Project:

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

Report No 3:

Water quality assessment and recommended monitoring for ASR pilot location Nga Bay

WP1: ASR Site development

Water Quality assessment

WP2: Monitoring

Monitoring Plan

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Summary

In the Partners for Water 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 in Hau Giang. This report provides an assessment of the water quality from the drinking water treatment plant in Nga Bay and the water quality of the native groundwater at the start of the pilot, to address the possible risks connected to ASR. The report takes the more generic overview of the monitoring plan (Report No 1) as the basis and specifies this to the pilot location by analyzing water quality data and giving site-specific monitoring recommendations.

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, no water quality problems are expected.

Prevention of clogging risks is an important goal of the ASR pilot. The relevant water quality parameters (such as TSS, iron and TOC) indicate that clogging risks are low. The water treatment prior to infiltration also decreases the risk of clogging. Over-infiltration can further decrease potential risks of clogging.

Pollution of native groundwater in target aquifer qp_1 is not likely, because of the great depth and presence of protecting clay layers, and the fact that pesticides were not found in the existing back-up wells. Still, we recommend monitoring pesticides. Based on scarce scientific literature, their presence in the treated surface water is likely. In addition, pesticides form a very broad group of compounds, and not all of them will be removed by the drinking water treatment. Next to pesticides, compounds of emerging concern can also pose a risk of contamination of the aquifer, but no data is available. From this point of view, it is important to also keep control of the infiltrated and recovered volumes, to avoid spreading of infiltrated water.

Risks of deteriorating water quality during storage cannot be excluded. The pilot itself will provide more insight into these risks. Risks exist on mobilization of metals like Mn and As although concentrations in the native groundwater seem rather low. In addition, risks of microbiological growth must be assessed by careful monitoring during the pilot.

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

A point of attention is the salinization risk from aquifers above or below the target aquifer. NAWAPI data from Q607 do not indicate salinity issues in the adjacent aquifers, however, DONRE data do show presence of saline water bodies in the shallow aquifers.

Although it is expected that risks of contamination or clogging are limited, it is still important to monitor the infiltration pilot well, as the surface water quality is expected to vary over time due to e.g., seasonal effects. In addition, hydrogeochemical reactions in the groundwater system might change over time and are not exactly known beforehand. Finally, water quality data on input and produced water can give information on the processes during infiltration. Therefore, a detailed monitoring scheme is recommended, including a list of parameters to analyze, sampling points and sampling times.

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Abbreviations

AOC	assimilable organic carbon
ASR	aquifer storage and recovery
ASTR	aquifer storage, transport and recovery
ATP	adenosine triphosphate
BGR	German Federal Institute of Geosciences and Natural Resources
BOD	biological oxygen demand
CDC	Provincial Department under the Ministry of Health
COD	chemical oxygen demand
DO	dissolved oxygen
DOC	dissolved organic carbon
DONRE	Department of Natural Resources and Environment
DW	drinking water
E.coli	*Escherichia coli*
EC	electric conductivity
Eh	redox potential
GFS	Geringfügigkeitsschwellenwerte (Insignificance thresholds)
GrwV	Grundwasserverordnung (German Groundwater Ordinance)
GW	groundwater
HAWASUCO	Hau Giang Water Supply and Sewerage and Urban Construction Joint Stock Company
IB	Infiltratiebesluit bodembescherming (Dutch Soil protection infiltration decree)
IoT	internet of things
LoRaWAN	low range wireless area network
MAR	managed aquifer recharge
MFI	membrane filtration/fouling index
MONRE	Ministry of Natural Resources and Environment
NAWAPI	National Center for Water Resources Planning and Investigation
NOM	natural organic matter
PFAS	per- and polyfluoroalkyl substances
PFW	Partners for Water
SAR	sodium adsorption ratio
SI	saturation index
SL	sea level
TDS	total dissolved solids
THMs	trihalomethanes
TOC	total organic carbon
TSS	total suspended solids
VN	Vietnam / Vietnamese
WP	work package
WTP	water treatment plant

1. Introduction

In the Partners for Water 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 in Hau Giang. The location Nga Bay City was chosen as the site for this ASR pilot for various technical and logistical reasons (see Report No 2, Radjkoemar et al., in preparation, for details).

This report gives a more detailed water quality assessment of

1) the water quality from the drinking water treatment plant in Nga Bay and
2) the water quality of the native groundwater

at the start of the pilot, in order to address the potential risks related to ASR, which are:

a) clogging of the wells,
b) deterioration of the water quality during storage,
c) unwanted spreading of infiltrated water in the aquifer system and associated potential contamination of ambient groundwater.

This report ends with recommendations for water quality monitoring to get more data to assess these risks and ensure a good functioning of the ASR system in the long term.

An overview and concept on water quality assessment in the province Hau Giang, the scope of the pilot and the monitoring requirements was given in the monitoring plan (Report No 1, Steinel et al. 2023).

2. Design of the 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 1). Raw water is treated with flocculation, sedimentation, sand filtration and chlorination before distribution to the network.

Additionally, two back-up wells G1 and G2[1] are 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 borehole logs and previous water samples give some information about the target aquifer qp_1 (around 160–190 m below SL) (see Report No 4, in preparation).

Figure 1: Overview of water treatment plant (WTP) of HAWASUCO in Nga Bay City (white outline) showing the location of existing infrastructure and the neighboring 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: Google Earth, photos: BGR.

For the conceptual design (see Report No 4, in preparation), 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 2). The system could be 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

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

passage in the aquifer and clogging issues in the injection well, ASR is likely to be the preferred option.

