

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



Title:	Technological and Economical guide for ASR-Coastal application
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Summary

ASR-Coastal is a Subsurface Water Solution (SWS) that has been developed in the past decade. It was extensively tested in the Subsol project. The practical concept includes multiple partially penetrating wells (MPPWs), which are used to store and recover fresh groundwater in brackish-saline, confined aquifers and to increase the vertical control on the infiltrated freshwater. Compared to conventional ASR, the use of MPPWs reduces freshwater losses resulting from buoyancy forces on the relatively light infiltrated freshwater.

The pilots in Nootdorp and Westland have proven that ASR-Coastal is a suitable SWS to reduce problems related to water quality or availability for horticulturalists with a seasonal variability of freshwater demand. Both systems contributed to the development of a reliable system for subsurface storage of freshwater in coastal areas with a brackish-saline subsurface. The installation in Westland has proven that ASR-Coastal can be combined with other systems, like reverse osmosis, to further improve freshwater management in coastal areas.

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 ASR-Coastal 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 ASR-Coastal Tool proposes a design and an operational scheme, and estimates the costs involved for installation and implementation.

1 Introduction

Subsurface Water Solution (SWS): ASR-Coastal

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

ASR-Coastal is one of these SWS concepts, and is the subject of this Technological and Economical guide. It is a tool that improves freshwater management in coastal areas by using multiple partially penetrating wells (MPPW). This technique reduces freshwater losses resulting from buoyancy forces on the light infiltrated freshwater by preferably infiltrating freshwater through the deepest well screens in times of surplus and recovering it again through the shallower well screens in times of demand (Figure 1-1).

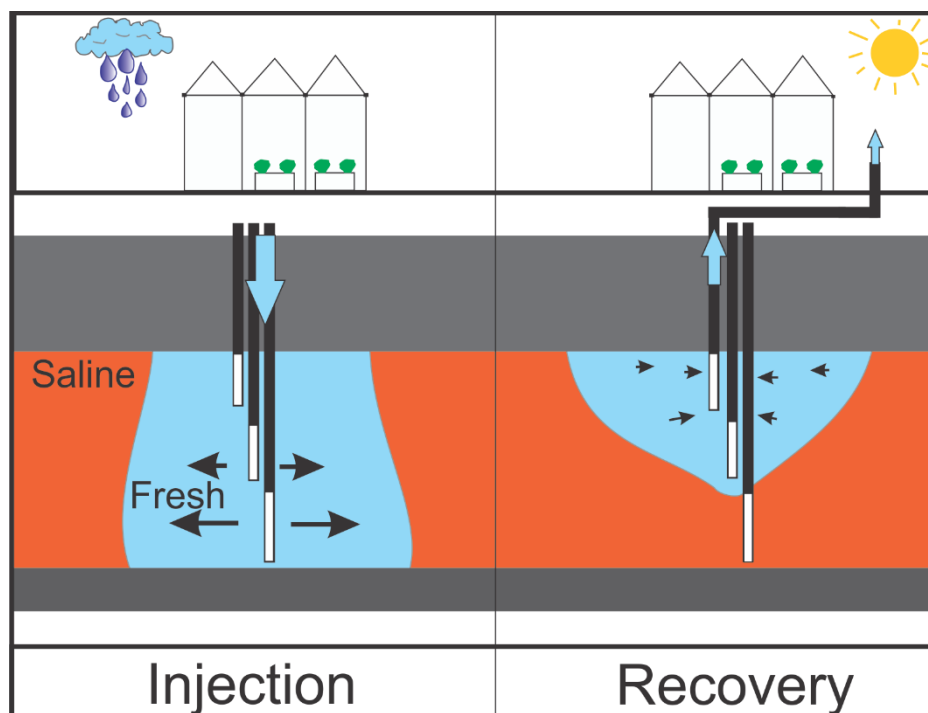


Figure 1-1 Cross-section of the subsurface where ASR-Coastal is applied in a brackish aquifer. Without the implementation of ASR-Coastal, a conventional ASR-system would result in an early recovery of brackish groundwater through the lower well screens as a result of buoyancy forces on the infiltrated freshwater.

Objectives

This Technological and Economical guide strives to:

- Provide future adopters with a broad view of the ASR-Coastal implementation and its site-specific nature by portraying the original pilot set-up and the latest improved versions of ASR-Coastal.

- Assist and guide future adopters in assessing the potential of realizing an ASR-Coastal set-up by providing a checklist of required activities and data.
- Increase and facilitate the market uptake of the ASR-Coastal concept for a sustainable freshwater resource management in coastal areas.

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 brackish-saline aquifers.

This guide facilitates identification of available options for the implementation of ASR-Coastal, 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 existing ASR-Coastal systems (Chapter 2). This is primarily based on the practical experiences gained throughout the implementation of ASR-Coastal at the reference field sites in Nootdorp and Westland, The Netherlands, where ASR-Coastal has been successfully in operation since 2012 to supply horticulture farmers with freshwater. Groundwater flow modelling has been carried out parallel to fieldwork, to improve the understanding of ASR-Coastal, 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 ASR-Coastal concept. Furthermore, the main obstacles, the reactions of the end users, and the perception of the ASR-Coastal concept in practice are covered in this guide.

This information is synthesized to create implementation guidelines of the ASR-Coastal concept. A process scheme of the required activities that constitute a preliminary feasibility study for implementation of ASR-Coastal 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 a first design of the ASR-Coastal set-up for his 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 ASR-Coastal concept, 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.

ASR-Coastal tool (Excel)

A Microsoft Excel tool to be used in parallel with this Technological and Economical guide has been developed. This tool can be used to obtain a first design, and the operational and economical parameters that are necessary along the process of realizing an ASR-Coastal system. An overview of how this tool should be used in parallel with the Technological and Economical guide is provided in Chapter 3. The simplicity of the tool makes it ideal to use for a preliminary feasibility study and contains some default information to fill in potential data gaps.

2 Background of ASR-Coastal

The ASR-Coastal 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, this set-up generally fails in confined coastal aquifers with brackish or saline groundwater due to dispersive and diffusive mixing between infiltrated freshwater and ambient groundwater (Ward et al., 2009), and especially due to buoyancy forces on the infiltrated freshwater (Zuurbier, 2012). As a solution to the mixing problem, Pyne (2005) suggested to infiltrate an extra volume of water to act as a buffer. However, this does not overcome the buoyancy forces on the infiltrated freshwater. With the development of multiple partially penetrating wells (MPPWs) (Zuurbier et al., 2014), an alternative and improved version of ASR became available for saline, confined aquifers which can, to a certain extent, counteract freshwater losses by buoyancy.

In the ASR-Coastal set-up, several MPPWs are installed at different depths within a brackish confined aquifer (Figure 1-1). The deeper well screens of the MPPW-ASR system are preferably used for freshwater infiltration in times of surplus (winter), thereby generating a freshwater body surrounded by ambient saline groundwater. Mainly during the storage phase of ASR, the light freshwater body will tend to move upwards due to the density difference between infiltrated freshwater (low density) and ambient brackish groundwater (high density). ASR-Coastal allows to respond to this issue by recovering the infiltrated freshwater through shallower well screens in times of demand (in summer or during periods of drought). The freshwater body is thus actively managed to increase the applicability of ASR and the potential recovery of freshwater.

Experiences at the Nootdorp reference site

In November 2011, an ASR-Coastal system was installed in a confined coastal aquifer in Nootdorp, located in the coastal province of Zuid-Holland in the west of the Netherlands (Figure 2-1). Nootdorp is situated in a deep polder with brackish seepage to the surface waters (de Louw et al., 2010) as a result of the local surface level having an elevation of 3.8 meters below sea level (m BSL). Chloride concentrations in the target aquifer are typically around 1,000 mg/L (Figure 2-1). Despite the scarcity of freshwater in the subsurface, the area is dominated by greenhouse horticulture with a typical high water demand and high quality standards concerning salinity. Rainwater from greenhouse roofs is therefore used as the main irrigation water source in this region.

