ADAPTIVE SUBSURFACE WATER SOLUTIONS ACROSS CONTINENTS

Anika Christiane Conrad, Maike März, Ronjon Chakrabarti

adelphi Research gGmbH, Department for Water, Alt-Moabit 91, 10559 Berlin, Germany.
E-mail: conrad@adelphi.de

Submitted 26 September 2019; accepted 23 December 2019

Abstract. Temporary water scarcity and saltwater intrusion in coastal aquifers are problems which are common in various parts of the world and can be addressed by subsurface water solutions (SWS). SWS comprise of various intelligent well and sensor configurations for different hydrogeological aquifer conditions. They can be combined for aquifer storage, (treatment), and recovery (AS(T)R), managed aquifer recharge (MAR), and various water reuse options including rainwater harvesting or treated waste water usage. To date, pilot SWS are implemented in the Netherlands, where they demonstrate highly beneficial applications for the above-mentioned purposes. This report presents the technology transfer to other coastal regions by utilising a participatory co-design approach with key stakeholders and institutions. The methodology developed mainly consists of two missions, which were applied to four target regions: Brazil, Mexico, Vietnam, and Cyprus. In these regions stakeholders were identified, framework conditions were assessed, and public events and project development workshops were conducted aiming to adapt the technology and implementation approach to the specific local requirements. General drivers and barriers were identified for institutional, political, legal, and socio-economic aspects. The report provides an outline of general implementation concepts, region-specific prerequisites, and ideas for follow-up projects.

Keywords: aquifer storage and recovery, innovative water technologies, subsurface water solutions, sustainable water management.

Introduction

Groundwater is a key natural recourse and home to a variety of ecosystems that provide valuable services supporting socioeconomic development worldwide (Griebler, Avramov, 2015). However, especially in coastal cities where many of the world's most productive and economic centres are located (UN-HABITAT, 2011), groundwater resources are suffering from increasing exploitation. This leads to sinking groundwater levels, soil subsidence hazards, higher contamination risks, and possibly saltwater intrusion. The World Economic Forum ranked the water crises fifth in terms of impact. The reason for this is the decreasing quality and quantity of freshwater, which have a negative impact on human health and economic activity (World Economic Forum, 2018).

In order to meet growing water demand and reduced groundwater availability in coastal areas a number of eco-innovative technology concepts (named as Subsurface Water Solutions (SWS)) for protection, enlargement, and utilization of freshwater resources in aquifers prone to salinization have been developed in the last years based on Managed Aquifer Recharge (MAR) and Aquifer Storage and Recharge (ASR) concepts (Zuurbier et al., 2016). Despite the great success of MAR and ASR in water storage and treatment in saltwater impacted aquifers, traditional MAR and ASR concepts face several challenges such as buoyancy effects and up-coning, which often make them inefficient. SWS tackle the issue of saltwater intrusion by practical tools and concepts combining innovations in water well design and configuration for a more robust, sustainable, and cost-efficient freshwater management in coastal areas. Pilots of the technology concepts have been successfully implemented in the Netherlands (Zuurbier et al., 2014; Zuurbier et al., 2015; Zuurbier et al., 2016), where they demonstrate capacity growth for sustainable freshwater supply, energy reduction, financial savings, and increased yields in food production.

The EU project H2020 "SUBSOL- bringing coastal SUBsurface water SOLutions to the market" was launched in 2016 with the aim of contributing to the establishment of SWS as a viable solution in other countries. A consortium of research institutes, technology small and medium sized enterprises (SMEs), consultants, and end-users such as Farmers, Hotels and public market places across Europe came together to jointly develop adapted concepts and solutions for different regions. The overall approach followed the subsequent aims: Continuation and market replication of successful full-scale pilots, standardization and commercialization including the development of business cases and decision support tools, assessment of market readiness as well as policy and legal framework conditions, capacity building activities, and joint development of solution concepts with local stakeholder in selected regions worldwide.

This article aims to inform about future SWS application options by presenting and discussing the approaches and results of transferring SWS into selected target countries, namely Brazil, Mexico, Vietnam, and Cyprus. The road map for these approaches is reprocessed in such a way that the SWS concepts can be
easily adapted for similar projects within different environmental and socio-economic contexts. The article is divided into a brief introduction to the general methodology of the technology transfer strategy, an overview of the three main SWS technology concepts (Freshkeeper, Freshmaker and ASR-Coastal) and the implementation concepts developed in close cooperation with local stakeholders for the target countries, whereby the Brazil case matured further than the cases in Vietnam, Cyprus and Mexico.

Methodology
Despite the technical progress that SWS reached in the last years in the Netherlands, a well-conceptualised strategic approach was needed in order to adapt the technology to local conditions and demands in the four target regions Brazil, Mexico, Cyprus, and Vietnam.

The overall approach of solution adaptation for the technology transfer was divided into four steps. In a first step information and experiences about the successful development and implementation of the technology were gathered at the SWS reference sites in the Netherlands. The second mission focussed on understanding the processes involved in the replication of SWS in other countries such as Baja California, Mexico, Greece, and Denmark, and distilling barriers and drivers for a successful transfer of the technology concept under varying conditions. A market scan, which includes a legal and policy framework analysis, was conducted in order to analyse the conditions in the target regions, which was complemented and verified by the third and fourth step, conducted in the target regions. In this article, these last two steps in are described in more detail and for simplicity reasons are referred to as first and second mission to the target regions.

Awareness building activities and assessment of framework conditions took place in the first mission in the period from December 2016 to March 2017. On this basis, the SubSol team conducted a further visit to each country one year later from January to April 2018 with the aim to build capacities and develop solution concepts in close cooperation with previously identified local stakeholders. For these missions a communication and dissemination plan (Bunsen et al., 2017) was developed. Throughout the entire project, a focus was on maintaining good cooperation with local key stakeholders. They were involved in the planning right from the beginning, resulting in divergent implementations of the two missions in each country as well as different types of stakeholders getting involved. The complementary trust building activities (Chakrabarti et al., 2017) will be described in more detail in a separate "Lessons learned" publication and will be touched on in this article.

