Subsurface Water Solutions (SWS):

Compilation of Technological and Economical Guides

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Preface

This introduction document accompanies the *Technological and Economical guides* which have been developed for 4 types of Subsurface Water Solutions (SWS) that have reached technology readiness level (TRL) 8 (i.e. “Actual system completed and qualified through test and demonstration”): Freshkeeper, Freshmaker, ASR Coastal and ASR reuse.

The Technological and Economical guides are meant for freshwater end-users, engineering companies and installers, technology providers, and consultants. They facilitate the identification of available options for SWS implementation, understanding of their key characteristics, and communication with policy makers and regulators to identify and address regulatory issues and potential barriers. This introductory document provides a brief overview of the existing SWS concepts and redirects the reader to the SWS that would be most suitable for the objectives, and thus to the Technological and Economical guide(s) one should read.

1. Introduction

Subsurface Water Solutions (SWS)

Coastal areas are the most densely populated, productive, and economically dominant regions of the world (Small and Nicholls, 2003). However, the associated high water demands put a tremendous pressure on freshwater resources and coastal ecosystems. This results in problems like overexploitation of freshwater aquifers, seasonal water shortage, seawater intrusion, and disappearance of wetlands. Further population growth, economic development, and climate change will intensify these issues (Vörösmarty et al., 2000). The sustainable development of these coastal areas may consequently be hampered and freshwater management will become a tough challenge.

Conventionally, aboveground solutions are sought for these problems, like construction of storage reservoirs or saltwater desalination. However, the subsurface may provide more robust, effective, sustainable and cost-efficient freshwater management solutions due to better water conservation and limited space requirements aboveground. For instance, the concept of subsurface storage and/or treatment known as managed aquifer recharge (MAR) is increasingly applied worldwide for water storage and treatment (Dillon et al., 2010, 2018). In coastal zones, however, the abstraction of (stored) freshwater is generally hampered by saline groundwater, causing early salinization of simple abstraction wells due to upconing and buoyancy effects (Figure 2-2, A and C, respectively) (Oude Essink, 2001; Ward et al., 2009). This makes traditional well configurations vulnerable to salinization and thus application of MAR often inefficient. The same holds for exploitation of fresh groundwater lenses formed by natural recharge, which is complicated by upconing of deeper saltwater (Figure 2-2, B). Therefore, the challenge is to optimize the management of natural freshwater resources in the subsurface for drinking and irrigation water, while not disturbing or even creating valuable ecosystem services in coastal zones.

As a response to these limitations, a set of practical concepts called Subsurface Water Solutions (SWS) has been developed in the past decade, and has been further improved and made market-ready within the Horizon 2020-project Subsol. These SWS have the ability to improve freshwater management in coastal aquifers. The common feature of the different SWS is to protect, enlarge and utilize fresh groundwater resources in coastal zones through advanced groundwater management. Three typical examples of SWS include (Figure 1-2:

a) The Freshkeeper, which aims at protecting wells against salinization during a sustained freshwater supply, by simultaneously abstracting fresh and brackish groundwater with two different wells (Figure 1-2: A, Section 0).
b) The Freshmaker, which aims at enlarging, protecting and utilizing shallow freshwater lenses in brackish to saline aquifers using Horizontal Directionally Drilled Wells (HDDWs). A HDDW located below the shallow freshwater lens abstracts brackish groundwater while another HDDW injects and abstracts freshwater from the freshwater lens (Figure 1-2: B, Section 0).
c) ASR Coastal, which aims at storing freshwater surpluses (of precipitation or treated waste water) in brackish aquifers by using Multiple Partially Penetrating Wells (MPPW) at different depths in a confined aquifer (Figure 1-2: C, Section 0).

The SWS have been designed with sophisticated and dedicated new well configurations and management strategies to obtain maximum control over the water resources far beyond the levels of control provided by standard water management techniques. The SWS have been applied by national and international consortia of research institutes, technology providers, and end-users in the drinking water and horticulture industry, supported by local and national authorities. These applications resulted in a sustainable freshwater supply, stimulation of food production, energy savings, and financial savings.

