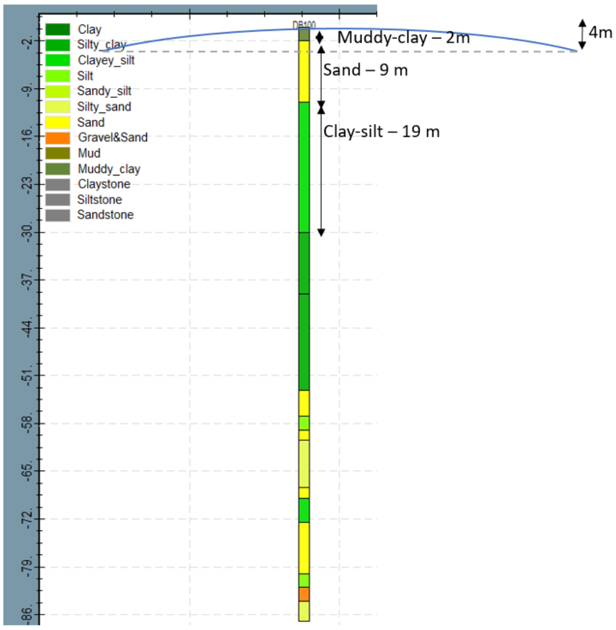
Figure 11-18: Wellbore schematic of well 3 at the BT3.



Layer	Descriptions	From (m)	To (m)	Thickness (m)
1	Land - made, yellowish brown	0.0	0.5	0.5
2	Fine - medium sand, yellowish brown, reddish brown	0.5	2.4	1.9
3	Medium sand with seashell, brownish grey	2.4	5.7	3.3
4	Clay with sand, blackish grey	5.7	6.8	1.1
5	Fine sand, blackish grey	6.8	7.2	0.4
6	Muddy clay, blackish grey	7.2	10	2.8

Figure 11-19: Well bore schematic of well 4 at the BT3.

A.2.4 Lithological column



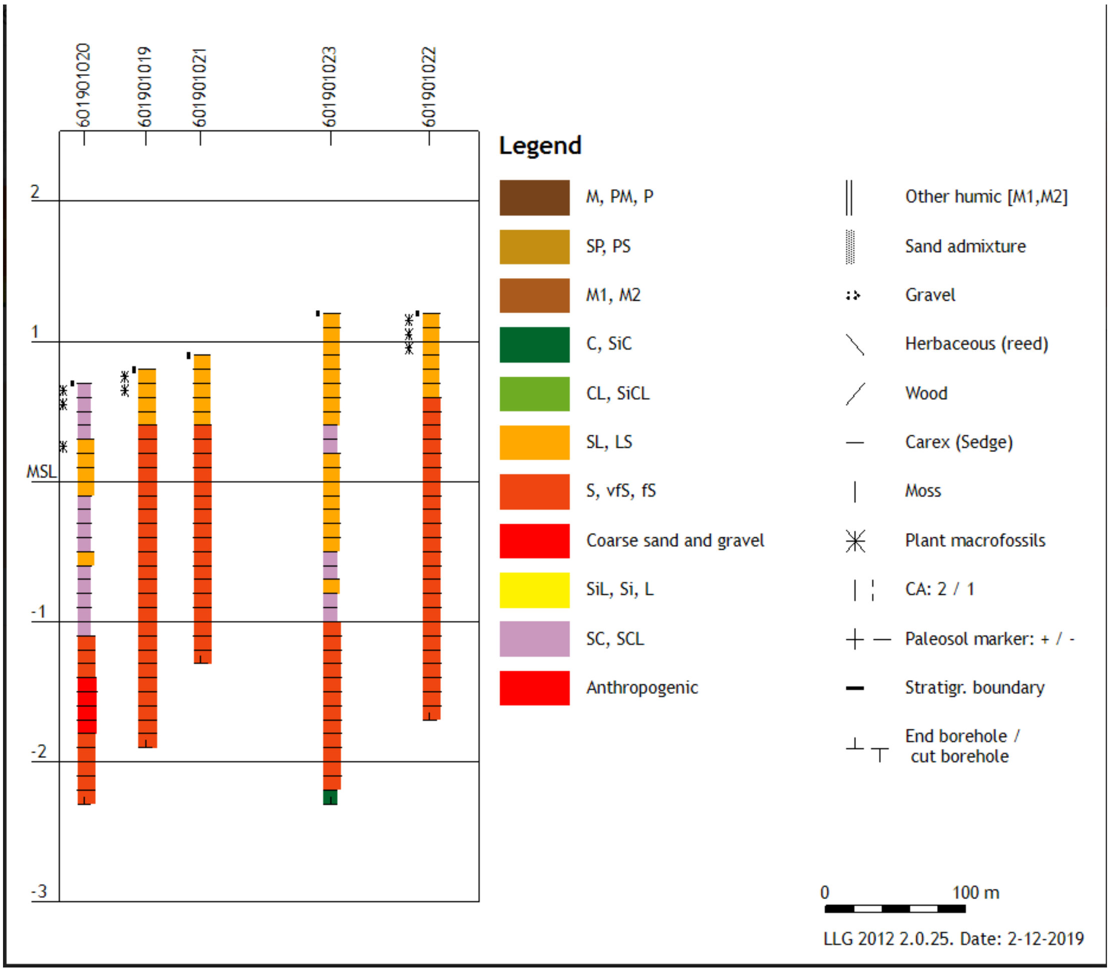


Figure 11-20: Lithological cross section at the BT3.

A.2.5 Lithological cross section

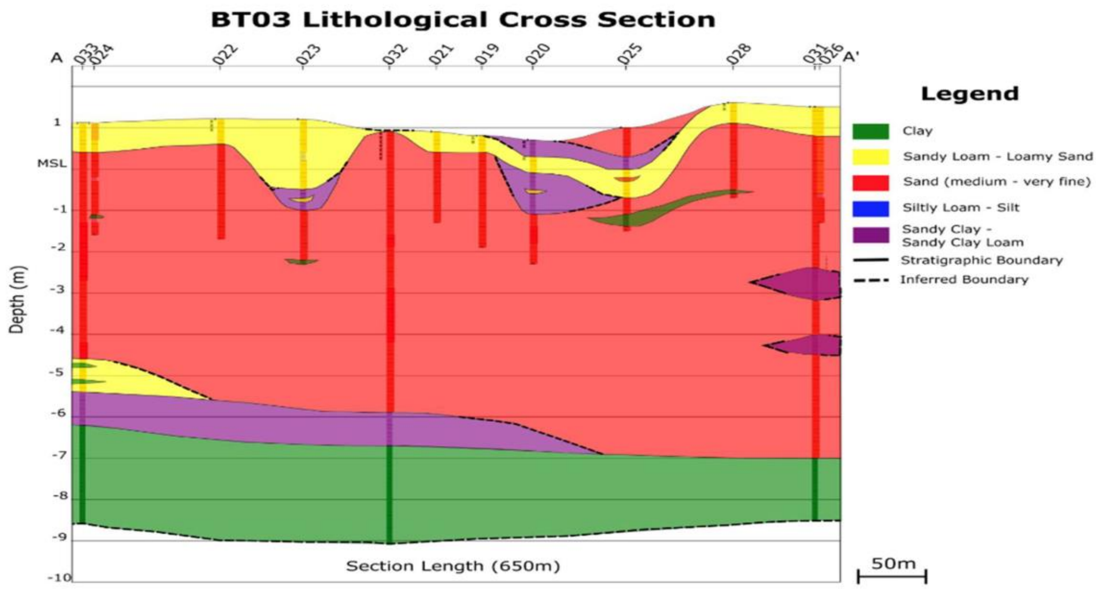


Figure 11-21: Lithological cross section of BT3.

A.2.6 Storage capacity

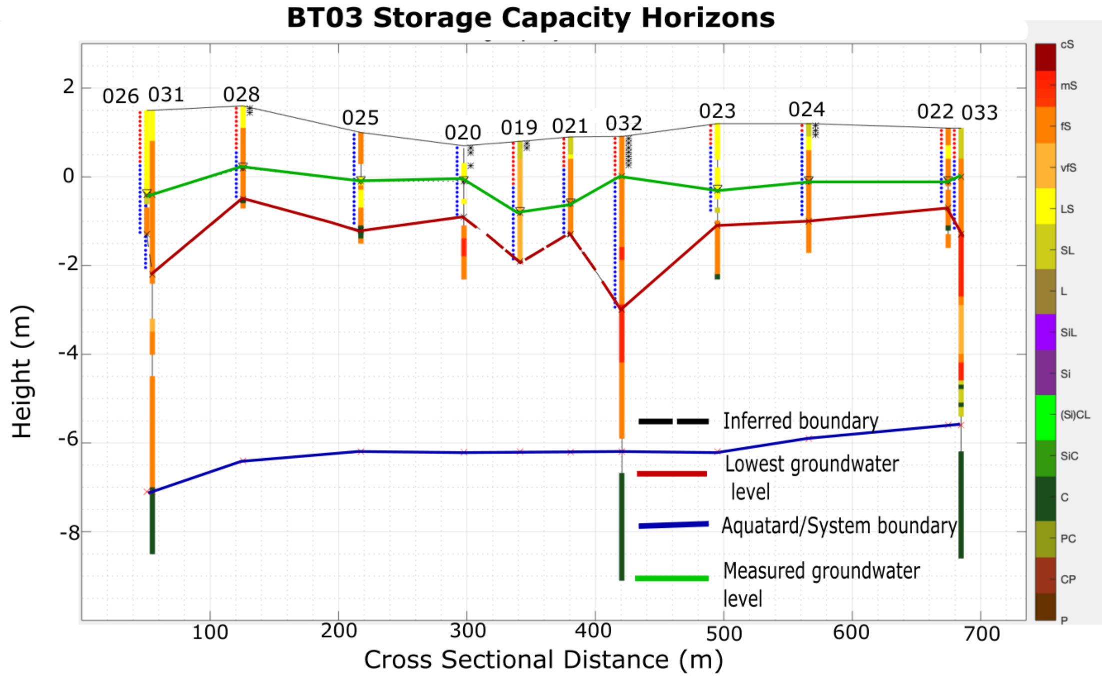


Figure 11-22: BT3 cross section depicting the surface level, groundwater level, lowest groundwater level and the base of the hydrogeological system.

