D1.5 – Technological and Economical guide for Freshmaker application

SUBSOL has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 642228

Title:	Technological and economical guide for Freshmaker application

Grant agreement no:	642228
Work Package:	WP1.2
Deliverable number:	D1.5
Partner responsible:	KWR Watercycle Research Institute
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Planned delivery date:	28 February 2018
Actual delivery date:	30 August 2018
Revised version:	22 October 2018
Dissemination level:	PU *PU = Public* *PP = Restricted to other programme participants (including the Commission Services)* *RE = Restricted to a group specified by the consortium (including the Commission Services)* *CO = Confidential, only for members of the consortium (including the Commission Services)*

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Summary

The Freshmaker is a Subsurface Water Solution (SWS) that has been developed within in the past decade and tested within Subsol. The practical concept enlarges, protects and sustainably utilizes shallow fresh groundwater lenses in brackish to saline aquifers by the interplay between overlying horizontal directional drilled wells (HDDWs).

A pilot was carried out in Ovezande (The Netherlands) since 2013. This pilot has proven that the Freshmaker is a suitable SWS to reduce problems related to water quality or availability for water users with a seasonal variability of freshwater demand. Improvement of the Freshmaker in Ovezande, and further improvement of the technique in Groede (The Netherlands), have both contributed to the development of a reliable system for subsurface storage of freshwater in coastal areas with a brackish-saline subsurface.

This Technological and Economical guide serves as a starting point for end users of freshwater (with a strong interest in a self-reliant freshwater supply), engineering companies and installers, technology providers, consultants, and water managers interested in the development of a Freshmaker at other coastal sites with temporary water shortages and a brackish-saline subsurface. Through a feasibility study of the water balance and the geohydrology at a specific site, the supporting Freshmaker Tool proposes a design and an operational scheme, and estimates the costs involved for installation and implementation.

1 Introduction

Subsurface Water Solution (SWS): The Freshmaker

Within the Subsol project, a set of practical concepts called Subsurface Water Solutions (SWSs) has been developed in the past decade. These SWSs provide a sustainable freshwater supply from coastal aquifers.

The **Freshmaker** is one of these SWS concepts, and is subject of this Technological and Economical guide. It is a tool that improves freshwater management in coastal areas by using horizontal directional drilled wells (HDDW). One HDDW is installed within a shallow freshwater lens, infiltrating freshwater in times of surplus and recovering it in times of demand. A second HDDW is installed below the shallow freshwater lens to intercept saline groundwater, to enforce freshwater storage, and to protect the shallow HDDW from salinization (Figure 1-1). With this interplay between overlying HDDWs, the Freshmaker enlarges, protects, and sustainably utilizes shallow fresh groundwater lenses.

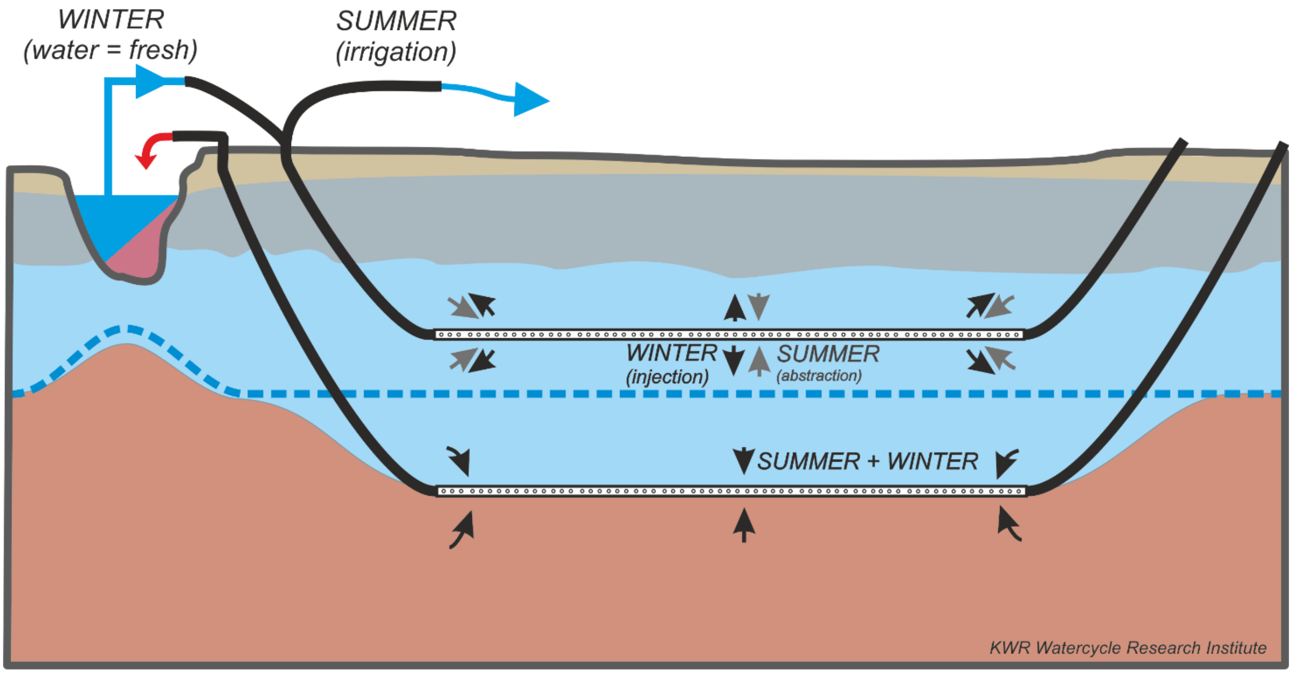

Figure 1-1 Cross-section of the Freshmaker technique applied in a shallow fresh groundwater lens within a saline groundwater aquifer.

Objectives

This Technological and Economical guide strives to:

- Provide potential users with a broad view of the Freshmaker implementation and its site-specific nature by portraying the original pilot set-up and the latest improved versions of the Freshmaker.
- Assist and guide potential users in assessing the potential of realizing a Freshmaker set-up by providing a checklist of required activities and data.

Target users of the guide

This guide is written for end users of freshwater (with a strong interest in a self-reliant freshwater supply), engineering companies and installers, technology providers, and consultants. These target users ideally have freshwater sources available but are dealing with temporary freshwater shortages in which the demand of freshwater does not meet the supply, and are situated in coastal areas with brackish-saline aquifers.

This guide facilitates identification of available options for Freshmaker implementation, understanding of its 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.

Content

The guide covers detailed background information and compiles the experiences and knowledge gained from the first Freshmaker system. This is primarily based on the practical experiences gained throughout the implementation of the Freshmaker at the reference field site in Ovezande, The Netherlands, where a Freshmaker has been successfully in operation since 2013. Groundwater flow modelling has been carried out parallel to fieldwork, to improve the understanding of the Freshmaker, to forecast future behaviour, and to analyse several scenarios. The results from groundwater flow modelling are also included in this guide to present future implications of the Freshmaker concept. Furthermore, the main obstacles, the reaction of the end user, and the perception of the Freshmaker concept in practice in Ovezande are covered in this guide.

Besides the Ovezande reference site, the guide also covers the development of an improved version of the low-cost HDDW at Groede (The Netherlands) and the exploration of an upscaled Freshmaker near 's-Heerenhoek (The Netherlands).

This information is synthesized to create implementation guidelines of the Freshmaker concept. A process scheme of the required activities that constitute a preliminary feasibility study for implementation of the Freshmaker at a specific location is included in Chapter 3.

A data checklist and a feasibility scheme are presented in Chapters 4 and 5, respectively. They guide the future user towards the initial design of the Freshmaker for a specific site (Chapter 6). A risk-assessment scheme and an economic analysis scheme are included in Chapter 7 and 8, to assess environmental risks and the costs of installation and operation of the Freshmaker, respectively. The general permitting and compliance processes are presented in Chapter 9. Lastly, the conclusions and take-away messages from this Technological and Economical guide are summarized in Chapter 10.

Freshmaker tool (Excel)

A Microsoft Excel tool to be used parallel with this Technological and Economical guide was constructed. This tool helps to create a first design, and to define operational and economical parameters that are necessary along the process of realizing a Freshmaker system. An overview of how this tool should be used parallel with the Technological and Economical guide is provided in Chapter 3. The simplicity of the tool makes it ideal to use it for a preliminary feasibility study and contains some default information to fill in potential data gaps.

2 Background of the Freshmaker

The Freshmaker strategy

Aquifer storage and recovery (ASR) is an efficient technique to bridge the seasonal mismatch between freshwater surplus and demand, and has been successfully applied in freshwater management for years. The conventional ASR setup consists of a single vertical, fully penetrating well that infiltrates freshwater into an aquifer and, after storage, recovers it again through the same well. However, exploitation of shallow and thin fresh groundwater lenses in brackish aquifers by means of vertical directional drilled wells is often hampered by upconing of brackish groundwater. With the development of horizontal directional drilled wells (HDDWs) (Cirkel et al., 2010), an alternative and improved version of ASR became available for saline phreatic aquifers and thin aquifers in general.

In the Freshmaker set-up, one HDDW is complemented by a deeper HDDW (Figure 2-1). The shallow HDDW acts as a horizontal ASR well, which is used for infiltration of freshwater in times of surplus (winter), thereby enlarging an existing thin freshwater lens, and for later recovery in times of demand (in summer or during periods of drought). The horizontal orientation of the well spreads the recovery of freshwater from the thin lens over a large area, thereby limiting the local effect of upconing (Oude Essink, 2001; Stoeckl and Houben, 2012). The deeper HDDW simultaneously intercepts brackish water to enlarge the natural fresh groundwater lens, protecting the shallow well from salinization (Zuurbier et al., 2015). The fresh-salt water interface is therefore actively managed to increase the applicability of ASR and the potential recovery of freshwater.

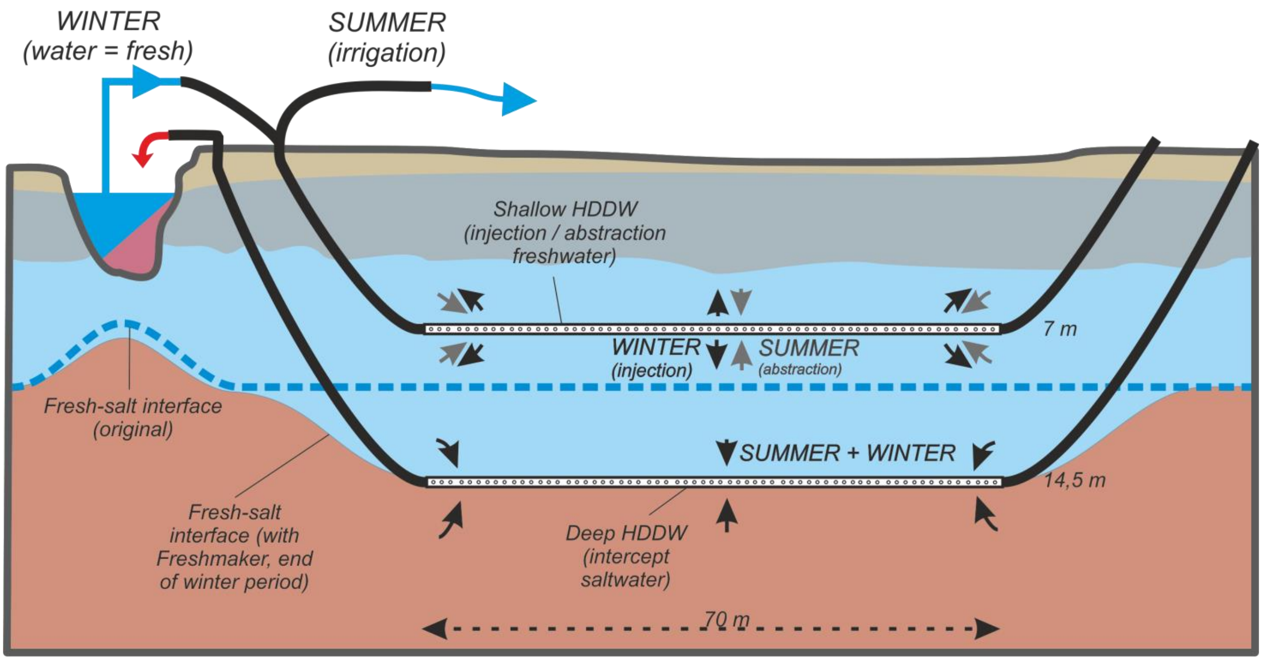

Figure 2-1 Cross-section of the Freshmaker concept in a brackish aquifer with a shallow freshwater lens.