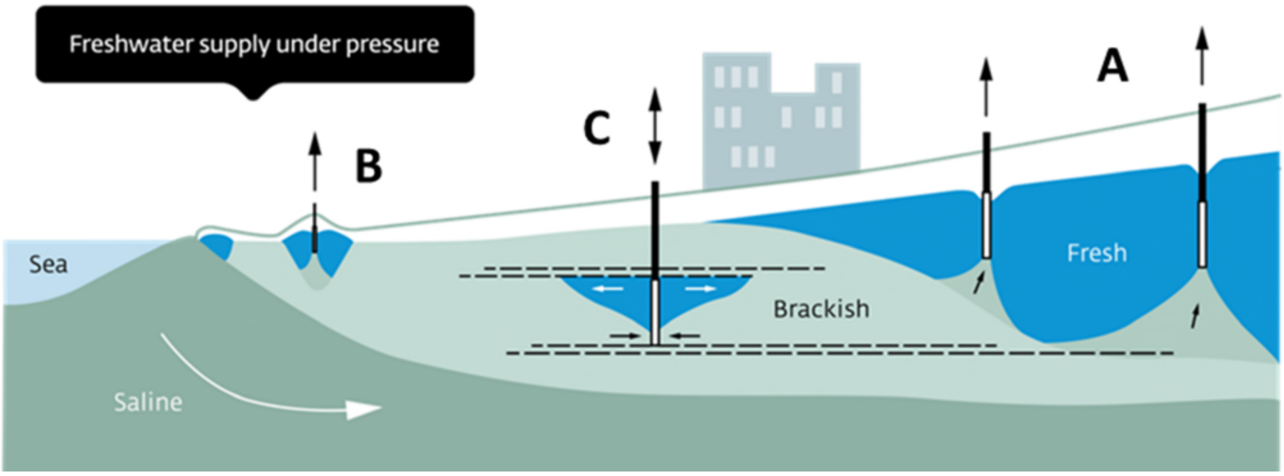

Figure 1-1 Example of a coastal area where fresh groundwater is under pressure, in a cross-section of the subsurface from the sea (left) towards inland (right). A and B are threatened by upconing of brackish groundwater due to overexploitation of freshwater from a shallow freshwater lens and a fresh groundwater aquifer, respectively. C represents a standard fully penetrating ASR well in a confined brackish aquifer. The infiltrated freshwater moves upwards at this location due to buoyancy and brackish water is recovered early at the bottom of the well.

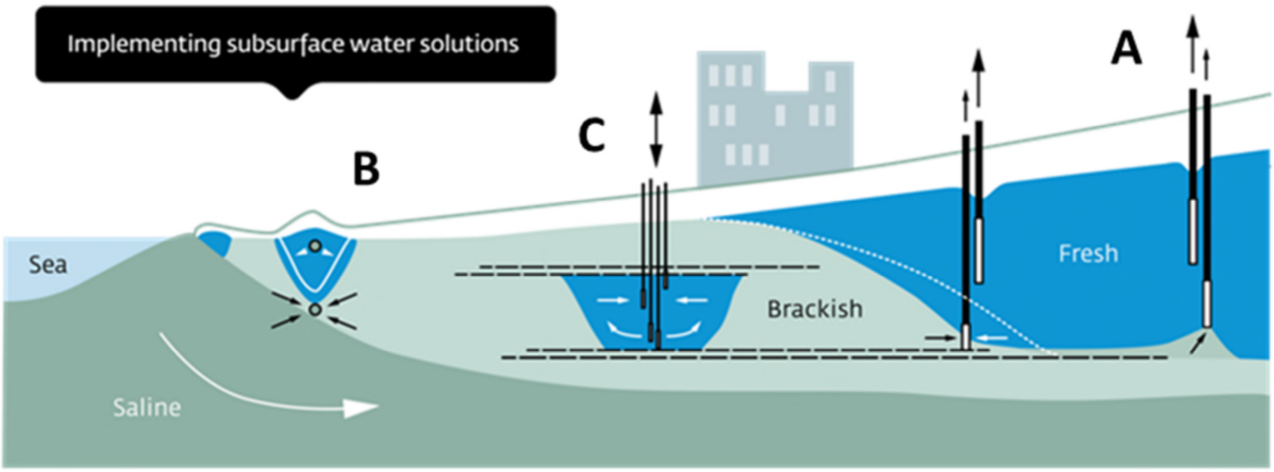

Figure 1-2 Example of a coastal area where fresh groundwater was under pressure and the SWS are being applied. The figure represents a cross-section of the subsurface from the sea (left) towards inland (right). A represents the application of the Freshkeeper technique in a fresh groundwater aquifer under threat of salinization due to upconing, B the application of the Freshmaker in a shallow freshwater lens, and C the ASR-Coastal technique in a confined brackish aquifer.

