Project:

ASR application for Domestic Fresh Water Supply in the Vietnamese Mekong Delta

Implementation Plan of an Aquifer Storage & Recovery (ASR) Pilot at the Nga Bay Water Treatment Plant of HAWASUCO

Hau Giang Province

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PARTNERS FOR WATER
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Summary

We believe that the location and set up at the water treatment plant of HAWASUCO in Nga Bay, Hau Giang province, meets all requirements for an aquifer storage and recovery (ASR) pilot based on the following success factors:

- Source water quantity: There is sufficient surplus source water available from the water treatment plant.
- Source water quality: The water quality of the treated water is of high quality and does not pose any risk for the operation of the system (clogging) and the contamination of the aquifer.
- Suitable aquifer: Results of sediment analysis show the presence of a hydrogeological favorable aquifer qp_1 consisting of 20 m of medium sand with only a 2.5 m thick layer of sandy loam. The overlying aquitard provides a very good protection against upward leakage as it consists of at least 5 m of stiff clay. The underlying aquitard provides a good protection against downward leakage as it consists of at least 5 m of silt loam.
- Storage capacity: As the groundwater level has dropped significantly over the last decades due to over abstraction and low natural recharge rates of the confined aquifer system, there has been sufficient storage space created in the aquifer to recharge water artificially.
- Recovery: The hydraulic gradient of the groundwater and hence groundwater velocity (estimated 3-8 m/year) on a regional scale is low. In the vicinity (1.5-2 km) downstream of the pilot there are only one smaller (170 m^3/day) active licensed wells abstracting water from qp_1. Hence, it is not expected that the recharged water will move quickly away from the pilot site and reach other users in the near future. Based on sedimentary analysis of the aquifer material physical clogging due to the mobilization of clay minerals and the precipitation of iron hydroxides should be monitored. The risk of aquifer contamination due to the release of trace elements especially for As, Cr, Ni and Zn seems low, but will be further investigated and monitored.
- Method: The ASR method using a single well for recharge and recovery of water is the most suitable method for deep confined aquifers and has been proven successful in many cases worldwide.
- Demand: In cases that the surface water is of insufficient quality (e.g. due to saline intrusion or pollution), the recharged groundwater provides an additional emergency storage to supply the water treatment system with source water. While currently the saline intrusions into the surface water system have not reached Nga Bay Town, it is expected that factors like climate change and riverbed incision will lead to years with saline intrusion also affecting the surface water salinity in the dry season at Nga Bay town. If this pilot is successful, it could be a model to be transferred to other locations in the Mekong Delta that are already experiencing saline intrusion during the dry season now.
- Monitoring: The pilot will be set up with a comprehensive monitoring scheme to allow detailed evaluation of the tests with respect to water quantity (infiltration rate, recovery efficiency) and water quality (source water quality, recovered water quality), as well as cost-benefit analysis (energy consumption, operational costs, infrastructure costs).
- Institutional arrangements: This project combines the operational capacities of the ASR well owner HAWASUCO, who has an interest in a secure water, with the scientific and technical expertise from a number of international organizations (Deltares, VEI, BGR, WWF), and the local expertise for well drilling of the Division of Water Resources Planning and Investigation in the South (DWRPIS).

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Abbreviations

Abbreviation	Meaning
ASR	aquifer storage and recovery
BGR	German Federal Institute of Geosciences and Natural Resources
BOD	biological oxygen demand
COD	chemical oxygen demand
CRMGG	“Climate resilient management of groundwater and geohazards” project
DBPs	disinfection by-products
DO	dissolved oxygen
DOC	dissolved organic carbon
DONRE	Department of Natural Resources and Environment
DWRPIS	Division of Water Resources Planning and Investigation in the South
E.coli	*Escherichia coli*
EC	electric conductivity
HAWASUCO	Hau Giang Water Supply and Sewerage and Urban Construction Joint Stock Company
IGRAC	International Groundwater Resources Assessment Centre
IoT	internet of things
LOI	loss of ignition
LoRaWAN	low range wireless area network
MAR	managed aquifer recharge
MFI	membrane filtration/fouling index
NAWAPI	National Center for Water Resources Planning and Investigation
NOM	natural organic matter
PfW	Partners for Water
SAR	sodium adsorption ratio
TDS	total dissolved solids
THMs	trihalomethanes
TOC	total organic carbon
TSS	total suspended solids
VEI	Vitens-Evides International
WWF	World Wildlife Fund

Purpose of this document

This implementation plan is designed to fulfil the requirements as outlined in Article 28 of Circular 03/2024/TT-BTNMT. It will explain the necessity for artificial recharge, describe the hydrogeology of the selected site and the water source to be used. Technical designs and the operational procedures are described.

In the Partner for Water (PfW) project "ASR application for Domestic Fresh Water Supply in the Vietnamese Mekong Delta", the ambition is to build an Aquifer Storage and Recovery (ASR) pilot location at the Nga Bay Water Treatment Plant of Hau Giang Water Supply and Sewerage and Urban Construction Joint Stock Company (HAWASUCO) in Hau Giang province with the objectives of:

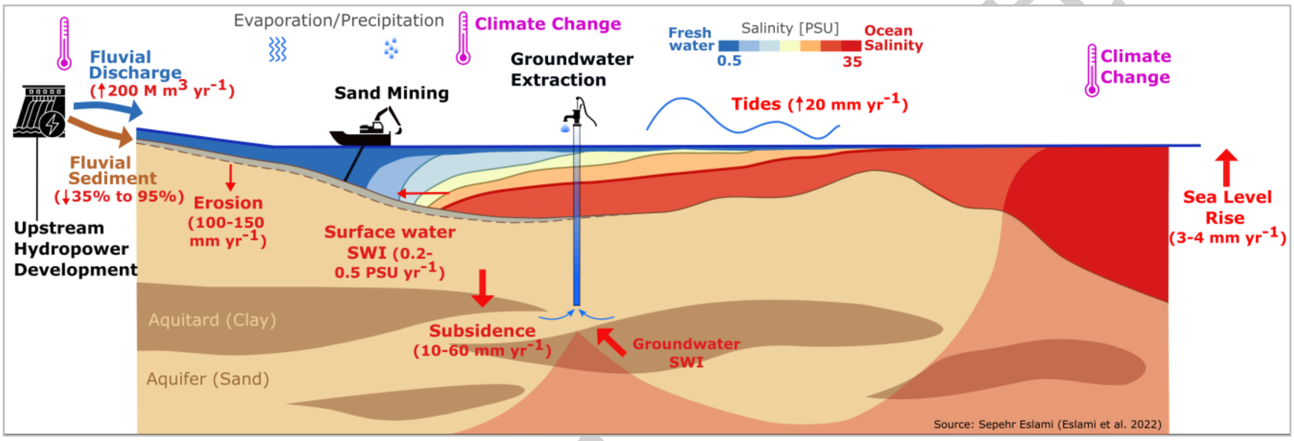
- successfully develop and demonstrate a functioning infiltration system in the local context based on the 'proof-of concept' (from the Netherlands, Chile, and other countries),
- showcase the capacity of ASR to provide sufficient freshwater in times of shortages,
- address local and federal authorities in bringing about a legal framework within which ASR is applicable, and
- create a coalition within the interested stakeholders towards a clear upscaling path.

The funding of this project was approved in June 2023 by the PfW and the project is envisaged to run until the end of 2025. The PfW consortium consists of Deltares, Vitens-Evides International (VEI) and HAWASUCO. The German Federal Institute of Geosciences and Natural Resources (BGR) under the "Climate resilient management of groundwater and geohazards" (CRMGG) project, the Division of Water Resources Planning and Investigation in the South (DWRPIS) and World Wildlife Fund (WWF) Vietnam act as cooperating and co-financing partners.

NOTE: This version of the document was prepared in Sep 2024. It has not yet been submitted to the Department of Agriculture and Environment (formerly DONRE) and has hence not been approved. It serves as a basis for further discussion.

1. Necessity of artificial recharge of groundwater

Natural resources of the Vietnamese Mekong Delta (VMD) are under significant pressure by climatic and anthropogenic forces. Sea level rise, upstream discharge anomalies, sediment starvation and hydrological regime shift due to upstream impoundments, riverbed/bank and coastal erosion, salt intrusion and subsidence are various struggles of the VMD in the context of global and regional change. Over the past two decades, salt intrusion into the surface water system of the VMD has proven to be increasing significantly and is expected to increase in the next three decades (Eslami et al. 2021). At the same time, significant subsidence rates in the delta are largely associated to depletion of the groundwater levels (Minderhoud et al. 2017). Furthermore, relying on surface water surpluses is increasingly unattainable owing to salt intrusion and accessibility especially in the context of urban domestic water supply. Here, the sustainable use of fresh groundwater can be a reliable source.



Source: Sepehr Eslami (Eslami et al. 2022)

Figure 1: An imaginary cross-section of the Mekong Delta through an estuarine channel, demonstrating various trends the delta is currently facing with estimates of their rates based on most recent scientific findings (Eslami 2022)

The Vietnamese Mekong Delta is considered as a hotspot for climate change impact. However, the geoscientific challenges the delta is facing (shown in Figure 1 above) is driven by a complex combination of climatic and anthropogenic stressors(Eslami 2022). The stress on freshwater resources due to salt intrusion demands innovative solutions to enable future-proof liveable cities. The pilot location, Hau Giang City, is in the heart of the Mekong Delta, struggling to sustainably supply its domestic freshwater demand. Given the hydrological regime shift in the Mekong River Basin (due to hydropower operations), sediment starvation due to upstream impoundments and sand mining and the resulting riverbed incisions, and given the accelerating relative sea level rise, increased saline water intrusion is inevitable. Hau Giang province, dealing with the consequences of the abovementioned drivers, provides a great location to showcase ASR applicability.

Salt intrusion in the riverine system of the VMD is a great problem over a short period of time in the year (2-3 months in the dry season). Deep Aquifer Storage and Recovery (ASR) offers a promising method to supply sustainable fresh groundwater when it is needed, while at the same time can help restoring groundwater tables, especially in urban areas as hotspots of land subsidence. ASR is a groundwater resources management technique for storing water in the subsurface during wet periods, and recovering that freshwater when needed (usually during dry periods) to fill the supply gap (USGS, 2019). ASR systems have already been successfully applied in other parts of the world (Dillon et al. 2019) . However, within Vietnam, despite great interest since the early 2000's, due to technical challenges and concerns over water quality, the method has not been applied outside of smaller research pilots. If the approval is granted, it counts as the first demonstration of ASR application, as a viable adaptation and mitigation method as climate adaptation. While the method has been tested in the Netherlands and around the world, it needs to be technically and administratively localized. We are therefore encouraged to build on this promising solution as an adaptive mitigation system that fits spatial and temporal dynamics of the challenges in the VMD and beyond. Building on our pre-feasibility study (Eslami and King 2022), we propose an innovative ASR system that a) fills the shortage gaps on demand, b) can be done provincially and bridges trans-provincial administrative hurdles, c) empowers the local provincial authorities to tackle their own shortage (a decentralized solution), d) can be phased gradually, and e) can help restore groundwater tables and reduce land subsidence. Beneficiaries of the project are primarily local water operators and local communities within the VMD, as well as the Ministry of Natural Resources and Environment (MONRE).

The pre-feasibility study (Eslami and King 2022) highlights the suitability of our approach when considering the availability of existing infrastructure, preparedness and willingness of our local partners, as well as quantitatively showing the physical suitability of the subsurface and upscaling potentials.

We therefore propose a pilot to install a single ASR system in Hau Giang Province with technical and financial support from the local water company (HAWASUCO), BGR, and WWF. We aim at building the first infiltration well in the VMD, operate and monitor the well during the project, demonstrate its success, disseminate the results and engage stakeholders for scaling up, and carry out bankability and cost-benefit analyses. We envisage results to provide a quantitative understanding of a decentralized ASR system as a solution to increase water availability by leveraging the deltaic subsurface, with huge potentials for upscaling to other areas (see the pre-feasibility study). With great support from various water companies, and other governmental and non-governmental institutes, the pilot lends itself to the desired scale-up.

The pilot attempts to address two of the main drivers of vulnerability in 1) salt intrusion and 2) subsidence, while assuring a sustainable freshwater supply to the rural and urban communities. Extensive research has been recently undertaken by Dutch institutions (e.g., Eslami 2022, Eslami et al. 2021, Minderhoud et al. 2017, Minderhoud et al. 2020) highlighting the problems faced within the VMD. Currently, the VMD accommodates some 17 million people and supplies ~50% of the Vietnam's food and is thus highly vulnerable to water scarcity. Evidence shows how surface water salinity is carried landward during the dry period, and the sometimes-inevitable groundwater extraction can cause the additional problem of land subsidence and is therefore not sustainable in the long run.

The proposed pilot area is in Nga Bay City, Hau Giang province in the Western part of the VMD. The advantages of this pilot are the following:

- Water level depletion is significant in the provincial urban centers which makes it easier to showcase effectiveness (or failure) of the system.
- The water operators have sophisticated water treatment facilities that eliminate the challenge of water quality limitations for infiltration.
- The people's committee partially own shares in the local water companies HAWASUCO and are fully familiar with the challenges facing freshwater security and are therefore cooperative towards administrative hurdles.
- Our pre-feasibility assessment shows a very high ASR suitability score.

2. Site setup and Conceptual Design of ASR pilot

2.1.Site setup

The pilot site had to be on one of the premises of the local water supply company HAWASUCO, who is the main partner of the project. HAWASUCO initially identified four potential sites in the Hau Giang province, where an ASR system could be of interest and where an initial quick scan of selection criteria such as access to the site, groundwater level, urgency, available water for infiltration, water quality, etc, indicate that ASR could be suitable. The four sites identified by HAWASUCO were Ngã Bảy, Cái Tắc, Long Thạnh & Long Mỹ.

A site visit was executed for a quick scanning of site selection criteria. Two of the potential sites (Long My and Nga Bay) have a surface water treatment plant on the premises, while the other two potential sites (Cai Tac and Long Thanh) receive treated surface water from Nga Bay via a pipeline and mix it with groundwater extracted at the site (Figure 2). Source water for the ASR pilot should be sourced from treated surface water and should not contain extracted groundwater, as this would decrease the efficiency of the pilot in enhancing groundwater reserves. Accordingly, if the sites Long Thanh or Cai Tac would be selected a separate water storage tank containing only treated surface water should be installed at the site to prevent the use of groundwater in the pilot.

It was finally concluded that Nga Bay would be the best site to install an ASR pilot for HAWASUCO as it has treated surface water surplus. There is currently no real demand for groundwater recovery, however, this might change in the mid- to long-term, if saline intrusions reach deeper into the delta. The location is spacious and has the most infrastructure.

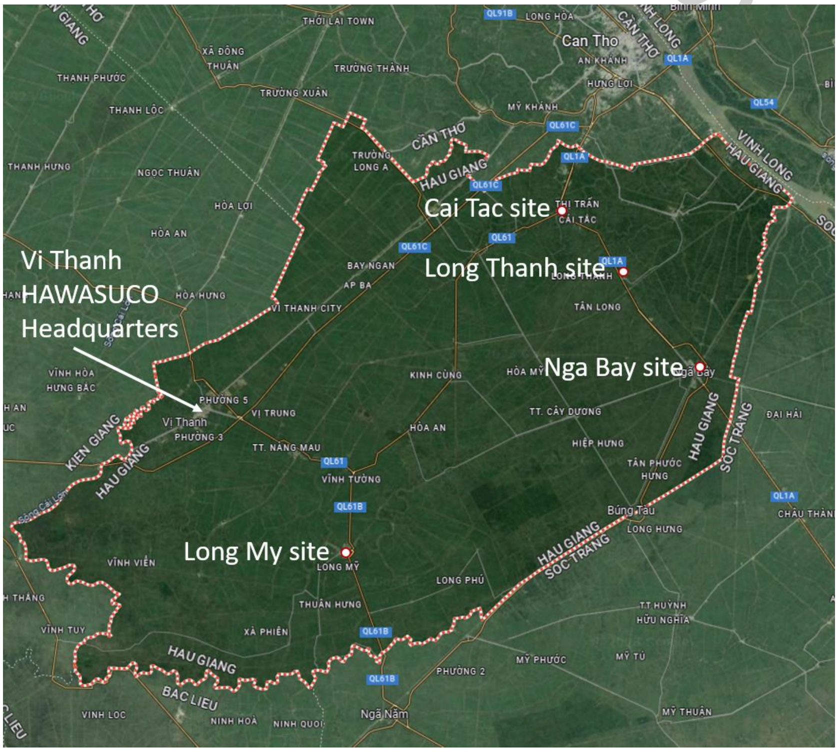


Figure 2: Four potential sites of HAWASUCO in Hau Giang province and HAWASUCO headquarters in Vi Thanh

2.2. Conceptual Design of ASR pilot

In Nga Bay City, HAWASUCO is extracting surface water from Cai Con canal connected to the Hau River (approximately 15 km distance along the canal, about 62 km upstream from the coast) as source for drinking water production (Figure 3). Raw water is treated with flocculation, sedimentation, sand filtration and chlorination before distribution to the network.

