Deltares

# Smart Integrated Surface/Groundwater supply management


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**Southern Institute for Water Resources Planning (Vietnam)**
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# Preface

The present document aims to inform the Embassy of the Kingdom of the Netherlands in Hanoi, Vietnam, on the activities carried out for the funding provided by that office for the agro-water contest to our consortium. The proposal consists of a quick-scan on a smart integrated surface-groundwater supply management methodology that incorporates storage of surface water in the groundwater system through an Aquifer Storage and Recovery (ASR) system. While the methodology relies significantly on hydrogeological knowledge of the geophysical system within the Mekong Delta, it also relies on availability and quality of freshwater in the surface water system. Therefore, it becomes a more sophisticated, and multi-disciplinary methodology. The provided funding is used for the purpose of the main following activities:

- Derive a basic understanding of the water demand and supply in the Mekong Delta.
- A 1st order impact analysis of the ASR application in the Mekong delta.
- Networking, stakeholder analysis.
- Identify potential local partners and pilot locations.
- Reaching out to potential donors.

While we envisage a large application for the proposed methodology, we have narrowed down the scope towards a low risk pilot demonstration project through water operators who have access to water treatment facilities and have the capacity to implement the methodology in the shortest time possible. In the course of this assignment, we have identified international and local commitment towards a pre-feasibility study and pilot demonstration projects. This secures a productive and promising follow-up almost immediately after the submission of this document. Therefore, by means of this document, on behalf of the consortium, we would like to invite the Embassy to a follow up conversation on the merits of the proposal and its potential in addressing water security in the Mekong Delta.

# 1 Introduction

## 1.1 Context

In the context of a changing climate and anthropogenic stresses on the Vietnamese Mekong Delta (VMD), freshwater supply is a major challenge for the rural and urban communities (Deltares, 2011; Renaud and Kuenzer, 2012). Figure 1 provides the latest (Eslami et al., 2021) projections of salt intrusion within the VMD for a range of mild to extreme scenarios, in response to climate change, land subsidence and riverbed level erosion. This shows the short to mid-term impact of salt intrusion with significant potential implications for freshwater supply to the delta. To adapt to the potential scenarios, a systems approach with a variety of solutions from different angles is needed. The present proposal attempts to reduce one of the drivers of vulnerability, subsidence, while assuring a sustainable freshwater supply to domestic, industrial and possibly aquaculturally consumption.

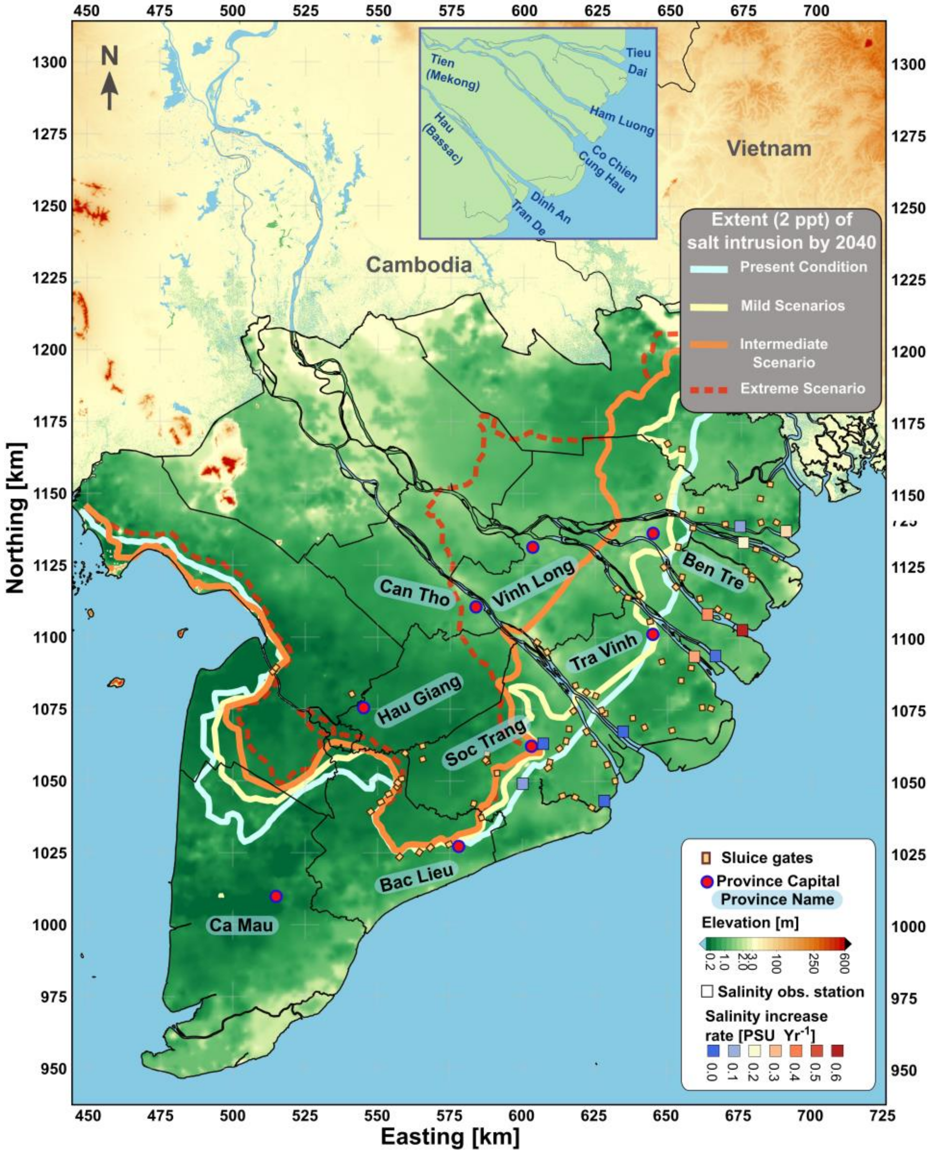



*Figure 1, Measured salt intrusion increase* (Eslami et al. 2019) *and the range of variation of projected saline water intrusion* (Eslami et al. 2021b) *under various scenarios until the year 2040.*

Currently, multiple industries, including domestic water companies and the aquaculture sector, mostly supply water shortages from the groundwater system, while the agriculture sector must supply from the surface water system. While groundwater extraction is a factor 40 smaller than the surface water demand, its resulting subsidence is nonetheless a great threat to the livelihood of the delta (Minderhoud et al., 2020, 2017). On the other hand, the surface water surplus cannot easily fill that gap due to its poor quality, extreme salt intrusion and accessibility up to local farmer's level.

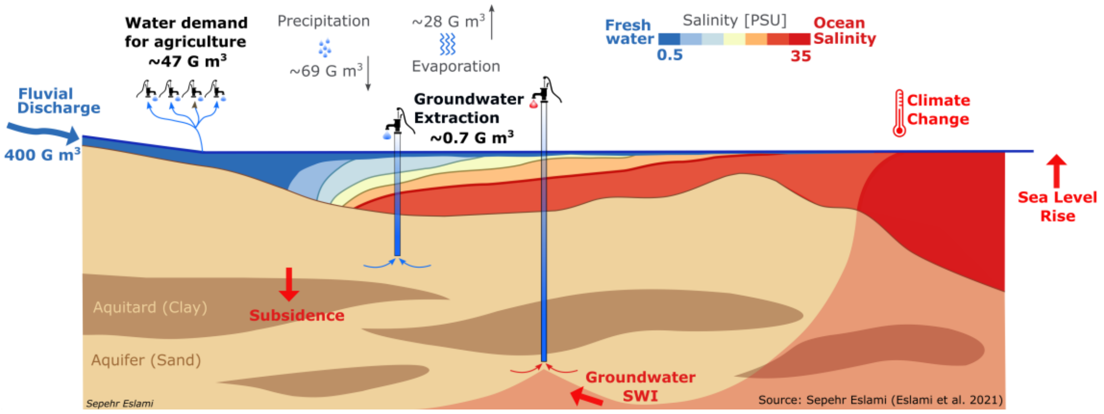



*Figure 2, An imaginary cross-section of the delta, demonstrating the yearly water balance.*

## 1.2 Water demand and supply

In this section, we address water demand in time and space from the sectors agriculture, aquaculture and domestic. Figure 2 shows the water balance within the Mekong Delta in terms of total fluvial discharge, water demand (fresh and brackish, surface and groundwater), precipitation and evaporation. Some 300-500 G m³ of fluvial freshwater inflow from the Mekong River is the most significant source to the VMD. With the strong monsoon-driven seasonality, only 4 to 8% of the total freshwater inflow generates during the dry season (~12-40 G m³/yr) and the rest is associated with the wet season. In total ~47 G m³ of the yearly water demand (~128 M m³/day) is supplied from the surface water system, out of which nearly 70% supplies the agricultural sector and 30% for the aquaculture sector (water demand data collected by SIWRP). Despite the very small portion of the dry season discharge (4-8%), 75% of the water demand is concentrated between December and April (5 months), stressing freshwater availability and increasing salt water intrusion. In addition, domestic use within the VMD is estimated at ~120 lit/day/per person, which adds up 44 m³/yr. This adds up to ~0.8-1 G m³/yr domestic consumption which is significantly smaller than agri-/aqua-culture consumption. This is in the same order of magnitude as the total groundwater extraction (0.7 G m³/yr) that is also used partially for aquaculture and domestic consumption.