Technological and Economical guides

A Technological and Economical guide has been developed for each SWS, covering the feasibility, and the technological and economic aspects of its implementation. These guides strive to increase and facilitate the market uptake of each SWS for a sustainable freshwater resource management in coastal areas in Europe and beyond. Each guide aims to provide future adopters with a step-by-step list of activities, which will result in a successful implementation of the SWS concept. Promoting sustainable water management in such a way is a major step in the societal transition towards a circular economy (ING, 2017).

In each Technological and Economical guide, first a detailed introduction of the corresponding SWS concept is presented. The experiences of already existing field implementations of SWS until August 2017 are compiled and synthesized to create guidelines that cover the existing technical set-ups. The reader will subsequently be guided through a checklist of activities and data requirements for the implementation of a specific SWS concept at the location of interest. A supplemented Microsoft Excel Tool allows to study the actual feasibility of a specific SWS concept at the location of interest, based on the water balance and geohydrology that are specified by the user. The initial appropriate design, operational parameters, and costs involved for a specific SWS concept are estimated based on this information. In addition, the reader is guided through the risk assessment and processes of permitting and compliance.

Target users of the Technological and Economical guides

In the context of solving freshwater management problems, especially in coastal areas, the Technological and Economical guides are meant for end-users of freshwater (with a strong interest in a self-reliant freshwater supply), engineering companies and installers, technology providers, and consultants. The Technological and Economical guides facilitate identification of available options for SWS implementation, understanding of their key characteristics (from a technical, environmental and economic viability point of view), and communication with policy makers and regulators to identify and address regulatory issues and potential barriers.

Contents of the Technological and Economical guides

The guidelines presented in these Technological and Economical guides are based on the knowledge gathered in the last decade. They are intended to guide the early adopters in their implementation of the SWS concepts.

The guidelines here provided are based on the field and practical experiences gained throughout the whole implementation process of SWS reference sites, with further developments realized within the context of the European SUBSOL project. The reference sites are the following:

1. Noardburgum (The Netherlands), where a Freshkeeper system has been in operation since 2009. The Freshkeeper is located in a well field that suffers from (and had been abandoned because of) salinization. The Freshkeeper has been successful in providing full and automated control of the fresh-brackish groundwater interface at the pilot well.
2. Ovezande (The Netherlands), where a Freshmaker has been successfully in operation since 2013, maximizing the freshwater recovery, by using horizontal directionally drilled wells and by intercepting saltwater.
3. Nootdorp and Westland (The Netherlands), where two ASR-Coastal pilots have been successfully in operation since 2012 to supply horticulture farmers with freshwater. The rainwater surplus collected on the roofs of the greenhouses is stored in the (brackish) subsurface and subsequently abstracted in times of demand. At the Westland pilot site, the brackish and salt water underlying the injected freshwater is being intercepted to protect the shallower freshwater.
4. Dinteloord (The Netherlands), where treated waste-water from a nearby sugar factory is stored in a brackish aquifer. The pilot has been successfully in operation since 2012.

For each of these SWS experiences, groundwater flow modelling has been carried out parallel to field work to get a better understanding of the system, to forecast future behaviour, and to analyse different scenarios. The results from groundwater flow modelling are part of the Technological and Economical guides and give the end-user a working framework and an idea of future implications of the SWS systems.

The Technological and Economical guides also cover the main obstacles, the reaction of the end-user, and the perception of each SWS-concept in practice.

In addition, the Technological and Economical guides describe some of the follow-up (and updated) pilots that currently exist for each SWS concept, and that are either upscaled or improved versions of the initial pilot. The aim is to provide the user with the original pilot set-ups and with an overview of their latest improved versions. Portraying several cases per SWS concept also provides the future user with a broader view of the concept in question, promoting the site-specific nature of the SWS.