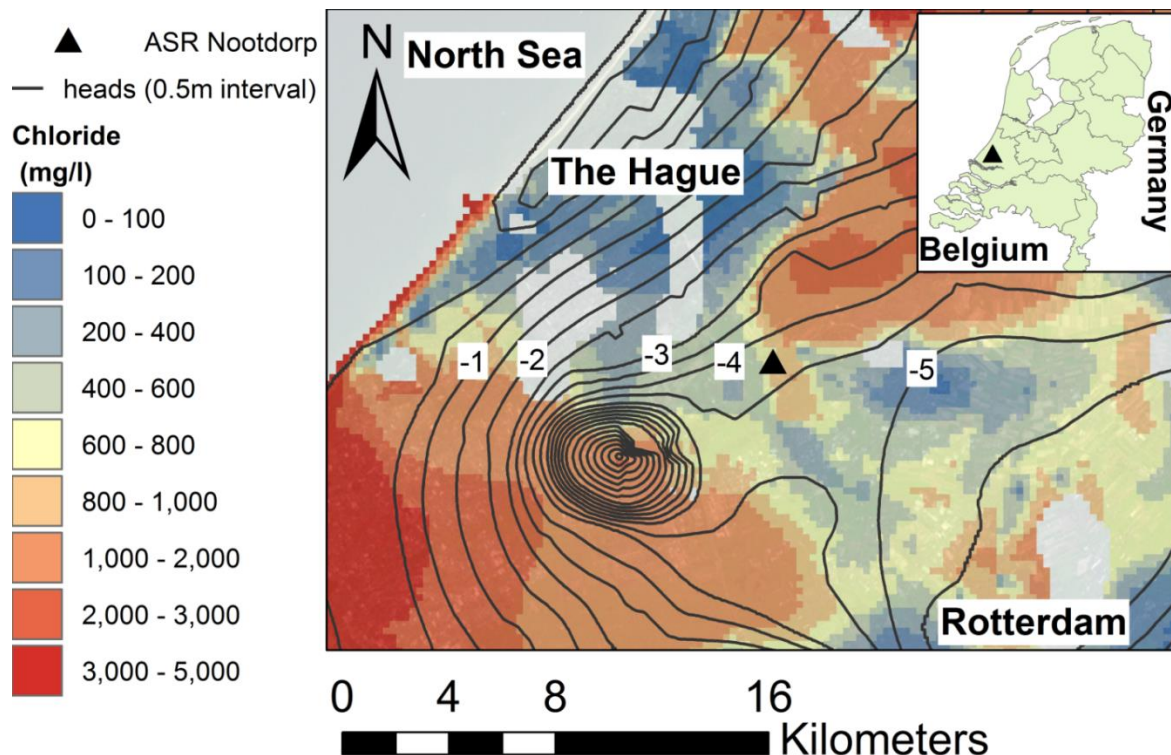


Figure 2-1 Regional piezometric head contours (TNO, 1995) and chloride concentrations (Oude Essink et al., 2010) in the centre of the ASR target aquifer, with location of the Nootdorp ASR field trial (black triangle). Blank areas indicate zones where the target aquifer is connected to a deeper aquifer.

Prior to installation of the ASR-Coastal system in Nootdorp, the end user collected rainwater from the 2 ha roof of his orchid-nursery greenhouse and stored this freshwater in large surface storage basins in times of surplus, for later use in times of demand. Seasonal storage of freshwater is an effective strategy for regions with a seasonal pattern in precipitation but a constant demand of freshwater. However, storage in surface basins had several drawbacks, including its high costs (about 1 €/ m³) and extensive spatial needs, which were the main reasons for the end user to switch from a surface basin to ASR-Coastal. In addition, surface storage can result in deterioration of the water quality. However, irrigation water quality requirements are very strict, because freshwater must have for example a chloride concentration <0.5 mmol/l (~18 mg/l Cl). This also means that only a very limited contribution of ambient brackish water to infiltrated rainwater is allowed upon recovery with the ASR system.

After characterization of the target aquifer and the native groundwater therein, a 34 m deep borehole was drilled, in which four MPPWs were installed at different depth intervals between 14 and 41 m below sea level (m BSL) throughout the confined target aquifer (Figure 2-2). Each well was outfitted with a valve in the infiltration and recovery pipeline, allowing manual adjustment of infiltration and recovery rates per individual MPPW-screen. After successful installation, rainwater collected by the greenhouse roof was stored in a 400 m³ rainwater storage tank, which could store 20 mm of rainfall, thereby enabling freshwater intake in periods with peak precipitation and managing potential variation in the

freshwater supply. Prior to infiltration, the roofwater was pre-treated by rapid and slow sand filtration to prevent well clogging by suspended particles.

Infiltration of the treated freshwater, preferably through the deepest well screens, started once a predefined level in the rainwater storage tank was reached and ceased when a set minimum level was reached. A 3 m high standpipe was used to provide a constant pressure for infiltration. Recovery of the stored freshwater, preferably through the shallower well screens, started automatically in times of demand when the predefined minimum level in a 90 m³ irrigation water tank was reached, and stopped once the predefined maximum level in this tank was reached (Figure 2-2 and Figure 2-3).

The resulting ASR operation was highly dynamic with frequent alternation of infiltration, storage, and recovery stages, automated and electronically logged via a central control unit with a programmable logical controller.

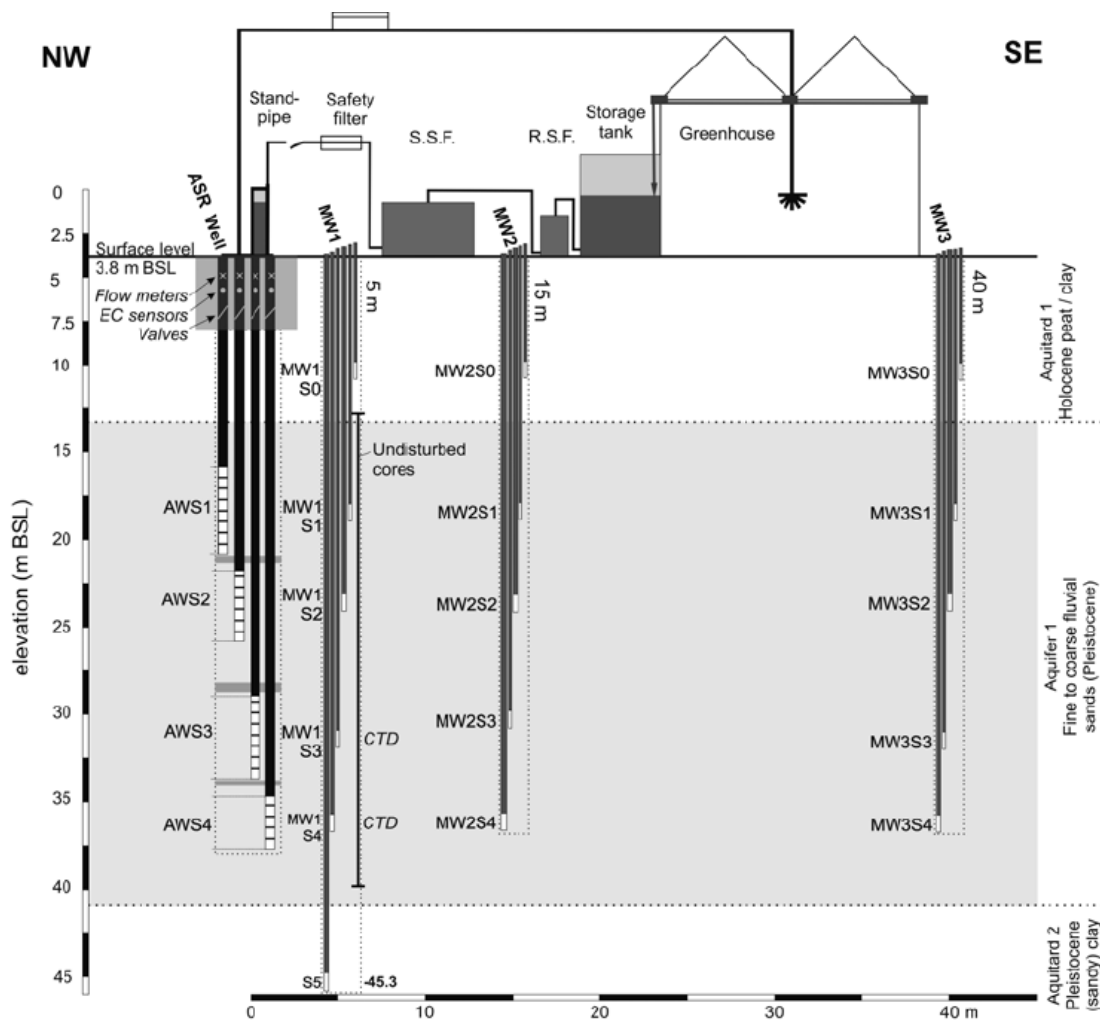


Figure 2-2 Schematic overview of the ASR-Coastal set-up at Nootdorp. MW = monitoring well, CTD = electrical conductivity, temperature, and pressure datalogger, R.S.F. = rapid sand filtration, S.S.F. = slow sand filtration (Zuurbier et al., 2014).



Figure 2-3 ASR-Coastal well field Nootdorp: infiltration well and monitoring equipment (A), monitoring wells (B) and storage tanks (C: one for rainwater, others for water reuse) (Zuurbier et al., 2014).

Geophysical measurements were also conducted to construct profiles of electrical conductivity of the subsurface. These procedures enable to analyse the distribution and dynamics of the freshwater body during infiltration and recovery with the ASR-Coastal system. 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.

Since the start of the implementation of ASR-Coastal in Nootdorp in 2012, the system has been in operation for 5-6 years. Based on the thorough documentation and interpretation of the field operation, model simulations, and analyses during the ASR-cycles of these years, it is concluded that:

- The Nootdorp ASR-Coastal system functioned rather smoothly and was always able to supply sufficient irrigation water to the local horticulturist. On average $\sim 7\,200\text{ m}^3/\text{yr}$ was recovered after infiltration of $\sim 14\,000\text{ m}^3/\text{yr}$, resulting in a recovery efficiency of 53.4%.
- The required maintenance was limited and the recovered water quality was very constant already after the first ASR-cycle, and met the end user's demands for irrigation of his orchids.
- With total costs of 0.61 euro/ m^3 , the ASR-Coastal system provided a significantly cheaper source of high-quality freshwater compared to alternatives.
- The spatial footprint of ASR-Coastal is virtually nil compared to the surface basin that was previously used by the end user.
- The owner will keep using the system as his only source of irrigation water.

