WaterJPI project

SMARTControl

Smart framework for real-time monitoring and control of subsurface processes in managed aquifer recharge (MAR) applications

Deliverable D2.1

Matrix of risks and remediation measures

Risks and remediation measures at different stages of MAR site development

Authors

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MAR hazards		Human health risk at end-point	Environmental risk at end-point	
			Native groundwater	Irrigation
1.Pathogens		H	H	L
2.Inorganic chemicals	Electric conductivity	L	L	H
	pH	L	L	L
	Sodium	L	H	L
	Chloride	L	H	H
	Boron	L	L	L
	Bicarbonate	L	L	L
	Arsenic	L	H	L
	Fluoride	U	U	U
3. Salinity and sodicity		L	L	L

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Short summary

This report assessses the MAR-associated risks at six MAR sites from which are at different stages of development: three case studies at feasibility and pilot stage and three case studies at operational stage. The risk assessment study was conducted based on recommendations of international guidelines. The report may be used to assist in clarifying which actions or further investigations are required to reduce the uncertainty of risks and, if necessary, to implement remediation measures. In addition, this report intends to show how site-specific hazards have been assessed to varying degrees depending upon the level of risk assessed at each project development stage.

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ABSTRACT

The types and objectives to apply managed aquifer recharge (MAR) are manifold and so are the risks that can arise during the planning, implementation and operation of a MAR facility. In general, operational, regulatory, business, human health, and environmental risks can occur and should be identified already during the planning and implementation stage to apply preventive measures and secure the safe and realibale operation of a MAR facility.

This report represents risk assessment based on recommendations of international guidelines (Alcalde-Sanz and Gawlik, 2017; NRMMC-EPHC-NHMRC, 2008; WHO, 2009, 2011) at six MAR sites which are at different stages of development. Three case studies are at the feasibility or pilot stage: two ASR systems in João Pessoa and Recife, Brazil and one induced bank filtration site at the Beberibe River in Brazil, and three case studies at the operational stage: one SAT system in the Ezousa catchment in Cyprus, and two infiltration basin systems in Hyères, France (Aquarenova site) and Berlin-Spandau, Germany. The entry-level assessment according to the Australian guidelines (NRMMC-EPHC-NHMRC, 2009) has been conducted for the feasibility or pilot scale schemes For fully operational MAR schemes, in addition to the entry-level assessment, the degree of difficulty assessment and the maximal risk assessment were carried out.

At all stages of site development, risk assessment helps to identify and characterize potential hazards that may cause risks to human health and the environment. This report may be used to assist in clarifying which actions or further investigations are required to identify and reduce the uncertainty of risks and to implement remediation measures if necessary. In addition, this report intends to show how site-specific hazards have been assessed to varying degrees depending upon the level of risk assessed at each project development stage.

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1. INTRODUCTION TO RISKS AND REMEDIATION MEASURES

The risks that can arise during the implementation and operation of a MAR facility are as diverse as the types and objectives to apply MAR. General risk types include the operational, regulatory, business, human health, and environmental risks (Nandha et al., 2015). Specific risks include e.g. the pathogen removal during the subsurface passage, clogging of the infiltration surface, geochemical reactions in the aquifer or the fate of trace-organic compounds. Each of this risks can lead, depending on the extent, to the application of remediation measures or even to the shut-down of a MAR facility. The identification of risks already during the planning and implementation stage is therefore crucial to implement preventive measures and to secure the safe and reliable operation of a MAR facility.

Risk assessment describes a process to assess the presence and severity of a risk while risk management also incorporates the prioritisation and appropriate strategies for risk reduction (Nandha et al., 2015).

Various guidelines have been developed amongst others to provide a scientific basis to guide the development of MAR projects, to minimize the time and effort for risk assessment and to make risk management as transparent as possible (NRMMC-EPHC-NHMRC, 2009). Risk management frameworks include e.g. the WHO Water Safety Plan (Bartram et al., 2009), the Austalian guidelines for MAR (NRMMC-EPHC-NHMRC, 2009), and the American guidelines for health and environmental risk management (EPA, 2009). Especially the Australian guidelines have been widely applied, also outside of Australia such as in Spain and Germany (Seis and Sprenger, 2015). This risk assessment presented here is based on recommendations of international guidelines (Alcalde-Sanz and Gawlik, 2017; NRMMC-EPHC-NHMRC, 2008; WHO, 2009, 2011).

Table 1. Overview of MAR projects and stages of development.

Name of MAR project	Source water	MAR type	End-use/ Objective	Project stage	Operational scale of recharge (Mm^3)
João Pessoa, Brazil	Rain water	ASR	Flood mitigation	Feasibility/ pilot scale	-
Landelino Rocha school, Brazil	Rain water	ASR	Flood mitigation	Feasibility/ pilot scale	-
Beberibe River, Brazil	River water	IBF	Drinking water	Feasibility/ pilot scale	-
Ezousa catchment, Cyprus	Reclaimed water	SAT	Irrigation	Operational scale	3-4
Aquarenova, France	River water	IB	Seawater mitigation	Operational scale	0.65*
Berlin-Spandau, Germany	River water	IB	Drinking water	Operational scale	20-25

*ASR = aquifer storage and recovery; IBF = induced bank filtration; SAT = soil aquifer treatment; IB = infiltration basins. *operates from November to April only*

MAR sites presented here are in different stages of development from feasibility/pilot scale investigations to operational scale (Table 1). For the feasibility or pilot scale, the entry-level assessment according to (NRMMC-EPHC-NHMRC, 2009) has been conducted. For operational MAR schemes, in addition to the entry-level assessment, the degree of difficulty assessment and the maximal risk assessment were carried out. At all stages of site development, risk assessment helps to identify and characterize potential hazards that may cause risks to human health and the environment.

Each MAR site underwent an entry-level assessment based on the Australian Guidelines (NRMMC-EPHC-NHMRC, 2009). The entry-level assessment consists of two checklists for assessing the viability and the degree of difficulty of the MAR project.

2. TOWARDS USING RAINWATER FOR AQUIFER STORAGE AND RECOVERY AT JOÃO PESSOA, BRAZIL

2.1 DESCRIPTION OF CASE STUDY

The João Pessoa case study is currently implemented using an Aquifer and Storage (AS) approach, collecting rainwater from the roof of the Hydraulics laboratory at the Federal University of Paraíba (UFPB). This is one of the first pilot-scale sites to be implemented in the region, which has a high population density and is prone to urban floods causing high damage. The MAR scheme intends to divert the runoff destined for the conventional drainage system into the aquifer (Figure 1, Table 2). This study aims to assess the feasibility of the use of rainwater as a water source for aquifer recharge for urban flood mitigation. Recovery of recharged water is not planned at this stage of development.

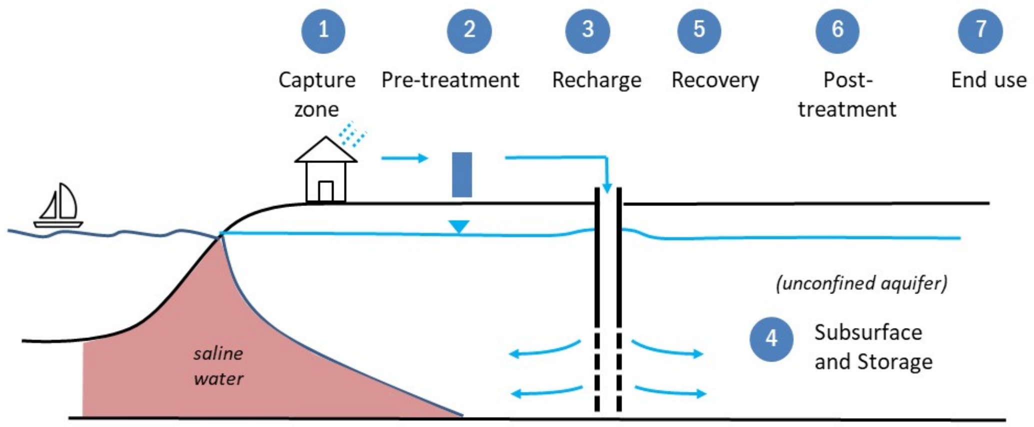

Figure 1. Schematic overview of MAR components at João Pessoa.

Table 2. Components of the João Pessoa MAR system.

#	MAR component	João Pessoa MAR site
1	Capture zone	Rooftop rainwater
2	Pre-treatment	Filter (to be defined)
3	Recharge	Well recharge by gravitation
4	Subsurface	Barreiras formation (unconfined aquifer)
5	Recovery	none
6	Post-treatment	none
7	End use	Non-potable by other users

The collected water will be injected by gravitational force into the unconfined aquifer, named Barreiras Formation (Furrier and Barbosa, 2016; Walter, 2018). Water tanks will be used as interim storage for the rainwater. Water volume, runoff and infiltration rates will be monitored. A simplified pre-treatment will also be installed in which rainwater will go through before it is introduced into the target aquifer. The system will be made up of two injection wells and six piezometers. However, during the project some piezometers can be used as injection wells to increase the amount of water to be injected. These eight wells will be dug distributed around the surroundings of the laboratory. At this stage, only two injection wells and two piezometers were under construction and had been concluded in May 2019 (Figure 2).

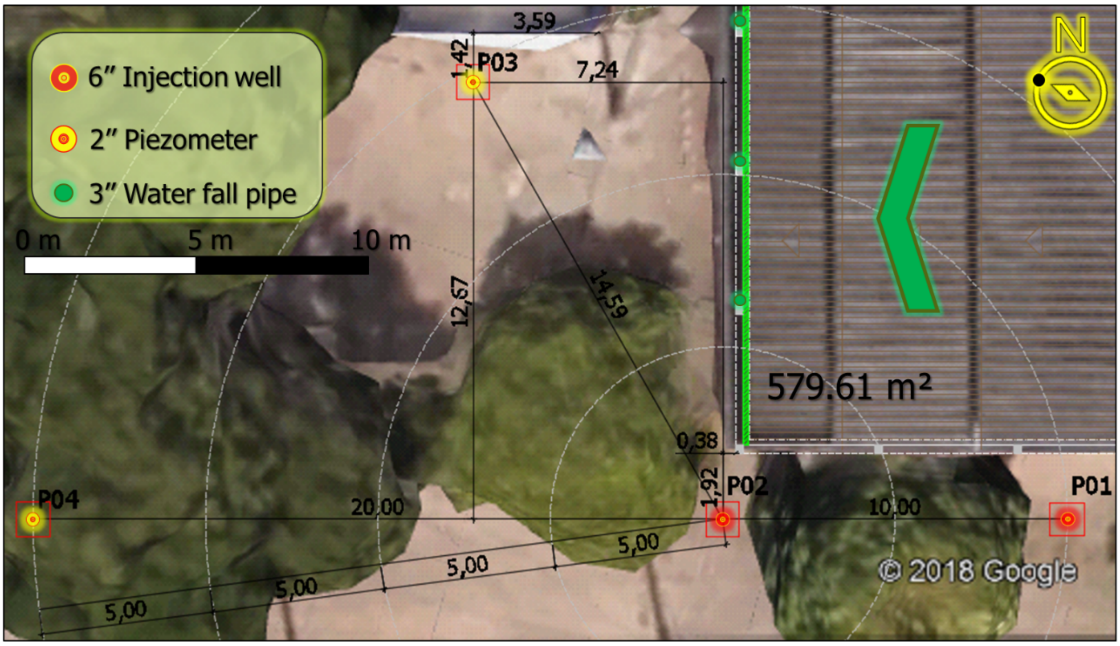

Figure 2. Conceptual design of the MAR scheme in the João Pessoa site.

Injection wells (P01 and P02) have the following dimensions: 6 inches diameter and 42 meters depth, with a 12-meter filter interval. Piezometers have similar dimensions, except for the diameter, which is 2 inches.

2.2 ENTRY-LEVEL ASSESSMENT

The following checklists (Table 3) intend to evaluate the apparent viability (Table 24) and the degree of difficulty (Table 4) of the MAR project.

Table 3. Entry-level assessment for João Pessoa case study.

#	Attribute	Answer and explanation
1.	Intended water use	
	Is there an ongoing local demand or clearly defined environmental benefit for recovered water that is compatible with local water management plans?	YES – environmental benefit is flood mitigation, no recovery planned at this stage, target aquifer mainly utilized for non-potable end-uses.
2.	Source water availability and right of access	
	Is adequate source water available, and is harvesting this volume compatible with catchment water management plans?	YES – Rainwater is abundant in the João Pessoa city (mean annual rainfall of about 2,145 mm with up to 70% rain from March to June). Rooftop catchment area of about 580 m², with up to 1,244 m³/year to be injected into the aquifer.
3.	Hydrogeological assessment	

#	Attribute	Answer and explanation
	Is there at least one aquifer at the proposed managed aquifer recharge site capable of storing additional water?	**YES** – Target aquifer is the unconfined Barreiras formation (alluv. sediments and sandstone, partially clay) with adequate storage capacity of about 30 m vadose zone.
	Is the project compatible with groundwater management plans?	**YES** – The objective of this MAR project (provision of flood mitigation environmental benefit) does not conflict with existing groundwater management plans.
4.	**Space for water capture and treatment**	
	Is there sufficient land available for capture and treatment of the water?	**YES** – The surroundings of the Hydraulics laboratory is an open space which guarantees enough space for the required treatment of the water. Usage of space and capture zone (rooftop) is authorized by UFPB.
5.	**Capability to design, construct and operate**	
	Is there a capability to design, construct and operate a MAR project?	**YES** – coordinated by Prof. Almeida from UFPB, monitoring and modelling by Laboratory of Water Resources and Environmental Engineering (LARHENA).

Entry-level answers positive allow proceeding to the degree of difficulty questionnaire.

Table 4. Degree of difficulty assessment for João Pessoa case study.

#	Attribute	Answer and explanation	Actions required?
1.	**Source water quality with respect to groundwater environmental values**		
	Does source water meet the water quality requirements for the environmental value of ambient groundwater?	**YES** – Rainwater meets Brazilian drinking water standards after simplified treatment; protection of aquatic ecosystems; primary contact recreation such as swimming, water skiing and diving; irrigation and non-potable uses such as park irrigation and car washing (Santana, 2012). The environmental values of ambient groundwater not clearly defined.	**NO** further actions required, definition of natural background values for target aquifer recommended.
2.	**Source water quality with respect to recovered water end-use environmental values**		
	Does source water meet the water quality requirements for the environmental values of the intended end uses of the water on recovery?	**YES** – Recovery not planned at this stage of development.	**NO.**
3.	**Source-water quality with respect to clogging**		
	Does source water have low quality; for example: total suspended solids (TSS) >10 mg/L; total organic carbon (TOC) >10 mg/L; total nitrogen >10 mg/L? And is the soil or aquifer free of macropores?	**YES** – likely to be low in nutrients. Suspended solids to be minimized. Aquifer free of macropores.	**YES** – Investigations regarding clogging is carried out; see section 0 for details.
4.	**Groundwater quality with respect to recovered water end-use environmental values**		
	Does ambient groundwater meet the water quality requirements for the environmental values of intended end uses of water on recovery?	**YES** – Since the objective of MAR scheme is flood mitigation and recovery is not planned, the question does not apply.	**NO.**

#	Attribute	Answer and explanation	Actions required?
5.	**Groundwater and drinking water quality**		
	Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?	**YES** – Target aquifer used for irrigation and other non-potable end-uses, minor drinking water end-use cannot be excluded.	**NO.**
6.	**Groundwater salinity and recovery efficiency**		
	Does the salinity of native groundwater exceed either of the following: (a) 10 000 mg/L (b) The salinity criterion for uses of recovered water?	**NO** – Data from several wells in the city show evidence of good groundwater quality, regarding salinity at least.	**NO.**
7.	**Reactions between source water and aquifer**		
	Are redox status, pH, temperature, nutrient status and ionic strength of groundwater similar to that of source water?	**NO** – Different water quality may lead to reactions.	**YES** – Investigations are required to evaluate geochemical reactions. The parameters examined in the quality analysis of water from P01 are not sufficient to evaluate this. Groundwater and rainwater quality parameters should be monitored on a regular basis for this evaluation.
8.	**Proximity of nearest existing groundwater users, connected ecosystems and property boundaries**		
	Are there other groundwater users, groundwater-connected ecosystems or a property boundary within 100–1000 m of the MAR site?	**NO** – There are no other groundwater users, since the site is located within the UFPB campus. No groundwater dependent ecosystems present.	**NO.**
9.	**Aquifer capacity and groundwater levels**		
	Is the aquifer confined and not artesian? Or is it unconfined, with a water table deeper than 4 m in rural areas or 8 m in urban areas?	**NO** – The unconfined aquifer has a water table of 30 m in the site, which is in the core of João Pessoa's urban area. Excessive groundwater mound height is not likely to occur, especially with the expected volume of water to be introduced into the aquifer.	**YES** – storage capacity is sufficient but recharge (and recovery) rates have to be assessed. See section 0 for details.
10.	**Protection of water quality in unconfined aquifers**		
	Is the aquifer unconfined, with an intended use of recovered water that includes drinking water supplies?	**NO** – Target aquifer is unconfined but drinking water not end-use of the MAR scheme	**NO.**
11.	**Fractured rock, karstic or reactive aquifers**		
	Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals?	**NO** – The aquifer is not composed of fractured rock or karstic media neither known to contain reactive minerals.	**NO.**
12.	**Similarity to successful projects**		
	Has another project in the same aquifer with similar source water been operating successfully for at least 12 months?	**NO** MAR projects in the target aquifer present. Even in Brazil, it is difficult to find similar projects.	**NO.**

#	Attribute	Answer and explanation	Actions required?
13.	Management capability		
	Does the proponent have experience with operating MAR sites with the same or higher degree of difficulty, or with water treatment or water supply operations involving a structured approach to water quality risk management?	**YES** – The Laboratory of Water Resources and Environmental Engineering (LARHENA) has large experience in hydrological monitoring, modeling and in hydrogeology. Prof. Almeida is the UFPB coordinator.	**NO.**
14.	Planning and related requirements		
	Does the proposed project require development approval? Is it in a built up area; built on public, flood-prone or steep land; or close to a property boundary? Does it contain open water storages or engineering structures; or is it likely to cause public health or safety issues (e.g. falling or drowning), nuisance from noise, dust, odour or insects (during construction or operation), or adverse environmental impacts (e.g. from waste products of treatment processes)?	**NO** – Well construction permits were given by the State Water Agency (AESA) and the Federal University of Paraíba (UFPB) has authorized the construction. Pilot scale investigation is not likely to cause public health or safety issues neither adverse environmental impacts.	**NO.**

2.3 SOURCE-WATER QUALITY WITH RESPECT TO CLOGGING

Quality analysis of rainwater regarding the referred parameters (TSS, TOC and total nitrogen) needs to be carried out. The clogging system will be designed considering the quantity of source water which can be properly stored in the aquifer with the minimum overflow possible. This analysis is already being carried out and is necessary to define the most appropriate strategy for clogging minimization, in terms of a simplified treatment of the source water.