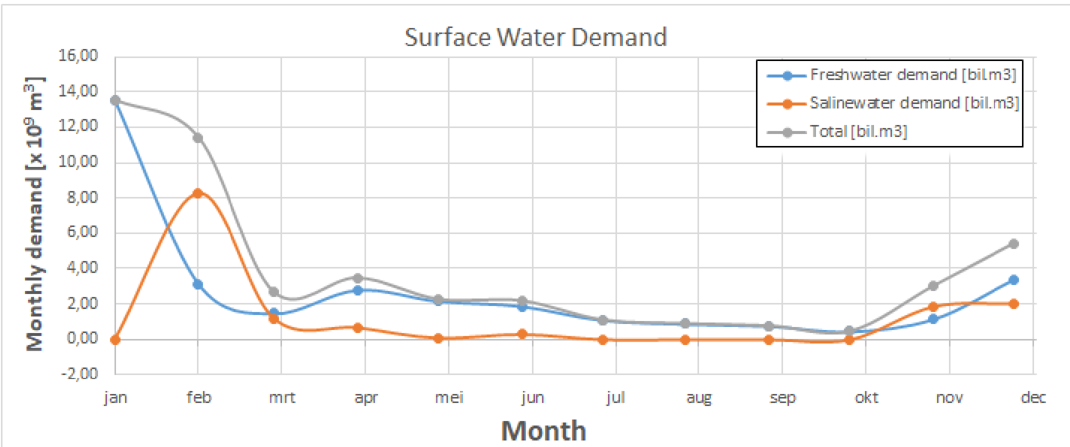
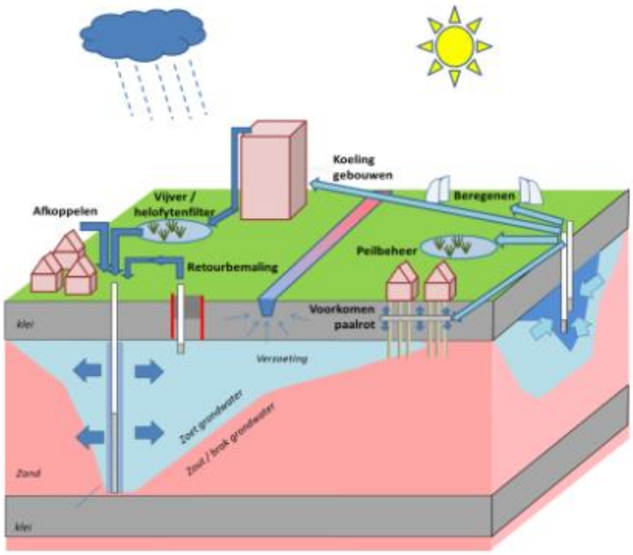



*Figure 3, Fresh and Saline water demand throughout the year (SIWRP).*

*Figure 4, Brackish groundwater extraction in a shrimp farm (Approx. 1 $m^3/m^2$ of the pond surface per crop).*

## 1.3 Summary of our solution




The objective of this proposal is to address "***freshwater resilience***" as well as "***physical resilience***". Sustainable un-interrupted supply water for water consumption (specifically domestic and industrial) can be achieved by a smart system of distributing and storing fresh water from the river (or an in-between treatment plant) in the subsurface during the wet season and extracting it from the subsurface when required. For the Mekong Delta, there is another important advantage. As the existing valuable groundwater resources are not exploited, and when it is adopted on a large scale, it has the potential capacity to restore the depleted groundwater levels, and subsequently, to diminish land subsidence rates. Here we show that this approach, in the short term, has the capacity to compensate for groundwater depletion while securing freshwater availability during the dry season. However, the challenge lies in adopting the right procedure that caters this distribution system. This proposal elaborates on development of a smart system with the following steps first at a pilot stage to scale up in the later stage:

1. Forecasts the surface water salinity (using existing tools).
2. Examines the present water quality and possibly makes improvements.
3. Compares the water storage capacity and requirement.
4. Stores water in pre-defined suitable deep aquifers (Aquifer Storage and Recovery).
5. Extracts from the aquifers when surface water supply does not meet the demand.

# 2 Organization

Our consortium is formed by well-known domestic (SIWRP, DWRPIS) and international institutes (Deltares, Witteveen + Bos, VEi), combining practical operational experience, consultancy and state-of-the-art applied research. The domestic institutes have a long track record in surface and groundwater resources management within and beyond the VMD and have the necessary infrastructure to technically support the pilot project development and later on adopt the spin-off in scaling up the approach. The international institutes, next to their world-wide track record on water cycle expertise, are among the most prominent institutes to have advanced the system understanding of the VMD in the past decade.

**Deltares** is an independent non-profit knowledge institute for applied research in the field of water and subsurface. Deltares develops and provides true world-class open-source modelling software used by scientists and engineers worldwide, such as the Delft3D-FM modelling software. Deltares is highly capable of providing the modelling services, project management, capacity building and consultancy, particularly because of the support by over 850 highly experienced (international) staff with global experience. Notably, Deltares' staff includes key experts on river, estuarine and groundwater dynamics and modelling, (fine) sediment transport and remote sensing techniques.

**Southern Institute for Water Resources Planning (SIWRP)** is an autonomous institution of water resources planning under the direct management of the Ministry of Agriculture and Rural Development (MARD) Vietnam. Its mandate is the basin-wide water resources development and planning at local, regional and provincial levels. SIWRP also provides socio-economic development solutions related to water resources and the environment, comprehensive and synchronized solutions for disaster mitigation, riverside and seashore training, environment conservation, and small-scale hydro-power plant development.

**Witteveen + Bos** is a Dutch engineering consultant (since 1946), with over 1,200 professionals across the Netherlands and 10 branch offices worldwide, including Ho Chi Minh City (Vietnam). W+B have ample experience in water management, including geohydrology, flood and drought management, irrigation, salinity and soil management. They combine this knowledge for development and design of concepts to improve environmental conditions as well as masterplans for integrated development of catchments, conduct (food) chain analysis and feasibility studies. They develop and operate monitoring networks for evaluation and analysis and set up organizations for operation and maintenance, such as waterboards.

**Division for Water Resources Planning in the South of Vietnam (DWRPIS)** is a public non-business unit directly under the National Water Resource Planning and Investigation Center, with the function of planning, basic investigation and observation of water resources in the provinces of the Southern Vietnam. It also performs consulting activities, services in the field of water resources in accordance with the Vietnam law.

**Vitens Evides international (VEi)** VEI was established in 2004 as a joint venture between the two largest water companies in the Netherlands, Vitens and Evides. VEI is firmly rooted in the Dutch water sector. Six Dutch partners (Vitens, Evides Waterbedrijf, WML, Waterbedrijf Groningen, Brabant Water and WLN) share their expertise with their colleague water operators around the world. VEI partners with water utilities on a not-for-profit basis and under the premise that knowledge is not for sale and work is carried out on a solidarity basis. The partnerships of VEI focus on building the resident capacity of water operator staff through on-the-job training/coaching. VEI deploys its water operator experts based on expressed needs of its WOP partners in the local context. This peer-to-peer interaction ensures that knowledge and a wealth of operational expertise can be shared with water operators across the globe. The results of these WOPs are consolidated in the form of improved operational performance of partner utilities and, ultimately, universal and equitable access to safe and affordable drinking water for more people.

# 3 Our Solution

## 3.1 Deep aquifer storage and recovery

Aquifer Storage and Recovery (ASR) is a water resources management technique for actively storing water in the groundwater system during the wet periods, for recovery when needed (usually during dry periods) (USGS, 2019). Water can be stored and extracted with vertical or horizontal wells. The wells can be used for both infiltration and extraction by using a pump that can both infiltrate and recover water. This technique is also called Managed Aquifer Recharge and is not a new technology at all; it has been applied in many different settings around the world (Dillon et al., 2019, 2009; Sprenger et al., 2017). Advantages of ASR systems are numerous (Faneca Sànchez et al., 2015): a. making use of the full 3D capabilities of the subsurface without the need of changing the land use at surface level (large storage space at no cost and less land is needed than for surface reservoirs); b. the aquifer storage does not loose water due to evapotranspiration; c. there is reduced risk of pollution; d. less impacts to the environment; e. water quality may be further improved with flow passages due to purification characteristics of the subsurface.