Additionally, there are two back up wells G1 and G2[1] situated on the premises. There is also an exploration well about 2 m east of G1, but it seems not to be connected to the same aquifer (either different depth, clogged screen or similar), as no drawdown was experienced in the exploration well during a 3-day pumping test in G1. The borelogs and previous water samples give some information about the target aquifer qp_1 (around 160 – 190 m below SL).

Figure 3: Overview of water treatment plant (WTP) of HAWASUCO in Nga Bay City (white outline) showing the location of existing infrastructure and the neighbouring water treatment plant (light blue outline) in cooperation with HAWASUCO. G1, G2: existing production wells, M1: monitoring well drilled in January 2024 by the project, ASR: proposed location for drilling ASR well. Source: GoogleEarth, Photos BGR.

For the conceptual design, it is envisaged to use the treated surface water before disinfection for injection in the ASR pilot to avoid any issues with disinfection by-products. Recovered water would then be fed back into the treatment system for full treatment before distribution for domestic water use (Figure 4). The system could have been an ASR system (aquifer storage and recovery: same well for injection and extraction) or an ASTR system (aquifer storage, transport and recovery: one well for injection and another well for extraction). As groundwater flow velocities are low, and ASTR systems result in more hydrogeochemical reactions along the passage in the aquifer and clogging issues in the injection well, ASR was chosen as the preferred option.

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[1] drilled in 2017, 171-192 m screen depth, tapping qp_1 aquifer, licensed for 1400 m^3/day each, max. 90 days/year

Infiltrating surface water into the selected aquifer is possible with an estimated infiltration rate of 35-90m³/h, which is considered a realistic average value based on water availability and well capacity. Analytical formulae suggest the aquifer can support the infiltration capacity required for the pilot.

An optimal ASR system and infiltration/extraction scheme would depend on various factors, including the volume needed to bridge periods of saltwater intrusion and environmental conditions. With an envisaged infiltration rate of about 35 m³/h over 24 hours per day, and 180 days a year, a total of >150 000 m³ could be infiltrated at one ASR well each year. With an estimated demand of about 10 000 m³/day at the Nga Bay plant, this would cover the full demand of about 15 days, or the partial demand of more days if the groundwater was used for dilution of slightly brackish surface water (e.g. 30 days if the mixing ratio of groundwater and surface water was 1:1).

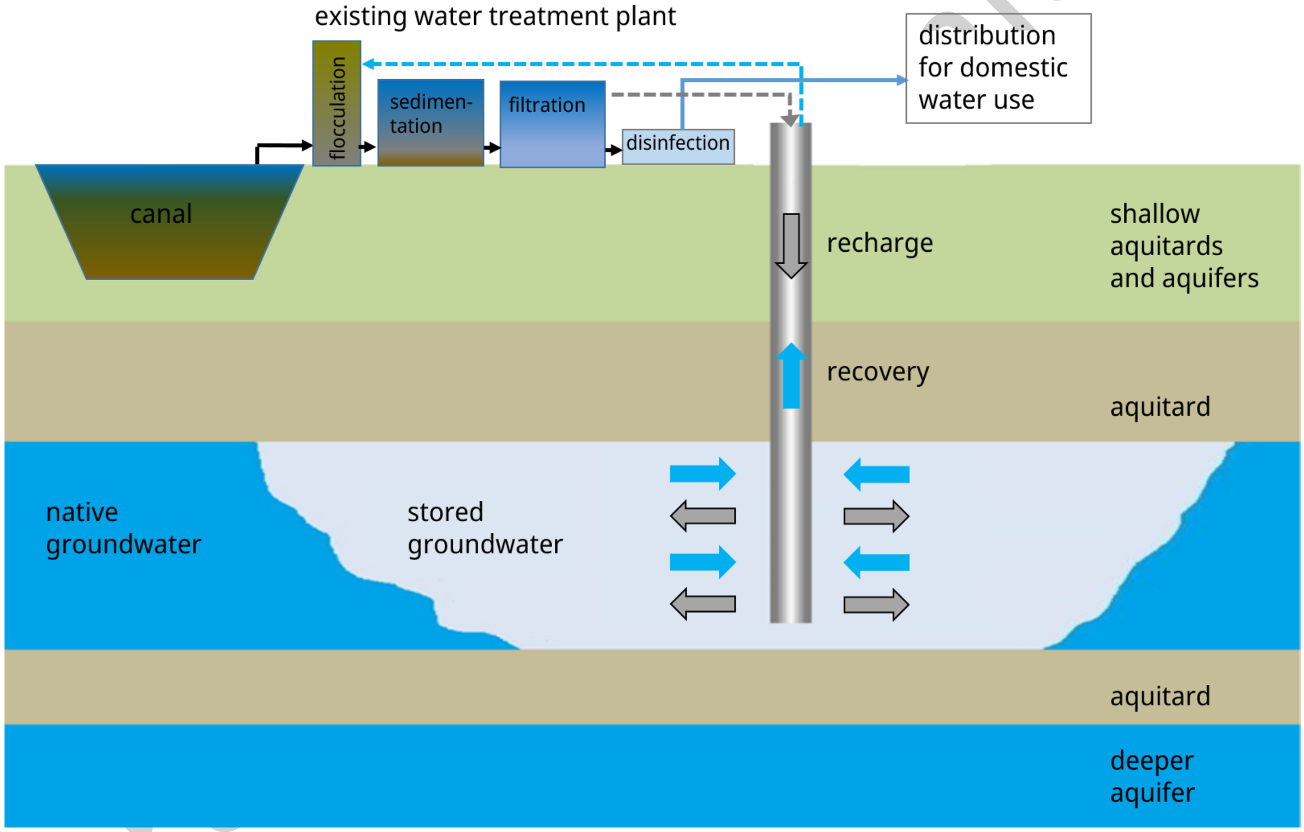

Figure 4: Conceptual design of water flow as ASR (aquifer storage and recovery: same well injection and extraction), which could be modified to ASTR (aquifer storage, transport and recovery: one well for injection and another well for extraction) using existing production wells. (Source: modified after Ji and Lee 2016).

3. Characteristics of the hydrogeological structure and water quality in the aquifer and assessment of water retention and storage capacity of the aquifer

3.1.Characteristics of the hydrogeological structure

At the Nga Bay site, there are 4 wells with information that can be used for the local hydrogeological description: G1, G2 (wells from HAWASUCO), HG1 (DWRPIS borelog), and HG-08 (Figure 5). The table (Table 1) below shows characteristics of the mentioned wells.

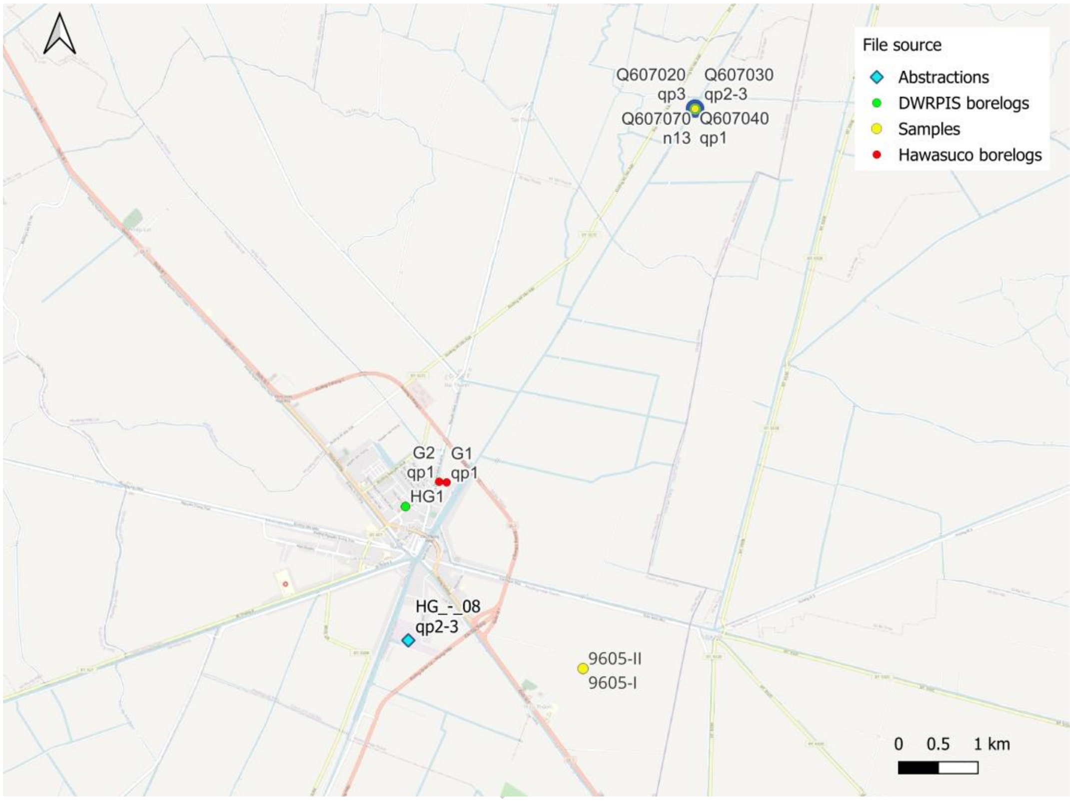

Figure 5: Location of boreholes site Nga Bay. Source: Google Maps

Table 1: Information on available borehole logs around Nga Bay

Wells	**File Source**	**Aquifers exploited**	**Depth of top and bottom aquifer (m)**	**Thickness of aquifers (m)**	**Discharge of existing wells (m^3/h)**	**Salinity of Groundwater**
G1 and G2	HAWASUCO borelogs	qp_1	171-192	34-60	70	Fresh-water <300 mg/l Cl
HG1	DWRPIS borelogs	qp_1, n_2^2 and n_2^1	130-190 238-275 300-360	60 37 60	--	--
HG-08	production well	qp_{2-3}	89-108	19	--	--
9605-I/II	Samples (salinity)	qp_3 and qp_{2-3}	68-79 144-155	--	--	2.2 1,3 (TDS g/l)

In this area, there are seven aquitards and seven aquifers, which are qh, qp_3, qp_{2-3}, qp_1, n_2^2, n_2^1 and n_1^3. The target aquifer of this ASR pilot is qp_1, found approximately between 170m and 190 m below ground level. In this area, qp_1 is confined and is approximately 20 m thick. The aquifer is composed of medium and coarse sand. Overlying and underlying the aquifer there are aquitards of clay and silt with no holding water capacity. Recently a pumping test was conducted at the site. Results indicate that the hydraulic conductivity in qp_1 could be between 90 and 120 m/d. However, potentially there are heterogeneities in the subsurface, which may indicate that this estimated value for the hydraulic conductivity is not representative of the whole aquifer. With the available data this is our best estimate.

Besides the point data, the maps created as input for the model developed in the Pre-feasibility study (Eslami and King 2022) and those developed by Gunnink et al. (2021), are available. Figure 6 shows the cross sections for Nga Bay (Gunnink et al. 2021). The first one shows the present aquifers and aquitards (hashed lines represent aquitards), and the second one the salinity distribution.

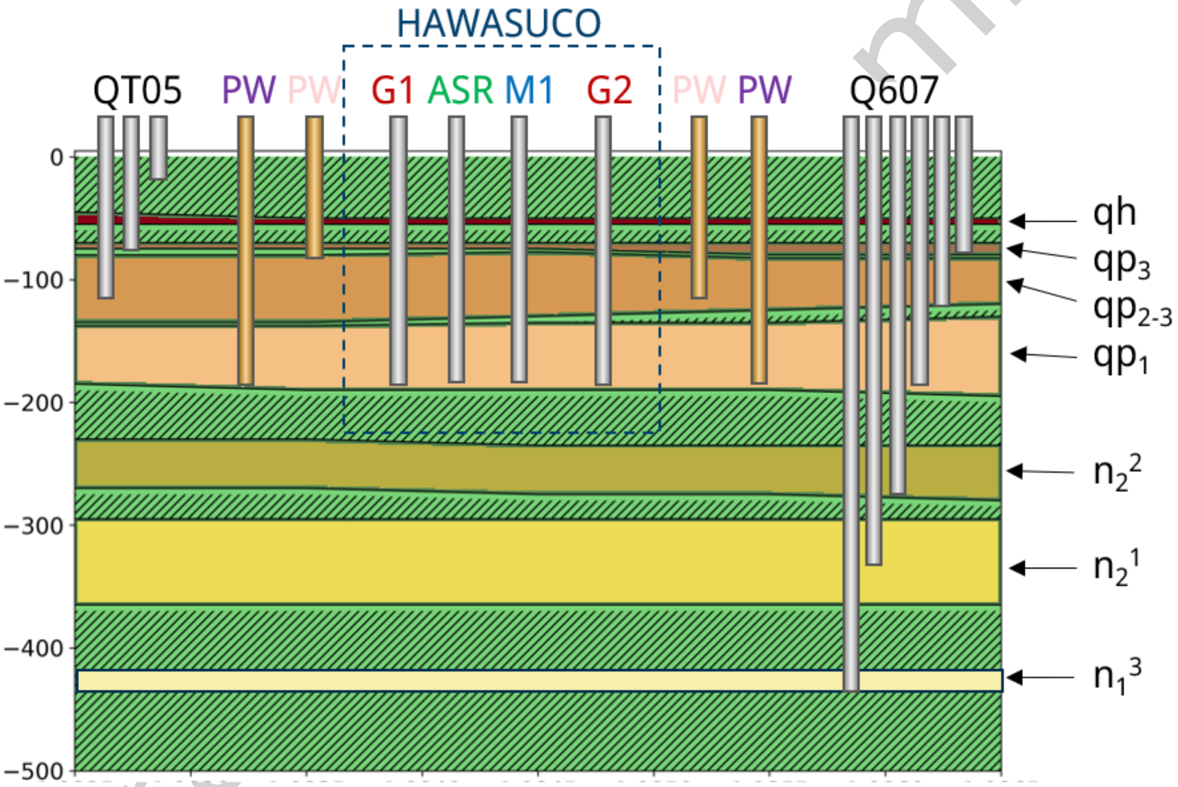

Figure 6: Modelled cross-section for Nga Bay area showing schematic aquifer distribution and well depth in the area (top) and salinity distribution (bottom) based on Gunnink et al. (2021)

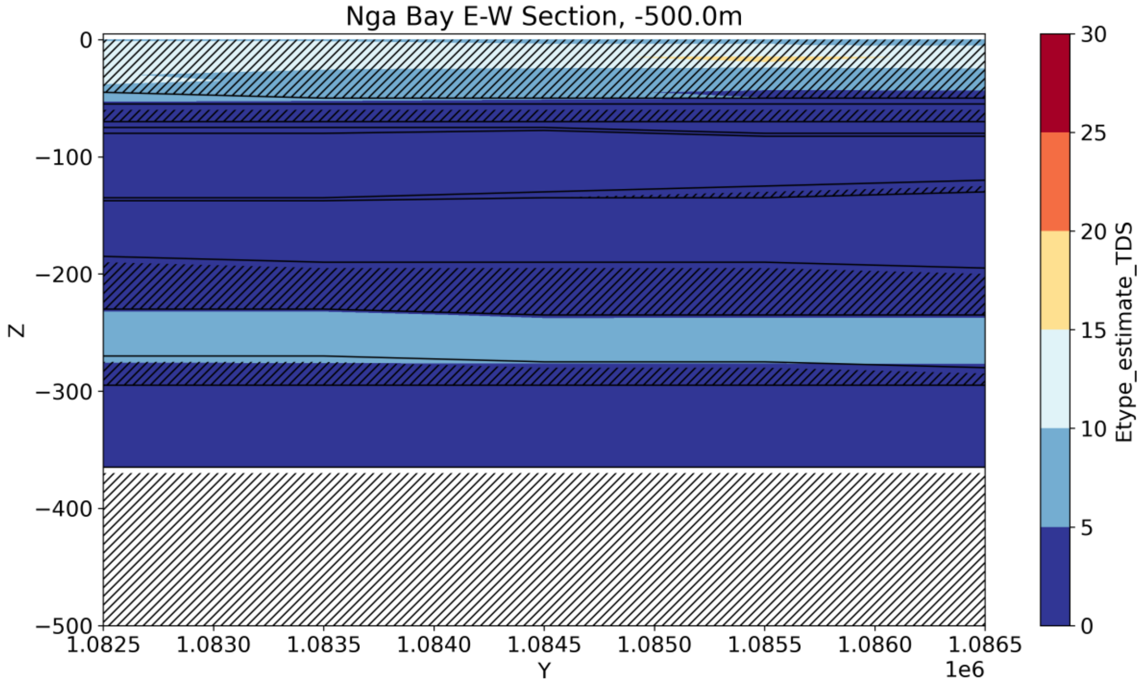

Figure 6 (cont.): Modelled cross-section for Nga Bay area showing schematic aquifer distribution and well depth in the area (top) and salinity distribution (bottom) based on Gunnink et al. (2021)

Based on the analysis of 18 sediments samples collected from the monitoring well M_1, the screen for this well (and planned for the ASR recharge well) is located at depths 167–187 m bgl in the aquifer qp_1. This 20-m layer is a **hydrogeological favorable aquifer** as it consists of medium sand with only a 2.5-m thick layer of sandy loam (Figure 7). The aquifer is dominated by quartz with minor components of siderite and feldspar. It contains only limited amounts of organic matter content (TOC < 0.08 mass%), and limited amounts of clay minerals, which is reflected in the low CEC values (<2 cmol+/kg), low loss of ignition (LOI) (1.16 mass%) and low aluminum and iron oxide concentrations (3.5 and 1.5 mass%, respectively). Only the sandy loam layer contains proven amounts of clay minerals in minor quantities and also higher concentrations of aluminum and iron oxide (> 5 %). Pyrite was not detected in the aquifer, which corresponds to the low total sulfur concentrations (< 0.06 mass%).