2.4 AQUIFER CAPACITY AND GROUNDWATER LEVELS

The target unconfined aquifer is known for having water of good quality, which is mainly used for non-drinking purposes, such as car washing and park irrigation. But in some parts, people actually drink this water. Hence, the referred benefit does not dispute with the objectives of local water management plans. Regarding the water management in the region as a whole, the approach recommended by Walter (2018) is the definition of at least a MAR pilot plant in the urban area to activate water resources in order to meet irrigation water demand, with an installed capacity of 1.8 million cubic meters per month. But the water source would be the surface water from the closest stream and injection would be by pumping. From this recommendation, it is very unlikely that this MAR scheme can possibly get to recharge as much volume by just utilizing rainwater in order to provide for irrigation demand (which is of three-quarters of 717 million cubic meters per year, the accumulated total water demand in the metropolitan region of João Pessoa).

2.5 CONCLUSIONS

The João Pessoa AS(R) project was developed as a research project to assess small-scale AS(R) viability. Due to the small-scale nature of the project and high quality of source water, an entry-level assessment was found to be suitable for assessing the risks to human health and the environment at this stage of development.

Based on the assessment it is concluded that a low risk of groundwater pollution from the MAR site is expected. The risk of clogging would be high if no pre-treatment solution was applied and needs to be properly evaluated. Low risk of adverse impacts on ecosystems is likely and a low risk of waterlogging or excessive groundwater mound height is expected as well. Furthermore, a low risk of aquifer matrix dissolution is expected, since the aquifer is not karstic or composed by fractured rocks. However, uncertainties are present since the current project lacks validation and verification data from existing projects in the region, since this is a pioneering initiative in the city of João Pessoa. The main necessity shown in the entry-level assessment is the knowledge of groundwater quality characteristics, since it wasn't possible to properly respond about potential adverse aquifer reactions between source water and the target aquifer. The comparison between source water and native water parameters is necessary for that matter. Relevant groundwater quality data is inexistent on a spatial scale (Walter, 2018). However, water quality monitoring has started in order to make this comparison possible in the surroundings of the João Pessoa site.

No salinity intrusion is found where the experiment is installed, mainly due to the topographic gradient and the relative distance and height to the mean sea level. However, it is believed that some outputs of the João Pessoa case study can be used to discuss how the system can be used to prevent saline water intrusion.

3. TOWARDS USING RAINWATER FOR AQUIFER STORAGE AND RECOVERY AT LANDELINO ROCHA SCHOOL, BRAZIL

3.1 DESCRIPTION OF CASE STUDY

The study area is in the Metropolitan Region of Recife (RMR). The RMR is located on the north-eastern coast of Brazil in the state of Pernambuco and includes the city of Recife, capital of Pernambuco and 13 surrounding municipalities (Cabral et al., 2008). With a total area of 2,768 km², RMR has a population of around 4 million inhabitants (IBGE, 2018), with a concentration in neighbourhoods such as Boa Viagem and Pina (Cabral et al., 2008). The pilot site is situated in one of these densely populated neighbourhoods—in Pina—at a public school called Landelino Rocha, which is about 340 meters from the sea. The coordinates are: 8°05'35"S, 34°53'01"W (Figure 3a).

3.2 CHALLENGES

The RMR's public water supply by the water and sanitation company for the State of Pernambuco (COMPESA) is mainly based on surface water storage through dam reservoirs (to 3/4) and groundwater resources (to 1/4) (Montenegro et al., 2016) and appeared to be highly insufficient due to short-term sensitivity of surface waters to hydro-meteorological processes, lack of infrastructure investments and insufficient public groundwater pumping capacity (Cary et al., 2015). Public water supply rationing led to almost the entire population starting to buy bottled water for drinking and cooking purposes, to install illegal access to public network, and both commercial and residential buildings in richer areas started to drill their own private wells (Petelet-Giraud et al., 2018).

The resulted increase in drilling of private wells led to groundwater exploitation in the past 25 years, especially in the deep Cabo aquifer in the heavily populated neighbourhoods Boa Viagem and Pina (Petelet-Giraud et al., 2018). At some points a reduction in piezometric levels up to 90 m in 25 years could be determined (Petelet-Giraud et al., 2018). Reduced recharge rates and rising pumping rates associated with the construction of improperly sealed wells have additionally exacerbated salinization of the deep aquifers caused by downward fluxes from the upper unconfined aquifer susceptible to saltwater intrusion from streams and mangroves as well as chemical and bacterial pollution from urban drainage channels (Bertrand et al., 2016; Cary et al., 2015; Chatton et al., 2016).

In addition to water scarcity and negative impacts on fresh groundwater resources, RMR is exposed to frequent intense rain events and resulting flood problems. One reason accelerating flood problems in Recife is its lowland topography. 81 % of the urban constructions are situated less than 30 m from the shoreline and 5 m below ground level, which makes around 45 % of its coast highly vulnerable to floods (Costa et al., 2010). Climate change even reinforces this causing sea level rise and frequent heavy rain events. In addition, rapid and unplanned urbanization processes resulted in a decrease of infiltration capacity of water in the soil and drainage systems are vulnerable to tidal oscillations (Silva Junior et al., 2017). MAR and in particular ASR could provide a mitigating solution addressing the above challenges (Coelho et al., 2018; Zuurbier et al., 2014).

The production well of the school was closed long ago due to salinization of the aquifer. Since then, the school has been receiving water from the public water company (COMPESA) with an average consumption of 32 m³/month (COMPESA 2015/16). However, the public water utility COMPESA also suffers from a water shortage and is increasingly looking for alternative solutions. The monitoring program conducted at a multi-piezometer at the Landelino Rocha school showed mean electrical conductivity (EC) values of about 7400 µS/cm for the lower Cabo aquifer, indicating brackish conditions (Paiva et al., 2017). Moreover, Paiva et al. (2017) observed that the tide had an indirect impact on the aquifers and may cause saltwater intrusion.

3.3 GEOHYDROLOGICAL CLASSIFICATION

The area of RMR is a multi-layered sedimentary aquifer system located in the estuarine area of the Capibaribe River and includes smaller rivers such as the Beberibe, Tejipió, Jordão and Jiquiá. It includes also substantial mangrove ecosystem, an area which has developed due to the tide penetrating into the estuarine area. RMR has been geologically formed by rocks of the crystalline basement and meso-cenozoic sediments of the coastal sedimentary basins Paraíba and Pernambuco. Both these basins are separated by a transverse structure of the Pernambuco Lineament with an east-west direction near the UTM 9,105,000 South (Batista, 2015). The area of interest for this study is located in the Recife plain, south of the Pernambuco Lineament. The elevation of this plain is very low, from 1 to 10 m above sea level (Cary et al., 2015).

a)

b)

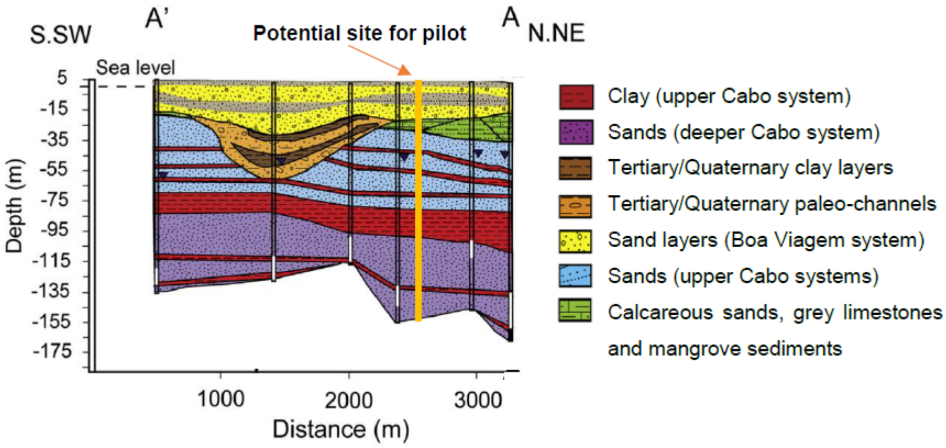

Figure 3. Photography (a), and lithological profile (Coelho et al. 2018) (b) of the project site.

3.4 DESCRIPTION OF PILOT MAR SCHEME

The pilot MAR scheme at the Landelino Rocha study site is currently under construction. At the moment (February 2020), it consists of a multiple partially penetrating well with two pipes (a 2" in diameter, PVC) with screens at different heights (133-141 m and 166-170 m) connected to the same aquifer, Lower Cabo. This setup makes it possible to recover the water at a heigher depth than it has been infiltrated. Figure 3a shows the campus of the school. In addition, another piezometer owned by the UFPE research team (2" in diameter) is available on the study site. This piezometer is intended to be one of the control points at which the success and impact of recharge tests conducted at the pilot plant can be measured. For more than two years, this piezometer is used to collect data through online sensors, which provide information about the tidal influence on the groundwater level and electrical conductivity of the different aquifer layers (Paiva et al., 2017).

Further elements of the pilot system, which are being planned, are: a rainwater harvesting system, a water tank, and a sand filter as a pre-treatment stage. A schematic overview of the entire pilot system is shown in Figure 4. Once the pilot system is complete, the rainwater will be collected on the school roof and then fed into a sand filter for pre-treatment. After removing the fine particles, the water will enter the water tank located next to the filter and is then injected by gravity into the Cabo aquifer via one well tube and can be recovered through the same or the second well tube.

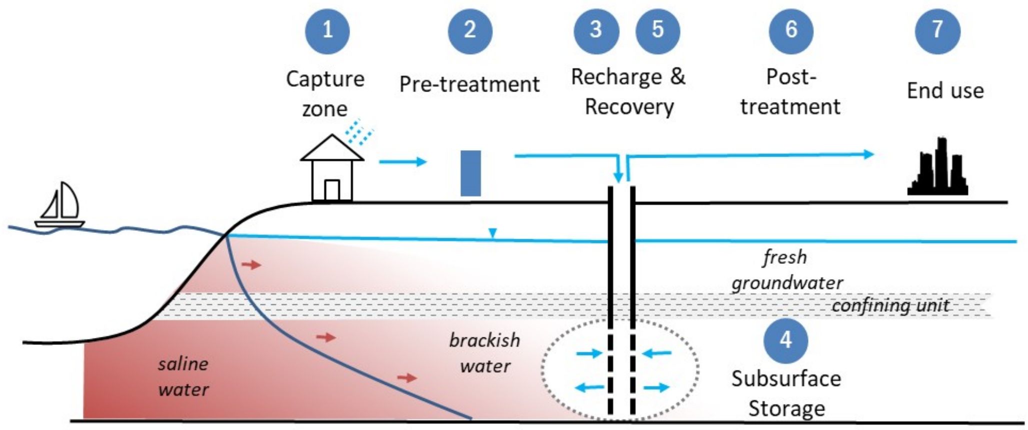

Figure 4. Schematic overview of MAR components at Landelino Rocha ASR Site.

The ASR pilot plant aims to show that MAR technology can be an effective solution for flood mitigation in RMR. Currently, heavy rainfalls especially in the wet season cause severe floods in Recife while the floodwater will flow afterwards unused into the sea. Furthermore, the protection and restoration of groundwater resources in highly vulnerable areas in Recife is also a goal of the pilot plant.

Table 5 details the components of the Landelino School system.

Table 5. Components of the Landelino School ASR system.

#	MAR component	Landelino Rocho ASR site
1	Capture zone	Rooftop rainwater
2	Pre-treatment	Sand Filter
3	Recharge	ASR well

#	MAR component	Landelino Rocho ASR site
4	Subsurface	Lower Cabo aquifer, sandstone
5	Recovery	ASR well (located in the same borehole as the recharge well with a screen at a higher level)
6	Post-treatment	NA
7	End use	NA

NA = not assessed at this stage, requires further investigations

The next two tables present a preliminary assessment exposing the existing information (Table 6) and a more detailed investigation of the risk involved in the MAR project (Table 7).

Table 6. Entry-level assessment for Landelino Rocha school ASR site.

#	Attribute	Answer and explanation
1.	**Intended water use**	
	Is there an ongoing local demand or clearly defined environmental benefit for recovered water that is compatible with local water management plans?	**YES** - Local water demand of Landelino Rocha school is 32 m^3/month; school well needed to be closed due to brackish groundwater (~ 7400 µS/cm). Therefore, the school is supplied by the public water utility which fights problems caused by increasing water shortage. Still, many surrounding houses abstract groundwater, putting groundwater resources increasingly under pressure. Aquifer recharge through rainwater infiltration into the subsurface would thus have two advantages: the use of a yet unused water resource and the recovery of currently used water reserviors such as dams and aquifers. The implementation of MAR sites is supported by the local legal framework (Art. 46 Decree 20.423/98 Art 46 §1). Art. 46 of Decree 20.423/98 obliges the local water and climate agency (APAC).
2.	**Source water availability and right of access**	
	Is adequate source water available, and is harvesting this volume compatible with catchment water management plans?	**YES** - There is precipitation all over the year (mean annual precipitation: 1450 mm (1961-1990) (Costa Sobrinho et al. 2015), especially during the rainy season between March and July (>250 mm/month). Pilot scale investigation do not conflict with catchment scale management plans.
3.	**Hydrogeological assessment**	
	Is there at least one aquifer at the proposed managed aquifer recharge site capable of storing additional water?	**YES** - The Cabo aquifer, $K = 5x10^{-6}$ m/s, $Ss = 1x10^{-4}$ - The hydraulic conductivity of the Cabo aquifer may be a limiting factor, as the value is relatively low compared to values recommended in literature. A study conducted by Silva (2004) found a mean recharge rate of 2m^3/h, that confirm the feasibility of a small ASR system. However, Fernandes et al. (2019) performed a preliminary injection test in the ASR well and found a recharge rate of 0.07m^3/h, which is a very low value. Only 360 L could be injected in the well during 5h of the test.
	Is the project compatible with groundwater management plans?	The proposed MAR projects does not conflict with the existing groundwater management plans.
4.	**Space for water capture and treatment**	
	Is there sufficient land available for capture and treatment of the water?	**YES** - Located on a school campus with sufficient space for a pilot plant plus treatment of harvested rainwater and water tank.
5.	**Capability to design, construct and operate**	

#	Attribute	Answer and explanation
	Is there a capability to design, construct and operate a MAR project?	**YES** - Universidade Federal de Pernambuco (UFPE) is responsible for all development stages and has the expertise to operate the project.

Table 7. Degree of difficulty assessment for Landelino Rocha school ASR site.

#	Attribute	Answer and explanation	Actions required?
1.	**Source water quality with respect to groundwater environmental values**		
	Does source water meet the water quality requirements for the environmental value of ambient groundwater?	**YES** - the use of rainwater for artificial groundwater recharge is generally considered low-risk of harming the ecosystem of the aquifer and human health.	**NO.**
2.	**Source water quality with respect to recovered water end-use environmental values**		
	Does source water meet the water quality requirements for the environmental values of the intended end uses of the water on recovery?	Likely **YES**.	**YES** - check rooftop rainwater quality parameters before recharge with respect to domestic end-uses
3.	**Source-water quality with respect to clogging**		
	Does source water have low quality; for example: total suspended solids (TSS) >10 mg/L; total organic carbon (TOC) >10 mg/L; total nitrogen >10 mg/L? And is the soil or aquifer free of macropores?	**YES** - initial assessment showed promising results but requires confirmation. See section 0 for details.	**YES** - check rooftop rainwater quality parameters before recharge with respect to clogging, test filter device for turbidity prior recharge.
4.	**Groundwater quality with respect to recovered water end-use environmental values**		
	Does ambient groundwater meet the water quality requirements for the environmental values of intended end uses of water on recovery?	**NO** - ambient groundwater does not comply with the drinking water standards. The Cabo aquifer shows too high EC values at the pilot site: 7400 µS/cm (Paiva et al., 2017).	**YES** - analysis of ambient groundwater quality parameters.
5.	**Groundwater and drinking water quality**		
	Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?	**YES** - the target aquifer is used for drinking water supply. Impact of ASR pilot is unlikely because of small scale of the project and large distance to drinking water supply.	**YES** - further investigation required to assess the impact on ecology near the site.
6.	**Groundwater salinity and recovery efficiency**		
	Does the salinity of native groundwater exceed either of the following: (a) 10 000 mg/L (b) The salinity criterion for uses of recovered water?	**YES** - see section 0 for details.	**YES** - recovery efficiency not assessed yet. Requires further investigations.
7.	**Reactions between source water and aquifer**		
	Are redox status, pH, temperature, nutrient status and ionic strength of groundwater similar to that of source water?	**NO.**	**YES** - investigations are required to evaluate geochemical reactions.