First mission to the target regions: Awareness generation and assessment of framework conditions

The first mission to the target regions intended to update the previously elaborated market scans of each target site including the identification of key stakeholder and potential application sites. Information on the hydrogeological, institutional and economic feasibility of SWS were collected, a gap analysis was conducted as well as implementation barriers were identified. During the visits, SWS technology concepts were presented to stakeholders and the applicability of SWS under local conditions was discussed. The market scans and consequently target region selection focused on the subsequent criteria:

- Presence of water scarcity and salinization problem
- Local technical knowledge and capacity (availability of information, local infrastructure, etc.)
- Economic feasibility (available financial resources, current water price, etc.)
- Political environment (presence of a sound legislation in place for groundwater abstraction, water injection, water reuse, type of political environment etc.)
- Institutional capacity (identification of stakeholders, stakeholder awareness of the problem, etc.)
- Needs and demand (presence of organized stakeholder groups and accessibility of them, attitude to innovations, importance of sustainability, etc.)
- Hydrogeological feasibility (presence of a suitable aquifer, type of underground material, etc.)

Second mission to the target sites: Capacity building and solution development

The second mission to the four selected target sites was carried out in close cooperation with the previously identified local key stakeholders. The main aim of this mission was to build capacities at the target sites by supporting local stakeholders with knowledge, tools and consulting services to develop strategies for the implementation of SWS based on the results of the previous mission. Finally, solution concepts for viable target sites were identified and substantiated, which built the basis for joint future projects.

A detailed overview of the mission’s approach is depicted in figure 1. The general structure follows three steps: Bilateral Meetings, a Public Event and a Project Development Workshop.

During Bilateral Meetings recent SubSol outcomes and SWS application ideas developed based on the lessons learned of the first mission at the target sites were presented and discussed jointly with key stakeholders. During this process, tools and guides developed for this purpose were used and recent results of full-scale pilot systems in the Netherlands were shared. In preparation for the public event as the next mission activity, presentation topics were assigned, and an agenda was developed.

The Public Event was open to all interested stakeholders including government authorities, researchers, engineers etc. In all four target sites, the event was hosted by a key stakeholder, who provided its facilities and took over the moderation. This was carried out by the Federal University of Pernambuco (UFPE) in Brazil, the technical committee for groundwater management (COTAS) in
Mexico, by the Water Development Department (WDD) in Cyprus and by the Division for water resources planning and investigation for the south of Vietnam (DWAPIS). The event involved four parts: 1) Overview on the current water management especially on groundwater and its constraints, 2) knowledge exchange on SWS technologies, best practise examples, introduction in technical tools developed in the SUBSOL project such as SWS location identification tools, technical and economic guide for SWS implementation etc., 3) Presentation on SWS application opportunities by local stakeholders followed by 4) a final discussion round.

As concluding step solution concepts were refined in a Project Development Workshop in which roles, responsibilities, and proposals for developing a project for the most favoured application options were discussed and agreed upon.

**Technical and Economical tool**

The basic viability of the developed concepts was verified with the SUBSOL tool: "Technological and Economical guide for ASR Coastal application". It serves a same-named guide and provides a simple method to develop a first feasibility study looking at water balance, hydrogeological aspects, capital expenditures (CAPEX), operational expenditures (OPEX), and creates an initial design and operational scheme based on the input information the user is requested to fill into an excel template. This tool was applied most successfully on one target site in Brazil. The application of the tool was only partially successful at other locations, due to the very different location conditions and stakeholder demands at the target regions. Consequently, resulting solution concepts differ greatly from the three original technology concepts, shortly described in the following section. Details of the results are presented in this article.

**Short excurse on the technologies at the reference sites**

The Subsurface Water Solutions are a set of different technology concepts that have been developed in recent years as robust, sustainable, and cost-effective solutions to protect, enlarge, and improve fresh water resources in coastline areas (see Fig. 2). They present an alternative to desalination plants and have already been applied in the Netherlands. Energy savings, increase in food production yields of about 20% due to increased freshwater availability, and financial savings (low ROIs) have been shown. SWS technology systems were near-market ready with a readiness level of 7 to 8 at the beginning of the SubSol project 2016.

Different well designs with combinations of wells extracting brackish water and infiltration wells injecting fresh water allow a control of the salt-freshwater interfaces with the aim of protecting wells, stopping saltwater intrusions, and/or improving the recovery efficiency of subsurface freshwater storages. Countries with a seasonal water shortage due to wet and dry seasons benefit in particular from improved storage and recovery options, ensuring a stable water supply year-round.

The following three paragraphs present three typical applications of SWS (Fig. 2) that served as a basis for solution patterns in the four target sites.

**Freshmaker**

Zuurbier et al. (2015) defines the Freshmaker concept as follows: The main aim of the Freshmaker concept is to enlarge natural freshwater lenses through temporal storage of freshwater in shallow, saline phreatic, granular, and thin aquifers as an alternative and improved version of Aquifer Storage and Recovery (ASR). The well design consists of two Horizontal Directional Drilled Wells (HDDW) that enable enlargement, protection, and utilization of freshwater lenses in shallow and brackish-saline aquifers. Moreover, the horizontal orientation of the wells
enables a limitation of upcoming during the freshwater recovery. Figure 2 shows the two HDDWs which are located over each other: The shallower well is used like an ASR well at which freshwater is injected and later recovered in times of demand whereas simultaneously the deeper well abstracts brackish water (or: intercepted) in order to enlarge the natural fresh groundwater lens and protect the shallow well from salinization. The first Freshmaker system was installed in the coastal Province of Zeeland and is running since 2013.

**Freshkeeper**

Zuurbier et al. (2016) defines the Freshkeeper concept as follows: The main aim of this concept is to protect freshwater wells prone to salinization in unconfined aquifers with stratified groundwater quality and a thickness of >20 m. With a well design consisting of Multiple Partially Penetrating Wells (MPPW) the fresh water and the upcoming brackish water is abstracted separately at different depths. The intercepted brackish water can be desalinated and hence is available as an additional freshwater source. The brine disposal will be injected into a deeper aquifer layer showing similar salinity levels. A Freshkeeper pilot system was successfully applied in Noordburgum, The Netherlands, and is running since 2013.

