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

Grant agreement no:	642228
Work Package:	WP1.1
Deliverable number:	D1.3
Partner responsible:	KWR Watercycle Research Institute
Deliverable author(s):	Ir. Ate T. Oosterhof (Vitens), Dr. Klaasjan Raat, Teun van Dooren MSc (KWR)
Quality assurance:	Dr. Gerard van den Berg (KWR), Dr. Klaus Hinsby (GEUS)
Planned delivery date:	28 February 2018
Actual delivery date:	27 September 2018
Revised version:	16 December 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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1 Introduction

Subsurface Water Solutions (SWS): The Freshkeeper

In the past decade, a set of practical concepts called Subsurface Water Solutions (SWS) has been developed, and have been further improved within the Subsol project. These SWS aim to secure freshwater supply from coastal aquifers where brackish and saline groundwater presence and intrusion may form a problem.

The **Freshkeeper** 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 extracting brackish groundwater in addition to extracting fresh groundwater. Two wells are installed, one with its screen in fresh groundwater for the extraction of freshwater. Another well is installed within the brackish groundwater to prevent the shallow fresh groundwater well from salinization and to potentially use brackish water as an additional source of freshwater upon the application of reverse osmosis (Figure 1-1). With this interplay of two wells, the Freshkeeper results in an increased fresh groundwater storage capacity in shallow coastal aquifers where fresh and brackish water are not structurally isolated or confined.

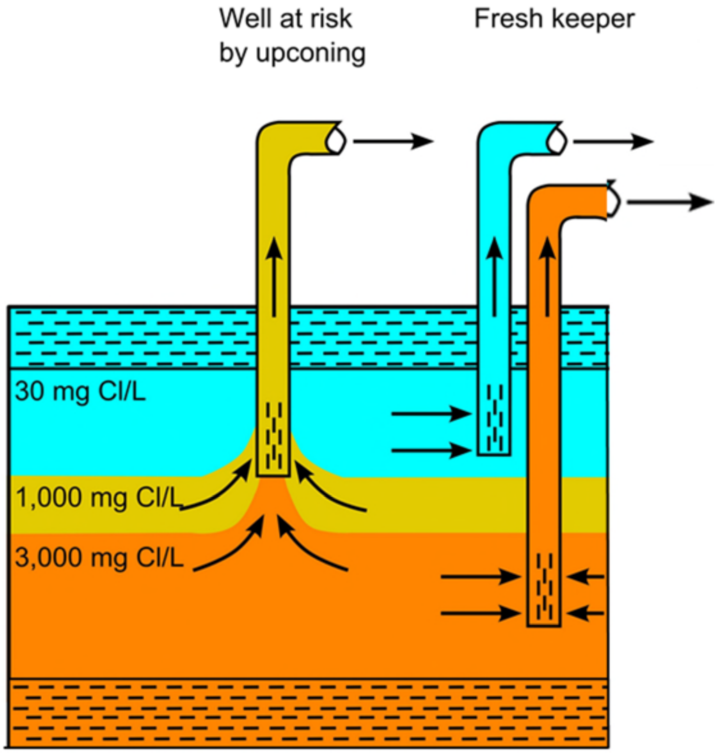

Figure 1-1 Cross-section of the subsurface where a normal well is at risk of salinization (left) and where the Freshkeeper technique is applied within the same aquifer (right). Without the implementation of the Freshkeeper, exploitation of fresh groundwater (blue) through a well without additional abstraction of brackish groundwater (orange) would result in upconing of brackish groundwater and salinization of the shallow fresh groundwater well.

Objectives

This Technological and Economical guide strives to:

- Provide future adopters with a broad view of the Freshkeeper implementation and its site-specific nature by portraying the original pilot set-up and the latest improved versions of the Freshkeeper.
- Assist and guide future adopters in assessing the potential of realizing a Freshkeeper set-up by providing a checklist of required activities and data.
- Increase and facilitate the market uptake of the Freshkeeper concept for a sustainable freshwater resource management in coastal areas in Europe and beyond.

Target users

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 the presence of brackish-saline aquifers.

This guide facilitates identification of available options for Freshkeeper 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 an existing Freshkeeper system. This is primarily based on the practical experiences gained throughout the implementation of the Freshkeeper at the reference field site in Noardburgum, The Netherlands, where a Freshkeeper has been successfully in operation since 2009. Groundwater flow modelling has been carried out parallel to fieldwork, to improve the understanding of the Freshkeeper, 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 Freshkeeper concept. Furthermore, the main obstacles, the reaction of the end-user, and the perception of the Freshkeeper concept in practice in Noardburgum are covered in this guide.

This information is synthesized to create implementation guidelines of the Freshkeeper concept. A process scheme of the required activities that constitute a preliminary feasibility study for implementation of the Freshkeeper at a specific location is included in Chapter 3. A data checklist and a feasibility scheme are presented in Chapters 4 and 5, respectively, and guide the future adopter towards the initial design of the Freshkeeper 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 Freshkeeper. 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.

2 Background of the Freshkeeper

The Freshkeeper strategy

In coastal areas, fresh groundwater extraction wells are commonly threatened by salinization, either as a result of horizontal seawater intrusion, or as a result of upconing of deeper brackish groundwater. If the production rate of a conventional groundwater extraction well(s) exceeds the rate of fresh groundwater recharge and/or freshwater flow to a well, brackish or salt water may intrude. This may force the groundwater extraction to be stopped. A more dedicated application of extraction wells can be used to mitigate this salinization, keeping freshwater production at foreseen levels.

In the Freshkeeper set-up, a conventional well with its screen in shallow fresh groundwater is complemented by a well with its screen in brackish groundwater. The fresh groundwater well is used for conventional extraction of freshwater in times of demand. The brackish well screen is simultaneously used for interception of brackish groundwater to prevent the fresh well screen from salinization. The arrangement of well screens that constitute a Freshkeeper depends on the characteristics of the subsurface and the nature of salinization. In the case of upconing of brackish groundwater, the brackish well screen should be positioned underneath the freshwater well screen within the brackish groundwater (Figure 2-1). In the case of horizontal seawater intrusion, the brackish well screen should be positioned more coastward with respect to the fresh well screen(s) (Figure 2-2).

The intercepted brackish groundwater may be disposed of or can on its turn be utilized as an additional source for freshwater supply by means of Brackish Water Reverse Osmosis (BWRO). The Freshkeeper can also provide a sustainable solution for concentrate disposal that is injected into a deeper confined aquifer with a similar groundwater salinity and composition as the BWRO concentrate (Figure 2-1 & Figure 2-2). The Freshkeeper results in a sustained fresh groundwater production capacity in shallow coastal aquifers where fresh and brackish water are not structurally isolated or confined, i.e. where salinization of fresh groundwater potentially occurs.