#	Attribute	Answer and explanation	Actions required?
8.	**Proximity of nearest existing groundwater users, connected ecosystems and property boundaries**		
	Are there other groundwater users, groundwater-connected ecosystems or a property boundary within 100–1000 m of the MAR site?	**YES** - the pilot system is in a residential area where other users may capture groundwater.	**YES** - assess area of influence of ASR site.
9.	**Aquifer capacity and groundwater levels**		
	Is the aquifer confined and not artesian? Or is it unconfined, with a water table deeper than 4 m in rural areas or 8 m in urban areas?	**YES** - ASR pilot is in the confined aquifer and the water table is about 40 m below surface. See section 0 for details.	**YES** - well dimensions and hydraulic properties of aquifer on site.
10.	**Protection of water quality in unconfined aquifers**		
	Is the aquifer unconfined, with an intended use of recovered water that includes drinking water supplies?	**NO**, see above.	**NO** actions required.
11.	**Fractured rock, karstic or reactive aquifers**		
	Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals?	**NO** - nothing reported.	**NO** actions required.
12.	**Similarity to successful projects**		
	Has another project in the same aquifer with similar source water been operating successfully for at least 12 months?	**NO** - there is not another example of operation in the same target aquifer.	**NO.**
13.	**Management capability**		
	Does the proponent have experience with operating MAR sites with the same or higher degree of difficulty, or with water treatment or water supply operations involving a structured approach to water quality risk management?	**NO** - only pilot scale investigations.	**YES** - if pilot investigations are promising it is required to identify an operator of the system.
14.	**Planning and related requirements**		
	Does the proposed project require development approval? Is it in a built up area; built on public, flood-prone or steep land; or close to a property boundary? Does it contain open water storages or engineering structures; or is it likely to cause public health or safety issues (e.g. falling or drowning), nuisance from noise, dust, odour or insects (during construction or operation), or adverse environmental impacts (e.g. from waste products of treatment processes)?	**YES** - drilling license acquired, it is in a built up and public area, close to residential buildings. There is no open water storages nor engineering structures.	**NO** further actions required at this stage.

3.5 SOURCE-WATER QUALITY WITH RESPECT TO CLOGGING

For the ASR pilot, further investigations are required as in the initial assessment only turbidity and Total Kjeldahl Nitrogen (TKN) have been investigated. The previous tests showed good results for TKN with 2.21 mg/L indicating a low risk for clogging. Whereas the results for turbidity showed a concentration of 12 NTU. Literature sources recommended using infiltration water with less than 0.1 or 3 NTU (Guttman and Negev, 2015). It should be kept in mind that only one rain event was assessed, wherefore exact statements can only be made after a more comprehensive study. The concentration of TOC has not been measured yet. A sand filter is being designed for pre-treatment. Preliminary tests will be made to investigate the efficiency of the treatment.

3.6 GROUNDWATER SALINITY AND RECOVERY EFFICIENCY

At the ASR pilot site the groundwater of the lower Cabo aquifer showed mean EC values of 7400 µS/cm (Paiva et al., 2017). Samples taken in January 2019 showed slightly lower EC values of 6000 µS/cm, which still indicate brackish conditions (1500–15000 µS/cm). However, the measured EC at the project site are relatively high compared to average values measured of the Cabo aquifer: 1246 µS/cm, n = 40 (Cary et al., 2015), 975 µS/cm (Coelho et al., 2018) and 926 µS/cm (Oliveira et al., 2017). The limit value given as fresh water standard is 500 µS/cm, which is exceeded by the EC value of the ambient groundwater.

The recovery efficiency will be analysed regarding the EC values of the installed sensors. Three sensors will be required. The first one to measure the EC of the water in the reservoir, another sensor to measure the EC value in the injection tube and the third one in the recovery tube. With these values an aquifer salinity profile can be presented.

3.7 AQUIFER CAPACITY AND GROUNDWATER LEVELS

References do not mention fractures in the Cabo aquifer, but a high clay content is reported. The Cabo aquifer is reported to be heterogeneous and shows thin clay intercalations, especially in the upper Cabo aquifer. Investigations are required to assess potential consequences of the clay layers during recharge and recovery. The hydraulic gradient can be analysed by installing one sensor in the injection well and another sensor in a monitoring well that is about 20 meters from it. Hydraulic head values will be used to determine the hydraulic gradients in the target aquifer.

3.8 CONCLUSIONS

The Landelino Rocha school ASR project was developed as a research project to assess ASR viability. Due to the small-scale nature of the project and high quality of injectant, an entry-level assessment was found to be suitable for assessing the risks to human health and the environment at this stage of development. However, the assessment showed that operational issues are the biggest challenges for further site development.

4. TOWARDS INDUCED RIVER BANK FILTRATION AT BEBERIBE RIVER, BRAZIL

4.1 CASE STUDY DESCRIPTION

The second MAR pilot system in RMR is an induced river bank filtration (IBF) site (Figure 5, Table 8). This methodology consists of pumping wells near the surface spring (river, lake, reservoir), generating a hydraulic head difference between the source and the water table inducing water through the porous medium until the production well. Therefore, the water produced by IBF is a mixture of water infiltrated from the surface spring and groundwater present in the aquifer (Freitas et al., 2017).

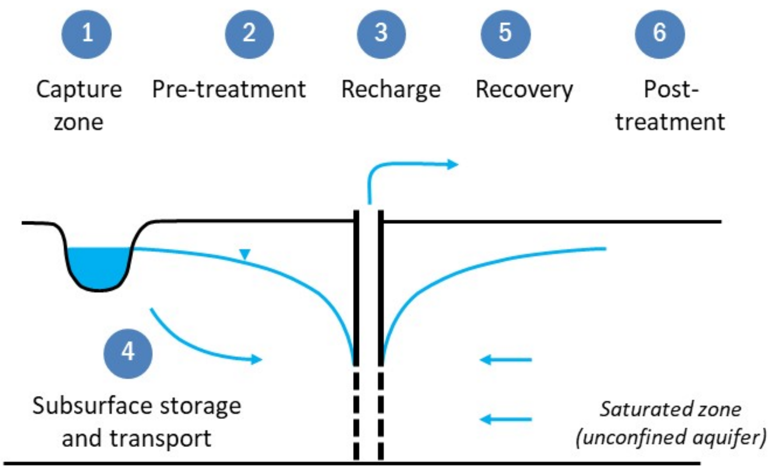

Figure 5. Schematic overview of IBF site at Beberibe River.

The experimental area of IBF pilot project is located in the Beberibe River basin, more precisely in the metropolitan region of Recife (RMR), on the border between the cities of Olinda and Recife, bounded by coordinates North 9,115,650 to 9,116,000 m and East 289,750 to 289,900 m, zone 25.

Table 8. Components of the Beberibe river IBF system.

#	MAR component	Beberibe river IBF site
1	Capture zone	Beberibe river water
2	Pre-treatment	None
3	Recharge	Induced bank filtration
4	Subsurface	Beberibe formation (semi-confined aquifer)
5	Recovery	4 production well
6	Post-treatment	Filter
7	End use	Drinking water

The experimental area of the IBF pilot project installed on the Beberibe riverbanks has a production well and seven monitoring wells since 2009. In 2012, three new production wells were drilled along the river (Figure 6). The production wells have a diameter of 15 cm, a depth of 15 m, with a filter section from 6 to 12 m depth. A prefilter layer around the well (filled with gravel) was constructed from 3 to 15 m and the void space around the well was filled with cement from the surface to 3 m deep. The operating flows of the four production wells are distinct, well 1, the first well to be drilled (2009) has a flow rate of 12.60 m³/h. Wells two, three and four (2012) have a flow of 9.57, 9.13 and 9.80 m³/h respectively. The pumped water goes through a preliminary filter and then is stored into a reservoir. This water is then pumped to the water and sanitation company (COMPESA) pumping station from where it will be sent to the treatment plant along with the COMPESA raw water.

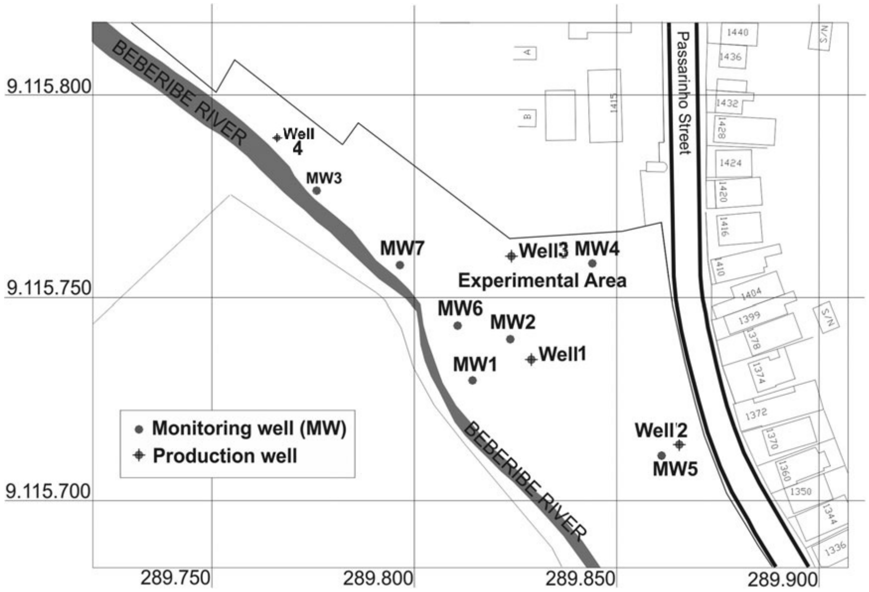

Figure 6. Bank filtration pilot at Beberibe river and location of production wells (Wells 1,2,3 and 4) and monitoring wells (MW1, MW2, MW3, MW4, MW5, MW6, AND MW7).

The Figure 7 and Figure 8 show 3 selected research points at the Beberibe River that were strategically selected to provide better representative coverage of the study area.

Figure 7. Location of research points on the Beberibe River (Albuquerque, 2015).

Figure 8. **PT1, PT2 and PT3 on the Beberibe River (Albuquerque, 2015).**

The discharge was calculated at these three points using a hydrometric windlass VALEPORT. The flow rates can be seen in Table 9 (Albuquerque, 2015).

Table 9. **Average flow at three points in a section of the Beberibe River.**

Points	PT1	PT2	PT3
Flow rate (m^3/s)	1.22	0.27	0.12

The IBF pilot system is located in the Beberibe aquifer, one of the most important in terms of water supply for the RMR population (Cabral et al. 2008). It is a semi-confined aquifer with an average thickness of 100m of sandstones with intercalations of mudstone. Figure 9 shows the longitudinal profile of the region elaborated from standard penetration wells named SW1, SW2, SW4 and SW6. These wells were later turned into observation wells, renamed MW1, MW2, MW4 and MW6. The location of these wells is shown in Figure 6.

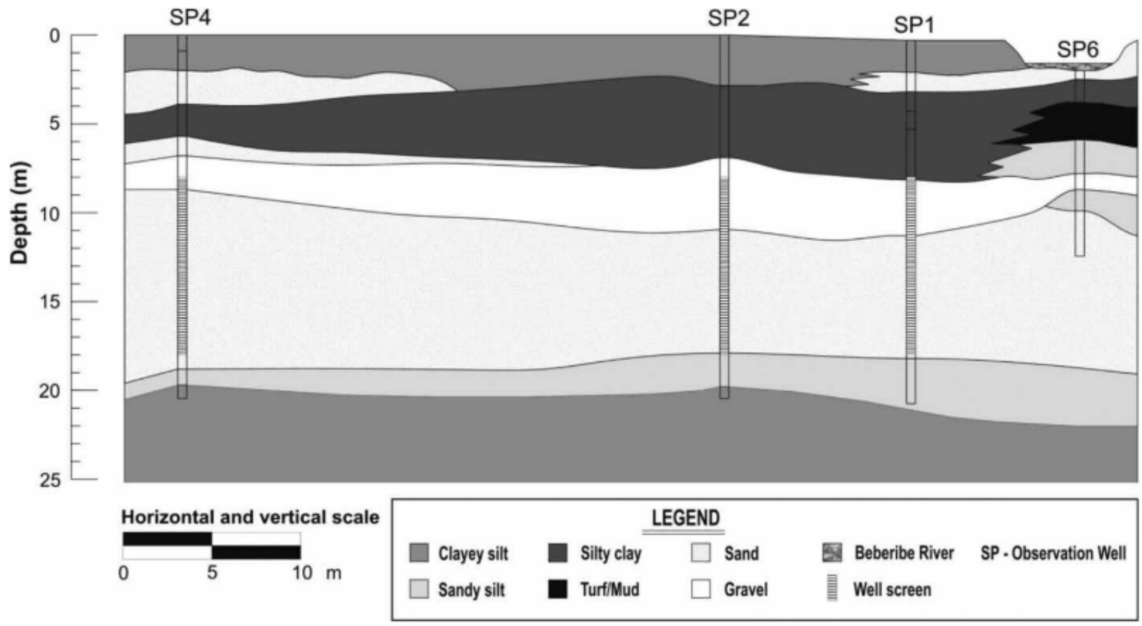

Figure 9. **Cross section of sediment layers perpendicular to the Beberibe River in Caixa d'Água Experimental Station, Olinda, PE, Brazil (Freitas et al. 2012).**

Paiva et al. (2010) conducted hydrogeological studies, tests for hydraulic conductivity assessment, water level and water quality monitoring in this study area. They proved that the pumped water is a mixture of groundwater and surface water infiltrated by induced recharge and that it has a better quality than river water, being within potability standards. In addition to the potential water interaction in the close section between the river and the production well, there is a high connection of the river with the aquifer in sections where the river underwent a retification process in its original gutter, contributing significantly to the river-aquifer interaction. Figure 10 shows the Beberibe river flow direction at the induced bank fitration area in the 70' and 90', showing the change over the time.

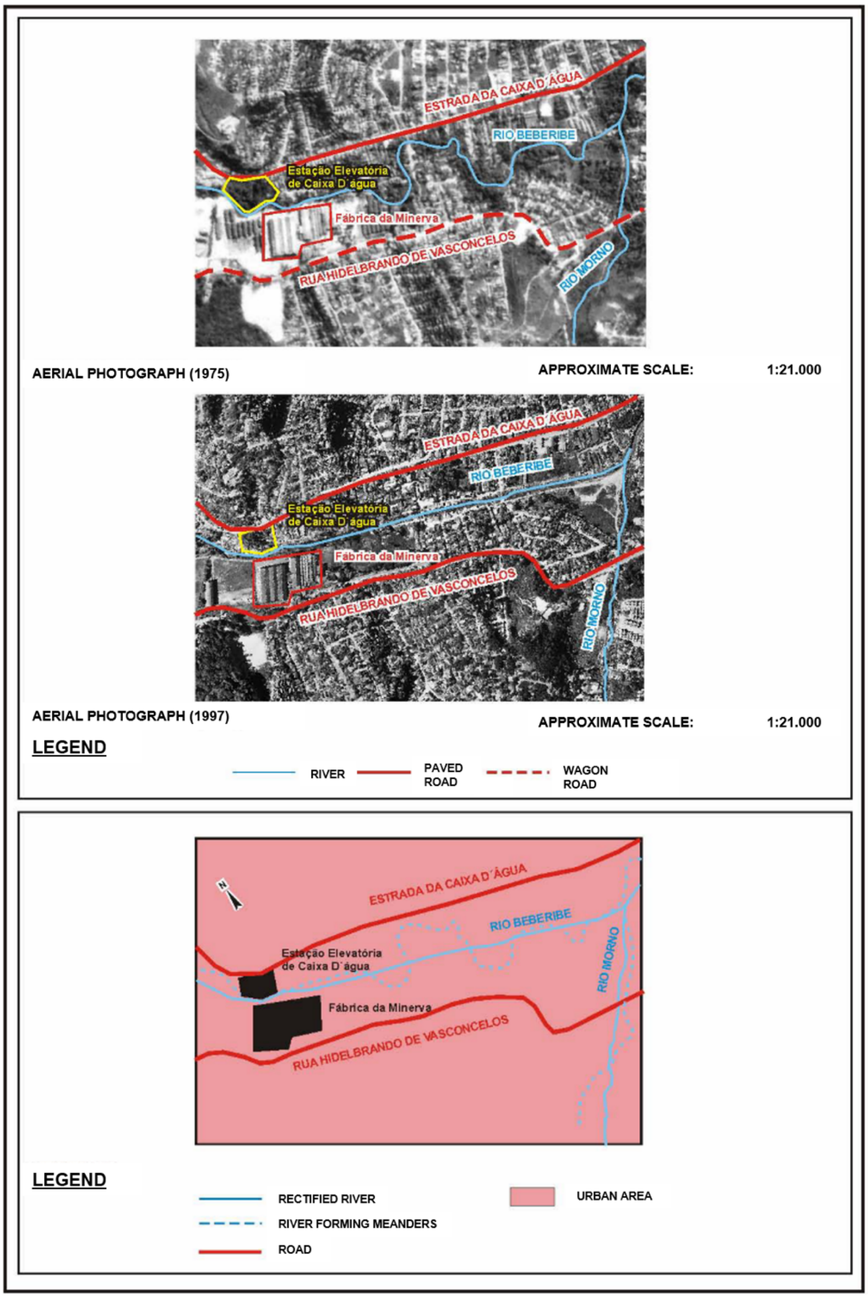

Figure 10. Aerial photographs from the 70's and 90's showing the advancement of urban occupation in Passarinho, Olinda (Adapted from Campos, 2003).