Compilation of the Technological and Economical guides

The present document compiles all Technological and Economical guides and gives guidelines for a successful implementation of the SWS techniques. It serves as an instruction manual for early adopters of SWS worldwide, and aims to provide them with:

- a brief overview of the existing SWS concepts (Chapter 2)
- a decision flowchart that redirects them to the SWS that would be most suitable for their objective, and subsequently to the Technological and Economical guide(s) they should read (Chapter 3)
- a brief compilation of experiences from current end-users of SWS (Chapter 4)

2. Subsurface Water Solutions (SWS)

Subsurface water solutions (SWS) have been developed over the past 10 years to respond to the freshwater challenges in coastal areas worldwide, such as seasonal water shortage, overexploitation of groundwater resources, salt water intrusion, land subsidence, and disappearance of wetlands. SWS protect, enlarge and utilize fresh groundwater resources through advanced groundwater management. New well designs and management techniques are implemented that allow an efficient freshwater management even in the presence of saline and brackish groundwater. The SWS approach is being implemented in several pilots by national consortia in the Netherlands (Noardburgum, Ovezande, Nootdorp, Westland, and Dinteloord) and planned within international consortia abroad (Denmark: Falster Island, Greece: Schinias, and Mexico: Maneadero).

The Freshkeeper

The Freshkeeper is a highly effective tool to prevent salinization of fresh groundwater resources (Figure 2-1). In the concept, one well is installed in a shallow fresh aquifer for the recovery of fresh groundwater. To protect this well from salinization by vertical (upconing) or horizontal (e.g. seawater intrusion) inflow of saline groundwater, an additional well is installed to intercept intruding brackish groundwater. The intercepted brackish water can be disposed of or may on its turn be used as an additional source for freshwater supply by means of Brackish Water Reverse Osmosis (BWRO). Disposal options for the intercepted brackish groundwater or the produced concentrate (by-product of BRWO) may include injection into a deeper confined aquifer with a similar groundwater salinity as the injected water. Figure 2-1 shows an example of a Freshkeeper system to prevent brackish water upconing (1), subsequent desalination with BWRO (2), and deep-well injection (3) of the BWRO concentrate. The Freshkeeper results in an increased fresh groundwater storage capacity in shallow coastal aquifers where fresh and brackish water are not structurally isolated nor confined.