The goal of ASR is to reduce the stress on the (fresh) groundwater reserves and mitigate land subsidence in places where the demand for fresh water exceeds the sustainable supply of groundwater. Figure 5 shows a conventional groundwater extraction system where groundwater is extracted by deep wells in the aquifers. The natural groundwater recharge to the deep aquifers is generally significantly smaller than the rate of the groundwater extraction which results in pressure drop and eventually land subsidence (depicted by red arrows) as it has also been widely reported within the VMD (Minderhoud et al., 2017). Furthermore, groundwater extraction in deltaic areas eventually results in additional salt water intrusion in the groundwater system (Gunnink et al., 2021).

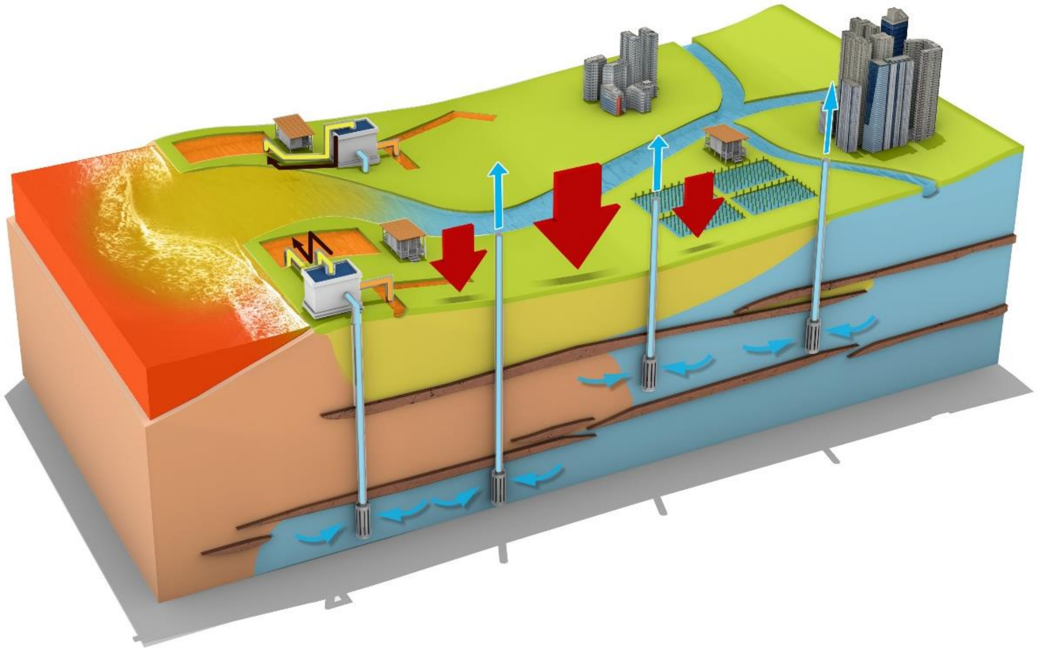


*Figure 5 representation of a traditional groundwater extraction system without ASR. The red arrows indicate significant land subsidence, while groundwater salinization of the fresh groundwater system is taking place.*

ASR implementation can act to stop, avoid or reverse (to a certain level) the above trends. Figure 6 upper panel shows an ASR system that extracts brackish groundwater when possible and infiltrates fresh surface water in deep aquifers in the wet season. This leads to retreatment of brackish groundwater and can also be recovered during the dry season. Furthermore, if the infiltration rate exceeds the extraction rates (demand), this methodology can restore groundwater table to its original level and (significantly) slow down the subsidence process.

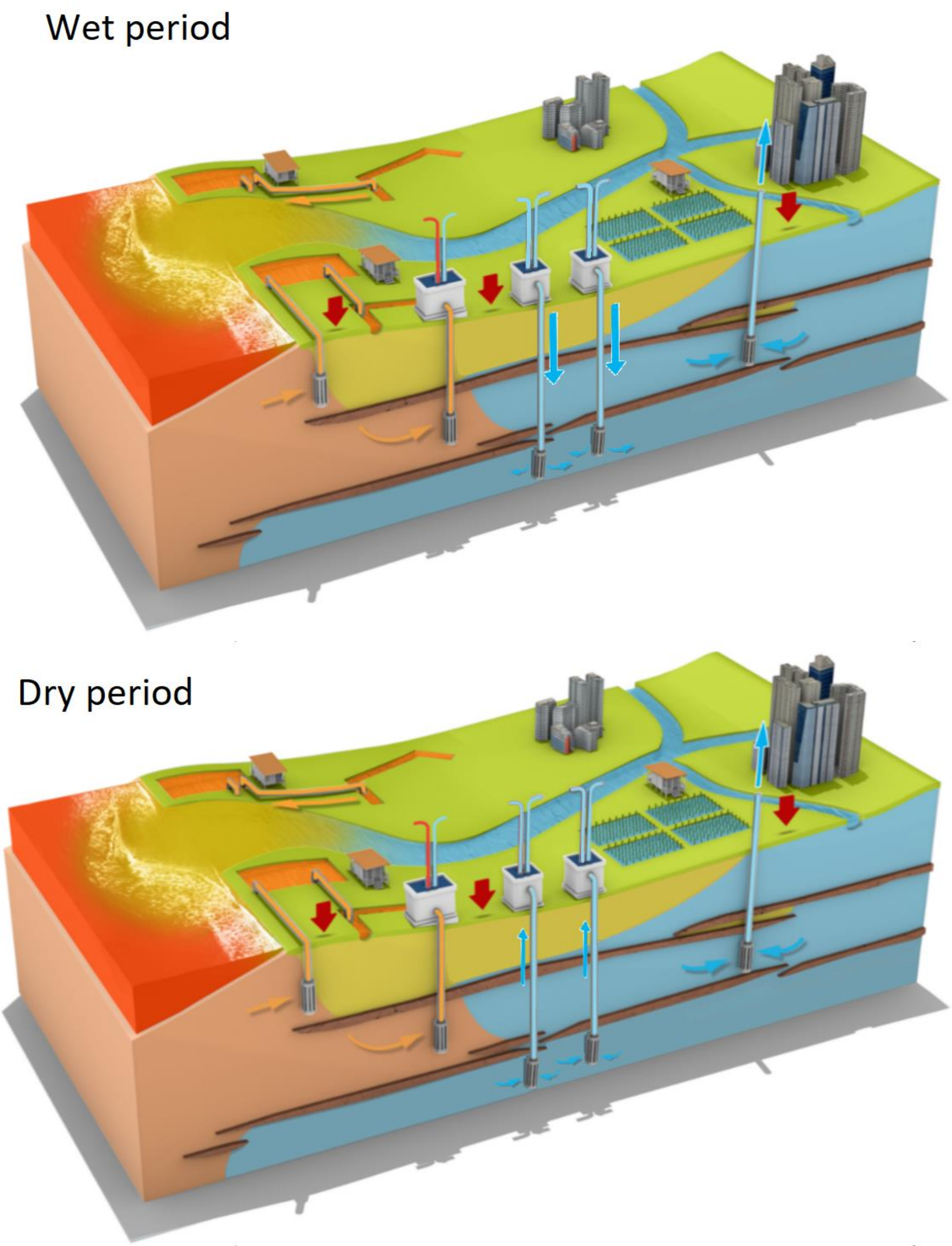



*Figure 6 Groundwater system where ASR is implemented, and brackish groundwater is used where and when possible. Top: In the wet period fresh surface water is stored into (deep) aquifers. The necessary groundwater demand in the wet period is still extracted. Bottom: During the dry period the stored fresh groundwater can be recovered. Land subsidence is mitigated to a certain extent, and the groundwater system is more sustainable for use by future generations.*

## 3.2 Challenges and resolutions

In order to examine the feasibility of an area for deep ASR feasibility maps should be drawn based on the following limitations/possibilities:

- **Surface water availability:** The amount of water that can be stored depends on available fresh surface water. In most of the VMD, this is not a limitation in volume as during the wet season enough fluvial discharge flows into the delta. However, in provinces such as Ca Mau and Bac Lieu that are distant to the main sources of freshwater, this can even become a partial but serious limitation. While there can be time limitations to the practice, the amount should still be sufficient. Depending on the location of the ASR system, this has to be addressed on a case by case basis. We advocate a delta-wide salinity forecast system to ensure the most accurate prediction, given timing, location, water quality issues (Bouwer, 2002; Hartog and Stuyfzand, 2017). However, as this may not be feasible in the pilot stage, we reduce this risk during that stage and aim to incorporate that in the scaling up stage of the project.
- **Technical (infrastructural) limitations** comprises of the pumping capacity, well depth and available infrastructure. If the pumps lack the capacity to infiltrate and/or recover water at desired flow rate and depth, ASR system will not operate efficiently. Furthermore, installation of the required infrastructure is subject to a cost-benefit analysis to evaluate the installation costs versus the investment return. These aspects will be addressed in the pre-feasibility phase of the project as they relate to specific pilot sites.
- **Physical limitations** are common in ASR systems and should be addressed in the pre-feasibility studies prior to pilot site selection. These limitations can be categorized in the following order:

  a) *Hydraulic conductivity*: Infiltration and recovery of fresh (ground)water is possible in homogeneous sandy aquifers. Sand and gravel have a high hydraulic conductivity compared to peat and clay layers. The high hydraulic conductivity makes infiltration and recovery possible at a higher flow rate, which is to be desired.

  b) *Available aquifer thickness*: The aquifer should be thick enough to infiltrate and recover the desired volume of water. When extracting water from a thin aquifer the hydraulic head drops relatively fast compared to a larger aquifer, as well as that the head drop is relatively large too. A large increase in hydraulic head could induce bursting of the confining layer above the aquifer, and a large decrease of the hydraulic head can result in increased compaction of the layer.

  c) *Clogging of the wells*: Physical, biological, and chemical clogging of injection wells results in the reduction of infiltration rates. Cleaning of clogged wells is part of the maintenance cost of an ASR system. When the wells clog too rapidly the maintenance cost can become too high and the system would not be profitable. Reducing the sediment load of the infiltrated water also reduces clogging. Biological and chemical clogging can be reduced by setting water quality threshold values. The water quality requirements will be discussed in Appendix 1.

  d) *Groundwater salinity of the aquifer:* The native groundwater salinity largely determines the recovery efficiency of an ASR system (Ward et al., 2009, 2008, 2007). The higher the native groundwater salinity, the more mixing between the background (brackish to saline) groundwater and infiltrated surface water will occur, reducing the fresh groundwater volume and thus the recovery efficiency. On top, the higher the native groundwater salinity, the more the fresh groundwater reserve will float upward towards the top of the aquifer due to density differences.

## 3.3 Scalability

Three of the main water-related challenges facing the Mekong Delta are:

1. Fresh groundwater resources depletion and salinization
2. Land subsidence in response to No.1
3. Surface water salt water intrusion

Based on an abundance of applied research over the past six years, in association with the institutes DWRPIS and SIWRP, we have developed delta-wide spatial characterisation of 1) existing resources of fresh groundwater (Gunnink et al., 2021), 2) the rate of extraction-induced land subsidence (Minderhoud et al., 2017) and 3) projections of saline water intrusion (see Figure 1 and Figure 7). Figure 7 summarizes these three maps and provides a ***minimum*** application scale of the offered solution. As the ASR technique can also be applied in brackish to light saline environments (see COASTAR consortium (2019)), the map with the availability of fresh groundwater resources is not considered (therefore, crossed). The overlap between the areas that experience significant subsidence and the areas affected by saline water during the dry season, defines the minimum geographical scale of the application. However, while this ASR solution is urgently available to the highlighted area, it is not limited to this and can even be used in areas not influenced by salinity in their surface water system and can simply be a solution for freshwater shortage in the dry season.

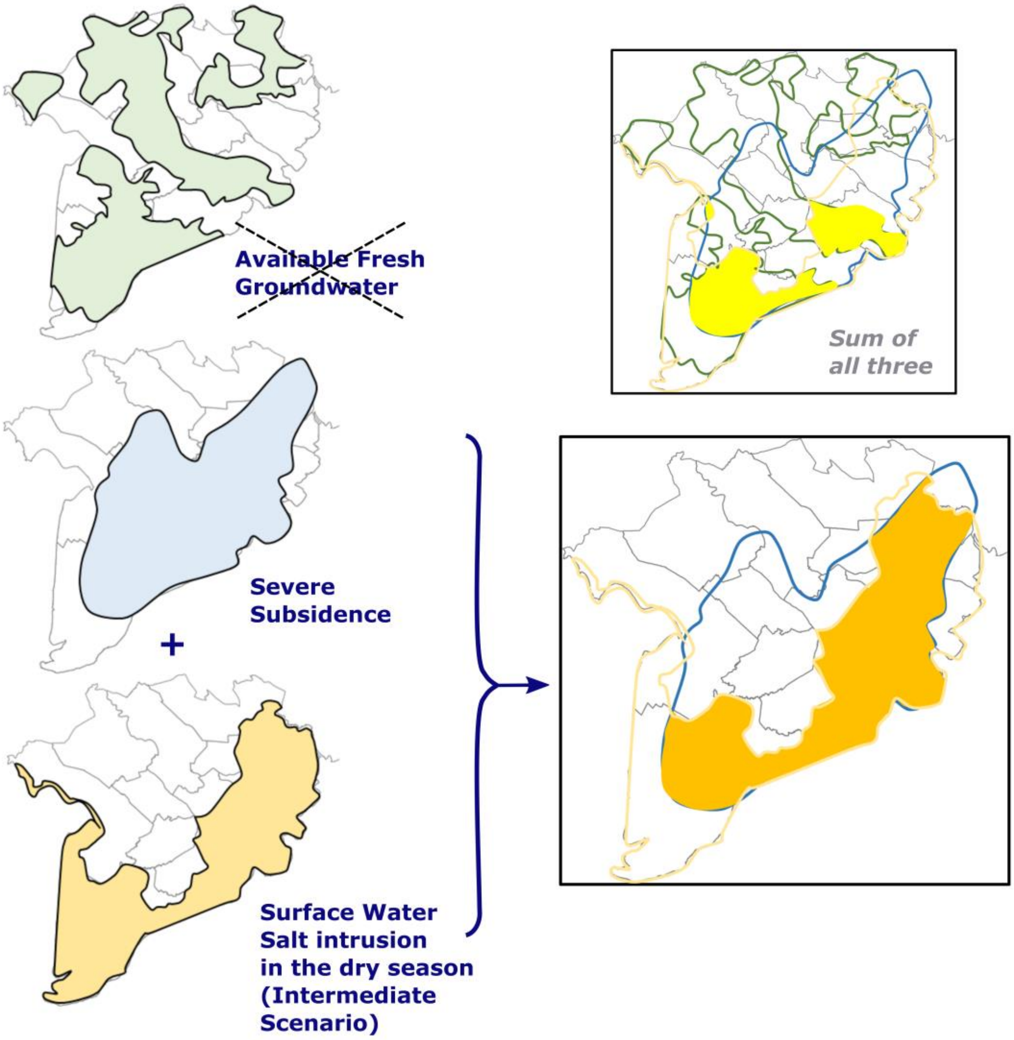



*Figure 7,a combined map of three main drivers of change in the Mekong Delta: available fresh groundwater, land subsidence and surface water saline water intrusion*

## 3.4 Business Model and Stakeholder Analysis

To structure a business plan without overhead and complexity, a business model canvas (BMC) is developed and provides a coherent view of business potentials, focused on targets and customer values. This BMC will guide the cost-benefit analysis during the pre-feasibility study. The nine key-driven elements in the BMC are:

1. Customer Segments: *The different groups of our potential customers*.
2. Value Proposition: *The fundamental needs of the target customers*.
3. Channels: *Different methods expected to be used to deliver the offered solutions/products*.
4. Customer Relationships: *The type of planned interactions to be build up with the customers*.
5. Key Partners: *Strategic relationships intended to be built with other interested parties*.
6. Key Activities: *Activities integral to set-up, operate and maintain the offered solution*.
7. Key Resources: *The required resources to operate and deliver the value proposition*.
8. Cost Structure: *The primary, secondary and sourcing costs incurred by our business*.
9. Revenue Streams: *The desired sources of cash flows earned from the value propositions*.

# Business Model Canvas

## Key Partners

- Global and local water engineering consultants and constractors
- Water equipment suppliers
- Water Supply Companies
- Water Research Institues
- Veil and Dutch Embassy
- NGO's (e.g., WWF & SNV), Governmental and International Sponsors/Donors

## Key Activities

'- Studies to assess the fesibility of project/investment proposal
- Filed trips and surveys to investigate the project/investment area
- Design and Install water monitoring equipment to measure and analyze water level and water quality
- Design and install the ASR at piloting sities and then upscaling to other potential sities
- Monitor and evalute the effeciency and cost-benifit of ASR
- Technical support for O&M
- R&D to tackle challenges and improve the applicability and technologies of ASR

## Key Resources

'- Human capital in water sciences and engineering for R&D
- Laboratories for experiments
- Water quality monitoring equipment
- Water treatment technologies and designs
- Water consulting and engineering services
- Knowledge transfer, state-of-art initiative and technologies, experts in the field, long-term cooperation and expertise
- Water data, information, modelling, operational management and forecasting software

## Value Proposition

'- To mitigate groundwater extraction and land subsidence.
- To mitigating salt intrusion in the groundwater system.
- To supply quality domestic freshwater gap during shortage/dry periods.
- Supply quality and uninterrupted freshwater tp the industry (except agriculture)

## Customer Relationships

'- Existing water distribution arrangements and customer support system.
- Special arrangements with the local and federal government.
- Special arrangements with the aquaculture sector.