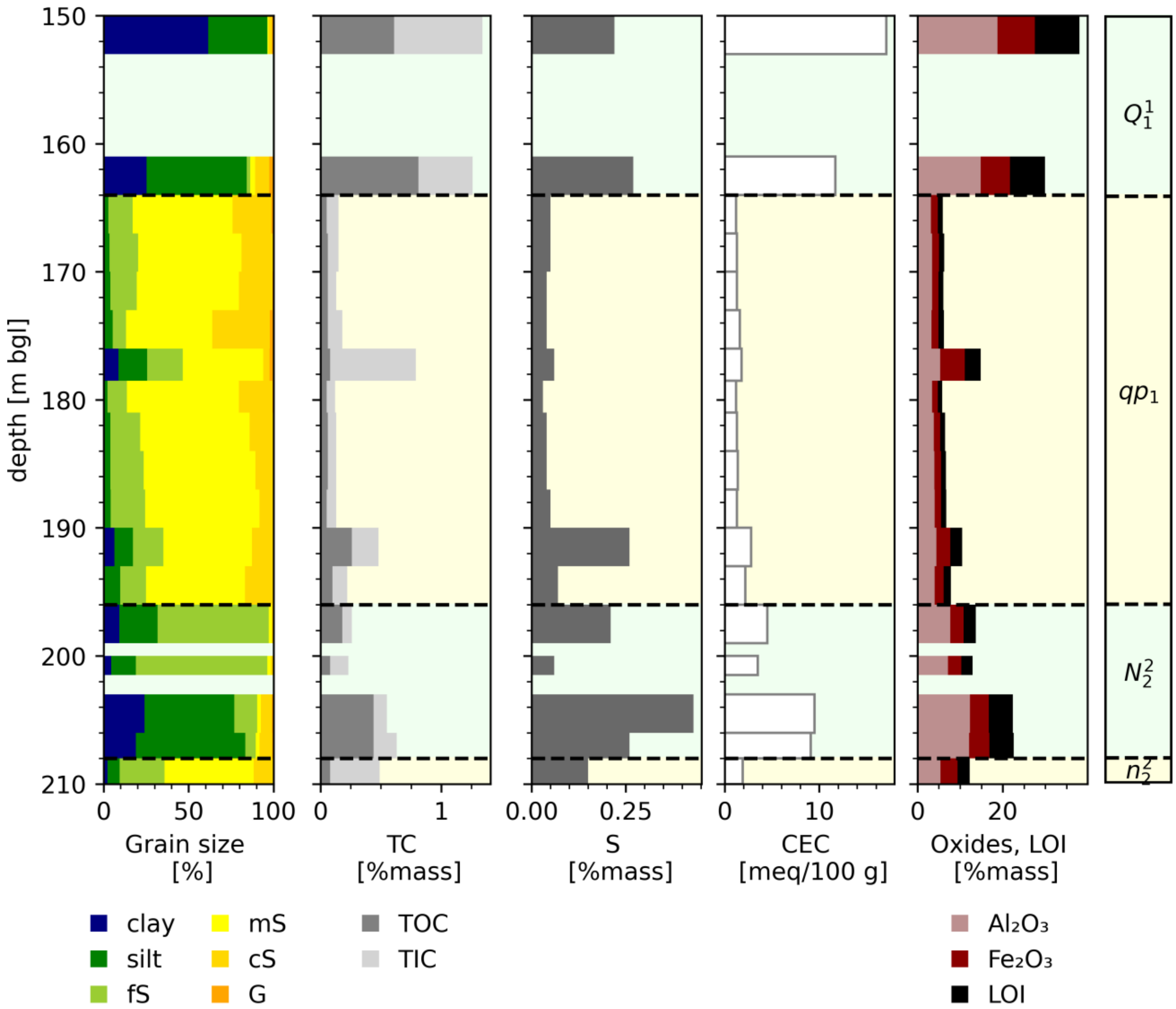

Figure 7: Stratigraphy and lithology of the M1 well summarizing the analysis results of grain size analysis, total carbon, organic carbon, total sulfur content, cation exchange capacity and selected XRF results.

The overlying aquitard Q_1^1 was detected at depths <150–156 m bgl based on core samples and was classified as clay with 96% fine materials. (Sample drilling only started at 150 m bgl, as drilling was destructive above. The drilling log indicates fine sediment started from about 144 m bgl). The consistency was very stiff in the field. The presence of clay minerals like mica/illite, kaolinite, chlorite and smectite was confirmed in the X-ray diffraction measurements and correlated with a higher cation exchange capacity (CEC) of 17 cmol+/kg. This is a typical value for sediments found in alluvial soils in the Mekong delta (Hai et al. 2005, Minh et al. 2023). CEC values are largely correlated to the concentration of smectite, which has a good ability to seal. The organic matter content and the total sulfur content is in the higher range compared to all analyzed samples, but still generally low with 0.61% TOC and 0.22% TS, respectively. The LOI was 10.4 mass%, which reflects the large presence of clay minerals and siderite.

Overall, it is estimated that the **overlying aquitard provides a good protection** against upward leakage. However, this is only one point and the lateral extend of the aquitard Q_1^1 thickness in the heterogeneous delta setting is difficult to estimate. The borelog at Q607 (about

5.5 km distance) shows an 8 m thick silt layer at 164–172 m depth and four (2–6 m thick) sandy silt layers between 134–164 m.

The underlying aquitard N_2^2 was detected from 196–204 m bgl based on the grain size distribution and was classified as a mixture of sandy loam (S14), loamy sand (S15) and silt loam (S16+S17). The presence of clay minerals like mica/illite, kaolinite, chlorite and smectite was confirmed for all samples by the XRD measurements and correlated with a higher CEC especially in the silt loam (S16) of 10 cmol+/kg, and a higher concentration of aluminum oxide concentration (7.1–12.3 mass%). The organic matter content and the total sulfur content is in the higher range compared to all analysed samples, but still generally low with ≤ 0.44% TOC and ≤ 0.43% TS, respectively. The LOI was up to 5.7 mass%, which reflects the presence of clay minerals and siderite.

Overall, it is estimated that the **underlying aquitard provides a good protection** against downward leakage. The borelog at Q607 shows a 22 m thick aquitard N_2^2 from 236–258 m depth.

3.2. Groundwater quality in the qp_1 aquifer

For groundwater, only scarce data are available for the local situation in Nga Bay. The target aquifer for the pilot is qp_1, at a depth of 170 – 190 m. In this aquifer, back up wells G1 and G2 are situated, and one sample from HAWASUCO (2016, just after drilling) is available. We sampled both back up wells on 27 October 2023 on a large list of parameters including pesticides.

NAWAPI has a national groundwater monitoring cluster (Q607) in Nga Bay (about 5.7 km north of HAWASUCO premises tapping into six aquifers (qp_3 to n_1^3). It was installed in 2019 and water quality data for 3 samples (April 2020, Sep 2020 and March 2021) are available for pH, Eh, major ions, some trace metals, NO_3, NO_2, PO_4 and COD (total 36 parameters).

Furthermore DONRE has a monitoring network for groundwater quality, with one location in of Nga Bay (QT5), but only penetrating until the qp_{2-3} aquifer (well screen around 111 m depth). So the target aquifer qp_1 for the ASR pilot is not reached. We received data from 2017 until 2021.

Currently, Nga Bay District has eight licensed wells in total, of which four are in qp_1 and four are in qp_{2-3}. The recent well survey found that only one well in qp_1 (170 m³/d) and two wells in qp_{2-3} (180 and 45 m³/d) are actually active, while the others are backup wells (including the two wells from HAWASUCO). We do not know the number of unlicensed wells in the district. The active well in qp_1 is at about 1.8 km distance from the HAWASUCO site. This information is valuable to assess potential spreading of the infiltrated water to other users and its potential flow direction.

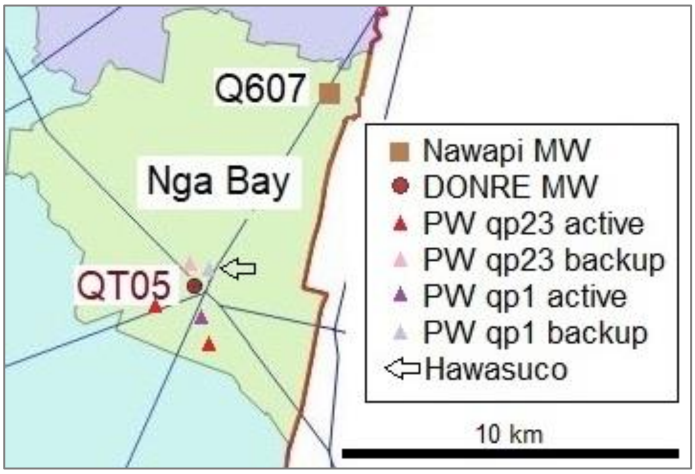

Figure 8: Groundwater monitoring well (MW) in Hau Giang from DONRE (QT) and NAWAPI (Q) and licensed production wells (PW) in Nga Bay district.

The samples from the backup wells on 27 October 2023 are the only relevant available data of the native groundwater quality in the target aquifer. Table 2 gives the results for the macroparameters in backup wells G1 and G2. The water type is anoxic, containing no nitrate (and no oxygen), but containing sulfate, iron and manganese in moderate concentrations. The rather high concentrations of ammonia (4.3 mg/L) and TOC (45 mg/L) are a point of attention in the drinking water treatment. The chloride concentration (14 resp. 20 mg/L) is low compared to the concentrations of sodium, potassium and magnesium. This indicates a sweetening groundwater type, caused by replacement of salt/brackish water by fresh water. Such sweetening processes can take very long periods of time.

Table 2: Groundwater quality results for macroparameters from the production wells G1 and G2 on 27.10.2023. Grey fields indicate values below the detection limit.

Parameters	**Unit**	**GW-QCVN 09-MT:2023**	**G1 (West)**	**G2 (East)**
pH		5.5-8.5	6.73	6.68
DO	mg/L		0.2	0.1
Temp	°C		31.0	31.3
EC	µS/cm		738	725
Colour			none	none
Smell and taste			none	none
Turbidity	NTU		0	0
Alkalinity	mg/L		319	309
TSS	mg/L		<5.0	<5.0
TDS	mg/L	1500	394	385
HCO_3	mg/L		316	311
Cl	mg/L	250	20.5	14.1
SO_4	mg/L	400	98.4	114
F	mg/L	1	0.2	0.1
Br	mg/L		<0.5	<0.5
Na	mg/L		84	79
K	mg/L		9.97	9.84
Ca	mg/L		25.4	27.2
Mg	mg/L		23	23.8
SiO_2	mg/L		41.9	42.4
Al	mg/L		<0.05	<0.05
As	mg/L	0.05	0.003	0.002
Ba	mg/L		0.17	0.16
Cd	mg/L	0.005	<0.001	<0.001

Parameters	Unit	GW-QCVN 09-MT:2023	G1 (West)	G2 (East)
Cr	mg/L	0.05	<0.005	<0.005
Cu	mg/L	1	<0.02	<0.002
Fe	mg/L	5	0.79	0.87
Mn	mg/L	0.5	0.06	0.06
Ni	mg/L	0.02	<0.005	<0.005
Pb	mg/L	0.01	<0.005	<0.005
Se	mg/L	0.01	<0.003	<0.003
Sr	mg/L		0.21	0.22
Zn	mg/L	3	<0.02	<0.02
$N-NH_4$	mg/L	1	**3.3**	**3.3**
$N-NO_3$	mg/L	15	<0.007	<0.007
$N-NO_2$	mg/L	1	<0.003	<0.003
$P-PO_4$	mg/L		0.3	0.3
TOC	mg/L		45.5	43.9
Coliforms	CFU/100 mL	3	<1	<1
E. Coli	CFU/100 mL	not detected	<1	<1
Enterococci, Streptococci faecal	CFU/100 mL		<1	<1
Total Phenol	µg/L	1	<0.3	<0.3

The concentrations of trace metals are favourable, with low concentrations of arsenic and barium, and absence of lead, cadmium, chromium, zinc and selenium.

Organic micropollutants were not found with the applied analysis methods for organochloropesticides, herbicides, carbamates, atrazines and triazole pesticides. It must be noticed that the reporting limits were rather high (1 µg/L) with respect to the general accepted limit of 0.1 µg/L.

The groundwater quality data from the national monitoring well Q607 for qp_1 aquifer (Q607040) (Table 3) shows a higher TDS, but an overall very similar water type compared to the results from G1 and G2. However, Q607040 shows significantly higher concentrations for nitrate, nitrite and phosphate, but lower ammonium concentrations compared to G1 and G2. This suggests that the water in the monitoring well is slightly more oxidized than the water in G1 and G2, which could be due to potential oxidization of the sample before the analysis during the storage and transport of the sample. As treated water is to be infiltrated in these reservoirs, these concentrations are not considered to be a problem, moreover since levels are not extremely high and water will be treated after extraction anyhow.

Groundwater quality data from the cluster of Q607 (Table 3) shows that at this location all aquifers are fresh (<1500 mg/L TDS), with Pleistocene aquifers around 600 mg/L TDS and higher TDS (928 – 1434 mg/L) for the Pliocene and Miocene aquifers. The latter also have elevated concentrations for sodium, but only the n_1^3 aquifer exceeds the groundwater guideline concentrations for chloride.

Table 3: Mean water quality data (mg/L) of national groundwater monitoring cluster Q607 in Nga Bay from 2020/21 (data provided by NAWAPI) compared to Vietnamese National Technical guidelines on groundwater (GW) and domestic water (DW). bold: concentrations exceeding VN-GW guideline.