A.2.7 Installed well

Figure 11-23: Installation of Well 1.

Figure 11-24: Well 2 (left) and landowner (upper middle) and Well 3 (lower middle) and location of Well 3 (right).

Figure 11-25: At Well 4.

A.2.8 Water quality monitoring location

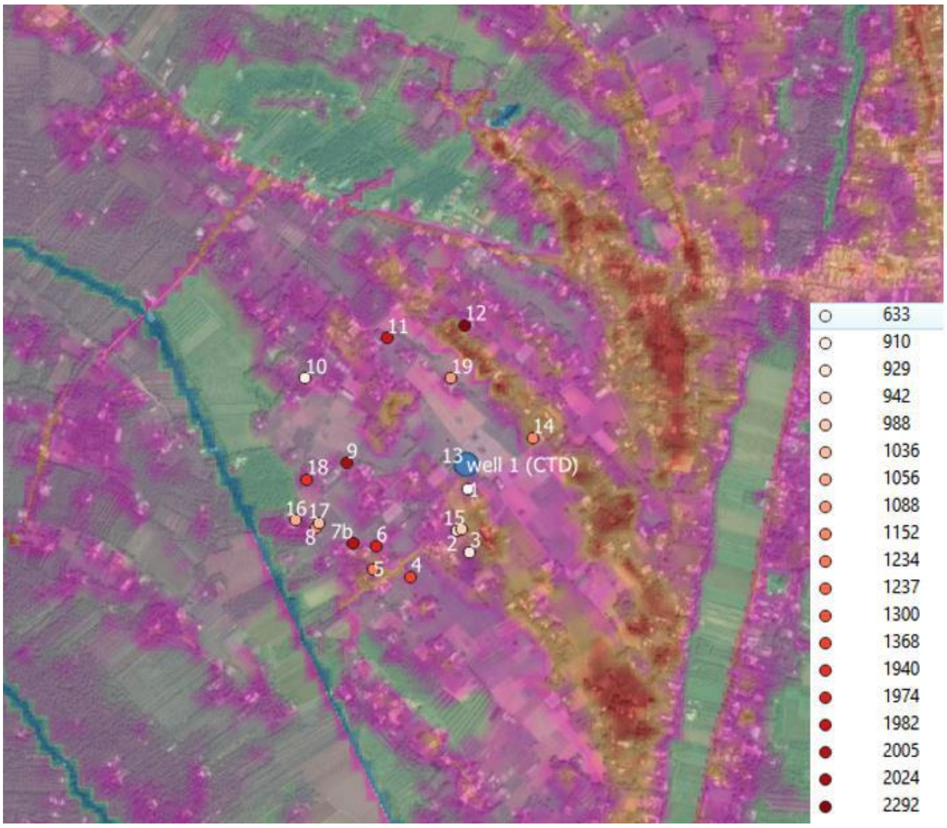


Figure 11-26: Salinity measurements in groundwater wells, legend showing the measured EC values in µS/cm.

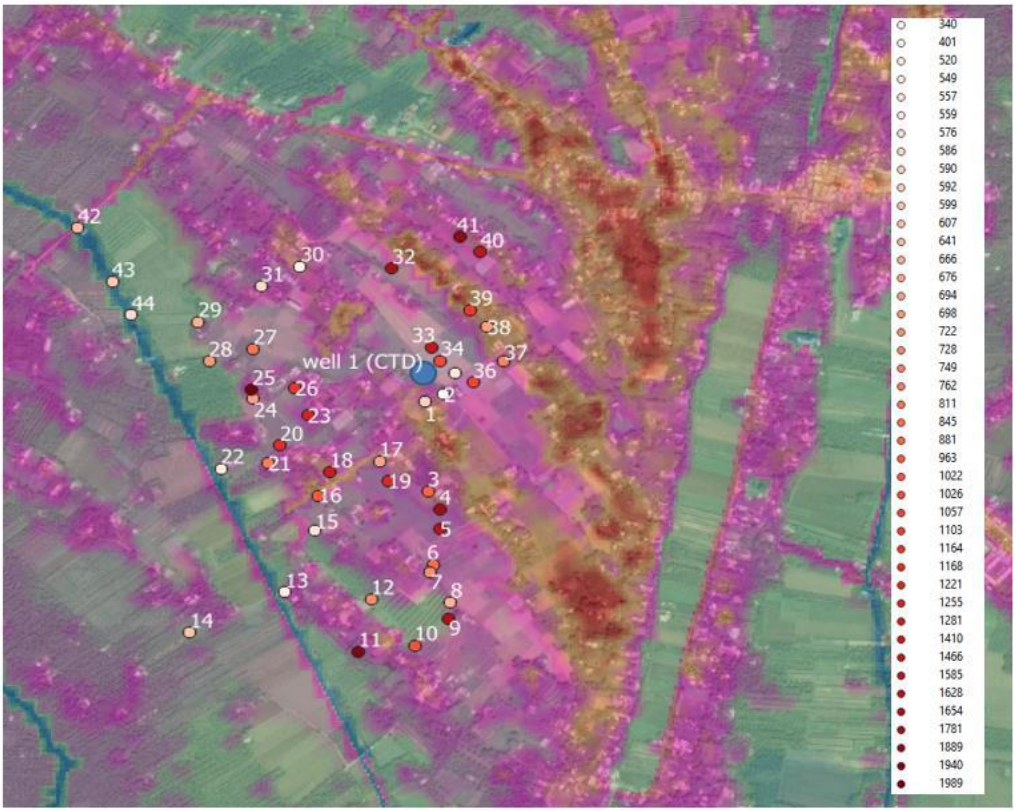
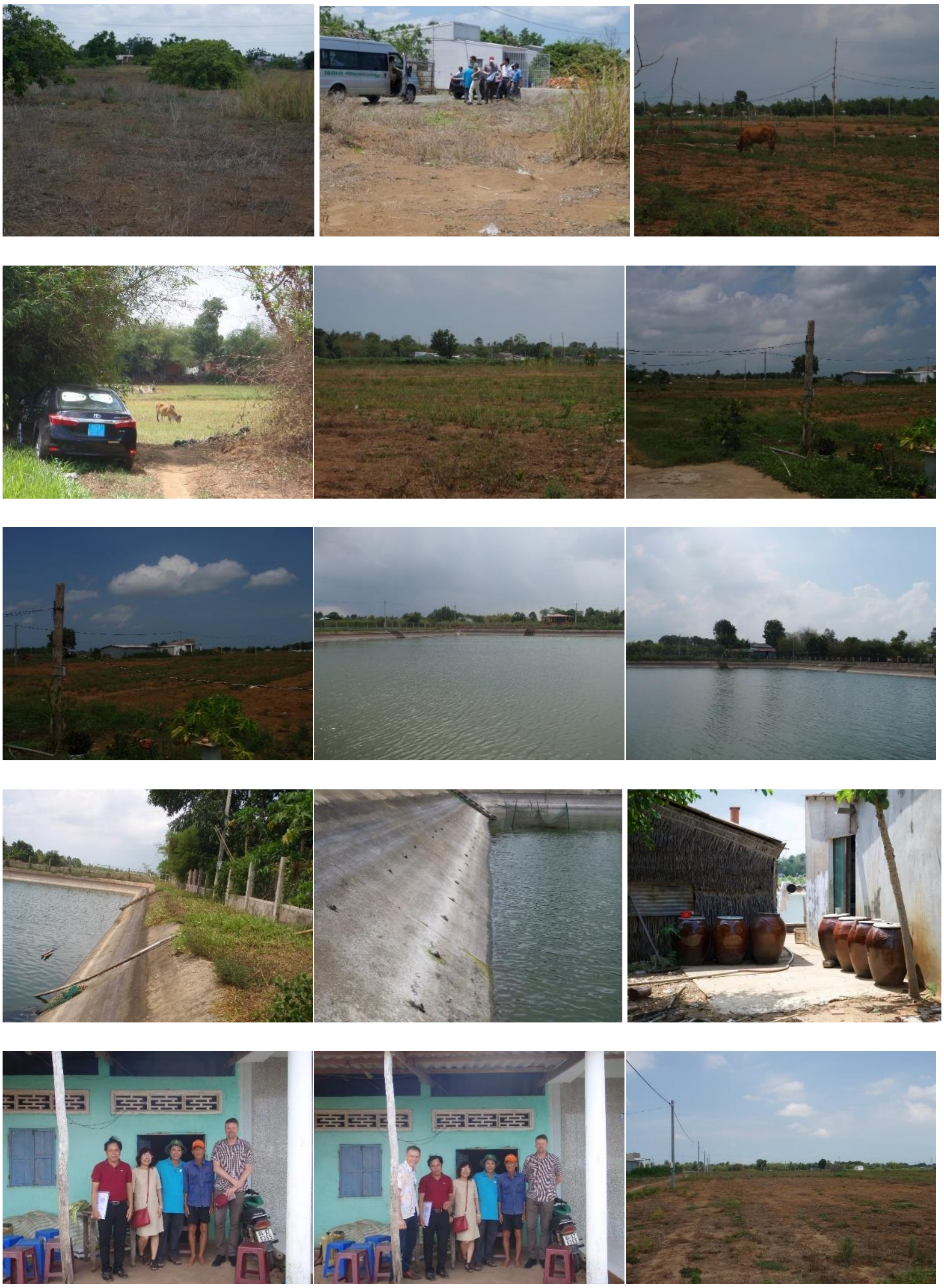