Experiences at the Westland reference site

In 2012, an ASR-Coastal system was installed in a confined coastal aquifer in 's-Gravenzande in the Westland region of the Netherlands (Figure 2-4). Due to brackish seepage, the groundwater in the target aquifer for ASR is brackish-saline, with chloride concentrations typically being around 4,000 mg/L (Figure 2-1). The area is dominated by greenhouse horticulture with a characteristic high water demand and high quality standards concerning salinity. Rainwater from greenhouse roofs is therefore used as the main irrigation water source in this region.

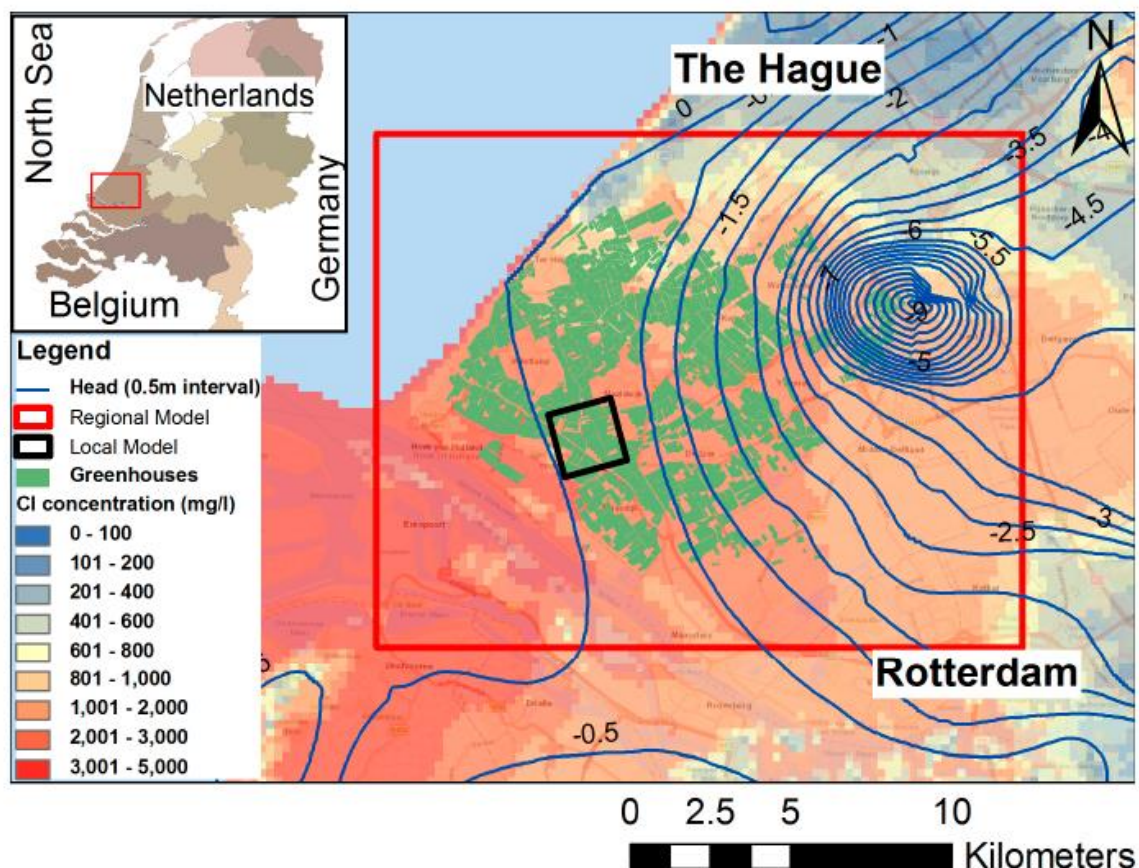


Figure 2-4 Regional piezometric head contours (TNO, 1995) and chloride concentrations (Oude Essink et al., 2010) in the centre of the ASR target aquifer, with location of the Westland ASR field site (black square).

The end user collected rainwater from the 27 ha roof of his tomato-nursery greenhouse and stored this freshwater in large surface storage basins in times of surplus, for later use in times of demand, but experienced periods in which the water demand or required water quality could not be met. He was already using a brackish water reverse osmosis (BWRO) system for additional freshwater supply. This approach however leads to a net overdraft of water (produced by desalination of brackish groundwater) from the aquifer, and therefore a risk of salinization.

Two 37 m deep boreholes were drilled, in which three MPPWs were installed at different depth intervals from 23 to 37 m below sea level (m BSL) throughout the confined target

aquifer (Figure 2-5). Each well was outfitted with a valve in the infiltration and recovery pipeline, allowing manual adjustment of infiltration and recovery rates per individual MPPW-screen. Collected rainwater was stored in storage basins, enabling freshwater intake in periods with peak precipitation and managing potential variation in the freshwater supply. Prior to infiltration, the roofwater was pre-treated by rapid and slow sand filtration to prevent well clogging by suspended particles. The ASR wells use a 3.2 m high standpipe to provide infiltration pressure for a total infiltration rate of 40 m³/h. Recovery can occur with a total rate of 50 m³/h in times of demand. The resulting dynamic ASR operation with frequent alternation of infiltration, storage, and recovery stages is comparable to the dynamic operation at the Nootdorp site.

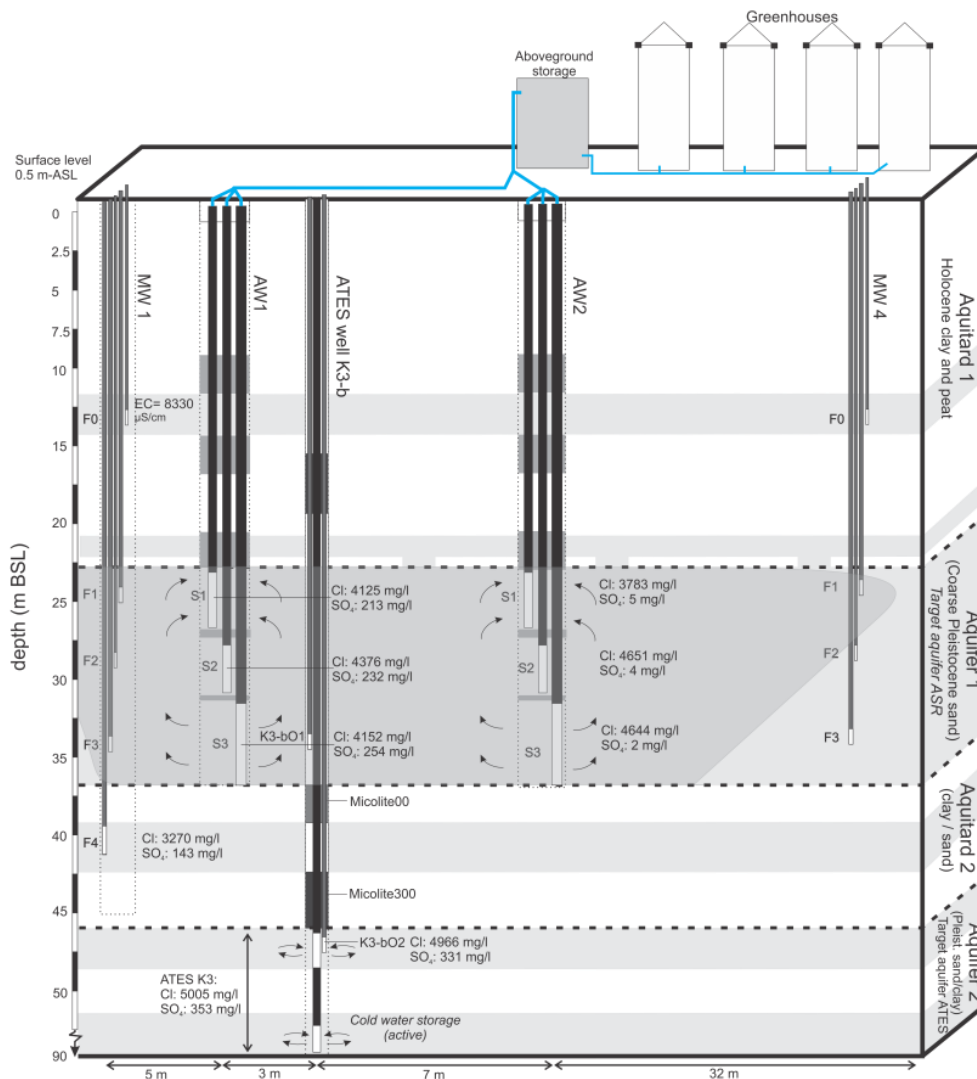


Figure 2-5 Cross-section of the Westland ASR site schematizing the geology, ASR wells, ATEs well, and the typical hydrochemical composition of the native groundwater. Horizontal distances are not to scale (Zuurber and Stuyfzand, 2017).