Experiences at the Ovezande reference site

The first Freshmaker system was installed in March 2013 in a shallow coastal aquifer in Ovezande, located in the province of Zeeland in the southwest of The Netherlands (Figure 2-2). Due to the surrounding Scheldt estuary and saline seepage, freshwater is scarce in the study area. Freshwater resources are limited to precipitation, inland river water supplied by pipelines, and local fresh groundwater lenses in sandy creek ridges. The Freshmaker pilot site in Ovezande is located on such a sandy creek ridge with, prior to installation of the Freshmaker, a local and generally thin freshwater lens of about 9 m and a mixing zone of approximately 6 m beneath (Figure 2-1 and Figure 2-2). Groundwater salinity below the mixing zone equals that of local seawater, with a chloride concentration of approximately 16,800 mg/l.

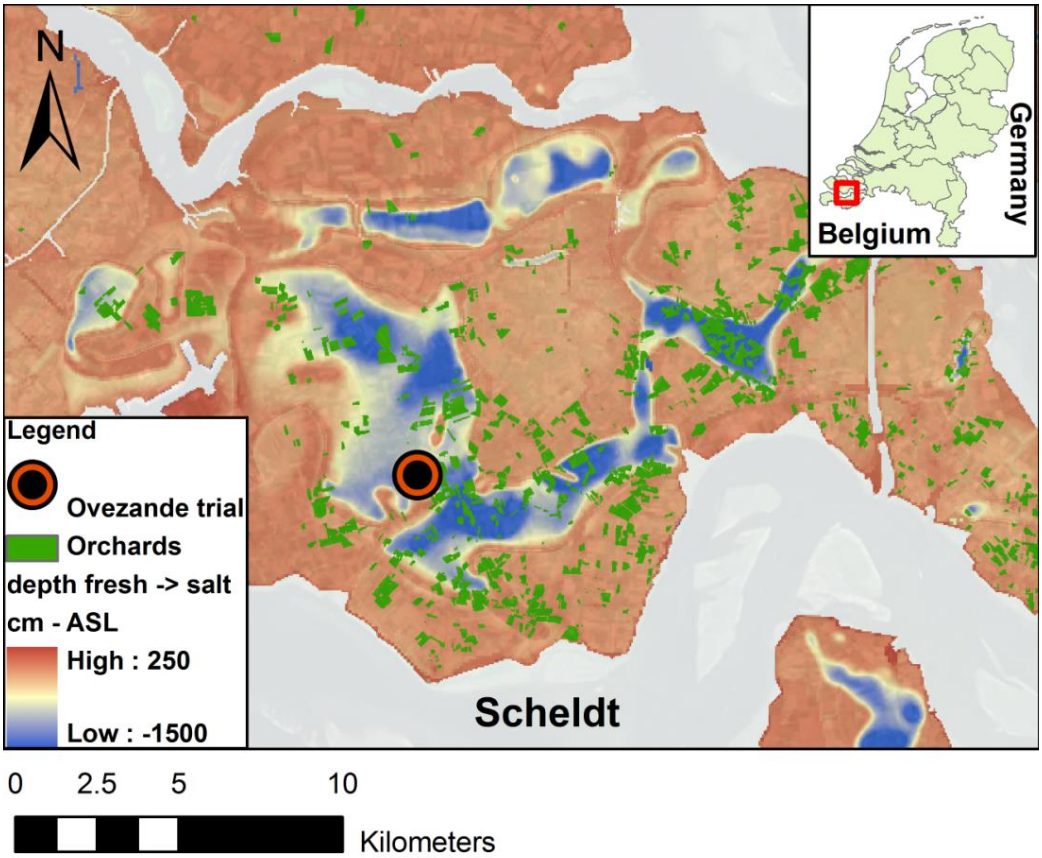

Figure 2-2 Overview of the study area. The depth of the fresh-salt interface that corresponds with a chloride concentration of 1,000 mg/L indicates the distribution of natural fresh groundwater lenses around the Freshmaker pilot site in Ovezande (Zuurbier et al., 2015).

Prior to installation of the Freshmaker in Ovezande, the water demand of the end user's pear-orchard could not be met, which led to crop damage several times in the past. This was mainly due to the limited seasonal availability of freshwater. Besides, the quality of water, when available, was not always sufficient, due to exceedance of a strict maximum chloride concentration of 250 mg/l for irrigation water of a pear-orchard in the growing season. His main reason to start with the pilot phase of the Freshmaker was thus to obtain a better water quality and a more constant water availability throughout the year.

After characterization of the target aquifer and the native groundwater therein, two superimposed 70 m long HDDWs (made of HDPE) were placed at ~7 m and ~14.5 m below the land surface (Figure 2-1). Depths were selected based on cone penetration tests aimed to avoid intervening clay layers. After successful installation, freshwater surpluses from a nearby water course were stored in a basin in 2013 – 2014, thereby enabling freshwater intake in periods with peak discharge in the water course and managing potential variations in the supply. Water pumped from the top of the basin was filtrated with a 200 micron screen filter and subsequently infiltrated into the freshwater lens through the shallow HDDW, using a 3 m high standpipe to provide a constant pressure for infiltration. Since November 2014, the basin detention (with settlement of fines) was replaced by a river bed-filtration system to pre-treat infiltration water. For recovery of the stored freshwater during periods of water shortage, the same shallow HDDW was used, thereby functioning as a horizontal ASR-well.

The deep HDDW intercepts brackish groundwater. This interception well protects the shallow HDDW from salinizing. The intercepted brackish groundwater is discharged to the local watercourse, with a permitted maximum of 40 m^3/d.

Figure 2-3 Installation of the horizontal directional drilled wells (HDDW) for the Freshmaker in Ovezande (Zuurbier et al., 2015).

Several monitoring wells were installed around the HDDWs to frequently sample the water for water quality analysis. Geophysical measurements were also conducted to construct profiles of electrical resistivity and electrical conductivity of the subsurface. Together these procedures enable to analyse the distribution and dynamics of the freshwater lens during operation of the Freshmaker. In addition, a groundwater flow and transport model was constructed to determine whether the model results are in line with real field data, to predict future performance, and to assess the hydrological effects in the surroundings (Van der Linde, 2015).

Since the start of the implementation of the Freshmaker in Ovezande, 5 ASR-cycles were run. Based on the documentation and interpretation of the field operation, model simulations and analyses during these cycles, the following conclusions were made:

- The system is able to store and supply around 5 000 m^3 per year.
- The system has an estimated maximum storage and recovery capacity of 6 000 m^3, based on groundwater modelling.
- Geophysical measurements indicate a 4 m increase in thickness of the freshwater lens during the injection phase, with the transition zone between fresh water and saltwater becoming as thin as 1 m.
- The measurements and models suggest there is an equilibrium or even gradual freshening of the groundwater at the Freshmaker site in between the ASR-cycles.
- Since the operation of the Freshmaker in Ovezande, the end user states there has been a significant reduction in problems related to quality or availability of irrigation water .
- Modelling and field observations confirm that the hydrological impacts of the Freshmaker on the surroundings are limited.
- Modelling indicates the additional advantage of a limited increase (+0.05 m) and reduction (-0.07 m) in drawdown during periods of injection and recovery, respectively. This prevents a significant decrease in freshwater availability near plant roots as well as land subsidence, which are potential negative consequences of ASR operations.
- Infiltration of surface water poses water quality risks, mainly related to pesticides in this agricultural region. By limiting the infiltration period to 15 November – 15 April (winter season), potential exceedance of the maximum concentrations of pesticides can presumably be prevented.
- Further automation of the Freshmaker’s operation via an automated control unit has been designed and is to be implemented in Ovezande and at future Freshmaker sites to automate the process of infiltration and interception.

- Clogging of the shallow HDDW in Ovezande was caused by insufficient pre-treatment (2013-2014) and biological growth in the well (2013-2017). River-bed filtration was already introduced in 2014 and later improved to overcome the former, and regeneration was successfully applied to combat the latter (see close-up 1).
- Based on the experiences at this pilot site, construction and maintenance of HDDWs and pre-treatment are identified as key aspects for the success of a Freshmaker. Chemical and mechanical regenerations of the HDDWs in Ovezande were introduced and a more robust and economically viable alternative for the HDDW-type used at the reference site was developed and successfully tested at the Groede site (see close-up 1).

For more detailed information on the pilots performed, the reader is referred to Subsol D1.4: Improved Freshmaker Reference site (TRL8) by Dr. Koen Zuurbier, Teun van Dooren MSc, Steven Ros MSc (June 2018).

Close-up 1: Improvement of the HDDW technology (Case Groede)

The development of robust, cost-efficient, and long-lasting HDDWs is vital for further application of the Freshmaker. As a first step to improve the HDDW technology, clogging and mechanical and chemical well regeneration to mitigate clogging were analysed at the Freshmaker reference site in Ovezande. Here, perforated HDPE pipes wrapped in geo-textile were used to form very simple well screens. During the system's operation, it was observed that HDDW2 (intercepting saline groundwater) remained relatively clean and showed no capacity loss. However, sand and significant biological growth were observed in HDDW1, which reduced the capacity of the shallow HDDW (infiltrating freshwater) during infiltration seasons. Upon realisation of the sand filter for pre-treatment of infiltration water, the infiltration capacity was better maintained, but still decreased slowly by biological growth and subsequent clogging. Chemical treatment of the shallow HDDW with H_2O_2 and Na-hypochlorite was found to be effective in removing biological growth and restoring the capacity of HDDW1. Complete recovery of the initial capacity by chemical and mechanical regeneration was, however, not attained. It should be noted that the clogging observed in Ovezande is related to the source of the water (surface water), which did not meet the standards for infiltration water (high MFI, high AOC). At the Ovezande site, an additional 5 m deep drain was later added right above HDDW1 to enlarge the pumping capacity in times of water demand.

As a second step to further develop a robust HDDW set-up, two HDDWs were installed at the 'Groede' site; one with a HDPE well screen wrapped in geotextile similar to the Ovezande site; and a more sophisticated one with a PVC wire-wrapped well screen (CSS Boode). Each well was placed in a perforated 125 mm HDPE pipe in order to pull in the well and protect the well screen (Figure 2-5). This perforated pipe was left behind and should permit sand and water to flow in. The inner well screens separate the water from the sand.

Although successfully installed, the simple HDDW wrapped in textile was observed to produce a lot of sand together with the abstracted water, due to a clear inflow of sand at 2/3 of the HDDW well screen. Removal of the well screen revealed damaged geotextile, but also hampered further successful re-lining. The first HDDW was therefore abandoned.

The CSS Boode HDDW was successfully installed at the Groede site. The PVC well screen segments allowed easy connection and insertion in the outer 125 mm HDPE pipe since they are provided with C-Type female flush butt joints with male adaptors. Only a minimal amount of sand was observed in the abstracted water after four weeks of operation with maximum capacity of the pump. Besides being a viable alternative, the CSS Boode is nearly as expensive as the HDPE wrapped in textile.