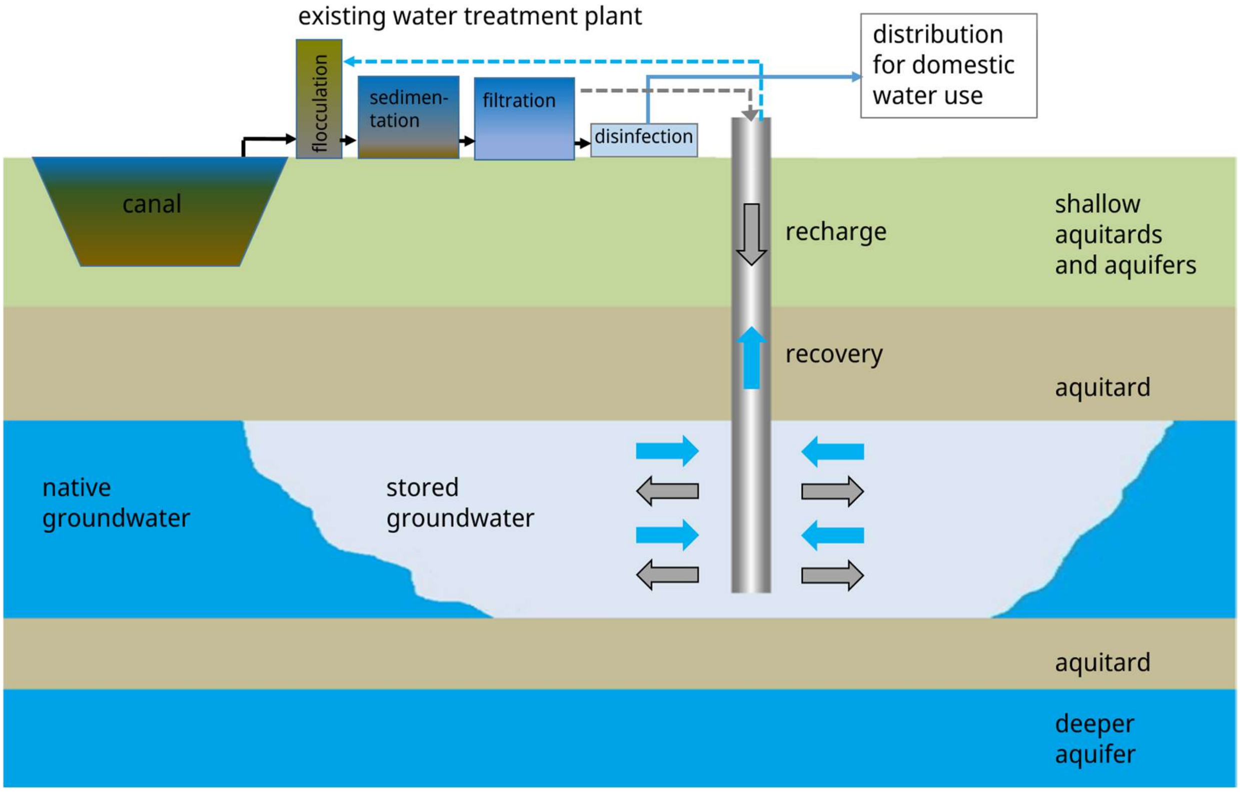

Figure 2: Conceptual design of water flow as ASR (aquifer storage and recovery: same well injection and extraction), which could be modified to ASTR (aquifer storage, transport and recovery: one well for injection and another well for extraction) using existing production wells. Source: modified after Ji and Lee 2016.

3. Risks and requirements with respect to water quality

Managed aquifer recharge schemes should be sustainable, i.e. be able to operate economically feasible and respecting environment and human health, so that the benefits outweigh the potential collateral damage. Inadequate consideration of source water quality and hydrochemical interactions between recharged water and the target porous medium may cause aquifer and groundwater contamination and consequently costly and time-consuming remediation efforts and clogging development could significantly lower the efficiency and expected lifespan of a MAR system (Fernández Escalante et al. 2022).

3.1. MAR regulations worldwide

There are no internationally defined minimum criteria as each scheme is different, but there are some overviews of existing MAR regulations (Report No 1, Steinel et al. 2023). The given thresholds for inorganic parameters in some relevant regulations are summarized in For the Netherlands, we only give numbers from the Infiltration Degree (Infiltratie Besluit, IB), which is specifically aimed at infiltration of water in the subsurface and was implemented in 2009. Since then, additional norms were determined to prevent groundwater pollution and comply to the

European Water Framework Directive. Since 2024, these various groundwater regulations are combined into the Omgevingswet (https://wetten.overheid.nl/BWBR0037885/2024-01-01).

Table 1. There are many more threshold values for a long list of organic pollutants for groundwater and drinking water, as well as disinfection by-products for drinking water regulations. Total pesticides residues including their (toxicologically) relevant metabolites should not be >0.5 µg/L and >0.1 µg/L for individual components in Europe for groundwater and drinking water. The threshold for total PFAS-20 is also 0.1 µg/L for drinking water in Germany. Depending on the quality of the groundwater and the intended use of the recovered water, both, the groundwater and the drinking water guidelines, might be relevant. For the Netherlands, we only give numbers from the Infiltration Degree (Infiltratie Besluit, IB), which is specifically aimed at infiltration of water in the subsurface and was implemented in 2009. Since then, additional norms were determined to prevent groundwater pollution and comply to the European Water Framework Directive. Since 2024, these various groundwater regulations are combined into the Omgevingswet (https://wetten.overheid.nl/BWBR0037885/2024-01-01).

Table 1: Threshold values from a range of different regulations for inorganic parameters (VN GW: QCVN 09-MT:2023/BTNMT (MONRE 2023); VN DW: QCVN 01-1:2018/BYT (MoH 2018); USA DW: National primary (and secondary in italics); drinking water regulations (USEPA 2009); Germany GrwV: Groundwater Ordinance (GrwV) (Bundesministeriums der Justiz 2010); Germany GFS: Insignificance thresholds ("Geringfügigkeitsschwellenwerte" (LAWA 2016); Germany TrwV: Drinking water Ordinance (Bundesministeriums der Justiz 2023); Netherlands: IB = Infiltratiebesluit bodembescherming (Ministry of Infrastructure and Waterworks 2009)). All parameters measured after filtration, except for turbidity, TSS, pH, EC and color. Further details on sampling and analysis methods can be found in the cited regulations.

	Unit	**Vietnam GW**	**Vietnam DW**	**USA DW**	**Germany GW**	**Germany GW-GFS**	**Germany DW**	**Netherlands IB**
pH		5.5-8.5	6.0-8.5	*6.5-8.5*			6.5-9.5	
Color	Pt-Co		15	*15*			0.5	
Turbidity	NTU		2	<0.3-5			1	
TSS	mg/L							0.5
EC	µS/cm						2790	
TDS		1500	1000	*500*				
Cl		250	250	*250*	250	250	250	200
SO_4		400	250	*250*	250	250	250	150
F		1	1.5	4		0.9	1.5	1
Br				0.01				
BrO_3	mg/L						0.01	
Na			200				200	120
N-NH_4		1	0.3		0.39*		0.39*	2.5
N-NO_3		15	2	10	11.3*		11.3*	5.6
N-NO_2		1	0.05	1	0.15*		0.15*	
P-PO_4					0.16**			0.4
Al			200	*50-200*			200	
As		50	10	10	10	3.2	10	10
B			300			180	1000	
Ba			700	2000		175		200
Be				4				
Cd		5	3	5	0.5	0.3	3	0.4
Co	µg/L					2		20
Cr		50	50	100		3.4	25	2
Cu		1000	1000	*1000*		5.4	2000	15
Fe		5000	300	*300*			200	
Hg		1	1	2	0.2	0.1	1	0.05
Mn		500	100	*50*			50	
Mo						35		