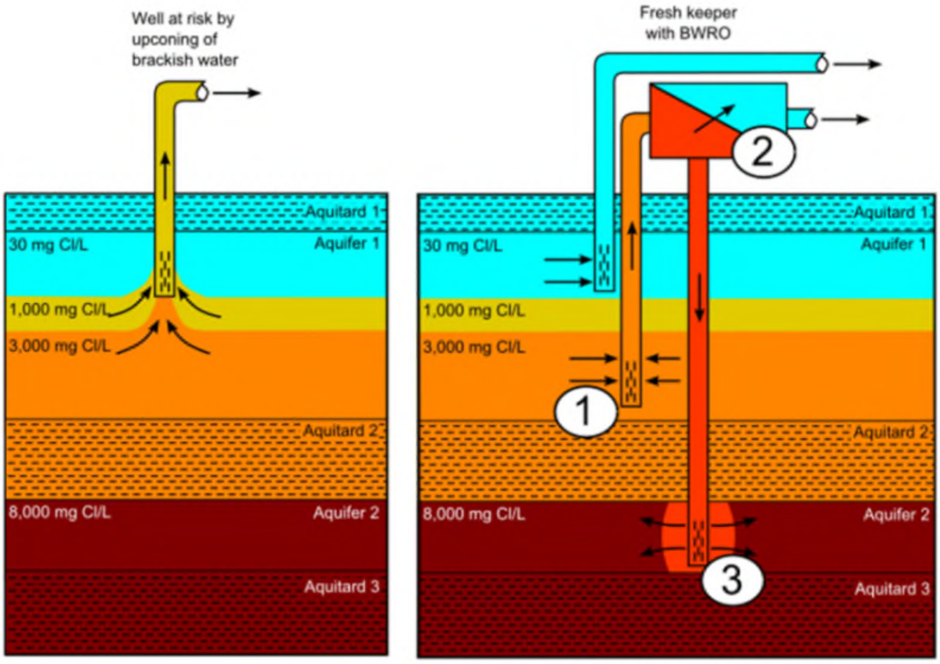

Figure 2-1 Cross-section of the Freshkeeper set-up and operation for a fresh aquifer with a threat of salinization by upconing of deeper brackish groundwater. 1.) Interception of brackish groundwater, 2.) Application of brackish water reverse osmosis (BWRO), 3.) disposal of BWRO-concentrate.

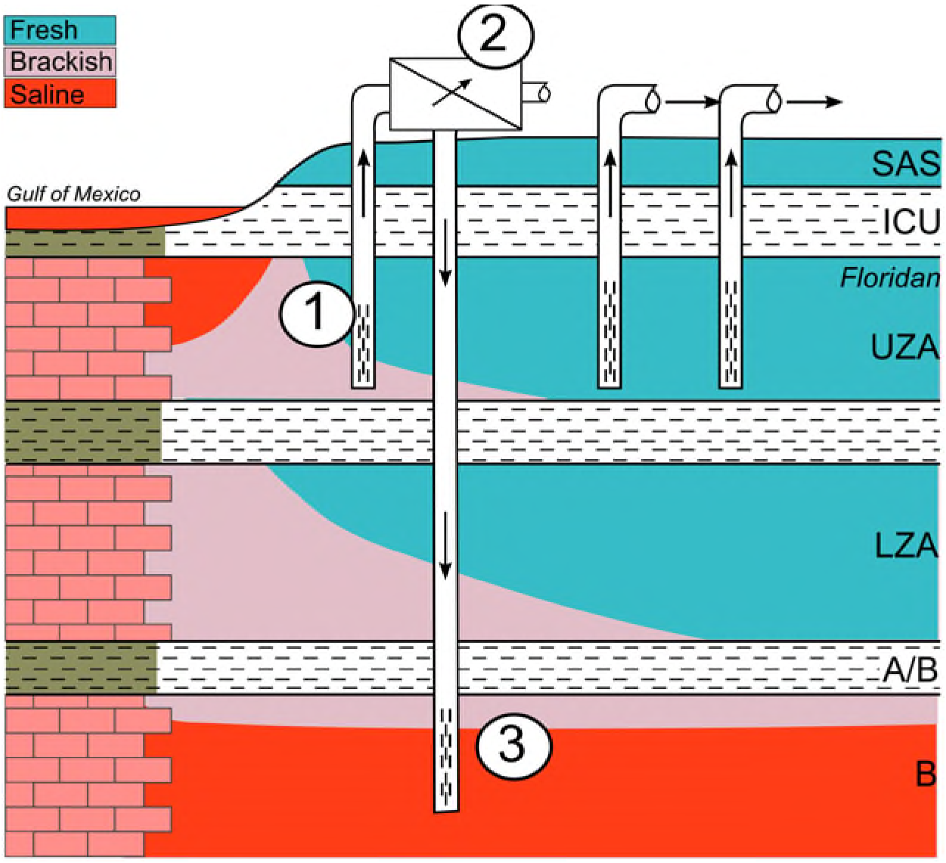

Figure 2-2 Cross-section of the Freshkeeper set-up and operation for a fresh aquifer with a threat of salinization by horizontal seawater intrusion. 1.) Interception of brackish groundwater, 2.) Application of brackish water reverse osmosis (BWRO), 3.) disposal of BWRO-concentrate.

Experiences at the Noardburgum reference site

Groundwater extraction in the northern part of the Netherlands is vulnerable to salinization, due to the presence of fossil, connate brackish groundwater in the lower parts of (freshwater) production aquifers. In 1993, drinking water company (later becoming) Vitens had to close the northern well field of production location Noardburgum, because of salinization of the freshwater abstraction wells due to upconing of the underlying brackish groundwater. This production stop lead to large investment losts, and the necessity to develop new water well field in areas less vulnerable to salinization.

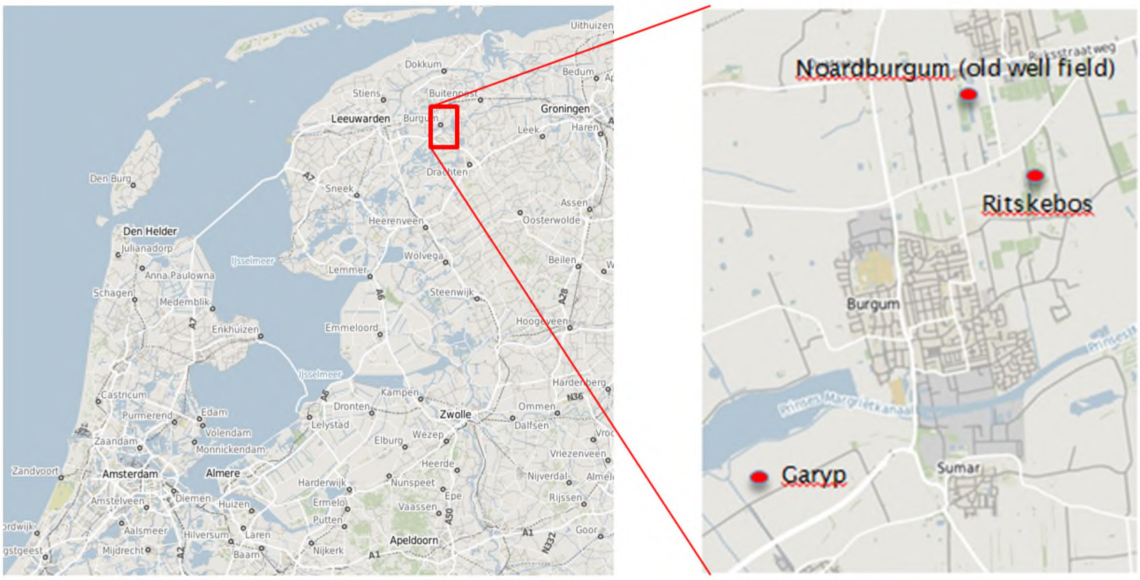

Figure 2-3 Well fields Noardburgum (abandoned in 1994), Ritskebos and Garyp, in the northen part of the Netherlands. Freshkeeper re

First Freshkeeper pilot 2009 - 2014

In 2002, the Freshkeeper concept was developed in theory by Grakist et al.. In 2009, Vitens started a first field pilot to test the Freshkeeper concept in an abandoned well field in Noardburgum, the Netherlands (Oosterhof et al., 2013). Fresh and brackish groundwater were abstracted simultanouesly (one well, two seperate filter screens) at similar abstraction rates (50 m^3/h). The freshwater was distributed directly to the nearby drinking water production plant; the abstracted brackish water was desalinated (brackish water reverse osmosis; BWRO), after which the fresh permeate was distributed to the production plant, while the BRWO concentrate was disposed of by deep well injection (seperate injection well) into the underlying (brackish) aquifer. This pilot ran until 2013, with unforeseen success regarding prevention of salinization: simultaneous abstraction of fresh and brackish groundwater had provoked a downconing of the fresh-brackish water interface, i.e. a freshening of the production aquifer. Results of this first Freshkeeper pilot have been described in various reports and proceedings, including Oosterhof et al., 2013; Raat et al., 2011 and Zuurbier et al 2016.