## Channels

'- Direct communications with the local and national government
- Water exhibitions / conferences / workshops / associations
- PPP: Private Public Partnership Program
- Advertisement on multiple media channels as well as influencer advertisement
- Global distribution channels with the key partners

## Customer Segments

'- The general public and households for domestic use
- Beverage companies: Lavie, Coca, Pepsi, Sabeco, Habeco
- Aquacultural sector *e.g.,* Minh Phu, Tan Vuong, Cuu Long

## Cost Structure

"- Primary costs related to R&D and innovation, pilot studies, water monitoring, equipment installation and operation, consultancy services
- Ongoing costs such as water treatment and ASR system maintenance, salinity and hydrodynamics forecast.
- Secondary costs such as marketing and fund raising"

## Revenue Streams

- Direct Billing and Higher margin product costs due to increasing social and environmental responsibility (PC's are open to modest increase in prices)
- Direct contracts with the industry
- Primary revenues: Technology Transfer
- State contracts to combat land subsidence in compliance to Resolution 120.
- Indirect revenues: higher profit earnings due to reduction of risk and damage costs;
- branding'

## 3.5 Pilot site and the local parties

In cooperation with VEi, we have identified two local parties that are seriously interested in evaluating ASR through a pilot project. The two identified partners are in two provinces of Soc Trang and Hau Giang (See Figure 8). The advantage of these pilot sites is that a) during the wet season, there is no need for a salinity forecast system as salinity hardly reaches the limits, b) the water operators do have sophisticated water treatment facilities that eliminates the challenge of water quality limitation for infiltration, c) the people's committee partially (in case of Soc Trang province) or largely (in case of Hau Giang Province) own shares in these companies and are fully familiar with the challenges facing freshwater security, therefore, cooperative towards administrative hurdles and d) water level depletion is significant in the province capitals which makes it easier to showcase effectiveness (or failure) of the system.


*Figure 8, Considered pilot locations*

Below is the profile of the two local partners:

- SOCTRANGWACO is the water service provider of Soc Trang City. It serves 365.670 people in Soc Trang City through 85,300 household connections and has as a water access coverage of 87%. In addition, the company services 6,619 private and institutional customers. The water access coverage among the 10,420 low income dwellers in Soc Trang City is 58% which is on the lower side. Water supply continuity is 24 h per day with a water quality that complies with WHO standards. However, during certain periods of the year, SOCTRANGWACO is facing high salinity levels in its surface water treatment resulting in interrupted supply for a part of the population for days and sometimes even weeks. SOCTRANGWACO is facing a very rapid increase in water demand because of an urban growth of more than 5% per year and is challenged with a high need for investments. At the same time, cost coverage levels (operating ratio) are low (0.95 in 2020).

- HAWASUCO is the water service provider of Vi Tranh City (or Hau Giang Province??). It serves 193,244 people in Vi Thanh city through 58,727 household connections and has as a water access coverage of 91%. In addition, the company services 8,952 private and institutional customers. The water access coverage among the 3,006 low income dwellers in Vi Tranh City is very low: 14%. Water supply continuity is 24 h per day with a water quality that complies with WHO standards.

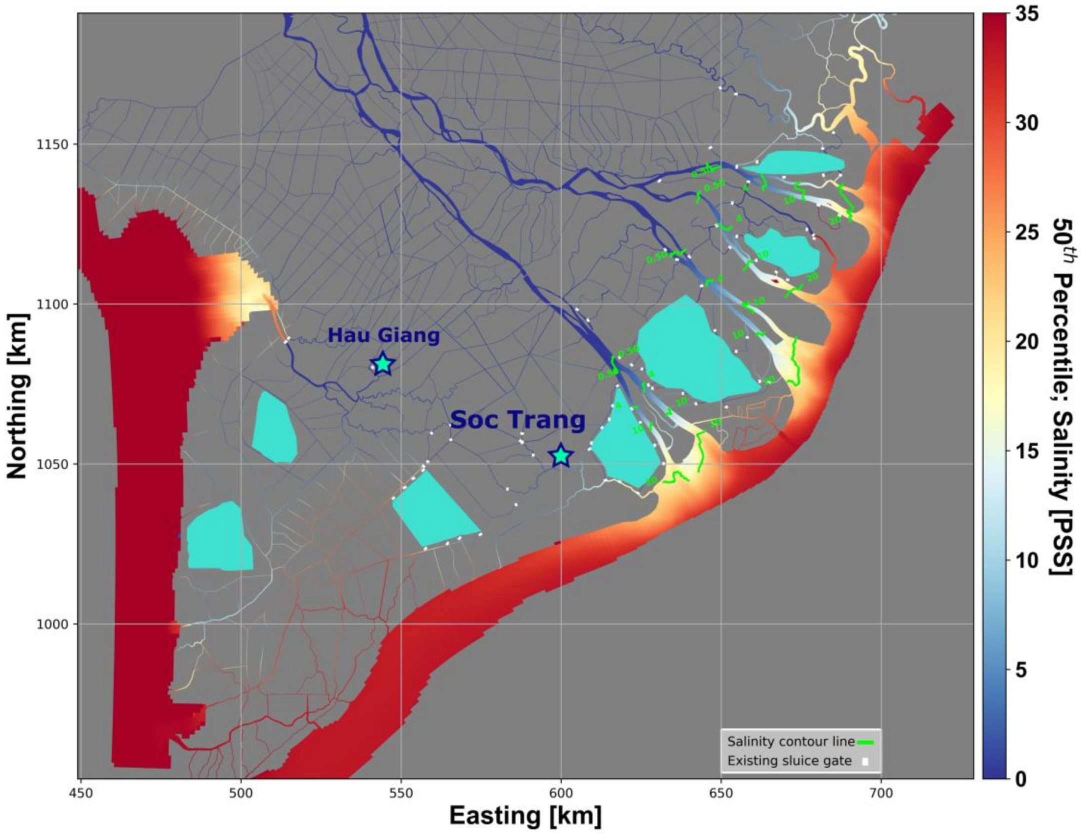
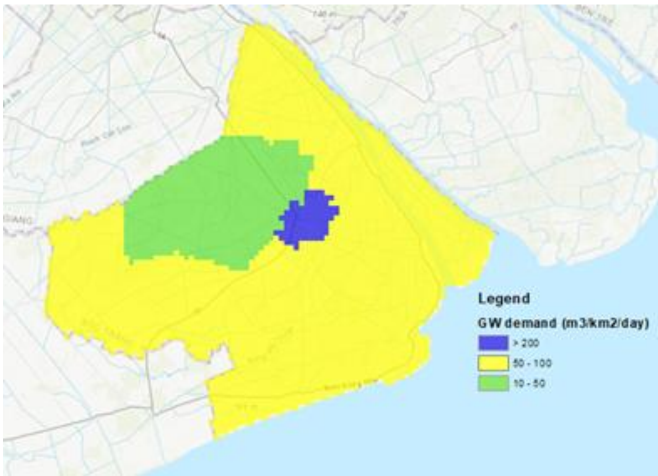



*Figure 9, Spatial variation of median salinity in the surface water system of the VMD during a four-month dry season (Eslami et al., 2021).*

## 3.6 Case-Study in Soc Trang Province

DWRPIS provided estimates of groundwater demand in m³/km²/day. Furthermore, the extraction data of DWRPIS consists of large industrial and drinking water company extractions as well as a list of smaller (agricultural/aqua-cultural) extractions classified per various aquifers. The data, along with an in-house tool, developed in the course of this proposal development, are used to assemble a 1st order estimate of the effect of existing extraction wells on groundwater heads.




Assumption: *In order to reduce the effect of the existing large groundwater extraction wells, infiltration wells can be placed at the location of large extractions*.