	Unit	**Vietnam GW**	**Vietnam DW**	**USA DW**	**Germany GW**	**Germany GW-GFS**	**Germany DW**	**Netherlands IB**
Ni		20	70			7	20	15
Pb		10	10	15	10	1.2	10	15
Sb			20	6		5	5	
Se		10	10	50		3	10	
Th				2		0.2		
Zn		3000	2000	*5000*		60		65
CN		10	50	200		10	50	10

* converted from NH_4, NO_3 and NO_2 mg/L, respectively, ** converted from PO4

3.2. Vietnamese regulations

As we are piloting a MAR site in Vietnam, the most relevant regulations are the Vietnamese ones. §39 of the current Vietnamese Law on Water Resources (LWR) (28/2023/QH15) (Government of Vietnam 2023) requires an "assessment of conformity in terms of quality, quantity, water retention and storage ability of aquifers; demands for exploitation and use of water resources and requirements for groundwater protection; assessment of socio-economic and environmental impacts" of MAR. The Ministry of Natural Resources and Environment (MONRE) is responsible for identifying areas for artificial recharge and approving MAR schemes. Organizations and individuals are encouraged to research on managed aquifer recharge solutions especially in areas where groundwater is degraded, depleted or polluted. However, there are no further regulations or technical guidelines specific to MAR yet, but the drafting of them has already started. For MAR research projects like this one, no approval from MONRE is currently needed.

The technical guideline for the minimum requirements of **domestic water quality** (QCVN 01-1:2018/BYT, MoH 2018) contains threshold values for 99 parameters. It applies as the standard for the treatment requirements of HAWASUCO. As we will be using treated surface water before chlorination, all these threshold values should be met for the **source water** of the pilot, except for residual chlorine and microbes.

The technical guideline on **groundwater quality** (QCVN 09-MT:2023/BTNMT, MONRE 2023) contains threshold values for 41 parameters. It should be considered as a minimum requirement for the infiltrated and recovered water quality (due to chemical reactions occurring in the subsoil) and for potential pollution of the groundwater, as the groundwater serves as backup source for domestic water supply at the location.

The threshold values are listed in Table 1 for inorganic parameters and Annex 1 for additional organic and microbial parameters.

3.3. Recommended values with respect to operational issues (clogging)

To prevent clogging and the failure of the system in quantitative terms, the following values are recommended by Dutch experts (Table 2). These recommendations are part of an official practical guideline for the management of infiltration equipment (Beernink and van der Schans 2023). The guideline is based on experiences with full-scale infiltration locations for drinking water and irrigation water purposes, mainly in the coastal zone of the Netherlands, but also on several worldwide MAR projects.

Next to these parameters, other parameters can also influence clogging behavior due to stimulation of chemical or microbiological processes. Parameters that might be of influence are sulfide and ammonium. However, no general threshold values are available for these parameters in relation to clogging.

In practice, not all parameters can easily be measured and not all preferred values can be met. Some clogging may occur by microbiological growth of material on the filter tube. The AOC parameter is an important indicator for the growth potential.

Chemical processes causing clogging occur primarily on the interface between injected and native water. Therefore, it is important to avoid over-abstraction. Over-infiltration is recommended for the first ASR cycle to keep a certain distance between this front and the filter tube.

Clogging can be managed by regular reversal of the flow and by applying techniques of mechanical cleaning. In practice, it is often observed that even though values are above-clogging criteria, no clogging occurs. As clogging processes are difficult to predict and the proposed project is a research project, we therefore propose to measure a selection of parameters from the list in Table 2 (also indicated in the proposed monitoring system in Report 1 and at the end of the current report), and carefully follow the permeability effects.

Table 2: Recommended minimum criteria for recharge water to prevent clogging (Beernink and van der Schans 2023)

Clogging process	**Parameter**	**Preferred values**
Chemical clogging (mineral precipitation)	Al (total dissolved)	<0.1 mg/L
	SI_{Ca}	<1
	Fe (III) / colloidal iron	<0.01 mg/L
Mechanical clogging	MFI (membrane filtration/fouling index)	<2 s/L^2
	TSS	<0.1 mg/L
	SAR (sodium adsorption ratio)	<3 / <6
Biological clogging	AOC (assimilable organic carbon/acetate)	<10 µg/L acetate-C
	DOC (dissolved organic carbon)	<2 mg/L
	ATP (adenosine triphosphate)	<10 ng/L
Physical clogging	Total gas pressure in groundwater	<atmospheric pressure

3.4. Recommended threshold values for this pilot

Based in the above compilation of regulations and recommendations from the 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.
- 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 3).

Table 3: 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

4. Available water quality data

4.1. Raw surface water

HAWASUCO has been testing the raw surface water in the canal for pH, BOD, COD, TSS, NO_3, NO_2, NH_4, PO_4, Cl, F, As, Fe, coliforms and *E. coli*. HAWASUCO provided data on quarterly basis from October 2019 until December 2022.

The environmental monitoring centre of the DONRE in Hau Giang is also undertaking regular monitoring of surface water (for pH, temperature, TSS, DO, BOD, COD, NH_4, NO_2, NO_3, PO_4, Fe, and coliforms). These data have not been requested from the DONRE, but some are already published (Thanh Giao 2020, Thuan 2022), but no specific data for Nga Bay are given.

Some publications (Binh Thanh et al. 2020, Duong et al. 2022) looked into the variations of surface water quality with respect to land use, tides and seasons for basic parameters like temperature, pH, DO, BOD, COD, TSS, NO_3, NH_4, PO_4, Fe and coliforms. Pesticides are not commonly monitored and only measured during some research projects (Chau et al. 2015, Toan et al. 2013), but no specific data for the Cai Con Canal was found.

4.2. Treated surface water

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, color, 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, dissolved sulfide, 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, dissolved sulfide, 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. Results are presented in chapter 5.

4.3. Groundwater

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 and had them analyzed for 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 all 6 aquifers qp_3 to n_1^3; Figure 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 (see report 1), with one location in Nga Bay (QT05, Figure 3), but only penetrating down to the qp_{2-3} aquifer (well screen around 111 m depth). Therefore, 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}. A recent well survey found that only one well in qp_1 (170 m^3/d) and two wells in qp_{2-3} (180 and 45 m^3/d) are actually active (Figure 3), while the others are back-up 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 south of the HAWASUCO site. Based on groundwater level contour lines from end of April 2020 (Dersch and Steinel 2021), the groundwater flow direction in the Nga Bay area is from the North to the South. This information is valuable to assess potential spreading of the infiltrated water to other users and the potential flow direction of the recharged water. Given the estimated flow velocity of 3-8 m/year (Hoang and Bäumle 2019, Pechstein et al. 2018), any recharged water is not likely to reach the production well in the near future.