Figure 2-4 The Boode CSS well screen (www.boode.com).

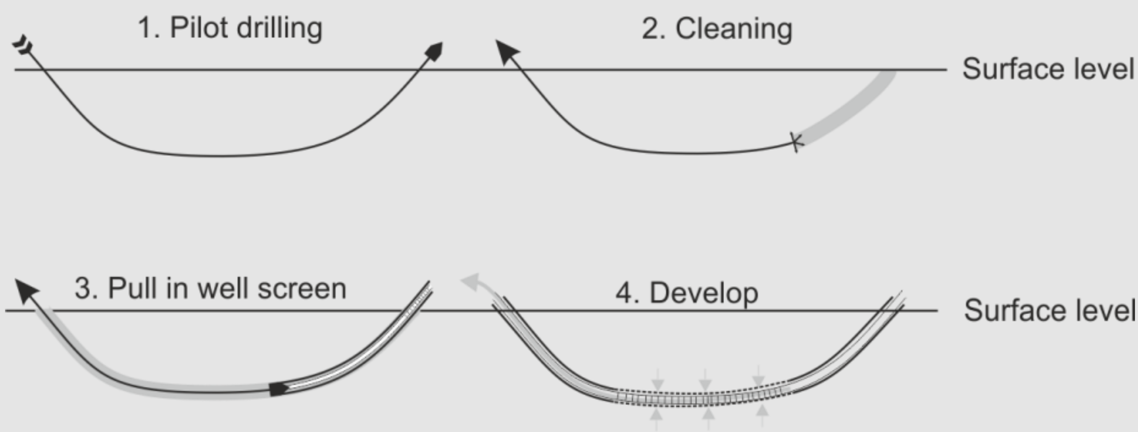

Figure 2-5 Drilling and installation strategy of the HDDWs in Groede

A third alternative to the tested materials is the stainless steel well, which does not require protection by the 125 mm HDPE perforated casing. However, they come with higher costs than the materials tested at the Groede site. Considering these observations, a robust and cost-efficient installation of HDDWs is preferably attained with the use of the wire-wrapped PVC wells (CSS Boode) because of its ease of installation, performance, and costs.

The adjustments to the original system in Ovezande have impacted the costs of the Freshmaker at the pilot site. However, based on the construction costs, the operational costs, the spatial claim on agricultural land, and the improved HDDW technology in Groede, the Freshmaker provides an economically very interesting alternative for irrigation water supply, with an estimated cost price of 0.54 €/m^3.

Close-up 2: Upscaling of the Freshmaker (Case 's-Heerenhoek)

A feasibility study was set up by KWR, Infram, Decisio en KplusV under the name of Fresh Force to explore the economic feasibility of a large-scale Freshmaker in 's-Heerenhoek.

Three different set-ups were studied that differed in location, extension, and distribution (Figure 2-6). The substratum at all three variants was suitable for Freshmaker application and there is no indication of disruptive clay layers within the target aquifer. The three variants are situated in the vicinity of clusters having a water demand.

The choice of variant FM1, in the westernmost zone, was based on a certain fresh water availability (in winter) and a favourable subsurface. It covers 283 ha, mostly consisting of fruit crops. Variant FM2 located on the easternmost part, covers 154 ha of cropland and was chosen as far to the east as possible due to salinization of the watercourse downstream in the southwest. Variant FM3 was a local Freshmaker without distribution, supplying an appropriate storage to supply around 25 ha of orchard and was analysed to compare costs of the 2 collective (FM-1 and FM-2) and individual systems (Table 2-1).

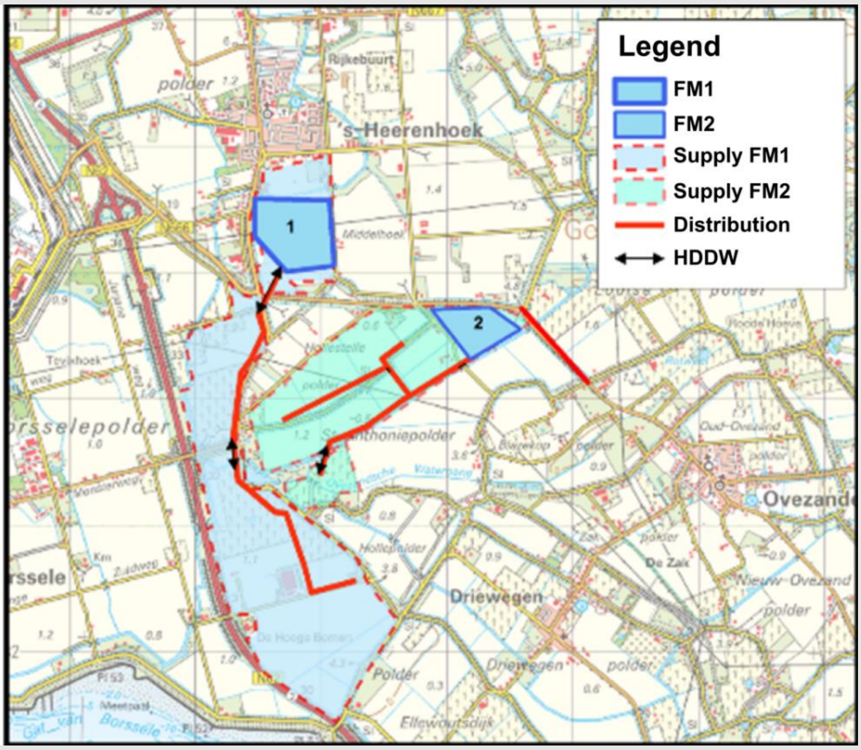

Figure 2-6 Distribution of the variants studied for the feasibility of upscaling a Freshmaker. FM1 and FM2 are storage sites using Freshmaker technology.

The shallow infiltration wells are drilled as shallow deep-drains and the deeper abstraction wells are drilled as HDDWs separated by a vertical distance of around 60m. The business case is built on the assumption that during one year there will be on average 100 mm fresh water abstracted from the subsurface and supplied via a booster-pump to local fruit growers through a distribution loop (Figure 2-7). The maximum capacity is 200 mm per summer, the cost price per m^3 is based on the average supply.

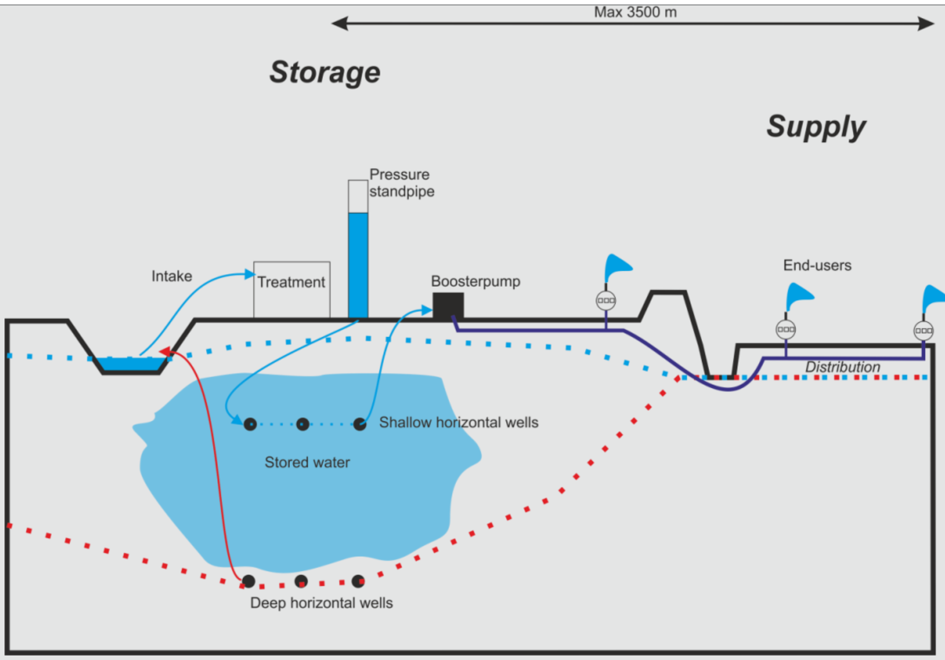

Figure 2-7 Application of a regional Freshmaker in a storage zone with distribution to areas where subsurface storage is not an option. Conceptual set-up, not to scale.

The investment and operational costs of such a prototype are compared for the three variants and the results are summarized as the price per cubic meter of water (Table 2-1). Variants FM1 and FM2 are also subdivided in different types of organizational forms that can be applied for the development of a regional Freshmaker. The first type is cooperative: the Freshmaker is implemented and exploited by the individual farmers. In the other scenario, a third party is implementing the system and selling the water to the farmers. All these results are compared to the case of an individual farmer installing a small-scale system.

In all cases, lifespan of the systems was 20 years. The depreciation period was 10 years and so was the pay-off time. The effect of a 'tax shield' was taking into account (reduction in taxable income).Based on the resulting cost-prices, it is concluded that:

- *The price of water provided by the Freshmaker is competitive with local piped river water (approximately 0.70 euro/m^3) and drinking water (>1 euro/m^3).*
- *Upscaling results in somewhat lower costs for the water supplied, but enormous scale advantages cannot be expected*

Table 2-1 Water production by the Freshmaker and the price per cubic meter of recovered water per variant.

	FM1: Cooperation	**FM1: Third party**	**FM2: Cooperation**	**FM2: Third party**	**FM3: Individual farmer**
Assumed average water demand (in m^3)	283.000	283.000	154.000	154.000	25.000
Annual total costs	€134.448	€ 122.742	€ 91.037	€ 83.163	€ 14.018
Price per cubic meter	**€ 0,48**	**€ 0,43**	**€ 0,59**	**€ 0,54**	**€ 0,56**

3 Process scheme

In this chapter, a general overview of steps to implement the Freshmaker concept at a specific location is provided, from problem definition to realization. Each of these steps is covered in detail in the following chapters.

The process can be sub-divided into the evaluation of two parts: feasibility assessment and design phase. The former involves the problem definition (water demand not met by water supply), the collection of data and the geo-hydrological feasibility study. The latter, the design phase, can be an iterative process by which the set-up design is optimized iteratively based on the economic study and on the risk-assessment.

Figure 3-1 provides an overview of the process steps. This overview integrates the titles of the worksheets in the Freshmaker Tool that can be used alongside this Technological and Economical guide (‘1. Water balance’, ‘2. Geohydrology’, ‘3. Design’, ‘4a. CAPEX’, and ‘4b. OPEX’). The user is recommended to follow these process steps and to use the corresponding worksheets of the Freshmaker Tool, after reading the README-worksheet therein. When all worksheets of the Freshmaker Tool are filled in correctly, an overview of the most relevant input and output is given in worksheet ‘0. Overview input & output’.