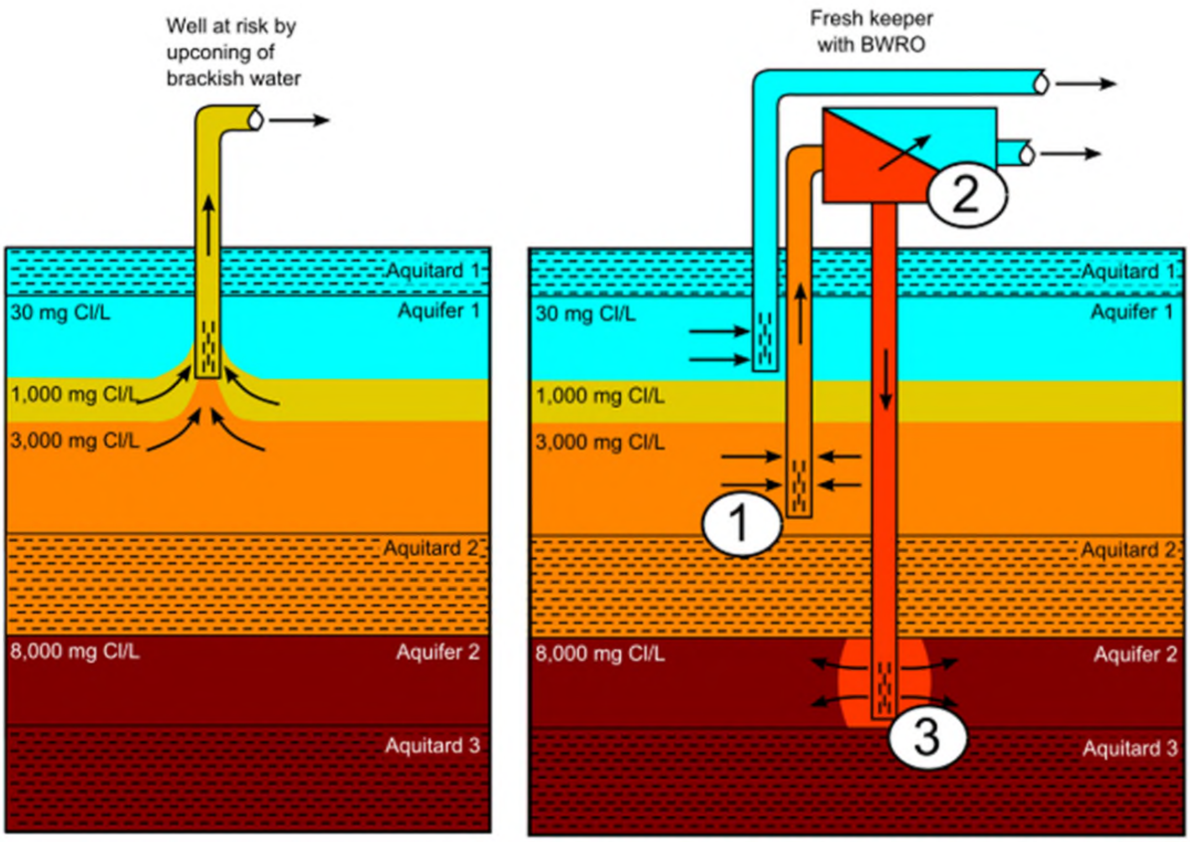

Figure 2-1 Cross-section of the Freshkeeper set-up and operation: The scheme on the left represents a well field at serious risk of upconing of brackish groundwater (salinization) due to over-exploitation. The scheme on the right presents the integrated solution: the Freshkeeper concept as explained in Section 0, with a fresh groundwater extraction well complemented by a brackish groundwater extraction well (1), brackish water reverse osmosis (BWRO) unit (2), and BWRO concentrate disposal in a deeper aquifer (3).

The Freshmaker

The Freshmaker is a concept that includes two horizontal directional drilled wells (HDDW) for injection and recovery of freshwater at shallow depth in a freshwater lens within a brackish aquifer (Figure 2-2). One HDDW is installed in the freshwater lens. The seasonal surplus of fresh surface water is injected through this well, and recovered via the same well in times of demand. This HDDW therefore acts as a shallow horizontal ASR well. The horizontal orientation allows to recover more freshwater compared to a vertical well before upconing of brackish groundwater limits the recovery of freshwater. A second, deeper horizontal well is installed to intercept the upconing brackish groundwater. This enlarges and protects the volume of the natural fresh groundwater lens, thereby increasing the volume of freshwater that can effectively be recovered from it.