4.2 ENTRY-LEVEL ASSESSMENT AND DEGREE OF DIFFICULTY ASSESSMENT AT BEBERIBE RIVER IBF SITE

The next two tables present the entry-level assessment (Table 10) and the degree of difficulty assessment (Table 11) at the Beberibe River IBF system.

Table 10. Entry-level assessment Beberibe River IBF site.

#	Attribute	Answer and explanation
1.	**Intended water use**	
	Is there an ongoing local demand or clearly defined environmental benefit for recovered water that is compatible with local water management plans?	**YES** - The public water supply currently only covers 84% of the total water demand. Increasing water resources by using riverbank filtration water has the potential to reduce this supply gap.
2.	**Source water availability and right of access**	
	Is adequate source water available, and is harvesting this volume compatible with catchment water management plans?	**YES** - at the bank filtration site, the Beberibe river has permanent flow. See Figure 8.
3.	**Hydrogeological assessment**	
	Is there at least one aquifer at the proposed managed aquifer recharge site capable of storing additional water?	**YES** - Unconfined aquifer of quaternary age. The thickness of the aquifer is 15m. An aquifer test was carried out in 2012 in the study area and showed the following values: $T = 2.3x10^{-3}$ m^2/s, $K = 2.03x10^{-4}$ m/s and $S = 1x10^{-3}$ (Demétrio et al., 2013). Hydraulic conductance of the riverbed and load of suspended solids in the river is unknown.
	Is the project compatible with groundwater management plans?	The proposed MAR projects does not conflict with the existing groundwater management plans.
4.	**Space for water capture and treatment**	
	Is there sufficient land available for capture and treatment of the water?	**YES** - The bank filtration system is in an area for which COMPESA is responsible. The system is already connected to a water treatment plant.
5.	**Capability to design, construct and operate**	
	Is there a capability to design, construct and operate a MAR project?	**YES** - In this case study, COMPESA is directly involved and has broad experience in construction and operation of wells.

The entry-level assessment for the Beberibe River IBF site suggests that river discharge of the Beberibe River may be a limiting factor for larger scale exploration.

Table 11. Degree of difficulty assessment for Beberibe River IBF site.

#	Attribute	Answer and explanation	Actions required?
1.	**Source water quality with respect to groundwater environmental values**		
	Does source water meet the water quality requirements for the environmental value of ambient groundwater?	**NO** - Beberibe River water is polluted, source water induced by pumping and abstracted, no risk of groundwater detoriation. Beberibe river quality: Turbidity: 34.03 NTU, Ammonia:	**NO.**

#	Attribute	Answer and explanation	Actions required?
		4.144 (mg l^{-1}), Total iron: 1.988 (mg l^{-1}) (Freitas et al. 2012).	
2.	**Source water quality with respect to recovered water end-use environmental values**		
	Does source water meet the water quality requirements for the environmental values of the intended end uses of the water on recovery?	**NO** - Beberibe River does not meet the Brazilian drinking water standards. The main source of contaminants is untreated sewage, which provides pathogenic microorganisms.	**YES** - microbial risk assessment, promising results are presented by (Freitas et al., 2012), absence of total coliforms and faecal coliforms. Currently, a sewage treatment plant is under construction close to the pilot location.
3.	**Source-water quality with respect to clogging**		
	Does source water have low quality; for example: total suspended solids (TSS) >10 mg/L; total organic carbon (TOC) >10 mg/L; total nitrogen >10 mg/L? And is the soil or aquifer free of macropores?	**YES** - but there is a potential of natural self-cleaning of the riverbed.	**YES** - investigation of hydraulic conductance of the riverbed and clogging under induced riverbank filtration conditions necessary.
4.	**Groundwater quality with respect to recovered water end-use environmental values**		
	Does ambient groundwater meet the water quality requirements for the environmental values of intended end uses of water on recovery?	**YES** - Ambient groundwater has drinking water quality.	**NO.**
5.	**Groundwater and drinking water quality**		
	Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?	**YES** - The target aquifer is used for drinking water supply.	**NO**.
6.	**Groundwater salinity and recovery efficiency**		
	Does the salinity of native groundwater exceed either of the following: (a) 10 000 mg/L (b) The salinity criterion for uses of recovered water?	**NO** - Recovered water with low salinity. Beberibe River EC = 196.6 µS/cm; Pumped water EC = 210.9 µS/cm (Freitas, 2012).	**NO.**
7.	**Reactions between source water and aquifer**		
	Are redox status, pH, temperature, nutrient status and ionic strength of groundwater similar to that of source water?	**NO** - There is a distinction between the groundwater and the source water quality. The river water is more polluted than the groundwater. The groundwater sample is collected at the IBF system production well.	**YES**. Further analysis on groundwater quality are needed.
8.	**Proximity of nearest existing groundwater users, connected ecosystems and property boundaries**		
	Are there other groundwater users, groundwater-connected ecosystems or a property boundary within 100–1000 m of the MAR site?	**YES** - Pilot system is in residential area. There are many users who capture the water from the confined aquifer, which does not affect the pilot system.	**NO -** since induced bank filtration recovers most of the water that is induced by the system.

#	Attribute	Answer and explanation	Actions required?
9.	**Aquifer capacity and groundwater levels**		
	Is the aquifer confined and not artesian? Or is it unconfined, with a water table deeper than 4 m in rural areas or 8 m in urban areas?	**NO** - Bank filtration is in the unconfined aquifer and the water table is less than 4 m.	**YES -** hydraulic properties of the aquifer, see Table 10, question 3.
10.	**Protection of water quality in unconfined aquifers**		
	Is the aquifer unconfined, with an intended use of recovered water that includes drinking water supplies?	**YES** - bank filtration occurs in the unconfined aquifer with recovered water for drinking water supply.	**YES** - evaluate the purification capacity of subsurface passage
11.	**Fractured rock, karstic or reactive aquifers**		
	Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals?	**NO.**	**NO** - reactive aquifer material not expected.
12.	**Similarity to successful projects**		
	Has another project in the same aquifer with similar source water been operating successfully for at least 12 months?	**NO** - this pilot site is the pioneer.	**NO.**
13.	**Management capability**		
	Does the proponent have experience with operating MAR sites with the same or higher degree of difficulty, or with water treatment or water supply operations involving a structured approach to water quality risk management?	**YES.** In a pilot scale.	**NO.**
14.	**Planning and related requirements**		
	Does the proposed project require development approval? Is it in a built up area; built on public, flood-prone or steep land; or close to a property boundary? Does it contain open water storages or engineering structures; or is it likely to cause public health or safety issues (e.g. falling or drowning), nuisance from noise, dust, odour or insects (during construction or operation), or adverse environmental impacts (e.g. from waste products of treatment processes)?	**YES** - We have already the construction and operating license from APAC and CPRH (executive and regulatory agencies). The bank filtration is in the COMPESA (public water company) area. The post-treatment is managed by COMPESA. The pumped flow is very insignificant compared to the captured water from COMPESA. The system has adequate capacity to receive this output.	**NO.** Unless an expansion of the pilot system is planned.

4.3 SOURCE WATER QUALITY WITH RESPECT TO RECOVERED WATER END-USE ENVIRONMENTAL VALUES

The Beberibe River water is polluted due to anthropogenic activities. The values of turbidity (34.03 NTU), ammonia (4.144 mg/l), total iron (1.988 mg/l), total coliforms (1,516 - 30,804 NMP/100 ml) and faecal coliforms (300 - 3,428 NMP/100 ml) exceed the maximum value allowed by the Brazilian legislation on potability - Ministério da Saúde, Decree n. 518/2004 (Freitas et al. 2012).

However, the water recovered by the production well complies with potability standards required by the Brazilian law and the rules of the World Health Organization for the physical-chemical parameters analysed: pH, turbidity, electric conductivity, ammonia in NH_3, nitrite in N, nitrate in N, total hardness in $CaCO_3$, biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total iron and total manganese (Freitas et al. 2012).

Currently, the recovered water goes through a preliminary filter and is stored in a reservoir. Then the water is mixed with the raw water from COMPESA, passing through the water treatment plant and as a last step distributed as drinking water. While the system was being tested, COMPESA agreed to combine IBF water with Beberibe river raw water. Recently, COMPESA already discusses the possibility of diverting water from IBF to the final stage of ETA, chlorination, and then to proceed for distribution.

4.2 CONCLUSIONS

The Beberibe river IBF system has been operating at pilot scale for 10 years. It provides a small amount of water to the COMPESA supply system. The limited flow of the river may be a limiting factor for the expansion of the system. Despite the small volumes, it is a contribution to the system that already works with the capture, treatment and distribution of the water management itself.

5. RECLAIMED WATER SOIL AQUIFER TREATMENT AT EZOUSA CATCHMENT, CYPRUS

5.1 CASE STUDY DESCRIPTION

In the Ezousa catchment near Paphos (Cyprus), a coastal city in the southwest of Cyprus, a MAR site based on Soil Aquifer Treatment (SAT) has been constructed since 2003 for irrigation purposes. This coastal area has an intense agricultural activity which supports the main urban centres that attract a growing number of tourists. Annual water demands for irrigation purposes are approximately 17 Mm^3, while 3 Mm^3 are consumed in tourism, including golf facilities (Christodoulou, personal communication, July 3, 2019). These demands exceed the sustainable water supply of the island, because groundwater reserves are being replenished at a slower rate than they are used. As a result, the Water Development Department of Cyprus (WDD) fostered the development of a MAR scheme in the Ezousa catchment by utilizing treated effluent for groundwater augmentation in the coastal aquifer. Wastewater is captured from Paphos urban area, consisting of about 36,000 inhabitants, and it is gathered at the Waste Water Treatment Plant (WWTP) station, where it is subjected to tertiary treatment as indicated in Figure 10.

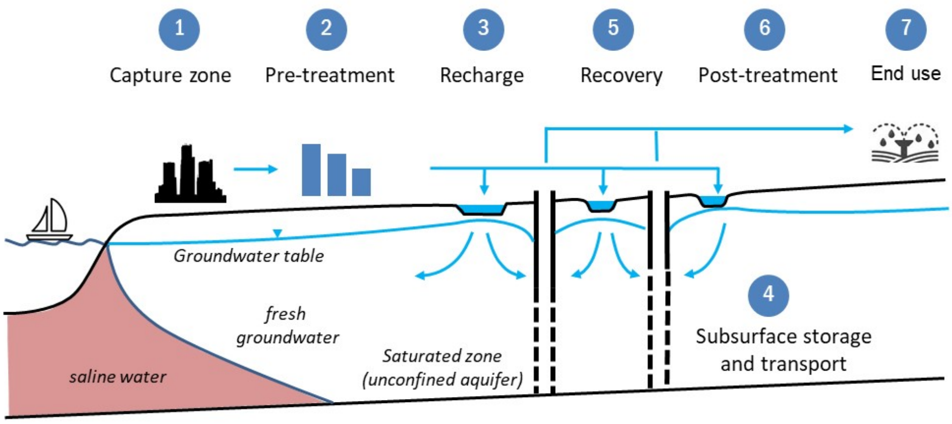

Figure 10. Schematic overview of MAR components at Ezousa SAT system.

From there, the treated effluent is transferred to infiltration basins through pipelines, where it percolates through the soil until it reaches the groundwater. Abstraction wells are used to recover the water from the aquifer. After recovery, the water is distributed without post-treatment to the end-users, who are mainly farmers involved with crop cultivation. The most common crop is citrus, while other vegetables such as tomatoes, cucumbers, spinach and lettuce are also present. The MAR components of the Ezousa SAT system are summarized in Table 12.

Table 12. Components of the SAT Ezousa system.

#	MAR component	Ezousa MAR site
1	Capture zone	Municipal wastewater
2	Pre-treatment	Activated sludge, sand filtration, chlorination (gas chlorine)
3	Recharge	5 infiltration basins
4	Subsurface	Ezousa river alluvial aquifer
5	Recovery	5 wells

#	MAR component	Ezousa MAR site
6	Post-treatment	None
7	End use	Irrigation

The recharge network consists of five shallow infiltration basins arranged in a series from the coastline to about 8 km upstream. Infiltration rates were found to range between 70 and 120 mm/h (1.68 - 2.88 m/d). Each infiltration site consists of two, four or six recharge ponds, with each pond having a surface area of 2,000 m^2 and a depth of 1.5 m (Figure 11).

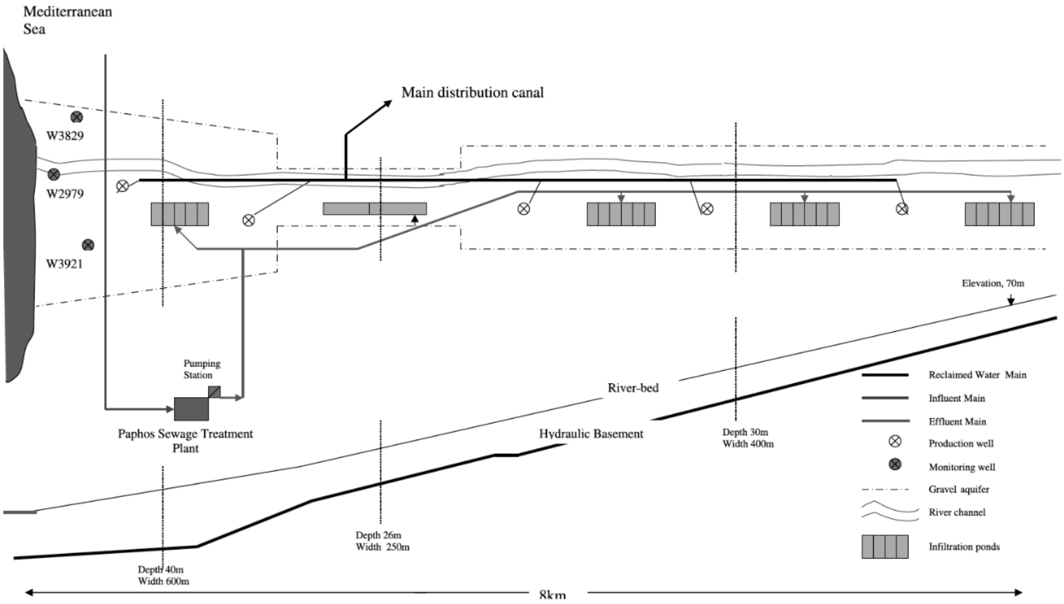

Figure 11. Recharge network of Ezousa MAR project (Christodoulou et al., 2007).

Each pond is designed with a 1 m overflow weir to avoid erosion of their embankments from excess flow. The operational approach is to maintain a significant unsaturated zone so as to maximize the amount of water recharged and optimize the quality of the recycled water by its passage through the soil matrix. The operational pattern of wet-dry fill cycles varies from pond to pond but normally each part of the cycle lasts between 5 to 7 days. The ponds are filled from a pressurized 500 mm ductile iron main. Groundwater withdrawal occurs at five wells located close to the infiltration basins, called production (or extraction) wells, from which the abstracted water is then distributed to the end-users through a canal. Details regarding the elevation and the absolute depth of these five wells are given in Table 13.

Table 13. Details regarding the five extraction wells of the Ezousa MAR system.

Borehole Number	Well head elevation [masl*]	Well depth elevation [masl*]	Well depth [m]
2954	43.0	25.0	18
2978	15.0	-25.0	40
2979	7.0	-2.5	9.5
2996	62.3	47.2	15.1
3026	74.6	53.6	21

**masl = meter above sea level*

5.2 ENTRY LEVEL ASSESSMENT

The SAT system in Ezousa is under operation for years and does not require entry-level assessment. However, the checklists may serve as introductory assessment to the MAR scheme (Table 14) and are intended to inform stakeholders and operators about hazards and possible remediation measures (Table 15).

Table 14. Entry level assessment-viability assessment at the Ezousa MAR facility.