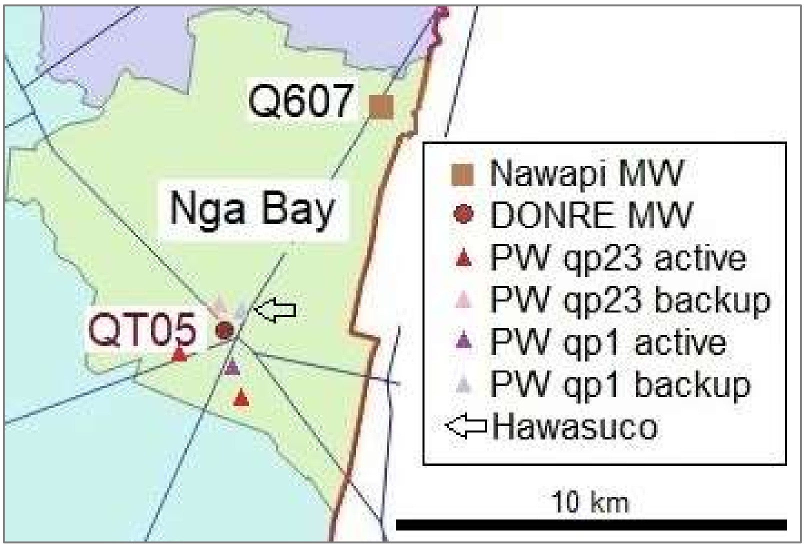

Figure 3: Groundwater monitoring well (MW) in Hau Giang from DONRE (QT) and NAWAPI (Q) and licensed production wells (PW) in Nga Bay district.

5. Presentation of relevant water quality data

5.1. Raw surface water Nga Bay intake – trends, seasonality

Table 4 gives the variations in water quality parameters of the raw intake surface water in Nga Bay during the last years. The original data can be found in Annex 2. Variations in concentrations are limited and a seasonal pattern cannot be recognized due to the rather low sampling frequency. The variation in the load of TSS can be a relevant issue for the treatment.

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

Parameter	Unit	Number	Min	Median	Max
pH		8	6.3	7.11	7.47
BOD_5 (at 20°C)	mg/L	10	7	10	14
COD	mg/L	10	12	17.5	22
TSS	mg/L	8	26	47	60
$N\text{-}NO_3$	mg/L	8	0.18	0.4	0.69
$N\text{-}NO_2$	mg/L	8	<0.01	0.034	0.04
$N\text{-}NH_4$	mg/L	8	<0.04	0.10	0.17
$P\text{-}PO_4$	mg/L	10	0.08	0.14	0.16
Cl	mg/L	8	18	22	32
F	mg/L	8	<0.1	<0.1	0.34
As	mg/L	10	<0.0001	<0.002	<0.005
Fe	mg/L	8	0.48	0.6	1.68
E. Coli	MNP/100 mL	10	nd	195	44800
Coliforms	MNP/100 mL	10	240	7500	24000

nd = not detected

5.2. Treated surface water at HAWASUCO WTP Nga Bay

Table 5 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 for temperature, pH, turbidity, residual chlorine, color, and *E. coli* bacteria (Annex 3). Some variations are seen for most parameters. All measurements are far below the Vietnamese limitations for produced drinking water.

The samples of treated water before and after chlorination taken on 27 October 2023 are presented in Table 6 (macroparameters, microbiological parameters and metals only) and Annex 4. 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 if this treated water were used for infiltration. An important indicator for the clogging risk is TOC, which has low values of 2–3 mg/L.

Table 5: Variations of water quality parameter for treated surface water (Source: HAWASUCO)

criteria	Unit	DW-QCVN 01-1-2018	number	Min	Median	Max
turbidity	NTU	2	17	0.13	0.23	0.73
pH		6.0–8.5	17	6.7	7.0	7.9
Temp	°C		15	18.8	25.0	29.8
Smell and Taste		none	17	none	none	none
Residual chlorine	mg/L	0.2–1.0	17	0.27	0.66	0.82
Color	TCU	15	17	<3.5	<3.5	5.43
Coliforms	CFU/100 mL	<3	17	0	0	0
E. Coli	CFU/100 mL	<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	0.7	1.00
$N\text{-}NO_2$	mg/L	0.05	4	0.004	0.004	0.006
$N\text{-}NH_4$	mg/L	0.3	4	<0.0095	0.02	0.07
TDS	mg/L	1000	4	69	87	160
F	mg/L	1.5	3	0.05	0.19	0.46
SO_4	mg/L	250	4	2.0	12.0	43.0
Al	mg/L	0.2	3	<0.004	0.017	0.043
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	0.020	0.020
Fe (total)	mg/L	0.3	4	<0.01	0.015	0.04
Mn	mg/L	0.1	4	0.006	0.009	0.012
Ni	mg/L	0.07	3	0.000	0.002	0.008
Zn	mg/L	2	4	0.040	0.120	0.120
Permanganate index	mg/L	2	3	0.30	0.60	1.00
Total hardness	mg/L	300	3	50	60	130
Cyanide (CN)	mg/L	0.05	1		0.008	

nd = not detected

Table 6: 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
Color		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

Parameters	**Unit**	**DW-QCVN 01-1-2018**	**SW (before disinfection)**	**SW (after disinfection)**
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 analysed and presented in Table 7. Three by-products were found in rather low concentrations, much lower than the Vietnamese limits for drinking water.

Table 7: 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

5.3. Groundwater quality aquifer qp_1

Samples from the back-up wells on 27 October 2023 are the only relevant available data of the native groundwater quality in the target aquifer. Full results are given in Annex 3: Treated surface water quality data collected from HAWASUCO

	turbidity	**pH**	**T**	**Smell and Taste**	**Residual chlorine**	**Colour**	**Coliforms**	***E. coli***	**S^{2-}**	**$N\text{-}NO_3$**	**$N\text{-}NO_2$**	**$N\text{-}NH_4$**	**Salinity**