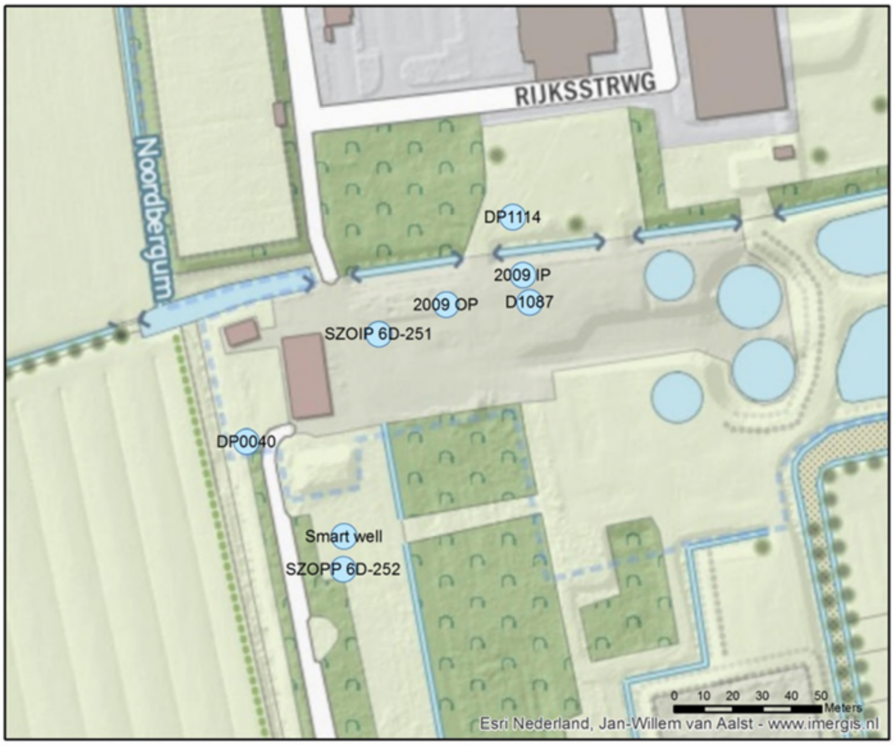

Figure 2-4 Well field Noardburgum, including the disposal- (2009 IP) and abstraction (2009 OP) wells of the first Freshkeeper pilot (2009 – 2013), the dedicated ('smart') well of the second Freshkeeper pilot (2014 – 2018), and the monitoring wells

Second Freshkeeper pilot (2014 – 2018)

In 2014, a follow-up Freshkeeper pilot was initiated at Noardburgum, with the goal to optimize freshkeeper design and operation: maximizing the freshwater recovery, while minimizing saltwater interception (Raat et al., 2015). This pilot site has been further developed within SUBSOL as one the Subsurface Water Solutions reference sites. This new Freshkeeper is a dedicated well with three different well screens in a single borehole. The shallowest screen (60 – 80 mBLS; meters below the land surface) is used for freshwater production by drinking water company Vitens. Freshwater is pumped at a fixed rate of 70 m^3/h. Brackish groundwater is abstracted from the second well screen (143 – 154 mBSL), at an adjustable rate of 5 to 23 m^3/h. The intercepted brackish water is not used for additional freshwater production, but is disposed of immediately by injection into the underlying, more saline aquifer through the deepest filter at a depth of 190 mBLS.

Results from this second Freshkeeper pilot have been reported in SUBSOL deliverable D1.2 Improved Freshkeeper Reference site (TRL7) (Oosterhof et al., 2018). This pilot rendered important insights in the aquifer's response to different pumping regimes. Close to the Freshkeeper well, the fresh-brackish interface could shift over 10 meters depth, depending on brackish water abstraction rate. This effect diminished to only about 1 – 2 meters at 45 meters distance, however, at larger distance, again a larger interface shift was observed. In setting up monitoring systems for Freshkeeper wells, it is thus not sufficient to only monitor salinity in the direct vicinity of the well as upconing at larger distances may be overlooked.

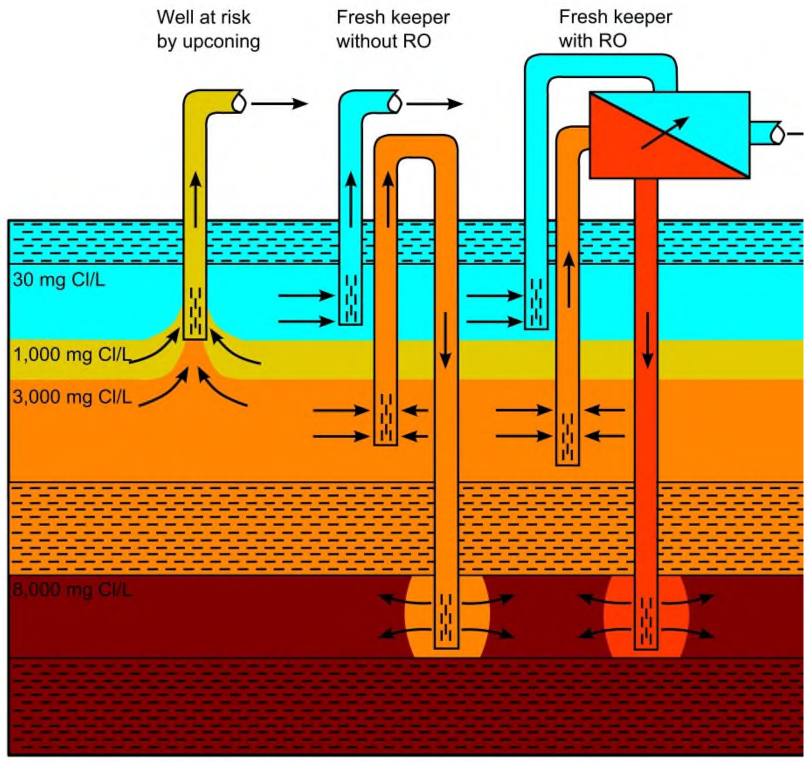

Figure 2-5 Freshkeeper concepts applied at well field Noardburgum. Freshkeeper with BWRO (right, 2009 – 2014 pilot) and Freshkeeper without BRWO, i.e. direct deep injection of the intercepted brackish groundwater.

Full scale Freshkeeper application at Noardburgum

Vitens has been looking for options to increase total drinking water production from well fields Noardburgum, Ritskebos and Garyp with at least 2 million cubic meters per year. In 2017, regional scale modelling and scenario analysis indicated that well field Noardburgum could be reopened to produce 2 million m^3/yr by applying the Freshkeeper concept in full-scale, either with or without subsequent desalination and reuse of the abstracted brackish water (Rijpkema and Van Doorn, 2017; SUBSOL deliverable D1.1). Another sustainable option to increase the total production in the northern Netherlands was to increase production at well field Ritskebos with 2 million m^3/y, yet with the risk of increased water well clogging at this site. Following these conclusions, Vitens decided to increase production through combined effort at Ritskebos and Noardburgum. As such, since April 2018 both Freshkeeper wells at Noardburgum have been put into production, abstracting 55 and 65 m^3/h of freshwater each, summing up to 1 million m^3/yr.