#	Attribute	Answer and explanation
1.	**Intended water use**	
	Is there an ongoing local demand or clearly defined environmental benefit for recovered water that is compatible with local water management plans?	**YES** - Economical activities at the region involve tourism and agriculture, with agriculture having the majority of local water demand. Particularly, 17 Mm^3 of water are consumed in agriculture, 3 Mm^3 n tourism, which are provided by groundwater sources and dams[1].
2.	**Source water availability and right of access**	
	Is adequate source water available, and is harvesting this volume compatible with catchment water management plans?	**YES** - Source water is treated effluent from Paphos WWTP (162 500 P.E.), 20,000 m^3/d of treated water of which 9,000-12,000 m^3/d (3.3 – 4.4 Mm^3/year) are used to supplement the Ezousa aquifer. Wastewater is treated up to the tertiary stage, consisting of sand filtration and chlorine disinfection (gas chlorine) for the removal of microorganisms to use the treated effluent for agricultural purposes.
3.	**Hydrogeological assessment**	
	Is there at least one aquifer at the proposed managed aquifer recharge site capable of storing additional water?	**YES** - The Ezousa alluvium aquifer is estimated to have total storage capacity of ~ 4.2 Mm^3 and hydraulic conductivity of avg. 90 m/day.
	Is the project compatible with groundwater management plans?	The SAT scheme is compatible with the national plans for groundwater management and aims to comply with EU directives (e.g. GWD (2006)). It is in line with efforts to increase water reuse in EU member states, for example JRC (2016).
4.	**Space for water capture and treatment**	
	Is there sufficient land available for capture and treatment of the water?	**YES** - capture and treatment facilities of effluent at Paphos plant are available.
5.	**Capability to design, construct and operate**	
	Is there a capability to design, construct and operate a MAR project?	**YES** - the design of the Ezousa MAR project has been assigned to Energoproject Holding Co. Hydroengineering who has years of experience and expertise on Water and Sewerage Engineering. The operator of the scheme is the Water Development Department with the support of the Geological Survey of Cyprus and the Cyprus State Chemical Lab which provides regular detailed water-quality analysis.

[1] Christodoulou, personal communication, May 19, 2019

Table 15. Degree of difficulty assessment at Ezousa MAR facility.

#	Attribute	Answer and explanation	Actions required?
1.	**Source water quality with respect to groundwater environmental values**		
	Does source water meet the water quality requirements for the environmental value of ambient groundwater?	**NO** - Some parameters exceed ambient groundwater concentrations, while others are below. Measurements of total and individual pesticides are missing. See Section 0 for details.	**NO** - dilution with reservoir water to comply with ambient groundwater quality. Measurements required for pesticides.
2.	**Source water quality with respect to recovered water end-use environmental values**		
	Does source water meet the water quality requirements for the environmental values of the intended end uses of the water on recovery?	**YES** - Treated effluent from the WWTP corresponds to Class A irrigation (see Section 0 and Table 19 for details).	**NO** - further actions required.
3.	**Source-water quality with respect to clogging**		
	Does source water have low quality; for example: total suspended solids (TSS) >10 mg/L; total organic carbon (TOC) >10 mg/L; total nitrogen >10 mg/L? And is the soil or aquifer free of macropores?	**YES** – As shown in Table 16, the maximum value of the Total Suspended Solids (TSS) exceeds the maximum recommended value. Presence of macropores: No	**YES** – observation of infiltration rates recommended. Possible remediation measures necessary such as adjusting dry/wet cycle, additional pre-treatment or cleaning of infiltration basins.
4.	**Groundwater quality with respect to recovered water end-use environmental values**		
	Does ambient groundwater meet the water quality requirements for the environmental values of intended end uses of water on recovery?	**NO** - The values of E. Coli, BOD_5, HCO_3, Ca and Mg exceed the recommended range of values for irrigation uses, as shown in Table 16 (indicated by red coloured values).	**YES** - mixing with treated effluent reduces the concentration of BOD_5, while further preventive measures are needed for the remaining parameters. For that purpose, larger representative sampling from ambient groundwater is required.
5.	**Groundwater and drinking water quality**		
	Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?	**NO** – Target aquifer is not used for drinking water production. Aquatic ecosystems not of high ecological significance.	**NO** further actions required.
6.	**Groundwater salinity and recovery efficiency**		
	Does the salinity of native groundwater exceed either of the following: (a) 10 000 mg/L (b) The salinity criterion for uses of recovered water?	**NO** – Target aquifer is not at high risk for seawater intrusion. EC values measured in boreholes are found to be well below 10,000 mg/L (Table 16).	**YES** – although not indicated by current data, it is recommended to include monitoring of EC at selected observation wells at the coastline as preventive measure.
7.	**Reactions between source water and aquifer**		

#	Attribute	Answer and explanation	Actions required?
	Are redox status, pH, temperature, nutrient status and ionic strength of groundwater similar to that of source water?	**NO** - Different water quality has the potential of producing chemical reactions, especially introduction of electron donors (e.g. C_{org}).	**YES** – although only minor influences on the final water quality expected. Eh measurements recommended at recovery wells.
8.	**Proximity of nearest existing groundwater users, connected ecosystems and property boundaries**		
	Are there other groundwater users, groundwater-connected ecosystems or a property boundary within 100–1000 m of the MAR site?	**NO** -There are about 37-40 wells abstracting groundwater for irrigation (WDD, internal report). No aquatic ecosystems of high value in the proximity of MAR facilities.	**NO** further actions required.
9.	**Aquifer capacity and groundwater levels**		
	Is the aquifer confined and not artesian? Or is it unconfined, with a water table deeper than 4 m in rural areas or 8 m in urban areas?	**YES** - Ezousa river alluvial aquifer is unconfined, with hydraulic conductivity increasing with increasing distance from the sea (50 -220 m/d). The water-table is found to be sufficiently deep most of the time due to the semi-arid conditions that prevail in the region. However, it is expected to become shallow under specific conditions, such as rainfalls and excessive basin recharge.	**YES** – basin recharge is recommended to be adapted to seasonal groundwater fluctuations through the use of suitable sensors.
10.	**Protection of water quality in unconfined aquifers**		
	Is the aquifer unconfined, with an intended use of recovered water that includes drinking water supplies?	**NO** – recovered water for irrigation only.	**NO** further actions required.
11.	**Fractured rock, karstic or reactive aquifers**		
	Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals?	**NO** - Ezousa aquifer consists of layers of sand and gravel material of moderate to high permeability with occasional lenses of silty clay and silt. As shown in Table 16, there are known carbonate elements, such as calcium carbonate, bio-carbonate and carbonate.	**NO** further actions required.
12.	**Similarity to successful projects**		
	Has another project in the same aquifer with similar source water been operating successfully for at least 12 months?	**NO.**	**NO** further actions required.
13.	**Management capability**		
	Does the proponent have experience with operating MAR sites with the same or higher degree of difficulty, or with water treatment or water supply operations involving a structured approach to water quality risk management?	**NO** - It is the first time that the Paphos WDD is involved in such MAR project.	**YES** - training of WDD staff recommended (e.g. regarding microbiological risk assessment, sensor usage, groundwater simulations)
14.	**Planning and related requirements**		
	Does the proposed project require development approval? Is it in a built up area; built on public, flood-prone or	**YES** -The project is fully operational since 2003, in accordance to the Cyprus provision standards. For further improvement of the	**YES** - pre-treatment adjustments and additional control points for

#	Attribute	Answer and explanation	Actions required?
	steep land; or close to a property boundary? Does it contain open water storages or engineering structures; or is it likely to cause public health or safety issues (e.g. falling or drowning), nuisance from noise, dust, odour or insects (during construction or operation), or adverse environmental impacts (e.g. from waste products of treatment processes)?	MAR scheme, a more detailed monitoring of the groundwater movement is required.	reclaimed water monitoring. Assessment of various factors, such as noise, dust, has been conducted, suggesting a low environmental impact.

5.2.1 Source water quality with respect to groundwater environmental values

In this subsection we conduct a comparison between the native groundwater and the treated effluent. Table 16 gives statistical details for various parameters based on data provided by the WDD. Red coloured values indicate concentrations above irrigation recommendations. We observe that the average concentrations found in treated effluent for TOC, COD, Cl, CO_3, NO_3, P-Total, Na and K exceed the corresponding values found in the samples of native groundwater, while the opposite occurs for $CaCO_3$, SO_4, and Ca**.** Regarding heavy metals, selenium is also above measured groundwater concentrations, contrary to Ni, Mn and Zn which are found in smaller concentrations than the native groundwater. Except for Ca, concentrations do not exceed the irrigation standards for all the above mentioned cases, while the values for Mg are well above the threshold values for both native groundwater and treated effluent. Overall, HCO_3, Ca, Cl and Mg are the parameters expected to have high risk if their concentrations are not reduced, for example along aquifer passage. Lastly, no data are available for TSS, N-total, total pesticides and individual pesticides in the native groundwater. Thus, further samples are needed in order to assess the risks related to the mixing between the treated effluent and the ambient groundwater.

5.2.2 Source water quality with respect to recovered water end-use environmental values

Next, the source water quality of the treated effluent after disinfection is compared to water quality for Class irrigation A through Table 16 and Table 17. The measured concentrations for HCO_3, Mg, BOD_5, and TSS exceed the recommended irrigation values, thus having a high risk of polluting the recovered water. As mentioned in the previous subsection, no irrigation standards are available for a number of parameters, namely TOC, COD, $CaCO_3$, SO_4, CO_3, N-total, P-total, K, Cu, Pb and B. Consequently, all these parameters are associated with an uncertain risk for contamination, while the remaining parameters are expected to have a low risk of pollution of recovered water.

Table 16. Basic water chemistry statistics for the sampling period 2003-2017 (WDD, internal report).

Parameter	Native groundwater BH4031			Treated effluent (WTTP)			Mixed groundwater			Recommended irrigation values (Ayers R. S. and Westcot D. W., 1985)
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	
E.C. (μS/cm)	1527	1786	2194	741	1484	2140	1300	1510	2082	700/3000*
pH	7.02	7.5	7.7	7.1	7.7	9.1	7.2	7.5	7.8	6.5/8.4

Parameter	Native groundwater BH4031			Treated effluent (WTTP)			Mixed groundwater			Recommended irrigation values (Ayers R. S. and Westcot D. W., 1985)
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	
***E. coli* (cfu/100 ml)**	0	1	2	0	0	0	0	1	2	<1
					Measured in mg/l					
TOC	0.9	1.39	2.05	5.7	7.34	8.8	0.5	1.42	2.4	NA
TSS	-	-	-	2.33	8.37	14.21	-	-	-	10
BOD_5	<1	3.7	14	<1	5	12	<1	2.2	7	10
COD	6	9.9	27	10	19.3	27	4	8.9	17	NA
$CaCO_3$	608	798	988	241	291	341	420	613	820	NA
Cl^-	105	129	155	144	228	312	115	170.8	276	107/142**
SO_4	364	600	842	129	175	213	198	329	625	NA
CO_3	0	0	0	0	3	9	0	1	3	NA
HCO_3^-	271	321	365	217	311	405	156	320	415	91.5
NO_3^-	1	3	5	5	11	17	4	11	20	22
P-Total	0.08	0.19	0.38	0.35	2	2.80	0.07	0.13	0.21	NA
N-Total	NA	NA	NA	0.9	4.3	9.4	NA	NA	NA	NA
Na^+	96	110	126	183	207	231	68	128	197	500
K^+	6	6	6	17	27	37	5	7	9	NA
Ca^{++}	208	241	269	55	63	71	127	163	244	41/120**
Mg^{++}	14	50	86	22	32	42	23	36	63	9/24
Cu	0.006	0.014	0.028	0.006	0.014	0.027	0.001	0.009	0.013	NA
Zn	0.053	0.133	0.208	0.016	0.038	0.057	0.003	0.046	0.061	2.0
Pb	0.004	0.009	0.014	0.008	0.016	0.018	0.005	0.008	0.03	NA
B	0.257	0.515	0.773	0.181	0.395	0.609	0.102	0.315	0.510	NA
					Measured in µg/l					
Cd	<0.06	0.2	0.7	<0.06	0.09	0.15	<0.06	0.2	0.604	10
Cr	0.30	1.03	2.49	0.26	1.2	2.47	0.3	1.24	4.9	100
Mn	3.0	127	560	11	47.3	108	15	79	565	200
As	0.30	1.14	2.49	0.26	1.19	2.47	0.1	2.7	7.4	100
Ni	1.0	12.81	44.67	1.0	6.76	21.84	0.30	7.60	30.91	200
Se	0.6	2.3	4.9	2.1	4.6	7.1	0.2	0.8	2.2	20

**Slight/moderate use restrictions; **sprinkler*

Table 17. Reclaimed water quality criteria for Class A agricultural irrigation

Indicative technology target	*E. coli* (cfu/100 ml)	BOD_5 (mg/l)	TSS (mg/l)	Turbidity (NTU)	Additional criteria
Secondary treatment, filtration, and disinfection (advanced water treatments)	≤ 10 or below detection limit	≤ 10	≤ 10	≤ 5	Legionella spp: $\leq 1{,}000$ cfu/l when there is risk of aerosolization

5.3 MAXIMAL RISK ASSESSMENT

In this section, 12 key hazards have been evaluated using a semi-quantitative risk assessment, for human health and the two environmental endpoints i) native groundwater and ii) irrigation (Table 18).

Table 18. Maximal risk assessment for Ezousa MAR project. L represents low risk, H represents high risk and U represents unknown risk.

MAR hazards		Human health risk at end-point	Environmental risk at end-point	
			Native groundwater	Irrigation
1.Pathogens		H	H	L
2.Inorganic chemicals	Electric conductivity	L	L	H
	pH	L	L	L
	Sodium	L	H	L
	Chloride	L	H	H
	Boron	L	L	L
	Bicarbonate	L	L	L
	Arsenic	L	H	L
	Fluoride	U	U	U
3. Salinity and sodicity		L	L	L
4. Nutrients	Nitrate	L	H	L
	Total nitrogen	L	H	L
	Total phosphorous	L	H	L
	Organic carbon	L	H	L
5.Organic chemicals	Pesticides	U	U	U
	Pharmaceuticals and others	U	U	U
6. Turbidity and particulates		U	U	U
7. Radionuclides		U	U	U
8. Pressure, flow rates, volumes and groundwater levels		H	L	L
9. Contaminant migration in fractured rocks and karstic aquifers		L	L	L
10. Aquifer dissolution and stability of well and aquitard - pumping wells observed to be stable after 30 years		U	U	U
11. Aquifer and groundwater-dependent ecosystems		L	L	L

MAR hazards	Human health risk at end-point	Environmental risk at end-point	
		Native groundwater	Irrigation
12. Energy, greenhouse gas considerations and economical assessment	L	L	L

5.3.1 Pathogens

In the maximal risks assessment, hazards to human health associated to pathogens are considered high because of elevated concentrations of pathogens in the source water and uncertainties about the performance of the treatment train. Except from *E. Coli* (see Table 17), measurements regarding other indicators or pathogens (e.g. rotavirus, cryptosporidium) in MAR influenced groundwater and treated wastewater after chlorination disinfection are missing.

Cultivation practices in Ezousa include crops eaten raw and where the edible portion is in direct contact with reclaimed water. Therefore, the highest water quality Class A applies which includes food and root crops consumed raw and covers all irrigation methods. From a human health perspective, minimum $\log_{10}$ removal requirements for Class A water are shown in Table 19.

Table 19. Minimum Log_{10} removal of treatment performance for irrigation (Alcalde-Sanz and Gawlik, 2017)

Reclaimed water quality class	Indicator microorganism	Group of microorganism	Performance targets for the treatment train ($\log_{10}$ reduction)
Class A	*E. coli*	Bacteria	≥ 5.0
	Total coliphages/F-specific coliphages/somatic coliphages*	Virus	≥ 6.0
	Clostridium perfringens spores/spore forming sulphite-reducing bacteria**	Protozoa	≥ 5.0

(*) Total coliphages is selected as the most appropriate viral indicator. However, if analysis of total coliphages is not feasible, at least one of them (F-specific or somatic coliphages) has to be analyzed.

(**) Clostridium perfringens spores is selected as the most appropriate protozoa indicator. However, spore forming sulfate-reducing bacteria is an alternative if the concentration of Clostridium perfringens spores does not allow to validate the requested $\log_{10}$ removal.

Alcalde-Sanz and Gawlik (2017) state that the required performance targets ($\log_{10}$ reduction targets) for the selected indicator microorganisms are to be reached considering the inflow to the WWTP as the initial point and the outlet of the additional treatment process as the final point. The performance of the technical pre-treatment (chlorination after activated sludge and slow sand filtration) at the WWTP is evaluated based on literature values (Table 20).

Table 20. Log_{10} removal rates of indicator organisms and pathogens of the treatment at WWTP Paphos (chlorination after activated sludge + slow sand filtration) (Zietzschmann et al., 2017)

Indicator microorganism	Group of microorganism	Performance of technical treatment
Total coliforms	Bacteria	2.4
Fecal coliforms	Bacteria	2.8
Enterococci	Bacteria	2.3
Clostridium	Bacteria	1.4
Giardia lambilia / spp.	Protozoa	0.2

Indicator microorganism	Group of microorganism	Performance of technical treatment
Cryptosporidium spp.		0.3
F-specific coliphages	Virus	0.6
Enterovirus		0.9

Based on this evaluation the technical pre-treatment for all groups of microoragisms is not in compliance with required minimum performance targets. Expecially protozoa, such as *Cryptosporidium* is known to be resistant to chlorine disinfection (WHO, 2006) and must be controlled by other means, such as ozone oxidation, membrane filtration or soil-aquifer passage. Taking the soil-aquifer passage as the additional treatment process, much higher removal rates can be assumed (Table 21).

Table 21. Log_{10} removal rates for the subsurface passage for bank filtration systems (WHO, 2011)

Group of microorganisms	Minimum removal (log_{10} reduction)	Maximum removal (log_{10} reduction)
Viruses	>2.1	8.3
Bacteria	2	>6
Protozoa	>1	>2

Removal rates shown in Table 21 are from bank filtration systems. These systems usually do not include a soil passage (i.e. unsaturated zone) such as SAT systems, but have a highly reactive hyporheic zone with organic rich layers favourable to removal of microorganism. As a first estimate, these numbers may serve as guiding values. It must be noted that removal during the soil-aquifer passage largely depends on hydraulic residence times, soil-aquifer type, pH and ionic strength. However, taking the performance of the technical treatment (Table 20) and the minimum removal of the subsurface as an additional treatment (Table 21), the various bacterias may show >3.4 – 4.8 log_{10} reduction, viruses >2.7 – 3 log_{10} reduction and protozoa >1.2 – 1.3 log_{10} reduction. All three groups of microorganisms are below required treatment performance (Table 19) for Class A irrigation water and indicate the requirements for further assessment.