Unit	NTU		°C		mg/l	TCU	CFU/100ml		mg/l				ppt
10.06.23	0.32	7.35		none	0.27	4.83	0	0	ND	1	0.005	0.07	0.1
22.01.22	0.23	7.25	18.8	none	0.82	<3.5	0	0	ND				
26.02.22	0.13	6.88	21.3	none	0.69	<3.5	0	0	ND				
13.03.22	0.15	6.92	24.3	none	0.71	<3.5	0	0	ND				
16.04.22	0.19	6.91	22.4	none	0.68	<3.5	0	0	ND				
16.05.22	0.40	6.93	23.3	none	0.63	<3.5	0	0	ND				
16.06.22	0.33	7.10	25.3	none	0.55	<3.5	0	0	ND				
12.07.22	0.40	6.93	25.0	none	0.63	5.43	0	0	ND				
10.08.22	0.28	6.65	26.7	none	0.53	3.94	0	0	ND				
10.09.22	0.46	6.75	21.1	none	0.70	3.94	0	0	ND	0.6	0.006	<0.01	0.01
01.10.22	0.23	6.97	25.3	none	0.76	<3.5	0	0					
13.11.22	0.14	7.13	24.3	none	0.57	<3.5	0	0					
10.12.22	0.16	6.98		none	0.66	<3.5	0	0	0.004	0.5	0.004	0.02	0
07.03.21	0.72	7.12	26.0	none	0.73	<3.5	0	0					
13.10.21	0.20	6.96	25.6	none	0.54	<3.5	0	0					
25.12.20	0.35	7.15	26.7	none	0.56	<3.5	0	0	ND	0.8	0.004	0.02	ND
07.06.20	0.73	7.90	29.8	none	0.71	3.0	0	0					

	F	**SO_4**	**TDS**	**Al**	**Cr^{6+}**	**Cu**	**Fe_{tot}**	**Mn**	**Ni**	**Zn**	**Permanganate**	**total hardness**	**cyanite**
Unit	mg/l												
10.06.23	0.46	43	160	<0.004	0.012	0.02	0.01	0.012	0.000	0.12	0.6	130	
22.01.22													
26.02.22													
13.03.22													
16.04.22													
16.05.22													
16.06.22													
12.07.22													
10.08.22													
10.09.22		14	97	0.043	0.008	0.02	0.02	0.006	0.001	0.12			
01.10.22													
13.11.22													
10.12.22	0.05	9.96	69	0.017	0.011	0.02	<0.01	0.008	0.002	0.12	0.3	60	
07.03.21													
13.10.21													
25.12.20	0.19	2.0	76		0.008	0.01	0.04	0.009	0.008	0.04	1	50	0.008
07.06.20													

ND: not detected

Annex 4.

Table 8 gives the results for the macro-parameters in back-up 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 concentrations (14 and 20 mg/L respectively) are 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 place over very long periods of time. The concentrations of trace metals are favorable, with low concentrations of arsenic and barium, and absence of lead, cadmium, chromium, copper, nickel, zinc and selenium.

Table 8: 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
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

Parameters	**Unit**	**GW-QCVN 09-MT:2023**	**G1 (West)**	**G2 (East)**
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

Organic micropollutants were not found with the applied analytical methods for organochloropesticides, herbicides, carbamates, atrazines and triazole pesticides. It must be noted 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 9) 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. The effect of oxidation should also be visible in the values of Fe^{2+} and Fe^{3+}, but unfortunately for G1 and G2 only Fe was reported and comparison is therefore not possible. As treated water is to be infiltrated in these reservoirs, these concentrations are not considered a problem, especially since levels are not extremely high and water will be treated after extraction.

Groundwater quality data from the cluster of Q607 (Table 9) shows that at this location, all aquifers are fresh (<1500 mg/L TDS), with Pleistocene aquifers (starting by qp) around 600 mg/L TDS and higher TDS (928–1434 mg/L) for the Pliocene and Miocene aquifers (starting by n). The latter also have elevated sodium concentrations, but only the n_1^3 aquifer exceeds the groundwater guideline concentrations for chloride.

Table 9: 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 guidelines.

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-NH_4	**1.79**	**1.60**	**1.31**	0.11	0.14	0.22	1.00	0.30
N-NO_2	0.51	0.56	0.55	0.005	0.002	0.005	1.00	0.05
N-NO_3	0.23	0.17	0.58	0.27	0.27	0.40	15.00	2.00
P-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

6. Evaluation of water quality data

6.1. 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. If the standards applicable for MAR projects in other countries around the world are considered, no water quality problems are to be expected.

6.2. Operational risks (clogging)

Prevention of clogging risks is an important goal of the ASR pilot. Clogging may 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. This way, the transition zone between infiltrate and native groundwater will be established at a secure distance from the filter. The background groundwater flow rate should also be considered. If background flow causes serious displacement of the injected volume during a ASR cycle, then a greater volume for 'over-infiltration' is needed. The flow rate could be estimated by exact groundwater level measurement in the neighborhood. This is not easily done however as suitable monitoring filters are scarce. Another option is to use direct flow sensors in the ASR-monitoring well.

Microbiological clogging may 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 may 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.

6.3. 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, the presence of pesticides in the treated surface water is likely at lower concentrations, based on the scarce scientific literature. Pesticides form a very broad group of compounds, differing in chemical behavior and required treatment. Removal is also difficult because of the low concentrations at which the pesticides are present and the even lower target concentrations. Therefore, it is likely that not all of them will be removed by the existing drinking water treatment in Nga Bay to sufficiently low concentrations, neither before recharge nor after recovery.

In addition, compounds of emerging concern can pose a risk of contamination of the aquifer, but no data is available. From this perspective, it is important to monitor and control the infiltrated and recovered volumes, to avoid unwished spreading of the infiltrated water.

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

6.4. Risks of deteriorating water quality of stored water

Risks of deteriorating water quality during storage cannot be excluded. The pilot itself will provide more insights in these risks. Risks of metal mobilization (e.g. Mn, Cr and As) exist, although concentrations in the native groundwater seem rather low. In addition, risks of microbiological growth must be assessed by careful monitoring during the pilot. At the ambient temperature 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 (see Report No 1, Steinel et al., 2023) do show presence of saline water bodies in the shallow aquifers at QT5 (about 1 km from the pilot site).

7. Recommended monitoring scheme

In the preceding text, we have shown that based on the present data, it is expected that risks of contamination or clogging are limited. Still, it is important to monitor the infiltration pilot well. This is especially important as the surface water quality is expected to vary over time, e.g. due to seasonal effects. In addition, hydrogeochemical reactions in the groundwater system might change over time and are not exactly known beforehand. Finally, water quality data on infiltrated and produced water can give information on the processes occurring during infiltration, storage and recovery. 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, and TOC;
  - Trace metals: Al, As, Ba, Ni, Zn;
  - No microbiology (i.e. *E. Coli/Enterococci, Streptococci faecal*);
  - No total phenols;
  - No pesticides;
  - No volatiles.

Table 10 summarizes the proposed set of parameters to analyze. 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.