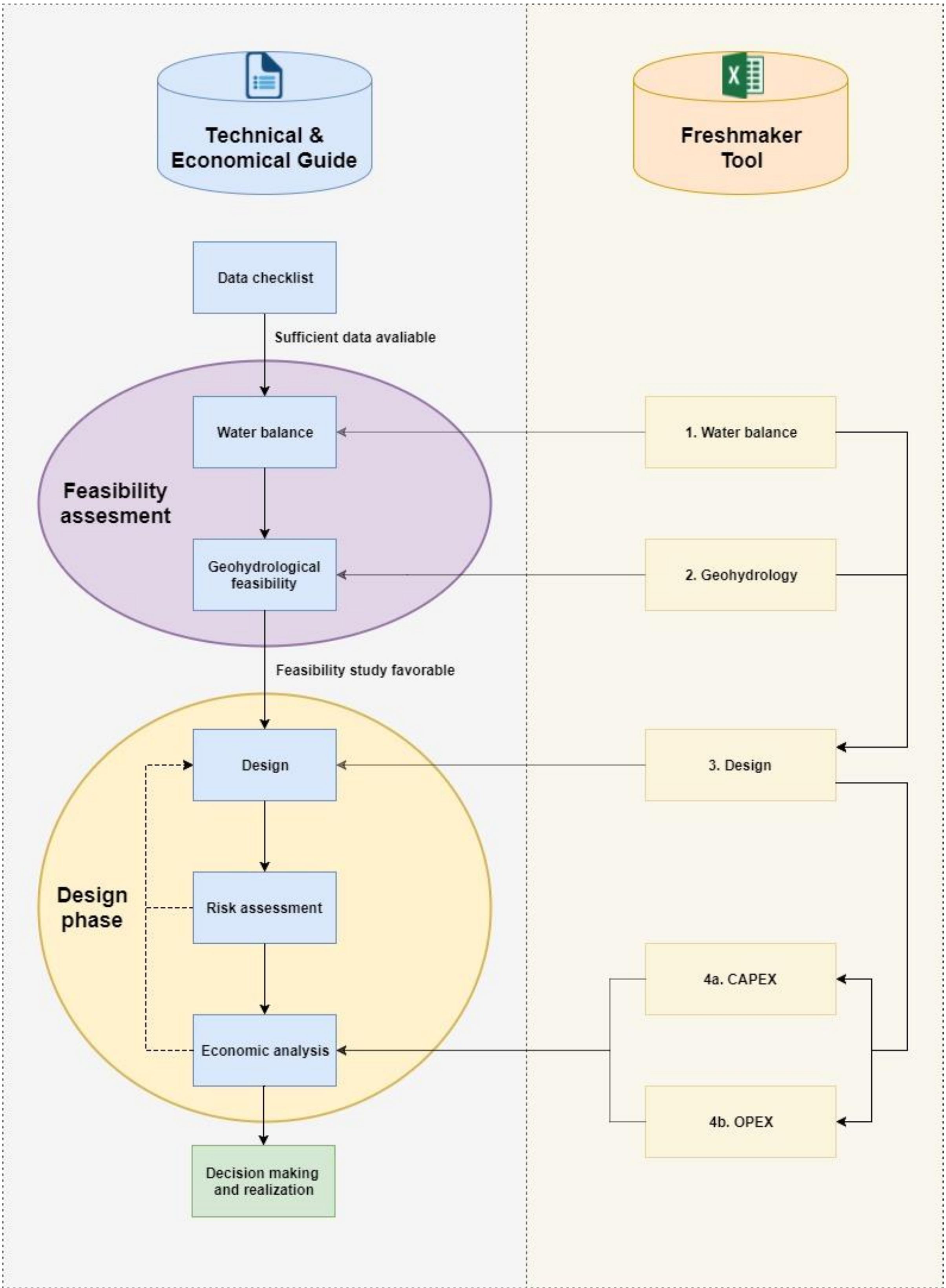

Figure 3-1 Process scheme of the Freshmaker implementation. The left side of the figure compiles the necessary steps to reach a decision regarding the implementation of the Freshmaker concept. The right part of the figure indicates for which steps the Freshmaker Tool is required alongside this Technological and Economical guide.

4 Data checklist

The data checklist (Figure 4-1) includes the material and information required to reach a well-funded decision on realising the Freshmaker concept at a specific site. The list covers data required along the whole process (Figure 3-1), which should be checked to ensure the information is available before starting with the process of realisation.

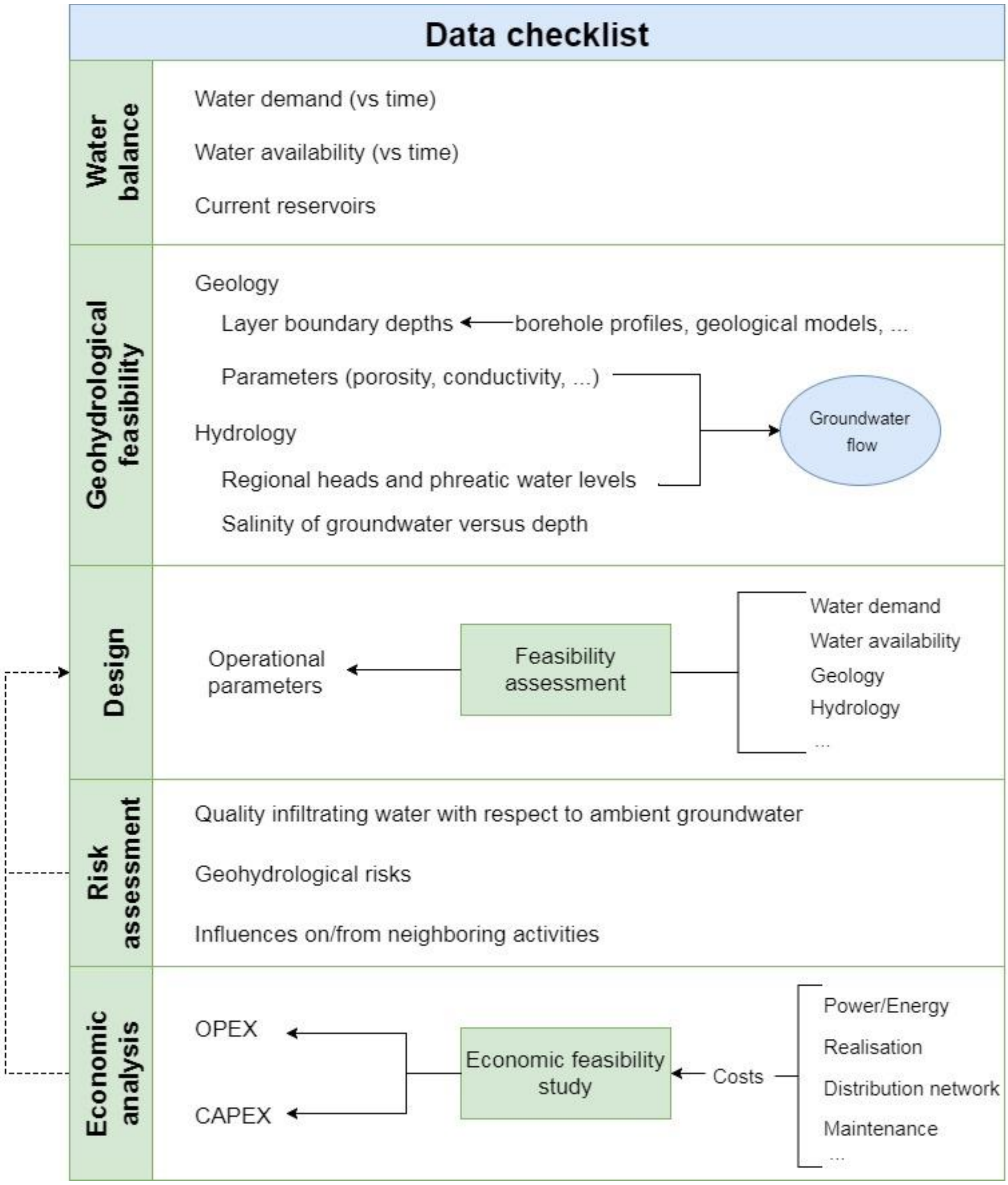

Figure 4-1 Data checklist prior to realisation of the Freshmaker.

5 Feasibility assessment

The feasibility assessment (Figure 5-2; added in Appendix 1 in A3 format) serves as a quick scan to determine the suitability of the subsurface and the water balance at a specific site for implementation of the Freshmaker concept. From here, the reader can start to use the Freshmaker Tool alongside this Technological and Economical guide. Worksheets ‘1. Water Balance’ and ‘2. Geohydrology’ can be filled-in by the user to assess the feasibility. When both the water balance and the geohydrology at a specific location are suitable for the implementation of the Freshmaker concept, an initial design is proposed with relevant operational parameters in worksheet ‘3. Design’.

During the feasibility assessment, the following conditions have to be checked:

- a (seasonal) mismatch between supply and demand;
- sufficient freshwater surplus to cover (a relevant part of) the shortcoming volume in times of shortage, i.e. the target storage volume (TSV);
- limited background, lateral groundwater flow (< 10 m/y);
- no seepage indications, e.g. the presence of a freshwater lens > 3 m in thickness;
- the presence of a shallow granular aquifer without intervening clay layers (≥ 0.5 m thick). Deep drilling (> 20 m) requires a bigger and more expensive drilling rig;
- the possibility to install the shallow HDDW within the shallow granular aquifer, at a minimal vertical distance of 4 m below the groundwater level, of 6 m from the deep HDDW, and of 1 m from an aquitard. A too thin and shallow aquifer may significantly increase the number of wells required. Example of an ideal Freshmaker subsurface set-up is given in Figure 5-1, together with examples of suitable subsurface types for Freshmaker implementation;
- If there are more suitable aquifers, the shallowest aquifer is preferred for installation of the Freshmaker.

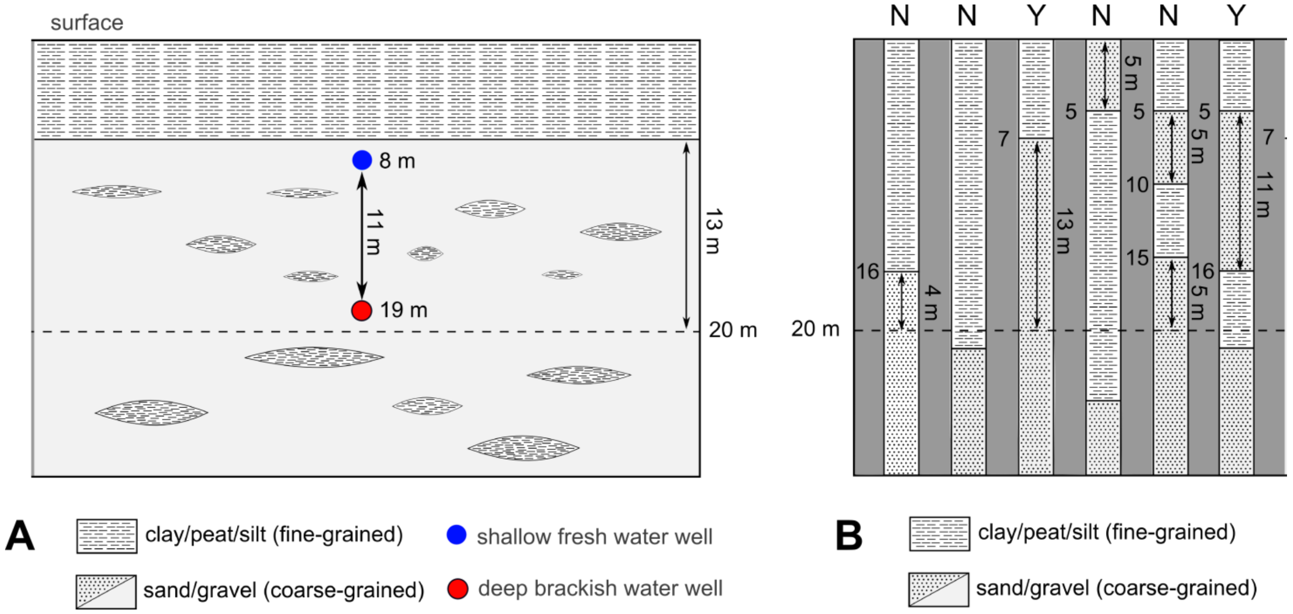

Figure 5-1 Visual representation of an ideal subsurface for a Freshmaker implementation (A), and examplary settings with suitable ranking of the subsurface for Freshmaker implementation (B) indicated by "Y" (yes: suitable) and otherwise "N" (No: not suitable).