In a later stage of the pilot at the Westland site, ASR-Coastal was complemented by a Freshkeeper and reverse osmosis ('ASRRO') to maximize the recovery of infiltrated

freshwater surpluses (Figure 2-6). Two separate RO-facilities were used. One was the original brackish water RO ('BWRO') plant already present at the site, abstracting water from the whole aquifer thickness at the fringe of the 'new' freshwater body, thereby feeding the BWRO with a mixture of water qualities. This BWRO-plant was designed to be fed by 40 m³/h of brackish groundwater and produce freshwater at an RO-recovery of 50%. An additional RO-plant (ASRRO) was connected to the ASR-wells to desalinate mixed water recovered from the deepest MPPW-screens below the freshwater bubble, similar to the Freshkeeper set-up (D1.2 and D1.3). Both RO-systems produce supplementary high-quality water and are used in combination with concentrate disposal in a deeper aquifer, resulting in net mining of the 'new' fresh groundwater system (Figure 2-6).

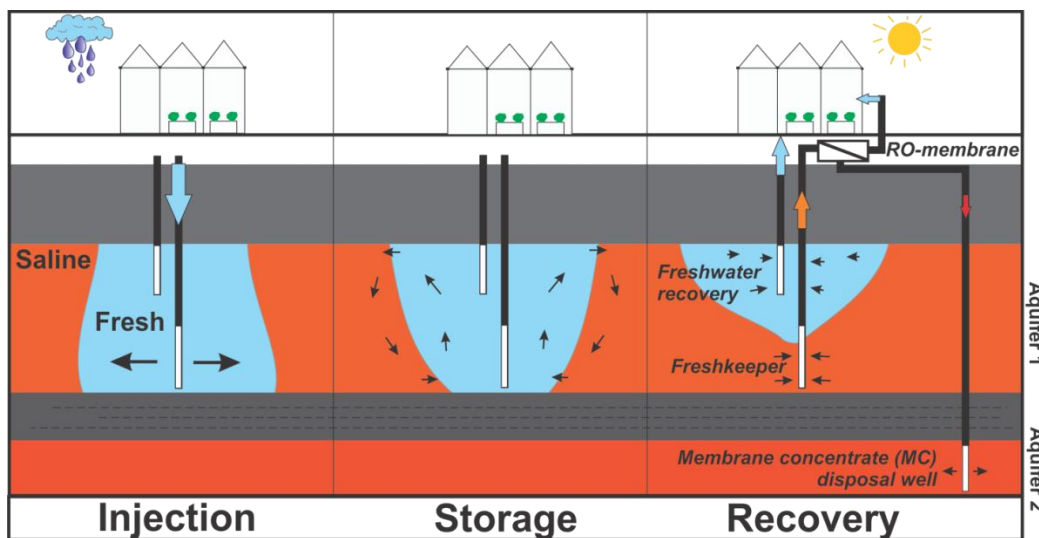


Figure 2-6 Concept of ASR-Coastal in Westland with multiple partially penetrating wells (MPPWs) and the Freshkeeper (ASRRO).

Also here, geophysical measurements were conducted to construct profiles of electrical conductivity of the subsurface. These procedures enable to analyse the distribution and dynamics of the freshwater body during infiltration and recovery with the ASR-Coastal system. 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.

Since the start of the implementation of ASR-Coastal in Westland in 2012, the system has been in operation for 5-6 years. Based on the thorough documentation and interpretation of the field operation, model simulations and analyses during the ASR-cycles of these years, it is concluded that:

- The Westland ASR-Coastal system functioned satisfactorily, but clearly suffered from saltwater leakage via an older borehole, which reduced the recovery efficiency from 40% to 22.5%.

- Per year, 7 500 to 16 000 m³ could be supplied, while 28 000 to 70 000 m³/yr was infiltrated. The ASR-Coastal system was not able to meet the yearly demand of the local horticulturist by itself.
- Yearly cleaning of the infiltration floater boxes and ASR wells was required at the start-up of the system after long periods without infiltration.
- Despite these additional obstructions, the total costs of recovered freshwater were acceptable (0.85 euro/m³).
- The net overabstraction of freshwater (produced by desalination of brackish groundwater) from the groundwater system could be mitigated to a large extent.
- The owner will keep using the system as additional fresh water supply and as a compensation for the use of BWRO (agreement with provincial water authority), together with aboveground rainwater storage and brackish water reverse osmosis.

3 Process scheme

In this chapter, a general overview of steps to follow for implementation of the ASR-Coastal 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, is 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 ASR-Coastal Tool that should 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 ASR-Coastal Tool, after reading the README-worksheet. When all worksheets of the ASR-Coastal Tool are filled in correctly, an overview of the most relevant input and output is given in worksheet '0. Overview input & output'.

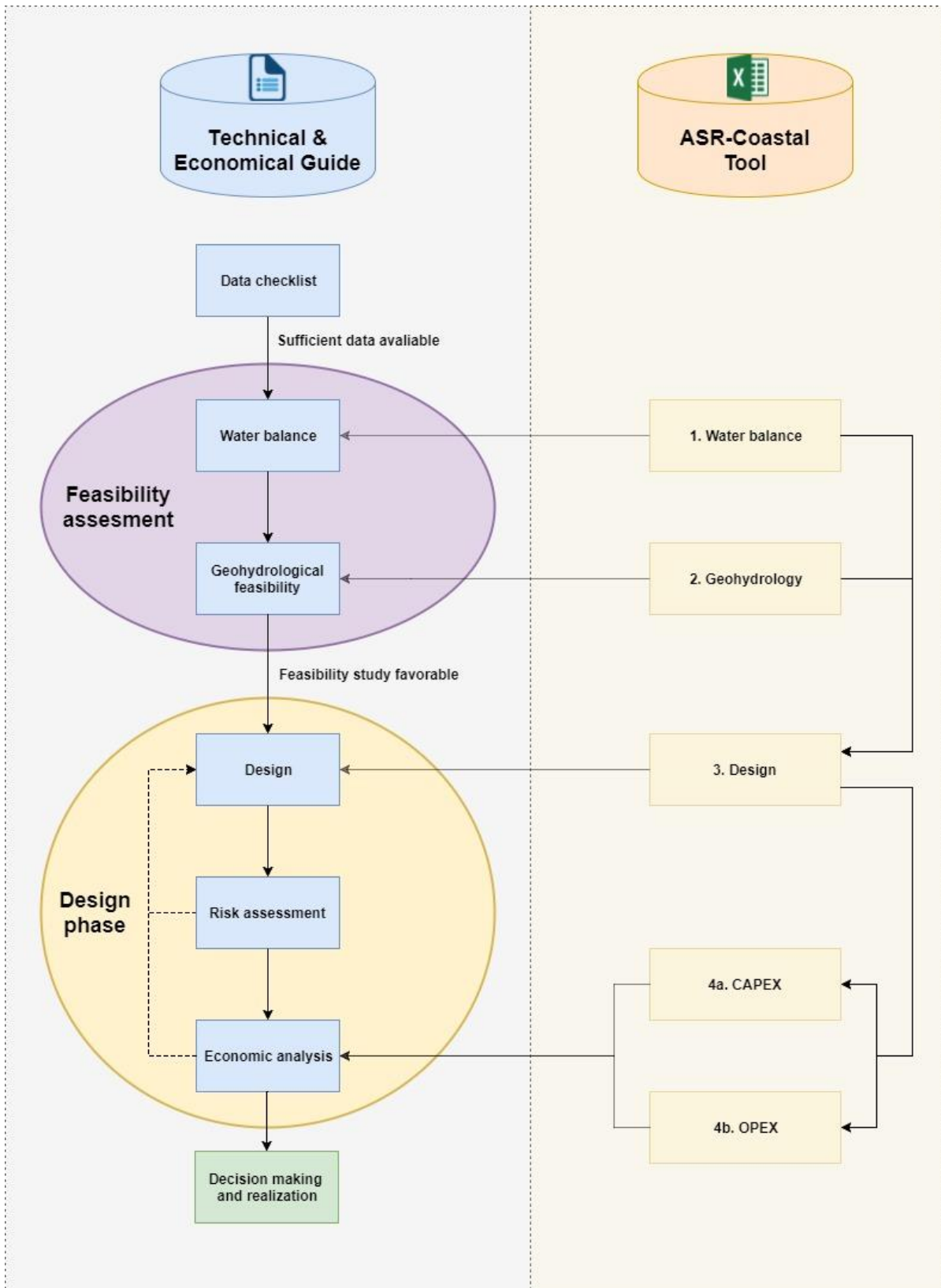


Figure 3-1 Process scheme of the ASR-Coastal implementation. The left side of the figure compiles the necessary steps to reach a decision regarding the implementation of the ASR-Coastal concept. The right part of the figure indicates for which steps the ASR-Coastal Tool is required alongside this Technological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

4 Data checklist

The data checklist (Figure 4-1) compiles the material and information required in order to reach a well-funded decision on realising the ASR-Coastal 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.