During the first water quality assessment on Oct 27, 2023, the Quatest3 laboratory from Ho Chi Minh City was used. Another option would be CASE lab in Can Tho. However, some parameters like AOC would not be available with either lab, hence these were not included in the table.

A number of parameters (pH, turbidity, DO, temperature, EC, Eh, color, Fe, Mn, Zn, NH_4, NO_3, NO_2) could also be measured by HAWASUCO either in the field or in their lab in Vi Thanh. Some parameters are sensitive for changes, e.g. in redox potential, and should be determined as much as possible in situ under undisturbed conditions (pH, DO, temperature, Eh), or using the right procedures regarding storage and fixation (Fe, Mn, Zn, NH_4, NO_3, NO_2).

Table 10: 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

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9. Annexes

Annex 1 Summary of international water quality threshold values relevant for ASR

In addition to parameters listed in Table 1, the following parameters are listed in diverse regulations:

Threshold values from a range of different regulations for inorganic parameters (VN GW: QCVN 09-MT:2023/BTNMT (MONRE 2023), VN DW: QCVN 01-1:2018/BYT (MoH 2018), USA DW: National primary (and secondary in italics) drinking water regulations (USEPA 2009); Germany GrwV: Groundwater Ordinance (GrwV) (Bundesministeriums der Justiz 2010), Germany GFS: Insignificance thresholds ("Geringfügigkeitsschwellenwerte" (LAWA 2016)), Germany TrwV: Drinking water Ordinance (Bundesministeriums der Justiz 2023), Netherlands: IB = Infiltratiebesluit bodembescherming (Ministry of Infrastructure and Waterworks 2009)

Parameters	**Unit**	**VN GW**	**VN DW**	**USA DW**	**DE GW**	**DE GFS**	**DE DW**	**NL IB**
Coliforms	CFU/100 mL	3	3				nd	
Escherichia coli		nd	1	nd				
Enterococci							nd	
Staphylococcus aureus			1					
Pseudomonas aeruginosa			1				nd	
Cryptosporidium				nd				
faecal coliforms				nd				
Giardia lambia				nd				
Legionella				nd			100	
Total Coliforms				5%				
enteric viruses				nd				
Clostridium perfringens							nd	
Total Phenol	µg/L	1	1			8		
Mineral oil	µg/L							200
Pesticide residues incl. metabolites, total	µg/L				0,5	0,5		0,5
Pesticide residues incl. metabolites, individually	µg/L				0,1	0,1		
PFAS-20, total	µg/L						0,1	
PFAS-4, total	µg/L						0,02	
Organochlorine pesticide residues	µg/L							0,1
Aldrin	µg/L	0,1				0,01		0,05
Dieldrin	µg/L	0,1				0,01		0,05
Heptachlor	µg/L	1		0,4		0,03		0,05
Heptachlor epoxide	µg/L			0,2		0,03		0,05
Hexachlorobenzene	µg/L			1		0,01		0,05
Methoxychlor	µg/L			40				0,05
4,4'-DDD	µg/L							0,05
4,4'-DDE	µg/L							0,05
4,4'-DDT	µg/L	1	1					0,05
α-endosulfan	µg/L					0,005		0,05
β-endosulfan	µg/L							0,05
Endrin	µg/L			2		0,01		0,05
Endosulfan-sulfate	µg/L							0,05
α-HCB	µg/L							0,05
β-HCB	µg/L							0,05
γ-HCH	µg/L							0,05
δ-HCH	µg/L							0,05
Herbicide residues								
2,4,5-T	µg/L			50				
2,4-D	µg/L		30	70				0,1
2,4-DB	µg/L		90					
MCPA	µg/L		2					0,1
MCPP (Mecopro)	µg/L		10					
2,4,5-TP (Fenopro)	µg/L		9					
Bentazone	µg/L							0,1

Parameters	Unit	VN GW	VN DW	USA DW	DE GW	DE GFS	DE DW	NL IB
Carbamate pesticide residues								
Oxamyl	µg/L			200				
Aldicarb	µg/L		10					
Carbofuran	µg/L		5	40				
Triazole pesticide residues:	µg/L					0,03		
Cyanazines	µg/L		0,6					
Hydroxyatrazine	µg/L		200					
Atrazine and chloro-s-triazine derivatives/pesticides residues:	µg/L		100					
Atrazine	µg/L			3				0,1
Dichloromethane	µg/L		20	5				
1,1,1-trichloroethane	µg/L		2000	200				
Carbontetrachloride	µg/L		2	5				
1,2-dichloroethene	µg/L		50					
Tetrachloroethene	µg/L		40	10		10		0,5
Trichloroethene	µg/L		20					0,5
Vinyl chloride	µg/L		0,3	2		0,5	0,5	
Benzene	µg/L	15	10	5		1	1	
Toluene	µg/L	1000	700	1000				
Xylene	µg/L	750	500	10000				
Ethylbenzene	µg/L	450	300	700				
Styrene	µg/L		20	100				
1,2-Dichloroethane	µg/L		30	5		3	3	
Acrylamide	µg/L		0,5				0,1	
Alachlor	µg/L		20	2				
Chlorpyrifos	µg/L		30					
Chlordane	µg/L		0,2	2		0,003		
Chlorotoluron	µg/L		30					0,1
Dichloprop	µg/L		100					
Isoproturon	µg/L		9					0,1
Methoxychlor	µg/L		20					
Molinate	µg/L		6					
Pendimetalin	µg/L		20					
Permethrin	µg/L		20					
Propanil	µg/L		20					
Simazine	µg/L		2	4				0,1
Trifuralin	µg/L		20					
2,4,6-Trichlorophenol	µg/L		200					0,1
Dibromoacetonitrile	µg/L		70					
Dichloroacetonitrile	µg/L		20					
Dichloroacetic acid	µg/L		50					
Formaldehyde	µg/L		900					
Monochloramine	µg/L		3000	4000				
Monochloroacetic acid	µg/L		20					
Trichloroacetic acid	µg/L		200					
Trichloroaxetonitril	µg/L		1					
Lindane	µg/L	0,02		0,2				
Diazinon	µg/L	20						
Parathion	µg/L	60				0,025		0,1
Trichloroethylene	µg/L	30		5				
Tetrachloroethylene PCE	µg/L	10		5				
1,1,1- trichloroethylene	µg/L	150		5				
PAHs total	µg/L					0,2	0,1	
Benzo(a)pyrene (PAHs)	µg/L			0,2		0,01	0,01	
Chlorobenzene, total	µg/L			100		1		
Dalapon	µg/L			200				
o-Dichlorobenzene	µg/L			600				
p-Dichlorobenzene	µg/L			75				
1,1-Dichloroethylene	µg/L			7				
cis 1,2-Dichloroethylene	µg/L			70				
trans 1,2-Dichloroethylene	µg/L			100				
Di(2-ethylhexyl)adipate	µg/L			400				
Di(2-ethylhexyl)phthalate	µg/L			6				