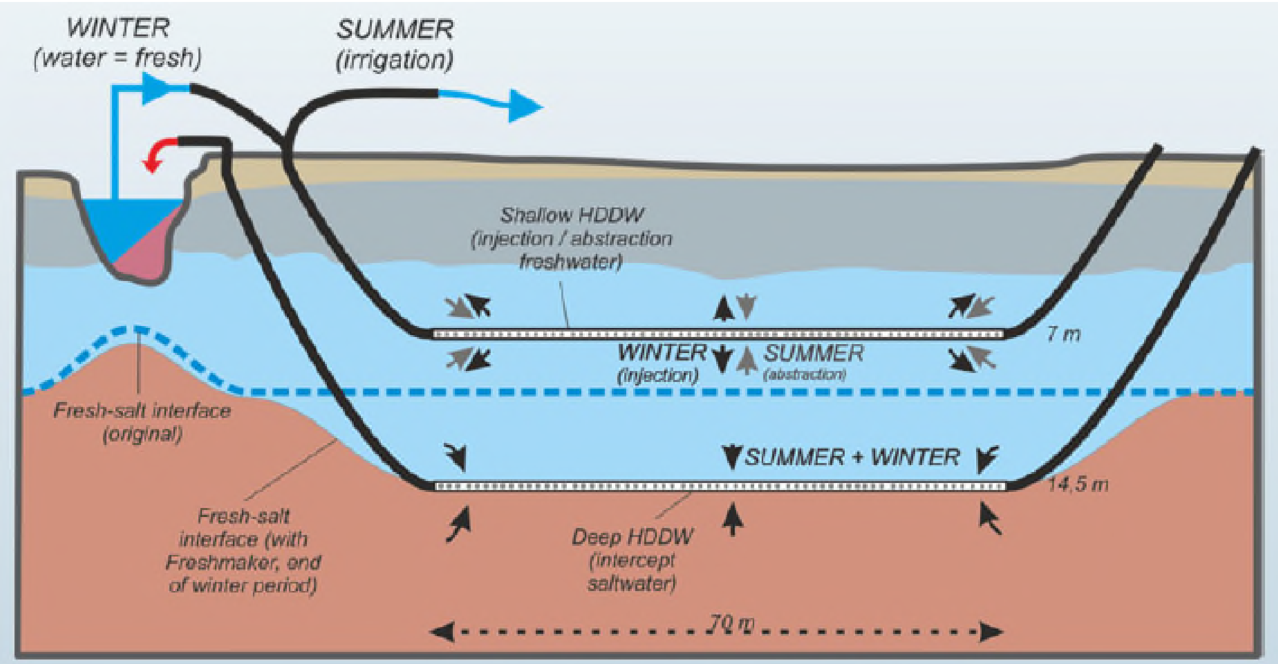

Figure 2-2. Cross-section of the Freshmaker set-up and operation. The surface freshwater surpluses are injected through the shallow HDDW. The deeper HDDW intercepts deep saline water, thereby protecting the shallow HDDW from salinization and enlarging the fresh groundwater lens. The resulting enlarged freshwater lens can be safely pumped through the shallow HDDW in times of demand, without the risk of upconing thanks to extraction of saline water by the deeper well.

ASR-Coastal

ASR-Coastal operates with independent multiple partially penetrating wells (MPPW) installed in a single borehole (Figure 2-3). In such a configuration, the freshwater can preferentially be injected in the deeper part of an aquifer during winter, followed by the preferential recovery of the buoyant freshwater at the top of the aquifer during summer. Because of the resulting limited intake of brackish groundwater at the bottom of the aquifer, ASR-Coastal improves the recovery efficiency of freshwater that has been stored in saline or brackish aquifers.