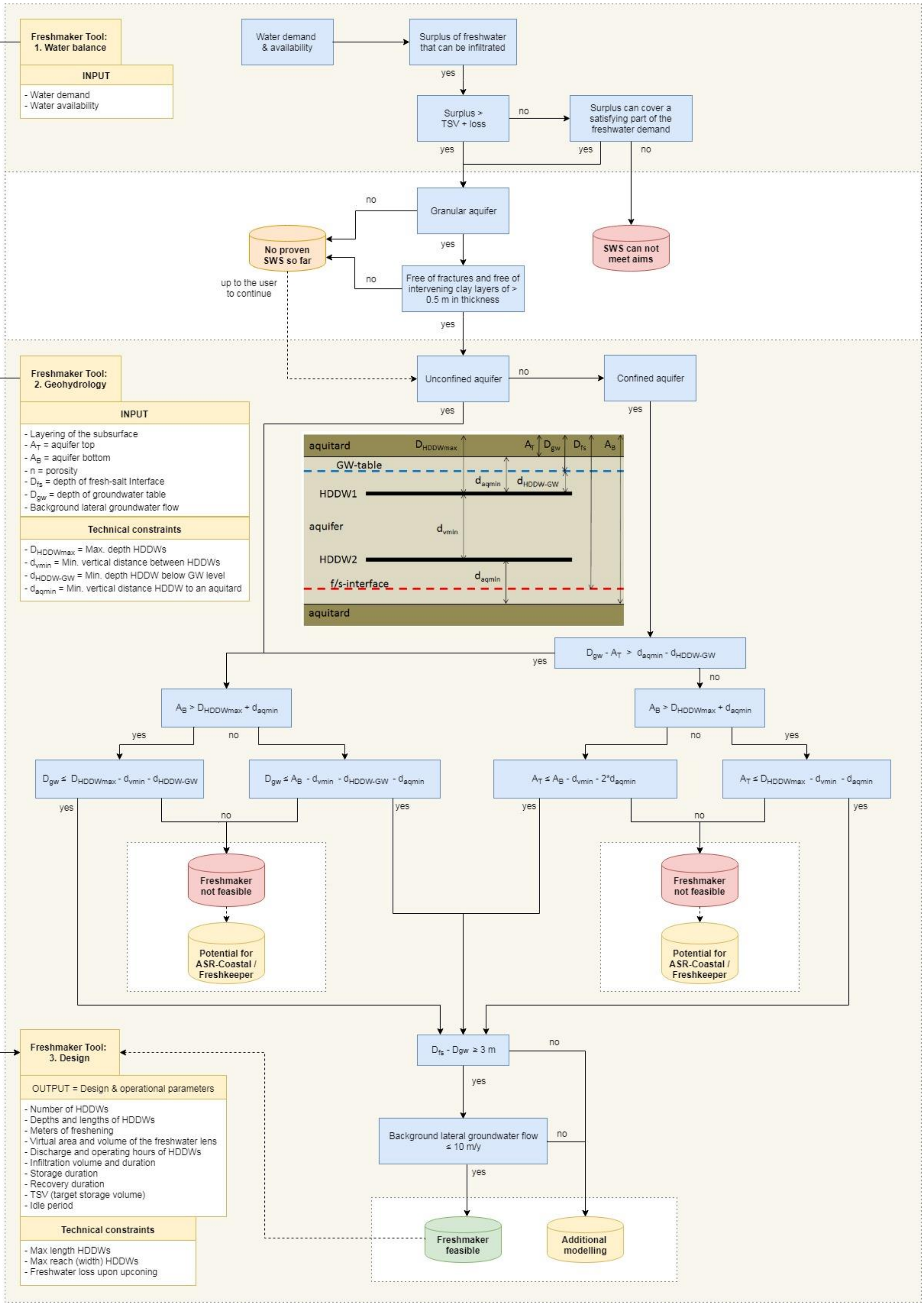

Figure 5-2 Feasibility assessment scheme for Freshmaker implementation, as implemented in the Freshmaker Tool.

6 Design

Worksheet ‘3. Design’ of the Freshmaker Tool is used to define the initial set-up and to estimate the scale of implementation based on the feasibility assessment in worksheets ‘1. Water balance’ and ‘2. Geohydrology’.

As output, the module suggests a design of the Freshmaker system and the related operational parameters (Figure 5-2). These include for example the total required length, depth, and number of HDDW’s, discharge and operating hours, energy consumption, duration of different ASR-phases (infiltration, storage, and recovery), and the target storage volume (TSV).

The suggested operation and design are a simplified representation of the eventual operation, since the water balance may be different every year. The operation may for example need adjustments more frequently in practice, depending on the timing of freshwater surplus and demand. Nevertheless, the Freshmaker Tool provides a suitable operation based on the feasibility assessment that can be used to assess the costs and risks of the implementation of the Freshmaker concept.

7 Risk-assessment

The risk-assessment allows to check whether the design and operational parameters of a Freshmaker satisfy all constraints either before realization or during (early) operation of the Freshmaker system. The risk-assessment can be used as a legal compliance checklist regarding (geo)hydrological influences.

The following steps should be taken during the proposal phase:

1. Risk-assessment of the infiltration water quality and of the possible spreading of contaminants (Figure 7-2 and Figure 7-3).
2. Determination of (geo)hydrological limitations based on flow rates, changes in hydraulic head, and maximum infiltration pressures. These changes in the geohydrology could impact on surrounding, vulnerable, natural processes and regions through subsidence or bursting of the overlying aquitard/aquifer (Figure 7-2 and Figure 7-4). The Freshmaker Tool can be used for the calculation of flow rates in worksheet '3. Design'.
3. Risk-assessment of possible interferences with nearby systems (in the same aquifer or in an adjacent one) (Figure 7-2 and Figure 7-5).

These steps are explained in more detailed flowcharts as part of the risk-assessment (Figure 7-2 - Figure 7-5).

Backgrounds

Subsidence:	This is caused by lowering the head in the target aquifer (below clay layers) and thereby the pore water pressure in overlying clay layers itself. A solid approach is calculating the total subsidence using Terzaghi's method (Terzaghi, 1943). A more dynamic (time-dependent) calculation can be done with the Koppejan method (Koppejan, 1948), which can result in lower subsidence rates in thick and very fine clay layers.
Soil bursting:	This can be caused by the pressure put on the injection well in unconsolidated sediments, exceeding the maximum pressure the overlying clay layer can handle (Figure 7-1). The weakest spot is the clay layer (restored by bentonite) right above the well itself (Olsthoorn, 1982). As a rule of thumb, a Δh (pressure head in the well above surface level) of 0.2 times the thickness (h) between surface level and the top of the gravel pack.
Clogging:	It is advised to assess the risk of clogging of the infiltration well(s) too, but close assessment is beyond the scope of this guide. In general, one should aim at minimizing concentration in the injection water to those mentioned in XX.

- Total suspended solids <0,1 mg/l
- Turbidity <1 NTU
- Total iron <0,01 mg/l
- Sodium Adsorption Ratio (SAR, at EC 40-100 mS/m) < 6 bij
- Dissolved Organic Carbon (DOC) < 2 mg/l
- Assimilable Organic Carbon (AOC, acetate-C) < 10 µg /l
- Modified Fouling Index (MFI) < 3-5 s/L

For further information, the reader is referred to the Clogging Monograph of IAH:

https://recharge.iah.org/working-groups/clogging-and-its-management.

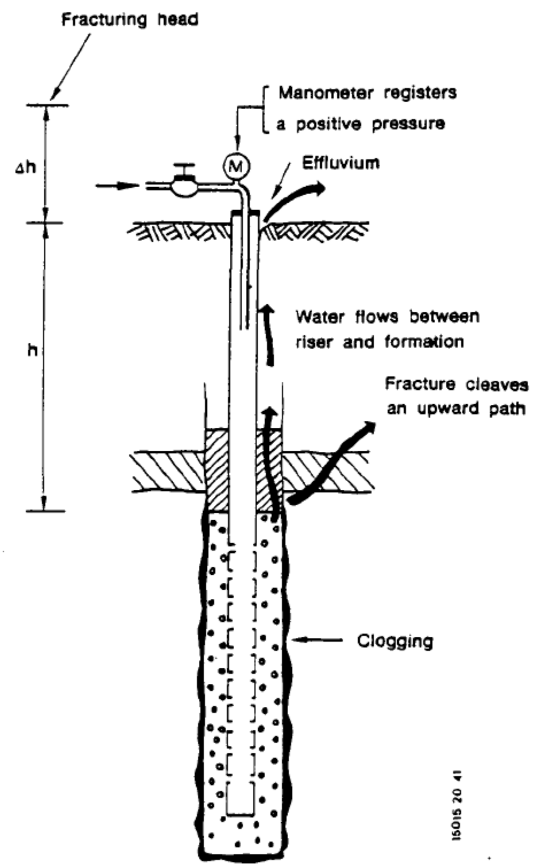

Figure 7-1 Fracturing or bursting of injection wells by applying too much pressure during injection

Water quality: When it comes to groundwater quality, the European Groundwater Directive is leading, setting strict quality limits for:

- Nitrate (50 mg/l max)
- Individual pesticides (0.1 µg/l max)
- The sum of pesticides (0.5 µg/l max)

Limits are also set by member states itself for separate groundwater bodies, but only for the following species: Cl, Ni, As, Cd, Pb, total-P. When it comes to SWS, especially infiltration of water surpluses may impact the groundwater quality. The EU guidelines demand that the standstill-principle is met during this activity, indicating that infiltration should not negatively impact the quality of the whole water body. I.e. concentrations exceeding the limits set by the Groundwater Directive or for the individual water bodies may not be exceeded in the infiltration water.

More relevant for the infiltration water quality in The Netherlands is the Infiltration Resolution for Soil Protection ('Infiltratiebesluit Bodembescherming'), setting national limits for various natural and antropogenic species. Strictly, this resolution is set-up for infiltration of surface water in the coastal dune area of the Netherlands. However, since other limits and frameworks are lacking, the same set of parameters and limits is commonly used to judge on infiltration of other water types as well. Exceedance of the limits is only allowed if (after approval):

- The setting is such that there is no risk of polluting the groundwater;
- The background concentrations in the groundwater are already high, these become the limit then;
- Negative effects by infiltration water with exceeding concentrations are mitigated in any way.

Different countries can have different national Acts to protect groundwater quality. More information on regulation can be found in the Subsol Knowledge Base.

Hydrological effects and interference

When a permit is requested, a supporting study should be send in to assess the hydrological effects and impacts on the surroundings. In this report, also the potential impact on surrounding groundwater users should be evaluated. The report should at least consist of:

- Name, address, e-mail address, and phone number of the holder of the permit;
- The geographical location of the wells, including a map;

- Description, size, reasoning, aims of the activity;
- Number, depth, diameter, and location of wells;
- Maximum capacities per hour, day, month, quarter of a year;
- Description of provisions made to mitigate negative effects
- Evaluation of the consequence of the activity (hydrological, interference);
- Duration of the activity.

In The Netherland, a permit request is generally reviewed in 6 weeks (small-scale application) or six month (large-scale) by the supervising authority.