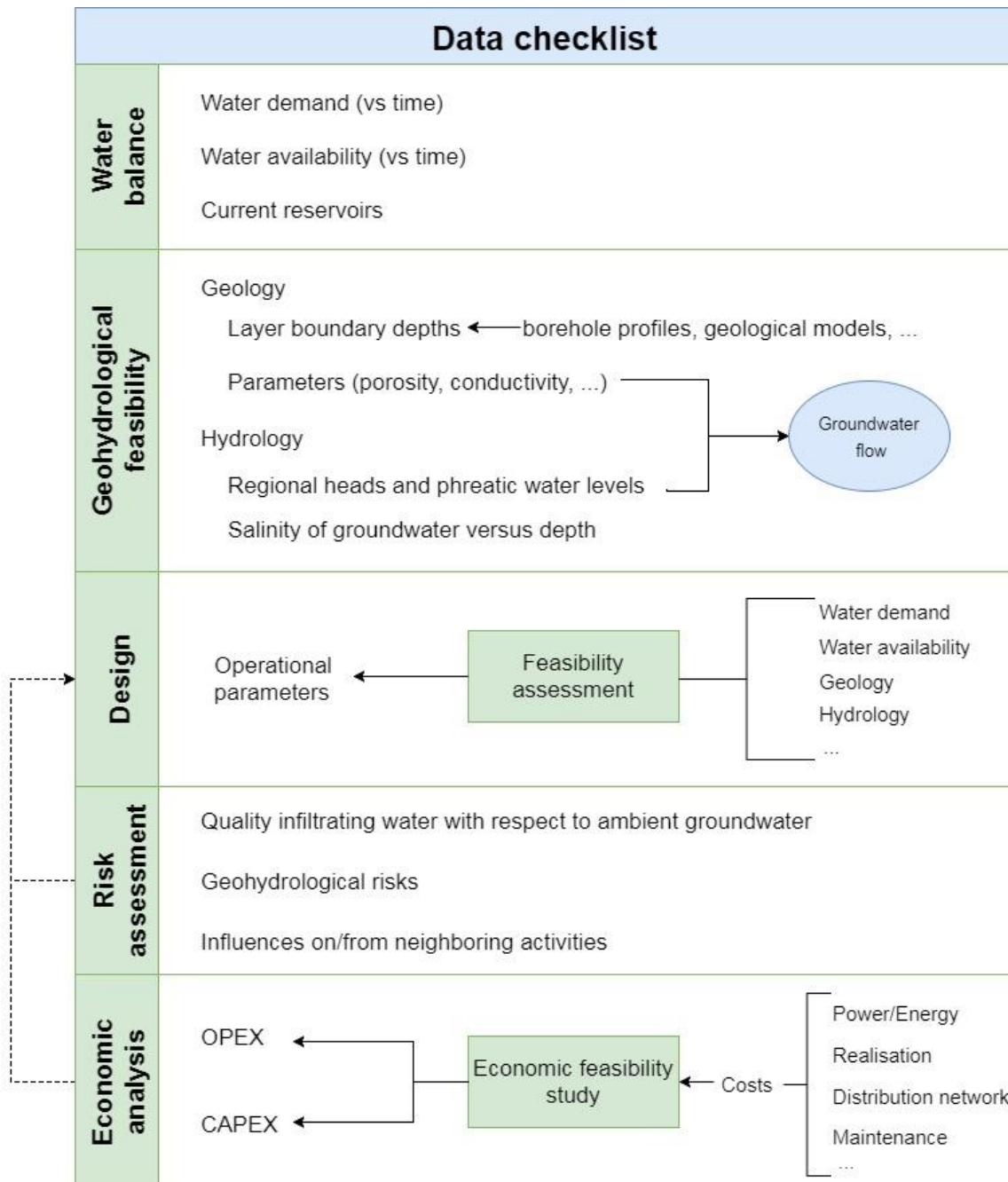


Figure 4-1 Data checklist prior to realisation of the ASR-Coastal concept.

5 Feasibility assessment

The feasibility assessment (Figure 5-1; 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 ASR-Coastal. From here, the reader can start to use the ASR-Coastal 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 ASR-Coastal concept, an initial design is proposed with relevant operational parameters in worksheet '3. Design'.

During the feasibility study, 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);
- the presence of a confined granular aquifer without intervening clay layers (≥ 0.5 m thick), overlain by a confining aquitard of > 3 m in thickness (or >1000 day of vertical flow resistance, if known).
- the possibility to install at least two and at most three MPPWs within the confined aquifer, at a minimal vertical distance of 4 m below the groundwater level, with vertical spacing of 1 m from another MPPW, and with vertical spacing of 1 m from an aquitard. One MPPW filter can have a length ranging from 3 m to 10 m.
- If there are more suitable aquifers, the aquifer with the least effect of buoyancy is preferred for installation of the ASR-Coastal system. This is often the shallowest aquifer.

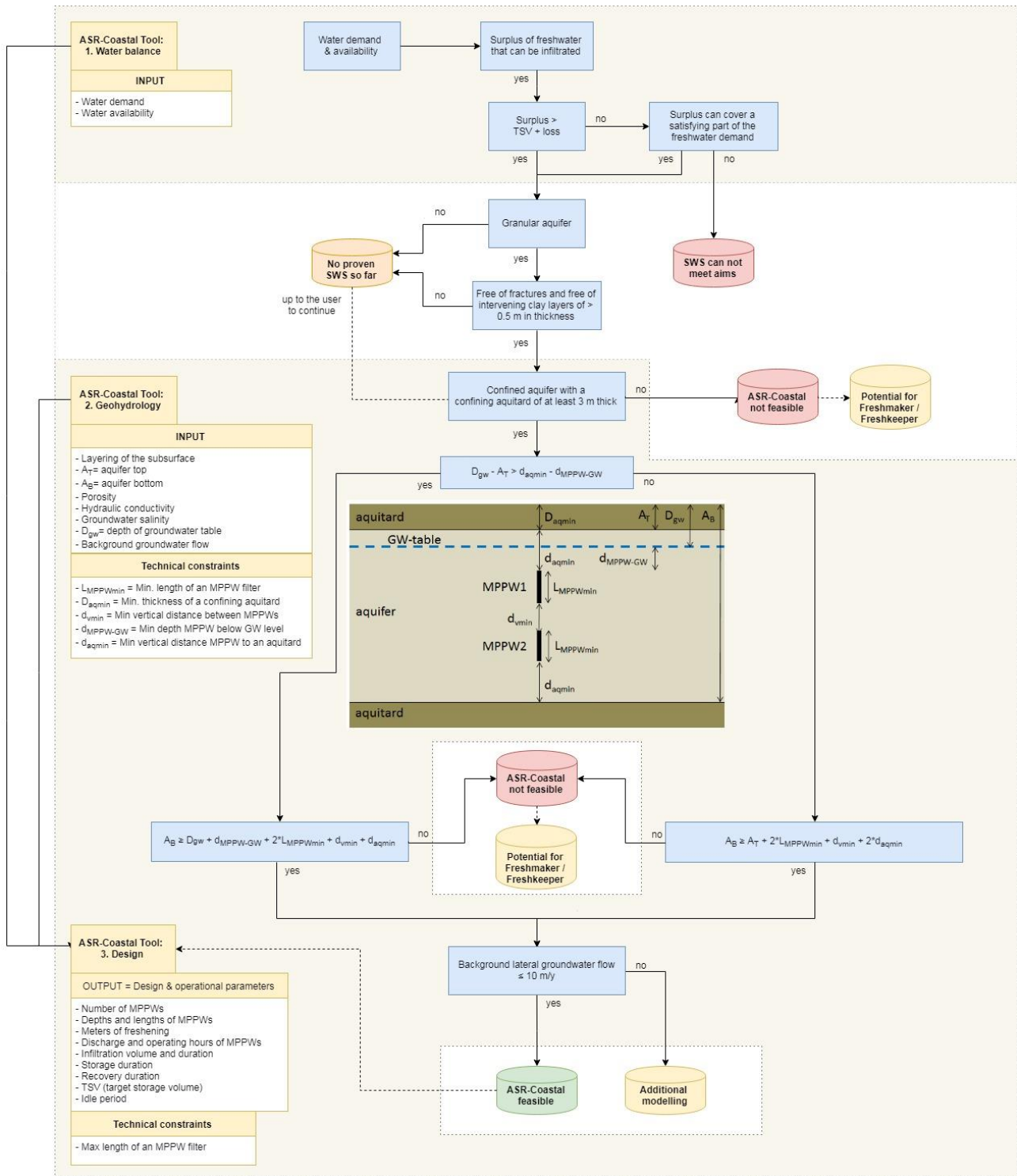


Figure 5-1 Feasibility scheme for ASR-Coastal implementation, forming the blue-print of the ASR-Coastal Tool.

6 Design

Worksheet '3. Design' of the ASR-Coastal 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 ASR-Coastal system with the related operational parameters (Figure 5-1). These include for example the total required length, depth, and number of MPPW'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 form a simplified representation of the eventual operation, since the water balance may be different each year. In practice, the operation may for example be adjusted more frequently, depending on the timing of freshwater surplus and demand. Nevertheless, the ASR-Coastal Tool provides a suitable operation based on the feasibility assessment that can be used to assess the costs and risks of implementation of the ASR-Coastal concept.