5.3.2 Inorganic chemicals

From maximal risk perspective chloride (Cl), magnesium (Mg) and bicarbonate (HCO_3) are critical parameters exceeding irrigation recommendations and therefore do not meet the targeted environmental value. Specifically, Cl has high risk of polluting the groundwater, thus has been identified with high risk in the summary table of MAR hazards (Table 20). Mg and bicarbonate have similar values to the native groundwater, suggesting a low possibility of deteriorating the quality of the groundwater flow. No measurements have been found associated with Fluoride (F) and Iron (Fe) which is left as part of future work.

5.3.3 Salinity and sodicity

The potential for mixing with saline native groundwater is low. However, seawater intrusion and the dynamic of the salinity ingress at the coast line are recommended to be included in monitoring programmes.

5.3.4 Nutrients

The treated effluent shows elevated concentrations of nutrients such as Nitrate, P-Total compared to native groundwater (Table 16). Nutrients are therefore considered as a high risk for the native groundwater chemistry. From the irrigational perspective nutrients are within the range of recommended values and do not pose a risk.

5.3.5 Organic chemicals

Organic chemicals have not been monitored yet. Thus, their risk assessment in Ezousa aquifer has been classified as unknown (uncertain risk) and requires further investigations.

5.3.6 Turbidity and particulates

The public health and environmental risks associated with turbidity in relation to managed aquifer recharge include:

- reduced disinfection performance, leading to increased risk from microbial pathogens
- increased risk of transporting a range of contaminants that can sorb to particles
- reduced permeability due to clogging (operational risk)

Turbidity has not been monitored in the project. Thus, the risk assessment of turbidity and particulates in Ezousa aquifer has been classified as unknown (uncertain risk) and requires further investigations. As shown in Table 16, the treated wastewater effluent TSS was on average 8.37 mg/l, which satisfies the Class A irrigation standards (Table 19), with some sample instances exceeding the expected value of 10 mg/l.

5.3.7 Radionuclides

Radionuclides are radioactive isotopes or unstable forms of elements. Limestone, pygens, sands and clays constitute the Ezousa plain aquifer, which are usually low in radioactivity. Volcanic and metamorphic rocks can potentially release radionuclides to groundwater. Since no measurements are available from Ezousa catchment, the risk level is unknown.

5.3.8 Pressure, flow rates, volumes and groundwater levels

Groundwater levels show large seasonal fluctuations of 10-20 m. Infiltration rates depend, among others, on the depth-to-water below the infiltration basin and to ensure maximal removal it is necessary to maintain a certain thickness of unsaturated zone. Hazards are associated to human health end-point. It is recommended to adjust basin recharge depending on seasonal water levels.

5.3.9 Contaminant migration in fractured rocks and karstic aquifers

The intended MAR scheme is located in Ezousa gravel aquifer which is neither karstic nor fractured aquifer. Hence, this category does not apply to the Ezousa gravel aquifer.

5.3.10 Aquifer dissolution and stability of well and aquitard - pumping wells observed to be stable after 30 years

It was found that mineral dissolution and precipitation at specific locations in the aquifer have minor influence on the final water quality (Tzoraki et al., 2018).

5.3.11 Aquifer and groundwater-dependent ecosystems

This does not apply to Ezousa MAR scheme since no valuable ecosystem have been identified in the catchment.

5.3.12 Energy, greenhouse gas considerations and economical assessment

The amount of electric energy required to transfer the treated water from the WWTP to the infiltration basins is estimated to be around 1600 MWh per year. The annual consumption of electric energy for water pumping from the aquifer is estimated to be around 3000 MWh (internal report of WDD). Regarding pollutant emissions, CO_2 emmisions correspond to 0.5% of the total emissions of air pollutants on a national level, thus its effects on the atmosphere are considered to be negligible. From an economical point of view producing treated water (17 cents per cubic meter (WDD)) is much cheaper than producing desalinated water (on average, 75 cents per cubic meter).

5.4 CONCLUSIONS

We have conducted a risk assessment of Ezousas MAR scheme, which can be used as a guide for further preventive measures by the authorities.

Inorganic chemicals, such as chloride, magnesium and bicarbonate exceed the recommended irrigation values, with chloride exhibiting the highest risk. Lack of data regarding pesticides suggests that further samples are needed to evaluate the associated risks, while a quantitative analysis on organic chemicals and turbidity is yet to be conducted.

Overall, a more efficient control of the groundwater levels should be employed in order to improve groundwater quality. We recommend the use of remote sensing technologies, which can be used to monitor recharge/discharge rates. This type of methods has been successfully applied on several scenarios, such as reducing seawater intrusion and maximizing removal of pollutant during percolation. A routine monitoring should be performed to verify that the reclaimed water effluent is in compliance with the Class A quality criteria.

According to Table 18, additional samples are required to assess the risks related to pesticides and pharmaceuticals existing in both treated effluent and groundwater. These samples should also provide information regarding quantities not previously considered, such as turbidity and particulates.

Also, further monitoring is required to better assess the risks associated with salinity and water levels respectively. For that purpose, five sensors (two sensors in the coastal region and three sensors in the region between Ponds 3 and 5) are currently being installing that can provide high quality measurements for water electrical conductivity, temperature and pressure. These measurements will help to monitor potential hazards of inorganic materials such as Chloride and Sodium in a systematic way, and to adjust the recharge/ discarge rates to ensure the maximum removal rates. Furthermore, nitrate concentration will be measured manually every three months to ensure that it does not exceed the recommended values.

Eventually, these data will be used in numerical simulations to assess the spatio-temporal pattern of water and salt movements in the alluvium aquifer. Combining the findings from the experiments and the simulations will help us design, test and implement different practices to manage the associated risks.

6 RIVER WATER INFILTRATION AT AQUARENOVA, FRANCE

6.1 DESCRIPTION OF CASE STUY

Suez, operating the drinking water service since 2012 in the city of Hyeres-les-Palmiers, has developed the Aquarenova program for abstraction, control and restoration of natural resource, leading to a sober economic development (Figure 12). Aquarenova focuses on two goals. The first one aims to reconquer network performance in a context of sharp increases in the summer consumption (x4). The second axis is the restoration of the main water resource of the city, the Bas Gapeau aquifer. It is first of all a real-time abstraction control, based on a continuous monitoring of water level and electrical conductivity (salinity proxy) on several piezometers. The gradients method shall optimize abstraction without risking saline intrusion (detected during early 2000s). The results measured since 2012 are very significant. Suez also conducts aquifer recharge works by abstraction into the coastal river Roubaud during winter, in order to form a piezometric mound to be used in summer. This replenishment is operational from November 2015 to ensure the city water autonomy and to protect the water resource against saline intrusion even under severe drought.

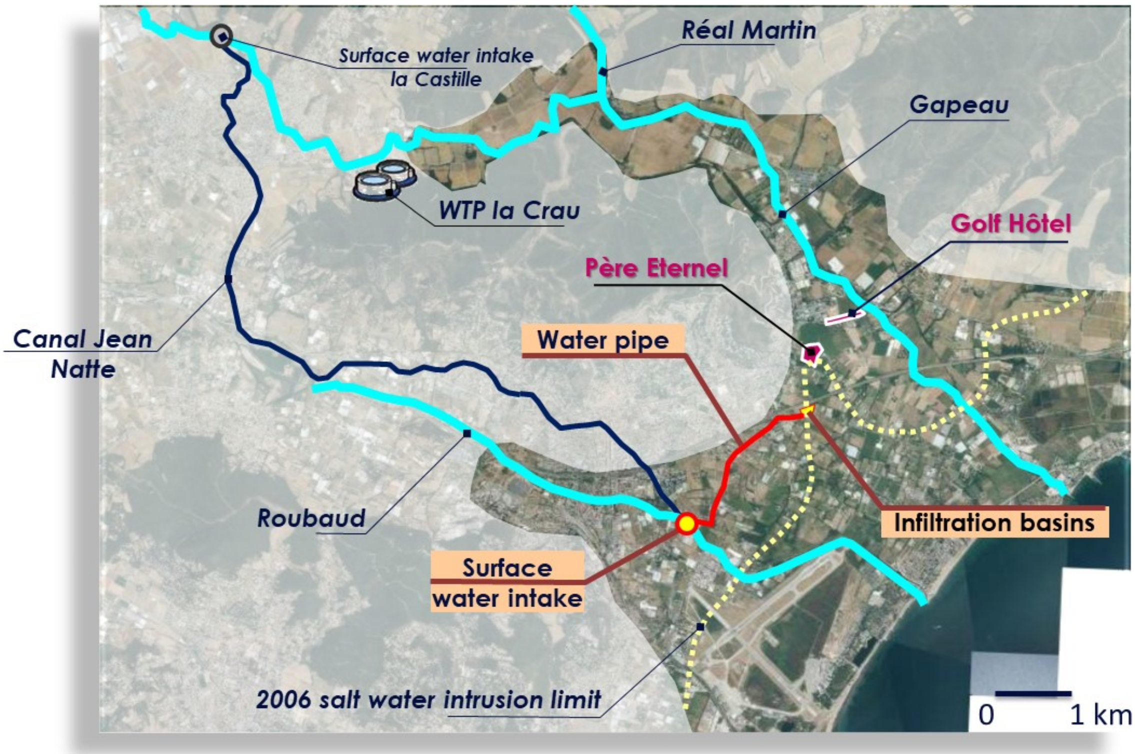

Figure 12. Site overview of the Aquarenova MAR project.

In this chapter, an analysis of the risks associated to the Aquarenova system with regard to drinking water and environmental uses is conducted. Figure 13 and Table 22 diplay the components of the Aquarenova MAR scheme.

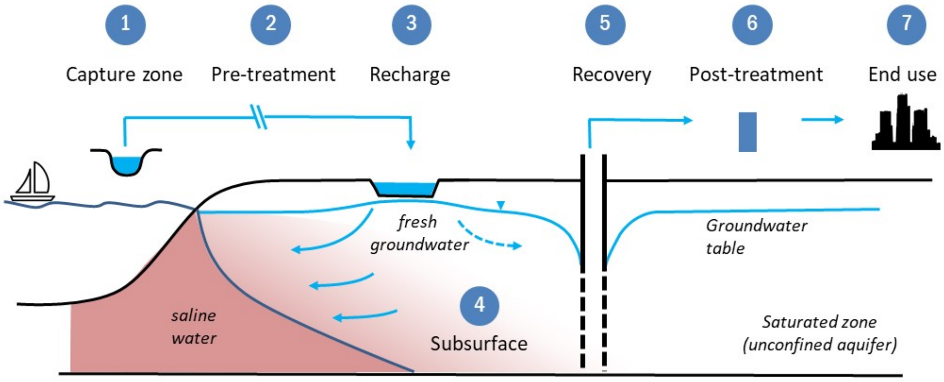

Figure 13. Schematic overview of MAR components at Aquarenova.

Table 22. Components of the Aquarenova. MAR system.

#	MAR component	Aquarenova MAR site
1	Capture zone	River Water
2	Pre-treatment	None, system shut down in case of exceedances of 13 parameters (see Table 23)
3	Recharge	Infiltration basins
4	Subsurface	Unconfined aquifer
5	Recovery	Drinking water wells 400 m upstream of the infiltration basins, recovered water <10%
6	Post-treatment	Chlorination at Père éternel water plant
7	End use	Drinking water, groundwater augmentation

The surface water for infiltration is abstracted from the Roubaud River by avoiding pre-treatment process, because the system is designed for shutting down in case of exceedance of one of the 13 monitored parameters (Table 23). The water is recharged to groundwater through two constructed infiltration basins with a total area of 1480 m^2. Then, most of the water allows the replenishment of the fresh water reserve to maintain a piezometric level above sea level (main objective of the recharge) while a part is recovered by the wells with a recovery rate <10%. The recovery rate was determined by using a numerical groundwater flow model. The aquifer itself is very locally confined in the area of the recharge basins and unconfined in the area of the wells. Afterwards, the recovered water goes to chlorination treatment process at Père éternel water plant before being distributed as drinking water (Figure 13 and Table 22).

Table 23. Water quality criteria for authorizing recharge at the Aquarenova MAR site.

Parameter	Measurement range	Lower threshold	Upper treshold	Purpose
pH	0 to 14	6	9	Pollution detection
Temperature	-20 to +35 °C	None	None	System operation
Electrical conductivity	0 to 2000 µS/cm	None	900 µS/cm	Pollution detection-Drinking water requirement
Turbidity	0.001 to 300 NFU	None	10 NFU	Clogging prevention
Ultra violet absorbtion	0.01 to 100 m^{-1}	None	None	Cloging prevention and pollution detection

Parameter	Measurement range	Lower threshold	Upper treshold	Purpose
ORP	-1000 to +1000 mV	None	None	Pollution detection
O_2	0.1 to 20 mg/L	None	None	Cloging from algae
Ammonium	0 to 1000 mg/L	None	None	Pollution detection- drinking water requirement
Nitrates	-	None	25 mg/l	Pollution detection-drinking water requirement
Potassium	-	None	None	Pollution detection
Chloride	-	None	100 mg/l	Drinking water requirement-saltwater monitoring
Hydrocarbons	Binary	No recharge if presence	No recharge if presence	Pollution detection
Mud level at intake	-	None	None	Pump operation
Level in Roubaud River		Enough water for pumping+ time period regulation authorization*	None	Environmental considerations for water life
Level in basin			Max level = Lower point of basin	
Level in well field aquifer			Max level = well field topography	Recharge not necessary

** the water intake has been designed to maintain a minimum discharge of 50 L/s. To do this, the section of the water intake occupies 2/3 of the width of the stream.*

Meassurements are automatic, performed continuously and stored every 15 minutes at SIRENE alert stations which is located at surface water intakes (see Figure 12):

- One at Castille for Intake from Gapeau river to canal Jean Natte (historical 15th century channel)
- One at Roubaud river (fed upstream by Canal Jean Natte) water intake that determines basins recharge

Figure 14 shows a detailed map of the infiltration site.

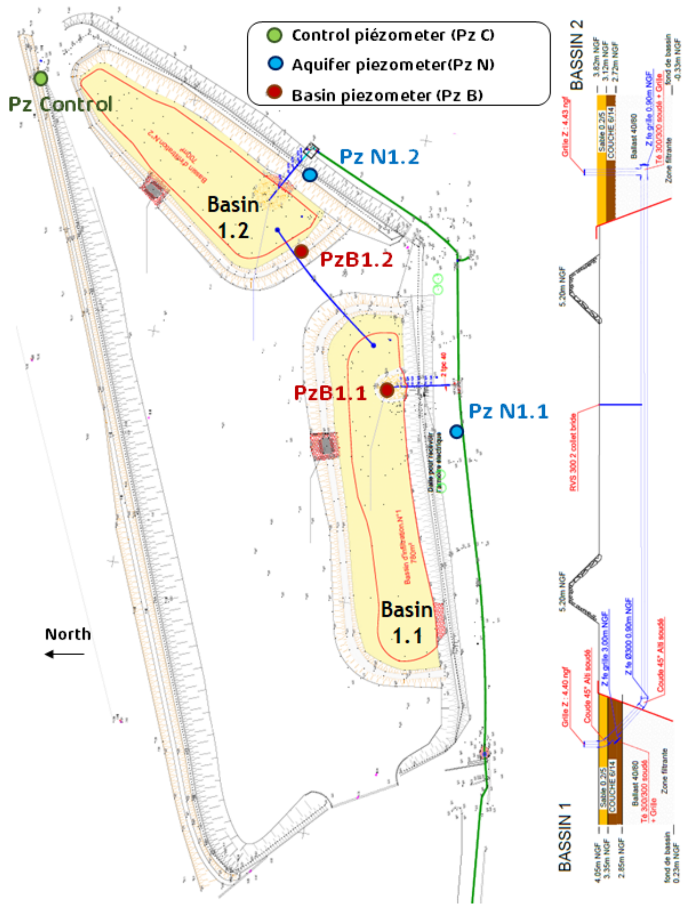

Figure 14. Detailed map of infiltration site.

6.2 ENTRY-LEVEL ASSESSMENT

The next table represents the entry-level exposing the existing information (Table 24).

Table 24. Entry-level assessment at the Aquarenova MAR site.

#	Attribute	Answer and explanation
1.	Intended water use	
	Is there an ongoing local demand or clearly defined environmental benefit for recovered water that is compatible with local water management plans?	YES - the Bas Gapeau alluvial aquifer is the main source of drinking water of the city of Hyères, situated in Gapeau alluvial area, 2.4 km far from Mediterranean sea. Between 2003 and 2011, high water deficits led to the establishment of drought committees and restrictions of use because of saltwater intrusion into the city's drinking water resources (Golf Hotel GH and Père éternel PE wellfields) that generated a chloride and conductivity exceedance of drinking water quality standards. The Aquarenova project has been implemented to avoid this problem.
2.	Source water availability and right of access	
	Is adequate source water available, and is harvesting this volume compatible with catchment water management plans?	YES - the raw water used for groundwater recharge comes mainly from Roubaud River (average discharge = 4 m^3/s). Existing infrastructure is Jean Natte canal, which is 100% supplied by the Gapeau River upstream from the confluence with the Réal Martin.