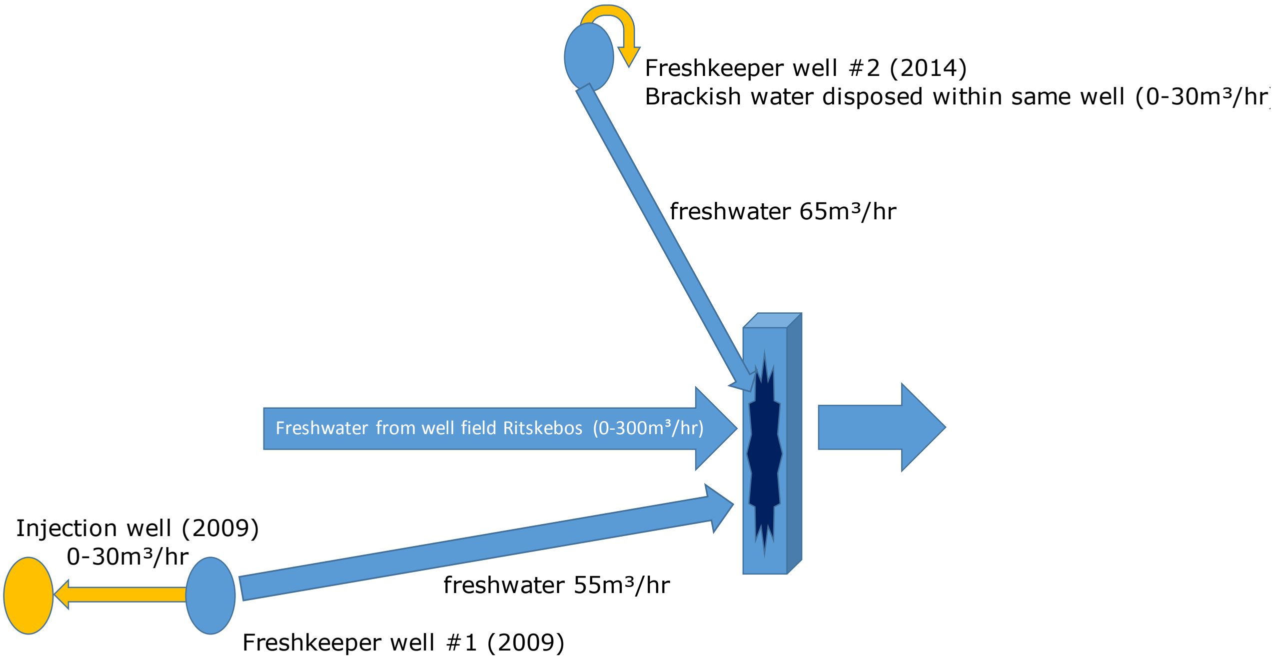

Figure 2-6 Freshkeeper concept applied full-scale at well field Noardburgum, the Netherlands

3 Process scheme

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

The process can be sub-divided in 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. At this point, it is important to notice that, unlike the SWS concepts Freshmaker and ASR Coastal, the Freshkeeper is often not applied in a ”pristine” setting. Instead, Freshkeeper is often applied as a countermeasure for salinization problems that have emerged in wells or well fields longtime (years, sometimes decades) after they have been put in production. For example, salinization problems in Noardburgum occurred only after four decades of operation of the well field. The same applies for the well field of the Town of Belleair, Florida, for which a Freshkeeper feasibility study was carried out in response to recent salinization (Ross et al., 2014)

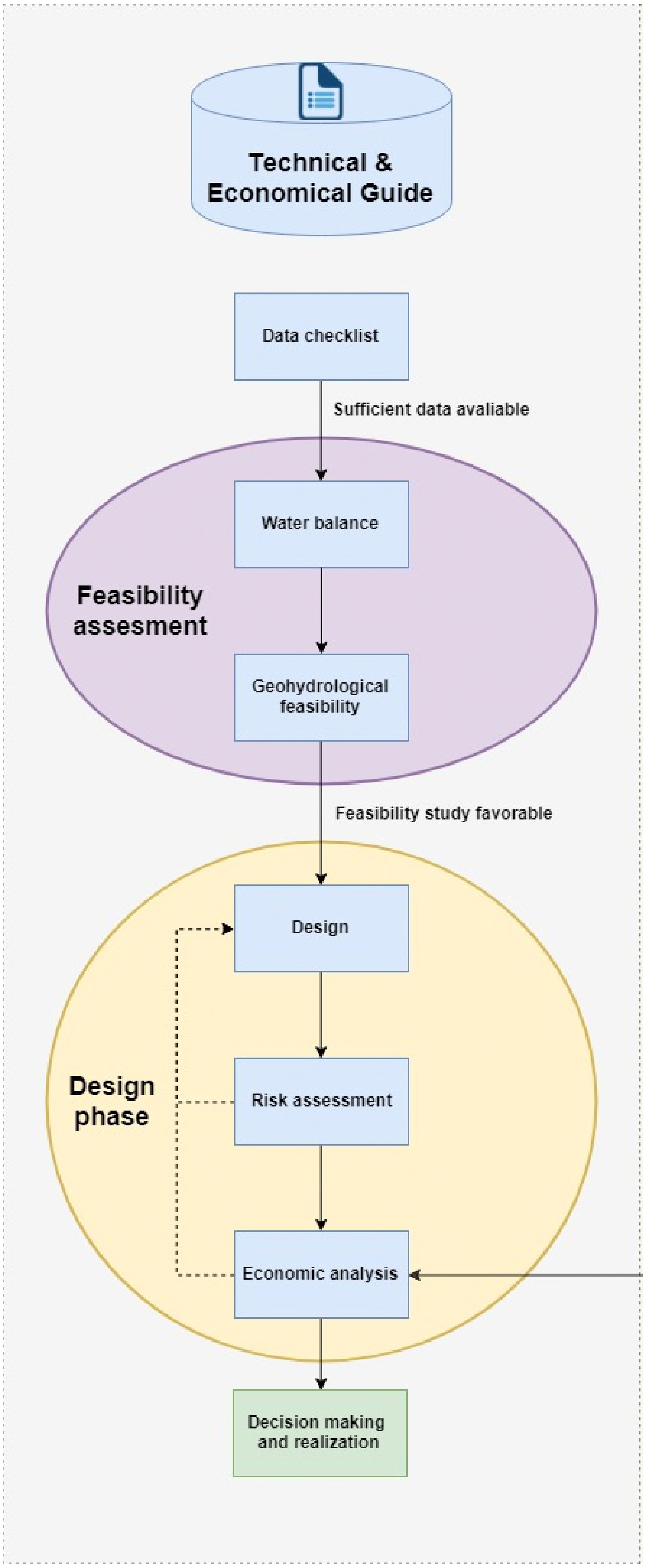

Figure 3-1 Process scheme of the Freshkeeper implementation, which compiles the necessary ste ps to reach a decision regarding the implementation of the Freshkeeper concept.