Figure 11-27: Surface water quality measurements, legend showing the measured EC values in µS/cm.

A.3 Field site TV2

A.3.1 Field impression













A.3.2 Coring location

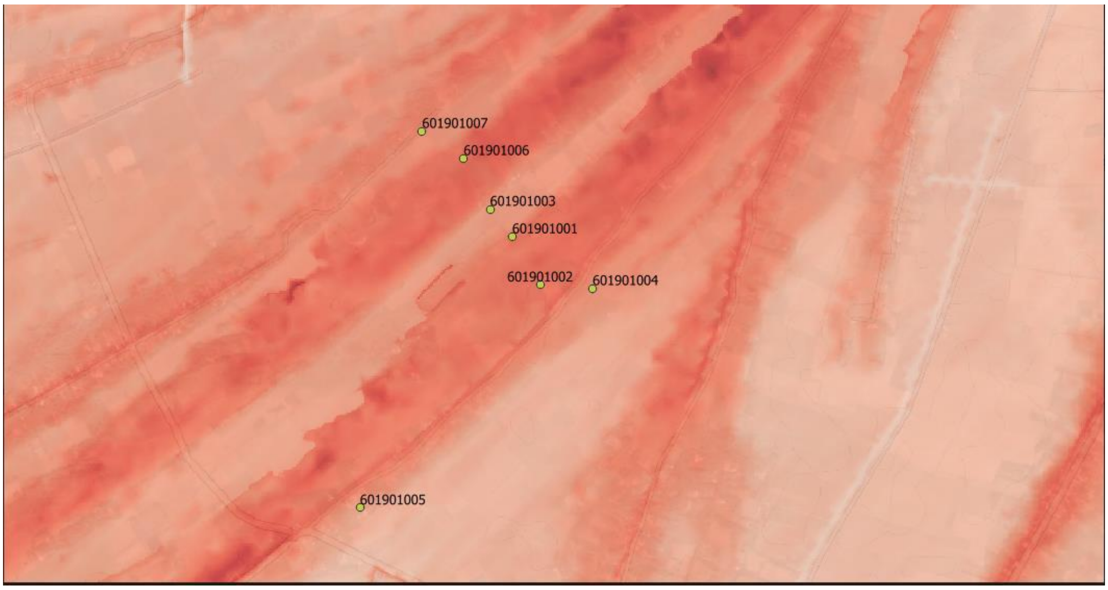


Figure 11-28: Coring location at the TV2.

A.3.3 Wellbore schematic

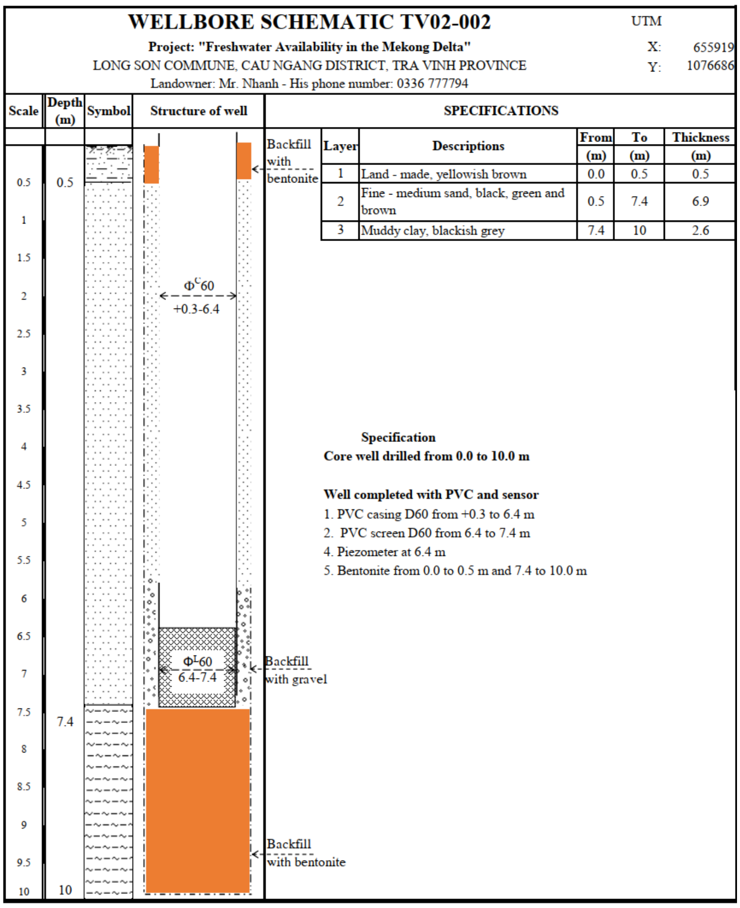
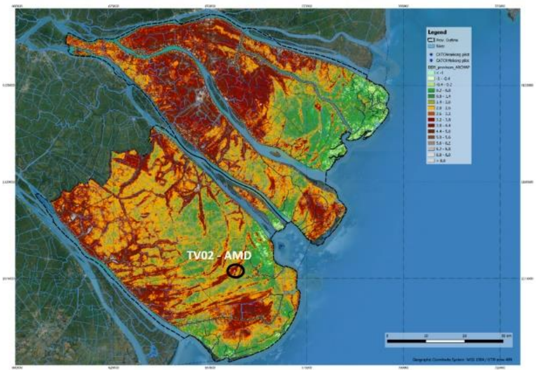
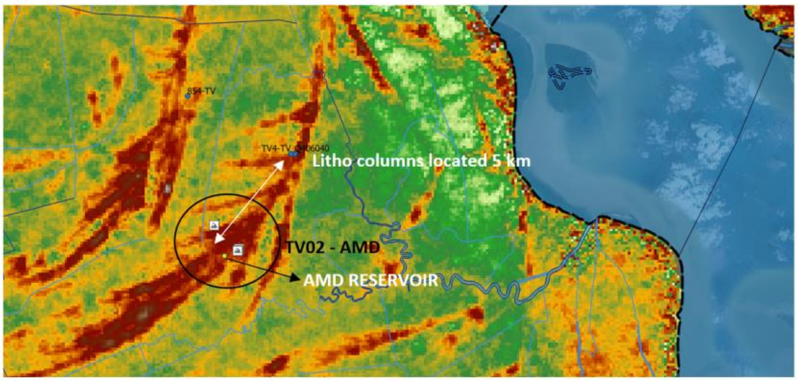


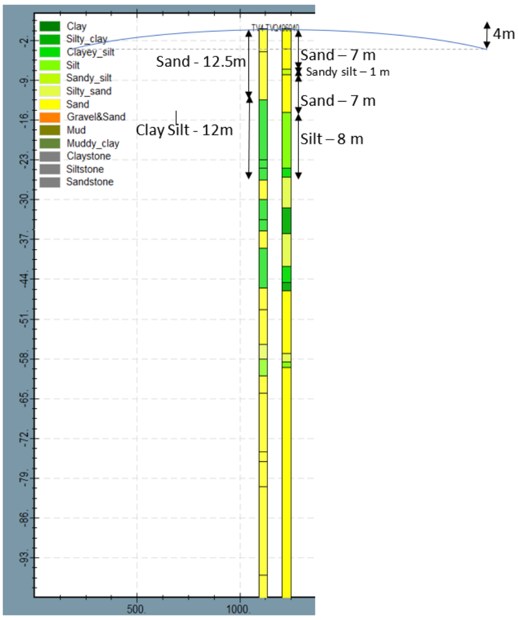
Figure 11-29: Well bore schematic of Well 2 at the TV2.

A.3.4 Lithological column





Sandy sediments up to 14 m with some thin sandy-silt layers.