**ASR-Coastal**

The main aim of the ASR-Coastal system is the improvement of the recovery efficiency of temporal freshwater storage in brackish and confined aquifers (Zuurbier et al., 2016). This is made possible by the well design MPPW used in the Freshkeeper system. In a single borehole two or more wells are installed enabling a deep injection and shallow recovery. With the help of this well design, losses of the stored freshwater due to buoyancy forces are reduced compared to normal ASR systems with only one filter for injection and recovery. Freshwater sources are mainly rainwater or reclaimed water. A successfully installed ASR-Coastal system can be found in Nootdorp supporting a Dutch coastal greenhouse horticulture area (Zuurbier et al., 2014).

**Results**

**Solution concepts at the target site in Brazil**

**Framework conditions**

In the Recife Metropolitan Region (RMR) a steady population growth and hence rising water demand has brought up impacts such as saltwater intrusion, degradation of water quality, and the ecological status, as well as potential subsidence. The water and sanitation company for the State of Pernambuco COMPESA supplies the metropolitan area mainly with surface water (8.6 m³/s) (Costa et al., 1998) and 2.3 m³/s with groundwater pumped from the lower Beberibe aquifer (Montenegro et al., 2016). However, only 85% of the demand for RMR can be covered with the supply by COMPESA (Batista, 2015). In addition, problems such as bad water quality are caused in particular by old pipes with leaks, through which the water gets in direct contact with pollution sources, such as sewage. These circumstances led to the fact that almost the entire population with higher income buys bottled water.

---

**Fig. 2. The three main Subsurface Water Solution concepts (Zuurbier et al., 2016)**
water for drinking and cooking and commercial and residential buildings have drilled their own private wells (Cabral et al., 2008). Other water sources include tank truck delivery systems and rainwater storage (used for example at the RioMar Shopping Centre (Moura et al., 2016). The increase in the drilling of private wells led to even higher reductions of groundwater levels, especially in the heavily populated neighbourhoods such as Boa Viagem, Pina, and Afoągos. In order to regulate this fast development, Recife's water agencies introduced a pumping permission zonation system (Cabral et al., 2008) which also led to licensing of existing and registration processes for new wells. In order to improve the control of compliance with these restraints, a comprehensive monitoring system is under construction, under which 100 wells will be equipped with sensors measuring groundwater level and electrical conductivity at selected locations in Recife. However, the increased water demand could not be met, and groundwater levels are further decreasing in critical neighbourhoods. Positive impacts of the measures were detected in few areas.

Institutional feasibility

With the strong aim and motivation to solve the existing water shortage conditions in the RMR, a wide variety of stakeholders showed their interest in new innovative solutions. Furthermore, public authorities and decision makers such as APAC and CPRH, responsible for enforcement of the legislation regarding the water resources in the region and the environmental compliance, assured their support in enabling conditions for the implementation of SWS with emphasis on a first pilot system to ensure success of SWS. Many research institutes and universities are active in MAR projects and quickly showed interest in integrating SWS technologies into the existing project BRAMAR, thus enabling a first SWS pilot plant in RMR. Stakeholders who showed special interest and support during the mission are: the Federal University of Pernambuco (UFPE), who is the coordinator of the SWS pilot system in the Pina neighbourhood, the State Agency for Water and Climate (APAC), responsible for planning and regulation of water resources in Pernambuco, the Urban Services Company of Recife (CSURB), the water utility of Recife COMPESA and the well driller and maintenance company Aqua Poços.

Solution concepts

One of the three most promising adapted SWS concepts for the RMR was implemented as a pilot plant. The pilot aims to partly cover the water demand of a public school located in the heavily populated neighbourhood Pina in the Boa Viagem neighbourhood. The existing well on the schoolyard had been abandoned due to high salt concentrations in the groundwater and the school was depending on the irregular public water supply. Together with a research group of the Federal University of Pernambuco an initial design for a fully automatic ASR-Coastal system was developed and will be implemented this year (2018) within the BRAMAR project. The design includes a rainwater harvesting system using the school roof as a catchment area, a water tank as a buffer, a rapid sand filter for pre-cleaning and a MPPW for injecting the water into the desired aquifer in which the water is stored until it is extracted again to meet the school’s water needs. Based on rainfall measurements of the last 60 years by APAC, the pilot plant would have been able to inject about 400 m³/year (including 30 % losses due to evaporation, etc.) into the aquifer. Since recovery efficiencies (RE) of 95 % are still too ambitious and a RE of 50 % is more likely as shown at the pilot plant in the Netherlands (Noodorp), only half of the water demand of the school of 380 m³/year (2015/2016, COMPESA) could be covered. UFPE researchers with the external support of adelphi will provide the on-site care of the SWS-pilot. This pilot system shall furthermore help to increase the public’s acceptance of SWS technologies and facilitate next project executions.

The second promising case site for SWS implementation is the injection of rainwater into the aquifer below two public markets in Afoągos neighbourhood of Recife. With a roof area of more than 10,000 m² the captured water will be sufficient to cover the water demand of the markets and in addition recharge the local aquifer Beberibe which is one of the most affected by groundwater level reduction. Until now, one of the markets already capture its rainwater, which CSURB plans to store in a soon to be constructed cistern with a capacity of 50 m³. An installation of an ASR Coastal could additionally store the water, which cannot be stored by the cistern during the rainy season and make it available proportionally for later use during the dry season. As a next step, the roof of the second market could also be provided with a rainwater harvesting system in order to receive a higher recharge potential. Other markets in the RMR also contain large roofs suitable for further SWS implementation.

Another potential implementation opportunity for SWS is the holiday resort Nannai. The hotel resort is located in Porto de Galinhas, a very popular holiday area with a large number of hotel resorts located a few meters from the coast. Saltwater intrusions have already caused the abandonment of many wells in this area. Dependent on groundwater abstraction for its hotel water supply the Nannai resort would greatly benefit from the implementation of an SWS technology for protecting the existing wells against salinization and hence ensuring water supply by groundwater abstraction. For this location, the Freshkeeper appears to meet many of the local requirements for a successful SWS implementation and could therefore be chosen as a suitable technology.

In summary, the solution concepts for improved aquifer recharge developed with local stakeholders in the target region RMR, Brazil, are:

1. Implementation of a pilot plant in a public school in the Pina neighbourhood based on the ASR-Coastal concept by injecting pre-treated rainwater harvested from the school’s roof top into the confined lower Cabo aquifer.
2. Equip public, roofed market places in the Afoągos neighbourhood of Recife with facilities based on the ASR-Coastal concept.
3. Protection of existing wells of the hotel resort Nannai in Porto de Galinhas from salinization by means of a Freshkeeper system.