#	Attribute	Answer and explanation
		Raw water is collected from November to April when no water is used for irrigation (winter water surplus) and when Gapeau river is at a minimum level for environmental considerations. In the period, water is used for recharge at an authorized flow of 50 L/s (corresponding to 4,320 m^3/day - 648,000 m^3/year). Golf Hôtel and Père Eternel wellfields are almost exclusively fed by the water of the Gapeau river filtered through its banks.
3.	**Hydrogeological assessment**	
	Is there at least one aquifer at the proposed managed aquifer recharge site capable of storing additional water?	**YES** - the recharge is carried out in the Bas Gapeau aquifer where the Golf Hôtel and Père Eternel wells are located. Gapeau Aquifer is an alluvial aquifer connected to river Gapeau. Its thickness is from 5 to 25 m and is characterized by high heterogeneity sedimentation from clays to gravels that leads to local discontinuous lenses in the aquifer. Transmissivity has a range from 10^{-1} to 10^{-4} m^2/s. Average flow velocity is 1 m/day, in confined (well area) and unconfined context depending (recharge basin area) on the zone.
	Is the project compatible with groundwater management plans?	**YES** - Aquarenova project will make it possible to secure the water withdrawal regardless of the climatic conditions while keeping the salt wedge away.
4.	**Space for water capture and treatment**	
	Is there sufficient land available for capture and treatment of the water?	**YES** – The city of Hyères les Palmiers owns the necessary land for the project (agricultural zone).
5.	**Capability to design, construct and operate**	
	Is there a capability to design, construct and operate a MAR project?	**YES** - SUEZ has 60 years of experience to design, implement and operate this type of site.

6.3 DEGREE OF DIFFICULTY ASSESSMENT

The degree of difficulty assessment was conducted for the Aquarenova MAR project (Table 25).

Table 25. Degree of difficulty assessment at Aquarenova site.

#	Attribute	Answer and explanation	Actions required?
1.	**Source water quality with respect to groundwater environmental values**		
	Does source water meet the water quality requirements for the environmental value of ambient groundwater?	**YES** – no pre-treatment is necessary on source water from river Roubaud, that naturally feeds the aquifer where wells abstract water. The Roubaud River is fed by the Jean Matte Canal which is itself supplied by the Gapeau River. Hyeres town abstracted in 2018 4.6 millions m^3 from two well fields in this aquifer.	**NO** - system is fully operational and satisfies drinking water requirements
2.	**Source water quality with respect to recovered water end-use environmental values**		
	Does source water meet the water quality requirements for the environmental values of the intended end uses of the water on recovery?	**YES** – most of the water recharged in the aquifer goes to the sea and is not used for drinking water or any other use. Its role is to maintain the salt wedge as far as possible from the wellfields. Only a small portion of the recharge water is captured	**YES** - an artificial recharge of only 157,000 m^3 in 2018-19 have been enough to satisfy uses.

#	Attribute	Answer and explanation	Actions required?
		by the wellfields and its quality is that of groundwater (same source: Gapeau river)	
3.	**Source-water quality with respect to clogging**		
	Does source water have low quality; for example: total suspended solids (TSS) >10 mg/L; total organic carbon (TOC) >10 mg/L; total nitrogen >10 mg/L? And is the soil or aquifer free of macropores?	**NO** (most of time) – since the raw water used for recharging the aquifer is surface water, these parameters are occasionally exceeded.	**YES** - to avoid replenishing the system when these parameters are exceeded, 2 continuous quality measurement stations have been installed. A total of 13 parameters are continuously monitored. If a parameter exceeds the set threshold value, the replenishment system will no longer function. The system resumes operation automatically when the parameter falls below this threshold value. See Table 23.
4.	**Groundwater quality with respect to recovered water end-use environmental values**		
	Does ambient groundwater meet the water quality requirements for the environmental values of intended end uses of water on recovery?	**YES** – EU groundwater body FRDG343 has an evaluated state according 2000/60/CE directive with Père Eternel and Golf Hôtel stations considered in good state.	**NO.**
5.	**Groundwater and drinking water quality**		
	Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?	**YES** – Bas Gapeau's groundwater has a very good quality. This water does not undergo specific treatment except chlorination for drinking water supply.	**NO.**
6.	**Groundwater salinity and recovery efficiency**		
	Does the salinity of native groundwater exceed either of the following: (a) 10,000 mg/L (b) The salinity criterion for uses of recovered water?	**YES** – the Bas Gapeau aquifer is in hydraulic connection with the sea. As such, a salt wedge exists naturally in this aquifer. During periods of drought and overexploitation of the resource, the salinity of groundwater may exceed 10,000 mg/l.	**YES** - the Aquarenova system keeps the salt level at its natural position.
7.	**Reactions between source water and aquifer**		
	Are redox status, pH, temperature, nutrient status and ionic strength of groundwater similar to that of source water?	**YES** – The quality of the recharged water is similar to the aquifer because their origin is common: the river Gapeau. However, the redox status are different between the groundwater (Eh < 0 - semi-confined aquifer) and the surface water used to recharge the aquifer (Eh> 0).	**NO.**
8.	**Proximity of nearest existing groundwater users, connected ecosystems and property boundaries**		

#	Attribute	Answer and explanation	Actions required?
	Are there other groundwater users, groundwater-connected ecosystems or a property boundary within 100 – 1000 m of the MAR site?	**YES** – The Bas Gapeau aquifer is hydraulically connected to the Gapeau River. Groundwater abstraction and recharge have an effect on the flow of the river and therefore a potential impact on this ecosystem. The abstraction carried out in the Roubaud River (surface raw water used for aquifer recharge) also has an impact on this ecosystem.	YES - Water level measures in Roubaud have been implemented for the preservation of fish life and to maintain a minimum biological flow: this level is a criterion for stopping recharge (see Table 23).
9.	**Aquifer capacity and groundwater levels**		
	Is the aquifer confined and not artesian? Or is it unconfined, with a water table deeper than 4 m in rural areas or 8 m in urban areas?	Next to the wellfields, the aquifer is unconfined. Next to the groundwater recharge site (located a few hundred meters downstream hydraulics), the aquifer is semi-confined and slightly artesian. In that part, the aquifer is covered with 2 to 3 m of very little permeable silts. The static level is located about 2-3 m deep.	**NO.**
10.	**Protection of water quality in unconfined aquifers**		
	Is the aquifer unconfined, with an intended use of recovered water that includes drinking water supplies?	**YES** - at the wellfields, the aquifer is unconfined. At the level of the groundwater recharge site (located a few hundred meters downstream hydraulics), the aquifer is semi-confined.	**NO.**
11.	**Fractured rock, karstic or reactive aquifers**		
	Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals?	**NO** - sandy aquifer.	**NO.**
12.	**Similarity to successful projects**		
	Has another project in the same aquifer with similar source water been operating successfully for at least 12 months?	**NO** - not in the same aquifer.	**NO.**
13.	**Management capability**		
	Does the proponent have experience with operating MAR sites with the same or higher degree of difficulty, or with water treatment or water supply operations involving a structured approach to water quality risk management?	**YES** – Suez is an expert in these topics. It is the only company in France to have implemented this type of site for 20 years.	**NO.**
14.	**Planning and related requirements**		
	Does the proposed project require development approval? Is it in a built up area; built on public, flood-prone or steep land; or close to a property boundary? Does it contain open water storages or engineering structures; or is it likely to cause	**NO** - question is not relevant, because the project is already in operation since end 2015.	**NO.**

#	Attribute	Answer and explanation	Actions required?
	public health or safety issues (e.g. falling or drowning), nuisance from noise, dust, odour or insects (during construction or operation), or adverse environmental impacts (e.g. from waste products of treatment processes)?		

6.4 MAXIMAL RISK ASSESSMENT

The maximum risk assessment is considered as a worst case scenario for human health or environment, as if there would not be any remediation measures in place (Table 26).

Table 26. Maximal risk assessment for the Aquarenova site.

MAR hazards		Human health risk at end-point	Environmental risk at end-point
1.Pathogens		L	L
2.Inorganic chemicals	Electric conductivity	H	H
	pH	L	L
	Sodium	L	L
	Chloride	H	H
	Boron	L	L
	Bicarbonate	L	L
3. Salinity and sodicity		H	H
4. Nutrients	Nitrate	L	L
	Total nitrogen	L	L
	Total phosphorous	L	L
	Organic carbon	L	L
5.Organic chemicals	Pesticides	L	L
	Pharmaceuticals and others	L	L
6. Turbidity and particulates		L	L
7. Radionuclides		L	L
8. Pressure, flow rates, volumes and groundwater levels		L	H
9. Contaminant migration in fractured rocks and karstic aquifers		-	-
10. Aquifer dissolution and stability of well and aquitard - pumping wells observed to be stable after 30 years		L	L
11. Aquifer and groundwater-dependent ecosystems		L	H
12. Energy, greenhouse gas considerations and economical assessment		L	L

L= Low risk; H= High risk

6.4.1 Groundwater salinity and recovery efficiency

The Aquarenova site has an early warning system in place which is composed of a piezometer network for the monitoring of groundwater salinity and recovery efficiency. The system includes the following components:

- Continuous measurement of water levels for 10 piezometers, to monitor that water level does not decrease under +0,4m above sea level. Piezometers are situated between well field and the Mediterranean sea;
- Vertical electrical conductivity for 7 piezometers every 3 months;
- Local piezometers (Pz N, Pz C, Pz B) for monitoring recharge and water quality (see Figure 14).

Before and after recharge period, water analyses are made on Pz C Piezometer in order to evaluate the evolution of groundwater quality.

6.4.2 Inorganic chemicals/ salinity and sodicity

At the intake:

- Electrical conductivity is controlled by the upper threshold of 900 µS/cm
- Chloride is controlled by the upper threshold of 100 mg/L

The salt wedge displacements have consequences on: (i) the drinking water supply if water quality (salinity) does not respect drinking water quality requirements,and (ii) the environment since the aquifer in a good state constitutes an environmental patrimony that has to be preserved, for itself and for associated aquatic environments (wet areas for example).

6.4.3 Pressure, flow rates, volumes and groundwater levels

The water management issue is saltwater intrusion evolution due to low groundwater levels that generates inflows from the sea in the freshwater aquifer. So piezometric level has to be monitored and maintained in order to avoid saltwater intrusion. This can be done by monitoring the low flow rates and catchment volumes (mainly for drinking water supplying) but this step is not sufficient: recharge had to be set up in addition.

6.4.4 Aquifer and groundwater-dependent ecosystems

The shallow aquifer is in relation with associated aquatic environments (wet areas, river). For this project for example, environmental compensation and measures for a specific species of plant (*Phalaris aquatica*) had to be set up and its development is monitored every year by an independent authority.

6.4.5 Other pollutants

Other pollutants (for example pesticides or nitrates) are monitored by sanitary authorities and operator because of human water consumption. Limits are respected, no particular problem is detected for the moment, and water supply is in function. So even though risk is always present since aquifer is not naturally protected, risk level is not significantly higher than other installations.

6.5 CONCLUSIONS

Restoring groundwater levels prevents saltwater intrusion for benefit of human water supply, patrimonial stakes and preservation of associated aquatic environments.

The Aquarenova site is designed to repel the saltwater wedge in the alluvial aquifer of the Lower Gapeau. The water used for groundwater recharge is of very good quality. Occasionally, the water is more turbid during rainy episodes, but the system implemented makes it possible to stop recharging when the turbidity exceeds 10 NTU. From this point of view, the risks are very low.

The main risk identified to date is the make-up capacity, which is currently limited to 50 L/s from November to April, or 648,000 m^3 over the period. Indeed, in the event of an exceptional drought cycle, it will be necessary to check that the volume replenished is sufficient for the piezometric levels to be higher than sea level (necessary condition to keep the saltwater wedge at a distance). The main risk therefore relates to an increase in salinity at the level of drinking water wells linked to the intrusion of the saltwater wedge. As part of the SMART-Control project, the piezometric monitoring network will be completed, notably on the left bank of the Gapeau river to better understand the dynamics of the saltwater in this sector. Water level and conductivity measurement probes will be installed.

The groundwater model implemented within the framework of the project will also make it possible to model climate scenarios to assess this risk.

7. INFILTRATION BASINS, TRENCHES AND NEAR-NATURAL PONDS OF THE WATERWORKS BERLIN-SPANDAU, GERMANY

7.1 DESCRIPTION OF CASE STUDY

The waterworks Berlin-Spandau was built for the public water supply of the once independent city of Spandau and began groundwater abstraction in 1897 by eight siphon pipe wells. Along with the population growth and growing water demand, the waterworks abstracts nowadays 25-30 Mm^3/year (Möller and Burgschweiger, 2008) and recharges 15-20 Mm^3/year through constructed infiltration basins and near-natural lakes/ponds and ditches.

The catchment of the waterworks Berlin-Spandau is situated in the vast Berlin-Warsaw ice-marginal valley (Urstromtal) and comprises in the central and southern part mainly urbanized areas and in the northern part uninhabited areas of the Spandau forest. The Spandauer Forst is one of the largest forest areas in Berlin and home to numerous groundwater-dependent ecosystems (GDE), such as the Kuhlake river system, swamps and wetlands (Teufelsbruch and Rohrpfuhl). The wetlands are designated as nature reserves and the entire Spandau forest is a Natura 2000 protected site (Figure 15) listed under both, the European Union (EU) Birds Directive and the Habitats Directive.

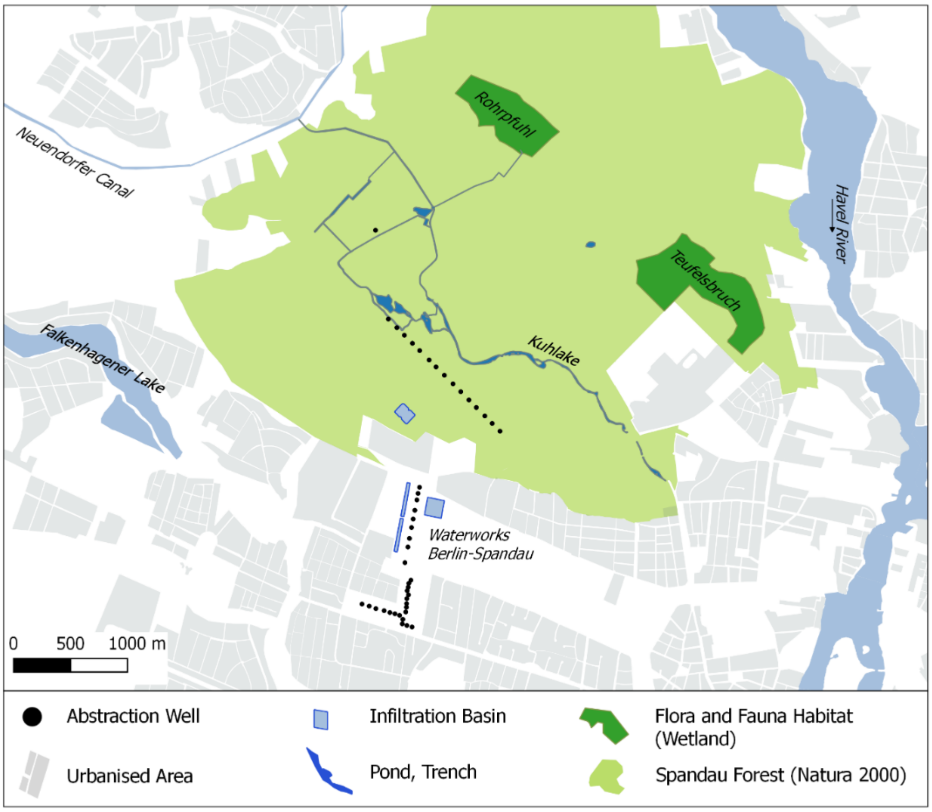

Figure 15. Overview of Waterworks Berlin-Spandau.

The source water for infiltration at the waterworks Berlin-Spandau is abstracted from the Upper Havel River and pre-treated in a Surface Water Treatment Plant (SWTP) by mechanical cleaning, flocculation and rapid sand filtration. The pre-treated water is then recharged to the groundwater through constructed infiltration basins and various lakes, trenches and ponds (Kuhlake).

The constructed infiltration basins have an infiltration area of approx. 54,000 m^2 and show infiltration rates of up to 3.4 m/d with large variation due to geometry and hydraulic properties of the subsurface. A layer of technical sand of approx. 0.4-0.8 m thickness covers each infiltration basin bed. The Kuhlake system consists of 137,000 m^2 of water area, of which approx. 59,000 m^2 are rivers/ponds and 78,000 m^2 are trenches. The Kuhlake is connected to the Neuendorfer Canal. In contrast to the constructed infiltration basins, the Kuhlake system is not maintained (e.g. cleaning) on a regular basis. Infiltration rates are therefore one order of magnitude lower. However, the recharge water percolates through the soil (Kuhlake) and/or the unsaturated zone and reaches the free water table of the aquifer. The aquifer itself consists of fluvial-glacial sand and marl deposits of quaternary to tertiary age. The water is recovered by 44 vertical wells and 1 horizontal well. The recovered water is aerated to precipitate dissolved iron/manganese and subsequently filtered through rapid sand filters, before being distributed to the water net as drinking water (Figure 16 and Table 27).