The majority of the large extraction wells are located near Soc Trang city and extract from the aquifer qp-23 (See Appendix 2). Figure 10 (left panel) shows the estimated effect of the present large industrial and drinking water extractions. The largest drawdown can be found near Soc Trang city with an estimated of ~4 m drop, which has resulted in significant subsidence in Soc Trang City as shown by Minderhoud et al. (2017). The same figure on the right panel shows how much groundwater head can be restored by infiltrating fresh surface water to the same aquifer with 3 times larger than the demand. This analytical analysis is just to showcase the significant potential of this practice on groundwater level management, and ultimately, its impact on slowing down land subsidence. As subsidence is an irreversible process, the future of the delta lies in solutions that either slow down subsidence process (like ASR) or promote elevation gain, e.g., through sedimentation.

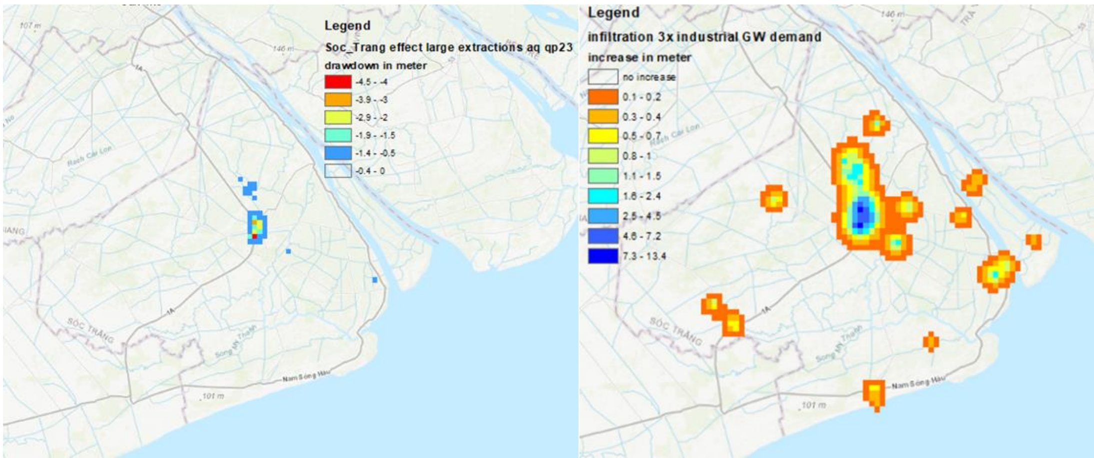



*Figure 10 Estimation (using a toolbox, see Appendices 2 anf 3) of the groundwater head decline of the qp23 aquifer in response to groundwater extraction over the past 5 years (left panel); estimated steady-state groundwater head increase in response to a continuous infiltration of surface water as much as three times larger than the demand (right panel).*

## 3.7 Steps Forward

In association with the partners, in Q3 2021, we will conduct a pre-feasibility study, directly on the above-mentioned pilot locations. This provides additional opportunity to dive into not only the technical aspects of the final implementation of the technique, but also its financial viability. Furthermore, our first contacts with SNV for a potential funding through DFCD (Dutch Fund for Climate and Development) has been positive. They specifically appreciate the separate physical and water resilience aspects of the project. This, together with the positive response of the local water companies, provides a perspective and platform to reach out to the government and encourage large-scale support for the solution. Table 1 below summarizes the expected mile-stones, as we plan to pursue in the next 2-3 years.

*Table 1, A basic overview of the steps ahead as we have aligned with the local and international partners.*

| Actions | Mechanism and envisioned timing |
|---|---|
| **Pre-feasibility study (Part-1)** | In association with VEi Q-3 & Q4 2021 |
| **Pre-feasibility study (Part-2)** | Part of EU-GWOP fund (in partnership with VEi) Q1 & Q2, 2022 |
| **Pilot project funding acquisition** | Already interested parties: SNV and WWF (DFCD) Q2-Q4, 2022 |
| **Pilot project** | In association with water operators 2022-2023 |
| **Feasibility Study** | 2022-2023 |
| **From pilot to scale** | Funding acquisition, Public-Private partnership, Automatization of the system in large scale (2023+) |
| **Monitoring and Maintenance** | 2023+ |

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# Appendix 1

## Water quality requirements

A major requirement of an ASR system is the expected water quality of infiltrated and recovered water. The recovered water should meet the local standards for the intended use. In addition to this, the storage reservoir water quality should not be contaminated so that anticipated future groundwater use is hampered. Finally, a secondary potential water quality effect is clogging due to microbiological or chemical interactions between infiltration water, ground water and/or the reservoir.

Depending on the intended use of the recharged water, contaminants such as metals, organic compounds, or nutrients such as nitrate of phosphate can cause issues. Elevated concentrations of dissolved solids or salts often pose water quality problems: the major soluble cations (calcium, magnesium and sodium) and anions (sulfate, chloride and bicarbonate) are often higher in recharge water than in native ground water (USGS, 2019). Natural and anthropogenic contaminants (pesticides, plastics, medicines) in the subsurface should be identified to avoid mobilization of the contaminants.

The interaction between groundwater and infiltrated surface water can create other problems such as mineral precipitation, enhanced biological growth and mobilization of trace elements. Redox processes in the subsurface can result in mobilization of arsenic, iron and manganese, and associated elements. Therefore, it is important to not only look at the water parameters separately but to gain knowledge if the interaction between the two water sources can create problems.

Water quality demands differ from country to country. Also, the water quality standards per source can differ. National water quality standards for surface water, groundwater and industrial wastewater have been described for Vietnam for different purpose or environment where the water is discharged. Table 2 - Table 4 show respectively the national Vietnamese water quality standards for surface water, groundwater and industrial wastewater discharge. In general, if the water quality is improved or the same, ASR is often possible. If the system deteriorates the water quality the system is (obviously) often not permitted.

Assessment whether water quality issues will arise ideally consists of the following steps:

1. Characterization of groundwater quality, infiltration water quality, and relevant water quality standards.
   Knowing the concentrations of the relevant water quality components in groundwater and infiltration water and relating these to the relevant water quality standards can give a first indication whether water quality issues can be expected, and if so, which.
2. Assessment of potential water quality issues based on hydrological and biogeochemical characteristics.
   As described before, direct and indirect water quality issues will be a result of reactions of the infiltrated water in the storage reservoir. To assess these, a schematic overview of the hydrologic and biogeochemical conditions can help. If possible, a hydrogeochemical model can be applied to assess potential effects (e.g. MODFLOW-PHREEQC).
3. Monitoring
   Even when basic properties of the infiltrated water and the storage reservoir are known and predictions can be made, uncertainties will remain. Therefore, water quality monitoring of the ASR system in practice remains important.

*Table 2 National technical regulation on surface water quality (QCVN 08-MT:2015/BTNMT).*

| TT | Parameter | Unit | Limitation Value | | | |
|---|---|---|---|---|---|---|
| | | | A | | B | |
| | | | $A_1$ | $A_2$ | $B_1$ | $B_2$ |
| 1 | pH | | 6-8,5 | 6-8,5 | 5,5-9 | 5,5-9 |
| 2 | $BOD_5$ (20°C) | mg/l | 4 | 6 | 15 | 25 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 3 | COD | mg/l | 10 | 15 | 30 | 50 |
| 4 | Dissolved Oxygen (DO) | mg/l | ≥ 6 | ≥ 5 | ≥ 4 | ≥ 2 |
| 5 | Total suspended solids (TSS) | mg/l | 20 | 30 | 50 | 100 |
| 6 | Amoni ($NH_4^+$ tính theo N) | mg/l | 0,3 | 0,3 | 0,9 | 0,9 |
| 7 | Clorua ($Cl^-$) | mg/l | 250 | 350 | 350 | - |
| 8 | Florua ($F^-$) | mg/l | 1 | 1,5 | 1,5 | 2 |
| 9 | Nitrit ($NO^-_2$ tính theo N) | mg/l | 0,05 | 0,05 | 0,05 | 0,05 |
| 10 | Nitrat ($NO^-_3$ tính theo N) | mg/l | 2 | 5 | 10 | 15 |
| 11 | Phosphat ($PO_4^{3-}$ tính theo P) | mg/l | 0,1 | 0,2 | 0,3 | 0,5 |
| 12 | Xyanua ($CN^-$) | mg/l | 0,05 | 0,05 | 0,05 | 0,05 |
| 13 | Asen (As) | mg/l | 0,01 | 0,02 | 0,05 | 0,1 |
| 14 | Cadimi (Cd) | mg/l | 0,005 | 0,005 | 0,01 | 0,01 |
| 15 | Lead (Pb) | mg/l | 0,02 | 0,02 | 0,05 | 0,05 |
| 16 | Crom VI ($Cr^{6+}$) | mg/l | 0,01 | 0,02 | 0,04 | 0,05 |
| 17 | Total Crom | mg/l | 0,05 | 0,1 | 0,5 | 1 |
| 18 | Copper (Cu) | mg/l | 0,1 | 0,2 | 0,5 | 1 |
| 19 | Zinc (Zn) | mg/l | 0,5 | 1,0 | 1,5 | 2 |
| 20 | Niken (Ni) | mg/l | 0,1 | 0,1 | 0,1 | 0,1 |
| 21 | Mangan (Mn) | mg/l | 0,1 | 0,2 | 0,5 | 1 |
| 22 | Mecury (Hg) | mg/l | 0,001 | 0,001 | 0,001 | 0,002 |
| 23 | Iron (Fe) | mg/l | 0,5 | 1 | 1,5 | 2 |
| 24 | Chất hoạt động bề mặt | mg/l | 0,1 | 0,2 | 0,4 | 0,5 |
| 25 | Aldrin | µg/l | 0,1 | 0,1 | 0,1 | 0,1 |
| 26 | Benzene hexachloride (BHC) | µg/l | 0,02 | 0,02 | 0,02 | 0,02 |
| 27 | Dieldrin | µg/l | 0,1 | 0,1 | 0,1 | 0,1 |
| 28 | Tổng Dichloro diphenyl trichloroethane ($DDT_S$) | µg/l | 1,0 | 1,0 | 1,0 | 1,0 |
| 29 | Heptachlor & Heptachlorepoxide | µg/l | 0,2 | 0,2 | 0,2 | 0,2 |
| 30 | Total Phenol | mg/l | 0,005 | 0,005 | 0,01 | 0,02 |
| 31 | Total oils & grease | mg/l | 0,3 | 0,5 | 1 | 1 |
| 32 | Total Organic Carbon, TOC | mg/l | 4 | - | - | - |
| 33 | Gross α activity | Bq/l | 0,1 | 0,1 | 0,1 | 0,1 |
| 34 | Gross β activity | Bq/l | 1,0 | 1,0 | 1,0 | 1,0 |
| 35 | Coliform | MPN or CFU /100 ml | 2500 | 5000 | 7500 | 10000 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 36 | E.coli | MPN or CFU /100 ml | 20 | 50 | 100 | 200 |