7 Risk assessment

The risk assessment allows to check whether the design and operational parameters of an ASR-Coastal system satisfy all constraints either before realization or during (early) operation of the ASR-Coastal 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 potential of contaminating the groundwater (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 ASR-Coastal 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 regarding 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 <math><0,1 \text{ mg/l}</math>
- Turbidity <math><1 \text{ NTU}</math>
- Total iron <math><0,01 \text{ mg/l}</math>
- Sodium Adsorption Ratio (SAR, at EC 40-100 mS/m) <math>< 6 \text{ bij}</math>
- Dissolved Organic Carbon (DOC) <math>< 2 \text{ mg/l}</math>
- Assimilable Organic Carbon (AOC, acetate-C) <math>< 10 \text{ } \mu\text{g/l}</math>
- Modified Fouling Index (MFI) <math>< 3-5 \text{ s/L}</math>

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

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

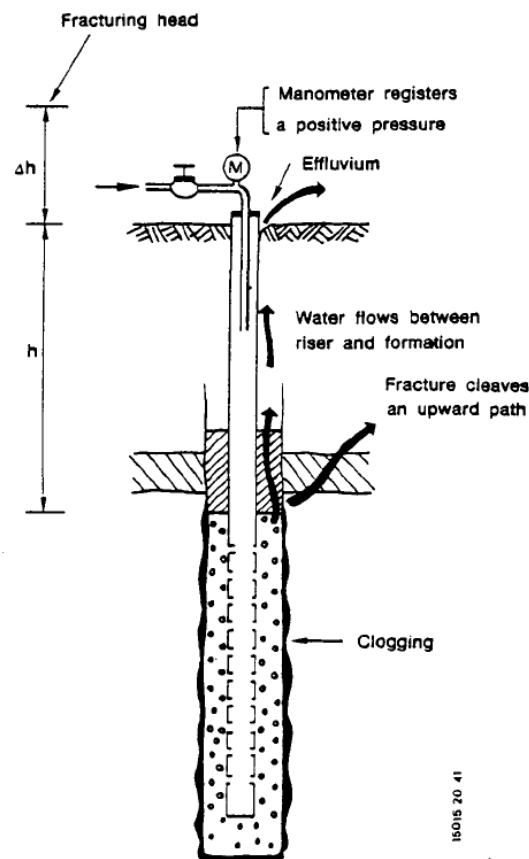


Figure 7-1 Fracturing or bursting of injection wells by applying too much pressure during injection

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.

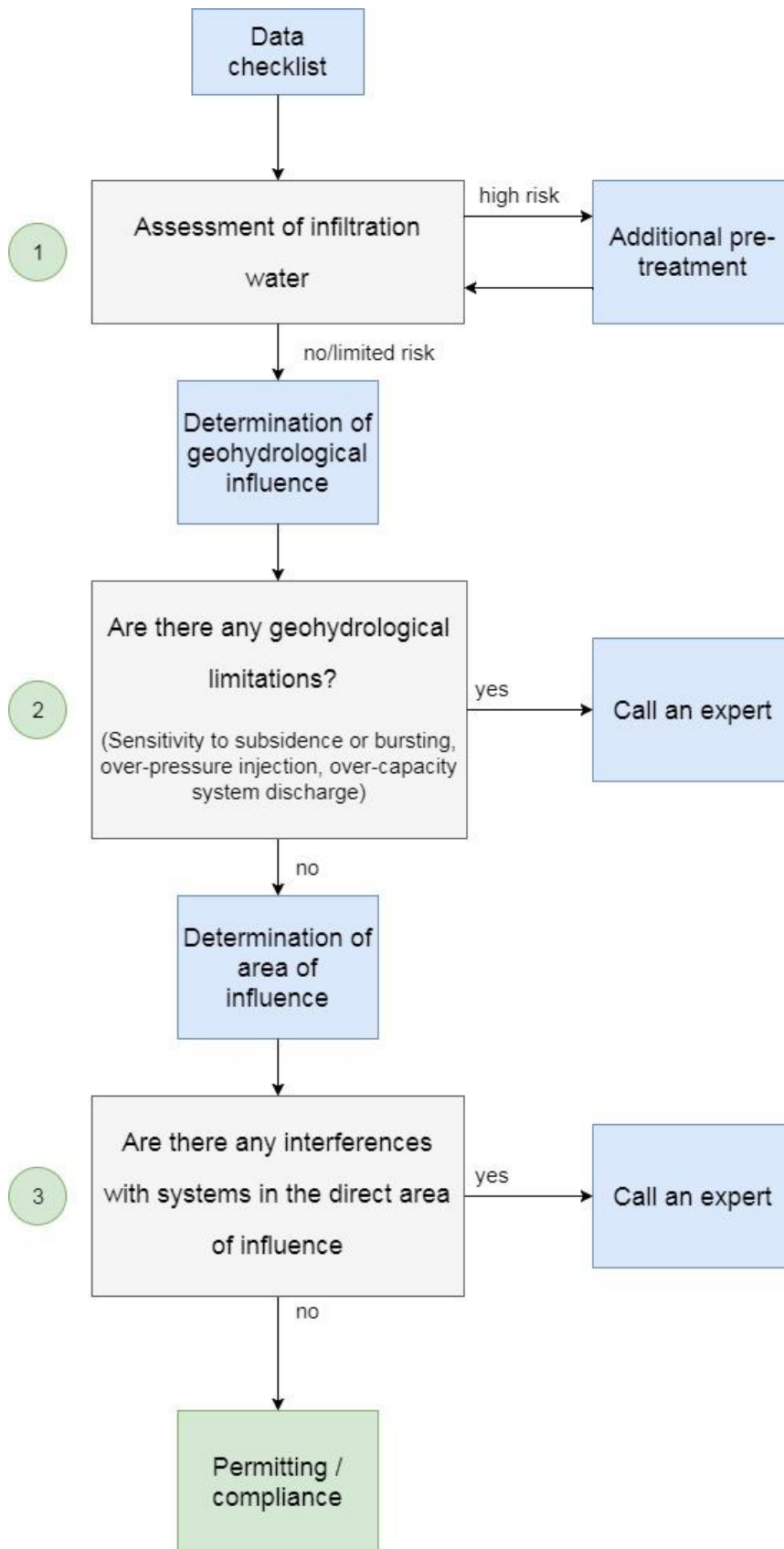


Figure 7-2 General risk assessment scheme, the circled numbers redirect to the elaborated schemes on the following pages and to the points given on the previous page.

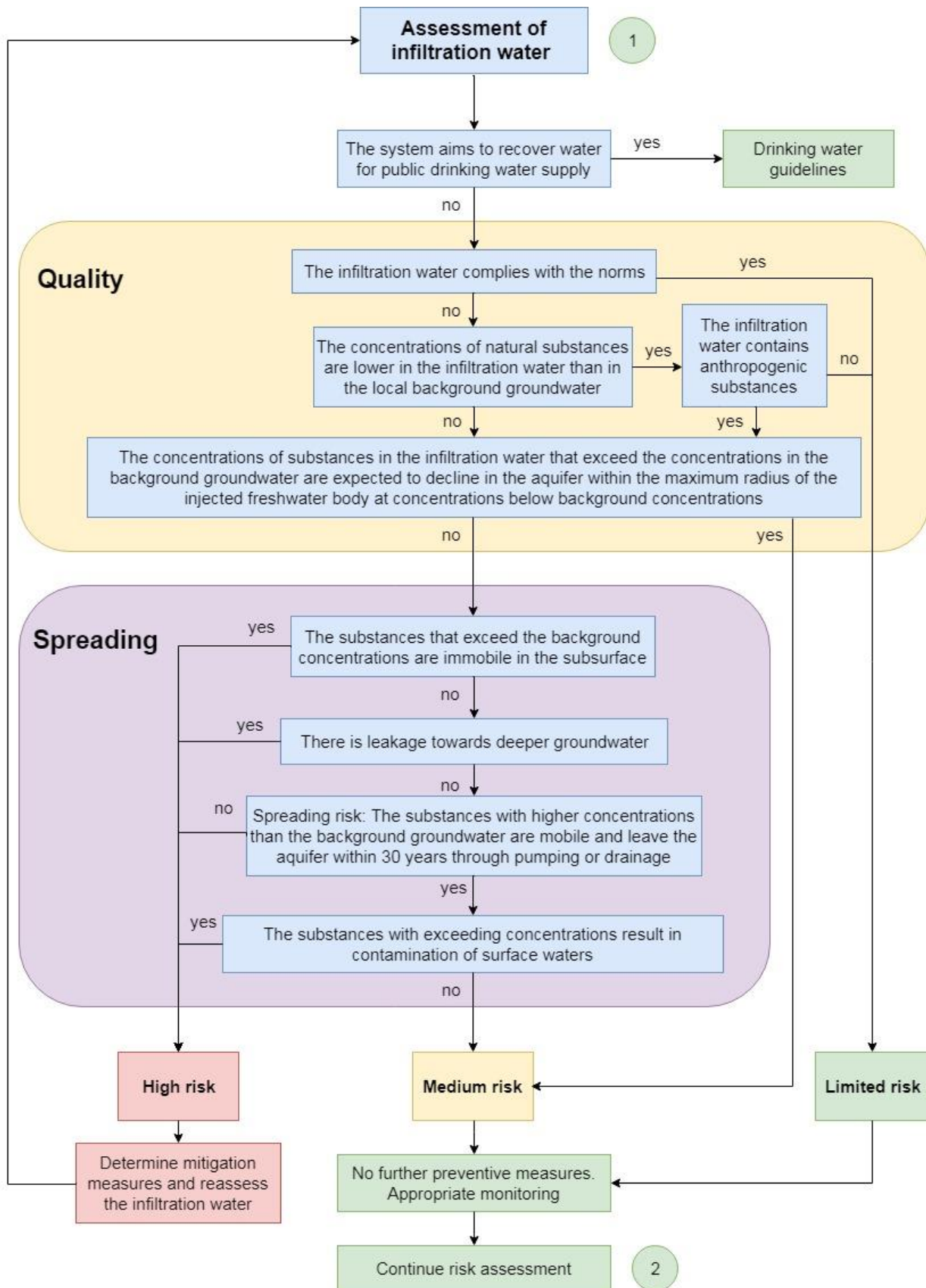


Figure 7-3 Risk assessment scheme regarding the quality and possible spreading of anthropogenic substances from the infiltration water to the subsurface.