In the following paragraph, the adapted solution concept for the Mercado Feira Nova de Afoagados (Example 2) is presented. The concept is based on the results retrieved from the Technical and Economical Tool for ASR-Coastal application, the results of which are presented in the following. Table 1 provides an overview of the necessary input data.

Table 1. Water balance and geohydrological input data for the Technical and Economical Tool

| Water balance         | Value                      |
|-----------------------|----------------------------|
| Annual water demand   | 2900 m³ (CSURB 2018)       |
| Annual precipitation  | 1884 mm (APAC 2018)        |
| Existing rain water harvesting system | Yes                       |
| Harvesting area       | 31,501 m² (CSURB 2018)     |
| Storage capacity      | A cistern is planned:      |
|                       | 500,000 m³                 |

| Geohydrology          | Value                      |
|-----------------------|----------------------------|
| Aquifer layers        | Boa Viagem and Beberibe    |
|                       | (Costa et al., 1998)       |
| Electrical conductivity| 751 µS/cm (Cary et al., 2015) |
| Salinity of the groundwater| 4024 mg TDS/L               |
| Hydraulic conductivity| 1.93 m/d                   |
| Groundwater table     | 93 m BLS                   |
| Porosity              | 0.13                       |
| Hydraulic head        | 26 m BLS                   |

(After Montenegro et al., 2006)

Figure 3 shows the water availability and demand of the market divided into a period of net availability depicting the month in which more water is available than demanded and a period of net shortage including the month in which the water demand extends the water availability. Hence, these periods define the possible duration of fresh water infiltration into the aquifer and the necessary duration of freshwater recovery, respectively. The target storage volume (TSV) is derived from the resulting water balance and represents the desired amount of recovered freshwater in the period of net shortage.

Fig. 3. Target storage volume over time for a dry year

Assuming the values listed in Table 1, the values shown in table 2 were obtained by applying the tool. The TSV is set as an average of 340 m³/year. The results in Table 2 show that this temporarily missing water volume can be covered by the considered ASR Coastal system, which is sufficient to prove the feasibility of the system in terms of water balance with recovery efficiency between 0.32 and 0.53. Moreover, an additional 3370 m³/year are available for recharging the local aquifer Beberibe, which in this implementation case represents not only a positive side effect, but also an independent objective. Therefore, the calculated process scheme by the tool needs to be adjusted to the case objectives. The authors recommend a maximal infiltration scheme and a recovery volume equal to the TSV.

Table 2. Total volumetric water balance for a dry year (yearly)

| Parameter                  | Value       |
|----------------------------|-------------|
| Availability               | 5930 m³/year|
| Demand                     | 2900 m³/year|
| Target Storage Volume (TSV)| 340 m³/year |
| Total freshwater availability to bridge the seasonal/temporal mismatch | 3370 m³/year |

Followingly, the tool examines the geo-hydrological feasibility of an ASR-Coastal implementation considering two criteria, which are the presence of a potential target aquifer and a background lateral groundwater flow less than 10 m/year. The aquifer has to fulfill certain requirements, such as: confined conditions and low buoyancy effect calculated from the saturated thickness of the aquifer, the hydraulic conductivity ad salinity.

As shown in figure 4 two feasible aquifer layers exist, from which the lower one is more suitable for the freshwater storage. The installation of two MPPWs in the target aquifer (here lower Beberibe) is recommended by the tool.

Fig. 4. Visual representation of the subsurface with suggested depths of the MPPW-layers’ tops and bottoms. Layer 1 is an unconfined aquifer, the Layers 2 and 4 are aquitards and Layer 4 is another aquifer.

The tool concludes the preliminarily feasibility study by determining the costs per gained litre (Table 3).

The price per m³ calculated by the tool is 12.25 EUR/m³. This result only refers to the amount of water that can be recovered for consumption. However, since
the city and the market benefit from the recharging of the aquifer as well, which is not considered in this calculation, the actual resulting costs are lower. In addition, due to lack of information, costs from the reference sites in the Netherlands were used which would be lower in Brazil. Nevertheless, the m³-price will still be high compared to COMPESA’s water prices. One solution would be to connect several roofs with each other to extend the recharge volume. In the case of the market Mercado Feira Nova de Afogados, there is an older market directly adjacent, which consists of a similar roof area. Furthermore, the local well drilling company Aqua Poços proposed to use old existing wells, which were closed due to high saltwater concentrations in the groundwater and could be reopened to save costs.

Table 3. Capital and Operational Expenditures

| Capital Ex. (CAPEX) | Total CAPEX | 75,796 € |
|---------------------|-------------|----------|
| Assumption financial depreciation | 20 years |
| CAPEX per year | 3,790 €/year |
| Cost of one cubic meter of water based on CAPEX | 11.29 €/m³ |

| Operational Ex. (OPEX) | Total OPEX | 6,455 € |
|------------------------|------------|---------|
| Assumption financial depreciation | 20 years |
| OPEX per year | 322,73 €/year |
| Cost of one cubic meter of water based on OPEX | 0.96 €/m³ |
| Total costs per m³ | 12.25 €/m³ |

Solution concepts at the target site in Mexico

Framework conditions

Baja California, a district in the north-west of Mexico, has experienced severe to extreme droughts in recent years. The city is economically dependent on agriculture and groundwater resources due to decreasing rain events, which currently only occur every seven years. In addition, a lack of surface water resources increasing intense exploitation of the groundwater resources. Consequently, many areas next to the coast suffer from water scarcity and groundwater salinization such as the regions San Quintin and Guadalupe Valley, which had been selected as target sites in the SubSol project. Both regions export a majority of their products to the United States: In San Quintin vegetables and fruits are grown and the Guadalupe Valley is famous for its vineyards. Due to increasing salt contents and lack of irrigation water agricultural land already needed to be taken out of production in Baja California.

In response to the steadily increasing salt content in groundwater, the state subsidizes over 90% of energy costs for desalination plants, which is why desalination plants are used in almost every major agricultural operation. However, desalination does not constitute a sustainable solution as brackish groundwater abstraction provokes further seawater intrusion into the groundwater and brine water remains as waste. Other measures carried out by regional authorities to counteract water scarcity are the reuse of reclaimed water stored in a few surface water reservoirs for non-edible crops or the installation of coastal wells similar to the Freshkeeper concept abstracting saltwater in order to stop saltwater intrusion.