Deltares

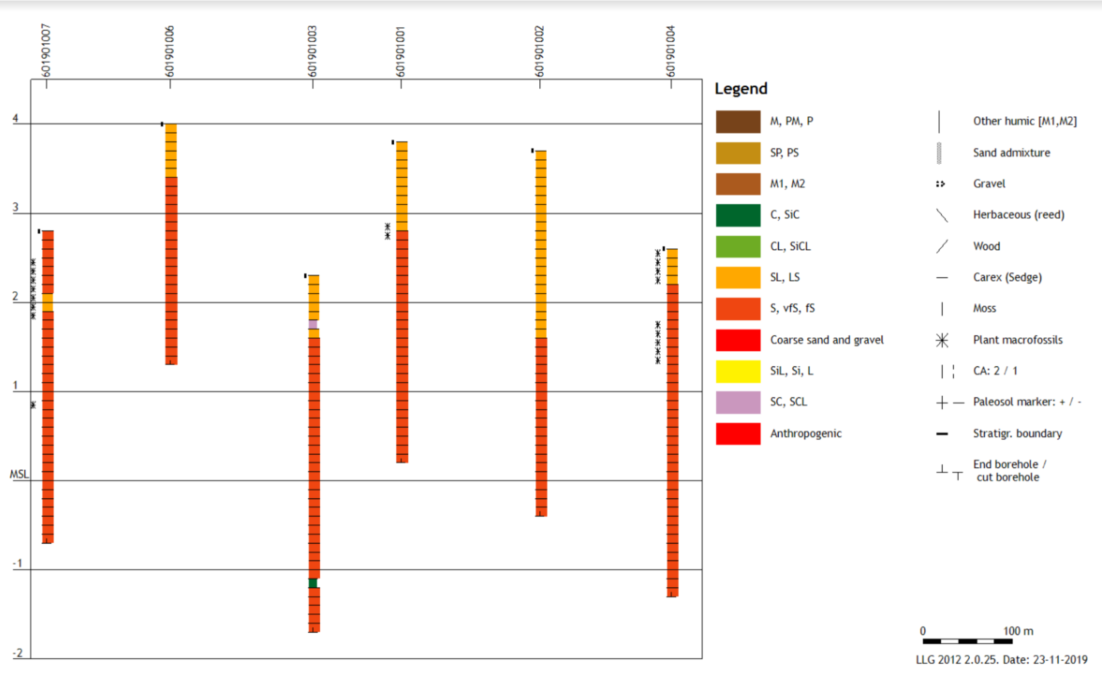


Figure 11-30: Lithological cross section at the TV2.

A.3.5 Lithological cross section

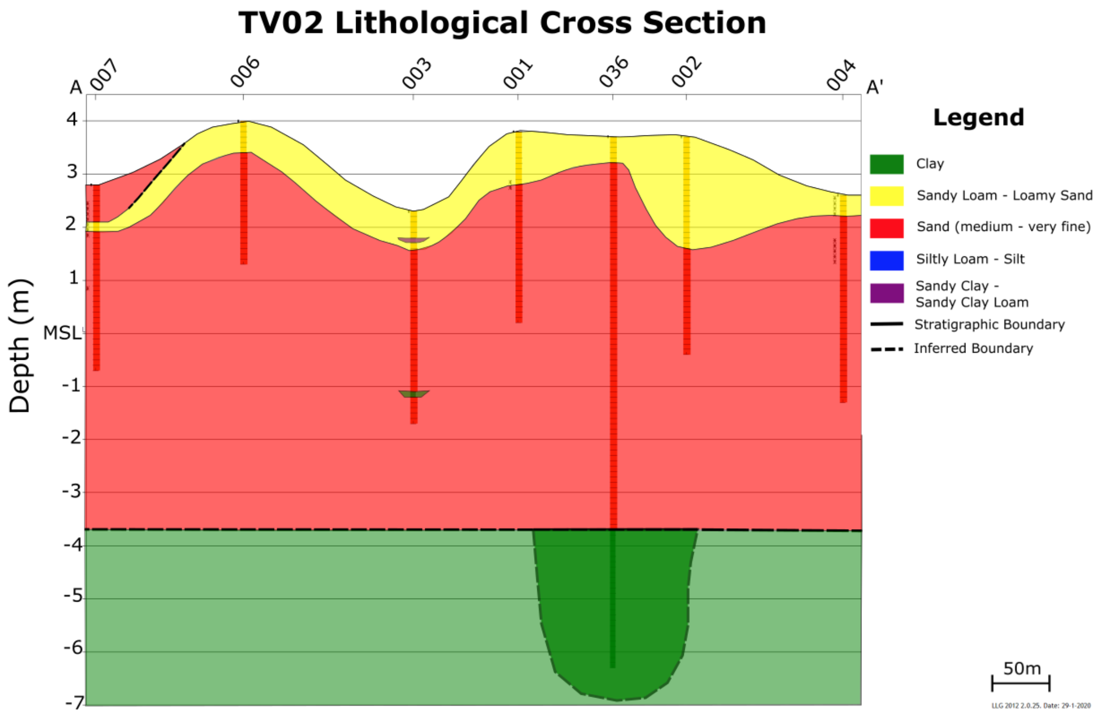


Figure 11-31: : Lithological cross section of TV2.

A.3.6 Storage capacity

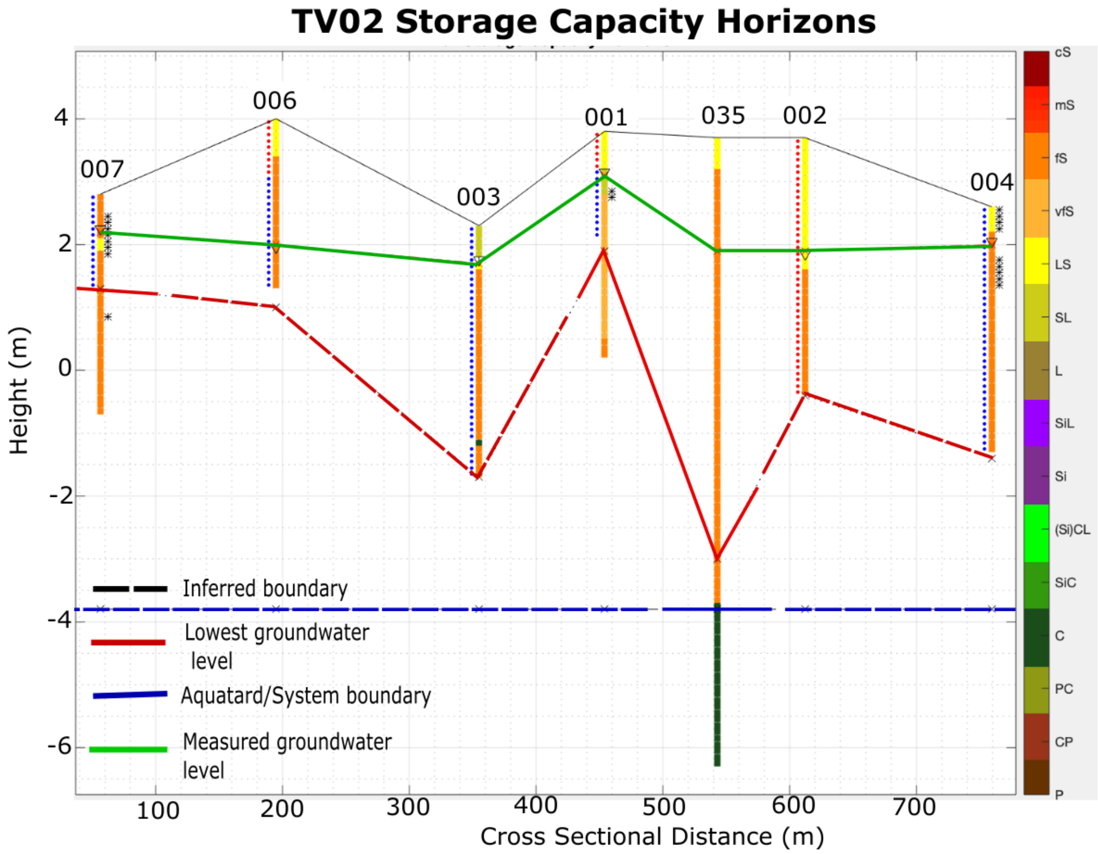


Figure 11-32: TV2 cross section depicting the surface level, groundwater level, lowest groundwater level and the base of the hydrogeological system.

A.3.7 Installed well

Figure 11-33: Well 1 installed at the TV2 site.

Figure 11-34: Well 2 installed at the TV2 site.