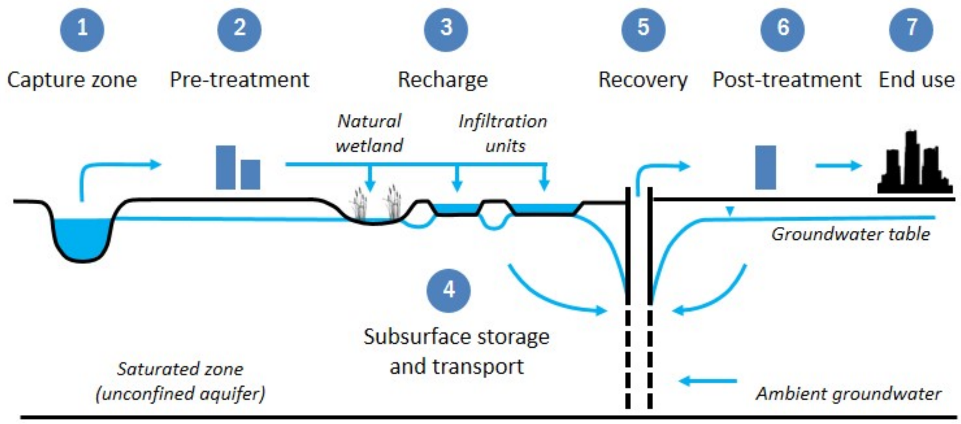

Figure 16. Schematic overview of MAR components at Berlin-Spandau.

Table 27. Components of the Berlin-Spandau MAR system.

#	MAR component	Berlin-Spandau MAR site
1	Capture zone	River Water (Upper Havel River)
2	Pre-treatment	Shell filter, flocculation, rapid sand filtration
3	Recharge	Wetlands, ditches, ponds, infiltration basins
4	Subsurface	Quaternay glacial and peri-glacial sands and marls, tertiary sands
5	Recovery	3 well fields (44 vertical wells, 1 horizontal well)
6	Post-treatment	Aeration, rapid sand filtration
7	End use	Drinking water, ecosystems

7.2 ENTRY LEVEL ASSESSMENT

The MAR facilities at Berlin-Spandau are under operation for several decades and do not require entry-level assessment. The checklist assessments (Table 28 and Table 29) may serve as introductory assessment to the MAR scheme.

Table 28. Entry-level assessment of Waterworks Berlin-Spandau.

#	Attribute	Answer and explanation
1.	**Intended water use**	
	Is there an ongoing local demand or clearly defined environmental benefit for recovered water that is compatible with local water management plans?	**YES** - the waterworks Berlin-Spandau currently abstracts on average 75,000 m³/day (1995-2017) of groundwater to cover part of Berlin´s drinking water demand. Environmental goals are defined to support groundwater dependant ecosystems in the waterworks (WW) catchment. Regulatory approval procedures are established and improved on a regular basis.
2.	**Source water availability and right of access**	
	Is adequate source water available, and is harvesting this volume compatible with catchment water management plans?	**YES** - source water is derived from the Upper Havel River. Average discharge of Upper Havel River is 13.1 m³/s (1977-2016), minimum discharge is 4.37 m³/s. Average abstraction for groundwater augmentation is 0.46 m³/s (1995-2017). Seasonal limitations during times of low discharge and high demand may occur.
3.	**Hydrogeological assessment**	
	Is there at least one aquifer at the proposed managed aquifer recharge site capable of storing additional water?	**YES** - the unconfined aquifer of Quaternary to Tertiary age is in hydraulic connection to infiltration ponds. It is the main aquifer of Berlin's drinking water supply.
	Is the project compatible with groundwater management plans?	
4.	**Space for water capture and treatment**	
	Is there sufficient land available for capture and treatment of the water?	**YES** - MAR infrastructure, inclusive pre- and post-treatment facilities are constructed and operated since the 1980´s.
5.	**Capability to design, construct and operate**	
	Is there a capability to design, construct and operate a MAR project?	**YES** - the operator Berlin Waterworks (Berliner Wasserbetriebe, BWB) has experience to operate and maintain infiltration ponds since the 1980´s at WW Spandau and abstraction wells since about 100 years.

At this entry level, some vulnerable points already become visible, e.g. answer to question two indicates vulnerability towards source water availability. However, abstraction volumes from the upper Havel are currently discussed and subject to future licensing procedures.

7.3 DEGREE OF DIFFICULTY ASSESSMENT

This part of the assessment is to show the site-specific risks and challenges and how remediation measures are implemented. It also aims to disclose residual risks that are subject to further improvements.

Table 29. Degree of difficulty assessment of Waterworks Berlin-Spandau.

#	Attribute	Answer and explanation	Actions required?
1.	**Source water quality with respect to groundwater environmental values**		

#	Attribute	Answer and explanation	Actions required?
	Does source water meet the water quality requirements for the environmental value of ambient groundwater?	**NO** - the highest environmental value of the aquifer is drinking water production. In addition, the conservation and restoration of GDE is the environmental goal.	**YES** - pre-treatment of source water in place to meet environmental values (see below).
2.	**Source water quality with respect to recovered water end-use environmental values**		
	Does source water meet the water quality requirements for the environmental values of the intended end uses of the water on recovery?	**NO** - Upper Havel River water does not meet the German drinking water standards (TrinkwV, 2018) for some parameter, e.g. pathogens.	**YES** - hygienic safety of recovered water is ensured by sufficient residence time in the subsurface. However, some wells with critical residence time require additional investigations to evaluate hazard attenuation processes during infiltration and recovery, see section 0 for further explanation.
3.	**Source-water quality with respect to clogging**		
	Does source water have low quality; for example: total suspended solids (TSS) >10 mg/L; total organic carbon (TOC) >10 mg/L; total nitrogen >10 mg/L? And is the soil or aquifer free of macropores?	NO - source water (Upper Havel River) nitrate and nitrogen without treatment annual average: NO_3-N < 1 mg/L TSS < 10 mg/L TOC ~ 5 mg/L No macropores known.	**YES** - although source water is of good quality, it is pre-treated to minimize clogging in infiltration basins and respect sensitive nutrient balance of GDE, see section 0 for further explanation.
4.	**Groundwater quality with respect to recovered water end-use environmental values**		
	Does ambient groundwater meet the water quality requirements for the environmental values of intended end uses of water on recovery?	**YES** - ambient groundwater from target aquifer has drinking water quality.	**NO** actions required.
5.	**Groundwater and drinking water quality**		
	Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?	**YES** - both drinking water and conservation of GDE.	**YES** - environmental monitoring of biological and hydraulic conditions of GDE in place.
6.	**Groundwater salinity and recovery efficiency**		
	Does the salinity of native groundwater exceed either of the following: (a) 10 000 mg/L (b) The salinity criterion for uses of recovered water?	**NO** - fresh water aquifer, electrical conductivity 300-500 µS/cm	**NO** actions required.
7.	**Reactions between source water and aquifer**		
	Are redox status, pH, temperature, nutrient status and ionic strength of groundwater similar to that of source water?	**YES** - similar pH, redox, ionic strength.	**NO** actions required.
8.	**Proximity of nearest existing groundwater users, connected ecosystems and property boundaries**		

#	Attribute	Answer and explanation	Actions required?
	Are there other groundwater users, groundwater-connected ecosystems or a property boundary within 100–1000 m of the MAR site?	**YES** - ~100 m to urban settlements (private garden irrigation) and ~1200 m to GDE measured from abstraction wells.	**YES** - to protect nearby settlements from rising groundwater levels.
9.	**Aquifer capacity and groundwater levels**		
	Is the aquifer confined and not artesian? Or is it unconfined, with a water table deeper than 4 m in rural areas or 8 m in urban areas?	**YES** - unconfined aquifer, water table 2-5 m below ground surface.	**NO** actions required.
10.	**Protection of water quality in unconfined aquifers**		
	Is the aquifer unconfined, with an intended use of recovered water that includes drinking water supplies?	**YES** - see above.	**NO** further actions required.
11.	**Fractured rock, karstic or reactive aquifers**		
	Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals?	**NO** - not highly reactive, siliciclastic porous media, minor lignite, some reductive dissolution of iron.	**NO** actions required.
12.	**Similarity to successful projects**		
	Has another project in the same aquifer with similar source water been operating successfully for at least 12 months?	**YES** - in Berlin about 70% of municipal drinking water is derived from MAR, i.e. induced bank filtration and infiltration ponds (Schulze, 1997; Statistisches Bundesamt, 2015).	**NO** actions required.
13.	**Management capability**		
	Does the proponent have experience with operating MAR sites with the same or higher degree of difficulty, or with water treatment or water supply operations involving a structured approach to water quality risk management?	**YES** - site owner is running MAR sites since decades.	**NO** actions required.
14.	**Planning and related requirements**		
	Does the proposed project require development approval? Is it in a built up area; built on public, flood-prone or steep land; or close to a property boundary? Does it contain open water storages or engineering structures; or is it likely to cause public health or safety issues (e.g. falling or drowning), nuisance from noise, dust, odour or insects (during construction or operation), or adverse	**NO** - not relevant since MAR scheme is running for decades.	**NO** actions required.

#	Attribute	Answer and explanation	Actions required?
	environmental impacts (e.g. from waste products of treatment processes)?		

7.4 MAXIMAL RISK ASSESSMENT

The maximal risk assessment gives an overview on potential hazards without any remediation measure in place. Human health at end-point is drinking water and the environmental risk at end-point are the GDE.

Table 30. Maximal risk assessment of waterworks Berlin-Spandau.

MAR hazards		Human health risk at end-point	Environmental risk at end-point
1.Pathogens – few abstraction wells with travel time	~50 days	H	L
2.Inorganic chemicals	Electric conductivity	L	L
	pH	L	L
	Sodium	L	L
	Chloride	L	L
	Boron	L	L
	Bicarbonate	L	L
3. Salinity and sodicity		H	L
4. Nutrients	Nitrate	L	H
	Total nitrogen	L	H
	Total phosphorous	L	H
	Organic carbon	L	H
5.Organic chemicals	Pesticides	L	L
	Pharmaceuticals and others	L	L
6. Turbidity and particulates		L	H
7. Radionuclides		L	L
8. Pressure, flow rates, volumes and groundwater levels		H	H
9. Contaminant migration in fractured rocks and karstic aquifers		-	L
10. Aquifer dissolution and stability of well and aquitard - pumping wells observed to be stable after 30 years		L	L
11. Aquifer and groundwater-dependent ecosystems		H	H
12. Energy, greenhouse gas considerations and economical assessment		L	L

7.4.1 Pathogens

From a hygienic perspective, German Drinking Water Guidelines (DVGW, 2006) recommend a mean residence time of at least 50 days to ensure sufficient removal of pathogens in the subsurface. Most abstraction wells of the waterworks Berlin-Spandau are in sufficient distance and depth to the area of recharge and subsurface residence times are estimated to be >>50 days. However, few wells at the well field north (between infiltration basins) show subsurface residence times, measured by environmental tracers, around 50 days (Sprenger et al., 2017).

Routine microbiological measurements are carried out in accordance to German Drinking Water Ordinance (TrinkwV, 2011) at the outlet of the waterworks after post-treatment and at the collecting main of the well fields. After post-treatment, bacteriological quality is in accordance to German Drinking Water Ordinance (TrinkwV, 2011). However, microbial measurements of the well field north show a few detections of *Coliform bacteria and Enterococcus*, while *E.Coli* was not detected (Table 31).

Table 31. Microbiology measured in source water at Upper Havel and well field north at WW Berlin-Spandau

Microbiology	Source water – Upper Havel River (cfu/100 mL)		Abstracted Groundwater – Well field north (cfu/100 mL)***	
	n/n positive	Min -Max	n/n positive	Min-Max
E.Coli	127/127	15 – 460*	365/0	0
Faecal streptococci	114/114	15 – 357*	-	-
Coliform bacteria	127/127	30 – 4600*	365/2	0 – 1
Enterococcus	256/256	7.5 - 93**	361/3	0 – 2
Clostridium perfringens	-	-	358/0	0

measured at Upper Havel (Konradshöhe), monthly measurements from 2005-2015 (SenUVK data unpublished); **measured at WW intake (Bürgerablage), fortnightly measurements from 2009-2019 (BWB data unpublished); * measured at well field main, fortnightly measurements from 2011-2019 (BWB data unpublished)*

According to §5 of the Drinking Water Ordinance (TrinkwV, 2011), pathogens may not be contained in drinking water "at concentrations which cause damage to human health", but certain thresholds or theoretical goals are not given. Viral indicators such as somatic coliphages or viral pathogens are not measured on a regular basis; no data for abstraction wells in Berlin-Spandau is available.

In order to achieve higher confidence of the subsurface as a hygienic barrier, and to confirm that safe water quality is being achieved, it is necessary to carry out verification measurements and theoretical principles based on WHO guidelines (WHO, 2016).

7.4.2 Nutrients, turbidity and particulates

In order to reduce algae formation and other biologically induced clogging processes in the natural and constructed recharge facilities, source water is pre-treated by mechanical cleaning via shell separator followed by rapid sand filtration through eight open multilayer rapid sand filters with prior addition of $FeCl_3$ and cationic polyacrylamide as flocculation aid. The primary objectives of SWTP are the retention of suspended solids (≤ 1 mg/L annual mean) and total dissolved phosphorus (≤ 50 µg/L annual mean). Though target values are met during most of the year, the main operational issue remains the clogging of the basin beds thereby reducing the infiltration rates. Since the clogging mainly develops on the surface of basins bed sand, it allows the mechanical removal of the upper layer material, washing and back filling to the basins. In case the infiltration rate decreases below a certain threshold (usually < 1 m/d), the cleaning procedure is started.

7.4.3 Pressure, flow rates, volumes and groundwater levels

To protect settlements in the proximity of the infiltration basins against elevated groundwater levels, infiltration volumes of some basins are restricted.

7.4.4 Aquifer and groundwater-dependent ecosystems

For the preservation of the GDE, seasonal threshold groundwater levels are established in the proximity of Teufelsbruch and Rohrpfuhl. Threshold levels correspond to near-natural groundwater levels that prevailed prior to the intensive use of groundwater. Groundwater levels are readily monitored by pressure transducers and assessed on a regular basis.

7.4.5 Organic chemicals

With increasing contributions of wastewater effluents in streams, the relative portion of wastewater-derived compounds such as pharmaceuticals will also increase. While the impact of wastewater-derived compounds is at some waterworks in Berlin an issue, the proportion of wastewater effluents at the Upper Havel during both, average and low flow conditions is <5% (Drewes et al., 2018). Hence, organic trace compounds in the Upper Havel River are likely absent or below health advisory values.

7.5 CONCLUSION

The drinking water production in Berlin-Spandau does not involve hygienic post-treatment on a regular basis. It is the dedicated goal of BWB to maintain a natural water treatment without additional technical (physical or chemical) treatment barriers. Therefore, subsurface residence time from the area of recharge to the abstraction is a crucial parameter to ensure sufficient attenuation for hygienic and other undesired substances. Hydraulic monitoring of abstraction wells with critical residence times should be taken into account. Monitoring may be based on heat transport of seasonal temperature fluctuations in source water and recovery wells.

The soil-aquifer passage is an effective barrier for pathogenic microorganisms, but uncertainties regarding site-specific transport properties exist. The maximal risk assessment suggests exceedances of microbial indicators at few abstraction wells with subsurface residence time ~50 days. Additional measures should be taken into account in particular because treatment train does not include physical or chemical post-treatment. These measures should be taken by the utility and overseeing regulatory bodies and should include a full risk assessment following principles of the WHO Water Safety Plan concept.

According to the identified hazards, modelling approaches to be realized within the SMART-Control project will focus on the hydraulic characterisation of the site in combination with quantification of microbial risk assessment. Different approaches will be tested to characterize microbial dynamics, e.g. online flow zytometry. Flow zytometry will help to understand the influence of operational practices (e.g. intermittent abtraction and infiltration) on microbial concentrations and to define microbial baseline.

8. SUMMARY AND CONCLUSIONS

The risk assessments at the various case study sites are useful to assist in clarifying which actions or further investigations are required to identify and reduce the uncertainty of risks and to implement remediation measures if necessary. These risks can be reduced but never entirely eliminated through high quality and more detailed aquifer characterisation. Monitoring can play a key role in the risk assessment and management process. Operational monitoring systems are of particular importance as they provide timely information for use as critical control points in the risk management plan, often includes supervisory control and data acquisition and web-based reporting systems that provide near real-time data (NRMMC, 2004).

Additional monitoring at the MAR sites e.g. for specific contaminants or on a more regular basis was identified as a measure to reduce the uncertainty of risks. At the case study sites, a real-time monitoring system, if not yet present, will be installed to accomplish this and groundwater sampling including laboratory analysis of specific parameters at some case study sites, such as nitrate in Cyprus, will be undertaken. In addition, the setup of numerical groundwater flow and transport models could help to answer specific risk-related questions regarding e.g. underground travel times (Berlin) or seawater intrusion (Recife, Brazil) especially when considering the newly gained groundwater measurement data through the real-time monitoring system.

SMART-Control proposes to develop and implement an innovative web-based, real-time monitoring and control system (RMCS) in combination with risk assessment and management tools. The experience gained during the compilation of the report will be used to develop a web-based risk assessment tool on the INOWAS platform (www.inowas.com) based on the Australian guidelines to assist in the entry-level risk assessment at MAR sites.

This report shows how site-specific hazards have been evaluated to varying degrees depending upon the level of risk assessed at each project development stage at various MAR sites. This report will contribute to the first step of the information value evaluation on the various case studies in order to assess the benefits brought by the RMCS under SMART-CONTROL project.

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