In response to the steadily increasing salt content in groundwater, the state subsidizes over 90% of energy costs for desalination plants, which is why desalination plants are used in almost every major agricultural operation. However, desalination does not constitute a sustainable solution as brackish groundwater abstraction provokes further seawater intrusion into the groundwater and brine water remains as waste. Other measures carried out by regional authorities to counteract water scarcity are the reuse of reclaimed water stored in a few surface water reservoirs for non-edible crops or the installation of coastal wells similar to the Freshkeeper concept abstracting saltwater in order to stop saltwater intrusion.

Due to different hydro-geological conditions both regions need to be considered independently of each other and hence different solution concepts were developed: San Quintin is adjacent to the sea and hence particularly affected by seawater intrusion, whereas the Guadalupe Valley is located further up a hill and groundwater contamination is caused by agricultural activity.

Institutional feasibility

Regional authorities as well as end users, especially farmers, who would be the drivers in a new project, are aware of the problem and were eager to develop and implement innovative solution concepts. In addition, universities and research institutes are motivated to support and conduct aquifer assessments and research on those solutions.

In San Quintin COTAS, the Technical Committee of the aquifer San Quintin and subsidiary of the National Water Commission (CONAGUA), helped to organize events and workshops. The SubSol team also received local support in the Guadalupe Valley by Adobe Guadalupe, one of the largest winemakers in the valley, who hosted the event.

Additional stakeholders who showed special interest and support during the missions are: the Secretary of agricultural development (SEDAGRO), researchers of the Autonomous University of Baja California (UABC) and of the Centre for Scientific research and Higher Education in Ensenada, Baja California (CISESE), and various farmers. Farmers represent the end-users of these technologies, such as Agricola Chumas and Agricola Sa Regis, San Quintin, and Monte Xanic, Viñedos El Cielo, and Viñedos L.A. Cetto, Guadalupe Valley.

Solution concepts

The San Quintin region lacks a wastewater infrastructure. This makes rainwater the only available freshwater source for aquifer recharge in this region. Two river basins were identified to be suitable for improving the river basin management: San Simon and Santo Domingo. The subsurface of the San Simon consists of a smaller lateral groundwater flow and thus subsurface water storage appears to be more feasible in this basin.

Improving the river basin management in this basin mainly comprises the construction of additional dams in order to capture water from heavy rainfalls and hence increase the infiltration volume into the aquifer. Potential negative impacts of constructing such dams could be the reduction of available irrigation water for farmers located downstream of the river, hence a considerate dimensioning of the dams is required.
So far only outdated basin management measures can be found in the region such as concrete walls to reduce the flooding’s of riparian agricultural land in case of high rising water levels as well as an asphalt canal which was built to prevent river water to infiltrate into the aquifer. These measures date back to the time when the basins where not dehydrated over most of the year and rainfall events occurred more frequently. Both, the flood preventions and asphalted canal show potential to improve water management if rearranged.

In summary, the main concluded solution concepts for improved aquifer recharge developed with local stakeholders in San Quintin are:

1. Improvement of river basin management of the river San Simon and Santo Domingo by means of small retention structures.
2. Rearrangement of existing flood prevention systems and of an asphalted canal.
3. Once a stable water supply is developed CONAGUA considers elaborating a waste water drainage system for reuse purposes and groundwater protection.

As in the San Quintin region, in the Guadalupe Valley, optimizations of the catchment area of rivers by dams and barriers to slow down runoff pose potential improvement measures for aquifer recharge.

In addition to rainwater, the Guadalupe Valley has access to reclaimed water due to its proximity to major cities, such as Ensenada, Tijuana. The transport of reclaimed water from a wastewater treatment plant in Tijuana through pipelines to the Guadalupe Valley is planned by a currently undertaken project in order to cover the water needs of the valley. By this measure, triple of the amount of demanded water in the entire valley is transferred into the region. Additionally, the wine yards have a four-month growth break in which no water is needed for irrigation. The excess reclaimed water has no defined purpose yet and thus could be used as source for recharging the Guadalupe aquifer. However, this reclaimed water contains high salt concentrations. Therefore, the use of halophytes for soil desalination was also considered. In the search for suitable infiltration sites in the valley, so-called aquifer pockets with very little to no lateral flow were discussed. It is anticipated that a study on identifying the exact location of such aquifer pockets and a feasibility study based on field measurements is soon to be carried out by the University of Ensenada.

In summary, the main concepts for improved aquifer recharge developed with local stakeholders in the Guadalupe Valley are:

1. Optimizing the catchment area by means of check dams and barriers to slow down runoff.
2. Infiltration of excess reclaimed water from Tijuana, which has no direct use in the agriculture.
3. Usage of aquifer pockets as infiltration sites.
4. Usage of halophytes for soil desalination.

Solution concepts at the target site in Vietnam

Framework conditions
As a target region in Vietnam the economic centre Ho Chi Minh City (HCMC) and the Mekong Delta were chosen. HCMC suffers from seasonal water scarcity during the dry season and pluvial flooding conditions during the wet season. Conditions for which ASR solutions in general and accordingly SWS seem very well suited at a first glance. Additionally, rapid urbanization and population growth since the 1980’s causes decreasing groundwater levels and hence induced subsidence, of which the latter even increases the risks of urban flooding during the rainy season, one of the most recognized urban water management issues in HCMC (Dan et al., 2006; Le Vo, 2007b). Decreasing groundwater levels have caused saltwater intrusion in various areas in HCMC (Ngo et al., 2015), which forces the HCMC’s water supply company Saigon Water Cooperation (SAWACO) to shut down some wells. In the Mekong Delta lean flows during the summer period, caused by a changing rainfall pattern as well as increased usage of surface water upstream, lead to saltwater intrusion into the estuary river network (UN, 2016). This leads to temporary shortfall of raw water for the surface water treatment plants, which source their water from the river. The need for a sustainable water management is high and urgent. The local authorities are aware of the problematic situation and the reasons for the water scarcity and various measures have already been implemented in recent years. A master plan for water resource management was developed, which limits the extraction of groundwater or even prohibits the installation of private wells for water extraction in the most water scarce areas. The plan aims to replace private wells with piped public water by 2025.