4 Data checklist

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

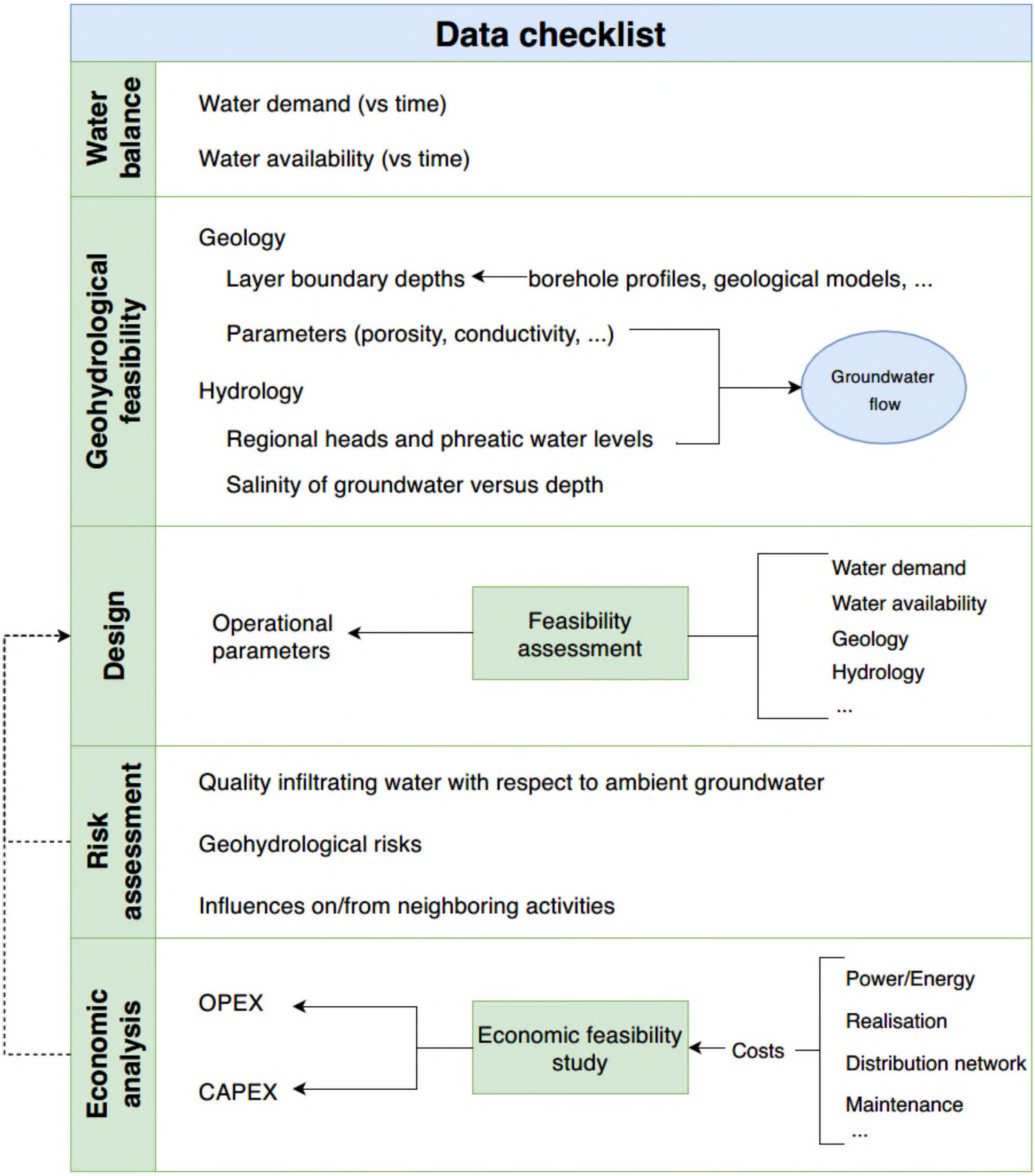

Figure 4-1 Data checklist prior to realisation of the Freshkeeper.

5 Feasibility assessment

The feasibility assessment (Figure 5-1) serves as a quick scan to determine the suitability of the subsurface and the water balance at a specific site for implementation of the Freshkeeper concept. When both the water balance and the hydrogeology at a specific location are suitable for the implementation of the Freshkeeper concept, an initial design should be developed with relevant operational parameters.

During the feasibility study, the following parameters have to be checked:

- a (seasonal) shortage of freshwater availability compared to the demand;
- fresh aquifer with risk of salinization;
- layering of the subsurface (type of sediment & thickness of layers);
- horizontal & vertical hydraulic conductivity, and porosity;
- depth of the groundwater table and the fresh-saltwater interface;
- vertical profile of salt concentrations. ;
- background lateral groundwater flow;
- potential placement depth of freshwater extraction well(s) and brackish water interception well(s);
- required extraction of freshwater and potential rate of brackish water interception.

When the application of the Freshkeeper is potentially feasible based on a quick scan of these parameters, additional modeling is suggested to develop an initial design and to determine the corresponding operational parameters. Freshkeeper is often installed as a countermeasure after salinization of an originally fresh abstraction well or well field has occurred. This implies that Freshkeeper designs have to be adaptive to the local situation. For example, when upconing is the dominant process of salinization, brackish water interception filters have to be placed below the freshwater filters, often for each individual well. In other cases, e.g. the Town of Belleair example, designating two or three of the most coastward water wells as brackish water interception wells may be sufficient to safeguard the land inward wells from salinizing.

Key feature of the Freshkeeper concept is the interception of intruding brackish groundwater. Any Freshkeeper application therefor implies that the brackish water (or brackish water reverse osmosis (BWRO) concentrate in case additional desalination is applied) can be disposed of. Potential disposal options include (1) discharge to surface water, (2) discharge to sea, (3) discharge to a sewage plant, and (4) re-injection into a (deeper) aquifer. In addition to costs, environmental impacts and regulations determine which disposal option, if any, is most viable.

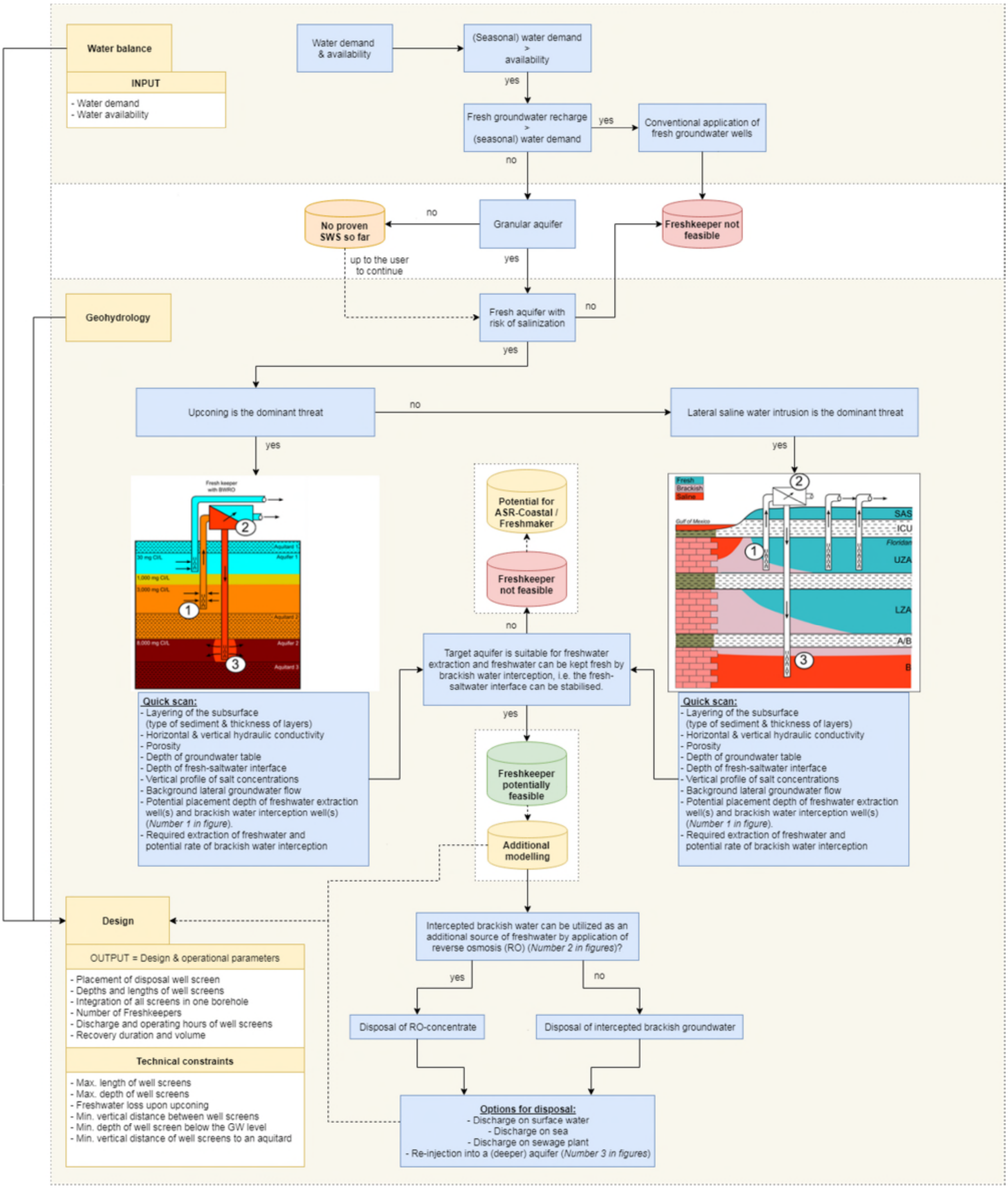

Figure 5-1 Feasibility assessment scheme for Freshkeeper implementation.