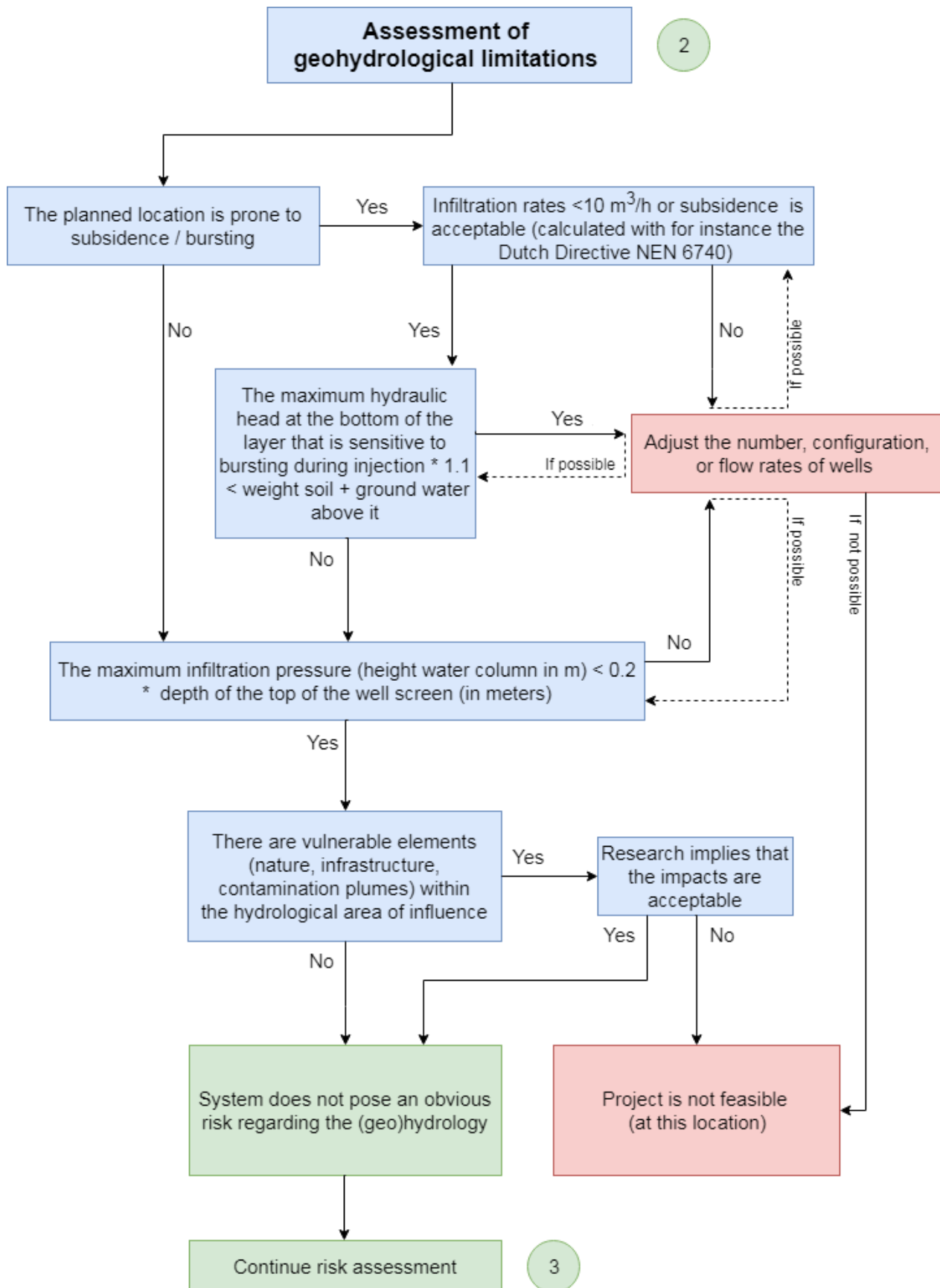


Figure 7-4 Geohydrology risk assessment scheme

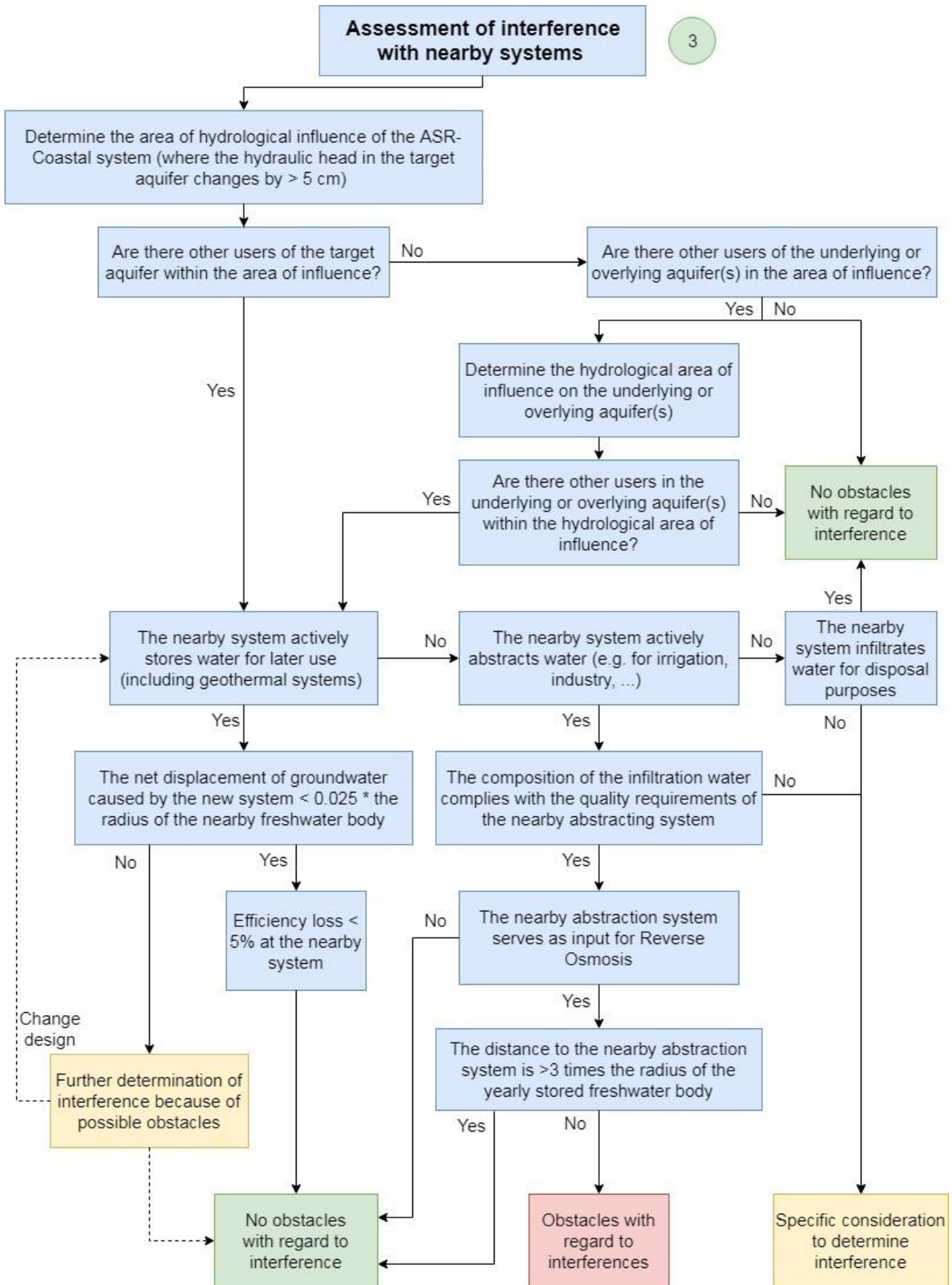


Figure 7-5 Hydrological Interferences risk assessment scheme

8 Economic analysis

The final step of the design phase, following the risk assessment, is the economic feasibility study of the ASR-Coastal 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).

Worksheet ‘4a. CAPEX’ of the ASR-Coastal 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 ASR-Coastal. 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 ASR-Coastal would involve. The resulting CAPEX is expressed in euro, euro/year and euro/m³.

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 ASR-Coastal system.

Worksheet ‘4b. OPEX’ of the ASR-Coastal 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 ASR-Coastal would involve. The resulting OPEX is expressed in euro, euro/year and euro /m³.

Summing the CAPEX (euros/m³) and OPEX (euros/m³) results in an overview of the total costs of realising ASR-Coastal at a specific site, and of recovering a cubic meter of freshwater by ASR-Coastal. 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 an ASR-Coastal system. A scheme of the economic feasibility study is provided in Figure 8-1.