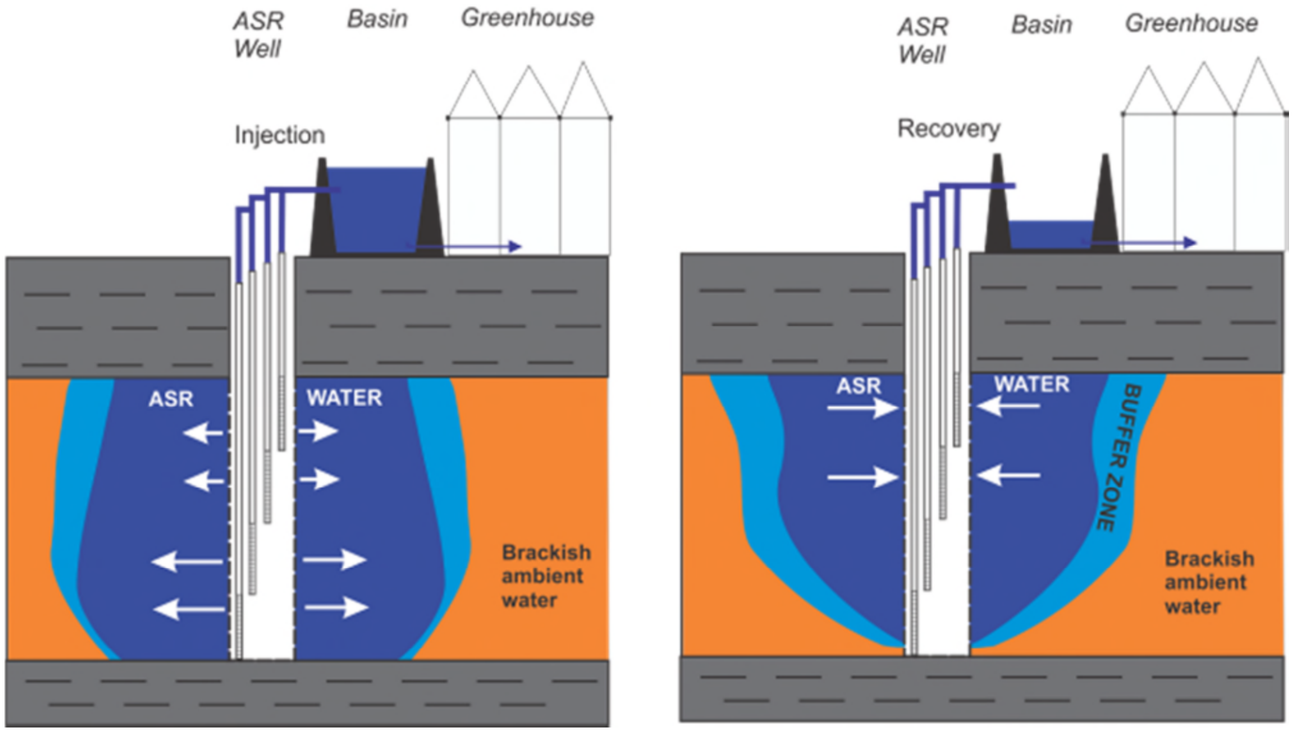

Figure 2-3 Cross-section of the ASR-Coastal set-up and operation: use of an MPPW in a single borehole that injects freshwater mainly in deeper parts of the aquifer and recovers water in shallower parts. This overcomes the early recovery of brackish or saline ambient groundwater at the bottom of the aquifer due to buoyancy forces.

3. SWS decision flowchart

The implementation of a certain SWS concept depends on the objective of the adopter, the amount and variation of freshwater surplus and demand, and the geo-hydrological constraints of the specific location. A decision flowchart was developed (Figure 3-1) in order to provide a general tool that can be promptly used by early-adopters to help them decide which SWS would be most suitable for their situation.