6 Design: flexible and adaptive

Based on a quick scan of the water balance and the hydrogeology described in previous section, followed by a feasibility assessment through additional modeling, an initial design of the Freshkeeper can be developed, including the scale of implementation and the operational scheme. This preliminary design includes for example the total required length and depth of well screens, the discharges and operating hours, and the energy consumption. The suggested operation and design are a simplified representation of the eventual operation, since the water balance may be different every year, and additional modeling is always required for determination of the dynamics of the fresh-salt interface. The initial design and the corresponding operation can be used to assess the costs and risks of the implementation of the Freshkeeper concept.

Even the best hydrological models always are a simplification of the real world, and exact aquifer system response, in particular fresh-saline distribution, to abstractions is difficult to predict. A reliable Freshkeeper design should thus be as flexible and adaptive as possible. This may be achieved in several ways, depending on the local situation and setup, e.g. lateral or vertical Freshkeeper system. The second Noardburgum Freshkeeper, for example, has been equipped with a submersible pump of which discharge rates can be adjusted. In this way, brackish water abstraction rates may be modified such that abstraction is minimal while still maintaining a stable fresh-brackish water interface in the production aquifer. For a detailed design of the Freshkeeper in Noardburgum, the reader is referred to *D1.2: Improved Freshkeeper Reference Site.* In a lateral Freshkeeper system, a modular setup may provide the required flexibility, enabling additional (existing) water wells to be designated as brackish water interception wells (“scavenger wells”).

A proper design includes an appropriate monitoring system. Groundwater systems may have a slow and delayed response to changes, as was the case in at the Noardburgum reference sites. Especially for Freshkeeper applied at the well field level, it is important to also monitor salinity distributions at larger distance (>100 m) from the Freshkeeper wells. Salinity can be monitored online with electrical conductivity (EC) sensors, while it may also be worthwhile to assess salinity depth profiles every year (or more frequent in the first year of operation) using geophysical measurements (e.g. EM39).

Close-up: Design of Freshkeeper at Noardburgum well field, the Netherlands

Freshkeeper wells have been installed at well field Noardburgum in 2009 and 2014, respectively (also see Chapter 2) . Since April 2018, both wells are fully integrated in the water production, producing 1 million cubic meters of fresh production water yearly. The first (2009) Freshkeeper well comprises of a fresh and a brackish water well screen and a separate well for deep-injection of the intercepted brackish water. The second (2014) Freshkeeper well combines abstraction and injection within one well. A summary of the construction details of this well are provided below. More details are provided in SUBSOL deliverable D1.2 Improved Freshkeeper Reference site (TRL7) (Oosterhof et al., 2018).

Dedicated abstraction and injection Freshkeeper well Noardburgum

Filter settings:

- well screen #1 for the abstraction of freshwater at a rate of 70 m^3/h from the aquifer at a depth of 60-80 m BLS.
- well screen #2 for abstraction of brackish groundwater at adjustable rate of 5 – 23 m3/h (default 13 m^3/h) from the aquifer at a depth of 143 - 154 m BLS
- one well screen for the disposal of intercepted brackish water in a deeper and more saline aquifer that is overlain by the Tegelen clay, at a depth of about 190 m BLS.

Design challenges of Freshkeeper well with multiple, integrated well screens:

- by standard, clay seals are installed in the borehole annulus where the well dissects natural clay layers, to prevent hydraulic connection between different aquifers. In addition, for this multi-screen well, clay seals had to be installed at depths between the separate well screens, in order to prevent short-circuiting of groundwater via the gravel pack;
- the (submersible) brackish water pump had three additional requirements: (1) flow of water was not allowed when this pump was out of operation. (2) the pumps and other parts of the well had to be resistant to corrosion because of the contact with brackish or saline water. (3) the pump required both automated as well as manual control.
- the well needs had to be designed such that all required measurement- and control devices fitted within a single borehole (and within the well-chamber). The installation should allow an easy replacement or removal in case of defects and repair. Additionally, leaks in the borehole that are caused by the placement of monitoring equipment had to be prevented.

Design summary:

The design of the dedicated Freshkeeper is presented in Figure 6.1. Additional and more specific information of the well and the subsurface, including the technical drilling tests are provided in Appendix 1 of SUBSOL D1.2 *Improved Freshkeeper Reference site (TRL7)* (Oosterhof et al., 2018).

- The well chamber has the standard lay-out of Vitens water supply;
- The borehole has a diameter of 900 mm in the first 145 m BLS and 700 mm below 145 m BLS.
- The diameter of the freshwater screen is 315 mm, of the brackish water extraction screen 250 mm and of the concentrate disposal screen 200 mm.
- A number of monitoring well screens were placed within borehole to monitor electrical conductivity (EC) and to monitor for well clogging. Due to the risks of well leakage or short-circuiting, the maximum number of monitoring wells within the borehole was 6. All monitoring screens have a diameter of 40 mm, except for one that has a diameter of 75 mm such that monitoring equipment (e.g. an EM-39 logger) would fit in..
- The submersible pump of the freshwater well screen has a fixed rate of 70 m^3/h. This makes the well screen less vulnerable to problems and saves costs of a frequency converter. In addition, it simplifies the management of the well field for the water company.
- The pump of the brackish water extraction well screen has an adjustable rate of minimum 5 to maximum 30 m^3/h. The pump of this well screen requires a high resistance to corrosion, since it extracts brackish or saline groundwater.
- During standstill, the infiltration well should be kept pressurized to prevent degassing of CO_2 from brackish water and subsequent gas clogging of the infiltration well.