A.3.8 Water quality monitoring location

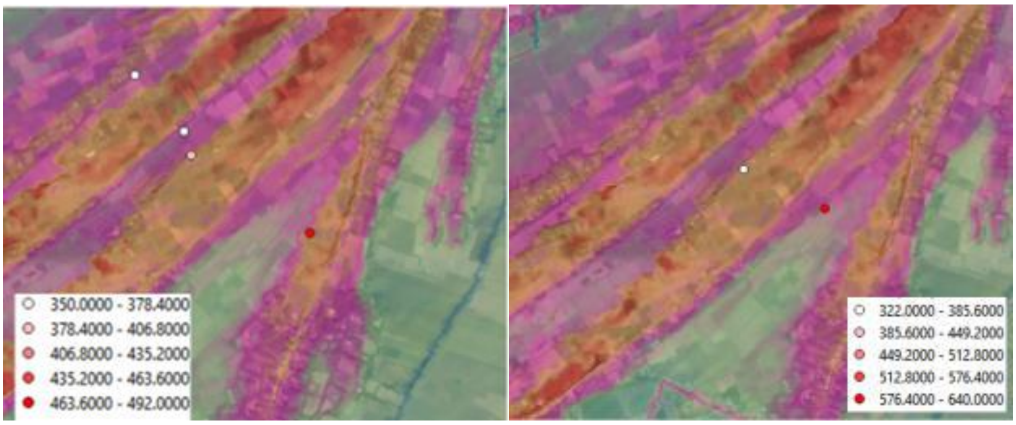


Figure 11-35: Surface water quality measurements (left) and salinity measurements in groundwater wells (right), legend showing the measured EC values in μS/cm.

B Appendix Workshop: Scoping phase, 7-8 May, 2019

Netherlands Enterprise Agency

WORKSHOP / HỘI THẢO

FAME: Freshwater Availability in the MEkong delta
FAME: Nguồn Nước Ngọt ở Đồng Bằng Sông Cửu Long

Date: 6th May 2019 / Ngày 6 tháng 5 năm 2019
Cuu Long Hotel / Khách sạn Cửu Long

Deltares WAGENINGEN UNIVERSITY & RESEARCH WACC Nelen & Schuurmans Royal HaskoningDHV PARTNERS FOR WATER

Workshop Agenda

Netherlands Enterprise Agency

10:00 – 10:15	**Registration**	**RHDHV**
10:15 – 10:30	Workshop intro, Participants presentation	RHDHV
10:30 – 10:50	Vietnam-Netherlands cooperation	Laurent Umans / Robert Proos Dutch Embassy/RVO
10:50 – 11:30	Freshwater Availability in the Mekong delta	Gualbert Oude Essink, Deltares
11:30 – 13:00	Lunch	
13:00 – 13:10	Water scarcity and water needs in Tra Vinh	DARD Tra Vinh
13:10 – 13:20	Water scarcity and water needs in Ben Tre	DARD Ben Tre
13:20 – 13:30	Groundwater use in Tra Vinh province	DONDRE Tra Vinh
13:30 – 13:40	Groundwater use in Ben Tre province	DONDRE Ben Tre
13:40 – 14:00	Mekong Delta Plan	Dung (WACC/WUR)
14:00 – 14:20	Adaptation to Climate Changes in the Mekong Delta	AMD (Tra Vinh/Ben Tre)
14:20 – 14:40	CATCH-Mekong project	Nguyen Hong Quan, WACC
14:40 – 15:00	Coffee break	
15:00 – 15:20	Quality and fresh/saline distribution of groundwater in the Mekong Delta	Hung Van Pham, DWRPIS
15:20 – 15:40	Groundwater and livelihood	Andrew White
15:40 – 16:00	SALINEPROVE project	IHE (presented by Gu Oude Essink - option)
16:00 – 17:30	Discussion session Methods, hydrogeological analysis, potential locations for pilots, cooperation – farmers	All – Leading Gu Oude Essink

Deltares WAGENINGEN UNIVERSITY & RESEARCH WACC DWRPIS Nelen & Schuurmans Royal HaskoningDHV Enhancing Society Together PARTNERS FOR WATER

Table 24: List of participants of workshop scoping phase

No	Name	Organization
1	Nguyễn Hồng Quân	Organizer
2	Phạm Văn Hùng	Organizer
3	Trần Đức Dũng	Organizer
4	Gualbert Oude Essink	Organizer
5	Robert Proos	Organizer
6	Laurent Umans	Organizer
7	Đỗ Thị Hoài Thanh	Organizer
8	Hoàng Vỹ	Translator
9	Huỳnh Yến Vân	Bến Tre DONRE
10	Lâm Văn Duyên	AMD Project Trà Vinh
11	Huỳnh Nghĩa Thọ	AMD Project Trà Vinh
12	Đoàn Thị Lan Anh	AMD Project Bến Tre
13	Nguyễn Khắc Hân	AMD Project Bến Tre
14	Mạc Tấn Lâm	Tra Vinh Water Supply
15	Vũ Đình Trác	Bến Tre DARD
16	Phạm Trung Tính	Bến Tre DARD
17	Lê Phước Toàn	Trà Vinh DARD
18	Lê Đăng Khôi	Tra Vinh Center of Water supply and sanitation for Rural
19	Trần Thanh Phong	Tra Vinh DONRE
20	Nguyễn Ngọc Quang	IFAD

Figure 11-36: Impression of workshop scoping phase.

Figure 11-37: Impression of workshop scoping phase.

C Appendix Online Workshop: Feasibility and upscaling, 2-3 September, 2021

Freshwater Availability in the Mekong Delta (FAME)

Mission Report

Second Workshop FAME: Feasibility and Upscaling of ASR systems in the Mekong Delta

1. The FAME Project

Freshwater Availability in the Mekong Delta (FAME) is a collaborative, multiphase project focusing on scoping, piloting and providing upscaling advice to national partners in Vietnam on how and where to implement Aquifer Storage and Recovery (ASR) systems. ASR systems could be farm scale solutions to address freshwater quality and availability issues being faced within the Ben Tre and Tra Vinh provinces of the Mekong Delta, Vietnam.

The objectives of FAME are:

- Selecting possible ASR locations in two coastal provinces; Ben Tre and Tra Vinh
- Collecting data and information to obtain insights to improve sustainable fresh groundwater resources management at farmer scale level
- Creating a provincial overview of the potential ASR technologies, such as possibility of restoring phreatic fresh groundwater, deep well infiltration, or the construction of fresh groundwater reservoirs
- Studying, designing and running of an ASR pilot for more sustainable fresh groundwater resources management and efficient water use in the pilot area
- Monitoring the status of surface and groundwater quality in the pilot area
- Making recommendations for upscaling potential ASR measures, plans and guidelines for sustainable water use and related potential for food security and livelihood systems in which surface and groundwater are integrated.

FAME started in December 2018 and it is planned to be completed at the end of 2021. Within FAME, three potential sites to install an ASR pilot have been evaluated; two sites in the province of Ben Tre and one site in the province of Tra Vinh. After conducting field work to characterize the sites, monitor the water levels in surface and groundwater, and conduct water quality analysis, Tra Vinh has been chosen as the site for the pilot installation. According to the approval document No. 1657/UBND-NN dated May 7, 2020 of the Tra Vinh Provincial People's Committee and Official Letter No. 1169/STNMT-QLTNB dated May 21, 2021 of the Tra Vinh

Department of Natural Resources and Environment responding to the proposal from Deltares– the representative of project partners, a pilot model of the ASR system is planning to be installed for the shallow groundwater, aquifer on the sand dunes from the lake invested through the AMD project in Long Son Commune, Cau Ngang district, Tra Vinh province in the last quarter of 2021. The pilot model will aim to store freshwater underground so it can be used during the dry season when surface water turns saline. The second workshop as scheduled in the project plan is expected to be held in Tra Vinh in the 3rd quarter in 2021. However, due to the co-vid crisis emerge in the southern Vietnam, it was finally organized virtually via Zoom Webinar platform from 14.00 to 16.30 pm on 27th August 2021. The objectives, tentative agenda and list of participants can be found detailed in following chapters.

Objectives of second workshop:
The workshop on feasibility and upscaling of ASR systems in the Mekong Delta is organized after the field work investigations phase, after more insights have been gained on the characteristics of the selected sites, and to introduce the ASR pilot that is planned to be installed in the Tra Vinh province.

The main goals of the workshop are:
- To give an update of the project progress
- To share new experiences of ASR in other areas
- To introduce the selected pilot site and installation planning
- To discuss findings on the feasibility of the ASR systems and the possibility for upscaling in the Mekong Delta

2. Workshop agenda

Time: 14.00 – 16.30 pm, 27th August 2021
Location: Zoom Webinar

Time	Description	Presenters
14.00 – 14.10	Panelists Introduction and Welcome section	Dr. Nguyễn Hồng Quân, Vietnam National University HCM City
14:10 – 14:20	Opening Speech and Presentation by the Embassy of the Kingdom of the Netherlands in Vietnam	Dr. Laurent Umans, First Secretary Water Management and Cimate Change
14:20 – 14:25	Mentimeter (Participant Introduction)	Ms. Mila Mahya, Deltares
14:25 – 14:35	Project overview and progress	Ms. Marta Faneca Sànchez, Deltare
14:35 – 14:45	Broader context, introduction to Aquifer Storage and Recovery (ASR) and related projects in Vietnam	Dr. Gualbert Oude Essink, Deltares
14:45 – 14:55	Dynamics of salt intrusion in the Mekong Delta	Dr. Sepehr Eslami, Deltares
14:55 – 15:05	Other similar international experiences	Ms. Marta Faneca Sànchez, Deltares
15:05 – 15:10	Break	
15.10 – 15.20	Introduction to the pilot site and installation planning	Mr. Phạm Văn Hùng , Division for Water Resources Planning and