*Note:*

*A1 – Applied to the surface water using for source of domestic water supply with normal treatments, for conservation of aquatic flora and fauna and other purposes as mentioned in A2, B1 and B2.*

*A2 - Applied to the surface water using for source of domestic water supply with appropriate treatments or use for other purposes as mentioned in B1 and B2.*

*B1 - Applied to the surface water using for source of irrigation, water yield or other uses requiring similar water quality or other purposes like B2.*

*B2 - Applied to the surface water using for source of waterway and other purposes with low quality water requirement.*

*Table 3 National technical regulation on underground water quality (QCVN 09-MT:2015/BTNMT).*

| No. | Parameters | Unit | Limitation Value |
|---|---|---|---|
| 1 | pH | - | 5,5 - 8,5 |
| 2 | Hardness (as $CaCO_3$) | mg/l | 500 |
| 3 | Suspended solids | mg/l | 1500 |
| 4 | COD ($KMnO_4$) | mg/l | 4 |
| 5 | Amôni (as N) | mg/l | 0,1 |
| 6 | Clorua ($Cl^-$) | mg/l | 250 |
| 7 | Florua ($F^-$) | mg/l | 1,0 |
| 8 | Nitrit ($NO^-_2$) (as N) | mg/l | 1,0 |
| 9 | Nitrat ($NO^-_3$) (as N) | mg/l | 15 |
| 10 | Sulfat ($SO_4^{2-}$) | mg/l | 400 |
| 11 | Xianua ($CN^-$) | mg/l | 0,01 |
| 12 | Phenol | mg/l | 0,001 |
| 13 | Asen (As) | mg/l | 0,05 |
| 14 | Cadimi (Cd) | mg/l | 0,005 |
| 15 | Lead (Pb) | mg/l | 0,01 |
| 16 | Crom VI ($Cr^{6+}$) | mg/l | 0,05 |
| 17 | Copper (Cu) | mg/l | 1,0 |
| 18 | Zinc (Zn) | mg/l | 3,0 |
| 19 | Mangan (Mn) | mg/l | 0,5 |
| 20 | Mecury (Hg) | mg/l | 0,001 |
| 21 | Iron (Fe) | mg/l | 5 |
| 22 | Selen (Se) | mg/l | 0,01 |
| 23 | Gross $\alpha$ activity | Bq/l | 0,1 |
| 24 | Gross $\beta$ activity | Bq/l | 1,0 |

| | | | |
|---|---|---|---|
| 25 | E.Coli | MPN/100ml | Not detectable |
| 26 | Coliform | MPN/100ml | 3 |

*Table 4 Nationcal technical regulation on industrial wastewater (QCVN 40:2011/BTNMT).*

| TT | Thông số | Đơn vị | Giá trị C | |
|---|---|---|---|---|
| | | | A | B |
| 1 | Temperature | oC | 40 | 40 |
| 2 | Color | Pt/Co | 50 | 150 |
| 3 | pH | - | 6 đến 9 | 5,5 đến 9 |
| 4 | BOD5 (20oC) | mg/l | 30 | 50 |
| 5 | COD | mg/l | 75 | 150 |
| 6 | Suspended solids | mg/l | 50 | 100 |
| 7 | Asen | mg/l | 0,05 | 0,1 |
| 8 | Mercury | mg/l | 0,005 | 0,01 |
| 9 | Lead | mg/l | 0,1 | 0,5 |
| 10 | Cadimi | mg/l | 0,05 | 0,1 |
| 11 | Crom (VI) | mg/l | 0,05 | 0,1 |
| 12 | Crom (III) | mg/l | 0,2 | 1 |
| 13 | Copper | mg/l | 2 | 2 |
| 14 | Zinc | mg/l | 3 | 3 |
| 15 | Niken | mg/l | 0,2 | 0,5 |
| 16 | Mangan | mg/l | 0,5 | 1 |
| 17 | Iron | mg/l | 1 | 5 |
| 18 | Total cyanide | mg/l | 0,07 | 0,1 |
| 19 | Total phenol | mg/l | 0,1 | 0,5 |
| 20 | Total mineral fats and oils | mg/l | 5 | 10 |
| 21 | Sunfua | mg/l | 0,2 | 0,5 |
| 22 | Florua | mg/l | 5 | 10 |
| 23 | Amoni (as N) | mg/l | 5 | 10 |
| 24 | Total nitrogen | mg/l | 20 | 40 |
| 25 | Total phosphorus (as P) | mg/l | 4 | 6 |
| 26 | Clorua<br>(not applicable when discharging into saline water and brackish water) | mg/l | 500 | 1000 |

| | | | | |
|---|---|---|---|---|
| 27 | Excess Chlorine | mg/l | 1 | 2 |
| 28 | Total organochlorine pesticides | mg/l | 0,05 | 0,1 |
| 29 | Total organophosphorus pesticides | mg/l | 0,3 | 1 |
| 30 | Total PCB | mg/l | 0,003 | 0,01 |
| 31 | Coliform | vi khuẩn/100ml | 3000 | 5000 |
| 32 | Gross α activity | Bq/l | 0,1 | 0,1 |
| 33 | Gross β activity | Bq/l | 1,0 | 1,0 |

*Note: Industrial waste waters containing the values of parameters and concentrations of substances which are equal to or lower than the values specified in the column A may be discharged into the water bodies using for sources of domestic/tap water supply. Industrial waste waters containing the values of parameters and concentration of substances which are lower than or equal to those specified in the column B are discharged only into the water bodies using for navigation, irrigation purposes or for bathing, aquatic breeding and cultivation, etc (not for serving tap water supply).*

# Appendix 2

## Methods

### Conceptual description groundwater head drawdown due to extractions

In this section the generic tool to determine the effect of a (combination of) well(s) on the groundwater head will be described in more detail. The necessary input parameters will be described together with the needed assumptions and the limitations of the tool.
The tool was built in python and uses the DeGlee formula (1) to calculate the steady state groundwater head change (m) of a homogenous aquifer with a confining layer. Both extraction and recovery wells can be implemented in the tool. The output is a map with the effect of the wells on the groundwater head in meters.

$$s(r) = \frac{Q_0}{2\pi kD} K_0 \left(\frac{r}{\lambda}\right) \qquad (1)$$

*s(r) = change in groundwater head (m) at distance r of the well*
*$Q_0$ = injection/extraction rate in m3/day*
*k = hydraulic conductivity of the aquifer (m/day)*
*H = thickness of the aquifer (m)*
*$K_0$ = Bessel function of the second kind of order 0*
*r = distance to the well (m)*

$$\lambda = \sqrt{kDc} \qquad (2)$$

*λ = distance at which the well influences the groundwater head (m)*
*k = hydraulic conductivity of the aquifer (m/days)*
*c = the resistance of the confining layer above the aquifer (days)*
*D = thickness of the aquifer (m)*

## Input parameters

The necessary input parameters describe the properties of a homogeneous aquifer and confining layer above the aquifer, placements of wells and their extraction/recovery rates. In order to use the tool for the VMD aquifer properties of seven aquifers (Figure 12, Minderhoud et al., 2017) in the VMD were collected. An open-source hydrogeological model of the VMD (Gunnink et al., 2021) was used to determine the mean thickness (H), mean hydraulic conductivity (k), and mean resistance (c) for each of the seven aquifers.
The thickness of the aquifers varies greatly over the Mekong delta (Figure 12). This results in a rough estimate on the parameter values. To reduce the error, the mean parameter values for the Soc Trang province were calculated. A smaller area results in a better representation of the parameter values in that area. Therefore, the tool performs better when zoomed in to a more regional or local scale than on a large regional or national scale. Table 5 shows the mean subsoil parameter values per aquifer for the Soc Trang province.