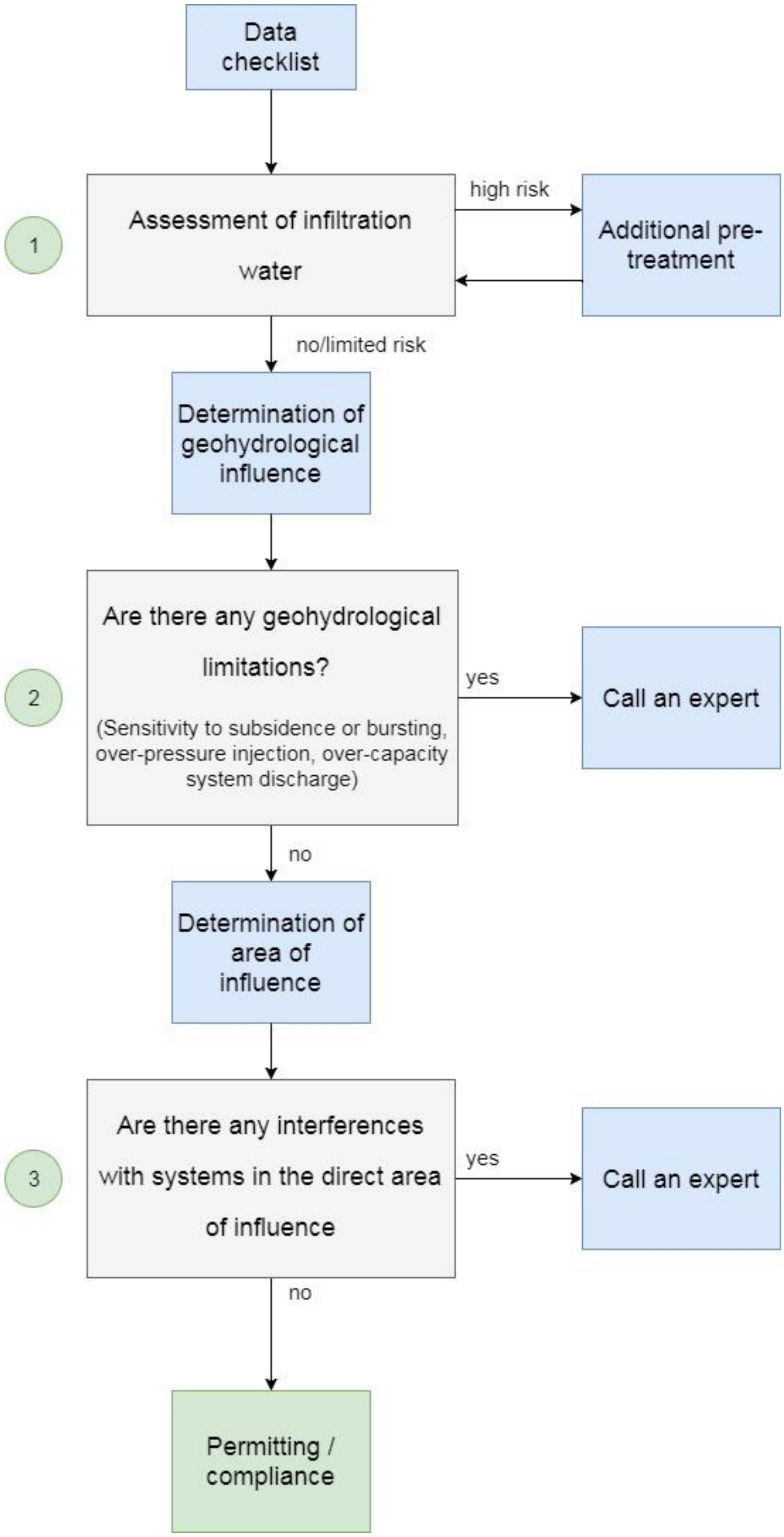

Figure 7-2 General risk-assessment scheme, the circled numbers redirect to the elaborated schemes on the following pages and to the points given on the previous page.

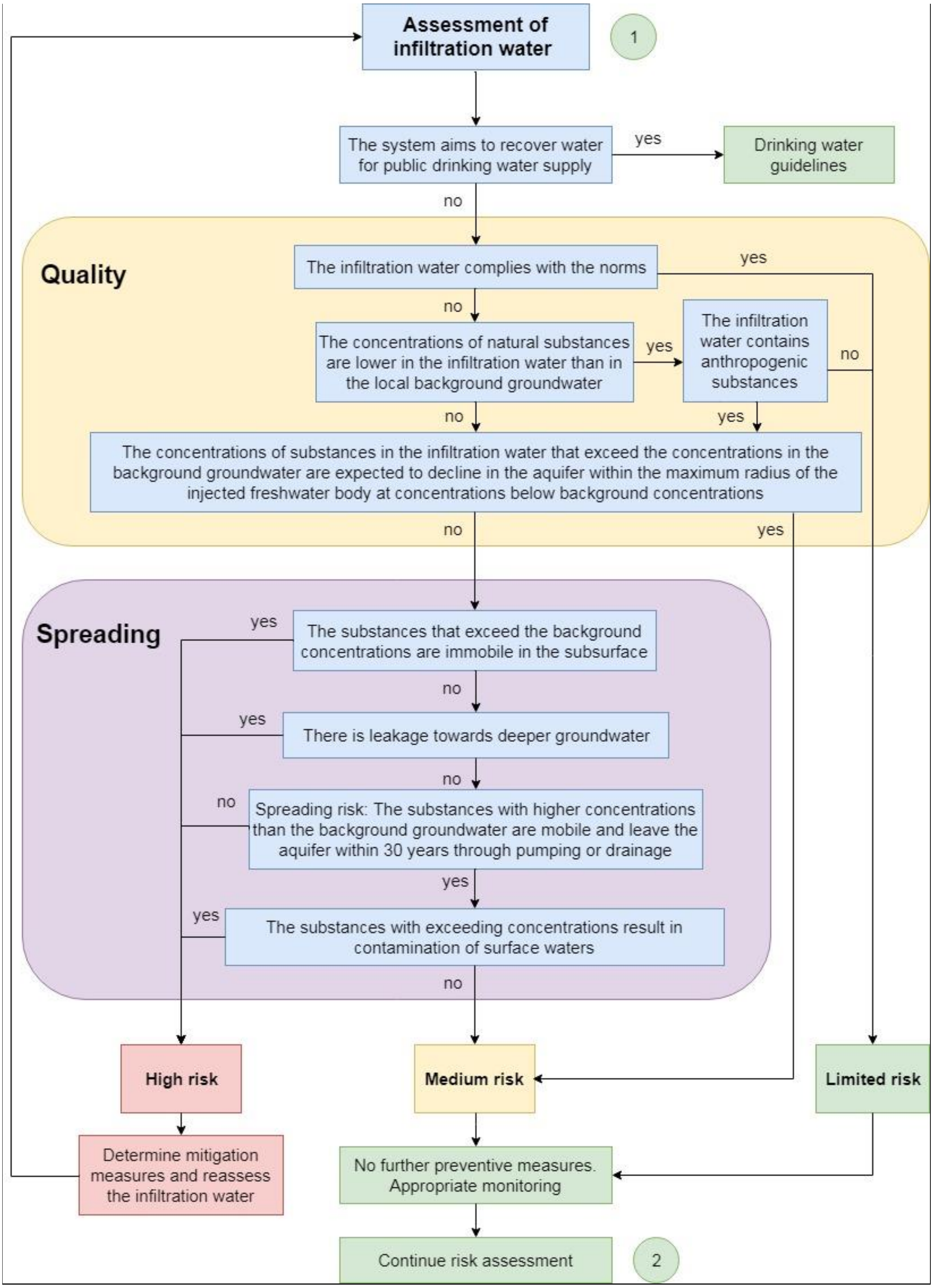

Figure 7-3 Risk-assessment scheme regarding the quality and possible spreading of anthropogenic substances from the infiltration water to the subsurface.

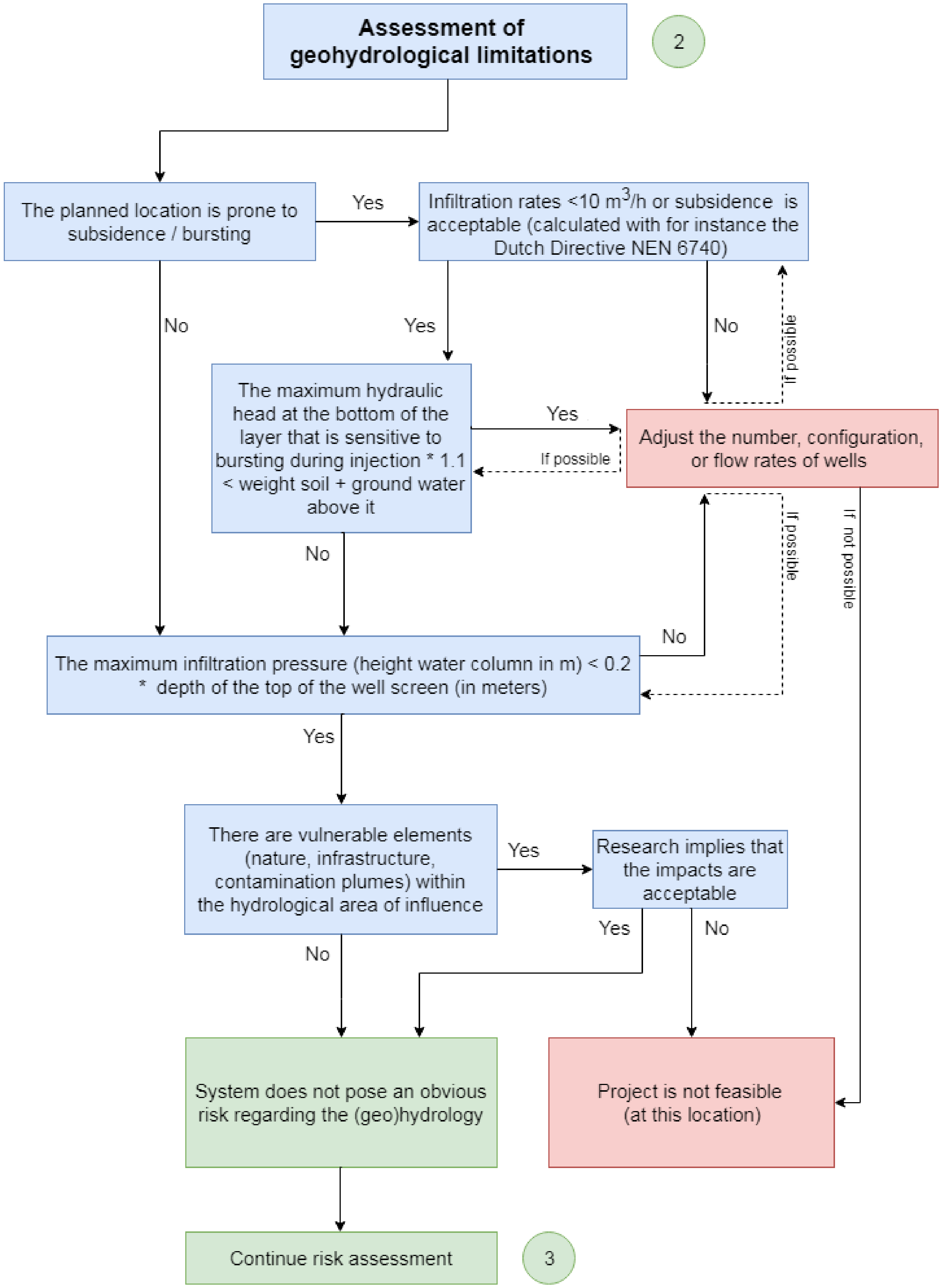

Figure 7-4 Geohydrology risk-assessment scheme.