		Investigation for the South of Vietnam
15.20 – 15.30	Potential for upscaling in the Mekong Delta – And what to do next	Dr. Gualbert Oude Essink, Deltares
15.30 – 15.45	Mentimeter	Ms. Mila Mahya, Deltares
15.45 – 16.15	Q&A and live discussion with panelists	Dr. Nguyễn Hồng Quân, Vietnam National University HCM City
16.15 – 16.20	Wrap-up and Closing	Dr. Gualbert Oude Essink, Deltares and Dr. Nguyễn Hồng Quân, Vietnam National University HCM City

3. List of participants

#	Name of participants	Organization	Email
1	Laurent Umans	Dutch Embassy	laurent.umans@minbuza.nl
2	Eunice Doan	NL Consulate General	doantranthaonguyen@hotmail.com
3	Uyen Pham Minh	Dutch Embassy	minhuyen18@gmail.com
4	Nguyen Ngoc Quang	IFAD	quangnguyenvn@gmail.com
5	Chinh	Tra Vinh DARD	chinhsnntv@yahoo.com.vn
6	Dang Anh Tam	Tra Vinh AMD PCU	anhtamtv@gmail.com
7	SME Tra Vinh	SME Tra Vinh	duan@smetravinh.vn
8	Cty CP Cấp thoát nước Bến Tre	Ben Tre Water Supply Company	infobewaco@gmail.com
9	Đoàn Lan Anh	SME Tra Vinh	lananhamdbt@gmail.com
10	Nghia Tho	Director of AMD Project Coordination Unit - Tra Vinh	nghiathoimpp@gmail.com
11	Trần Thanh Phong	Tra Vinh DONRE	phongphu2004@gmail.com
12	TP.TNB-Nguyễn Thanh Nghiêm	Tra Vinh DONRE	ntnghiem2003@yahoo.com
13	Ben Tre DONRE	Ben Tre DONRE	phongtainguyenbentre@gmail.com
14	Tra Vinh Water Supply Company	Tra Vinh Water Supply Company	trawacotv@gmail.com
15	Châu Trương - Sở TN&MT tỉnh Sóc Trăng	Soc Trang DONRE	ttnchau@gmail.com
16	Ben Tre AMD Project	AMD Project Coordination Unit - Ben Tre	vangamdbt@gmail.com
17	Lê Quang Răng	DARD Tra Vinh	vanphongsnntv@gmail.com
18	Kim Oanh	DRAGON Institue, Can Tho University	hpkoanh111@gmail.com
19	Kim Oanh_DRAGON Institute	DRAGON Institue, Can Tho University	hpkoanh111@gmail.com
20	Như Ý Lê	Can Tho University	leny@ctu.edu.vn
21	Loc Nguyen	Can Tho University	ntloc@ctu.edu.vn
22	VQThanh-CTU-VN	Can Tho University	quocthanh@ctu.edu.vn
23	Van Pham Dang Tri	Can Tho University	vpdtri@ctu.edu.vn
24	Lê Thị Huỳnh Như	UAH	18510501634@uah.edu.vn
25	Andrew Wyatt (IUCN)	IUCN	andrew.wyatt@iucn.org
26	Anke Steinel	BGR	anke.steinel@bgr.de

27	TS. Trần Đăng An- TLUS	Thuy Loi University	antd@tlu.edu.vn
28	Arthur van Dijk	STUDIOA	arthur@studioa.nl
29	Thanh Binh Nguyen	Hanoi University of Science	binh.gis.cefd@hus.edu.vn
30	Doan Van BINH	Vietnam Germany University	binhdv0708vl@gmail.com
31	Chu Bui Dinh	WWF Vietnam	chu.buidinh@wwf.org.vn
32	ĐH Kiến Trúc TPHCM	HCMC University of Architect	chuanhtuan.j5@gmail.com
33	Cuong Hung Pham	Worldbank	cphamhung@worldbank.org
34	DangThanhLam		dangthanhlamvn@gmail.com
35	Dinesh Aryal WB	Worldbank	daryal@worldbank.org
36	Duy Truong (PIC)	Royal HaskoningDHV Vietnam	duy.d.truong@rhdhv.com
37	Duy Nguyen - WWF Vietnam	WWF Vietnam	duy.nguyenphuong@wwf.org.vn
38	Nguyen Quoc Dinh# VIGMR	VIGMR	gomquang@gmail.com
39	Tung Dao	TUDELFT	h.t.dao-1@tudelft.nl
40	Han		hanvo87@gmail.com
41	Ha Pham	Bochum University	hapham2310@gmail.com
42	Harro Stolpe eE E	RUHR-UNI-BOCHUM	harro.stolpe@rub.de
43	Hoang Lan Huong	VD-OFICE	hlh@vd-ofice.org
44	Hong Xuan Do	UMICH	hongdo@umich.edu
45	WB165271	WORLDBANK	hqaddumi@worldbank.org
46	Nguyen Hue	GeoViet	hue.geoviet@gmail.com
47	Tran Hung	GeoViet	hung.geoviet@gmail.com
48	Hung Dinh	GeoViet	hungdx.iwrp@gmail.com
49	JICA_Ishimaru	Japan Intern. Coop. Agency (JICA)	ishimaruhiroki140@yahoo.co.jp
50	Katrin Brömme	RUHR-UNI-BOCHUM	katrin.broemme@ruhr-uni-bochum.de
51	Triet Nguyen - Ruhr University of Bochum	RUHR-UNI-BOCHUM	khanhtriet.nguyen@ruhr-uni-bochum.de
52	Bùi Lê Khánh_MARD CPO	MARD CPO	lekhanh.bui@gmail.com
53	Le Manh-IGPVN/BGR	IGPVN	lemanh.igpvn@gmail.com
54	Leonie	ARCADIS	leonie.koenders@arcadis.com
55	Linh	DFAT - Australia Embassy	linh.nguyen7@dfat.gov.au
56	Tuyet Anh	Hanoi University of Science	ltanh1111@gmail.com
57	PhuongMai_Thuyloi University	Thuy Loi University	maiswru@tlu.edu.vn
58	Marc Descloitres	UNIV-GRENOBLE-ALPES	marc.descloitres@univ-grenoble-alpes.fr
59	Marc Goichot	WWF Greater Mekong	marc.goichot@wwfgreatermekong.org
60	Marco Abbiati	Unibo	marco.abbiati@unibo.it
61	Marta Faneca# Deltares	Deltares	marta.faneca@deltares.nl
62	Martin Dersch	GIZ	martin.dersch@giz.de
63	Marcel Dupuis	WWF Netherlands - DFCD Cooridnator	mdupuis@wwf.nl
64	Michael Waters	ICEM Principal Water Resources Engineer	michael.waters@icem.com.au
65	Nguyễn Công Minh	Institue of Water Resources Planning (IWRP)	minhnc.iwrp@gmail.com
66	Thanh Tâm - Đơi vị ĐH Kiến Trúc TPHCM	Ho Chi Minh City University of Architect	ngothanhtam981@gmail.com
67	Nguyễn Thị Hồng	Hanoi University of Science	nguyenthihong.hus@gmail.com
68	Nguyễn Hoàng Tiến		nguyentiencctl@gmail.com

69	Nguyễn Trung Nam	Southern Institute of Water Resources Planning	nguyentrungnam47v@gmail.com
70	Nguyễn Nguyệt	Witteveen+bos	nguyet.nguyen@witteveenbos.com
71	Nhung Truong		nhung.truong@gmail.com
72	Paul Pavelic	CGIAR	p.pavelic@cgiar.org
73	Nga Phạm Thị Thúy		phamnga3789@gmail.com
74	THANG PHAN		phandang.t@gmail.com
75	Thuy Duy		pttduy2804@gmail.com
76	Quoc Quan Tran		quantranquoc@gmail.com
77	Le Quoc Tuan (NLU)	HCMC University of Agro-Forestry	quoctuan@hcmuaf.edu.vn
78	Quyen Le	IWRP	quyensiwrp@gmail.com
79	Hồng Sơn Trương	Thuy Loi University	sontruonghong85@gmail.com
80	Tjeerd Dijkstra - Blue Dragon Vietnam	Blue Dragon Vietnam	t.dijkstra@vechtstromen.nl
81	Tibor Stigter	UN-IHE	t.stigter@un-ihe.org
82	Ho Sy Tam	Thuy Loi University	tamhs.cttl@tlu.edu.vn
83	Tanya Huizer	ARCADIS	tanya.huizer@arcadis.com
84	Thaianh Nguyen	FAO	thaianh.nguyen@fao.org
85	Hoàng Tiến Thành	Institute of Water Resources Planning (IWRP)	thanhht.iwrp@gmail.com
86	Thúy Ngà	HCMC University of Architect	thuyngaqhk19uah@gmail.com
87	Thủy Nguyễn Thị Thu	UEH	thuyntt@ueh.edu.vn
88	Tinh Huynh Quoc	WWF Vietnam	tinh.huynhquoc@gmail.com
89	Thanh Truong Quoc	HCMC University of Technology	tquocthanh@hcmut.edu.vn
90	Tran Ngoc Anh CEFD	Hanoi University of Science	tranngocanh@hus.edu.vn
91	Tú Trần Anh	HCMC University of Technology	trantu@hcmut.edu.vn
92	Yen Truong - Root	Root	truonghoangyenfeb28@gmail.com
93	Trương Huỳnh Khánh Ngọc		truonghuynhkhanhngoc@gmail.com
94	Trần Nguyệt	VD-OFFICE	ttn@vd-office.org
95	Tu Le Hoang	HCMC University of Agro-Forestry	tu.lehoang@hcmuaf.edu.vn
96	Tuan-Dung Hoang-VNU Hanoi	Vietnam National University	tuandung@vnu.edu.vn
97	Tung Luong		tung.vanluong@gmail.com
98	Ute Arnold	UNI-BONN	uarnold@uni-bonn.de
99	Vương Việt Hưng	MARD CPO	vuongviethung84@gmail.com
100	Gualbert Oude Essink	Deltares*	g.oude.essink@gmail.com
101	Phuong Trang Dinh	Deltares*	trang.dinh@deltares.nl
102	Sepehr Eslami	Deltares*	sepehr.eslamiarab@deltares.nl
103	Philip Minderhoud Deltares/WUR	Deltares*	philip.minderhoud@deltares.nl
104	Marcel Marchand	Deltares*	marcel.marchand@deltares.nl
105	Thắng Phạm	Royal HaskoningDHV Vietnam*	thang.pham@rhdhv.com
106	Đỗ Thanh	Royal HaskoningDHV Vietnam*	thanh.do@rhdhv.com
107	Hong Quan Nguyen	ICED - HCMC National University*	nh.quan@iced.org.vn
108	Mila (Mila)	Deltares*	mila.mahya@deltares.nl
109	Pham Van Hung	Division for Water Resources Planning and Investigation for the South of Vietnam*	hungtnnmn@gmail.com