Well ID	**Q607 020**	**Q607 030**	**Q607 040**	**Q607 050**	**Q607 060**	**Q607 070**	**VN**	**VN**
Aquifer	**qp_3**	**qp_{2-3}**	**qp_1**	**n_2^2**	**n_2^1**	**n_1^3**	**GW**	**DW**
TDS	639.0	606.3	605.0	1007.0	928.7	**1434.0**	1500	1000
pH	7.1	6.9	7.0	7.6	7.6	7.9	5.5-8.5	6.0-8.5
COD	0.96	1.07	0.63	0.72	1.09	1.04		
Na	95.4	113.1	99.6	**343.8**	**320.8**	**500.0**		200
K	8.3	9.8	10.4	6.3	6.3	4.8		
Ca	37.9	29.7	30.4	5.2	5.4	9.8		
Mg	41.3	26.3	34.0	9.5	7.3	14.1		
Cl	34.7	21.6	19.7	149.4	110.1	**354.1**	250	250
SO_4	154.7	154.7	158.8	156.1	130.6	161.5	400	250
HCO_3	345.8	317.3	317.3	527.8	543.1	616.3		
F	0.42	0.39	0.39	**1.09**	0.96	1.76	1.00	1.50
SiO_2	44.9	56.6	48.8	34.1	26.2	34.4		
$N\text{-}NH_4$	**1.79**	**1.60**	**1.31**	0.11	0.14	0.22	1.00	0.30
$N\text{-}NO_2$	0.51	0.56	0.55	0.005	0.002	0.005	1.00	0.05
$N\text{-}NO_3$	0.23	0.17	0.58	0.27	0.27	0.40	15.00	2.00
$P\text{-}PO_4$	3.32	2.65	2.72	2.40	1.96	1.73		
Al	0.000	0.000	0.017	0.000	0.000	0.000		0.200
As	0.001	0.004	0.003	0.010	0.008	**0.014**	0.050	0.010
Cd	0.000	0.000	0.000	0.000	0.000	0.001	0.005	0.003
Cr	0.001	0.001	0.001	0.001	0.001	0.002	0.050	0.050
Cu	0.006	0.006	0.006	0.010	0.006	0.019	1.00.	1.00.
Fe^{2+}	0.44	0.60	0.34	0.07	0.17	0.12	5.00	0.30
Fe^{3+}	0.36	0.60	0.36	0.50	0.12	0.08		
Hg	0.0002	0.0002	0.0002	0.0003	0.0002	0.0005	0.001	0.001
Mn	0.08	0.04	0.02	0.02	0.00	0.00	0.500	0.100
Pb	0.000	0.000	0.000	0.000	0.000	0.001	0.010	0.010
Zn	0.006	0.006	0.006	0.010	0.006	0.019	3.000	2.000

3.3.Assessment of water retention and storage capacity of the aquifer

We estimate the storage capacity of the aquifer as the amount of water that could be injected into the aquifer at this site before the groundwater hydraulic head in the aquifer reaches the surface. For well capacity, we can simply use the analytical formula (equation 1) of De Glee (1930). This takes into account aquifer transmissivity, the depth of the groundwater level and the diameter of the ASR well. The analytical formula is given by:

$$Qin = \frac{2\pi kD(h_{in} - h_o)}{ln\left(\frac{\sqrt{kDc}}{r_{put}}\right)}$$

Equation 1:

Where:k = aquifer hydraulic conductivity = 100 m/d; D = aquifer thickness = 20 m; c = resistance = 1000 d; r_{put} = radius of well (m) = 0.2 m; h_{in} = infiltration pressure (m+ ground level) = 0; h_0 = head in aquifer (m+ ground level) = -12 m

The maximum infiltration rate in the ASR well was then calculated to be 710 m^3/h, which translates to a storage capacity of 6.22 Mio m^3/year. This maximum infiltration rate is about 20 times higher than is envisaged for the pilot, hence we consider there to be sufficient storage space in the aquifer at the site.

4. Assessment of the suitability of quantity and quality of the source water used for artificial recharge of groundwater

4.1.Source water quantity

Assuming a recharge rate of about 35 m³/h, this would result in a maximum of 840 m³/day. During discussions with HAWASUCO, the company explained that the maximum treatment capacity of the Nga Bay Treatment plant is 7 000 m³/d, while the current demand is below 5000 m³/day.

Accordingly, they could easily make available 840 m³/day for the ASR pilot.

4.2.Water quality assessment

The water quality of the injected water needs to be of high quality for two main reasons:

(1) Prevent clogging and hence failure of the ASR system. Main concerns for clogging are suspended solids, nutrients, organic matter and oxygen. It also depends on the grain size distribution of the aquifer and the gravel pack.

(2) Prevent contamination of the ambient groundwater, which is used for domestic water supply. Main concerns for contamination are the mobilization of geogenic trace metals through redox reactions in the aquifer, as well as trace organic contaminants that are not removed in the surface water treatment plant and would end up in the aquifer.

In Nga Bay City, HAWASUCO is extracting surface water from Cai Con canal connected to the Hau River (approximately 15 km distance along the canal, about 62 km upstream from the coast) as source for drinking water production (see Figure 3). Raw water is treated with flocculation, sedimentation, sand filtration and chlorination before distribution to the network (Figure 8). It is envisaged to use the treated surface water before disinfection for injection in the ASR pilot to avoid any issues with disinfection by-products. Recovered water would then be fed back into the treatment system for full treatment before distribution for domestic water use (see Figure 4).

Figure 9: Flocculation tank (left), settling tank (middle) and filtration tank (right) at Nga Bay WTP.

4.2.1. Treated surface water quality results

Apart from regular testing for residual chlorine, pH, and turbidity (online measurements), the treated water is tested by HAWASUCO on a monthly basis for turbidity, pH, smell/taste, residual chlorine, colour, As, coliform, and *E. coli* and on a biannual basis for additional parameters like NH_4, NO_2, NO_3, Al, Cr, Cu, Fe, Mn, Ni, Zn, S_2, SO_4, F, TDS, salinity, total hardness, cyanide and permanganate index.

HAWASUCO has the facility to analyze for pH, turbidity, EC, Cl with Hanna instruments and NH_4, NO_3, NO_2, Fe, Mn and Zn with a HACH DR6000 spectrometer. Coliform and *E. coli* are analyzed by the CDC of Hau Giang (provincial Department under the Ministry of Health). Other parameters like As, Al, Cr, Cu, Ni, S_2, SO_4, F, TDS, hardness, cyanide, permanganate index are analyzed by CASE lab in Can Tho.

For Nga Bay, HAWASUCO supplied us with the biannual analysis for 4 samples (Dec 2020, Sep 2022, Dec 2022, June 2023) and 16 samples for monthly analysis.

At the beginning of our project, we sampled treated water of Nga Bay both before and after chlorination. The samples were analyzed on a large list of parameters (total 125) including pesticides and volatile organic compounds.

Table 4 gives the variation of water quality parameters measured in the treated water (drinking water) after chlorination in the period 2019-2023. It includes a monthly sampling in 2022, analyzed on temperature, pH, turbidity, residual chlorine, color, and coli bacteria (Table 4). Relevant variation is seen for temperature and pH. But all measurements are far below the Vietnamese limitations for produced drinking water.

The samples taken on 27 October 2023 of treated water before and after chlorination are presented in Table 5 (macroparameters, microbiological parameters and micro-metals only). The results are favorable for infiltration purposes with low aluminum and iron concentrations and low turbidity, indicating the filtration removes almost all suspended substances via flocculation. Also favorable is the soft and freshwater type with low concentrations of calcium, magnesium and chloride.

Clogging risks seem rather low in case of using this treated water for infiltration. An important indicator for the clogging risk is TOC, which has low values of 2 – 3 mg/l.

Table 4: Variations of water quality parameter for treated surface water (Source: HAWASUCO)

criteria	**Unit**	**DW-QCVN 01-1-2018**	**number**	**Min**	**Mean**	**Max**
turbidity	NTU	2	17	0.13	0.32	0.73
pH		6.0 - 8.5	17	6.7	7.1	7.9
Temp	°C		15	18.8	24.4	29.8
Smell and Taste		none	17	none	none	none
Residual chlorine	mg/l	0.2 - 1.0	17	0.27	0.63	0.82
Colour	TCU	15	17	<3.5	<3.5	5.43
Coliforms	CFU/100ml	<3	17	0	0	0
E. Coli	CFU/100ml	<1	17	0	0	0
S^{2-}	mg/l	0.05	12	nd	nd	0.004
$N\text{-}NO_3$	mg/l	2	4	0.50	0.73	1.00
$N\text{-}NO_2$	mg/l	0.05	4	0.004	0.005	0.006
$N\text{-}NH_4$	mg/l	0.3	4	<0.0095	0.04	0.07
TDS	mg/l	1000	4	69	101	160
F	mg/l	1.5	3	0.05	0.23	0.46
SO_4	mg/l	250	4	2.0	17.2	43.0
Al	mg/l	0.2	3	0.017	0.030	0.043

criteria	Unit	DW-QCVN 01-1-2018	number	Min	Mean	Max
As	mg/l	0.01	0			
Cr^{6+}	mg/l	0.05	4	0.008	0.010	0.012
Cu	mg/l	1	4	0.010	0.018	0.020
Fe (total)	mg/l	0.3	4	<0.01	0.02	0.04
Mn	mg/l	0.1	4	0.006	0.009	0.012
Ni	mg/l	0.07	3	0.000	0.003	0.008
Zn	mg/l	2	4	0.040	0.100	0.120
Permanganate index	mg/l	2	3	0.30	0.63	1.00
total hardness	mg/l	300	3	50	80	130
cyanite	mg/l	0.05	1		0.008	

nd = not detected, mean value does not consider samples with concentrations below detection limit

Table 5: Results of treated surface water before and after chlorination from Nga Bay WTP on Oct 27, 2023 Grey fields indicate values below the detection limit.

Parameters	**Unit**	**DW-QCVN 01-1-2018**	**SW (before disinfection)**	**SW (after disinfection)**
pH		6.0-8.5	6.62	6.6
DO	mg/L		4.0	4.4
Temp	°C		30.1	30.1
EC	µS/cm		150	149
Colour		15	none	none
Smell and taste		none	none	none
Turbidity	NTU	2	0	0
Alkalinity	mg/L		47.3	47.0
TSS	mg/L		<5.0	<5.0
TDS	mg/L	1000	78.2	80.7
HCO_3	mg/L		50.1	50.1
Cl	mg/L	250	13.5	14.9
SO_4	mg/L	250	7.2	7.5
F	mg/L	1.5	<0.1	<0.1
Br	mg/L		<0.5	<0.5
Na	mg/L	200	6.84	<0.2
K	mg/L		2.56	2.7
Ca	mg/L		13	13.90
Mg	mg/L		4.41	4.67
SiO_2	mg/L		9.86	9.63
Al	mg/L	0.2	<0.05	<0.05
As	mg/L	0.01	<0.001	<0.001
Ba	mg/L	0.7	0.02	0.02
Cd	mg/L	0.003	<0.001	<0.001
Cr	mg/L		<0.005	<0.005
Cu	mg/L	1	<0.02	<0.02
Fe	mg/L	0.3	<0.02	<0.02
Mn	mg/L	0.1	<0.02	<0.02
Ni	mg/L	0.07	<0.005	<0.005
Pb	mg/L	0.01	<0.005	<0.005
Se	mg/L	0.01	<0.003	<0.003
Sr	mg/L		0.06	0.06
Zn	mg/L	2	<0.02	<0.02
$N\text{-}NH_4$	mg/L	0.3	<0.08	<0.08
$N\text{-}NO_3$	mg/L	2	0.09	0.09
$N\text{-}NO_2$	mg/L	0.05	<0.003	<0.003
$P\text{-}PO_4$	mg/L		<0.02	<0.02
TOC	mg/L		2	3.1
Coliforms	CFU/100 mL	3	**16**	<1
E. Coli	CFU/100 mL	1	<1	<1
Enterococci. Streptococci faecal	CFU/100 mL		<1	<1
Total Phenol	µg/L	1	<0.3	<0.3

Trace metals were not found to exceed detection limits in the samples. The same holds for the several analyzed pesticides and volatile organic micropollutants. For pesticides, it should be noted that reporting limits of 1 µg/L are 10 times higher than the European and USA requirement of 0.1 µg/L. Disinfection by-products were also analyzed and presented in Table 6. Three by-products were found in rather low concentrations, much lower than the Vietnamese limits for drinking water.

Table 6: Concentration of disinfection by-products in treated domestic water from 27.10.2023. Grey fields indicate values below the detection limit.

Parameter	**unit**	**VN-DW limit**	**SW (after disinfection)**
Bromoform	µg/L	100	<1.0
Dibromochloromethane	µg/L	100	3
Bromodichloromethane	µg/L	60	10
Chloroform	µg/L	300	18
Bromate (BrO_3^-)	µg/L	10	<0.004
Chlorate (ClO_3^-)	µg/L		<0.01
Chlorite (ClO_2^-)	µg/L		<0.01

4.2.2. Native groundwater quality

The samples from the backup wells on 27 October 2023 are the only relevant available data of the native groundwater quality in the target aquifer. Table 7 gives the results for the macroparameters in backup wells G1 and G2. The water type is anoxic, containing no nitrate (and no oxygen), but containing sulfate, iron and manganese in moderate concentrations. The rather high concentrations of ammonia (4.3 mg/L) and TOC (45 mg/L) are a point of attention in the drinking water treatment. The chloride concentration (14 resp. 20 mg/L) is low compared to the concentrations of sodium, potassium and magnesium. This indicates a sweetening groundwater type, caused by replacement of salt/brackish water by fresh water. Such sweetening processes can take very long periods of time.

Table 7: Groundwater quality results for macroparameters from the production wells G1 and G2 on 27.10.2023. Grey fields indicate values below the detection limit.

Parameters	**Unit**	**GW-QCVN 09-MT:2023**	**G1 (West)**	**G2 (East)**
pH		5.5-8.5	6.73	6.68
DO	mg/L		0.2	0.1
Temp	°C		31.0	31.3
EC	µS/cm		738	725
Colour			none	none
Smell and taste			none	none
Turbidity	NTU		0	0
Alkalinity	mg/L		319	309
TSS	mg/L		<5.0	<5.0
TDS	mg/L	1500	394	385
HCO_3	mg/L		316	311
Cl	mg/L	250	20.5	14.1
SO_4	mg/L	400	98.4	114
F	mg/L	1	0.2	0.1
Br	mg/L		<0.5	<0.5

Parameters	**Unit**	**GW-QCVN 09-MT:2023**	**G1 (West)**	**G2 (East)**
Na	mg/L		84	79
K	mg/L		9.97	9.84
Ca	mg/L		25.4	27.2
Mg	mg/L		23	23.8
SiO_2	mg/L		41.9	42.4
Al	mg/L		<0.05	<0.05
As	mg/L	0.05	0.003	0.002
Ba	mg/L		0.17	0.16
Cd	mg/L	0.005	<0.001	<0.001
Cr	mg/L	0.05	<0.005	<0.005
Cu	mg/L	1	<0.02	<0.002
Fe	mg/L	5	0.79	0.87
Mn	mg/L	0.5	0.06	0.06
Ni	mg/L	0.02	<0.005	<0.005
Pb	mg/L	0.01	<0.005	<0.005
Se	mg/L	0.01	<0.003	<0.003
Sr	mg/L		0.21	0.22
Zn	mg/L	3	<0.02	<0.02
$N\text{-}NH_4$	mg/L	1	**3.3**	**3.3**
$N\text{-}NO_3$	mg/L	15	<0.007	<0.007
$N\text{-}NO_2$	mg/L	1	<0.003	<0.003
$P\text{-}PO_4$	mg/L		0.3	0.3
TOC	mg/L		45.5	43.9
Coliforms	CFU/100 mL	3	<1	<1
E. Coli	CFU/100 mL	not detected	<1	<1
Enterococci, Streptococci faecal	CFU/100 mL		<1	<1
Total Phenol	µg/L	1	<0.3	<0.3

The concentrations of trace metals are favorable, with low concentrations of arsenic and barium, and absence of lead, cadmium, chromium, zinc and selenium.

Organic micropollutants were not found with the applied analysis methods for organo-chloropesticides, herbicides, carbamates, atrazines and triazole pesticides. It must be noticed that the reporting limits were rather high (1 µg/L) with respect to the general accepted limit of 0.1 µg/L.

The groundwater quality data from the national monitoring well Q607 for qp_1 aquifer (Q607040) (Table 8) shows a higher TDS, but an overall very similar water type compared to the results from G1 and G2. However, Q607040 shows significantly higher concentrations for nitrate, nitrite and phosphate, but lower ammonium concentrations compared to G1 and G2. This suggests that the water in the monitoring well is slightly more oxidized than the water in G1 and G2, which could be due to potential oxidization of the sample before the analysis during the storage and transport of the sample. As treated water is to be infiltrated in these reservoirs, these concentrations are not considered to be a problem, moreover since levels are not extremely high and water will be treated after extraction anyhow.