Parameters	**Unit**	**VN GW**	**VN DW**	**USA DW**	**DE GW**	**DE GFS**	**DE DW**	**NL IB**
Dinoseb	µg/L			7				0,1
2,3,7,8-TCDD (dioxin)	**pg/L**			0,03				
Diquat	µg/L			20				
Endothall	µg/L			100				
Ethylene dibromide	µg/L			0,05				
Glyphosate	µg/L			700				
Haloacetic acids (HAA-5)	µg/L			60			60	
Hexachlorocaclopentadiene	µg/L			50				
Pentachlorophenol	µg/L			1		0,1		0,1
Picloram	µg/L			500				
Polychlorinated biphenyls (PCBs) total	µg/L			0,5		0,01		
Total Trihalomethanes (TTHMs)	µg/L			80			50	2
Toxaphene	µg/L			3				
1,1,2-Trichloroethane	µg/L			5				
Anthracene	µg/L					0,1		0,02
Sum Benzo[b]fluoranthene and Benzo[k]fluoranthene	µg/L					0,03		0,1
Sum Benzo[ghi])perylene and Indeno[123-cd]pyrene	µg/L					0,002		0,1
Dibenz[a,h]anthracene	µg/L					0,01		0,1
Fluoranthene	µg/L					0,1		0,1
Naphthaline and Methylnaphthaline, total	µg/L					2		0,1
1,2-Dibromoethane	µg/L					0,02		
Trichloromethane	µg/L					2,5		
Ether oxygenates (e.g. MTBE, ETBE and TAME), total	µg/L							
Nonylphenol	µg/L					0,3		
total Chlorophenoles	µg/L					1		
Pentachlorobenzene	µg/L					0,007		
Azinphos-methyl	µg/L					0,01		
Dichlorovos	**pg/L**					0,6		100
Disulfoton	µg/L					0,004		
Diuron	µg/L					0,1		
Etrimfos	µg/L					0,004		
Fenitrothion	µg/L					0,009		
Fenthion	µg/L					0,004		
Hexazinon	µg/L					0,07		
Malathion	µg/L					0,02		
Mevinphos	**pg/L**					0,2		100
Phoxim	µg/L					0,008		
Trichlorofon	µg/L					0,002		
Trifluralin	µg/L					0,03		
Bisphenol A	µg/L						2,5	
Adsorbable organic halides	µg/L							30
Phenantrene	µg/L							0,02
Chrysene	µg/L							0,02
Disinfection by-products								
Monochlorobenzen	µg/L		300					
1,2-dichlorobenzen	µg/L		1000					
Trichlorobenzen	µg/L		20			0,4		
1,2,4-trichlorobenzene	µg/L			70				
Hexachloro butadien	µg/L		0,6					
1,2-dibromo-3 chloropropan	µg/L		1	0,2				
1,2-dichloropropan	µg/L		40	5				
1,3-dichloropropen	µg/L		20					
Bromoform	µg/L		100					
Dibromochloromethane	µg/L		100					
Bromodichloromethane	µg/L		60					
Chloroform	µg/L		300					
Bromate (BrO_3^-)	µg/L		10					
Chlorate (ClO_3^-)	µg/L						70	
Chlorite (ClO_2^-)	µg/L			1000			200	

Parameters	Unit	VN GW	VN DW	USA DW	DE GW	DE GFS	DE DW	NL IB
Epichlorohydrin	µg/L		0,4	TT		0,1	0,1	
Chlorine (as Cl2)	mg/L			4				
Chloramines (as Cl2)	mg/L			4				
Chlorine dioxide (as Cl2)	mg/L			8				
Other parameter								
Total radioactive activity α	Bq/L	0,1						
	pCi/L			15				
Total radioactive activity β	Bq/L	1						
	millirems /yr			4				
Radium 226	pCi/L			5				
Radon-222	Bq/L						100	
Uranium	µg/L			30			10	
Tritium	Bq/L						100	
asbestos	Million fibres/L			7				

Annex 2: Raw surface water quality data collected from HAWASUCO

	pH	BOD_5	COD	TSS	N-NO3	N-NO2	N-NH4	P-PO4	Cl	F	Fe	As	*E. Coli*	coliform
Unit	-	mg/L										µg/L	MNP/100ml	
12.2022	6.94	7	13	30	0.39	<0.01	0.10	0.08	18	<0.1	0.93	<2	KPH	240
08.2022	6.86	7	16	48	0.34	0.034	0.16	0.16	32	<0.1	0.48	<1	4800	2400
06.2022	7.47	10	18	42	0.4	0.033	0.08	0.16	24	<0.1	0.50	<0.1	KPH	4300
04.2022	7.19	11	16	60	0.4	0.038	0.16	0.14	28	<0.1	0.50	<2	15	7500
12.2021	6.98	14	20	50	0.45	0.040	0.13	0.16	18	0.34	0.60	<2	93	9300
10.2021	6.30	13	22	60	0.48	0.035	0.09	0.14	18	<0.1	0.50	<2	240	9300
06.2021	7.31	7	12	46	0.18	0.028	<0.04	0.14	30	<0.1	0.65	<2	KPH	<3
03.2021	7.30	12	19	58	0.44	0.030	0.10	0.12	20	<0.1	0.60	<2	480	9300
12.2020		10	19					0.14				<2	930	24000
09.2020		7	12					0.12				<5	1500	7500
06.2020	7.12	12	19	44	0.69	0.037	<0.04	0.14	18	<0.1	0.59	<5	750	4300
10.2019	7.09	10	17	26	0.23	0.030	0.17	0.11	25	<0.1	1.68	<5	150	9300