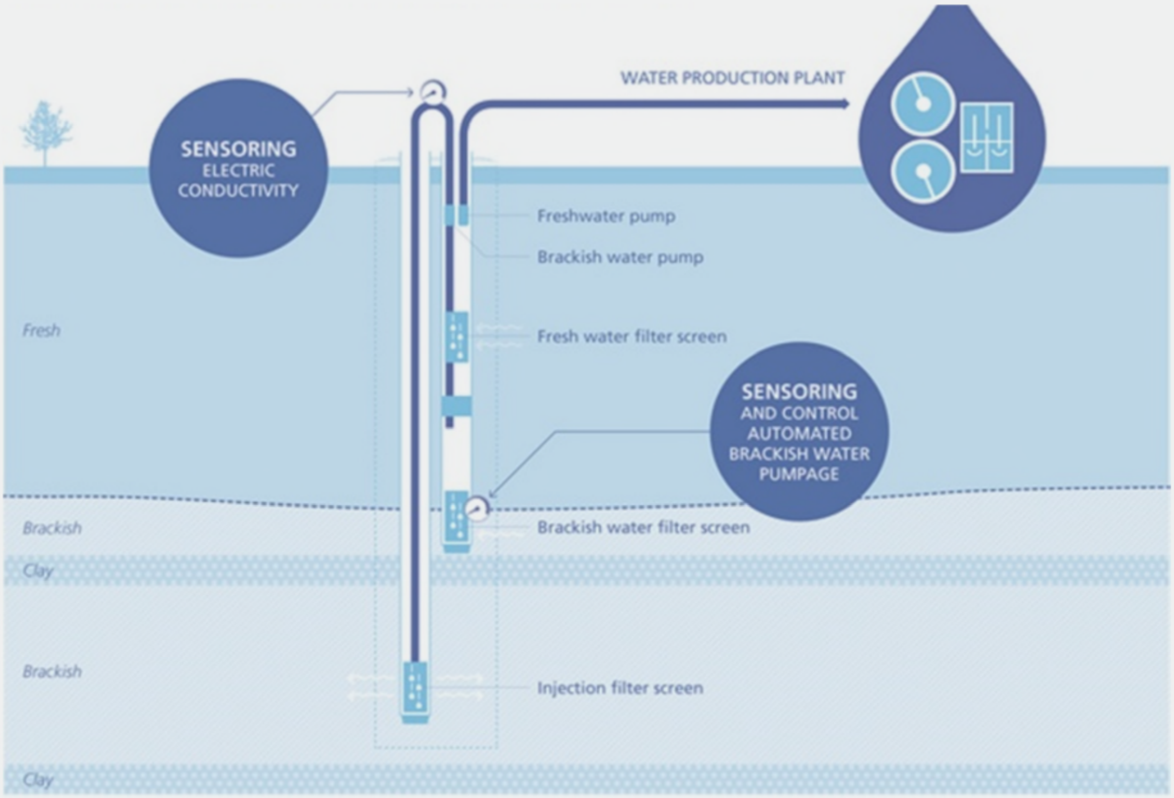

Figure 6-1 Schematic of the Noardburgum Freshkeeper well with three well screens in one integrated borehole. The discharge rate of submersible pump of the brackish extraction filter can be adjusted automatically, such that fresh-to-brackish water extraction is optimized.

7 Risk assessment: disposal options

The risk assessment allows to check whether the design and operational parameters of a Freshkeeper satisfy all constraints either before realization or during (early) operation of the Freshkeeper system. The risk assessment can be used as a legal compliance checklist regarding hydrogeological influences and the options for disposal of the brackish groundwater (or BWRO concentrate when desalination is applied). The following steps should be taken during the proposal phase:

1. Determination of hydrogeological limitations based on flow rates, changes in hydraulic head, and maximum infiltration pressures. These changes in the hydrogeology could impact surrounding vulnerable natural processes and regions through subsidence of the overlying aquitard/aquifer
2. Risk assessment of possible interferences with nearby systems (in the same aquifer or in an adjacent one).
3. Disposal options for abstracted brackish groundwater.

Steps 1 and 2 are common steps for any groundwater abstraction, and risk assessment and permitting is generally a straight forward process. In the many cases where Freshkeeper is applied as a countermeasure against occurring salinization of existing wells or well fields, the additional groundwater abstraction is within the boundaries of the existing permits.

Step 3, the disposal of the abstracted brackish groundwater (or BWRO concentrate when desalination is applied), is the Achilles heel of the Freshkeeper concept. In the Netherlands, BWRO and subsequent deep-well injection of the concentrate is widely applied in the greenhouse industry. Also, drinking water companies plea to keep this disposal option open, as long as injection is into a deeper, confined and more saline aquifer. Other disposal options include discharge to sea, surface water and WWTPs (wastewater treatment plant). All are applied in the Netherlands, though not as widely as deep-well injection. Table 7-1 gives an overview of disposal options applied in the Netherlands.

Table 7-1 Disposal options for brackish water and brackish water reverse osmosis concentrate (BWRO) in the Netherlands.

Disposal option	**Remarks / State of play**
Disposal to sea	Disposal to sea has the lowest environmental impact of all disposal options: the disposed brackish groundwater of BWRO concentrate is diluted easily, volumes are relatively small compared to the large volume of the (North) sea. In Delft, the Netherlands, a former industrial well field still abstracts (brackish) groundwater to prevent water tables rising too high. The brackish groundwater is disposed to sea via a pipeline. Economically, disposal to sea may not be attractive because of large investment costs in (expensive) pipelines
Disposal to surface water	Disposal to surface water is generally not in line with the Water Framework Directive (WFD) and therefore not allowed for. For one research pilot, drinking water company Oasen has been granted permission to dispose to a local river, after proving that the (relatively small) waste stream was sufficiently diluted within tens of meters from the outlet
Disposal to WWTP	Disposal to a WWTP (wastewater treatment plant) may be a viable option if the brackish water inflow is relatively small compared to the WWTP base flow, and will not harm the treatment capacity of the plant. This disposal option is under review by Vitens for one of its well fields central in the Netherlands, where the Freshkeeper concept may be applied.
Deep well injection <150 m depth	This disposal option is widely applied by greenhouse farmers in the Neterlands. In general, the injected BWRO concentrate is less saline than the disposal (brackish) aquifer, and thus injections are in line with the WFD and the underlying Groundwater Directive. However, despite lower salinity, depending on local conditions, concentrations of some trace elements may be higher in the injectate than in the disposal aquifer. Not all regional authorities in the Netherlands favor this disposal option, and debate on policy is ongoing. See for example Faneca Sanchez et al., 2012.
Deep well injection >150m	In Dutch law, injection at depths larger than 150 meters reside under the Mining Act. However, in permitting, authorities follow the WFD and its prevent and limit principle. The Noardburgum disposal are at depths >150 m. Permits were issued, as salinity and concentrations of other relevant elements were lower in the injectate than in the disposal aquifer. Dutch drinking water companies plea to keep this disposal option open. See Raat et al., 2009 and Raat et al., 2011 for further information

8 Economic analysis

The final step of the design phase, following the risk assessment, is the economic feasibility study of the Freshkeeper. Two components are analyzed for this purpose: CAPEX and OPEX. A scheme of the economic feasibility study is provided in Figure 8-1.

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).

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 Freshkeeper system.

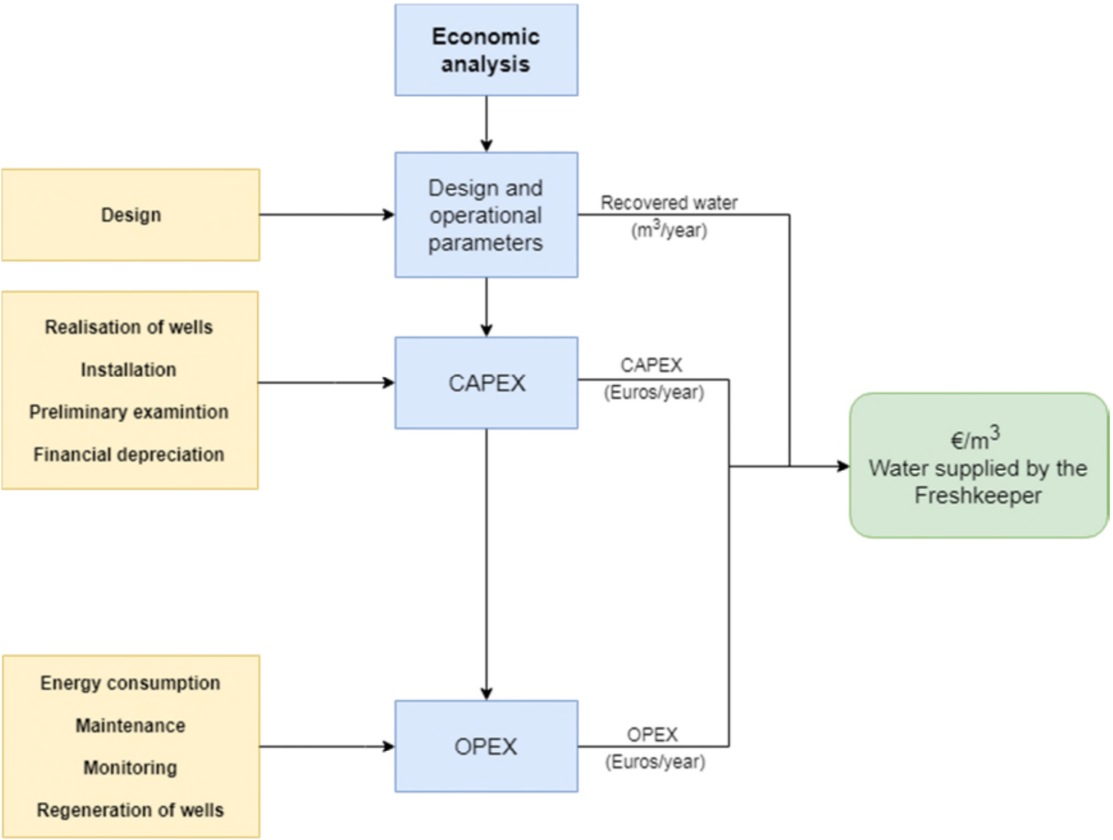

Figure 8-1. Scheme of the economic analysis to be performed after the risk assessment for a complete feasibility study.