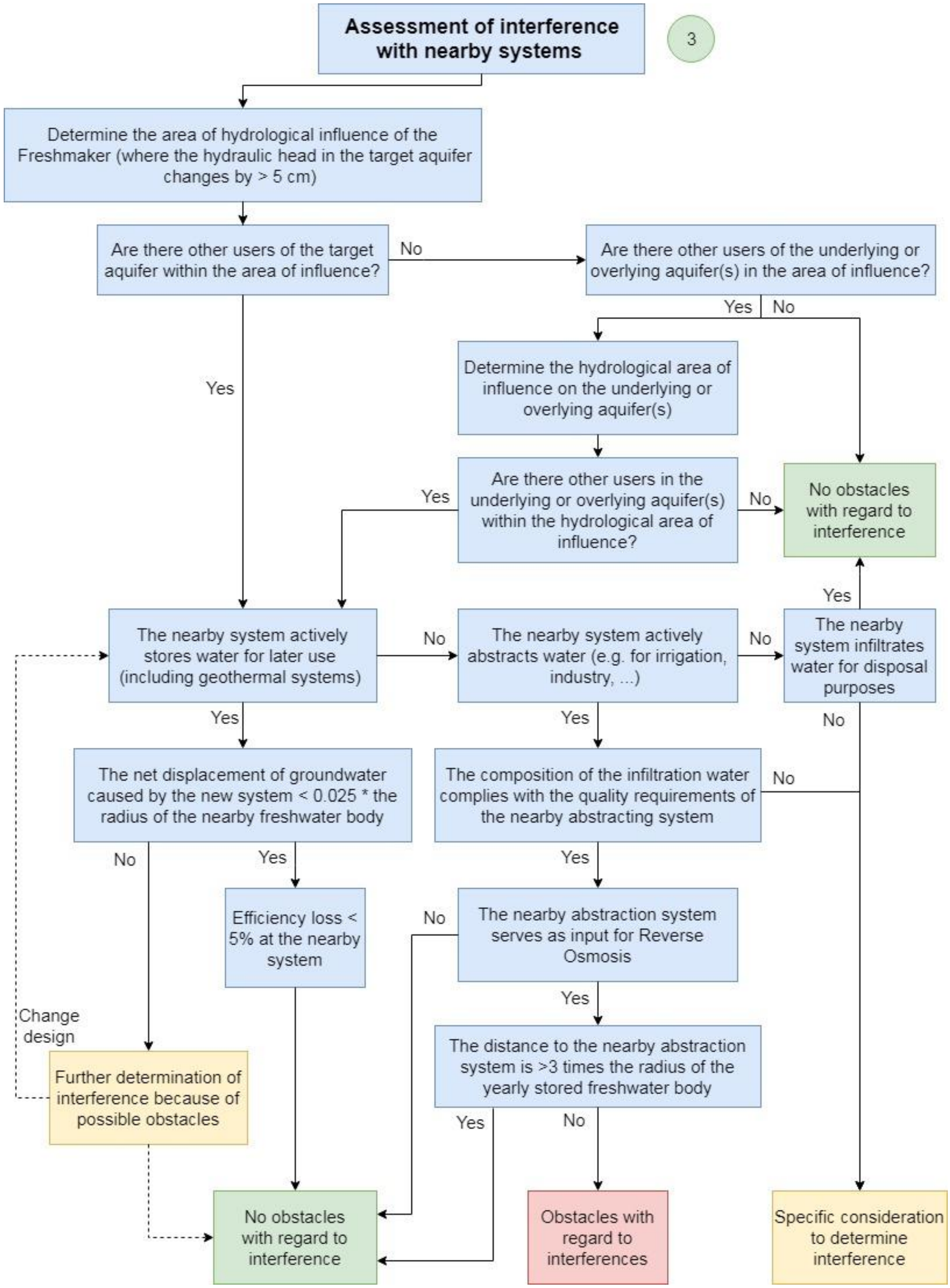

Figure 7-5 Hydrological Interferences risk-assessment scheme.

8 Economic analysis

The final step of the design phase, following the risk-assessment, is the economic feasibility study of the Freshmaker installation. Two components are analysed for this purpose.

CAPEX:

The first component of the economic feasibility study is the assessment of the capital expenditure or capital expense ("CAPEX"). This expenditure is of a non-recurring nature and is employed in acquisition and assembling of permanent assets. These expenses are usually incurred during the initial phase of the project and their benefits continue over a long period (mostly during the whole lifetime of the installation).

Workheet '4a. CAPEX' of the Freshmaker Tool allows to calculate the CAPEX from the proposed design in worksheet '3. Design', based on pre-defined prices corresponding to three different scenarios: 1. Best case (lowest possible costs), 2. Average (expected costs) and 3. Worst case (highest possible costs) for installation, distribution and preliminary examination/realization of the Freshmaker. In addition, the user can specify a dedicated scenario with his/her own expected costs in scenario 4 (Dedicated: specific input), or as a percentage of the average costs in scenario 5 (Dedicated: percentage). The user can indicate the relevant scenario in worksheet '4a. CAPEX' from a drop-down menu. The result is an overview of the capital expenses (CAPEX) that a Freshmaker would involve. The resulting CAPEX is expressed in euros, euros/year and euros/m^3.

OPEX

The second component of the economic feasibility study is the assessment of the operational expenditure (OPEX), which includes the on-going costs of running a Freshmaker system.

Worksheet '4b. OPEX' of the Freshmaker Tool allows to calculate the OPEX from the initial investment (CAPEX), from the proposed operational parameters in worksheet '3. Design', and from pre-defined prices corresponding to three different scenarios: 1. Best case (lowest possible costs), 2. Average (expected costs) and 3. Worst case (highest possible costs) for energy consumption, maintenance, monitoring, and regeneration of wells. In addition, the user can specify a dedicated scenario with his/her own expected costs in scenario 4 (Dedicated: specific input), or as a percentage of the average costs in scenario 5 (Dedicated: percentage). The user can indicate the relevant scenario in worksheet '4b. OPEX' from a drop-down menu. The result is an overview of the operational expenses (OPEX) that a Freshmaker would involve. The resulting OPEX is expressed in euros, euros/year and euros /m^3.

Summation of the CAPEX (euros/m^3) and OPEX (euros/m^3) results in an overview of the total costs of realising the Freshmaker at a specific site, and of each cubic meter of freshwater recovered by the Freshmaker. This can subsequently be compared to the current market price of water from alternative sources and installations to determine the total benefit that comes with a Freshmaker system. A scheme of the economic feasibility study is provided in Figure 8-1.

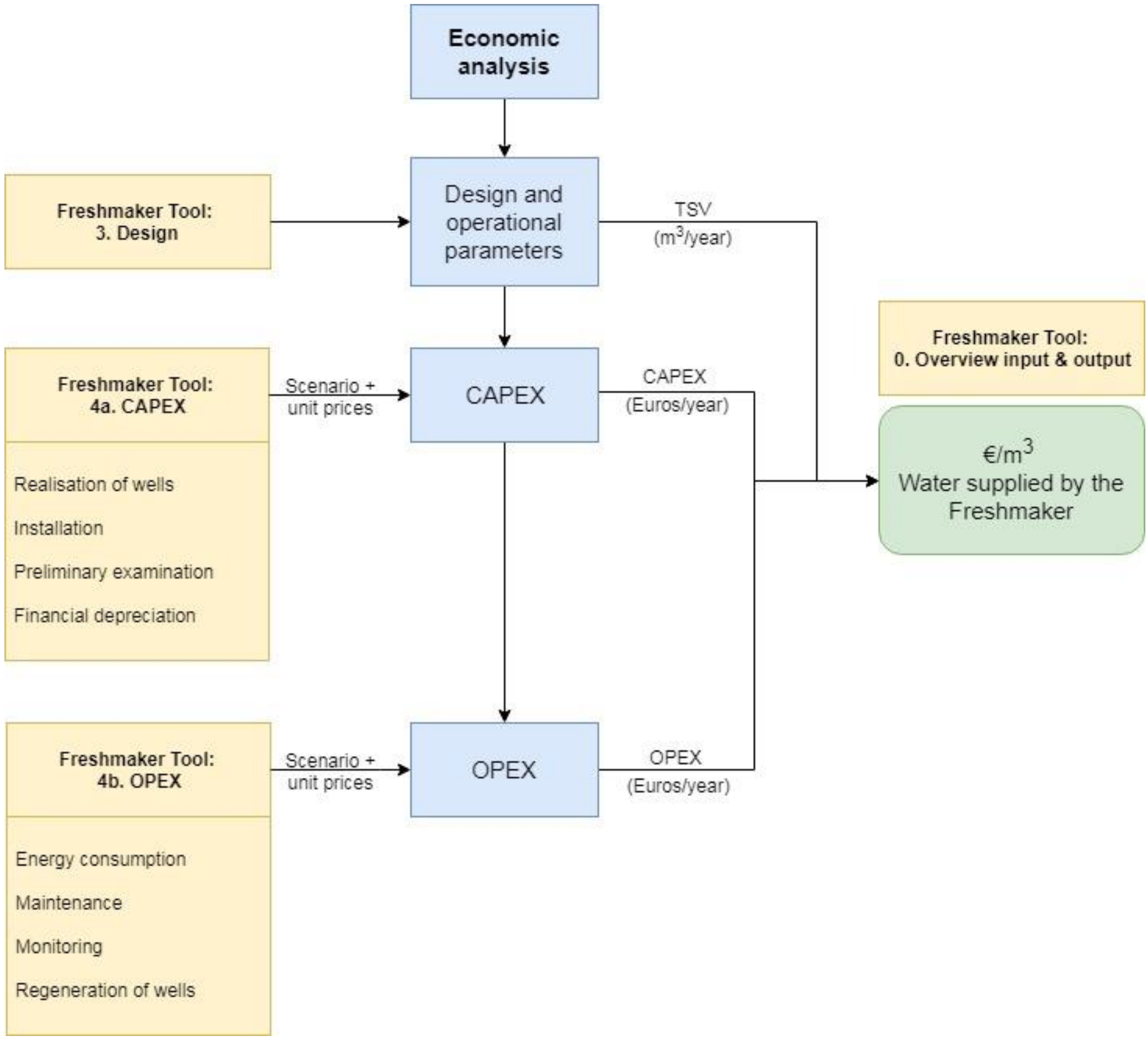

Figure 8-1. Scheme of the economic analysis to be performed after the risk-assessment for a complete feasibility study. This scheme includes the information of the Freshmaker Tool that is needed to calculate the costs per cubic meter of water produced by a Freshmaker system.

9 Permitting / compliance

Requesting the permit

If all previous steps were favourable for the realisation of a Freshmaker, the next step is to ask for a permit for the installation. This request generally consists of a form on which details regarding the activities are notes (well locations, pumping rates, depth of well screens, etc.) and a report are memo describing the hydrological effects in the surroundings. If there are no geohydrological limitations, nor negative consequences related to water quality or interference (Chapter 7: ‘Risk assessment’), the permit may be granted by the licensing authority in charge.

Evaluation of effects during operation

Once a permit is granted, the construction and installation must be done following the appropriate regulations and requirements established by the licensing authority (Figure 9-1). In addition, the licensing authority must be able to assess potential negative effects identified in the preliminary risk-assessment with an assessment of operational residual risk (Figure 9-1). The experiences during first applications in The Netherlands indicate that this will mainly concern assessment of the water quality to be injected, which can be measured once the pre-treatment is completed.

During the operational phase upon commissioning, the user must compare and report the actual effects and impacts of the system to what was identified in the risk-assessment studies. For example, during the Subsol pilots and replication sites, most information for evaluation was obtained after commissioning using:

1. Pressure transducers to monitor the head in the ASR wells
2. Piezometers equipped with pressure transducers to monitoring the impact on groundwater heads and phreatic water levels.
3. Electronically recording water meters to register pumping over time.
4. Performing a pumping test to obtain relevant hydraulic parameters and improve the groundwater model.
5. Sampling of infiltration water

The results must be compared with the predicted hydrological effects from the risk-assessment (Chapter 7) and be reported in an evaluation report.