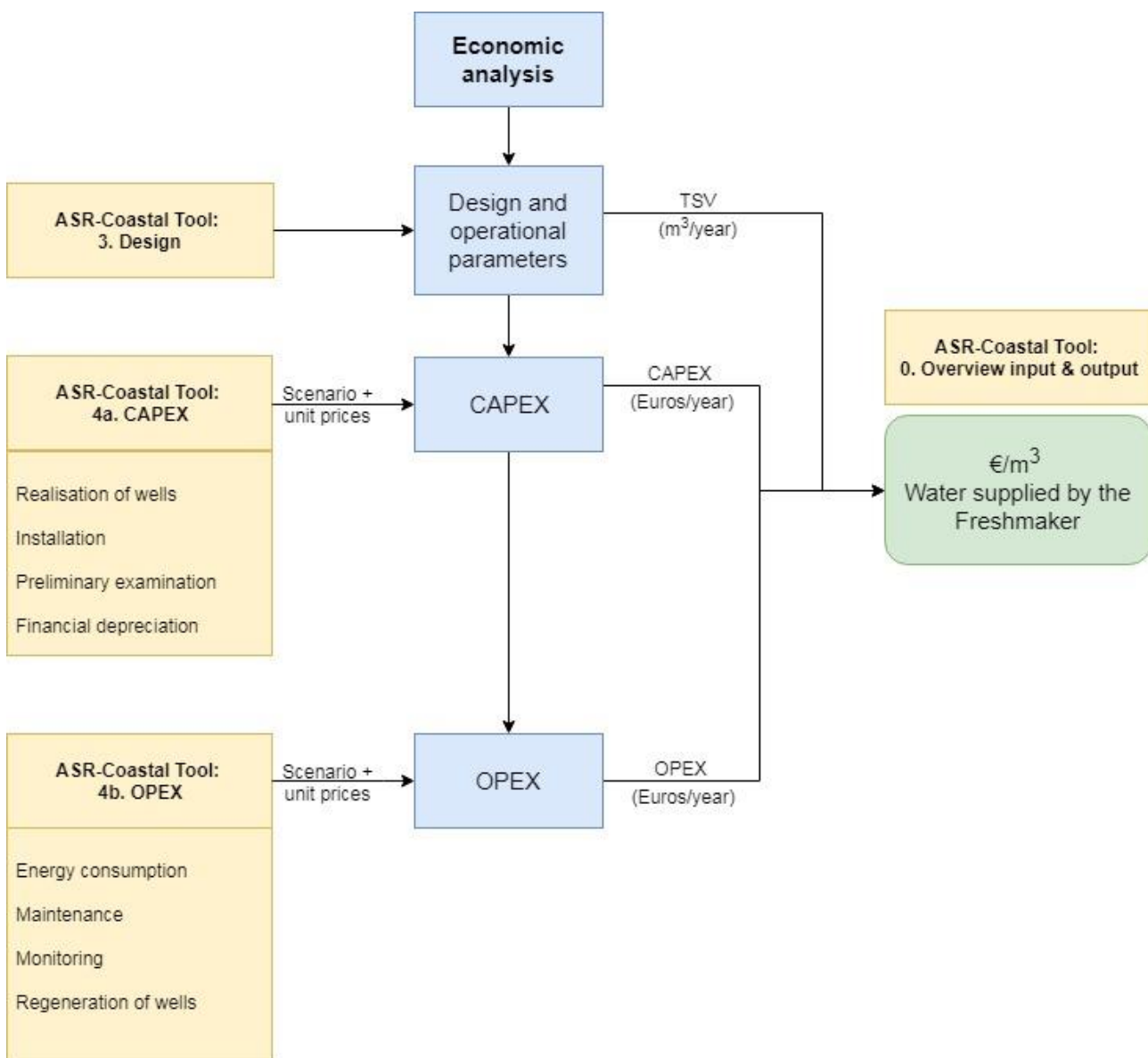


Figure 8-1. Scheme of the economic analysis to be performed after the risk assessment for a complete feasibility study. This scheme includes the information of the Excel Tool that is needed to calculate the costs per cubic meter of water produced by an ASR-Coastal system.

9 Permitting / compliance

Requesting the permit

If all previous steps were favourable for the realisation of ASR-Coastal, the next step would be 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 (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.

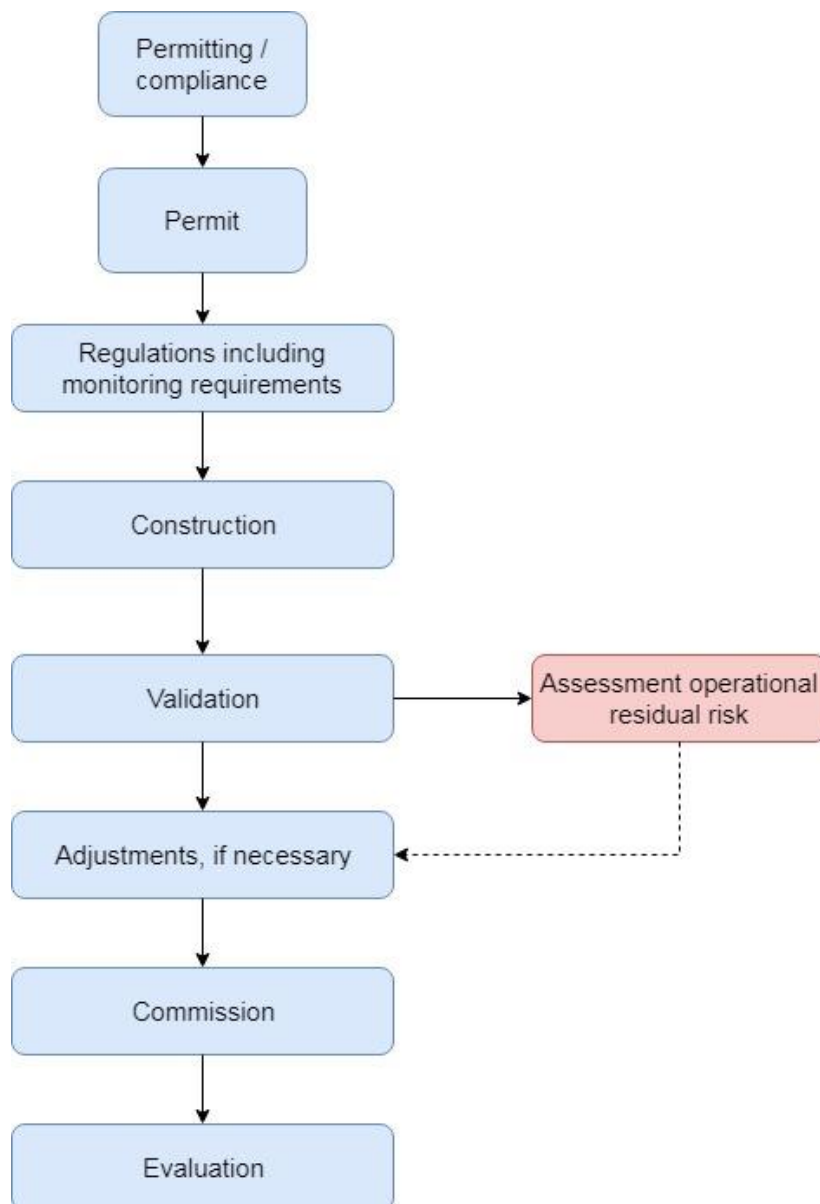


Figure 9-1. Permitting/compliance scheme.

10 General reflections on ASR-Coastal: when can it be a solution?

In this guide, detailed flow schemes provide a guide to potential users of ASR-Coastal. Based on the flow schemes and the experiences from the field pilots, the general take-home messages are summed up below:

- The benefits of ASR-Coastal consist of an enhanced freshwater recovery. This enhancement is not a fixed amount, because it strongly depends on site-specific conditions. Most benefits from ASR-Coastal are expected in areas that have a medium to poor suitability for conventional ASR. Sites that are demonstrably unviable for conventional ASR will often remain unviable, even with ASR-Coastal;
 - *The enhanced freshwater recovery has been demonstrated in unconsolidated sand aquifers in The Netherlands and therefore is most reliable for similar conditions elsewhere, such as delta's, alluvial fans, beach and creek ridges.*
- Since part of the water always moves out of zones where it can be recovered and mixing with ambient groundwater is inevitable, an average recovery of 100% of the freshwater is impossible. Generally, some over-infiltration is required to recover sufficient water. Alternatively, desalinization can be applied to raise the (net) recovery of freshwater.
- ASR-Coastal is no more than a balancing tool, like normal ASR systems: it connects moments of (any) freshwater surplus with later moments of demand. So, availability of a freshwater surplus is vital. ASR is not a water producing technology, but a clever, large-volume subsurface storage technology.
- The set-up of ASR-Coastal, using the MPPW instead of a single vertical well, introduces flexibility to deal with (uncertain) aquifer conditions. But, the possibility to operate the well as a single vertical well (if appropriate) is maintained.

Like with conventional ASR, water quality aspects, hydrogeological effects, and potential interference with nearby elements should be carefully evaluated beforehand. The ASR-coastal tool with its flow charts can be used as a guide for this evaluation. The presented pilots show that meeting all water quality requirements can be a challenge.

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Appendix 1: feasibility assessment scheme