Institutional feasibility
Local stakeholders strongly support the development of a pilot project for testing SWS technologies in and around HCMC and in the Mekong Delta. Examples for supportive stakeholders are, for example, the Ministry of Natural Resources and Environment (MONRE), Department of Natural Resources and Environment (DONRE – the regional division of MONRE), Saigon Water Company (SAWACO), and the Division for water resources planning and investigation for the south of Vietnam (DWAPIS).

Solution concepts
Three potential target sites that seem to be most suitable for SWS pilot system implementation in HCMC and Mekong Delta have been identified. In the southern part of HCMC industry areas like Binh Chanh, Nha Be, and Can Gio and domestic building complexes like Nha Be and Sala City district 2 where identified for possible SWS implementations. The groundwater in these areas has turned saline or brackish in the last decades. According to the available information, the geohydrology seems challenging for a SWS implementation. The aquifer contains an irregular mixture of seven confined and unconfined
layers (Le Vo, 2007a; Hagenvoort, Tri, 2013). This makes it necessary to firstly conduct an in depth feasibility study. The potential technical solutions could be the ASR Coastal system adapted to the specific layering of the aquifers.

The second area was identified in the Thanh Hai District, Thanh Phu District, and Ben Tre District in the Mekong Delta, where agriculture and aquaculture are the most prominent economies. Here sand dunes could be used for storing fresh water. A Freshmaker based solution could infiltrate harvested rainwater or treated surface water from the rivers during the rainy season into the shallow widely extended sand dunes and make the water available for the dry season when the water supply which is generally groundwater-based turns saline (UN, 2016).

The third possible sites for pilot SWS implementation are coastal industrial sites in Ca Mau and Tra Vinh. One example is the production site of the Fertilizer and Gas plant in Ca Mau, at the southernmost tip of the Mekong Delta whose water supply is also disrupted due to saline water intrusion into the estuary rivers (Nhan et al., 2007). The water price which is usually 0.2–1 $/m³ during the water supply period increases to 3-10 $/m³ when it is interrupted as it has to be brought by tanker boats or trucks. The source for infiltration into a shallow Freshmaker based concept could be rainwater, which can be harvested from the rooftops of the factories. Ongoing rainwater harvesting projects plan to install surface reservoirs that could be complemented with underground aquifer storage options.

On the policy level, it was also discussed to set up regulation for groundwater users especially real estate companies for obligate infiltrating certain fresh water amounts. Currently a 16 ha rainwater reservoir is planned, with an annual precipitation of 2400 mm, 3-4 M m³/year could be harvested from the rooftops.

**Solution concepts at the target site in Cyprus**

**Framework conditions**

Cyprus suffers from several years of severe drought and an increasing demand of water, which in combination aggravates the critical long-standing water scarcity problems of the island. Several aquifers along the coast are at risk of drying out and due to saline contamination, many wells had to be abandoned because of seawater intrusion, irrigation-induced salinization (Milnes, 2011), and nitrate contamination (Georgiou, 2002).

The Cypriots are aware of their water scarcity problems and examine regular monitoring and research programs. However, numerous measures taken by the Water Development Department (WDD) to counteract the sinking fresh water availability could only marginally improve the situation over the past five years. The little success in water body protection is due to several factors such as decreased annual rainfalls, an overall increased water demand and almost no behavioural changes in the individual water consumption of the population. In 2016, Turkey supported Northern Cyprus’s water supply through a water pipeline. In addition, the southern part of the Island had to attain additional water shipped-in from Greece during this time. In the 1960s, local authorities started a rainwater collection program with the aim of "Not a drop of Water to the Sea". As a result, the storage capacity of the dams has been increased from 6 Mm³ to 300 Mm³, which also lead to the fact that no perennial streams exist on the island anymore (Hochstrat, Kazner, 2009). In addition, Cyprus started to overcome water shortages by implementing desalination plants (four in South Cyprus). For instance, 90% of Lefkosia’s domestic water supply is generated by desalination.

Besides dams and desalination, groundwater bodies remain the main water sources on the island. The Akrotiri aquifer is one of the most important porous aquifers in Southern Cyprus with an area of 45 km². The average annual extraction rates dropped from 14 Mm³/year to only 8 Mm³/year after 1990, due to saving measures by the authorities and salinization of wells. The Cyprus Water Development Department, one of the key site partners and host of the public event, studies the islands water scarcity and operates MAR sites in Cyprus reusing reclaimed water for many years. Artificial recharge of natural water bodies proved to be one of the promising instruments to counteract the continuously growing water stress. At the Ezousas aquifer, an ASR site operating for more than 12 years achieves promising results on water storage. Another similar project started two years ago at the Akrotiri aquifer. The new site at the Akrotiri aquifer is still in its optimization phase and has great potential for improvement.

**Institutional feasibility**

The main institution responsible for the water-management, -policy, and -protection in Cyprus is the Water Development Department (WDD), who had also hosted the public event for SWS. WDD has stated to have a strong interest in further developing SWS projects. In addition to the WDD, the International Water Research Centre NIREAS-IWRC, who hosted the project development workshop, the Geological Survey Department (GSD) and the Cyprus Institute showed special interest and support for implementing adapted SWS concepts. Hence, the key stakeholders and institutions for SWS project development are in favour of future activities reflecting a high institutional feasibility.

One short coming though could be that due to the politically unsolved situation a cooperation of stakeholders from Southern and Northern Cyprus does not seem possible. This is specifically problematic in a sense that important water streams as well as aquifer (e.g. Kokochnohria, Akrotiri, and Mesiatoria) do not stop at administrative borders and natural interdependencies require a cooperation of the different administrations. The conclusion was to focus on southern aquifers that clearly have their catchment in one administrative region.

**Solution concepts**

In the case of Cyprus, rainwater is already used very efficiently. Therefore, the usage of reclaimed water is most appropriate for aquifer recharge purposes. However, this water resource is also limited partly due to the lack of
wastewater infrastructure outside the cities and the fact that most of the treated water is already used in the agriculture. In the Kiti region, which proved to be suitable for SWS implementation from a geological point of view no additional reclaimed water resources are currently available. Hence, an improvement and expansion of the wastewater infrastructure is needed in order to develop a more efficient strategy for the collection of water sources for infiltration.