Groundwater quality data from the cluster of Q607 (Table 8) shows that at this location all aquifers are fresh (<1500 mg/L TDS), with Pleistocene aquifers around 600 mg/L TDS and higher TDS (928 – 1434 mg/L) for the Pliocene and Miocene aquifers. The latter also have elevated concentrations for sodium, but only the n_1^3 aquifer exceeds the groundwater guideline concentrations for chloride.

Table 8: Mean water quality data (mg/L) of national groundwater monitoring cluster Q607 in Nga Bay from 2020/21 (data provided by NAWAPI) compared to Vietnamese National Technical guidelines on groundwater (GW) and domestic water (DW). bold: concentrations exceeding VN-GW guideline.

Well ID	**Q607 020**	**Q607 030**	**Q607 040**	**Q607 050**	**Q607 060**	**Q607 070**	**VN**	**VN**
Aquifer	qp_3	qp_{2-3}	qp_1	n_2^2	n_2^1	n_1^3	**GW**	**DW**
TDS	639.0	606.3	605.0	1007.0	928.7	**1434.0**	1500	1000
pH	7.1	6.9	7.0	7.6	7.6	7.9	5.5-8.5	6.0-8.5
COD	0.96	1.07	0.63	0.72	1.09	1.04		
Na	95.4	113.1	99.6	**343.8**	**320.8**	**500.0**		200
K	8.3	9.8	10.4	6.3	6.3	4.8		
Ca	37.9	29.7	30.4	5.2	5.4	9.8		
Mg	41.3	26.3	34.0	9.5	7.3	14.1		
Cl	34.7	21.6	19.7	149.4	110.1	**354.1**	250	250
SO_4	154.7	154.7	158.8	156.1	130.6	161.5	400	250
HCO_3	345.8	317.3	317.3	527.8	543.1	616.3		
F	0.42	0.39	0.39	**1.09**	0.96	1.76	1.00	1.50
SiO_2	44.9	56.6	48.8	34.1	26.2	34.4		
$N\text{-}NH_4$	**1.79**	**1.60**	**1.31**	0.11	0.14	0.22	1.00	0.30
$N\text{-}NO_2$	0.51	0.56	0.55	0.005	0.002	0.005	1.00	0.05
$N\text{-}NO_3$	0.23	0.17	0.58	0.27	0.27	0.40	15.00	2.00
$P\text{-}PO_4$	3.32	2.65	2.72	2.40	1.96	1.73		
Al	0.000	0.000	0.017	0.000	0.000	0.000		0.200
As	0.001	0.004	0.003	0.010	0.008	**0.014**	0.050	0.010
Cd	0.000	0.000	0.000	0.000	0.000	0.001	0.005	0.003
Cr	0.001	0.001	0.001	0.001	0.001	0.002	0.050	0.050
Cu	0.006	0.006	0.006	0.010	0.006	0.019	1.00.	1.00.
Fe^{2+}	0.44	0.60	0.34	0.07	0.17	0.12	5.00	0.30
Fe^{3+}	0.36	0.60	0.36	0.50	0.12	0.08		
Hg	0.0002	0.0002	0.0002	0.0003	0.0002	0.0005	0.001	0.001
Mn	0.08	0.04	0.02	0.02	0.00	0.00	0.500	0.100
Pb	0.000	0.000	0.000	0.000	0.000	0.001	0.010	0.010
Zn	0.006	0.006	0.006	0.010	0.006	0.019	3.000	2.000

4.2.3. Assessment of clogging and potential water-sediment interactions

Clogging, a major obstacle in ASR applications, causes declines in recharge rates and ultimately the failure of systems (Jeong et al. 2018). Based on the X-ray diffraction results, the medium sand does not contain significant amounts of expandable clay minerals (smectite). Their presence and other non-expandable clay minerals was only confirmed for the sandy loam layer within the aquifer. As the sandy loam layer with 2.5-m thickness is about 12.5% of the total thickness, physical clogging due to swelling of smectites might be possible. It is usually more problematic, when fresh water is recharged into brackish or saline groundwater (Konikow et al. 2001, Torkzaban et al. 2015), which is not the case at the Nga Bay site.

Clogging due to the migration of interstitial fines such as kaolinite, illite or chlorite could be possible as illite was found as minor constituent in three samples. As the velocity in the pores is changing during stopping and starting of the injection and recovery cycles, fines might be remobilised and block the pore throats (Martin 2013). A low percentage of interstitial smectite clays (2–5%) in sands resulted in no observable signs of clogging due to clay dispersion at a sandy aquifer field site (Martinez et al. 2022).

Physical clogging can also happen if bentonite used in the rotary drilling is still present at the interface between the gravel pack and the aquifer adjacent to the recharge well. It could cause permanent reduction of effective hydraulic conductivity, if the well has not been developed properly (Martin 2013). Other forms of clogging (chemical or biological) cannot be judged from the sediment analysis.

Hence, **clogging should be monitored during the operation**.

Geochemical processes include adsorption, desorption, solution, precipitation, cation exchange, clay swelling, and several others. There are a number of redox reactions happening when oxidized surface water is recharged to anoxic groundwater. Of special importance is pyrite oxidation, as it releases mobile oxyanions (such as arsenate, chromate, molybdate, vanadate) and mobile cations such as nickel and zinc. The formation of sulfuric acid reduces the pH and can mobilize other adsorbed trace metals. Multiple ASR sites have experienced a decrease in recovered water quality due to geogenic metal mobilization related to pyrite oxidation (Brown et al. 2006, Fakhreddine et al. 2021, Rafiq et al. 2022), however, at our site pyrite was not detected in the aquifer materials

Based on the X-ray fluorescence results, there is only limited amounts of arsenic in the aquifer material (5.8 mg/kg) and slightly more (10 mg/kg) in the silt loam layer, however, X-ray fluorescence analysis of arsenic using glass beads has to be taken with care because arsenic may evaporate during heating of samples. Trace elements of concern could be chromium with 250 mg/kg, nickel (41 mg/kg) or zinc (28 mg/kg). Overall, the concentration of trace elements as analyzed by X-ray fluorescence glass beads does initially not raise great concerns, but they should be monitored in the recovered water.

On the other hand, dissolved iron will lead to the precipitation of amorphous hydroxides. Reductive dissolution of Mn- and Fe-oxides starts after oxygen is completely depleted and nitrate is being reduced (Stumm and Morgan 1995). While the precipitation of minerals will lead to co-precipitation and adsorption of trace metals, their dissolution will in turn mobilize previously incorporated or adsorbed trace metals (Antoniou et al. 2012, Bahr et al. 2002).

Dissolution of minerals also applies to carbonates, e.g. calcite, siderite, when the groundwater becomes undersaturated by recharge waters with lower ionic strength (Johnson et al. 1999). The decrease of pH due to release of CO_2 during organic matter degradation also accelerates dissolution of carbonates (Herczeg et al. 2004). The interplay between oxidative/reductive changes induced by ASR and dissolution/precipitation reactions with minerals can be complex (Rafiq et al. 2022). Close to the recharge well, these reactions can occur at the same time in different places or in the same place at different times of the ASR cycle.

Based on the X-ray fluorescence results, iron oxides concentrations are low (1.5 mass%) in the medium sand, but higher (5.8 mass%) in the silt loam layer and could be largely present as siderite ($FeCO_3$) and partially as pyrite, which could be at risk of dissolution. Even though oxidative dissolution of siderite is a slow process (Duckworth and Martin 2004), siderite dissolution effects might be seen during extended ASR operation (Antoniou et al. 2012, Rafiq et al. 2022). The subsequent formation of amorphous iron oxides, iron hydroxides or goethite, would contribute to a potential clogging risk.

4.2.4. Evaluation of source water quality used for artificial recharge of groundwater

Standards and guidelines

Assuming treated water (before chlorination) will be used for the ASR pilot, all measured water quality parameters are far below Vietnamese standards for drinking water and groundwater.

When standards for MAR projects from other countries in the world are considered, also no water quality problems are expected.

Operational risks (clogging)

Prevention of clogging risks is an important goal of the ASR pilot. Clogging can arise from particles in the infiltration water or chemical and/or microbiological processes. Clogging by particles is not expected when using the treated water as infiltrate. Chemical clogging can be expected when oxidation reactions between the aerobic infiltrate and iron and manganese in the native groundwater occur around the filter. This clogging can be avoided by applying a little “over-infiltration” during the first cycles. The transition zone between infiltrate and native groundwater will keep a secure distance from the filter then.

Microbiological clogging can occur in the zone around the infiltration filter too, and the clogging risk will diminish by the same scheme of ‘over-infiltration'. Some mechanical or chemical cleaning can be needed to remove biofouling in the filter. TOC and NH_4 values of the treated surface water indicate a very low risk of microbiological growth, but measurements of chemical and physical parameters during the pilot are necessary to assess this risk.

Risks of spreading pollution in aquifers

Pollution of native groundwater in target aquifer qp_1 is not likely, because of the great depth and presence of protecting clay layers. Pesticides were not found in the groundwater from the existing back up wells. Although no high levels (>1 µg/L) of pesticides were measured, still, the presence of pesticides in the treated surface water is likely at lower concentrations, based on the scarce scientific papers. Pesticides form a very broad group of compounds, differing in chemical behavior. Most of them will probably not be removed by the existing drinking water treatment in Nga Bay neither before recharge nor after recovery.. Also from this point of view, it is important to keep control of the infiltrated and recovered volumes, to avoid unwished spreading of infiltrated water.

The risk of spreading of pollution can also be enhanced by abstractions in the direct neighborhood. As we know now, the number of licensed abstractions in aquifer qp_1 is very small, but the number of non-licensed abstractions is unknown.

Risks of deteriorating water quality of stored water

Risks of deteriorating water quality during storage cannot be fully excluded. The pilot itself will provide more insight in these risks. Risks exist on mobilization of metals like Mn and As, although concentrations in the native groundwater and sediments seem rather low. Also, risks of microbiological growth must be assessed by careful monitoring during the pilot. At the ambient temperatures of around 30°C growth of infecting bacteria/organisms can pose a serious risk.

By using non-disinfected infiltrate, the risk of forming undesired chlorinated compounds in the aquifer can be minimized.

Another important point of attention is the salinization risk from aquifers above or below the target aquifer. This risk requires monitoring of dynamics in chloride concentrations and pressures during the several cycles of the pilot. The NAWAPI data from Q607 do not indicate salinity issues in the adjacent aquifers, however, the DONRE data do show presence of saline water bodies in the shallow aquifers at QT5 (about 1 km from the pilot site).

5. Technical design solutions

5.1. Aquifer Storage and Recovery method for the artificial recharge pilot

Aquifer Storage and Recovery (ASR) is a groundwater resources management technique for actively storing water in the deeper groundwater system during wet periods, and recovering the fresh water from the subsurface when needed (usually during dry periods) (e.g., USGS, 2019). For confined aquifers, source 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 extraction system that can both infiltrate and recover water. This ASR technique is one method out of a range of different

Managed Aquifer Recharge (MAR) methods and is not a new technology. It has been applied in many different settings and in many different technical configurations around the world (Dillon et al. 2009, Dillon et al. 2019, Rambags et al. 2013, Sprenger et al. 2017). However, the challenge of the technology is that it needs to be localized and fit to the local conditions. Furthermore, local experience and capacity needs to be developed to make sure the method is applied appropriately and to the standards required for domestic freshwater supply.

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. smoothing out demand and supply fluctuations in using the subsurface when needed (also during strategic emergency situations);
f. raising groundwater tables and hydraulic heads, managing land subsidence and salt water intrusion;
g. water quality may be further improved with flow passages due to purification characteristics of the subsurface.

The goal of our ASR pilot is to reduce the stress on fresh groundwater reserves and mitigate land subsidence in places where the demand for fresh water exceeds the sustainable supply of groundwater.

5.2.Location and technical specifications of works for ASR pilot

For our pilot, one ASR well will be drilled at the water supply plant of HAWASUCO in Nga Bay, Mekong Delta, Vietnam, which will be suitable for recharge and extraction in aquifer qp_1 of at least $35m^3$/hr and 60 m^3/hr[2] respectively. During the pilot period, water will be infiltrated and recovered in a number of shorter cycles to test the recharge capacity and recovery efficiency of the ASR system and to assess water quality changes.

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[2] Final quantities can only be determined after capacity tests have been done with the realized well.

5.2.1. Location

The well will be installed in Nga Bay on the premises of HAWASUCO. In January 2024, the monitoring well (M_1) was installed at the site. The new ASR well should be installed between the production well G1 of HAWASUCO and the monitoring well M_1 (see Table 8).

Figure 10 shows a sketch of the drilling site along with the position of the existing and proposed wells. The **ASR well (ASR_1)** should be located **12-15 m west from the monitoring well M_1.** The exact location should be determined in the field according to the field conditions. For the location of ASR_1 some trees may have to be cut.

Table 9: Coordinates (EPSG:3405 - VN-2000 / UTM zone 48N) and details of existing wells at HAWASUCO premises in Nga Bay Town. Exact location of ASR_1 to be decided in the field.

Well	X	Y	Distance to G1 (m)	screen depth (mbgl)
G1	590229	1085487	0	171-192
G2	590323	1085479	94	171-192
M_1	590272	1085488	42	167-187
ASR_1	590255	1085488	25-30	168-188

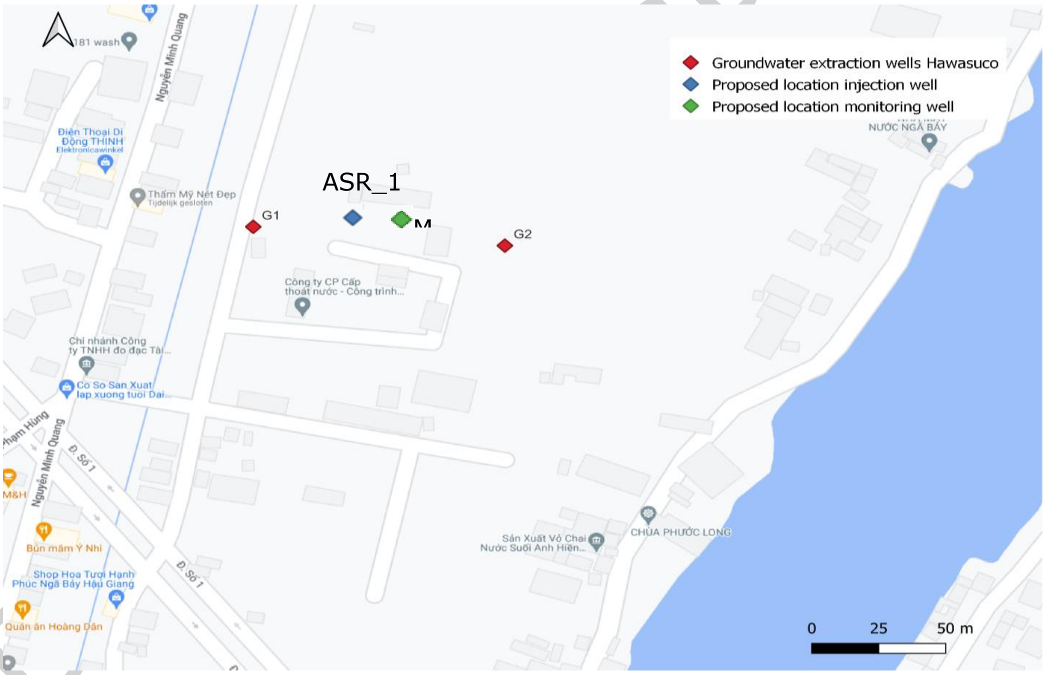

Figure 10: Location for the ASR well between the existing extraction well G1 and the new monitoring well M_1

The diversion of treated source water will happen before chlorination of the water and the water will be piped to the ASR well. The recovered water will be connected to the pipes coming from G1 well. These pipes lead to the top of the flocculation tank and groundwater will be oxygenized to allow for the removal of iron and manganese.

5.2.2. Work program

The main purpose of the final ASR well is to obtain good injection and extraction capacities of water into and out of aquifer qp_1.Therefore, it is essential that the ASR well is installed properly. It has to be ensured that **no hydraulic connections** between aquifers exist within the borehole/well after well installation is completed. Leakage trough the annular may seriously disturb the proper functioning of the ASR well.