Assessment by authority

Based on the results of such an evaluation, the licensing authority can request adjustments of the regulations and requirements of the system, if necessary.

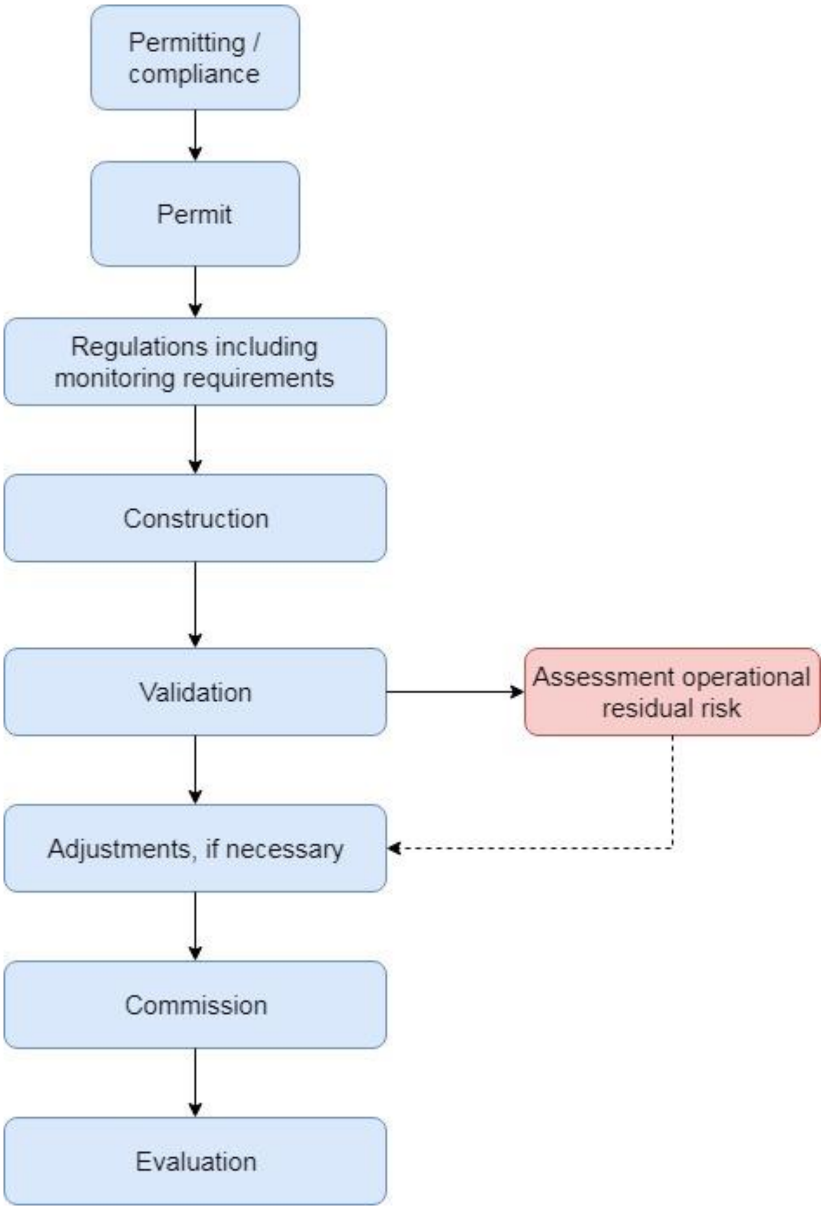

Figure 9-1. Permitting/compliance scheme.

10 Conclusions

The Freshmaker enlarges, protects, and sustainably utilizes shallow fresh groundwater lenses in brackish aquifers by the interplay between overlying HDDWs. The pilot in Ovezande has proven that the Freshmaker is a suitable SWS to reduce problems related to water quality or availability for horticulturalists with a seasonal variability of freshwater demand. Improvement of the Freshmaker in Ovezande and further improvement of the technique in Groede, have both contributed to the development of a reliable system for subsurface storage of freshwater in coastal areas with a brackish-saline subsurface.

Based on the capital and operational expenditures of the current Freshmaker sites, freshwater can be recovered from the subsurface in times of demand at a price of ~0.54 €/m^3, which is competitive with local piped water and drinking water. Upscaling of a Freshmaker and collaboration with other parties can result in somewhat lower costs for the water supplied, but enormous scale advantages cannot be expected.

This Technological and Economical guide serves as a starting point for end users of freshwater (with a strong interest in a self-reliant freshwater supply), engineering companies and installers, technology providers, consultants, and water managers interested in the development of a Freshmaker at other coastal sites with temporary water shortages and a brackish-saline aquifer in the subsurface. Through a feasibility study of the water balance and the geohydrology at a specific site, the supporting Freshmaker Tool proposes a design and an operational scheme, and estimates the costs involved for installation and implementation.

It is advised to follow every step in this guide as good as possible. Yet, a successful completion of every step does not provide a 100% guarantee for successful application of the Freshmaker.

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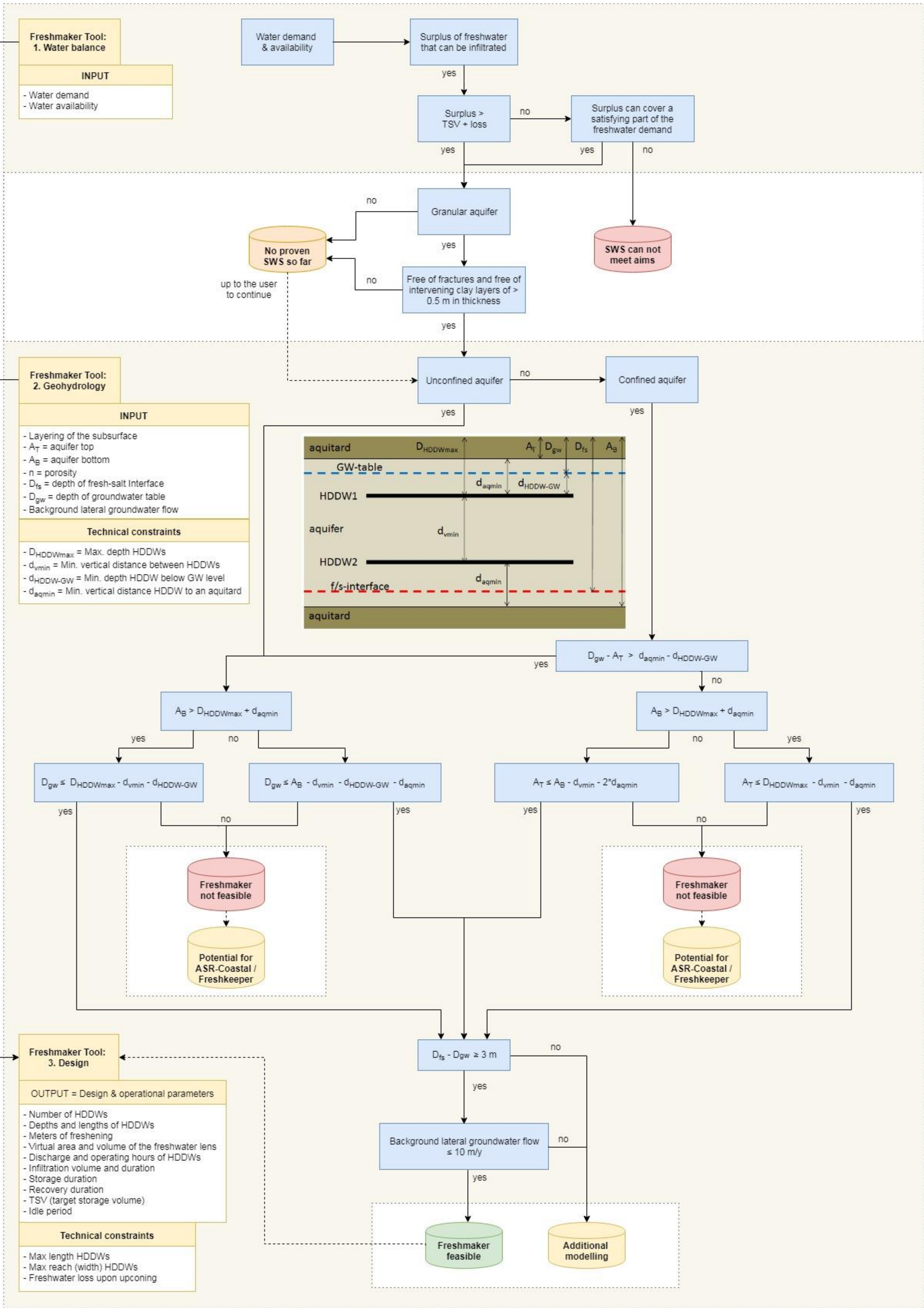
Appendix 1: feasibility assessment scheme

SubSol



Freshmaker Tool:
1. Water balance
INPUT
- Water demand
- Water availability
Water demand & availability
Surplus of freshwater that can be infiltrated
yes
Surplus > TSV + loss
no
Surplus can cover a satisfying part of the freshwater demand
yes
yes
no
Granular aquifer
no
No proven SWS so far
SWS can not meet aims
yes
up to the user to continue
no
Free of fractures and free of intervening clay layers of > 0.5 m in thickness
yes
Freshmaker Tool:
2. Geohydrology
INPUT
- Layering of the subsurface
- A_T = aquifer top
- A_B = aquifer bottom
- n = porosity
- D_{fs} = depth of fresh-salt Interface
- D_{gw} = depth of groundwater table
- Background lateral groundwater flow
Technical constraints
- $D_{HDDWmax}$ = Max. depth HDDWs
- d_{vmin} = Min. vertical distance between HDDWs
- $d_{HDDW-GW}$ = Min. depth HDDW below GW level
- d_{aqmin} = Min. vertical distance HDDW to an aquitard
Unconfined aquifer
no
Confined aquifer
yes
yes
aquitard
$D_{HDDWmax}$
A_T
D_{gw}
D_{fs}
A_B
GW-table
d_{aqmin}
$d_{HDDW-GW}$
HDDW1
aquifer
d_{vmin}
HDDW2
d_{aqmin}
f/s-interface
aquitard
$D_{gw} - A_T > d_{aqmin} - d_{HDDW-GW}$
yes
no
$A_B > D_{HDDWmax} + d_{aqmin}$
$A_B > D_{HDDWmax} + d_{aqmin}$
yes
no
no
yes
$D_{gw} \leq D_{HDDWmax} - d_{vmin} - d_{HDDW-GW}$
$D_{gw} \leq A_B - d_{vmin} - d_{HDDW-GW} - d_{aqmin}$
$A_T \leq A_B - d_{vmin} - 2*d_{aqmin}$
$A_T \leq D_{HDDWmax} - d_{vmin} - d_{aqmin}$
yes
no
yes
yes
no
yes
Freshmaker not feasible
Potential for ASR-Coastal / Freshkeeper
Freshmaker not feasible
Potential for ASR-Coastal / Freshkeeper
Freshmaker Tool:
3. Design
OUTPUT = Design & operational parameters
- Number of HDDWs
- Depths and lengths of HDDWs
- Meters of freshening
- Virtual area and volume of the freshwater lens
- Discharge and operating hours of HDDWs
- Infiltration volume and duration
- Storage duration
- Recovery duration
- TSV (target storage volume)
- Idle period
Technical constraints
- Max length HDDWs
- Max reach (width) HDDWs
- Freshwater loss upon upconing
$D_{fs} - D_{gw} \geq 3$ m
no
yes
Background lateral groundwater flow ≤ 10 m/y
no
yes
Freshmaker feasible
Additional modelling