The implementation of SWS solutions has shown to be most suitable for the optimization of existing MAR sites at the Ezousas (operating for 12 years) and Akrotiri (operating for 2 years). Both sites are fed with reclaimed water from the nearby cities Paphos and Limassol. Monitoring programs at the Akrotiri site showed that salinity concentrations of the groundwater could already be reduced by recharging the aquifer with reclaimed water through ponds. However, little knowledge exists on the formation of the freshwater bubble in the subsurface during infiltration and thus an improved control management in order to maximize the recovery efficiency is needed. By integrating aspects of the Freshmaker concept, saline groundwater from a deeper zone could be extracted in order to increase the storage space for the infiltrated fresh water while reducing buoyancy effects.

To support the current research focus of the Cyprus institutes, new projects should consider purification capacity of the underground passage and the fate of various parameters especially organic substances such as pharmaceuticals, drugs etc. contained in reclaimed water. The implementation of online sensors for two main water quality parameters salinity and nitrate would be an important measure.

In summary, the solution concepts for improved aquifer recharge developed with local stakeholders in Cyprus are:

1. Improvement and expansion of the wastewater infrastructure, especially in the Akrotiri and Kiti region.
2. Improvement of control management at the existing site at the Akrotiri aquifer by means of integrating aspects of the Freshmaker concept.
3. Optimization of the purification capacity of the underground passage at the two existing sites at the Akrotiri and Ezousas aquifer.

Drivers and barriers for the transfer of subsurface water solutions to the four target regions

Each target region differs in terms of requirements for adapting SWS approaches and the approach for implementation options. This is due to varying baseline conditions and identified cooperation opportunities with local stakeholders. A general lesson learned was to be flexible on the technical concept and adapt it to the local conditions and requirements as early as possible.

This chapter tries to indicate the most important drivers and barriers, which had been experienced during the missions for SWS implementation in terms of institutional, political and legal, economical as well as social aspects.

Institutional aspects

Three common drivers that strongly influence the institutional feasibility for the implementation of new projects are: good stakeholder identification, good establishment of contacts, the precise assessment and involvement of the needs and interests of various stakeholders from all levels, and the comprehensive analysis of existing knowledge and projects on MAR.

In the target regions such as Mexico and Brazil, already existing good stakeholder contacts and trust was very helpful for further stakeholder involvement and expanding stakeholder networks. Particularly in Mexico, it was especially difficult to establish new contacts remotely due to the difficult accessibility by email, which makes personal contacts an absolute prerequisite.

For successful development of new solution concepts, it was particularly important to involve various stakeholders from all levels and to take time to identify their needs and interests. Only in this way, it can be guaranteed that all possible barriers are considered. For instance, direct injections of water into the aquifer are an uncommon practice in many countries and are under stringent regulations. Early involvement of public authorities is important in order to gain their trust and interest enabling the way for the implementation of adapted SWS concepts. Already existing studies and projects on managed aquifer recharge supported the acceptance of the SWS concepts.

Political awareness/legal framework

Important for a SWS supportive environment are: existing political awareness, integration of sustainable water management in action plans and the importance of the site location for politics. The target site in Brazil (RMR), for instance, is one of the most important ports for tourism and trade of Brazil, whereas the selected target sites are important for agriculture in the case in Mexico and Cyprus. In Brazil, for instance a law specifically mentions that the government should provide incentives to private entities for artificial aquifer recharge (Decreto Nº 20.423). This law helps to gain the support of the public authorities.

However, most countries have stringent regulations on the quality of water that is used for aquifer recharge. This often is not met by reclaimed water. Thus, additional pre-treatment is required. Especially strict is the norm in Mexico, which prescribes drinking water quality for the injected/infiltrated water into the aquifer. This would require a very thorough, reliable, and constant monitoring and an elaborate pre-treatment, which seems to be unrealistic due to the too high complex for many implementations. The implementation of such an ASR project requires stronger support of an appropriate legal framework. With regard to water scarcity there should be an exception, which allows the modification of the requirement of drinking water quality for ASR to a “better quality than groundwater”. A legal alternative represents the infiltration over surface waters such as artificial pools or riverbeds. In Cyprus, the regulations for injection are similar to the norms in Mexico as EU norms apply. In
Brazil, these regulations are more softened, posing that the injected/infiltrated water should not represent a threat for the water reserves quality (Decreto N° 20.423). Still permission of the public water authority is required, and the legal framework demands the implementer to demonstrate the technical, economic, and sanitary feasibility in order to guarantee groundwater quality preservation.

**Economic aspects**

The current price per m³ at the reference sites ranges between of € 0.48 to € 0.59 for the Freshmaker and € 0.61 to € 0.85 for AR coastal. The price for an m³ produced at smaller plants such as the example of the public Mercado in chapter Resulted solution concepts at the target sites Brazil is even higher. However, SWS technologies still offer a more cost-efficient water management option in comparison to desalination as seen in Cyprus, where in 2010, the price of drinking water from desalination plants was between 0.82–1.39 EUR/m³ depending on the region [WDD]. However, in Mexico this economic advantage is not given as the state subsidizes over 90% of the energy costs for desalination plants in response to the increasing salt content of the groundwater. Consequently, desalination plants are used in almost every major agricultural operation. From the environmental perspective, SWS still remain the more sustainable solution, than brackish groundwater abstraction which still promotes seawater intrusion and brine water remains as waste for which a sustainable disposal method needs to be developed.

**Social aspects**

From the social perspective for all target regions, it can be summarized that despite the awareness of the benefits of SWS concepts, there is scepticism and persistent stakeholder opposition towards groundwater recharge due to water quality concerns. These concerns are related to the risks of drinking water resource pollution or, as it is the case in Mexico, the uptake of pollutants in the food chain and hence a negative impact on the export market in the US is feared.

In order to overcome these fears of stakeholders, the following steps turned out to be successful to increase public acceptance:

- Active involvement of stakeholders over the whole process.
- Good communication of results of best-practise examples at reference sites.
- Presenting results from reference and replication sites.
- Implementation of a pilot plant, in order to gain acceptance for implementing a similar system on a bigger scale.