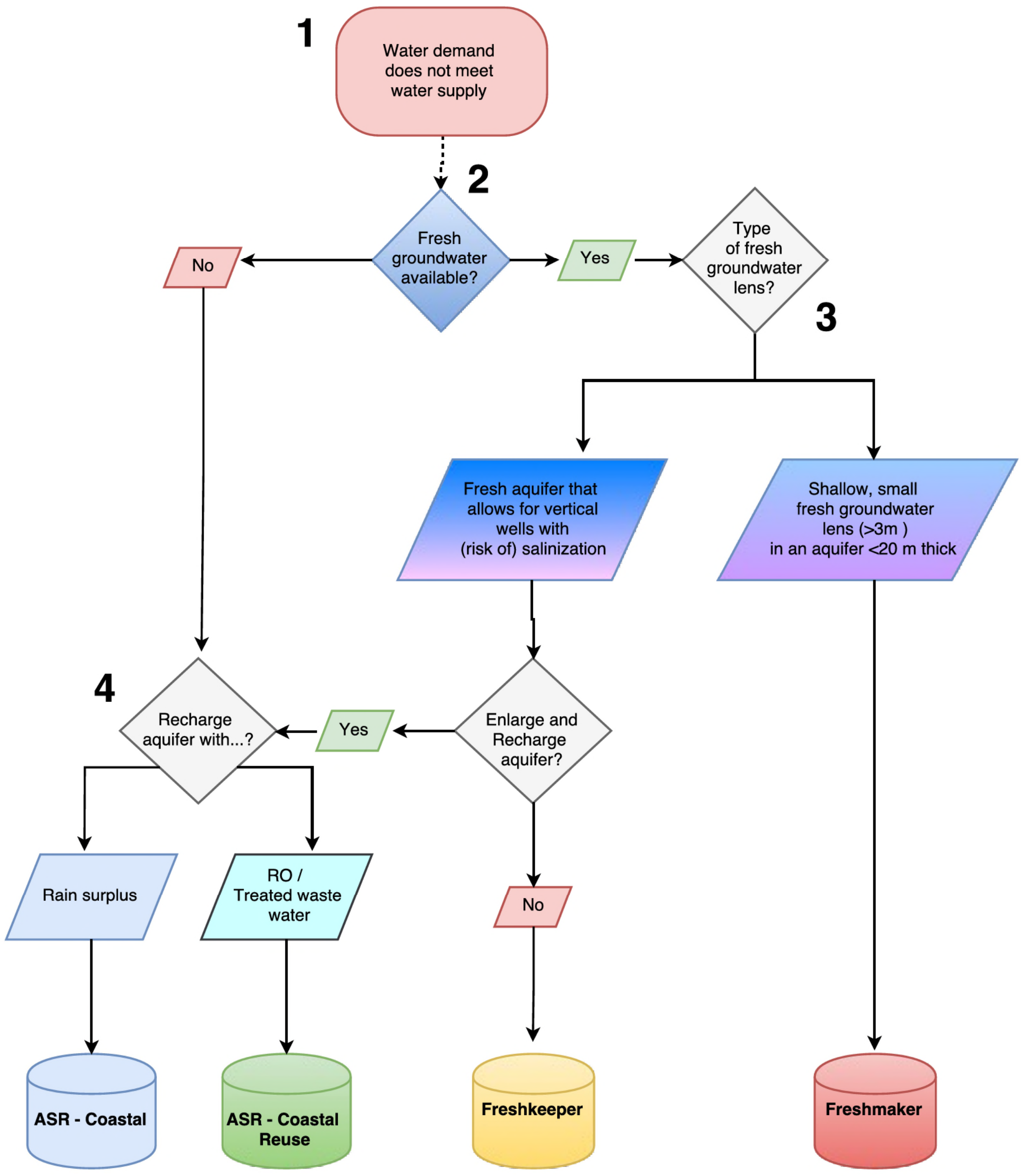

Figure 3-1 SWS decision flowchart.

The SWS Decision flowchart directs the reader towards the most suitable SWS concept for a certain problem related to freshwater management in coastal areas. The following questions should be considered (Figure 3-1):

1. Mismatch freshwater surplus and demand:
   - Is there a consistent or seasonal mismatch between the surplus and demand of freshwater?

2. Availability of fresh groundwater:
   - Is fresh groundwater (Cl content <150 mg/l, (Stuyfzand, 1989)) present in the subsurface (aquifer)?
   → 'Yes' → 3.
   → 'No' → 4.

3. Type of freshwater lens above brackish or saline groundwater (>300 mg Cl/l):
   a. Is the thickness of the fresh groundwater lens limited to several meters (more than 3) in an aquifer less than 20m thick?
      → Ideal setting for **The Freshmaker**.
   b. Is the fresh aquifer thicker and is extraction of this groundwater through vertical wells possible but under threat of salinization through upconing of brackish groundwater?
      → Ideal setting for **The Freshkeeper.**
   c. In addition to b., are there plans to enlarge the freshwater resource by recharging the aquifer in times of surplus?
      → 4.

4. Type of freshwater used to recharge the aquifer:
   a. Is there a surplus of collected precipitation?
      → Ideal setting for **ASR-Coastal**
   b. Is there a surplus of freshwater that has been previously treated (treated waste water or product of reverse osmosis (RO))?
      → Ideal setting for **ASR-Coastal Reuse**

Through these steps and questions of the SWS decision flowchart, the reader is quickly directed towards a certain SWS concept. The reader should consequently study the corresponding Technological and Economical guide to identify available options for the SWS implementation and to understand its key characteristics from a technological, environmental and economic viability point of view.

The corresponding Technological and Economical guides are presented in the following specific deliverables:

- **D1.3** - 'Technological and Economical guide for full-scale **Freshkeeper** application'.

- **D1.5** - 'Technological and Economical guide for **Freshmaker** application'.

- **D1.7** - 'Technological and Economical guide for **ASR-Coastal** application'.

- **D2.6** - 'Technological and Economical guide for **ASR-Coastal Reuse** application'.

4. Experiences from current users

Via online interviews, the experiences from current SWS end users within Subsol were inventoried. The replies showed that SWS in these cases was found an interesting alternative to aboveground storage and groundwater use (upon desalination), mainly because of the limited claim on land (and thereby lower costs) and the sustainability. Permitting can be a bottleneck. SWS is considered user-friendly and the first users are satisfied with SWS. Most of the users would advise SWS to their fellow water users, with the reservation that the conditions should be favourable.

Table 1: Experiences of end users at the Subsol SWS pilots.

Aspect	Experiences of end users at SWS pilot
Alternative water supply for?	Aboveground basin / reservoir Groundwater extraction (+desal)
Before SWS: water quality problems?	None to sometimes
Before SWS: water quantity problems?	None to yearly
Main driver for SWS?	Water availablility, spatial footprint, water quality improvement, sustainability
How hard was the transition? (Scale 1 to 5)	2.3
Impact of realisation phase? (Scale 1 to 5)	1.8
How hard was it to obtain the permits? (Scale 1 to 5)	2.8
How user-friendly is the SWS? (Scale 1 to 5)	3.5
How satisfied are you with the SWS? (Scale 1 to 5)	4.5
Would you advice SWS to your fellow water users?	75% will
Remarks	Try to keep the operation simple. The extremely low turbidity is a big advantage.

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