*Project partners ……: Provincial Authorities

4. Questions and Answers:

Questions and Answers were given in Q&A box in Zoom Webinar which provided a good interactive platform between participants and presenters. All Q&A are summarized in the following table.

Q&A extracted from Q&A box

#	QUESTIONS	QUESTIONERS	EMAIL OF QUESTIONERS	ANSWERS
1	Good to note the answers to mentimeter are anonymously.	Philip Minderhoud Deltares/WUR	philip.minderhoud@deltares.nl	Will stress that at the 2nd session. Thanks Philip
2	You mentioned effects of land subsidence on salinity intrusion. Can you kindly explain the mechanisms?	Doan Van BINH	binhdv0708vl@gmail.com	Lower lands and related phreatic water levels means more upward groundwater flow from the deeper system (this is called seepage). This upward flow causes also saline groundwater from the deeper groundwater system, leading to salinization. We see that in other deltaic areas too; in the low-lying delta of the Netherlands, salinization of the surface water system in polders is mainly due to saline upward groundwater flow. Answer to “Ben Tre and Tra Vinh are largely diked and controlled by sluice gates. I think for those areas, no matter of land subsidence inside the dikes, salinity intrusion has little influence.”: in reality, it is the saline groundwater that causes salinity intrusion and can still enter into the system, as salt groundwater intrusion and from the deeper systems (with sea-level rise even more). E.g. in Ben Tre, the groundwater systems is already saline and the deeper part more.
3	Ben Tre and Tra Vinh are largely diked and controlled by sluice gates. I think for those areas, no matter of land subsidence inside the dikes, salinity intrusion has little influence.	Doan Van BINH	binhdv0708vl@gmail.com	Indeed there are sluice gates, but if salt intrusion increases, maintaining the freshwater zones with sluice gates will become non-feasible. Also subsidence, can lower the primary and secondary channel bed levels, and that's the mechanism that it contributes to salt intrusion. however, this mechanism has limited impact on overall salt intrusion in Ben Tre and Tra Vinh. However, this mechanism is important in Ca Mau and stations further from the river
4	How often do you monitor water quality, and what to monitor? (POPs, heavy metals)	Nguyen Quoc Dinh, VIGMR	gomquang@gmail.com	It will be presented in Mr. Hung's presentation.
5	Q1: Which is the criteria for selecting ASR locations?	TS. Trần Đăng An-TLUS	antd@tlu.edu.vn	There are some criterias (geology, soil, topography, water quality, land owners ...)
6	In the same line, why the ground water quality is needed to be controlled?	Quoc Quan Tran	quantranquoc@gmail.com	because the WQ of the aquifers cannot be compromised. otherwise, this can take long to recover, and may have significant impact beyond the area of interest We have to control the quality of source water used for recharge because it might bring unqualified water such as saltwater, contaminated water to pollute the aquifer.

7	Indeed, water quality of aquifers is important. However, I believe that we are trying to keep the higher groundwater level to increase the volume of water in the shallow aquifer. This requires focus on the water level (and water volume) rather than water quality as we should not introduce any extra water into the system but the nature recharge. By doing that, there will be no harm for the water quality in the groundwater aquifer. So, this issue still confuses me.	Quoc Quan Tran	quantranquoc@gmail.com	Thanks Tuan. We considered hydrological information i.e. water level + water quality + some others. You are right, nature recharge is always good. However, it'll take some time. ASR learn the natural principles but try to make it faster and more efficient (i.e. keep surface/rain water in the system). Of courses, we have to make sure we do not harm the groundwater aquifer.
8	Hydrogeologically, it would be great if more detailed information of the criteria can be provided.	TS. Trần Đăng An-TLUS	antd@tlu.edu.vn	Sure An. There were just examples. Key physical (+social) information were included. I'll check if/when we can share the report.
9	It would be very much appreciated if all the powerpoint presentations can be made available to participants please!	Michael Waters, ICEM Principal Water Resources Engineer	michael.waters@icem.com.au	Yes, it's possible. We will share to all (registered) participants.
10	Sepehr, did you include sluice gates in your model simulating surface saline water intrusion? I agree that without sluice gate included, more land subsidence causes more surface saline intrusion. However, the fact is sluice gates existing in place, some centimeters land subsidence may have not yet influence saline intrusion in compartments. From you research, how much land subsidence (quantitatively) increases surface water intrusion WITH sluice gates? Thanks!	Doan Van BINH	binhdv0708vl@gmail.com	Dear Doan, yes! present and future planned sluice gates are included. so salinity does not increased in the freshwater zones, but salinity does increase beyond those zones. If you see the article (it's open access). the point is when salinity increases further inland, WQ becomes an issue in these freshwater zones as we may not be able to circulate frequently as available freshwater becomes limited. So our projections are INCLUDING the sluice gates. I encourage you to have a look at these two papers that go into the background of this exeercise: https://esurf.copernicus.org/articles/9/953/2021/ https://www.nature.com/articles/s43247-021-00208-5

11	Thank you for your answer. I have one question left regarding the recharge. As the model presented by Eslami includes the climate change impact in its scenarios. I wonder the projected change rate of recharge in the study area. How it changes in the different scenarios (together with the water level in the river - which is considered a computed in the river model)	Quoc Quan Tran	quantranquoc@gmail.com	The recharge is generally not influenced much with the surface water scenarios, and that's because recharge takes place in the wet season, and we believe at least in the foreseeable future there will be sufficient freshwater in the wet season despite climate (environmental) change.
12	How do you envision to continue the project in 2022 if the system is not yet installed and will require monitoring, operation and maintenance for some time to make any conclusions?	Anke Steinel	anke.steinel@bgr.de	This is indeed an issue, and it is not solved yet. We have to start up a discussion with the Dutch funding organization, and with local authorities. On one site, we already have a French research group (Marc Descroites et al) that want to continue with o.a. geophysical research. On top, we could bring in national and international students to gain field experience knowledge. To be continued anyway. You have suggestions yourself?
13	How much does it cost? For example, for storage water for 1ha of the agricultural area? Is it suitable for framing scale in the MKD, it relatively small and scatter? Thank you!	Trung Nam_SIWRP	nguyentrungnam47v@gmail.com	Mr. Hung will say something about this in his presentation
14	who is the owner of the land of the pilot site? Who will be the beneficiary?	Anke Steinel	anke.steinel@bgr.de	the government managed the land (the reservoir) + some farmer's land. The communities (farmers) around the site are beneficiary.
15	Thank you for the interesting information. Can you advise the cost for the pilot system you showed? How long do you expect the system to operate before restoration of the infiltration is required? thankyou	Paul Pavelic	p.pavelic@cgiar.org	Live answer was given. In summary: the total costs of this pilot system is higher than an operational system as we also executed additional (applied scientific) measurements to understand how the ASR system works on a daily basis. Determining the minimum operational costs has not yet determined yet.
16	Is there any risk of creating high water tables that could have adverse effects on crops? For instance, in the Netherlands farmers always want to lower the GW levels for their farming practices.	Marcel Marchand (Deltares)	marcel.marchand@deltares.nl	We will install several monitoring wells in the field where the ASR pilot is installed and also outside, a few meters far away. In the monitoring wells we will install water level sensors. With this information we can regulate how much water can be pumped from the reservoir, so that groundwater level rise, but not too much