The realization of a properly working ASR well (underground part) should comprise the following steps. For each step, technical recommendations are provided as follows:

- **Drilling the borehole**: the drilling should be uninterrupted until completion of the ASR well. The details are described in section 5.2.4. i.
- **Borehole logging:** after completion of the drilling, logging should take place, see section 5.4.2 ii.
- **Final design:** With the results of the logging and the previous samples taken from M_1 (Appendix 2), the final installation design of the ASR well should be decided, see sections 5.2.4 iii based on initial design (Appendix 1).
- **Well Installation:** the pipes should be installed and the backfilling of the annular should take place according to the final design, see section5.2.4. iv.
- **Well development:** the well should be developed by air flushing and pumping water as described in section5.2.4. v.
- **Capacity testing:** the performance of the well should be tested by a step-drawdown test as described in section5.2.4. vi.
- **Determination of aquifer properties:** a pumping test should be carried out. Well ASR_1 should be used for the pumping, and M_1 and G1 should be used to monitor groundwater levels. For details of the pumping test, see section 5.2.4. vii
- **Site clean up:** After drilling and installation is complete, the site needs to be returned to its original state, and all tailings, materials and debris should be removed.
- **Documentation:** a drilling completion report should be written as described in section5.2.4. viii.

5.2.3. Environmental compliance

Negative environmental impacts from well construction and installation must be avoided. All work should comply with the MONRE Circular No. 75/2017/TT-BTNMT (29.12. 2017) on *"Regulations on water resources protection during drilling, excavating, exploring and extraction of groundwater"*. Contamination with oil or gasoline must be avoided (Figure 11).

Figure 11: Example of bad practice with the drilling site contaminated by hydrocarbons (Source: BGR, 2020)

5.2.4. Technical Specifications

i. Drilling the borehole

It is expected that the drilling technique will be the direct flush mud-rotary technique in order to fully penetrate the aquifers. Access options to the site for the drilling rig and materials should be discussed with HAWASUCO.

The drilling company should be aware of the static groundwater levels (GWL) in the target aquifer and overlaying aquifers when setting up the drilling equipment (static GWL in qp_1 was around 12.3 m bgl[3] in Jan 2024). Static GWL can be checked before the start, using the new M_1 monitoring well.

Casings and/or drilling fluids may be used where collapsing overburden requires support. The amount of drilling mud should be as low as acceptable, as it will be the first clogging barrier when it is not removed completely during developing the well. A clean source of water should be used for drilling: it is suggested to use treated water directly from a tap at the premises.

The first 15 meters should be drilled with a large diameter of **700** mm and secured with a steel drilling casing to prevent collapse. The following 35 m (down to 50 m total depth) should be drilled with 600 mm diameter. The final drilling depth of the ASR_1 should be 195 m (aquifer qp_1), with final drilling diameter **400 mm** from 50–195 m depth (see Table 8).

The bore should be clean, straight and defect-free.

Table 10: Well information

No	**Borehole**	**final aquifer**	**total depth (m)**	**drilling diameter (mm)**
1	**ASR_1**	**qp_1**	**195**	
			0-15	700 with steel casing
			15-35	600
			50-195	400

ii. Geophysical measurement (borehole logging)

Borehole logging should be carried out in the open borehole, before installing the pipes, to the final depth (195 m). The measuring tool is a Matrix's Carota (USA). This is a digital measuring tool, which is controlled by a computer program. Measuring parameters include:

- Natural gamma intensity (G); measuring unit: CPS.
- Self-bias potential (SP); measuring unit: mV.
- Point Resistance (R); measuring unit: ohms
- Resistivity by standard polar systems (R8 ÷ R64); measuring unit: ohm.m.
- Solution Resistivity (Fres); measuring unit: ohm.m.

iii. Final design of the ASR well

The final design of the ASR well should be decided after analyzing the geophysical measurement results in the field and previous lithological logs from the monitoring well M_1 (see Appendix 2). Before starting the installation of the pipes, a detailed drawing of the design with screen depth should be prepared. The backfill design should also be drawn with the indicated depths of backfill

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[3] Below ground level

material. The initial well design is shown in Appendix 1. Drilling and well design should follow this initial design. However, the design may be subject to change to ensure that the well is fully penetrating the aquifer.

iv. Well installation and backfilling of annular space

In the top 45 meters, a PVC casing with diameter of **315 mm** should be installed to ensure sufficient space for the submersible pump, the injection line and the monitoring tube for the ASR aspects of the well (Table 2). From 45-195 m PVC-casings (diameter: **168 mm**) and screen (diameter: **168 mm**, depth from 168-188 m) should be installed according to the final design. A reducing socket should be used to reduce the diameter from 315 mm to 168 mm (see Table 2 for initial design).

Quality installation of PVC casing and screens is key. The PVC casings should be able to sustain sediment pressure avoiding the risk of collapsing using the pressure class 12.5 ATO.

Screen slot size and gravel pack should match the particle size of the aquifer formation, and should be chosen to prevent formation material to enter the well. From the drilling and sampling results of the monitoring well M_1, it became clear that the sands present in the qp_1 aquifer consist of coarse sands (Appendix 2). Particle size median is approximately 0.4 mm.

PVC shavings should not be present on either the inner or the outer surfaces. The PVC screen should be wrapped by **inox (steel) gauze** (max 0.6 mm space). **Mechanical centralizers**, which are made of an inert material, should be placed at reasonable distances (about each 6 m).

The borehole should be lined full depth with PVC casing and screen with an end cap at the bottom. The surface casing should initially protrude 0.7 m above ground level.

Backfilling of the annular space

The ASR well should **NOT** be constructed with natural completion. As already mentioned, it is essential to prevent hydraulic connections between aquifers along the bore. Therefore, the annular space (space in between the PVC screen/casing and the borehole wall) must be backfilled by **gravel pack** (at the depth of aquifer qp_1) and liquid grout (at the level of the aquitard and above laying aquifers). Gravel pack class could be **0.8-1.25 mm or 1.0-1.6 mm.** To prevent mixing of the liquid grout with the gravel pack a layer of 2 m sand/fine gravel pack (using moderate fine sand, e.g. the smallest size of gravel pack material available in Vietnam) should be filled above the coarse gravel pack. The rest of the annular should be filled with **liquid grout** (see Table 9).

Backfilling should be made with a (semi-flexible) PVC or HDPE **tremie pipe** (60 mm) which can be lowered simultaneously with the PVC pipes. The bottom part of the tremie pipe should end 2 meters above the top of the aquitard, as presented in Appendix 3. In this way, the tremie pipe can first be used to drop the gravel pack. Afterwards a thin support layer of fine gravel should be dropped and finally the liquid grout should be applied, while lifting the tremie pipe, so it should be about 2 m above the current backfilling surface at all times.

Table 11: Initial design of ASR well

Depth (m)	**drilling diameter (mm)**	**PVC pipe type**	**PVC pipe (OD mm)**	**PCV pipe (ID mm)**	**PVC pipe pressure class (ATO)**	**annular fill**
0-15	700	casing with reducing socket at 45 m	315	300	12.5	liquid grout
15-45	600					liquid grout
45-50			168	160		liquid grout
50-155	400					liquid grout
155-166						liquid grout
166-168						sand pack
168-188		screen				gravel pack
188-194		sand trap with bottom cap				gravel pack
194-195		none	-	-	-	gravel pack

v. Cleaning (developing) the well

After finalizing, the well should be cleaned in several steps until the well delivers clear water.

- First step: Air flushing until clean water is pumped.
- Second step: Minimum 24 hours of intermittent pumping.
- Final step: Cleaning well bottom (sand free) with air flushing (sucking).
- Finally, the bottom depth should be measured to ensure the well is cleaned to the bottom

vi. Well performance test

After developing the well, a well performance test should be executed. Data and interpretation (by DWRPIS) of the data should be shared with the team

During the performance test with the new ASR well, drawdown should be measured in the well with 4-5 pumping steps:

Every step should last for 2 hours of pumping with an increasing extraction rate of 15, 30, 45 and 60 (final 5th step 75 if possible) m^3/hr.

Manual measurements (conform standard procedure, 1 minute-15 minute) of groundwater level drawdown should be performed during the extraction and until full recovery (90%) after step 5 back to the original GWL (taking tidal fluctuations into account).

As a backup to the manual measurements, data loggers should be installed in M_1 and G1 and ASR1 with 1-minute recording interval. Data loggers will be provided by the VEI/BGR team. Loggers should be installed 2 hours before the well performing test starts.

The discharge rates have to be documented every 15 minutes in the first hour, afterwards every 30-60 minutes.

vii. Pumping test

Finally, the pumping test program consists of pumping with a submersible pump at a constant rate in well ASR_1, and monitoring groundwater levels in wells G1, monitoring well M_1 and ASR_1. With this set up a final determination of the aquifer hydraulic parameters can be done. A detailed pumping test (24 hrs) and monitoring plan should be discussed beforehand with the project team; assistance on site for programming the divers is most preferable.

viii. Documentation

During the entire period of drilling, development and pump testing of the borehole, a detailed record of all works executed has to be ensured. It is advised that a person administers these records – free of other duties and on-site at all times.

After completion of the borehole, a Drilling Report including detailed lithological records and records on well design and construction (documenting the actual, measured well design) shall be provided.

The record shall consist of the following:

- Driller's lithological log with depths and water inflows recorded, penetration rates and circulation losses;
- Drilling log giving depth every thirty minutes, with data on drilling method, water pressure, drill bit type and exact diameter and other operations used;
- Casing/screen tally specifying lengths, numbers, types, exact inner and outer diameters, centralizers, bottom caps, screen slot size, etc.
- Gravel pack, formation stabilizer, backfill and liquid grout sealing records
- Development records including times and notes on water color, clarity and silt content.
- Geophysical Logging records of the 5 parameters
- Step-drawdown test results
- Pump test results (measurements), and interpretation of results

5.3. Solutions for monitoring water quantity and quality during the artificial recharge cycle

5.3.1. Monitoring groundwater quantity during the ASR pilot

A suitable aquifer for ASR is defined by the amount of water that can be recharged to and recovered from the aquifer. The **storage capacity** depends on the extent of the aquifer, its permeability, transmissivity and its confinement. For confined aquifers, it is important not to over-pressurize the aquifer and cause rupture of the confining layer.

The **recovery efficiency** is defined as the percentage of water volume injected compared to the water volume that can be recovered within the target water quality criteria. As in our case we are using fresh high quality water in a fresh good quality aquifer, it might not be possible (or required) to distinguish between the recovery of recharged water and ambient groundwater.

The recovery efficiency can be reduced due to:

- high regional hydraulic gradients, which is in general not the case in the Mekong Delta, but local drawdowns around large production wells might influence local gradients,
- highly saline aquifers, which is not the case for our pilot,
- highly inhomogeneous aquifers (e.g. karst, fractured rock), which is not the case in the Mekong delta, or
- leaky aquifers resulting in loss to over- or underlying aquifers, which is likely in the Mekong Delta, but not necessarily a problem, as groundwater is extracted from many aquifers.

The main concern with well performance is **clogging**. This reduction in porosity occurs mainly around the injection well and leads to a decrease in injection rate and an increase in hydraulic head. To remediate excessive clogging, periodical purging or backflushing of the well will be required.

The aim of water quantity monitoring is hence to assess:

1. infiltration rates
2. recovery rates
3. well efficiency (i.e. clogging)
4. costs and benefits (costs per m^3)

The following parameters should hence be monitored:

- recharge volume (flow rate over time at injection well)
- recovery volume (flow rate over time at recovery well)
- groundwater table changes at recharge, recovery and monitoring wells
- energy requirements for recharge and recovery

All above parameters should be monitored with (semi-)automatic sensors to give high frequency readings. Hence, the following **sensors** are required:

- water level + temperature + EC at ASR well, and monitoring well
- flow meter at ASR well for inflow (recharge) and outflow (recovery)
- energy consumption meter at recharge booster pump (if any) and recovery pump

Ideally, data from these sensors is logged and transmitted automatically. IoT-enabled devices are making it easier and cheaper than ever to capture real time monitoring data and deliver these data—in the form of graphical visualizations—to users in a matter of seconds. A low power wide area network (LPWAN) application, known as LoRaWAN, should enable the transfer of encrypted data over the whole premises of HAWASUCO (need to be checked if any building get in the way of the signal), while maintaining low-power consumption. LoRaWAN requires a local receiving gateway (base station) to transfer the incoming packets from the IoT sensor nodes to a network server to be decoded, after which a formatted (JSON) object (data) can be forwarded to a back-end database for storage and/or a front-end server for visualization

Otherwise, logged data have to be retrieved manually at regular intervals.

In addition, it would be advisable to conduct **geodetic levelling** for all wells to be able to fully compare the measured groundwater levels with each other.

5.3.2. *Monitoring groundwater quality during the ASR pilot*

The aim of the water **quality** monitoring is to assess the:

1. clogging potential,
2. pollutants posing a risk for groundwater quality and domestic water quality,
3. quality of the recovered water,
4. interactions taking place in the disturbed groundwater system (model geochemical reactions occurring from the infiltration of oxygenated surface water to anoxic groundwater and during passage in the underground).

Temporally, water quality changes are maximal during the initial ASR operating cycles. During consecutive cycles, the groundwater in the storage zone will be completely exchanged and geochemical reactions will have adjusted to the new equilibrium of the stored water, especially if not all injected water is recovered. However, in very heterogeneous aquifers diffusion processes might require several cycles to flush the residual ambient groundwater from lenses and layers of low hydraulic conductivity (Pavelic et al. 2006).

Spatially, water quality changes are greatest around the injection well, where the number of pore flushes, geochemical variations and the hydraulic gradient are highest. In the main storage zone, the number of pore flushes is reduced and water quality changes are less pronounced as the water has been pre-equilibrated around the well. Depending on the differences between injectant and ambient groundwater, the differences in water quality in the buffer zone furthest away from the well could nevertheless still be significant (Dillon et al. 2005), while a stable injectant water quality “bubble” will be established after a significant number of cycles.

For all schemes, biogeochemical interactions with the aquifer matrix like **ion exchange**, **redox reactions** and **dissolution/precipitation** will have an impact on the recovered water quality. Accordingly, attention should be paid to field parameter (pH, redox potential, temperature, EC), major ions as well as trace metals that could be released during dissolution.

The **organic matter** present in the anoxic aquifer would undergo oxidation and potentially release dissolved organic carbon and nitrogen compounds.

When recovering water for potable use, trace organic pollutants in the recharge water are of concern. However, these would already be a concern for drinking water supply without the ASR scheme. If they are mobile and are recovered, they would undergo a second treatment, as the recovered water would be treated again before distribution into the network. If they are absorbing to the aquifer matrix or degraded during the relatively long residence time, and not be recovered, recovered water quality would be improved by natural attenuation. In any case, it would not be expected that the concentration of trace organic pollutants would be increased by the passage through the aquifer, as they are anthropogenic and not found in the aquifer sediments.

We recommend the following monitoring scheme:

- Sampling points: input (treated water before chlorination), output and monitoring well; as well as existing production wells G1 and G2.
- Sampling times: choose sufficient sampling points in time to cover changes during ASR operation, as well as potential changes in surface water quality due to seasonal effects etc. The exact sampling frequency depends on the operational cycling scheme. Most changes are expected towards the end of each recovery cycle, when the mixing front approaches the well.
- Parameters:
    - pH, turbidity, EC, DO, temp, TDS, HCO_3, Cl, SO_4, Ca, Na, K, Mg, NH_4, NO_3, PO_4, Fe, Mn, TOC.
    - Trace metals: Al, As, Ba, Ni, Zn

Table 12 summarizes the proposed set of parameters to be analyzed. Actual frequency will be depending on cycle length, results of previous samples, as well as technical and financial considerations.

Continuous measurements would be undertaken with (semi-)automatic equipment to be installed in the inflow and outflow pipelines of the ASR well, as well as in the monitoring well and in G1 and G2 production well (if feasible from technical and financial aspects). For measurement of EC in the groundwater, it would be required to lower the EC-instrument to the screen depth.

Monitoring of water quantity (flow volumes in and out of the ASR well and groundwater level) as well as energy consumption of recovery pump should be done (semi-)automatically as well. If feasible, IoT equipment (Internet-of-things) using LoRaWan could be used.

Table 12: Suggested parameters and frequencies for water quality monitoring during ASR cycles.