CAPEX and OPEX may vary widely for Freshkeeper applications, depending on scale (well or well field), system setup (including or excluding BWRO) and whether or not existing wells may be used and turned into brackish water interception wells (“scavenger wells”). In general, Freshkeeper is not the most sophisticated concept, and in € per m3 production costs will be higher, but not extraordinary higher than ordinary freshwater abstraction.

Again, it should be noted that Freshkeeper is often applied as a countermeasure against salinization of existing wells or well fields. While CAPEX and OPEX are relevant, they may rule out when the “costs of inaction” are evaluated. Not taking action, i.e. not applying Freshkeeper, may result in substantial investment losses as wells may have to be abandoned and/or production may have to be decreased. Freshkeeper (CAPEX and OPEX, summed in net present value; NPV) should thus be evaluated against alternative options to secure freshwater supply for that specific location or regions. These options may include shifting to full BWRO or importing (drinking) water over long distances, which are often costly measures compared to solving problems locally.

9 Permitting / compliance

Requesting the permit

If all previous steps were favourable for the realisation of a Freshkeeper, 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 or memo describing the hydrological effects in the surroundings. If there are no geohydrological limitations, nor negative consequences related to water quality or interference, and brackish water disposal is viable (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, at the Subsol pilots and replication site, most information for evaluation was obtained after commissioning using:

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

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.

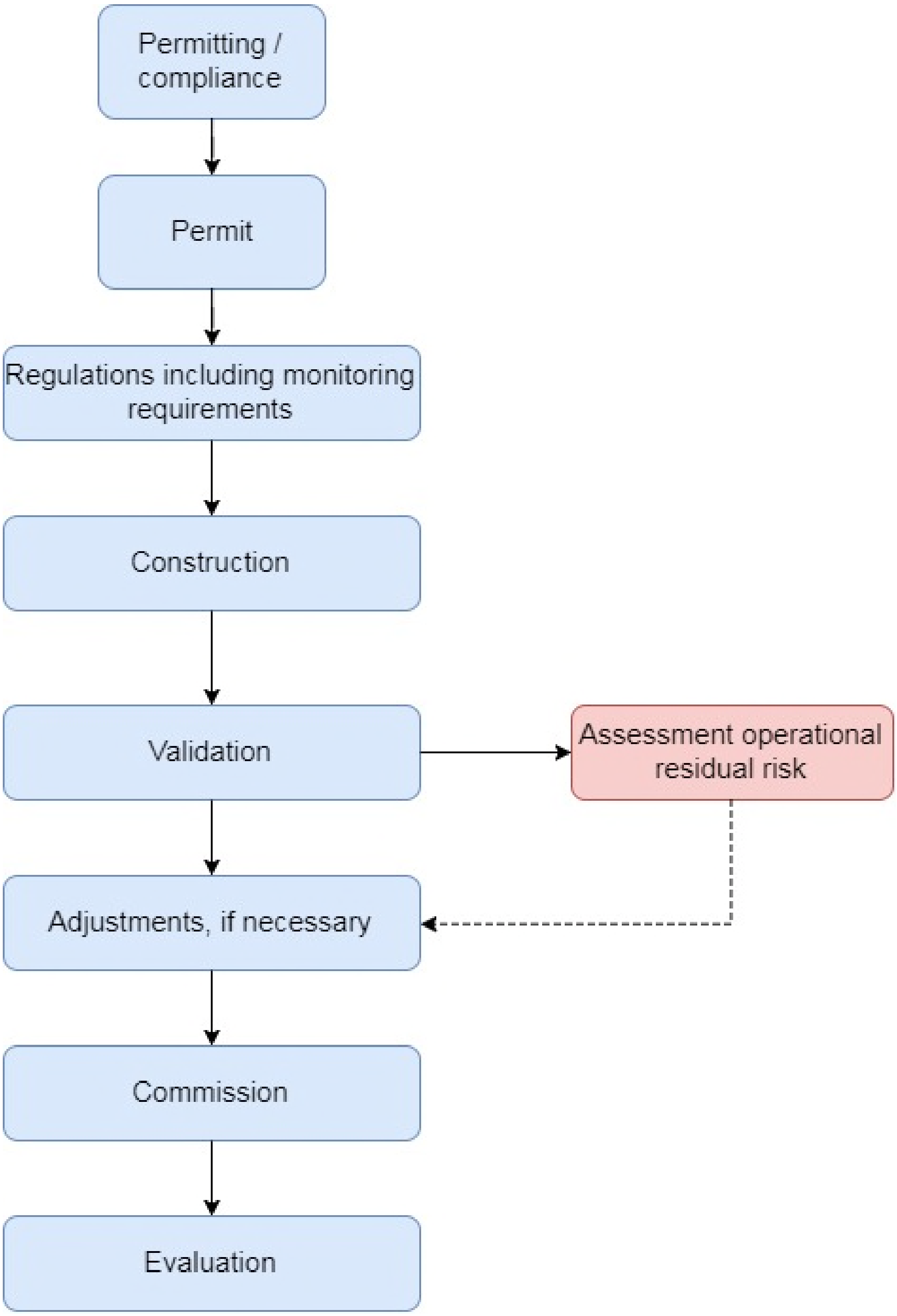

Figure 9-1. Permitting/compliance scheme.

10 Conclusions

Freshkeeper is a tool that can improve freshwater management in coastal areas by extracting brackish groundwater in addition to extracting fresh groundwater. Two wells are installed, one with its screen in fresh groundwater for the extraction of freshwater. Another well is installed within the brackish groundwater to prevent the shallow fresh groundwater well from salinization and to potentially use brackish water as an additional source of freshwater upon the application of reverse osmosis. With this interplay of two wells, the Freshkeeper results in an increased fresh groundwater storage capacity in shallow coastal aquifers where fresh and brackish water are not structurally isolated or confined.

Freshkeeper has been successfully tested at the abandoned (salinized) well field Noardburgum, the Netherlands, in two successive pilots (2009 – 2014; 2014 – 2018). Since April 2018, water company Vitens has reopened the Noardburgum well field using the Freshkeeper concept to produce 1 million cubic meters of drinking water per year.

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 Freshkeeperr at other coastal sites with risks of salinization of water wells or aquifers. This step-by-step guide helps in decision making following the route from feasibility study to design, risk assessment, economic analyses and permitting/compliance. Freshkeeper is often evaluated as a countermeasure against salinization of existing wells or well fields. Thus, in economic analysis, the “costs of inaction”, i.e. doing nothing, should also be evaluated, as well as other options to secure freshwater supply from these wells at risk. The Achilles heel of the Freshkeeper is the disposal of the intercepted brackish water (or BWRO concentrate). There are several disposal options, including deep-well injection, yet permitting is not always straightforward.

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 Freshkeeper.

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