*Table 5 Subsoil parameters per aquifer for the Soc Trang province.*

| **aquifer** | k [m/day] | C [days] | H [m] |
|---|---|---|---|
| **qh** | 6 | 1940 | 26 |
| **qp3** | 40 | 1347 | 15 |
| **qp23** | 43 | 5539 | 16 |
| **qp1** | 10 | 13111 | 26 |
| **n22** | 45 | 29353 | 24 |
| **n21** | 29 | 52211 | 29 |
| **n13** | 9 | 145225 | 88 |

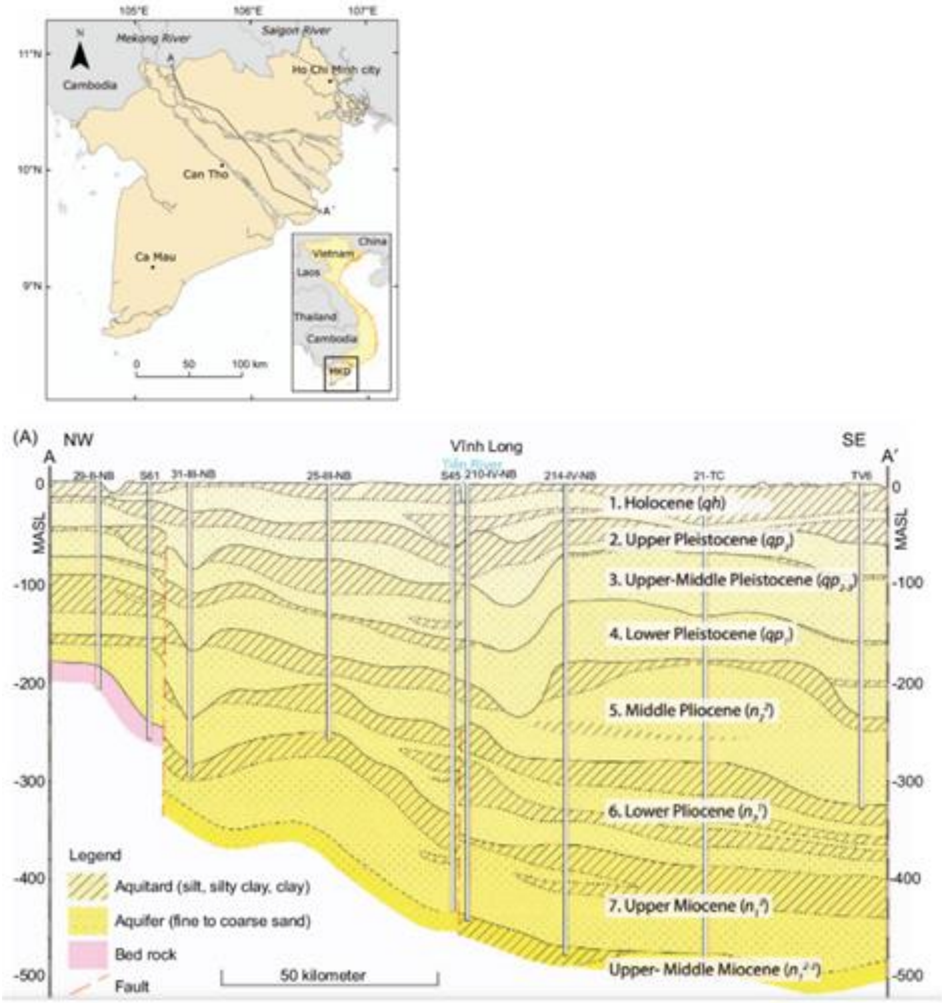


*Figure 11 Top: Location of the cross section, Bottom: Cross-section of the seven described aquifers in the Mekong delta (Minderhoud et al., 2017).*

# Appendix 3

## Computed increase in hydraulic head due to groundwater infiltration for the Soc Trang Province

In this exercise, an infiltration well is placed for each squared kilometer in the Soc Trang province. The placement of the wells is shown with green dots in Figure 13. In every well, fresh surface water is infiltrated at the rate of the demand for that specific area (see Figure 10). The total amount of infiltrated water is ca. 230.000 $m^3$/day. Figure 14 shows the effects on the hydraulic head in the aquifer qp23, given a certain infiltration rate.

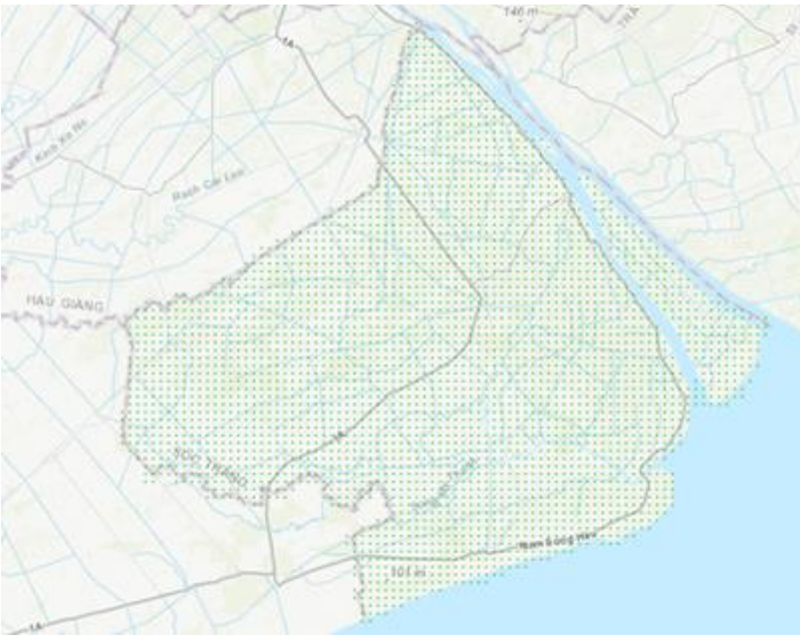


*Figure 12 Hypothetical positions of infiltration wells (green dots) in the Soc Trang Province.*

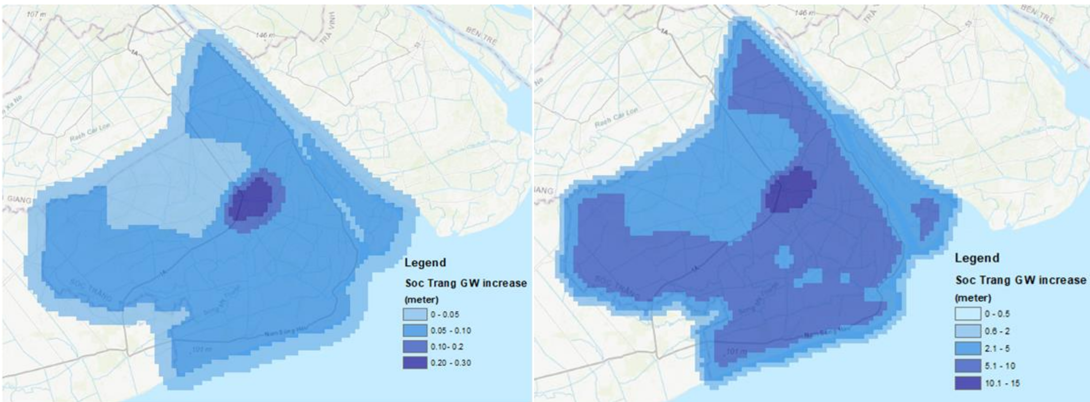


*Figure 13 Estimated increase in hydraulic head: left panel: the effect of infiltrating in a well per $km^2$ in the Soc Trang province (without extracting the infiltrated water in the dry period) for as much as the 230,000 $m^3$/day water demand in total; right panel: 50 times the water demand (11.5 M $m^3$/day).*

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