Where	**Why**	**Parameter**	**Suggested frequency for manual measurement**	**Potential for high frequency (semi-) automatic monitoring**
Recharge water quality	clogging potential	turbidity	daily - weekly	high
		DO	daily - weekly	maybe
		Fe, Al, Mn	weekly – bimonthly	no
		DOC	weekly - bimonthly	maybe
	biogeochemical processes	pH, redox potential	daily - weekly	maybe
		EC, temp	daily - weekly	high
		Na, Ca, Mg, K, SiO_2, Cl, SO_4, HCO_3	bimonthly - monthly	no
Recovered water quality	biogeochemical processes	pH, redox potential	daily	maybe
		EC, temp	daily	high
		Na, Ca, Mg, K, SIO_2, Cl, SO_4, HCO_3	bimonthly	no
	metal mobilization	Al, As, Ba, Ni, Zn	daily – weekly	no
	organic matter degradation	DOC	weekly – bimonthly	maybe
		NO_3, NO_2, NH_4	daily - weekly	no
Monitoring well / production wells	biogeochemical processes	pH, redox potential	weekly - bimonthly	no
		EC, temp	weekly - bimonthly	maybe (at screen depth)
		Na, Ca, Mg, K, SIO_2, Cl, SO_4, HCO_3	bimonthly - monthly	no
	metal mobilization	Al, As, Ba, Ni, Zn	bimonthly - monthly	no
	organic matter degradation	DOC	bimonthly - monthly	no
		NO_3, NO_2, NH_4	bimonthly - monthly	no

Based on a compilation of regulations and recommendations from the worldwide practice, it is recommended to use the following threshold values for this pilot:

Infiltration water will adhere to VN domestic water guidelines (QCVN 01-1:2018/BYT) (MoH 2018), except for microbes and free chlorine as water before chlorination will be used. In addition, it is recommended to adhere to the following lowered thresholds to limit clogging of the ASR system and contamination of the aquifer (Table 13).

Table 13: Recommended additional or lowered thresholds for infiltration water

parameter	unit	VN-DW (QCVN 01-1:2018/BYT)	Recommended threshold for this ASR pilot	process
turbidity	NTU	2	1	mechanical clogging
DOC	mg/L		2	biological clogging
$P\text{-}PO_4$	mg/L		0.16	
Al	µg/L	200	100	chemical clogging
Fe	µg/L	300	100	
Mn	µg/L	100	50	
Ni	µg/L	70	20	contamination
CN*	µg/L	50	10	
total pesticides*	µg/L		0.5	

* will not be measured regularly during the pilot

The envisaged set up of the monitoring equipment can be found in Appendix 4.

6. Description of the trial/experimental operation procedure

After the installation of the below ground and above ground part of the ASR well and the installation of all monitoring equipment, it is envisaged to conduct 4 testing cycles with increasing length of recharge and storage (Table 14). The recovery phases are shorter than the recharge phases, as the recovery flow rate higher (60 m^3/d) compared to an recharge rate (35 m^3/d) and an overinfiltration of recharge water is beneficial to prevent geochemical changes in the aquifer reaching the recovered water. The length of the cycles will be short at the beginning to be able to assess initial potential issues. The last cycle should be about 120 days to match the length of recharge of a real operational ASR system.

Table 14: ASR testing cycles

Cycle no	**recharge (days)**	**storage (days)**	**recovery (days)**
1	4	4	2
2	10	10	5
3	30	30	15
4	120	30	10

The length and number of cycles might be adjusted due to operational or project time line considerations.

7. Description of the procedures for operating and managing works for artificial recharge of groundwater.

A number of work packages for the pilot have been defined by the project:

WP1 – ASR Site Development

This includes acquiring the necessary permits, to assess the water quality of the source awter and native groundwater, define monitoring parameters, install a monitoring well, design the ASR well and then developing the ASR site.

WP2 – Operation and monitoring

This includes the actual operation of the ASR pilot, monitoring and technical assessment of monitoring results.

WP3 – Upscaling

This includes the development of upscaling scenarios and assessing the financial viability of ASR schemes based on cost-benefit analysis. It also looks at a governance analysis as well as capacity building of the water supply operators. It also entails workshop for stakeholder and experts to disseminate the findings and discuss further upscaling steps.

The partners of the consortium and of the supporting institutions have different responsibilities for these work packages and activities within the work packages.

- HAWASUCO: They are the main partner and will provide the source water for the ASR pilot, develop and execute the above-ground installation for the ASR well and be in charge of day-to-day operation of the system. They are in charge of dealing with all regulatory issues related to the ASR pilot and will support the governance analysis.
- Deltares: They are responsible for the oversight and management of the project. They will assess the technical results of the pilot against the success criteria and conduct the cost-benefit analysis.
- VEI: They are the technical experts for site selection, the design and construction of the monitoring and ASR well including oversight during drilling and well development. They also support the development of the water quality monitoring concept.
- BGR: The CRMGG project is supporting the water quality assessment, monitoring concept, installation of monitoring equipment, financing of the drilling of the ASR well as well as water quality analysis.
- DWRPIS: They are in charge for a technically sound drilling and development of the monitoring and ASR well under guidance from VEI experts.
- WWF: They are responsible for assess upscaling scenarios and the financial bankability as well as stakeholder engagement.

All partners will be involved in the dissemination of results and the governance analysis through collaborative workshops.

Detailed instructions for the day-to-day operation of the system are currently under development and on-the-job training will be conducted for HAWASUCO staff.

Bibliography

Antoniou, E.A., van Breukelen, B.M., Putters, B. and Stuyfzand, P.J. (2012) Hydrogeochemical patterns, processes and mass transfers during aquifer storage and recovery (ASR) in an anoxic sandy aquifer. Applied Geochemistry 27(12), 2435-2452.

Bahr, J., Grundl, T., Harrington, G., Krohelski, J. and Werner, M. (2002) A Review of Aquifer Storage Recovery Techniques. Aquifer Storage Recovery Technical Advisory Group (ed), p. 40, Wisconsin Department of Natural Resources.

Brown, C.J., Hatfield, K. and Newman, M. (2006) Lessons learned from a review of 50 ASR projects from the United States, England, Australia, India, and Africa.

De Glee, G.J. (1930) Over grondwaterstromingen bij wateronttrekking door middel van putten. Thesis, Delft University of Technology, Delft, The Netherlands.

Dillon, P., Pavelic, P., Page, D., Beringen, H. and Ward, J. (2009) Managed aquifer recharge: an introduction, p. 64, National Water Commission, Canberra, Australia.

Dillon, P., Stuyfzand, P., Grischek, T., Lluria, M., Pyne, R.D.G., Jain, R.C., Bear, J., Schwarz, J., Wang, W., Fernandez, E., Stefan, C., Pettenati, M., van der Gun, J., Sprenger, C., Massmann, G., Scanlon, B.R., Xanke, J., Jokela, P., Zheng, Y., Rossetto, R., Shamrukh, M., Pavelic, P., Murray, E., Ross, A., Bonilla Valverde, J.P., Palma Nava, A., Ansems, N., Posavec, K., Ha, K., Martin, R. and Sapiano, M. (2019) Sixty years of global progress in managed aquifer recharge. Hydrogeology Journal 27(1), 1-30.

Dillon, P., Toze, S., Pavelic, P., Skjemstad, J., Davis, G., Miller, R., Correll, R., Kookana, R., G-G., Y., Herczeg, A., Filderbrandt, S., Banning, N., Gordon, C., Wall, K., Nicholson, B., Vanderzalm, J., Le Gal La Salle, C., Gibert, M., Ingrand, V., Guinamant, J.-L., Stuyfzand, P., Prommer, H., Greskowiak, J., Swift, R., Hayes, M., Oâ Hara, G., Mee, B. and Johnson, I. (2005) Water Quality Improvements during Aquifer Storage and Recovery. Vol 1: Water Quality Improvements Processes, p. 347, CSIRO Land and Water, Australia.

Duckworth, O.W. and Martin, S.T. (2004) Role of molecular oxygen in the dissolution of siderite and rhodochrosite1 1Associate editor: U. Becker. Geochimica et Cosmochimica Acta 68(3), 607-621.

Eslami, S. (2022) Environmental change in a mega-delta. Dynamics of salt intrusion in the Vietnamese Mekong Delta, Utrecht University, The Netherlands, Utrecht.

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. and van der Vegt, M. (2021) Projections of salt intrusion in a mega-delta under climatic and anthropogenic stressors. Communications Earth & Environment 2(1), 142.

Eslami, S. and King, J. (2022) Pre-Feasibility study of ASR application in the Vietnamese Mekong Delta, p. 51.

Fakhreddine, S., Prommer, H., Scanlon, B.R., Ying, S.C. and Nicot, J.-P. (2021) Mobilization of Arsenic and Other Naturally Occurring Contaminants during Managed Aquifer Recharge: A Critical Review. Environmental Science & Technology 55(4), 2208-2223.

Faneca Sànchez, M., Bashar, K., Janssen, G., Oude Essink, G.H.P., Vogels, M., Snel, J., Zhou, Y. and Stuurman, R. (2015) SWIBANGLA: Managing salt water intrusion impacts in coastal groundwater systems of Bangladesh, p. 153, Deltares, UNESCO-IHE, Jahangirnagar University.

Gunnink, J.L., Pham, H.V., Oude Essink, G.H.P. and Bierkens, M.F.P. (2021) The three-dimensional groundwater salinity distribution and fresh groundwater volumes in the Mekong Delta, Vietnam, inferred from geostatistical analyses. Earth Syst. Sci. Data Discuss. 13, 3297-3319.

Hai, N.Q., Egashira, K., Ha, P.Q. and Duc, H.Q. (2005) Selected Chemical Properties of Alluvial Soils in Vietnam. J. Fac. Agr.,Kyushu University 50(1), 233-242.

Herczeg, A.L., Rattray, K.J., Dillon, P.J., Pavelic, P. and Barry, K.E. (2004) Geochemical processes during five years of aquifer storage recovery. Ground Water 42(3), 438-445.

Jeong, H., Jun, S.-C., Cheon, J.-Y. and Park, M. (2018) A review on clogging mechanisms and managements in aquifer storage and recovery (ASR) applications. Geosciences Journal 22.

Ji, H.W. and Lee, S.-I. (2016) Assessment of Risk Due to Chemicals Transferred in a Watershed: A Case of an Aquifer Storage Transfer and Recovery Site. Water 8(6), 242.

Johnson, J.S., Baker, L.A. and Fox, P. (1999) Geochemical transformations during artificial groundwater recharge: soil-water interactions of inorganic constituents. Water Research 33(1), 196-206.

Konikow, L.F., August, L.L. and Voss, C.I. (2001) Effects of Clay Dispersion on Aquifer Storage and Recovery in Coastal Aquifers. Transport in Porous Media 43(1), 45-64.

Martin, R.e. (2013) Clogging issues associated with managed aquifer recharge methods, IAH Commission on Managing Aquifer Recharge, Australia.

Martinez, M.B., Widdowson, M.A., Bott, C., Holloway, D., Heisig-Mitchell, J. and Wilson, C. (2022) Demonstration of Managed Aquifer Recharge in a Coastal Plain Aquifer: Lessons Learned. Groundwater 60(5), 668-674.

Minderhoud, P.S.J., Erkens, G., Pham, V.H., Bui, V.T., Erban, L., Kooi, H. and Stouthamer, E. (2017) Impacts of 25 years of groundwater extraction on subsidence in the Mekong delta, Vietnam. Environmental Research Letters 12(6), 064006.

Minderhoud, P.S.J., Middelkoop, H., Erkens, G. and Stouthamer, E. (2020) Groundwater extraction may drown mega-delta: projections of extraction-induced subsidence and elevation of the Mekong delta for the 21st century. Environmental Research Communications 2(1).

Minh, V., Tri, L.Q., Khoa, L., Du, T., Vu, P., Tran Van, D. and Dong, N. (2023) Rice Soil Fertility Classification in the Mekong Delta, Vietnam. AGRIVITA Journal of Agricultural Science 45(1), 56-68.

MoH (2018) National technical regulation on Domestic Water Quality QCVN 01-1:2018/BYT. Ministry of Health (ed), Ha Noi.

Pavelic, P., Dillon, P., Barry, K. and Gerges, N. (2006) Hydraulic evaluation of aquifer storage and recovery (ASR) with urban stormwater in a brackish limestone aquifer. Hydrogeology Journal 14, 1544-1555.

Rafiq, M.R., Ahmed, K.M., Rietveld, L.C. and van Breukelen, B.M. (2022) Monitoring and inverse modelling of hydrogeochemical processes during managed aquifer recharge in Southwestern Bangladesh. Applied Geochemistry 146, 105472.

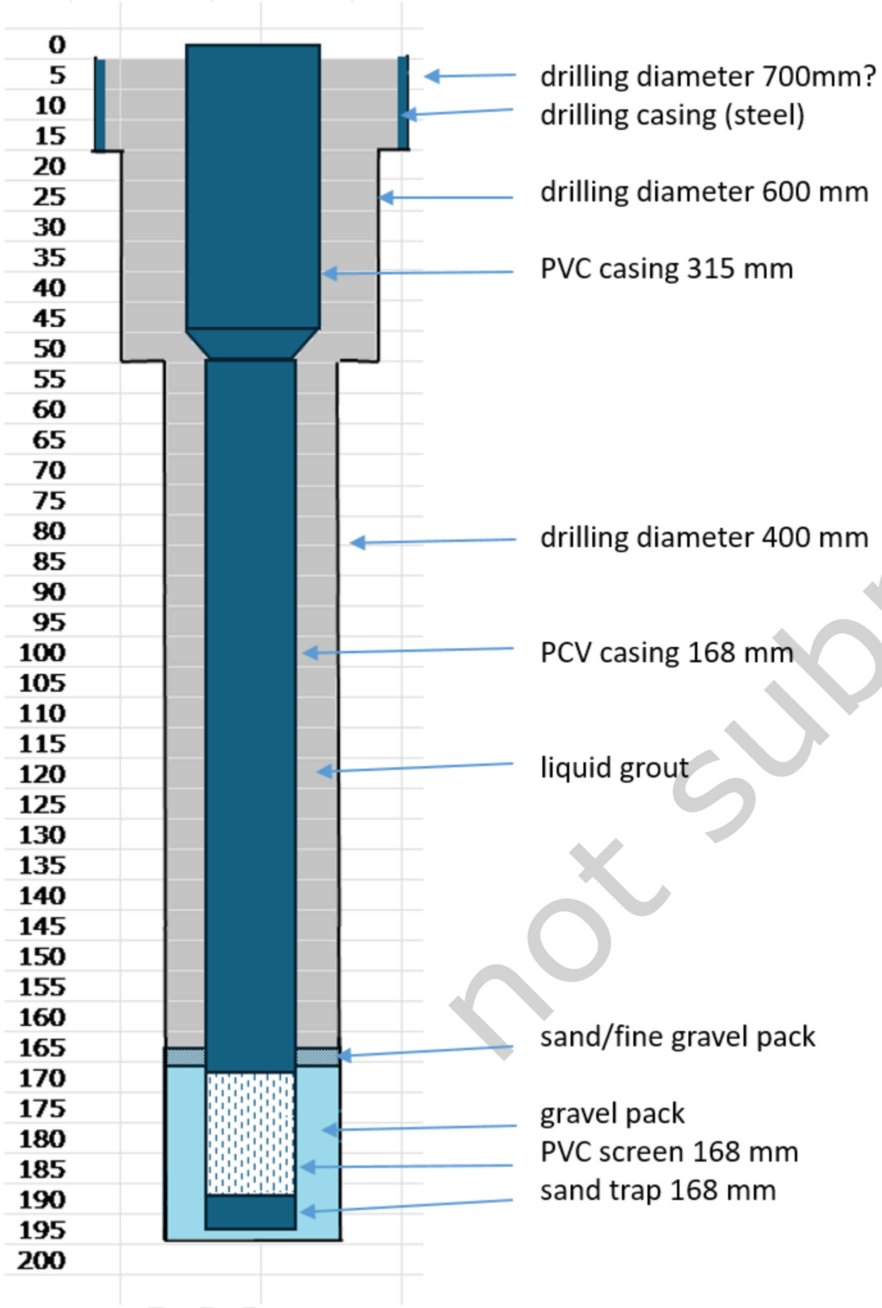
Rambags, F., Raat, K., Zuurbier, K., Berg, G. and Hartog, N. (2013) Aquifer Storage and Recovery (ASR) Design and operational experiences for water storage through wells.

Sprenger, C., Hartog, N., Hernández, M., Vilanova, E., Grützmacher, G., Scheibler, F. and Hannappel, S. (2017) Inventory of managed aquifer recharge sites in Europe: historical development, current situation and perspectives. Hydrogeology Journal 25(6), 1909-1922.