Annex 3: Treated surface water quality data collected from HAWASUCO

	turbidity	pH	T	Smell and Taste	Residual chlorine	Colour	Coliforms	*E. coli*	S^{2-}	$N\text{-}NO_3$	$N\text{-}NO_2$	$N\text{-}NH_4$	Salinity
Unit	NTU		°C		mg/l	TCU	CFU/100ml		mg/l				ppt
10.06.23	0.32	7.35		none	0.27	4.83	0	0	ND	1	0.005	0.07	0.1
22.01.22	0.23	7.25	18.8	none	0.82	<3.5	0	0	ND				
26.02.22	0.13	6.88	21.3	none	0.69	<3.5	0	0	ND				
13.03.22	0.15	6.92	24.3	none	0.71	<3.5	0	0	ND				
16.04.22	0.19	6.91	22.4	none	0.68	<3.5	0	0	ND				
16.05.22	0.40	6.93	23.3	none	0.63	<3.5	0	0	ND				
16.06.22	0.33	7.10	25.3	none	0.55	<3.5	0	0	ND				
12.07.22	0.40	6.93	25.0	none	0.63	5.43	0	0	ND				
10.08.22	0.28	6.65	26.7	none	0.53	3.94	0	0	ND				
10.09.22	0.46	6.75	21.1	none	0.70	3.94	0	0	ND	0.6	0.006	<0.01	0.01
01.10.22	0.23	6.97	25.3	none	0.76	<3.5	0	0					
13.11.22	0.14	7.13	24.3	none	0.57	<3.5	0	0					
10.12.22	0.16	6.98		none	0.66	<3.5	0	0	0.004	0.5	0.004	0.02	0
07.03.21	0.72	7.12	26.0	none	0.73	<3.5	0	0					
13.10.21	0.20	6.96	25.6	none	0.54	<3.5	0	0					
25.12.20	0.35	7.15	26.7	none	0.56	<3.5	0	0	ND	0.8	0.004	0.02	ND
07.06.20	0.73	7.90	29.8	none	0.71	3.0	0	0					

	F	SO_4	TDS	Al	Cr^{6+}	Cu	Fe_{tot}	Mn	Ni	Zn	Permanganate	total hardness	cyanite
Unit	mg/l												
10.06.23	0.46	43	160	<0.004	0.012	0.02	0.01	0.012	0.000	0.12	0.6	130	
22.01.22													
26.02.22													
13.03.22													
16.04.22													
16.05.22													
16.06.22													
12.07.22													
10.08.22													
10.09.22		14	97	0.043	0.008	0.02	0.02	0.006	0.001	0.12			
01.10.22													
13.11.22													
10.12.22	0.05	9.96	69	0.017	0.011	0.02	<0.01	0.008	0.002	0.12	0.3	60	
07.03.21													
13.10.21													
25.12.20	0.19	2.0	76		0.008	0.01	0.04	0.009	0.008	0.04	1	50	0.008
07.06.20													

ND: not detected

Annex 4: Water quality data collected on 27.10.2023

In addition to results presented in Table 6, Table 7 and Table 8, the following results were measured (µg/L).

	unit	G1 (West)	G2 (East)	SW (before disinfection)	SW (after disinfection)
	Organochlorine pesticide residues				
Aldrin	µg/L	< 0.05	< 0.05	< 0.05	< 0.05
Dieldrin	µg/L	< 0.05	< 0.05	< 0.05	< 0.05
Heptachlor	µg/L	< 0.05	< 0.05	< 0.05	< 0.05
Heptachlor epoxide	µg/L	< 0.05	< 0.05	< 0.05	< 0.05
Hexachlorbenzen	µg/L	< 0.05	< 0.05	< 0.05	< 0.05
Methoxychlor	µg/L	< 0.05	< 0.05	< 0.05	< 0.05
4.4'-DDD	µg/L	< 0.05	< 0.05	< 0.05	< 0.05
4.4'-DDE	µg/L	< 0.05	< 0.05	< 0.05	< 0.05
4.4'-DDT	µg/L	< 0.05	< 0.05	< 0.05	< 0.05
α-endosulfan	µg/L	< 0.05	< 0.05	< 0.05	< 0.05
β-endosulfan	µg/L	< 0.05	< 0.05	< 0.05	< 0.05
Endrin	µg/L	< 0.05	< 0.05	< 0.05	< 0.05
Endosulfan-sulfate	µg/L	< 0.05	< 0.05	< 0.05	< 0.05
α-HCB	µg/L	< 0.05	< 0.05	< 0.05	< 0.05
β-HCB	µg/L	< 0.05	< 0.05	< 0.05	< 0.05
γ-HCH	µg/L	< 0.05	< 0.05	< 0.05	< 0.05
δ-HCH	µg/L	< 0.05	< 0.05	< 0.05	< 0.05
	Herbicide residues				
2.4.5-T	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
2.4-D	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
2.4-DB	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
2.4-DP	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
MCPA	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
MCPP (Mecopro)	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
2.4.5-TP (Fenopro)	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Bentazone	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Bentazone	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Fipronil	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
	Carbamate pesticide residues				
Oxamyl	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Methomyl	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Aldicarb	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Carbofuran	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Carbaryl	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Propurxur	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Isoprocarb	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Fenobucarb	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Methiocarb	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Imidacloprid	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Thiabendazole	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Cerbendazime	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Aldicarb sunfone	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Aldicarb sulfoxide	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
	Triazole pesticide residues:				
Hexaconazole	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Propiconazole	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Tebuconazole	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Fenbuconazole	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Difenconazole	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Penconazole	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Epiclohydrin	µg/L	-	-	-	< 0.15
Cyanazines	µg/L	< 0.25	< 0.25	< 0.25	< 0.25
Hydroxyatrazine	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Atrazine	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Desisopropyl atrazine	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Desethyl atrazine	µg/L	< 1.0	< 1.0	< 1.0	< 1.0
Desisopropyl desethyl atrazine	µg/L	< 1.0	< 1.0	< 1.0	< 10

	unit	G1 (West)	G2 (East)	SW (before disinfection)	SW (after disinfection)
	Volatiles				
Dichloromethane	µg/L	-	-	-	< 2.0
1.1.1-trichloroethane	µg/L	-	-	-	< 0.5
Carbontetrachloride	µg/L	-	-	-	< 0.5
1.2-dichloroethene	µg/L	-	-	-	< 0.5
Tetrachloroethene	µg/L	-	-	-	< 0.5
Vinyl Chloride	µg/L	-	-	-	< 0.1
Benzene	µg/L	-	-	-	< 0.5
Toluene	µg/L	-	-	-	< 0.5
m+p-xylene	µg/L	-	-	-	< 1.0
o-xylene	µg/L	-	-	-	< 0.5
Ethylbenzene	µg/L	-	-	-	< 0.5
Styrene	µg/L	-	-	-	< 0.5
Monochlorbenzene	µg/L	-	-	-	< 0.5
1.2-dichlorobenzene	µg/L	-	-	-	< 0.5
1.2.3-trichlorobenzene	µg/L	-	-	-	< 0.5
1.2.4-trichlorobenzene	µg/L	-	-	-	< 0.5
1.3.5-trichlorobenzene	µg/L	-	-	-	< 0.5
Hexachloro butadien	µg/L	-	-	-	< 0.25
1.2-dibromo-3 chloropropan	µg/L	-	-	-	< 0.5
1.2-dichloropropane	µg/L	-	-	-	< 0.5
1.3-dichloropropene	µg/L	-	-	-	< 1.0