**Conclusion**

Although water scarcity and groundwater salinization are widely spread problems, SWS as implemented in the Netherlands are not of the shell solutions that can be applied without having a more in depth look into the specific local conditions. Natural circumstances related to hydrogeological conditions, regulatory environments determining the usage of water sources as well as the socio-economic frameworks require an adaptation of the general concepts. A participatory co-design approach for the concept often reveals information gaps indicating the necessity for in-depth research studies in order to judge on the basic feasibility of SWS. In cases of sufficiently available information, monitored and evaluated pilot projects are required to convince large-scale implementers of the proof of technology under the deviating conditions. The close cooperation with stakeholders in the four regions covered in this article showed that these steps can be taken and show the way forward for the site-specific application of SWS. Conclusively for most target sites, research proposals have been developed and are submitted to donor agencies for public funding as the advantages of the technological solutions benefit the wider public. On the other hand, the knowledge on the basic functionality of the technology would be a prerequisite to attract private investment. In other cases where private benefits are in the foreground and commercially exploitable solutions are feasible, solutions could possibly be developed in cooperation with companies. Currently, research proposals for feasibility studies for SWS application have been developed for Brazil, Vietnam, and Cyprus whereby solution development for Mexico is still being looked into.

**Acknowledgements**

The article is based on results from project activities carried out in the SUBSOL project. SUBSOL has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 642228.

**References**

APAC (Agência Pernambucana de Águas e Clima). 2018. *Monitoramento Pluviométrico (1961-2018)* [online], [cited 22 August 2018]. Available at: http://www.apac.pe.gov.br/metereologia/monitoramento-pluvio.php#

Batista, J.C., 2015. *Superexploração de águas subterrâneas, o caso de Recife. MS: Thesis*. Universidade de São Paulo, São Paulo, Brasil.

Bunsen, J.; Müller, A.; Stahr, C.; Chakrabarti, R. *Communication and dissemination plan, 2017* [online], [cited 26 September 2019]. Available at: http://www.subsol.org/

Cabral, J. J. S. P.; Farias, V. P.; Sobral, M. d. C.; Paiva, A. L. R. d.; Santos, R. B. 2008. *Groundwater management in Recife*. *Water International*, 33(1), 86–99. https://doi.org/10.1080/02508060801927648

Cary, L.; Petelet-Giraud, E.; Bertrand, G.; Klopmann, W.; Aquilina, L.; Martins, V.; Hirata, R.; Montenegro, S.; Pauwels, H.; Chatton, E.; Franzen, M.; Aurouet, A. 2015. *Origins and processes of groundwater salinization in the urban coastal aquifers of Recife (Pernambuco, Brazil): A multi-isotope approach*. *Science of the Total Environment*, 530-531, 411–429. https://doi.org/10.1016/j.scitotenv.2015.05.015

CELPE. *Payscale tables and final prices of electrical energy, 2018* [online], [cited 26 September 2019]. Available at: http://servicos.celpe.com.br/Documents/Forms/AllItems.aspx
1st SWIM-SWICA Joint Saltwater Intrusion Conference. 24-29 September 2006, Cagliari-Chia Laguna, Italy.

Moura, M.; Souza, J. A. d.; Silva, S. R. d. 2016. Rainwater use for non-potable purposes: The case of Riomar shopping-Recife. *International Journal of Civil & Environmental Engineering IJCEE-JIENS*, (16), 19-23.

Ngo, M. T.; Lee, J. M.; Lee, H. A.; Woo, N. C. 2015. The sustainability risk of Ho Chi Minh City, Vietnam, due to saltwater intrusion. *Geosciences Journal*, 19(3), 547-560. https://doi.org/10.1007/s12303-014-0052-4

Nhan, D. K; Be, N. V; Trung, N. H. 2007. Water use and competition in the Mekong Delta, Vietnam. In: Be, T. T; Singh, B.T.; Miller, F. (Eds.). Challenges to Sustainable Development in the Mekong Delta: Regional and Nation Policy Issues and Research Needs. *The Sustainable Mekong Research Network*, 143–188.

SEDRU (Secretaria de Desenvolvimento Regional, Politica Urbana e Gestão Metropolitana). 10 May 2016. *Planilha orçamentária de custos* [online], [cited 22 August 2018]. Available at: http://site.sabara.mg.gov.br/wp-content/uploads/2017/09/poco-artesiano-maquina-planilha.pdf

SINAPI. 2010. *Planilha Orçamentária: Sistema de abastecimento de água. CNN (Confederação Nacional de Municípios)* [online], [cited 22 August 2018]. Available at: http://portal.cnm.org.br/sites/9400/9430/ORCAMENTO.PONTETIPLA.pdf

UN-HABITAT. 2011. *The economic role of cities*. Nairobi: United Nations Human Settlements Programme.

UN (United Nations). *Viet Nam: Drought and saltwater intrusión situation update No. 2, 2016* [online], [cited 26 September 2019]. Available at: http://www.un.org.vn/en/publications/doc_details/500-viet-nam-drought-and-saltwater-intrusión-situation-update-no-2-as-of-14-april-2016.html

World Economic Forum. *The Global Risks Report: 13th Edition, 2018* [online], [cited 26 September 2019]. Available at: https://www.weforum.org/reports/the-global-risks-report-2018

Zuurbier, K. G.; Kooiman, J. W.; Groen, M.A.M.; Maas, B.; Stuyfzand, P. 2015. Enabling successful aquifer storage and recovery of freshwater using horizontal directional drilled wells in coastal aquifers. *Journal of Hydrologic Engineering, 20*(3), B4014003. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000990

Zuurbier, K. G.; Raat, K. J.; Paalman, M.; Oosterhof, A. T.; Stuyfzand, P. J. 2016. How subsurface water technologies (SWT) can provide robust, effective, and cost-efficient solutions for freshwater management in coastal zones. *Water Resources Management, 31*(2), 671-687. https://doi.org/10.1007/s11269-016-1294-x

Zuurbier, K.G.; Zaadnoordijk, W.; Stuyfzand, P. J. 2014. How multiple partially penetrating wells improve the freshwater recovery of coastal aquifer storage and recovery (ASR) systems: A field and modeling study. *Journal of Hydrology, 509*, 430–441. https://doi.org/10.1016/j.jhydrol.2013.11.057