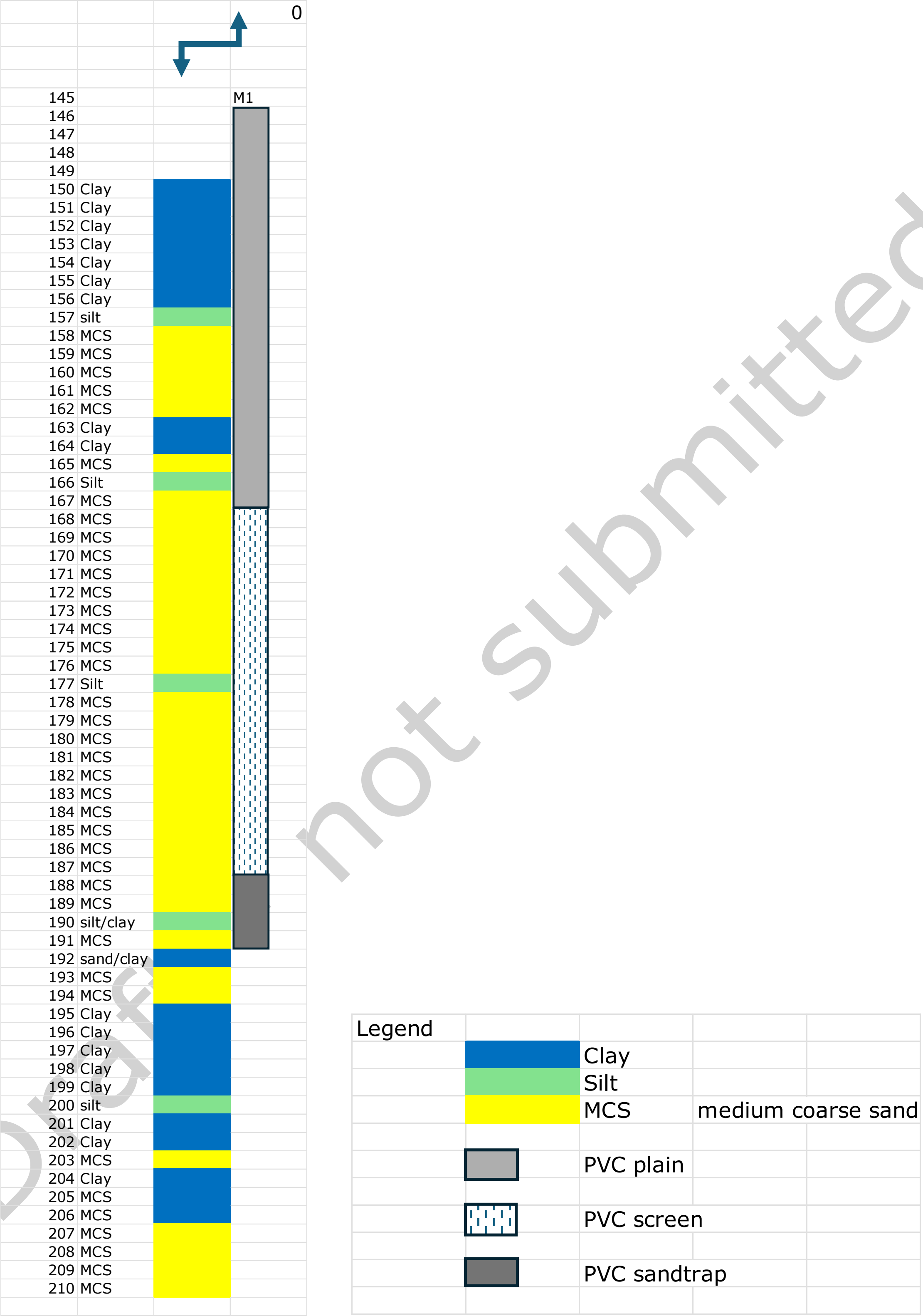
Stumm, W. and Morgan, J.J. (1995) Aquatic Chemistry: Chemical Equilibria and Rates in Natural Waters.

Torkzaban, S., Bradford, S.A., Vanderzalm, J.L., Patterson, B.M., Harris, B. and Prommer, H. (2015) Colloid release and clogging in porous media: Effects of solution ionic strength and flow velocity. Journal of Contaminant Hydrology 181, 161-171.

Appendix 1: Proposed design of ASR well



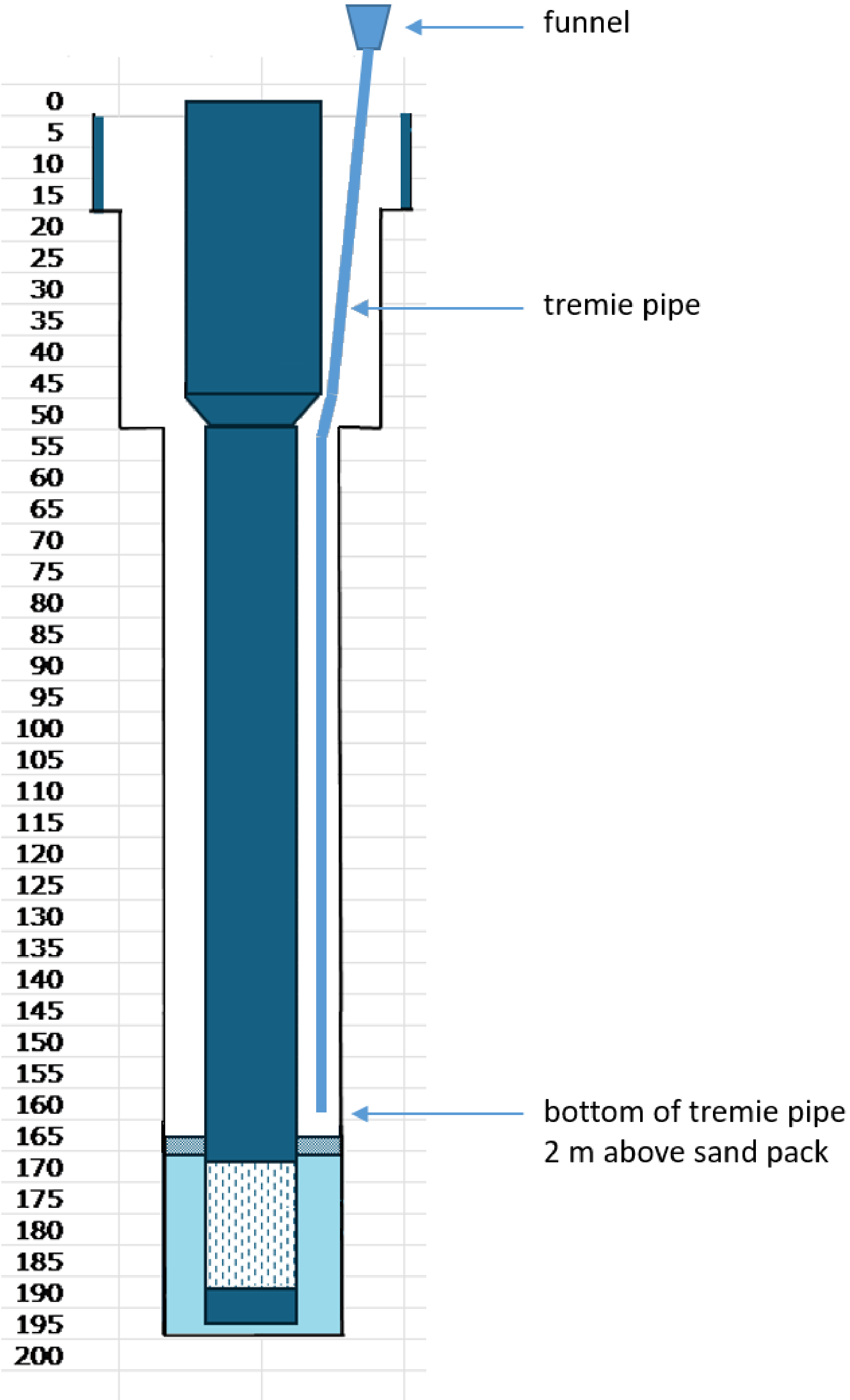
Appendix 2: Results of drilling and design of monitoring well M1



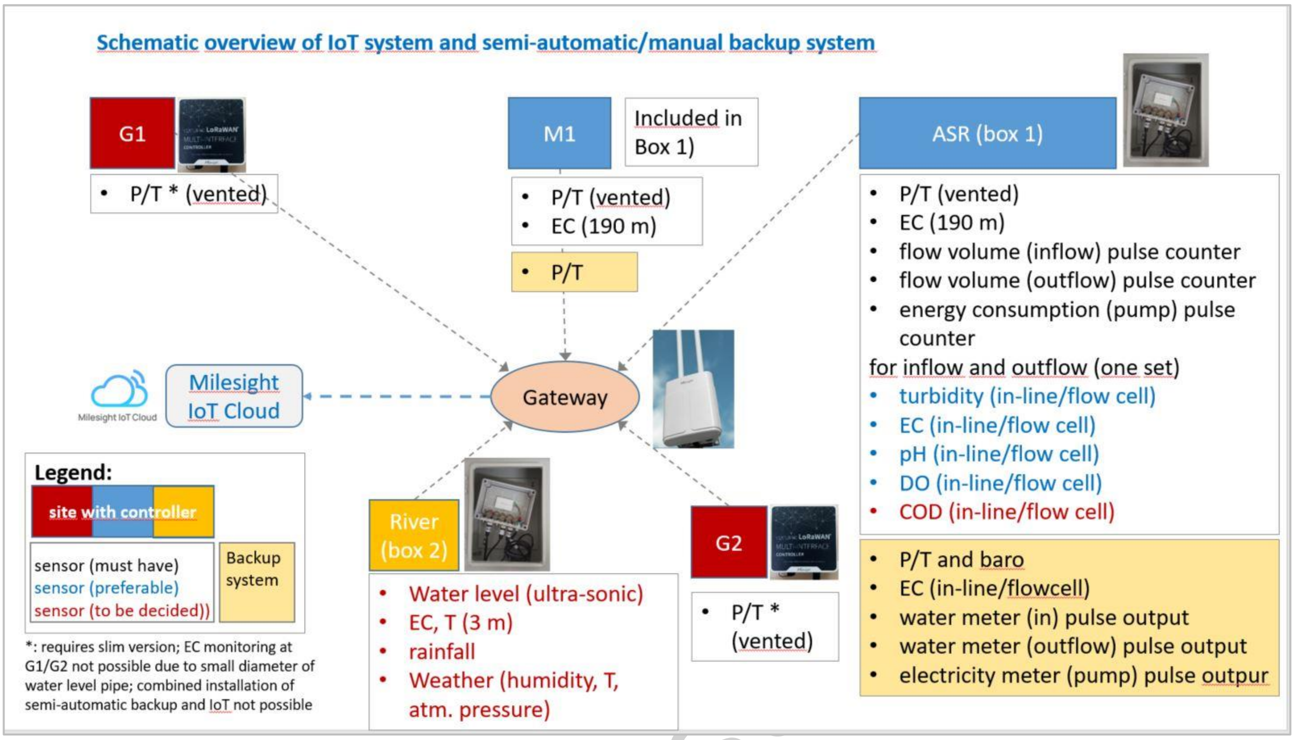
145	
146	
147	
148	
149	
150	Clay
151	Clay
152	Clay
153	Clay
154	Clay
155	Clay
156	Clay
157	silt
158	MCS
159	MCS
160	MCS
161	MCS
162	MCS
163	Clay
164	Clay
165	MCS
166	Silt
167	MCS
168	MCS
169	MCS
170	MCS
171	MCS
172	MCS
173	MCS
174	MCS
175	MCS
176	MCS
177	Silt
178	MCS
179	MCS
180	MCS
181	MCS
182	MCS
183	MCS
184	MCS
185	MCS
186	MCS
187	MCS
188	MCS
189	MCS
190	silt/clay
191	MCS
192	sand/clay
193	MCS
194	MCS
195	Clay
196	Clay
197	Clay
198	Clay
199	Clay
200	silt
201	Clay
202	Clay
203	MCS
204	Clay
205	MCS
206	MCS
207	MCS
208	MCS
209	MCS
210	MCS

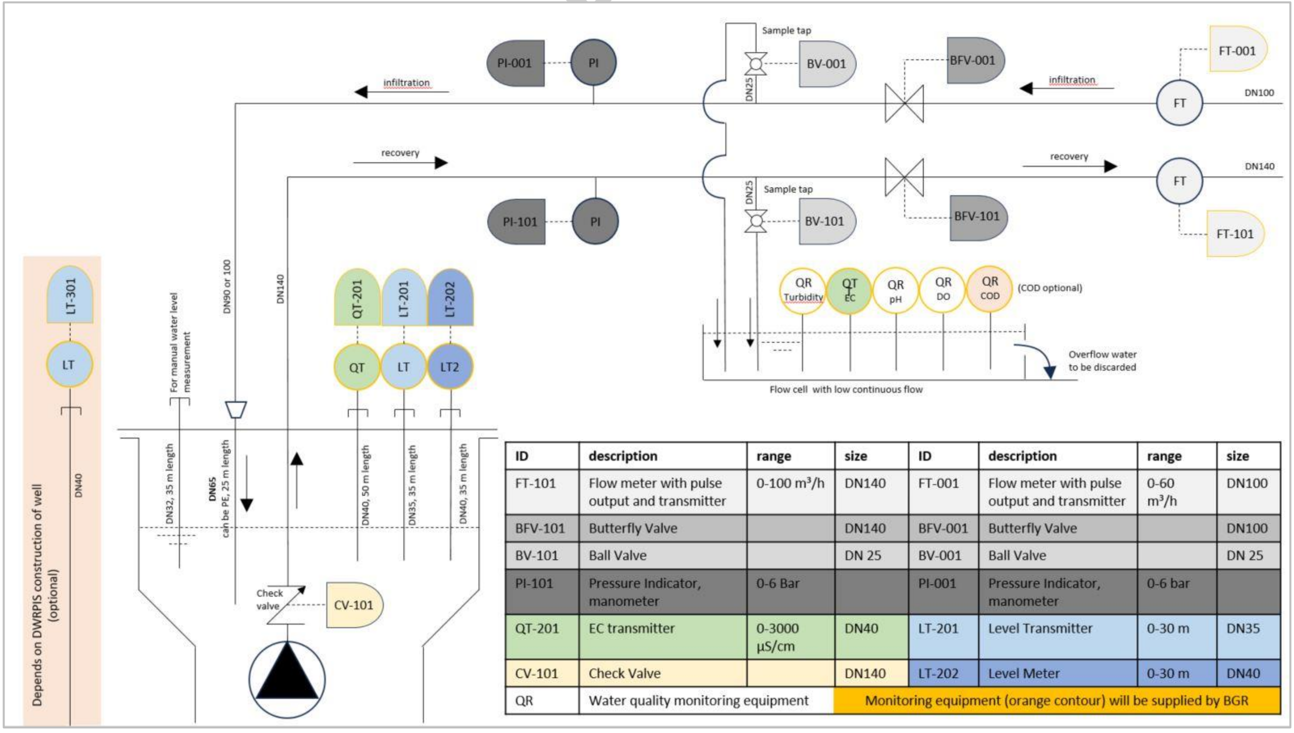
Sketch of the drilling result and final design of monitoring well M1 and target aquifer qp_1 (drill description starts at 150 meter depth).

Appendix 3: Method of backfilling the annular



Appendix 4: Schematic design of monitoring equipment and above-ground design of ASR well head





ID	description	range	size	ID	description	range	size
FT-101	Flow meter with pulse output and transmitter	0-100 m³/h	DN140	FT-001	Flow meter with pulse output and transmitter	0-60 m³/h	DN100
BFV-101	Butterfly Valve		DN140	BFV-001	Butterfly Valve		DN100
BV-101	Ball Valve		DN 25	BV-001	Ball Valve		DN 25
PI-101	Pressure Indicator, manometer	0-6 Bar		PI-001	Pressure Indicator, manometer	0-6 bar	
QT-201	EC transmitter	0-3000 µS/cm	DN40	LT-201	Level Transmitter	0-30 m	DN35
CV-101	Check Valve		DN140	LT-202	Level Meter	0-30 m	DN40
QR	Water quality monitoring equipment		Monitoring equipment (orange contour) will be supplied by BGR				