17	Thank you Eslami. The groundwater recharge indeed mostly occurs in the wet season. However, it also appears in the dry season too (even limited). In different scenarios, it may increase or decrease or change in intensity (together with precipitation). Sometimes, it helps to maintain the groundwater in the shallow aquifer. This is found in the Neogene Aquifer in the border of Belgium and the Netherlands. I wonder if you account for it? If yes, how large is its range of change?	Quoc Quan Tran	quantranquoc@gmail.com	This is a question that requires a multi-disciplinary response, allow us to get back to you on this one.
18	I'm curious about the level of participation of local governments to previous phases of this project. To be successful in scaling up initiatives like this, not only technical aspects but governmental challenges need to be taken into account	Hong Xuan Do	hongdo@umich.edu	Good point, Hong! We've been working closely with the local government. We need to consult the govement for installing. I'll ask the panel list (to local officials) to respond your questions.
20	Currently, since deep aquifers (qp23, qp1, n22) are major overexploited in the MKD. Based on your practice experiences in the MKD, do you have any suggestions for applying the ASR for deep aquifers (confined aquifers)? It is potential or not?	Le Manh-IGPVN/BGR	lemanh.igpvn@gmail.com	We are defining and developing together with Deltares a business case for deep aquifer recharge for urban water supply. Sepehr could inform you more on this.
21	Thank you for all the interesting presentations. From what I understand, you are investigating changes on the water supply side of the water balance, but are there opportunities to reduce water demand?	Leonie	Leonie.koenders@arcadis.com	Reducing water demand, by better management of the cycles, reducing waste, changing the crop patterns, or changing crops themselves is indeed one of the many solutions in the adaptation toolkit. There are ample opportunities for water use efficiently, for increasing water productivity (especially in rice) and by transforming the agricultural production systems towards other crops.

22	Extremely interesting session - thank you! This is Halla Qaddumi (from the WB). Would like to explore options for scaling up MAR in the Mekong Delta including to serve domestic water supply.	WB165271	hqaddumi@worldbank.org	Dear Halla, Great to see your enthusiasm! Indeed we can explore this solution as we already discussed in the recent exchange.
23	What are the environmental effects after scaling up one ASR?	Tung Dao	h.t.dao-1@tudelft.nl	This requires a bit of elaboration, allow us to get back to this question in an email.

5. Live Sessions

Panellists have shared their views and opportunities to upscale ASR in Mekong Delta. Some important notes are summarized below:

Mr. Laurent Umans (Dutch First Secretary Water Management and Climate Change in Vietnam) emphasized the importance of Aquifer Storage and Recovery as a subsurface opportunity for solving the pressing water problem in Vietnam and especially the Mekong Delta. The Netherlands have been working with the Water Resources Institute under MONRE to identify the gap between water demand and water supply, and how we can close this gap which will become larger in the future under Business as Usual activities. Obviously, there are a lot of water retention possibilities in the upper delta (An Giang and Dong Thap), but we need water retention and storage feasibility and possibility in the coastal zone of the delta. Such important information is provided through this FAME project for follow-up researches.

Dr. Nguyen Ngoc Quang: IFAD and AMD Ben tre and Tra Vinh Project have cooperated with FAME project members in 1st participatory workshop and field trips for site selections in Ben tre and Tra Vinh. IFAD is planning to give two provinces a new investment as follow-up of AMD project (Phase 3) focusing on enhancing water resource management and infrastructure investments. It is expected to see an ASR successful pilot in Long Son, Tra Vinh province that can be upscaled in the Ben Tre and Tra Vinh as well as Mekong Delta as an important solution to solve water scarcity issues. IFAD is eager to work with and support the FAME project on upscaling it in Mekong Delta.

Mr. Tho, Director of AMD also shared his experiences and participatory of AMD PCU Tra Vinh in FAME project's activities (workshops, site selection and field works). He shows his support and expectations for ASR pilot as well as his willingness to help the project any obstacles might raise toward a successful pilot for Tra Vinh. He also shared some information regarding to AMD Phase 3 which could be an opportunity for upscaling ASR study.

Mr. Pham Hung Cuong – WB: shared his concerns about the costs of ASR system that he thought it would be costly and challenging for a very small scale. He suggested to think about an alternative solution to link freshwater from other canals/ different upper water sources / main rivers down to the sandy areas along the coastline and build up additional reservoirs to store more water out there to help reduce the cost of system. Integrated management from upper delta to the coastal zone with water infrastructures is crucial to make effective uses of different water resources in more sustainable way.

D Appendix Online Workshop: ASR pilot installation and upscaling possibility, 21 December 2021

On:

- the ASR Pilot Installation
- the upscaling possibility of ASR systems in the Mekong Delta

Freshwater Availability in the Mekong Delta Project (FAME)
Dự án Nguồn nước ngọt vùng đồng bằng sông Cửa Long

Online Workshop on / Hội thảo trực tuyến về:

ASR Pilot Installation and Upscaling Possibility of Aquifer Storage and Recovery - ASR systems in the Mekong Delta

Lắp đặt thử nghiệm mô hình trữ nước nhân tạo ASR và Tiềm năng nhân rộng trên vùng đồng bằng sông Cửu Long

21th December 2021 / Ngày 21 tháng 12 năm 2021

Workshop Agenda

21th December 2021

Time/Thời gian	Nội dung chương trình / Description	Người trình bày / Presenters
15:00 – 15:05	Chào mừng và Giới thiệu đại biểu và chào mừng / Panellists Introduction and Welcome section	TS./Dr. Nguyễn Hồng Quân (Đại học Quốc gia thành phố Hồ Chí Minh/ Vietnam National University HCM City)
15:05 – 15:10	Phát biểu khai mạc của Đại sứ quán Vương quốc Hà Lan tại Việt Nam / Opening Remarks by the Embassy of the Kingdom of the Netherlands in Vietnam	TS/Dr. Laurent Umans, Bí thư thứ nhất phụ trách Quản lý TN Nước và Biến đổi khí hậu / First Secretary Water Management and Cimate Change
15:10 – 15:20	Trình chiếu Video về dự án FAME / Video on FAME project	
15:20 – 15:30	Mô tả lắp đặt hệ thống thử nghiệm ASR tại Cầu Ngang, Trà Vinh/ ASR Pilot installation description at Cau Ngang, Tra Vinh province	Mr/Ông. Phạm Văn Hùng, Liên đoàn Quy hoạch và Điều tra Tài nguyên nước miền Nam / Division for Water Resources Planning and Investigation for the South of Vietnam

E Appendix Summary interviews farmers

Questions Interviews

1. Do you have a well?
2. Since when does the farmer use this well?
3. what depth does the well go?
4. What design does the well have?
5. What is the capacity of the well? (pressure/discharge of pump)
6. What is the water in the well used for?
7. Are there problems with the amount of water coming from the well in the dry season?
8. Are there problems with salinity in the well in the dry season?
9. What months do these problems occur?
10. Is there a difference with the past years in availability and quality?
11. Do you use the surface water that is in connection with the main canals?
12. Are there problems with the quantity?
13. Are there problems with salinity in the ditches?
14. What months do these problems occur?
15. Is there a difference with the past years in availability and quality?
16. If you have more water would you use it?
17. If there is less would you change it?

When water is used for crops:

1. What crops are irrigated with this water?
2. What crops does the farmer produce during the dry season?
3. Does the farmer have a break in producing?
4. What is the cropping schedule (with months) of the farmer?
5. What crops does the farmer has knowledge of for producing (what did he produce in the past)?
6. What kind of irrigation system does the farmer have?
7. How often does the farmer irrigate his crops?
8. How long does the farmer irrigate his crops?
9. How big is the field the farmer irrigates?
10. Does the farmer produce the crops for own use or is it to sell at the market?
11. What is the average price the farmer can sell a kilogram for at the market?
12. How many kilograms does the farmer produce on average per year?

When water is used domestically or for cows:

1. What kind of domestic activities is the water used for?
2. Does the domestic activity depend on the quality of the water from the well?
3. Is there a change in use from the rainy season into the dry season?
4. How many buckets of water does the person think they extract per day for domestic use?
5. How many cows does the farmer have?
6. Do they also get the water from the groundwater-well?
7. How many buckets do the cows drink per day?
8. Are the cows fed by grass from own land and is this grass irrigated? (Go to crop questions)
9. What are the cows bred for?
10. How many cows are sold at the market every year?
11. How much does the farmer get for a cow?
12. How old is the cow when the farmer takes it to the market?
13. How many buckets of milk do the cows produce per day?
14. How old are the cows when they start producing milk?
15. At what age are the cows sold after producing milk?

F Appendix links promotion material

- Website Deltares
  https://www.deltares.nl/en/projects/freshwater-availability-mekong-delta-fame/

- Video of the project:
  https://www.youtube.com/watch?v=kuVdWHzmPGU

- Link to the database of the potential maps (Nelen & Schuurmans, lizard)
  fame.lizard.net/viewer

- Linkedin
  https://www.linkedin.com/posts/deltares_water-scarcity-due-to-salinization-poses-activity-6881172267095662592-GRRs
  https://www.linkedin.com/posts/deltares_freshwater-availability-in-mekong-delta-activity-6876792583520083968-jysy/

Deltares is an independent institute for applied research in the field of water and subsurface. Throughout the world, we work on smart solutions for people, environment and society.

Deltares